

Statistical Analysis of Protection Current Transformer Performance Based on Error Ratio and Knee Voltage on 20 kV Feeder at Bangka Transmission and Substation Service Unit

Maisa Sapitri¹, Asmar², Welly Yandi³, Rudy Kurniawan⁴
^{1,2,3,4}Electrical Engineering Department, Bangka Belitung University, Indonesia

ARTICLE INFO

Article historys:

Received : 23/03/2025
Revised : 28/03/2025
Accepted : 24/04/2025

Keywords:

Current Transformer; Knee Voltage;
Ratio Error; Statistical Analysis;
Protection System

ABSTRACT

Current Transformers (CTs) are essential components in power system protection, ensuring accurate current measurement for relay operations.. This study evaluates the accuracy of protection CTs used in 20kV feeders at the Bangka Transmission and Substation Service Unit. Measurements were conducted on CTs with 5 and 7 years of usage to analyze ratio error and knee voltage compliance with IEC 61869-2 standards. The results indicate that all CTs meet the standard, with ratio errors below 1% and knee voltages exceeding 60V. Normality tests confirmed that the data are normally distributed, allowing statistical analysis using t-tests. The t-test results showed no significant difference in ratio error and knee voltage between CTs used for 5 and 7 years. This study concludes that aging over this period does not significantly affect CT accuracy, ensuring continued reliability in power system protection.



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Corresponding Author:

Asmar
Electrical Engineering Department, Bangka Belitung University, Indonesia
Email: asmarubb2@gmail.com

1. INTRODUCTION

Current Transformers (CT) are one of the important components in power systems, especially in protection and measurement applications. CTs function to reduce high currents from the electrical network into lower, safe currents that can be measured or used by protection devices.

Current Transformers operate based on the principle of electromagnetic induction, where a large primary current generates a magnetic field that is induced in the secondary winding. The resulting secondary current is then used for measurement or as an input for protection relays in the power system. One of the most critical parameters in CTs is the current ratio, which is the comparison between the primary current flowing through the CT and the secondary current produced. This parameter is essential in determining the performance of the transformation and the accuracy of the measurement. It ensures that the high current on the primary side is proportionally converted into a smaller, safe current for measurement and protection devices, so that the power system can accurately detect and respond to faults [1, 2, 3].

CTs used in protection must be capable of operating effectively under both normal conditions and during faults in the power system. Several factors must be considered in implementing protection CTs, including accuracy, knee point, safety factor, and burden. CTs must provide accurate current values even during current surges under fault conditions. The more accurate a CT is, the smaller its measurement error will be [4]. There are several common types of errors, namely ratio error, phase error, and composite error. Ratio error measures the difference between the actual secondary current

and the ideal value based on the CT's transformation ratio, while phase error indicates the angular deviation between the primary and secondary currents that can affect the timing and accuracy of the protection system. Composite error is the combination of these two errors, providing an overall picture of the CT's inaccuracy under certain load conditions [5].

Measurement errors in CTs can also be caused by saturation conditions. The saturation condition is influenced by the knee point voltage and the safety factor [6, 7]. The knee point voltage is the voltage at which the CT core begins to saturate, so that the relationship between the primary and secondary currents is no longer linear; a higher knee point indicates that the CT can withstand current surges during fault conditions for a longer period without distorting its measurements [8]. On the other hand, the safety factor (or accuracy limit factor) is a multiplier that describes how far the CT can operate beyond its nominal current before its accuracy starts to significantly deteriorate, essentially providing a safety margin so that the CT can continue to deliver reliable signals to the protection system [9, 10].

CT measurement errors are also influenced by the burden connected to the CT. The burden on a protection CT refers to the total impedance connected on the secondary side, usually measured in VA, and includes measurement equipment, relays, cables, and other connections. This burden is very critical because an excessively high burden can cause an increase in the secondary voltage, resulting in a decrease in measurement accuracy and potential errors, especially under high current fault conditions [11, 12].

The standard governing protection CTs is IEC 61869-2. This standard is designed to ensure accurate current measurements under both normal operating conditions and fault conditions by emphasizing important parameters such as transformation ratio, accuracy class, knee-point voltage, and secondary burden, so that CTs can deliver consistent and reliable signals to the protection system. This standard categorizes protection CTs into several classes, including the 5P and 10P classes. A comparison between these two classes is presented in Table 1 [13].

Table 1. Comparison of protection CT classes 5P and 10P

Parameter	Class 5P	Class 10P
Composite Error	Maximum 5%	Maximum 10%
Ratio Error	Maximum 1%	Maximum 3%
Accuracy Limit Factor (ALF)	5, 10, 20, etc.	5, 10, 20, etc.

Given the crucial role of protection CTs, it is essential to conduct periodic measurements for each unit. These measurements help ensure that the protection CTs in use still comply with standard requirements. Additionally, the collected data can be utilized for estimation and analysis to determine whether the overall use of CTs remains within the specified standard limits.

This study aims to:

- a. Assess whether the protection CTs meet the standard limits for ratio error and knee-point voltage.
- b. Estimate the allowable range of ratio error and knee-point voltage in protection CTs.
- c. Evaluate the significance of differences in ratio error and knee-point voltage between CTs with 5 years of usage and those with 7 years of usage.

2. RESEARCH METHOD

Statistical methods are employed to analyze the data on ratio error and knee voltage in this study. The measured CT ratio errors are compared against established standards. In this research, the ratio error being evaluated is determined for a burden of 15 VA at secondary current levels of 100%, 120%, and 200% of the CT's nominal secondary current.

Meanwhile, the knee voltage measurement results should be compared with the calculated values. The knee voltage (V_k) is determined using the Accuracy Limit Factor (ALF), the nominal secondary current of the CT (I_n), and the burden resistance (R_B), as shown in the following equation [11]:

$$V_k = ALF \times I_n \times R_B \quad (1)$$

$$R_B = \frac{\text{Burden (VA)}}{I_n} \quad (2)$$

All CTs used in this study have a ratio of 400/5 (nominal secondary current of 5 amperes), class 5P, an Accuracy Limit Factor (ALF) of 20, and a nominal burden of 15 VA. Based on the CT data, Equation 1, and Equation 2, the standard knee voltage of the CT is 60 V.

The data analysis process is shown in Figure 1.

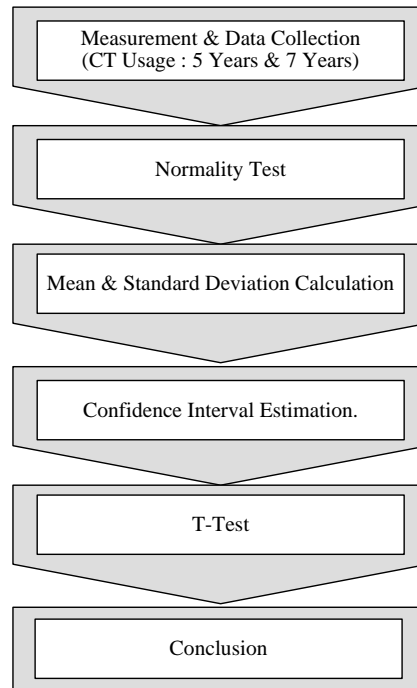


Figure 1. Data Analysis Process

2.1. Measurement and Data Collection

The first step is to collect measurement data on CT ratio error and knee voltage. These data were measured using a CT analyzer in 2024. The number of data points for CTs with a usage duration of 5 years and 7 years is 20 each. The data were obtained from measurements of CTs located in medium voltage feeders (20 kV) at the Bangka transmission and substation service unit, specifically in the Pangkal Pinang, Air Anyir, Toboali, Kelapa, Muntok, Koba, and Sungailiat feeders.

2.2. Normality Test

After the data is collected, the next step is to perform a normality test to ensure that the data distribution approximates a normal distribution. The Kolmogorov-Smirnov test is applied to each group, and if the resulting significance value (typically > 0.05) indicates that the data meets the normality assumption, it qualifies for further parametric statistical analysis [14].

2.3. Mean and Standard Deviation Calculation

The calculation of the mean (\bar{x}) and standard deviation (s) is performed to describe the central value and data variation [14]. The mean is calculated as follows :

$$\bar{x} = \frac{1}{n} \sum x_i \quad (3)$$

While the standard deviation is obtained from :

$$s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} \quad (4)$$

where x_i represents each measurement value and n is the sample size. This calculation provides a comprehensive overview of the CT performance in both usage duration groups.

2.4. Confidence Interval Estimation

Next, parameter estimation is performed by constructing a confidence interval for each variable. This estimation uses the following formula [14]:

$$\bar{x} \pm t \frac{s}{\sqrt{n}} \quad (5)$$

where t is the critical value of the t-distribution at a specific confidence level (e.g., 95%). This confidence interval range indicates the lower and upper bounds where the true population parameter is expected to lie, providing an estimate of the measurement error margin.

2.5. T-test

To determine whether there is a significant difference between CTs used for 5 years and 7 years, an independent t-test is conducted [14]. If the variances of both groups are equal, the t-value is obtained using the formula:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (5)$$

with s_p as the pooled standard deviation, calculated using:

$$s_p = \sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}} \quad (6)$$

and the degrees of freedom are :

$$df = n_1 + n_2 - 2 \quad (7)$$

The t-value obtained from the equation above is compared with the critical value (from the t-table) at a specified significance level (e.g., $\alpha = 0.05$) to assess whether there is a significant difference between the CT groups with usage durations of 5 years and 7 years. If the t-value falls between -t table and t table, the conclusion is that there is no significant difference between CTs with 5-year and 7-year usage durations.

In addition to comparing the calculated t-value with the t-table, conclusions can also be drawn based on the significance level. If the calculated significance is greater than 5%, then the conclusion is that there is no significant difference between CTs with 5-year and 7-year usage durations. To facilitate the analysis process, the statistical parameters in the equations above will be calculated using statistical software.

3. RESULTS AND DISCUSSION

Figure 2 shows the measurement of protection CTs using a CT analyzer. The measurement results for CTs with a usage duration of 5 years are presented in Table 2, while those for CTs with a usage duration of 7 years are presented in Table 3.



Figure 2. Measurement of ratio error and knee voltage of protection CTs

Table 2. The measurement results of ratio error and knee point voltage on CTs with a usage duration of 5 years

No	Substation	Feeder	Current Ratio Error in % at % of Rated Current			Knee Voltage (Volt)
			100%	120%	200%	
1	GI 150kV KLP	Bakik	0.177	0.18	0.189	71.58
2	GI 150kV KLP	Dalil	0.446	0.448	0.457	71.35
3	GI 150kV KLP	Mayang	0.415	0.421	0.437	71.83
4	GI 150kV KLP	Parit 3	0.451	0.454	0.456	72.40
5	GI 150kV KLP	Pelangas	0.425	0.431	0.446	72.22
6	GI 150kV KLP	Simpang Yul	0.438	0.444	0.449	73.57
7	GI 150kV KLP	Beriga	0.436	0.44	0.443	73.48
8	GI 150kV MTK	Kemang Masam	0.260	0.271	0.262	72.07
9	GI 150kV MTK	Menjelang	0.159	0.163	0.165	73.35
10	GI 150kV SLT	Gunung Muda	0.111	0.113	0.119	75.32
11	GI 150kV SLT	Parai	0.106	0.118	0.124	70.22
12	GI 150kV SLT	Air Ruay	0.334	0.341	0.343	73.05
13	GI 150kV TLB	Air Banten	0.338	0.35	0.355	74.82
14	GI 150kV TLB	Kaposang	0.227	0.234	0.237	73.17
15	GI150kV KOBA	Padang Mulia	0.432	0.437	0.442	71.67
16	GI150kV KOBA	Tungkal	0.429	0.434	0.439	75.22
17	GI150kV KOBA	Paku	0.135	0.140	0.146	71.37
18	GI150kV KOBA	Palas	0.234	0.235	0.245	73.36
19	GI150kV KOBA	Terentang	0.344	0.346	0.350	71.90
20	GI150kV KOBA	Tungkal	0.125	0.127	0.129	73.80

Table 3. The measurement results of ratio error and knee point voltage on CTs with a usage duration of 7 years

No	Substation	Feeder	Current Ratio Error in % at % of Rated Current			Knee Voltage (Volt)
			100%	120%	200%	
1	GI 150kV PKP	Batu Rusa	0.462	0.464	0.473	73.66
2	GI 150kV PKP	Pangkal Balam	0.205	0.213	0.214	74.43
3	GI 150kV PKP	Cengkong Abang	0.155	0.157	0.16	72.87
4	GI 150kV PKP	Air Itam	0.434	0.439	0.452	74.68
5	GI 150kV PKP	Eks Mendo Barat	0.439	0.444	0.457	73.42
6	GI 150kV PKP	Eks Sumerejo	0.350	0.354	0.357	72.3
7	GI 150kV PKP	Transmart	0.320	0.334	0.340	72.35
8	GI 150kV PKP	Kampung Jeruk	0.130	0.137	0.141	69.65
9	GI 150kV PKP	Jelitik	0.242	0.246	0.256	74.75
10	GI 150kV PKP	Bukit Intan	0.560	0.562	0.576	70.85
11	GI 150kV PKP	BTC	0.415	0.416	0.417	71.06
12	GI 150kV PKP	Depati Hamzah	0.386	0.393	0.396	72.65
13	GI 150kV PKP	Bukit Baru	0.316	0.319	0.320	72.15
14	GI 150kV PKP	Lampur	0.465	0.466	0.470	71.35
15	GI 150kV PKP	Lontong Pancur	0.416	0.418	0.419	71.41
16	GI 150kV PKP	Rangkui	0.146	0.147	0.150	70.22
17	GI 150kV PKP	Siloam	0.185	0.187	0.190	69.00
18	GI 150kV PKP	Simpang Katis	0.134	0.135	0.137	71.97
19	GI 150kV AA	Provinsi	0.382	0.389	0.392	74.61
20	GI 150kV AA	Soekarno Hatta	0.217	0.226	0.229	72.43

From the results in Table 2 and Table 3, it can be seen that all CTs provide ratio errors that meet the standard, which is below 1% (0.01). Likewise, the knee voltage of all CTs also complies with the standard, being

greater than 60 volts. Next, we will discuss whether there is a significant difference between CTs that have been used for 5 years and those used for 7 years.

Table 4. Results of Normality Test, Mean, Standard Deviation, and Estimation

Parameter	Usage duration of 5 years.				Usage duration of 7 years.			
	Current Ratio Error in % at % of Rated Current			Knee Voltage (Volt)	Current Ratio Error in % at % of Rated Current			Knee Voltage (Volt)
	100%	120%	200%		100%	120%	200%	
Asymptotic Significance (Normality test results)	0.355	0.345	0.247	0.965	0.849	0.800	0.854	0.988
Mean	0.301	0.306	0.312	72.788	0.318	0.322	0.327	72.291
Standart Deviation	0.131	0.131	0.132	1.367	0.132	0.131	0.134	1.667
Confidence Interval Estimation (sig. 5%)	0.301±0.061	0.306±0.061	0.312±0.062	72.788±0.640	0.318±0.062	0.322±0.061	0.327±0.063	72.291±0.780

The results of the normality test using the Kolmogorov-Smirnov (K-S test), as shown in Table 4, indicate that all data have an Asymptotic Significance value greater than 0.05 (5%). Therefore, all data are normally distributed, and the t-test can be applied to these data. If we observe the mean error value of the CT ratio, it appears at first glance that the average for a usage duration of 7 years is higher than that of 5 years. However, this cannot be concluded as evidence that a CT with a usage duration of 5 years is better than one with 7 years.

Table 5. T-test results for the comparison between CT usage duration of 5 Years and 7 Years

Parameter	t-value	Significance
Ratio Errors at 100% Nominal Current	-0.406	0.687
Ratio Errors at 120% Nominal Current	-0.384	0.703
Ratio Errors at 200% Nominal Current	-0.373	0.712
Knee voltage	1.031	0.309

Since the number of data points for the 5-year and 7-year usage durations is 20, the t-table value is 2.2024. The calculated t-values in the table 5, all fall between -2.2024 and 2.2024. Similarly, the significance values obtained are all greater than 5% (0.05). Based on these results, it can be concluded that there is no significant difference in ratio error and knee voltage between CTs that have been used for 5 years and those used for 7 years.

4. CONCLUSION

The protection CTs used on the 20kV feeder at the Transmission Service Unit and Bangka Substation remain within the standard requirements. The ratio error is below 1%, and the knee voltage exceeds 60 volts. Furthermore, there is no significant difference between CTs that have been in operation for 5 years and those used for 7 years.

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