 DOI: 10.35382/TVUJS.14.8.2024.98

ANALYZING THE PROBLEM OF REACTIVE POWER USING MIKRO PFR120 RELAY

Nguyen Thanh Hien[1*], Trieu Quoc Huy[2], Bui Thi Thu Thuy[3]

Abstract – *Managing and operating low-voltage distribution grids or high-voltage grids, requiring electricity supply to ensure voltage quality, improving power factors, and prioritizing generating active power on the grid to supply energy to electrical loads is very important, serving in daily life and industrial production. Therefore, reactive power compensation is an effective solution with significant economic benefits. The commonly applied reactive power compensation techniques in low-voltage power networks are fixed-type and automatic-type reactive power compensation. This paper focuses on the calculation and experiment of static reactive power compensation and automatic reactive power compensation on a 12-level capacitor model using a Mikro PFR120 relay with an MFM384 multimeter. The study compared theoretical results with experimental measurements to validate the theoretical calculations. These measurements were taken from an MFM384 multimeter and a Mikro PFR120 relay, recording parameters related to static and automatic reactive power compensation on our model. This comparison demonstrates the accuracy of theoretical calculations. The recorded results achieved an accurate value of 98% to 100%.*

Keywords: automatic compensation experiment, compare calculations with experiments, fixed compensation experiment, Mikro PFR120 control relay.

I. INTRODUCTION

With Vietnam's economic development, electricity as a kind of clean energy has become indispensable in people's daily lives and work [1]. An increase of reactive power in all areas of industry and the national economy is observed. Using electrical equipment with a low power factor increases reactive power, leading to several negative consequences for power quality and grid losses. Therefore, the issue of reactive power compensation to reduce power loss in the grid and increase the reliability of power supply for industrial enterprises needs attention [2]. To solve the power quality problems mainly resulting from electrical loads with low power factor [3], static reactive power compensation and automatic reactive power compensation are primarily applied in power grids. Therefore, understanding the importance of using and developing research in the field of reactive power compensation, major universities around the world have built advanced laboratories to help lecturers and students participate in research and study on reactive power compensation control models to study two types of static and automatic compensation problems [4]. This study focuses on theoretical calculations and experiments of two issues: static reactive power compensation and automatic reactive power compensation on a capacitor bank model using a Mikro PFR120 relay. Based on theoretical calculations, the accuracy of theoretical calculations compared to experiments is determined so that lecturers can study problems related to reactive power compensation in the management and operation of real power grids.

II. LITERATURE REVIEW

In recent years, there have been many research projects on power compensation in the power grid [1–8], the problem of reactive power compensation aims to improve the energy efficiency of electrical equipment, reduce power and voltage

[1,2,3]Tra Vinh University, Vietnam

*Corresponding author: nthien@tvu.edu.vn

Received date: 27th June 2024; Revised date: 14th November 2024; Accepted date: 13th January 2025

losses in the power grid, and increase the voltage at the end of the power supply line. To ensure power quality, stabilize voltage, and reduce grid losses due to low load power factors, according to electricity industry regulations, the load power factor must meet the requirement of 0.9 to 1. From the benefits of reactive power compensation, studies related to capacitor compensation are essential for practical applications such as designing and manufacturing capacitor compensation devices, control cabinets, and manufacturing control relays. Currently, the techniques for calculating reactive power compensation in the power grid have two forms: fixed reactive power compensation and automatic reactive power compensation using control relays through the load's current, voltage, and power factor signals. Many researchers have done reactive power composition or related to load characteristics to solve the problem with voltage stability [5–8]. Ayalew et al. [5] managed dynamic reactive power reserves based on optimal power flow and Bender's decomposition technique to improve voltage stability. Goel et al. [6] used a static synchronous compensator (STATCOM) to enhance voltage stability, which is applied in high voltage compensation problems. According to the study of Aye et al. [7], the use of parallel capacitor banks to compensate reactive power for industrial loads to increase the power factor from 0.95 to 0.98 has brought benefits such as reducing losses in the power supply circuit, improving the voltage at the source end, maintaining the nominal voltage and reducing electricity consumption costs. Roos et al. [8] highlighted the need to address harmonic filtering in reactive power compensation studies. Harmonics can distort voltage, and installing filters during switching operations is presented as the most practical solution. From practical requirements, most power-consuming devices impact power factors, which also cause power loss, significantly affecting power quality and annual operating costs. Reactive power compensation significantly improves power system performance. It increases voltage levels, reduces power losses, and enhances operational efficiency. This paper analyzes reactive power compensation on a capacitor compensation model. The analysis utilizes a Mikro PFR120 control relay and an MFM384 multimeter. Experimental results are presented and compared with theoretical values. The specific research objectives are to calculate the types of resistive and reactive load parameters, resistive load combined with reactive load, calculate capacitor capacity, calculate typical fixed and automatic compensation problems to perform experiments, and make comments between the theoretical basis and experimental results. The experimental results are accurate with theoretical calculations.

III. RESEARCH METHODS

In the experiments, the reactive power compensation problem is performed on a 12-level reactive power compensation capacitor model, as shown in Figure 1. The wiring diagram of the Mikro PFR120 relay controller is shown in Figure 2.

Fig. 1: Reactive power compensation model uses Mikro PFR120 relay

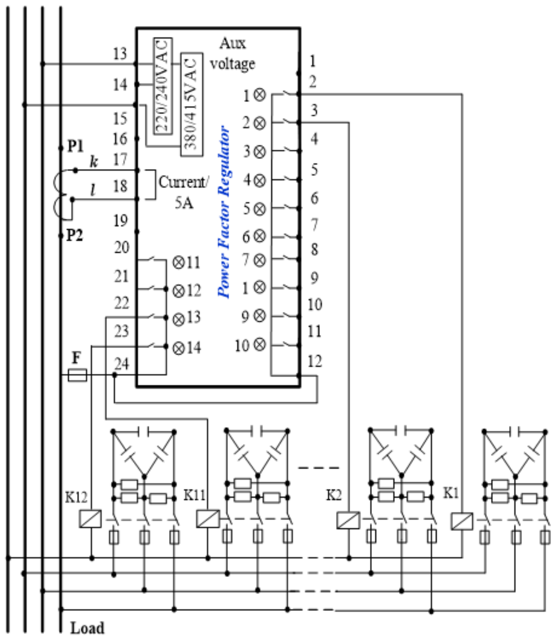

Fig. 2: Wiring connection diagram of Mikro PFR120 Relay

A. Experimental samples and experimental procedures

The first experimental sample in this research is to determine theoretical calculation results compared to the experimental results measured at MFM384 meters and the Mikro PFR120 relay. The system operates with a 3-phase voltage of 400 V and a frequency of 50 Hz during fixed compensation.

The second experimental sample determines the results between theoretical calculations compared to experimental results measured on the MFM384 copper graph and the Mikro PFR120 relay. The system operates with a 3-phase voltage of 400 V and a frequency of 50 Hz during automatic reactive power compensation.

Step 1: Calculate the theory based on the parameters of resistive load, reactive load, and compensation capacitor on the Mikro PFR120 relay compensation capacitor model.

Step 2: Calculate the theory of fixed compensation (static compensation) and automatic compensation and create a data table based on the electricity load graph.

Step 3: Select compensation capacitors according to the calculation requirements of the fixed compensation problem (static compensation) and the automatic compensation problem according to the resistive load and reactive load models.

Step 4: Wire the load model and compensation capacitors for the fixed compensation problem (static compensation). Wire the resistive load model, reactive load, and compensation capacitors into the calculated Mikro PFR120 Relay switches for the automatic compensation problem.

Step 5: Experiment and record the results displayed on the MFM384 meter and the Mikro PFR120 Relay.

Step 6: Make a table to record the results, compare, comment, and draw a graph.

B. The first experimental sample implementing the fixed reactive power compensation problem

A star-connected, three-phase resistive load ($R_3 = R_6 = R_9 = 180\ \Omega$) was tested at 400 V.

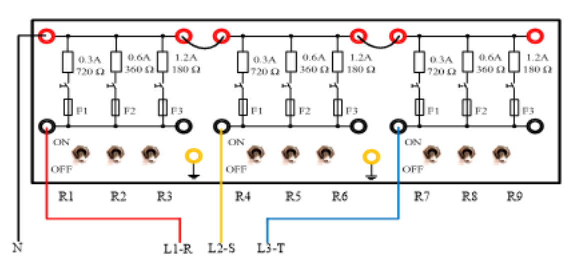

Fig. 3: Resistive load model

Three-phase active power is calculated using Equation (1).

$$P = \frac{U_d^2}{R}\ (W) \quad (1)$$

Three-phase apparent power is calculated using Equation (2).

$$S = P\,(VA);\ Q = 0\ \text{Var};\ \cos\varphi = 1 \quad (2)$$

Table 1: Resistive load parameters

U_d (V)	f (Hz)	R_3=R_6=R_9 (Ω)	P (W)	S (VA)	cosφ
400	50	180	889	889	1

A three-phase star-connected reactive load experiment was conducted using inductors with a self-inductance coefficient of 1.15 H (L_2 = L_5 = L_8), a frequency of 50 Hz, and a voltage of 400 V.

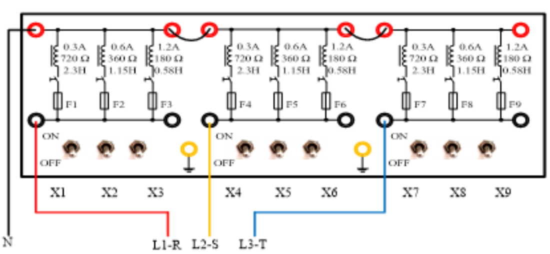

Fig. 4: Reactive load model

Reactive load is calculated using Equation (3).

$$X_L = L.\omega = L.2.\pi.f\,(\Omega) \quad (3)$$

Three-phase reactive power is calculated using Equation (4).

$$Q = \frac{U_d^2}{X_L}\ \text{(VAr)} \quad (4)$$

Three-phase apparent power is calculated using Equation (5).

$$S = Q(VA);\ \ \text{P} = 0\ \text{W};\ \sin\varphi = 1 \quad (5)$$

Table 2: Reactive load parameters

U_d (V)	f (Hz)	L_2=L_5=L_8 (H)	X_2=X_5=R_8 (Ω)	Q (VAr)	S (VA)
400	50	1.15	361	443	443

A three-phase star-connected capacitor bank with a capacitance of 4 μF (C_{3phase}) was tested at 50 Hz and 400 V. The reactive power of a single-phase capacitor is calculated using Equation (6).

$$\begin{aligned} Q_{C\text{-1phase}} &= U_{\text{phase}}^2 .2.\pi.f_n.C_{\text{1phase}} \\ &= \left(\frac{400}{\sqrt{3}}\right)^2 .2.\pi.50.12.10^{-6} = 201(VAr) \end{aligned} \quad (6)$$

The reactive power of a three-phase capacitor is calculated using Equation (7).

$$\begin{aligned} Q_{C\text{-3phase}} &= 3.Q_{C\text{-1phase}} \\ &= 3.201 = 603 \quad \text{(VAr)} \end{aligned} \quad (7)$$

The reactive power of the three-phase capacitor is calculated using Equation (8).

$$Q_{C\text{-3phase}} = 3U_{\text{phase}}^2.2\pi.\text{f}.\text{C}_{\text{1phase}} = 603(\text{VAr}) \quad (8)$$

Table 3: Calculate the reactive power of the capacitor

U_d (V)	f (Hz)	C_{1phase} (μF)	C_{3phase} (μF)	$Q_{C\text{-}1phase}$ (VAr)	Q_{C_3phase} (VAr)
400	50	12	4	201	603

A three-phase star-connected resistive load (R_3 = R_6 = R_9 = 180 Ω) was tested. A separate three-phase star-connected reactive load experiment was conducted using inductors with a self-inductance coefficient of 1.15 H (L_2 = L_5 = L_8), operating at 50 Hz, and having a reactive load of 361 Ω (X_2 = X_5 = X_8). A three-phase reactive capacitor bank with a capacitance of 4 mF (C_{3phase}), as detailed in Table 4, was also utilized.

Table 4: Parameters of resistive load, reactive load, and capacitor capacity

U_d (V)	f (Hz)	C_{1phase} (μF)	C_{3phase} (μF)	$R_3 = R_6 = R_9$ (Ω)	$X_2 = X_5 = X_8$ (Ω)
400	50	12	4	180	361

Figure 5 shows the experimental wiring diagram for a fixed capacitor with a capacitance of 4 μF (C_{3phase}).

Active power is calculated using Equation (9).

$$P = \frac{U_d^2}{R}\,\text{(W)} \quad (9)$$

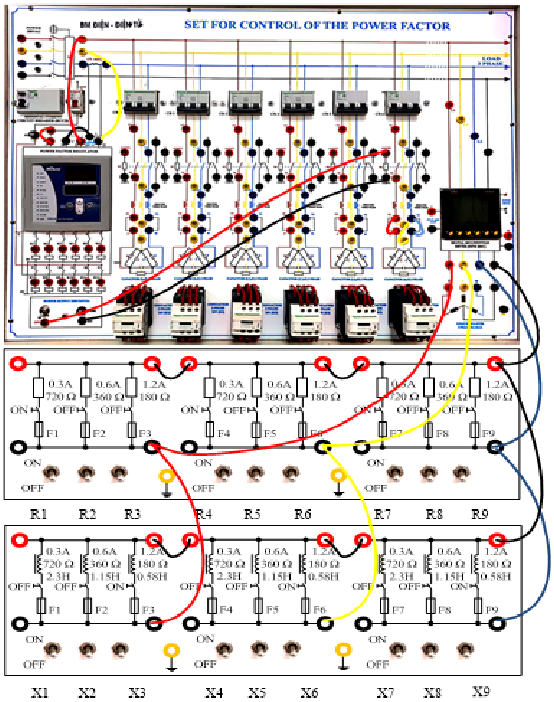

Fig. 5: Experimental wiring diagram of fixed condenser with capacitor C_{3phase} = 4 μF.

Reactive power is calculated using Equation (10).

$$Q = \frac{U_d^2}{X_L} \text{(VAr)} \quad (10)$$

Apparent power is calculated using Equation (11).

$$S = \sqrt{P^2 + Q^2} \ (VA) \quad (11)$$

The power factor ($cos\varphi$) is calculated using Equation (12).

$$\cos\varphi = \frac{P}{S} \quad (12)$$

The load current is calculated using Equation (13).

$$I = \frac{S}{\sqrt{3}.U_d} (A) \quad (13)$$

Table 5: Calculation parameters for three-phase resistive loads $R_3 = R_6 = R_9 = 180\ \Omega$; reactive load $X_2 = X_5 = X_8 = 361\ \Omega$ without reactive power compensation

U_d	f Hz	P (W)	Q (VAr)	S (VA)	I(A)	cosφ
400	50	889	443	933.3	1.35	0.95

Three-phase capacitor reactive power (and corresponding capacitance) is calculated using Equations (14) and (15).

$$Q_C = 3.U_{phase}^2.2.\pi.f_n.C_{1phase}\,(VAr) \quad (14)$$

$$\text{or: } Q_C = 3.\left(\frac{U_d}{\sqrt{3}}\right)^2.2.\pi.f_n.C_{1phase}\,(VAr) \quad (15)$$

The reactive power after capacitor installation is calculated using Equation (16).

$$Q_{bu} = Q - Q_C\,(VAr) \quad (16)$$

The three-phase apparent power after installing the capacitor is calculated using Equation (17).

$$S_{bu} = \sqrt{P^2 + Q_{bu}^2}\,(VA) \quad (17)$$

After installing the capacitor, the load current is calculated using Equation (18).

$$I_{bu} = \frac{S_{bu}}{\sqrt{3}.U_d}(A) \quad (18)$$

After installing the capacitor, the power factor (cos) is calculated using Equation (19).

$$\cos\varphi_{bu} = \frac{P}{S_{bu}} \quad (19)$$

The reactive power compensation capacitor (and its corresponding capacitance) is calculated using Equation (20).

$$Qc\_tt = P.(tg\varphi - tg\varphi c)\ (kVAr) \quad (20)$$

When selecting capacitors, consider the following conditions, choosing values based on available manufacturer specifications.

$$U_C \geq U_{Source};\ Q_C \geq Q_{C-tt} \quad (21)$$

Based on the first experimental sample calculations, the wiring was connected, and the experimental results were recorded.

C. The second test sample performing the problem of automatic reactive power compensation

A laboratory load model, consisting of resistive and reactive components, enables users to adjust the load via a switching system (NO/NC). The electrical load configuration depicted in Figure 6 is used to calculate and experiment with automatic reactive power compensation. The objective is to raise the power factor ($cos\varphi$) to 0.95 by industry regulations. The system operates at a supply voltage of 400 V and a frequency of 50 Hz.

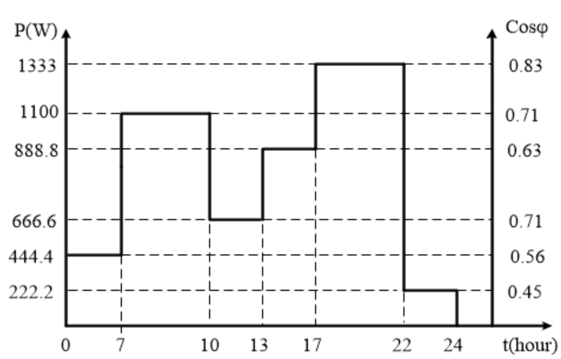

Fig. 6: Electric load chart

Reactive power and load current were calculated using Equations (22) and (23) based on the load diagram shown in Figure 6.

$$Q = P.tag\varphi\ (VAr) \quad (22)$$

$$I = \frac{\sqrt{P^2 + Q^2}}{\sqrt{3}.U_d} (A) \quad (23)$$

Resistor parameters on laboratory load model:

$R_1 = R_4 = R_7 = 720\ \Omega; R_2 = R_5 = R_8 = 360\ \Omega; R_3 = R_6 = R_9 = 180\ \Omega;$

Reactance parameters on laboratory load model:

$L_1 = L_4 = L_7 = 2.3H; X_1 = X_4 = X_7 = 722\ \Omega;$
$L_2 = L_5 = L_8 = 1.15H; X_2 = X_5 = X_8 = 360\ \Omega;$
$L_3 = L_6 = L_9 = 0.58H; X_3 = X_6 = X_9 = 182\ \Omega;$

Table 6: Calculation of electrical load parameters from the load chart in Figure 6

t (hour)	R (Ω)	P (W)	X (Ω)	Q (VAr)	cosφ	I(A)
0÷7	360	444.4	240.2	666.1	0.56	1.16
7÷10	144	1111.1	145.4	1100	0.71	2.26
10÷13	240	666.6	240.2	666.1	0.71	1.36
13÷17	180	888.8	145.4	1100	0.63	2.04
17÷22	120	1333.3	182	879.1	0.83	2.3
22÷24	720	222.2	360	444.4	0.45	0.72

The reactive power of the capacitor is calculated using Equation (24).

$$Q_{C-tt} = P.(tag\varphi - tag\varphi_C) \quad (24)$$

Table 7: Calculating automatic capacitor reactive power over time

t (hour)	P (W)	Q (VAr)	cosφ	cosφc	Qc-tt (VAr)
0÷7	444.4	666.1	0.56	0.95	511.4
7÷10	1111.1	1100	0.71	0.95	736.8
10÷13	666.6	666.6	0.71	0.95	422.1
13÷17	888.8	1100	0.63	0.95	803.5
17÷22	1333.3	879.1	0.83	0.95	457.7
22÷24	222.2	444.4	0.45	0.95	367.9

The three-phase capacitor reactive power on the laboratory load model is calculated using Equation (25).

$$Q_C = 3.U_{phase}^2.2\pi.f.C_{1phase} \quad (25)$$

Based on the calculation results presented in Table 7, the following three-phase capacitor reactive capacities were selected for the Mikro PFR120 Relay's control switch 'K':

Capacitor parameters on laboratory load model.

$C_{1-phase} = C_{2-phase} = 6\ \mu F;$

$C_{1-3phase} = C_{2-3phase} = 2\ \mu F.$

The formula for calculating the reactive capacitance (capacity) is given by Equation (26).

$$Q_{C1\_3phase} = Q_{C2\_3phase} = 3.U_f^2.2\pi.f.C_{1phase} = 3\left(\frac{400}{\sqrt{3}}\right)^2.2\pi.50.6.10^{-6} = 301 \quad (VAr) \tag{26}$$

The calculation results of other capacitor values are as follows:

$C_{3\text{-phase}} = C_{4\text{-phase}} = 7.5\ \mu F;$
$C_{3\text{-3phase}} = C_{4\text{-3phase}} = 2.5\ \mu F.$
$Q_{C3\_3\ phase} = Q_{C4\_3\ phase} = 377\ VAr.$
$C_{5\text{-phase}} = 9\ \mu F;\ C_{5\text{-3 phase}} = 3\ \mu F;$
$Q_{C5\_3phase} = 452\ VAr.$
$C_{6\text{-phase}} = 12\ \mu F;\ C_{6\text{-3phase}} = 4\ \mu F;$
$Q_{C6\_3phase} = 603\ VAr.$

Table 8: Summary of calculation of reactive power of three-phase capacitors

U_d (V)	400	C_{1phase} (μF)	C_{3phase} (μF)
f (Hz)	50		
Q_{C1_3phase} (VAr)	301	6	2
Q_{C2_3phase} (VAr)	301	6	2
Q_{C3_3phase} (VAr)	377	7.5	2.5
Q_{C4_3phase} (VAr)	377	7.5	2.5
Q_{C5_3phase} (VAr)	452	9	3
Q_{C6_3phase} (VAr)	603	12	4

Based on the capacitor capacity calculation parameters in Table 8, the capacitor values for the PFR120 control relay's control keys were chosen as follows:

Control switch K1: $QC1 = 301\ VAr$
Control switch K2: $QC5 = 452\ VAr$
Control switch K3: $QC6 = 603\ VAr$

A capacitor capacity control table, corresponding to the 'K' switches on the Mikro PFR120 relay, was created and is shown in Table 9.

Table 9: Capacitor capacity at the 'K' switches of the Mikro PFR120 relay

t (hour)	0÷7	7÷10	10÷13	13÷17	17÷22	22÷24
$Q_{C\text{-tt}}$(VAr)	511.4	736.8	422.1	803.5	457.7	367.8
Control switch	K3	K1; K2	K2	K3; K1	K2	K2
Q_C(VAr)	603	301; 452	452	603; 301	452	452

The Mikro PFR120 relay controller operates by sequentially switching in capacitors, starting with the smallest and progressing to the largest. Within a closed loop, the capacitor changed is the first to be switched out.

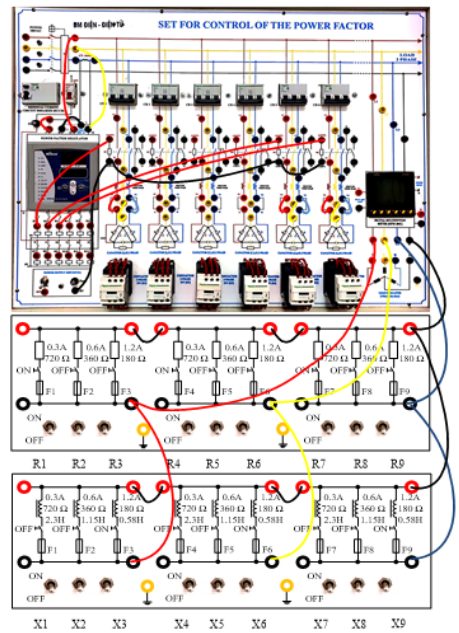

Fig. 7: Connector on Relay Model Mikro PFR120

The current power factor during reactive power compensation and the power factor after automatic compensation were calculated using Equations (27) and (28), respectively.

$$I_{bu-tt} = \frac{\sqrt{P^2 + (Q - Q_c)^2}}{\sqrt{3}.U_d} (A) \tag{27}$$

$$\cos\varphi_{bu-tt} = \frac{P}{\sqrt{P^2 + (Q - Q_c)^2}} \tag{28}$$

The wiring was connected based on the second test sample calculations, and the experimental results were recorded.

IV. RESULTS AND DISCUSSION

Using the first experimental sample, the fixed reactive power compensation was investigated. This involved calculating a capacitor bank's resistive, reactive, and required capacitive reactance (and corresponding capacitance) with capacitance value C_{3phase} = 4 μF. The study conducted wiring and tested the problem of reactive power compensation, with the results shown in Tables 10, 11, and 12.

Table 10: Calculation of parameters for three-phase resistive loads; $R_3 = R_6 = R_9 = 180\ \Omega$ reactive load $X_2 = X_5 = X_8 = 361\ \Omega$, when three-phase capacity C_{3phase} = 4 μF

P (W)	Q (VAr)	Qc (VAr)	Q_{bu}=Q-Qc (VAr)	S_{bu} (VA)	I_{bu}(A)	$\cos\varphi_{bu}$
889	443	603	-160	903	1.3	-0.98

Table 11: Measurement of parameters in MFM384 meters

I_{bu}(A)	I_{bu}(A) MFM 384	Exact value %	$\cos\varphi_{bu}$	$\cos\varphi_{bu}$ MFM384	Exact value %
1.3	1.3	100	-0.98	-0.98	100

Table 12: Measurement of parameters in Mikro PFR120

I_{bu}(A)	I_{bu}(A) PFR120	Exact value %	$\cos\varphi_{bu}$	$\cos\varphi_{bu}$ PFR120	Exact value %	Lamp PFR120
1.3	1.29	99	-0.98	-0.98	100	'CAP'

The results in Table 5 demonstrate that the calculated and measured resistance and reactive loads achieve a power factor of 0.95, meeting industry standards. Therefore, reactive power compensation is unnecessary. However, if the experiment installs a capacitor with 3-phase capacitance C_{3phase} = 4 μF, the theoretical calculation results and experimental results are presented in Tables 10, 11, and 12. The power factor measured at the MFM384 meter displays '-' or display lamp on the screen of the Mikro PFR120 relay 'CAP' is due to the capacitor capacity (capacitance) being more significant than the calculated value when compensating, leading to overcompensation. When implementing the problem of reactive power compensation on the power grid, it is necessary to calculate reactive power compensation to increase the power factor according to electricity industry regulations (reaching 0.95 or more and not exceeding 1). Therefore, the capacity of the capacitor must be selected following the reactive power of the load to be compensated to avoid excess compensation. The power triangle during the experiment is shown in Figure 8. When measuring at the MFM384 meter and the Mikro PFR120 relay, calculations, and experimental results were recorded to be 99% to 100% accurate compared to the theoretical calculation results.

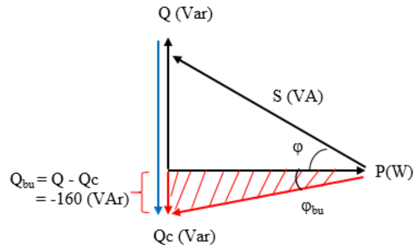

Fig. 8: Power triangle when compensating excess reactive power

The automatic compensation problem was calculated and performed from the second experimental sample using the load-switching method via the control switch system (NO/NC). The results are shown in Table 13 and Figure 9.

Table 13: Automatic compensation calculation of parameters and experiments when measuring in MFM384 meters and Mikro PFR120 relay

t (hour)	0÷7	7÷10	10÷13	13÷17	17÷22	22÷24
I(A)	1.16	2.26	1.36	2.04	2.3	0.72
I_{bu-tt}(A)	0.65	1.7	1.0	1.31	2.0	0.32
I_{bu}(A) MFM384	0.64	1.73	1.0	1.32	2.0	0.32
I_{bu}(A) PFR120	0.64	1.73	1.0	1.32	2.0	0.32
Exact value %	99	98	100	99	100	100
$\cos\varphi_{bu-tt}$	0.99	0.95	0.95	0.98	1.0	1.0
$\cos\varphi_{bu}$ MFM384	0.99	0.96	0.96	0.97	0.98	1.0
$\cos\varphi_{bu}$ PFR120	0.99	0.96	0.96	0.97	0.98	1.0
Exact value %	100	99	98	99	98	100

Diagrams of current and power factors were created without and with reactive power compensation.

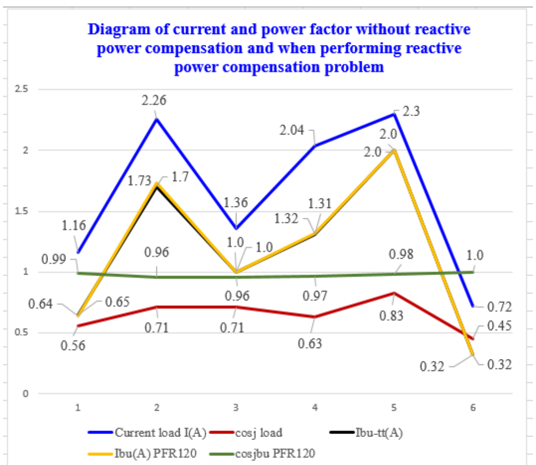

Fig. 9: Current and power factor diagram without compensation and compensation

Table 13 and Figure 9 show the results of reactive power compensation calculations. These results guided the selection of capacitors for the Mikro PPR120 controller's switches. Experiments confirmed that the compensated current was lower than the initial uncompensated load current, demonstrating reduced reactive power. Results recorded at the MFM384 meter and Mikro PFR120 control relay show that the power factor reaches 0.95 or more. Record the current value after compensation with theoretical calculations accurate from 98% to 100%; the calculated power factor after compensation compared to the experiment is from 98% to 100%.

V. CONCLUSION

This article has analyzed problems related to fixed and automatic compensation based on theoretical calculations and performed experiments to record the relevant values displayed on the MFM384 multi-function meter and Mikro PFR120 control relay. The highlight of this research method is a theoretical calculation, followed by an experimental comparison of the results between the MFM384 measurement chart and the PFR120 capacitor control relay on the 12-level Mikro capacitor model. The research results show that the theoretical calculation compared with the experiment is accurate from 98% to 100%, which is also the knowledge to research reactive power compensation in the management and operation of the actual power grid. The proposed future research direction is to use the 12-level capacitor and low-voltage line models to calculate reactive power compensation on the power grid, considering the voltage distortion caused by harmonics.

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