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INFLUENCE OF BURDEN ON THE ACCURACY OF CURRENT TRANSFORMER AT HIGH FREQUENCY

Mr. Oudom Siv

A Thesis Submitted in Partial Fulfillment of the Requirements
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Field of Study	Electrical Engineering
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อุดม ชิพ : ผลกระทบของโหลดที่มีต่อความแม่นยำของหม้อแปลงกระแสที่ความที่สูง (INFLUENCE OF BURDEN ON THE ACCURACY OF CURRENT TRANSFORMER AT HIGH FREQUENCY) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร.คมสัน เพ็ชรรักษ์, 77 หน้า.

เนื่องจากการเพิ่มขึ้นของการใช้งานอุปกรณ์อิเล็กทรอนิกส์กำลังในระบบไฟฟ้า จึงทำให้พบปัญหาในการใช้งานมากมายโดยเฉพาะเรื่องกระแสฮาร์โมนิกส์ โดยทั่วไปแล้ว กระแสฮาร์โมนิกส์จะส่งผลต่อการทำงานของสายเคเบิล ตัวเก็บประจุ หม้อแปลง และวงจรของระบบสื่อสาร ดังนั้นเมื่อหม้อแปลงกระแส (CT: Current Transformer) ทำงานที่ความถี่สูงจะทำให้การวัดนั้นไม่แม่นยำ เพราะว่าโดยทั่วไปแล้ว CT จะทำงานในช่วงความถี่ของอุตสาหกรรมคือ 50/60 Hz และไม่ได้ออกแบบมาเพื่อวัดกระแสความถี่สูง ยิ่งไปกว่านั้นไม่มีมาตรฐานที่แนะนำให้ทดสอบการใช้งานของ CT ในช่วงความถี่ต่าง ๆ โดยในการที่จะประเมินความแม่นยำของ CT นั้นทาง IEC 61869-2-2012 และ IEEE C57.13-2008 ได้กำหนดค่าความผิดพลาดสูงสุดที่ยอมรับได้ด้วยค่าโหลดเฉพาะที่จะทำให้เกิดค่าตัวประกอบกำลังไฟฟ้า 0.8 (IEC 61869-2-2012) และ 0.9 (IEEE C57.13-2008) ตามลำดับ อย่างไรก็ตาม CT จริง ๆ จะใช้สายในการเชื่อมต่อกับอุปกรณ์การวัด ค่าโหลดของ CT จึงประกอบไปด้วยค่าความต้านทานและค่าความเหนี่ยวนำ จากเหตุผลดังกล่าวจะมีผลกระทบจากค่าของโหลดซึ่งมีผลต่อความแม่นยำของ CT ในแต่ละช่วงความถี่ได้

ในวิทยานิพนธ์นี้ได้ใช้ค่าโหลดหลายค่าที่มาจากค่าโหลดมาตรฐานของ IEC และ IEEE ที่กระแส 10 A และที่ความถี่ตั้งแต่50 Hz ถึง 1 kHz (ค่ากระแสฮาร์โมนิกส์ถึงลำดับที่ 19) ในการทดสอบ CT เนื่องจากค่าของโหลดขึ้นอยู่กับความถี่ ผู้เขียนจึงเสนอค่าโหลด 2 กรณีเพื่อที่จะคำนวณหากระแสทุติยภูมิของ CT ผลการทดสอบพบว่าในกรณีที่ 1 ค่าความผิดพลาดจะสอดคล้องกับค่าที่ยอมรับได้จาก IEC 61869-2-2012 ที่ความถี่ 50 Hz อย่างไรก็ตาม ค่าความผิดพลาดจะเพิ่มขึ้นสูงมากเมื่อความถี่เพิ่มขึ้น ในกรณีที่ 2 ค่า ความผิดพลาดที่ความถี่สูงจะลดลงโดยเฉพาะอย่างยิ่งเมื่อใช้ค่าโหลดมาตรฐานของ CT แม้ว่าค่าความผิดพลาดในกรณีที่ 2 สามารถยอมรับได้ตาม IEC 61869-2-2012 ทุกความถี่เมื่อใช้ค่าโหลดมาตรฐาน สำหรับค่าโหลดค่าอื่นที่ไม่ใช่ค่าโหลดมาตรฐานจะส่งผลให้ค่าความผิดพลาดสูงขึ้นเล็กน้อย ดังนั้นในงานวิจัยนี้จึงใช้ค่า ความผิดพลาดจากการทดสอบกระแสความถี่เดียวเป็นตัวปรับค่าความผิดพลาดในการวัดของ CT ผลการแก้ค่าแสดงให้เห็นว่าความผิดพลาดมีค่าลดลงเล็กน้อยเท่านั้น

ภาควิชา วิศวกรรมไฟฟ้า ลายมือชื่อนิสิต ....

สาขาวิชา วิศวกรรมไฟฟ้า ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

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5670562821 : MAJOR ELECTRICAL ENGINEERING
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OUDOM SIV: INFLUENCE OF BURDEN ON THE ACCURACY OF CURRENT TRANSFORMER AT HIGH FREQUENCY. ADVISOR: ASST. PROF. KOMSON PETCHARAKS, Ph.D., 77 pp.

Poor quality of measurement happened when current transformer (CT) operated at high frequency, because it is typically constructed to operate only at the industrial frequency (50/60 Hz) and is not designed and tested for harmonic frequencies. Moreover, no standard provided the recommend practice for the application of CT over wide frequency range. In order to guarantee the accuracy of CT, IEC 61869-2-2012 and IEEE C57.13-2008 provided the limits of current error with the specified burden which shall have power factor of 0.8 and 0.9 lagging, respectively. Therefore, the influence of burden on the accuracy of CT over wide frequency range is investigated. This work used the several burden based on both IEC and IEEE standard burdens. The single frequency current of 10 A at frequency from 50 Hz to 1 kHz and the harmonic current up to 19^{th} order were injected to CT. Because the value of burden was proportional to the test frequency, the author proposed two cases of burden to calculate the output current of CT. From the test results, for the first case, the ratio error corresponded to the limits of current error according to IEC 61869-2-2012 at frequency of 50 Hz. Unfortunately, the ratio error dramatically increased with increasing frequency. In second case, the high ratio error at high frequency was reduced, especially when the standard burden as manufacturer declared was the burden of CT under test. Although the ratio error in second case was acceptable according to IEC 61869-2-2012 at all test frequencies when standard burden was used, for other burden, the ratio error was slightly high. Therefore, this work used the ratio error from the single frequency current test as the correction factor (*CF*) to correct the ratio error. As results, the ratio error was slightly reduced.

Department: Electrical Engineering Student's Signature ....
Field of Study: Electrical Engineering Advisor's Signature ....
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List of abbreviations

ε	: Ratio error
β	: Phase angle of current transformer
ΔZ_b	: Deviation between $Z_{b,f\text{-}cal}$ and $Z_{b,f\text{-}mea}$
A_h	: Magnitude of harmonic component
C'_m	: Parasitic capacitances of winding
f	: Test frequency
f_1	: Fundamental frequency
h	: Harmonic order
$i(t)$	: Current in time domain
I_L	: Maximum demand load current
I'_m	: Magnetizing current of winding
I_p	: Injected current
I_p'	: Standard current
I_p''	: Individual current
I_s	: Output current of current transformer
k	: Rated ratio of current transformer
$kI_{s\text{-}f}$	: Measured current by using frequency dependence burden
$kI_{s\text{-}f\text{-}cor}$	: Measured current after correction
$kI_{s\text{-}fix}$	: Measured current by using fix burden and multiplying with k
L_b	: Inductance of burden
L'_m	: Current transformer inductance
L_s	: Leakage inductances of secondary winding
L'_P	: Leakage inductances of secondary winding
n	: Maximum harmonic order
N	: Sample of a current waveform
I_{rms}	: The rms value of current
I_{sc}	: Maximum short circuit
R_b	: Resistance of burden from calculation
R'_m	: Resistance of core loss
R'_P	: Resistances of primary winding
R_s	: Resistances of primary winding
R_w	: Wire resistance
t	: Time
V_s	: Voltage across burden
$X_{b,f\text{-}cal}$	: Reactance of burden from calculation
X_w	: Wire reactance
Z_b	: Burden of current trasformer
$Z_{b,f}$	: Frequency dependence burden
$Z_{b,f\text{-}cal}$	: Frequency dependence burden from calculation
$Z_{b,fix}$	: Fix burden
$Z_{b,f\text{-}mea}$	: Frequency dependence burden from measurement
Z_w	: Wire impedance
CF	: Correction Factor
CT	: Current Transformer

e.m.f	: Electromotive Force
FFT	: Fast Fourier Transform
ICT	: Inductive current transformer
MEA	: The Metropolitan Electricity Authority
NIMT	: The National Institute of Metrology
RCF	: Ratio correction factor
r.m.s	: Root Mean Square
SMD	: Surface mount device
TCF	: Transformer correction factor
THD	: Total Harmonic Distortion
VA	: Volt-amperes

Chapter 1 : Introduction

Due to the development of technology, the extensive use of power electronic creates new challenge for studying power system operation. Nowadays the operating of power system reaches to maximal performance limits. The effects on operation system and equipment may include damage, disruption of process, misoperation and other such anomalies. In addition, the economic issues become more interesting because equipment damage and repairing system cost time and money. The influence of electromagnetic phenomena causes the product damage in industrial sectors.

Power quality is the study of characterization of voltage and current deviations from ideal sinusoidal of the power system. IEEE Standard 1159-2009 defines power quality as [1]: "*The term power quality refers to a wide variety of electromagnetic phenomena that characterize the voltage and the current at a given time and at a given location on the power system".* In recent years, emphasizing on and concerning for the power quality at industry, commercial establishments and residences are increasing. Many problems occur in power system such as insulation breakdown, overheat of equipment, power interruption, metering error or increasing loss because many disturbances such as interruption, voltage sag and swell, flicker, transient, harmonic and so on have been occurred. These problems have undesirable economic industrial impacts and need to evaluate the economic impacts of power quality [2, 3]. Some power quality indices, for example the total distortion and the root mean square value, are recommended in [1, 4].

During poor power quality event in power system, the monitoring of power quality, which is the evaluation of a general quality index that provides a reliable information about the location of the sources producing distortion and the measurement of their effects on power quality, has become a major interest. The goals of some measurements are the evaluation power quality, the location of sources of producing distortion, the detection of resonances or electromagnetic interference condition, and the resolve billing inequities. All of these influence to the economics of power system [5, 6]. Moreover, the various types of equipment in power-quality measurements are multi-meter, oscilloscope, current probe, search coil, and power-quality meters and analyzers, as mentioned in [1]. In addition, one of current probe is current transformer (CT) which is used in measurement and protection purposes. Current transformer is mostly installed as transducers in power systems.

The stability and reliability of operation system need to maintain in various aspects of power system operation to avoid problems which occur in grid. Thus, the aspect of power quality, which deals with voltage and current characteristics, control system and harmonic prediction, is the main topic in recent year, as mentioned in [7].

1.1. Impact of harmonic on power quality measurement

One of an important power quality problems is the harmonic distortion, and many studies deal with this [6, 8-13]. The harmonic distortion statement is difficult to forecast due to the variety of unknowns such as detail of consumer and characteristic of system. Generally, the harmonic currents are produced by consumers and flow back to the power system and affect other users. The total of harmonic voltage supplied to other users is a function of the overall effects of harmonic current which is produced by the load of all consumers. This phenomena causes deviation of sinusoidal waveform which is considered as distortion, often refer to as harmonic distortion [12, 14, 15]. Harmonic is current or voltage with frequencies which are integer multiples of the fundamental frequency. In electric power system, the main sources of harmonics may be classified such as nonlinearity of transformer, rotating machine, semiconductor based power supply system, control system and arcing device [7, 16].

Furthermore, the presence of harmonic in the power system threatens to sensitive equipment like adjustable speed drives, power electronic loads, computers etc. Occasionally, power electronic devices can misoperate due to harmonic distortion and cause a malfunction of the customer's process. Likewise, harmonic can affect operation of cable, capacitor, transformer, generator, communication circuit, metering, and protective relays. Thus, IEEE 519- 2014 [8] provides recommended practice for the harmonic evaluation in power systems, which is widely accepted by the industries and utilities, system shall operate within limits current harmonic in order to minimize the effects of harmonic distortion. From this recommended practice, the current may contain harmonic up to 50^{th}. Moreover, harmonic estimation technique, which is an important role in harmonic monitoring and control in power system, is briefly reviewed in [17].

Due to the increased level of the conductive disturbances in the power system, the accuracy of CT in presence of harmonic distortion is the main purpose of study. However, CT is typically constructed to operate only at the industrial frequency (50/60 Hz) and is not designed and tested for harmonic frequencies. The technical report about the instrument transformer application for power quality lists complete information about test and measurement techniques for power quality instruments [18]. The information regarding general requirement of instrument transformers and CT specific standard give guidance in the usage of CT for measurement and protection at rated frequency from 15 Hz to 100 Hz, are providing in [19, 20]. These standards are general requirements and do not cover the measurement at high frequency purpose. Thus, knowing the accuracy of CT at high frequency, which is very important, is carried out.

1.2. Objective and Scope of this thesis

The objective of this research is to explore the correction of ratio error of CT at wide frequency range when the burdens correspond to IEC and IEEE standards are loaded to the CT. At this aim, a technique for measuring the ratio error of CT is also proposed in this dissertation. This work used the low voltage metering ring-CT for the evaluation and the correction of the ratio error of CT over frequency range from 50 Hz up to 1 kHz. Moreover, the standard burdens had power factor 0.8 lagging according to IEC 61869-2-2012 [19] and power factor 0.9 lagging according to IEEE C57.13-2008 [20] and the resistive burden also included in this study.

1.3. Contribution of this thesis

The benefit of this study is the reduction of ratio error produced by the variation of the burden over the wide range frequency. It means to improve accuracy of the CT, simultaneous to improve the measuring of power quality over wide frequency range. Consequently, in order to avoid substitution of the conventional CT in power system, this correction give idea to the utility for saving cost.

1.4. Organization of this thesis

The detail of the thesis will be given in the following Chapters. After the introduction in this chapter, chapter 2 reviews the backgrounds of CT and the theory involved the experiment on the ratio error of CT such as the standard burden and the accuracy class of CT according to IEC standard and IEEE standard. This chapter also provide the discussion on harmonic current as well as give some ideas about the variation of impedance. Chapter 3 describes the equipment used in the test and the procedure to establish the test. Here, the accuracy of standard CT as well as the discussion of burden in detail are included in this chapter. Chapter 4 offers the analysis of results with interpretations and discussion. The conclusion of all investigations is given in chapter 5. The appendix offers all results of CTs under test.

Chapter 2 : Literature review

This chapter presents the background and the theoretical review of study. Some information about harmonic performance are presented in section 2.1. The practical recommendations about CT from IEC and IEEE standards are presented in section 2.2. The characteristic and the correction of frequency response of CT from previous studies are discussed in section 2.3 and 2.4, respectively. The guideline to make measurement of burden is outlined in last section.

2.1. Overview of harmonic current

Harmonic distortion, caused by nonlinear load in the power system, can be expressed as a sum of pure sinusoids in which the frequency of each sine wave is an integer multiple of the fundamental frequency of the distorted wave. The sum of sinusoids can be referred to as a Fourier series whose concept is commonly applied in problems of harmonic analysis.

Several expressions are known in order to describe the harmonic contents of a current waveform. The first expression is always used is the root mean square (rms) value of current which indicates the magnitude of a current and includes the fundamental and all the harmonic components, as given in equation (2-1) where I_h is the harmonic current and h is harmonic order. The rms value of current can be calculated based on N samples of a current waveform. This expression can be given in equation (2-2).

$$I_{rms} = \sqrt{\sum_{h=1}^{\infty} I_h^2} \tag{2-1}$$

$$I_{rms} = \frac{1}{N} \times \sqrt{\sum_{h=1}^{N} I_h^2} \tag{2-2}$$

The most commonly expression which presents the level of distortion waveform is Total Harmonic Distortion (THD). The power quality and the effect of a compensation can be determined by looking at the THD of the supply current and the load current. Ideally, the THD of the supply current will equal zero percent (0 %) indicates the absence of harmonic currents. The definition of THD is mentioned in [21] and is given by equation (2-3) where I_1 is the fundamental harmonic current.

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \tag{2-3}$$

Since the problems caused by harmonics are interesting around the world, the electrical standard for limiting the level of harmonic current and voltage has drafted. IEEE Standard. 519, 2014 provides limits for harmonic distortion to ensure that voltage harmonic distortion is kept low by limiting the harmonic currents which are produced by end users. This standard is being quickly adopted by the Metropolitan Electricity Authority, MEA, in Thailand for the limit harmonic current of inverter for PV rooftop.

Table 2-1 corresponds to the limits for harmonic current emission for systems rated 0.12 kV - 69 kV.

Table 2-1: Current limits for systems rated 0.12 kV - 69 kV.

Individual harmonic order (odd harmonics)[a]	**Maximum harmonic current distortion in % of I_L[b]**
$3 \le h < 11$	4.0
$11 \le h < 17$	2.0
$17 \le h < 23$	1.5
$23 \le h < 35$	0.6
$35 \le h < 50$	0.3
Total harmonic distortion THD = 5%	

[a]Even harmonics are limited to 25% of the odd harmonic limits above.
[b]For this table $I_{sc}/I_L < 20$, where I_{sc} is maximum short-circuit current at the point of connection and I_L is maximum demand load current (50 or 60 Hz) during normal load operating conditions.

The research methodology for determining the ratio error of CT in presence of harmonic distortion can use injected current with percentages of 2nd to 19th harmonics. Their rms values are in accordance with Table 2-1.

Generally, the odd harmonic presents in harmonic waveform cause both the positive and the negative half cycles of a waveform have identical shapes. Because most harmonic producing loads look the same to both polarities, only odd harmonic is preferred for simplification in most studies in power system. The type of odd harmonic phase sequence rotation is summarized [22]:

- Harmonics of order h = 1, 7, 13… are generally positive sequence.
- Harmonics of order h = 5, 11, 17… are generally negative sequence.
- Triplens (h = 3, 9, 15…) are generally zero sequence.

Likely, when the load equipment or the measurement device has something wrong, the even harmonic appears often in waveform. Some cases are excluded such as half-wave rectifiers and arc furnaces. From Table 2-1, there are notable that the rms value of even harmonic components are small comparing to fundamental harmonic current. Hence, most studies focused on only odd harmonic as common harmonic produced by load. For example if the fundamental current is 10 A, from Table 2-1, the third harmonic is 400 mA and the second harmonic is only 100 m A.

The principal effect of certain harmonics such as even harmonic and triplens harmonic are indicated as follows.

The second harmonic has a significant impact on peak voltage asymmetry. It seems like aggressive harmonic; but, its magnitude is not high, not more than 0.5 %. For other even harmonics, they are rare in supply source. Less research study is interested in the disturbance of the 2nd harmonic. Hence, it is not investigated in this thesis.

The third harmonic (or the other triplens, i.e. 9th, 15th, etc.), is zero-sequence, arithmetically adds up the potential of the neutral. The presence of zero sequence current can be observed by following symptoms such as high neutral current, high peak and high average phase current, high total harmonic distortion of the current, etc. Because of the additional losses in the neutral current path, the third harmonic has strong effect on communication lines, even though the load is balance but nonlinear.

The fifth harmonic, is generally negative sequence, is a predominant component in the harmonic voltage waveform. Most measurement studies have confirmed its significant appearance at all voltage levels in power system.

The seven, eleven, and thirteen harmonics also present in supply voltages. However, their magnitudes are lower than the magnitude of fifth harmonic. When the resonance phenomena occurred in power system, their presence are more significant than the fifth harmonic.

Usually, the power system analysis of harmonic orders above the 25^{th} to 50^{th} (depend on the system) are negligible. The harmonic components in these ranges, which may cause interference with low-power electronic devices, do not affect to the power system. Moreover, some data are insufficiently accurate and cannot be collected to analyze at these frequency ranges.

2.2. Metering current transformer

CT is typical current transducer in power measurement. This device can measure a high current and can correctly duplicate this high current to a low current. Two main purposes to CT application are metering and protection. As mentioned in section 1.2, in this chapter, the author studied only CT for metering purpose and some information and specification for using CT, based on IEC 61869-2-2012 [19] and IEEE C57.13-2008 [20].

2.2.1. Definition

A CT is defined as "*an instrument transformer in which the secondary current, under normal conditions of use, is substantially proportional to the primary current and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections*" [1]. CT, which has a limited bandwidth, can be used in metering and protection purposes.

For the operation of CT, many parameters affect the measurement errors such as amplitude of current, percentage of harmonic current, accuracy class of CT, and type of burden. The CT model in Figure 2-1 can be used to analyze the cause of errors. In this model, R'_P, R_s, L'_P *and* L_s represent resistances and leakage inductances of primary and secondary winding, R'_m is the resistance of core loss, L'_m is CT inductance, C'_m represents parasitic capacitances of winding and Z_b is burden of CT and I'_m relates to magnetizing current of winding.

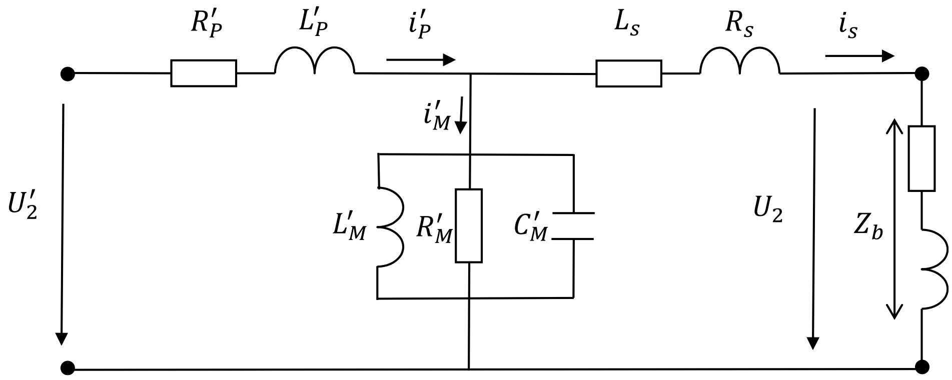


Figure 2-1: Circuit equivalent of current transformer.

According to IEEE standard [20], the higher errors will occur when magnetization current increases. Commonly, the accuracy of CT is better than 3% to measure harmonics currents in frequency range up to 10 kHz. If CT burden is inductive, a small error will occur. Coil type CT has good accuracy (both for ratio and phase angle, error is less than 5% for frequency up to 5 kHz). At upper 40th harmonic and for very low burdens, the quality of measurement decays rapidly. In some cases, ratio error increases with frequency, in other case decrease [18].

2.2.2. Frequency response

The impacts of CT on power quality monitoring vary according to adopted and designed technologies. Frequency response of conventional CT defined only for linear systems. In general, CT is not linear devices but usually operate only in linear region.

Figure 2-2 shows an approximate frequency range of instrument transformer [23]. This chart does not consider the main features of each technology which is available today such as material or technology of the sensor, size, temperature, voltage coefficient and so on. The limits of frequency response depend on several parameters, even within the same technology, are not represented as continuous lines but they are drawn with dotted lines [23].

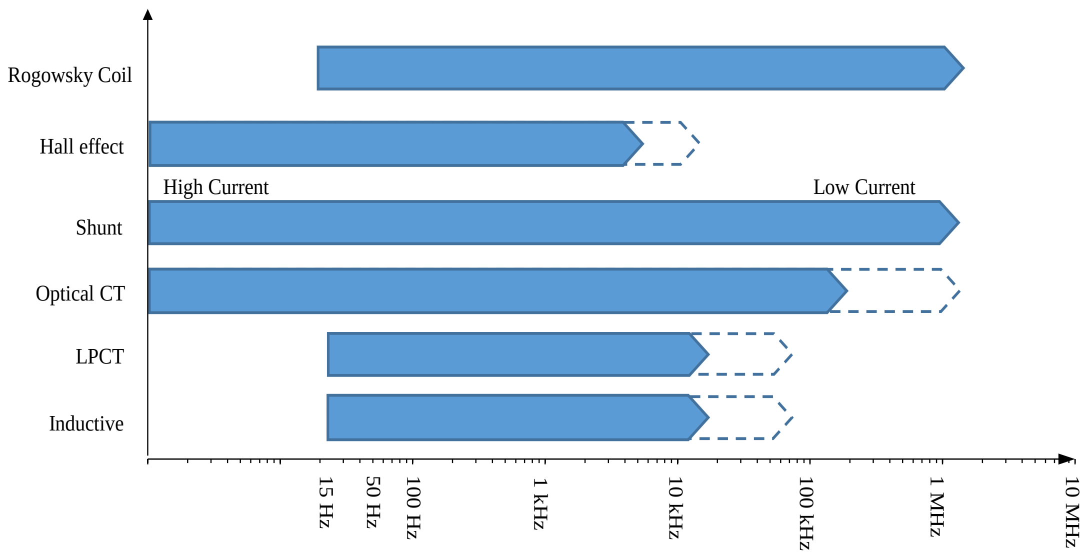


Figure 2-2: CT technologies frequency range according to present experience [23].

Following on this line, the bandwidth of metering CT cannot hold rated accuracy above 1 kHz and is unusable for harmonics above the 15th and transients. Some CTs, for example toroid CT (solid core), can be linear up to frequencies in tens of kHz, laboratory measurement reveled this point. However, obtaining the information of CTs, which are being used over the frequency range considered, is important. Anyways, IEC standard [23] defined that the frequency response for CT differs according to manufacturer, type, accuracy class, turns ratio, cross section and core material and burden. This standard also confirmed that the frequency response of the inductive current transformers have significant effect of transformer capacitances at high frequency, but this impact is negligible up to 40th harmonic.

2.2.3. Standard burden

The burden is the load imposed on the secondary side of the CT and defines as the total impedance in ohms or the total volt-amperes (VA) with a specified power factor value. The relationship between burden in ohms and in volt-amperes is

$$ohm = \frac{volt\ amperes}{(rated\ output\ current)^2} \tag{2-4}$$

A burden of CT is sum of the impedance of the individual devices which includes a short run of wire, a meter, as well as the instrument itself, as shown in Figure 2-3. Z_{in} in this figure is the input impedance of the measuring device.

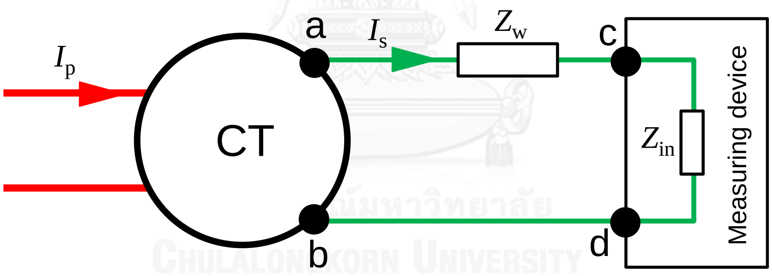


Figure 2-3: Practical use of CT and measuring device.

Choosing a correct burden of CT is very importance to reduce ratio error of CT and resistive burden is advisable in measurement [23]. However, the CT shall have an accuracy class and a power factor of burden Z_b corresponds to IEC standard [19] or IEEE Standard [20]. The Figure 2-3 shows the reason why these two standards specified the standard of burden must have certain lagging power factor e.g. 0.8 or 0.9 but not be resistive burden. From across point a-b in Figure 2-3, we can see that the CT and the measuring device must be connected by using wire. The wire impedance Z_w consists of wire resistance R_w (which depends on the material, cross-section area and wire length) and wire reactance X_w (which depends on the wire layout, e.g. parallel wire or twist-pair, etc.).

Therefore, the burden obviously consists of resistance and inductance, which causes measurement error since the burden increases with increasing frequency, power factor decreases as frequency increases. Then, CT output will result in harmonic current higher than with a pure resistive burden. Thus, the power factor of burden should be as high as possible, in order to avoid impedance increase with frequency and the consequent magnetizing current enhancement. The standard burden of both IEC and IEEE standards are described in following section.

A. IEC standard 61869-2-2012

The standard values of burden for metering CT are 2.5 - 5.0 – 10 - 15 and 30 VA and can be defined as impedance in ohms with rated output current of 5 A by using equation (2-4). Also, the standard burden shall have power factor of 0.8 lagging at 50 Hz. The resistance and inductance of standard burdens are calculated and shown in Table 2-2.

Table 2-2: Standard burdens for power factor of 0.8 lagging with rated output current of 5A (at 50 Hz).

Standard burden (VA)	**Impedance (ohm)**	**Resistance (ohm)**	**Inductance (mH)**
2.5	0.1	0.08	0.19
5	0.2	0.16	0.38
10	0.4	0.32	0.76
15	0.6	0.48	1.15
30	1.2	0.96	2.29

B. IEEE standard C57.13-2008

For metering CT with 5 A rated output current, the standard burdens shall have resistance and inductance with power factor 0.6 to 1 lagging. At specific condition, the standard burden shall have power factor of 0.9 lagging at 60 Hz. Table 2-3 showed these parameters.

Table 2-3: Standard burdens for power factor of 0.9 lagging according to IEEE Standard (at 60 Hz).

Burden designation	**Total Power (VA)**	**Impedance (ohm)**	**Resistance (ohm)**	**Inductance (mH)**
B-0.1	2.5	0.1	0.09	0.116
B-0.2	5.0	0.2	0.18	0.232
B-0.5	12.5	0.5	0.45	0.580
B-0.9	22.5	0.9	0.81	1.040
B-1.8	45.0	1.8	1.62	2.080

- If a CT secondary winding is rated at other than 5 A, ohmic burdens for specification and rating shall be derived by multiplying the resistance and inductance of the table by $[5/\text{ampere rating}]^2$, with the VA at rated current, the power factor, and the burden designation remaining the same.
- These standard burden designations have no significance at frequencies other than 60 Hz.
- The impedance tolerance is +5% and –0%.

2.2.4. Accuracy class

The accuracy class, is the most important for metering CT, is expressed as the percentage error for a known current, burden and power factor. Currently, there are two standards which describe the accuracy class of CT.

A. IEC standard 61869-2-2012

The accuracy of inductive current transformer (ICT) is specified at rated frequencies from 15 Hz to 100 Hz. The standard accuracy classes are defined in IEC standard [19] as:

0.1 - 0.2 - 0.2s - 0.5 - 0.5s - 1 - 3 - 5

For all classes, the power factor of burden shall be 0.8 lagging except at 5 VA, a power factor of 1 shall be used, with minimum value of 1 VA. This standard use the ratio error to limit the performance of CT. The ratio error is given by the formula:

$$\varepsilon = \frac{kI_s - I_P}{I_P} \times 100\% \quad (2\text{-}5)$$

Where k is the rated ratio of CT; I_P is the primary current and I_s is the secondary current.

For classes 0.1-0.2-0.5 and 1, IEC standard [19] defined limits of current (ratio) error and phase displacement, is shown in Table 2-4, with the burden which can assume any values from 25% to 100% of the rated output .

Table 2-4: Limits of current error and phase displacement for measuring CT according to IEC standard (at 15 Hz to 100 Hz).

Accuracy class	± Percentage current (ratio) error at percentage of rated current shown below				± Phase displacement at percentage of rated current shown below							
					Minutes				Centiradians			
	5	20	100	120	5	20	100	120	5	20	100	120
0.1	0.4	0.2	0.1	0.1	15	8	5	5	0.45	0.24	0.15	0.15
0.2	0.75	0.35	0.2	0.2	30	15	10	10	0.9	0.45	0.3	0.3
0.5	1.5	0.75	0.5	0.5	90	45	30	30	2.7	1.35	0.9	0.9
1.0	3.0	1.5	1.0	1.0	180	90	60	60	5.4	2.7	1.8	1.8

B. IEEE standard C57.13-2008

Accuracy classes for metering CT are based on the requirement of transformer correction factor (TCF) which shall be within the specified limits when the burden has the value of the power factor from 0.6 to1.0, Table 2-5 shows these limited values.

Table 2-5: Standard accuracy class for metering service and corresponding limits of transformer correction factor (0.6 to 1.0 power factor of metering load) according to IEEE standard (at 60 Hz). Note: Approximately equal to RCF if β is small.

Metering accuracy class[b]	**At 100% rated current**[a]		**At 10% rated current**	
	Minimum	**Maximum**	**Minimum**	**Maximum**
0.3	0.997	1.003	0.994	1.006
0.6	0.994	1.006	0.988	1.012
1.2	0.988	1.012	0.976	1.024

[a]For CT, the 100% rated current limit also applies to the current corresponding to the continuous thermal current rating factor.
[b]For 0.15 metering accuracy class, see IEEE Standard C57.13.6.

The TCF of CT at 0.6 lagging power factor is as follows:

$$TCF = RCF + \frac{\beta}{2600} \tag{2-6}$$

Where $RCF = \frac{I_P}{kI_s}$ is ratio correction factor and β is the phase angle (in minutes) for CT.

And the relationship between ratio correction factor (*RCF*) and ratio error (ε) is

$$RCF = \frac{1}{\frac{\varepsilon}{100} + 1} \tag{2-7}$$

Also, the application of CT shall be at frequency 60 Hz. At specified conditions for CT, the standard burden shall have power factor of 0.9 lagging (as shown in Table 2-3) and accuracy of CT shall be maintained at 10%, and at 100% of rated primary current. When the burden is lower than the standard burden, the accuracy class is not obligatorily equal to the accuracy class at the specified standard burden.

If the CT specifies the accuracy class with the maximum burden, it will confirm for other lower burdens with that class too. In contrast, if the accuracy class is specific only to that burden assigned, the accuracy class of CT will not guarantee for other burdens unless specification [15].

2.3. Characterization of CT over wide frequency range

The development of methodology and measuring system for the evaluation of the accuracy of current transformer at higher harmonics, are necessary. The usage of a test signal consisting of multiple harmonics from 2nd to 13th to determine the accuracy of current transformer and to optimize the range of CT secondary winding load with highest accuracy is described in [24].

Many authors have been proposed the method of inductive CT characterization in the presence of harmonic distortion and pointed out that the CT had lower accuracy for distorted signals than accuracy for sinusoidal signal [18, 25, 26]. Similar approach is described in [27], it concluded that the CT errors are strongly affect by the waveform of the current source. Moreover, the CT errors increase with increasing frequency and the burden contributed significant to the phase displacement and the amplitude error [28-30]. Therefore, the measurement error of the current transformer depended on several parameters such as amplitude of current, percentage of harmonic current, accuracy class of current transformer, and type of burden.

The behavior of CT at higher frequencies with the evaluation of harmonic magnitude is presented in [18]. The test results showed that the magnitude of measurement of CT had impact to harmonic emission level calculation. Although the performance of CT with pure resistive burden was better, we should be awarded of the ratio error of CT in the presence of inductive part of burden which can lead to high ratio error with increasing frequency. Thus, the secondary circuit should have low inductance, including the connection of cable between CT and meter.

The explanation of the ratio error of CT with distorted current is proposed in [30]. The test conducted with two window CTs and used resistive load as burden of CT. The analysis of results showed that the distortion of primary current and secondary winding load caused the ratio error. The increasing ratio error depended on these two parameters.

From these previous studies, we notice that the ratio error of CT was significant in the presence of harmonic distortion in primary current. It means that the accuracy of CT was low at high frequency. Moreover, the secondary winding load (burden) also affected to the accuracy of CT at nominal frequency and other various frequencies. When the power factor of burden accorded with IEC standard or IEEE standard, the ratio error of CT shall have special consideration. Therefore, this problem leads the author to propose the experiment to define the frequency response of CT at wide frequency range with influence of burden.

2.4. Correction of the frequency response of CT

Considering the correction methods to increase the accuracy of measurement by using CT become interesting topic. Some research studies focused on the method for the compensation of the ratio error and phase error based on the insertion of a properly analog circuit at the secondary winding [31, 32], while others place their emphases on a correction algorithm executed on the measured secondary current by a digital processing [21, 33, 34].

Moreover, the improved technique for compensating CT in a wide frequency range (1 Hz to 40 kHz), based on the identification of a digital filter compensating the transformer frequency response, provided with analog-to-digital converters and digital-to-analog converters for experimental, has been proposed [35]. It was a real time digital method base on the identification of a digital filter over frequency range of 1 Hz to 40 kHz. In this study, the filter is also implemented on a FPGA board and provided with analog-to-digital converters and digital-to-analog converters. In this method, the optimization technique is used for the objective of optimality and the computational complexity of the solution. The experimental results have shown that the performance of CT over wide frequency range was improved, the ratio error increased by a factor about six for time delay time of compensation. Another important point in this compensation technique was that if the compensation device accidentally move down, as it did not modify CT operation, the output of CT can still adopt without compensation and all connected devices can operate at normally condition.

However, no authors in these previous studies specify the type of CT (metering or protection) and provide the exact value of burden of CT for all measurement errors and compensations in experiments. From IEC 61869-2-2012 [19] or IEEE C57.13-2008 [20], the standard burden must have power factor of 0.8 or 0.9 respectively; in contrast, the experiments on ratio error of CT in previous studies were done only with resistive burden. Thus, no researchers have carried out to explore a method for the compensation of ratio error at high frequency when used the standard burden.

2.5. Impedance at high frequency

Nowadays, there are many types of impedance measuring instruments corresponding to each measurement technique. Measurement ranges and accuracy are specified for impedance measurement. Sometimes the instrument show an unexpected result (too high, too low or tolerance ±1 %.). The incorrect measurement technique or the natural behavior of the component cause the error. The following section will provide the behavior of impedance and their measurement.

2.5.1. Parasitic of passive components

Neither purely resistive, nor purely reactive, all circuit components have parasitic which is unwanted resistance in capacitors, unwanted inductance in resistors, unwanted resistance in capacitors or unwanted capacitance in inductors. When we determine an impedance parameter value for a circuit component (resistor, inductor, or capacitor), it is important to thoroughly understand what the value indicates in reality, because some applications need pure resistance or precise value of impedance. The parasitic of the component, the inherent impedance parameter values and the measurement error sources such as the test fixture's residual impedance, affect the value of impedance and the accuracy of measurement. Figure 2-4 showed the instance of the some parasitic such as resistance of winding, stray capacitance and lead inductance for inductor and resistor [36].

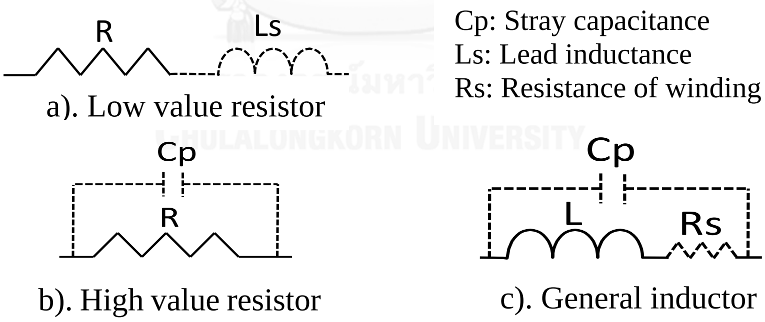


Figure 2-4: The parasitic of RL component.

In short, three kinds of value must consider such as ideal, real, and measured. The knowledge of these values are essential to understand the impedance value obtained by measurement.

- **The ideal value** is the value of a passive component such as resistor, inductor, or capacitor that omits the effects of parasitic. In the real world, the ideal value is only interesting by academic study. The model of a passive component is assumed as a purely resistive or reactive element which does not vary with frequency.

- **The real value** is the sum of the ideal value and the value of a component's parasitic. The real value depends on the frequency because the value of parasitic makes a different impedance value for a different frequency.
- **The measured value** is the value obtained by the measurement instrument. Generally, the instrument's inherent residuals are occurred between the equipment under tested and the measurement instrument. The measured value always has error when compared to real values and differ slightly intrinsically from one measurement to another. The varying value can be considered as the measurement uncertainties or the accuracy of instrument. The judgment of the quality of measurement is the comparison of the measured value and the real value.

2.5.2. Component dependency factors

The measured value of impedance depends on several conditions such as test signal level, test frequency, type of impedance material and the used process of manufacturer. Because of the presence of parasitic, frequency dependency commonly affect to value of impedance. Therefore, when the application of impedance with the existence of the parasitic and the presence of harmonic, the error always occur.

For example, the illustration in Figure 2-5 was the frequency dependence impedance obtained by measuring and their deviation compare to ideal value. In Figure 2-5, the left vertical-axis was valid for the measured value of impedance while the right vertical-axis was valid for their deviation (dash line). At frequency of 50 Hz, impedance was equal 0.19 Ω and increased to 2.13 Ω when frequency is up to 1 kHz. This impedance was measured four times and each measurement gave the different value approximate 2%. Therefore, we took the average of these values. Moreover, the dashed line in this figure showed the deviation of impedance value between measured value and real value (from calculation). The errors occurred because of the parasitic of component and the inherent impedance.

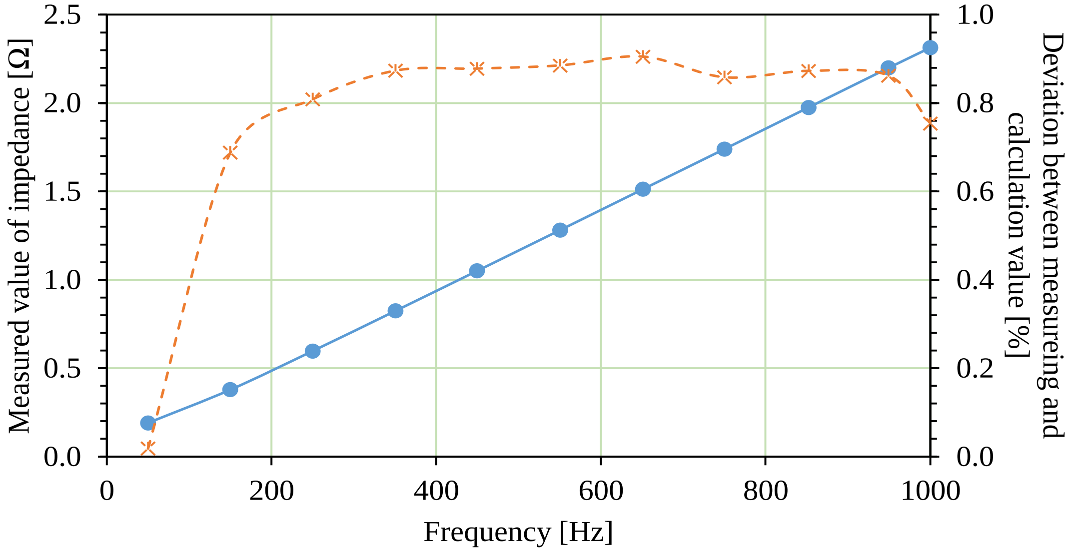


Figure 2-5: The frequency dependence value of impedance by measuring and the deviation between measuring and calculation value of impedance.

2.6. Presentation of this thesis

Nowadays, because the application of power electronic device is increasing, the effect of the harmonic current increases in system. A case in point is the implementation of CT in the presence of harmonic current source. As mentioned in section 1.1, no standards provided the recommend practice of CT at higher frequency than rated frequency. In application of CT, we can note that there were several parameters such as current amplitude, accuracy class of CT, magnetization of coil and type of burden which effected to its ratio error. Because the value of impedance varied with the frequency, the burden of CT made the accuracy of CT may be low, when CT is utilized at high frequency or is transformed the harmonic current. The experiments to quantify the ratio error are possible but an accurate value of burden was difficult to obtain, especially for burden beside resistance.

As mentioned in section 2.2.3, the CT shall have an accuracy class as defined in IEC or IEEE with a burden Z_b across point a-b in Figure 2-3. This figure also gave the reasons why IEC and IEEE standard mentioned the power factor of burden is 0.8 or 0.9 not the resistive burden.

However, resistive burden R_{in} is sometimes advised in the measurement of high frequency current [23]. Likely, from previous researches discussed in 2.3, the researchers made experiments on the CT at high frequency with only resistive burden. Nevertheless, as shown in Figure 2-3, the burden of CT is obviously consisted of resistance and inductance, i.e. $Z_b = Z_w + Z_{in} = Z_w + R_{in}$. Thus, at constant current I_s, the voltage across R_{in} is varied as the voltage across Z_w is changed with the frequency of the current. Here, the power factor of burden decreased with increasing frequency. Therefore, [23] suggested that power factor of the burden should be as high as possible (i.e. resistive burden), in order to offset the effect of increasing impedance of Z_w with frequency. Again, when we look at Figure 2-3, sometime the power factor is high because of increasing of Z_w. Therefore, the violation of power factor of 0.8 or 0.9 according to IEC standard or IEEE standard, respectively, occurred.

As the information of the accuracy of CT over wide frequency range based on IEC standard burden or IEEE standard burden is lacked as well as considering the fact that the application of CT are similar to Figure 2-3. One can see the strong interaction between the accuracy of CT and the exact value of burden. The author intends using a very precise value of burden and very accurate test on the ratio error of CT. This investigation carried out the influence of burden on accuracy of CT over wide frequency range because it involved to the power quality measurement, especially the economic impact.

Chapter 3 : Test procedure and equipment

This section describes the procedure and equipment for testing the accuracy of CT at high frequency. The tests are based on the standard burden corresponding to IEC and IEEE standards. The discussion on the burden under investigation and the verification of accuracy of standard CT are provided in this chapter.

3.1. CTs under investigation

From previous studies, we assumed that the ratio error occurred when inductive CT was used at high frequency. The ratio error of CT depended on several parameters such as amplitude of current and accuracy class of CT. On the other hand, the burden also effected to frequency response of CT, especially when the value of burden was varied with frequency. As mentioned in section 2.2.3, the burden of CT must have power factor of 0.8 or 0.9 lagging according to IEC 61869-2-2012 or IEEE C57.13-2008, respectively. Moreover, no standards specified the performance of CT at high frequency. Therefore, the experiment on CT to characterize the influence of burden on frequency response is investigated.

In order to characterize the ratio error of CT, the experiments were conducted on three ring CTs. Figure 3-1 showed CTs under test and Table 3-1showed the nameplate of CT.

(a) *(b)* *(c)*

Figure 3-1: Three CTs under test (a). CT1, (b). CT2 and (c). CT3.

Table 3-1: The specification of CTs under test.

Rated CT	**CT 1**	**CT2**	**CT3**
Ratio	150 A / 5 A	200 A / 5 A	400 A / 5 A
Burden	5 VA	10 VA	5 VA
Class	1	1	1
Frequency	50/60 Hz	50/60 Hz	50/60 Hz

The important equipment in this test was the burden Z_b which was defined as the total impedance across point a and b at secondary side of CT or $Z_b = Z_w + Z_{in}$ (as discussed in section 2.2.3). This work adopted several types of burdens whose power factors are according to IEC and IEEE standards. Moreover, the resistive burdens were taken into the consideration. All types of these burdens will be presented in section 3.2.

3.2. Determination of Burden

As discussion about the burden of CT in previous sections, there were two standards which provided the different power factor of burden for metering CT. IEC 61869-2-2012 [19] mentioned that the power factor of burden shall be 0.8 lagging at 50 Hz and the power factor of 0.9 lagging at 60 Hz is given by IEEE C57.13-2008 [20].

Hence, the author constructed the burden of CT by using many metal-film resistors in parallel and in series with toroid core inductor in order to obtain the power factor as the standards declared. Moreover, the experiment used resistive burdens which were constructed by a few surface mount device (SMD) resistor in parallel to ensure that it had a very small inductance.

In this test, the single current with adjustable frequencies was injected to CT. Then, CT transformed this signal to secondary side with the same frequency injected. As we knew that the value of impedance varied according to the test frequency. Therefore, two cases study of burden Z_b were considered to analyze the frequency response of CT:

- **First case:** The value of Z_b was fixed. It means that the value of Z_b was calculated or measured only at 50 Hz and this value was used to calculate I_s of CT at 50 Hz and other frequencies. In this case, the Z_b was called *fix burden*, $Z_{b,fix}$.
- **Second case:** The value of Z_b was depended on the frequency of I_s. In this case, the Z_b was called *frequency dependence burden*, $Z_{b,f}$.

In addition, $Z_{b,f}$ was obtained by measurement and calculation. The values of $Z_{b,f}$ from the measurement, by using 4287A Precision LCR Meter, will be called $Z_{b,f\text{-}mea}$ and the values of $Z_{b,f}$ from the calculation will be called $Z_{b,f\text{-}cal}$ and calculated by using equation (3-1). The value of $Z_{b,f\text{-}cal}$ deviated from the real value of $Z_{b,f\text{-}mea}$. Thus, the deviations ΔZ_b of these burdens were found in equation (3-2). The following sub-sections were the discussion on burden based on each standards.

$$Z_{b,f-cal} = \sqrt{R_{bc}^2 + X_{b,f-mea}^2} \tag{3-1}$$

$$\Delta Z_b = \frac{Z_{b,f-cal} - Z_{b,f-mea}}{Z_{b,f-mea}} \times 100 \tag{3-2}$$

where $X_{b,f\text{-}cal} = 2\pi f L_b$, f is the test frequency and ΔZ_b is the deviation.

Some techniques to measure the value of burden and the discussions of all burdens based on both standards are provided in next sub-section.

3.2.1. Measuring the value of burden

In general, many types of impedance measuring instruments, corresponding to each measurement technique, are available. The best instrument for a particular measurement depends on the parameters required such as the magnitude, the range of frequency, and the accuracy. Nowadays the technology of LCR meter is extensively for high accuracy required with wide range of frequency. In this study, 4287A Precision LCR Meter, as shown in Figure 3-2, is used to measure the absolute value and the power factor of burden.

Figure 3-2: 4287A Precision LCR Meter.

A. General information for using LCR Meter

The capabilities of this LCR meter can make measurements with selectable test frequency, adjustable measured equivalent circuit mode (e.g. series and parallel), and other parameters. Often, there are confusions of choosing the right parameters to measure certain components to obtain accurate reading on the display of instrument. Some important comments and tips provide some knowledge for applying in measurement with certain settings to achieve an accurate measurement.

– *Measurement frequency*: The choice of measurement frequency shall reflect the application of the component since the reactance is a function of frequency.
– *Measurement level*: The test condition shall reflect the usage of the component and changing temperature can affect measured value.
– *Equivalent circuit*: Figure 3-3 present the two models of components. Where X, R_s and R_p are the reactance of the component, the series resistance and the parallel resistance, respectively.

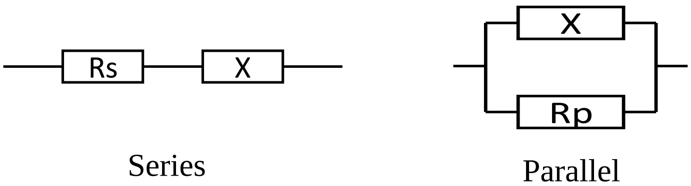


Figure 3-3: The equivalent of circuits of impedance.

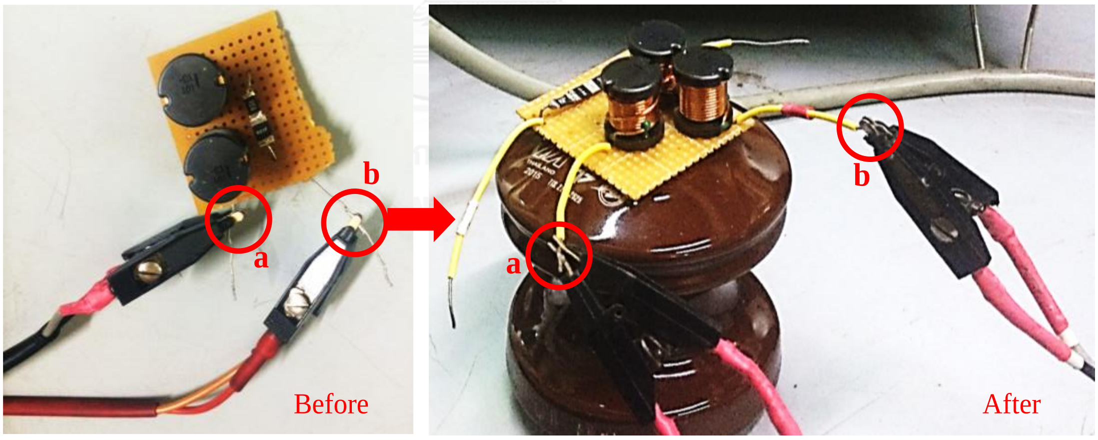
Choosing the model to measure depend on some conditions. When the reactance is large, the series resistance might be negligible; so the better measurement may be the parallel model. Conversely, when the reactance is small, the parallel resistance might be negligible, so the series model can be used. Thus, the guideline prefers using the parallel circuit model for large inductance and the series circuit model for small inductance.

- Measuring the impedance magnitude and phase angle are preferable since the resistance and reactance can be calculated from these two parameters. Intuitively, a pure resistance or a mixture of resistance and reactance can regard to the phase angle.
- Checking the accuracy specifications and reviewing the manual of meter are recommended.

B. The error of measurement in this test

In addition, this work used 4287A Precision LCR Meter to make sure that value of burden was quite similar to standard burden and to verify resistive burden did not have inductive effect at the frequency range considered.

From one measurement to another, the values of burden were not the same. Firstly, the author did not considered about the terminal point of measured burden, as shown in Figure 3-4 (a). It means that the terminal points a and b was not fixed for each measurement. As results, the voltage level across the component made noticeably the error of the measured value. Then, to solve this problem, the terminal points a and b were fixed for each measurement by marking point, as shown in Figure 3-4 (b). Although the error of measurement was reduced, the tolerance of measured value still had. Hence, taking average value of all measurement was considered to get value close to the real value.



(a) (b)

Figure 3-4: The measurement technique, (a) not fix terminal point of burden and (b) fix the terminal point of burden.

3.3. Burden in this investigation

3.3.1. Based on IEEE standard burden

According to IEEE standard [20], the power factor of burden shall be 0.6 to 1.0 lagging. In the specific condition of this test, several burdens with the approximately power factor of 0.9 at 60 Hz and two resistive burdens were constructed. Figure 3-5 presented the constructions of burden A-F and their values were shown in Table 3-2.

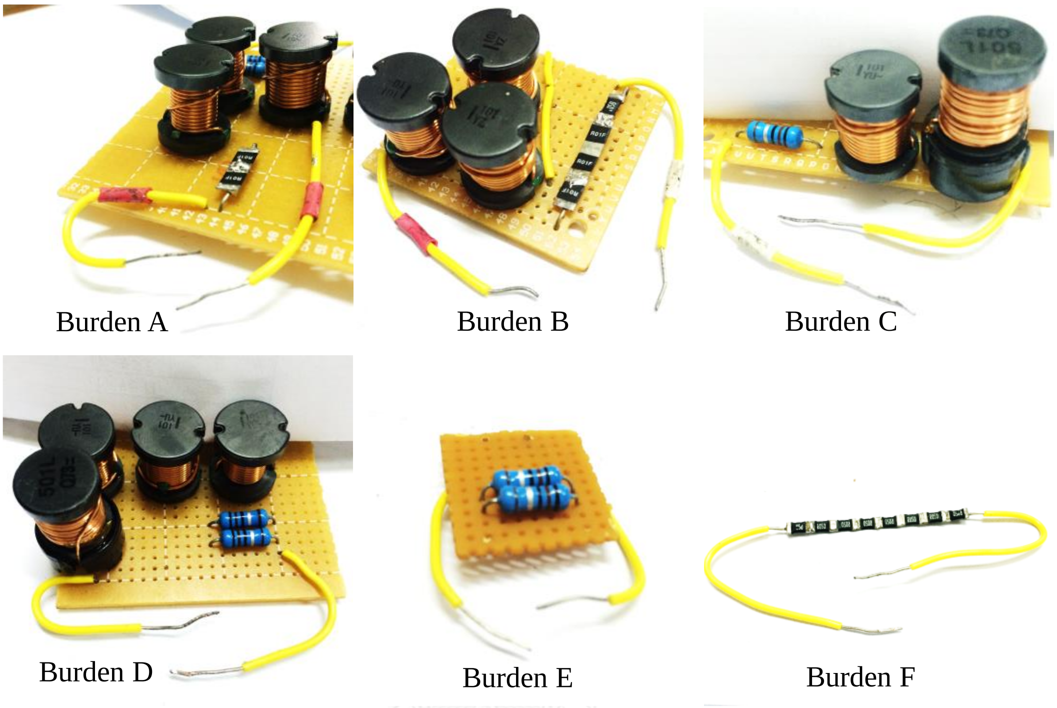


Figure 3-5: The constructions of burden A-F based on IEEE standard burden.

Table 3-2: Burdens for testing CT, at 60 Hz.

Burden	Z_b (Ω)	R_b (Ω)	L_b (mH)	PF	% of standard burden
A	0.122	0.107	0.155	0.88	61
B	0.210	0.184	0.267	0.88	105
C	0.411	0.362	0.514	0.88	205
D	0.576	0.530	0.597	0.92	288
E	0.6	0.6	0	1	300
F	0.4	0.4	0	1	200

All the values in this table were the fix burden $Z_{b,fix}$ and were used to calculate the output current I_s of CT. Burden A to burden C had power factor roughly equal 0.9. Burden B was noted as the standard burden for CT1 and CT3 and burden C was the standard burden for CT2. In order to see the effect of inductance, the author decreased the L/R ratio of the burden, burden D was a case in point. In addition, the resistive burdens such as burden E and burden F were included in this investigation.

Furthermore, the values of $Z_{b,f}$ were presented in Table 3-3. As mentioned above, these values were obtained from the calculation and the measurement and were varied with the value of test frequency from 60 Hz to 1 kHz.

Table 3-3: The value of $Z_{b,f\text{-}cal}$ and $Z_{b,f\text{-}mea}$, [Ω], at frequency from 60 Hz to 1 kHz.

Frequency [Hz]	Burden A		Burden B		Burden C		Burden D	
	$Z_{b,f\text{-}cal}$	$Z_{b,f\text{-}mea}$	$Z_{b,f\text{-}cal}$	$Z_{b,f\text{-}mea}$	$Z_{b,f\text{-}cal}$	$Z_{b,f\text{-}mea}$	$Z_{b,f\text{-}cal}$	$Z_{b,f\text{-}mea}$
60	0.122	0.122	0.210	0.210	0.411	0.411	0.576	0.576
150	0.174	0.179	0.307	0.313	0.597	0.603	0.814	0.815
250	0.256	0.266	0.453	0.464	0.873	0.885	1.115	1.157
350	0.345	0.360	0.611	0.627	1.173	1.190	1.532	1.535
450	0.435	0.455	0.771	0.791	1.477	1.499	1.919	1.922
550	0.527	0.552	0.935	0.961	1.790	1.817	2.318	2.322
650	0.620	0.650	1.100	1.131	2.105	2.137	2.721	2.725
750	0.712	0.747	1.263	1.298	2.416	2.454	3.120	3.124
850	0.807	0.847	1.432	1.472	2.739	2.781	3.534	3.538
950	0.898	0.942	1.593	1.638	3.046	3.093	3.928	3.932
1000	0.945	0.990	1.677	1.721	3.206	3.253	4.134	4.135

In order to see clearly about the effect of measurement and calculation, the values of $Z_{b,f}$ and their deviation ΔZ_b were plotted in Figure 3-6.

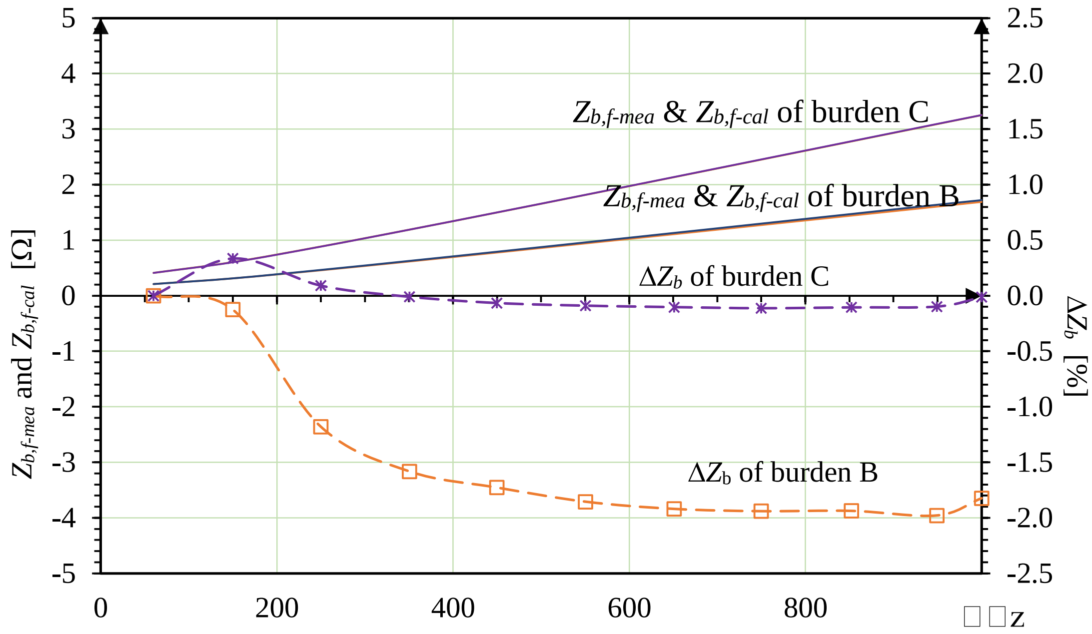


Figure 3-6: The comparison between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ for standard burden B and C.

In this Figure, the left vertical-axis was valid for the value of $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ while the right vertical-axis was valid for ΔZ_b (dashed line). Anyways, because the characteristic of these burdens were similar, the author showed only burden B and C in this figure. We can notice that there were small errors between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ for burden C, less than 1 %, and for burden B, less than 2%.

3.3.2. Based on IEC standard burden

According to the IEC 61869-2, the CT shall guarantee its ratio error at any burdens between 25% and 100% of the declared burden. The declared burden or the standard burden, shall have a power factor of 0.8 lagging. Figure 3-7 presented the construction of burden A-F. The burden A to burden C, which showed in Table 3-4, have power factors approximately equal to 0.8 lagging at 50 Hz. For burden E and burden F, the values were equal to the values in Table 3-2. All the values in this Table 3-4 were the fix burden $Z_{b,fix}$ and were used to calculate the output current of CT.

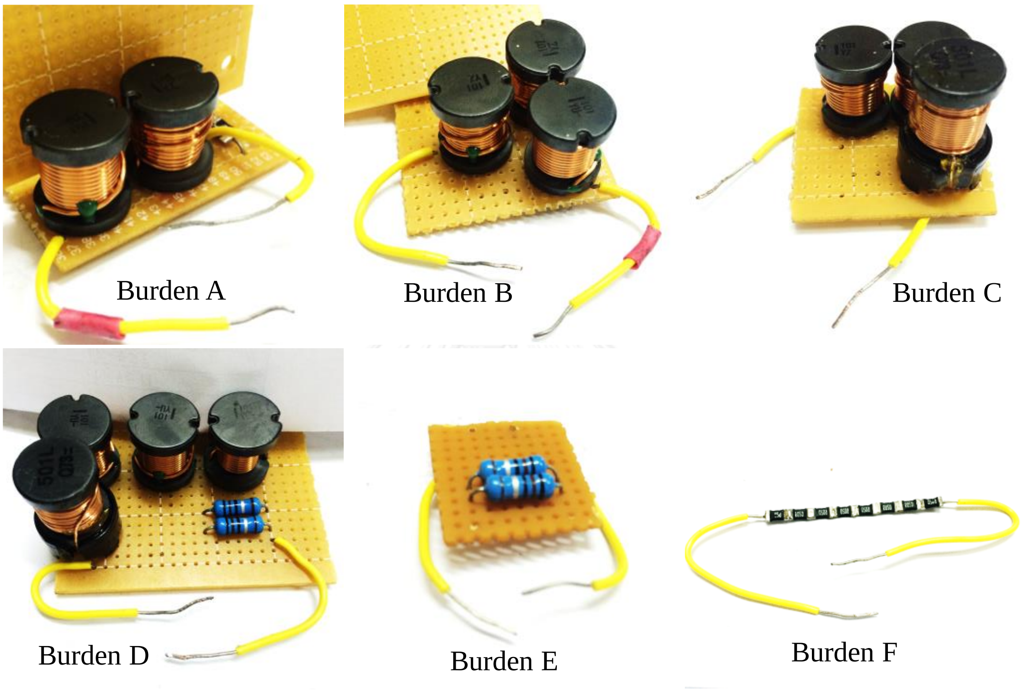


Figure 3-7: The construction of burden A-F based on IEC standard burden.

Table 3-4: Burden for testing CT, at 50 Hz.

Burden	**Z_b (Ω)**	**R_b (Ω)**	**L_b (mH)**	**PF**	**% of standard burden**
A	0.133	0.105	0.258	0.79	66
B	0.190	0.152	0.365	0.80	95
C	0.403	0.328	0.746	0.81	201
D	0.571	0.533	0.653	0.93	285
E	0.6	0.6	0	1	300
F	0.4	0.4	0	1	200

Moreover, the values of burden which are called the frequency dependence burden $Z_{b,f}$ are showed in Table 3-5. These values were obtained by measuring and calculating at frequency from 50 Hz to 1 kHz.

Table 3-5: The value of $Z_{b,f\text{-}cal}$ and $Z_{b,f\text{-}mea}$, [Ω], at frequency from 50 Hz to 1 kHz.

Frequency [Hz]	Burden A		Burden B		Burden C		Burden D	
	$Z_{b,f\text{-}cal}$	$Z_{b,f\text{-}mea}$	$Z_{b,f\text{-}cal}$	$Z_{b,f\text{-}mea}$	$Z_{b,f\text{-}cal}$	$Z_{b,f\text{-}mea}$	$Z_{b,f\text{-}cal}$	$Z_{b,f\text{-}mea}$
50	0.133	0.133	0.190	0.190	0.403	0.403	0.571	0.571
150	0.265	0.267	0.376	0.378	0.775	0.777	0.814	0.815
250	0.418	0.423	0.592	0.579	1.216	1.220	1.155	1.157
350	0.577	0.584	0.817	0.824	1.674	1.679	1.532	1.535
450	0.736	0.744	1.041	1.050	2.132	2.138	1.919	1.922
550	0.898	0.908	1.270	1.281	2.599	2.607	2.318	2.322
650	1.060	1.072	1.499	1.513	3.067	3.076	2.721	2.725
750	1.219	1.234	1.725	1.740	3.528	3.538	3.120	3.124
850	1.384	1.401	1.958	1.975	4.006	4.016	3.534	3.538
950	1.541	1.559	2.180	2.199	4.459	4.470	3.928	3.932
1000	1.623	1.639	2.296	2.313	4.696	4.704	4.134	4.135

In addition, the values $Z_{b,f}$ of some burden like burden B and burden C are shown in Figure 3-8 and ΔZ_b is also included.

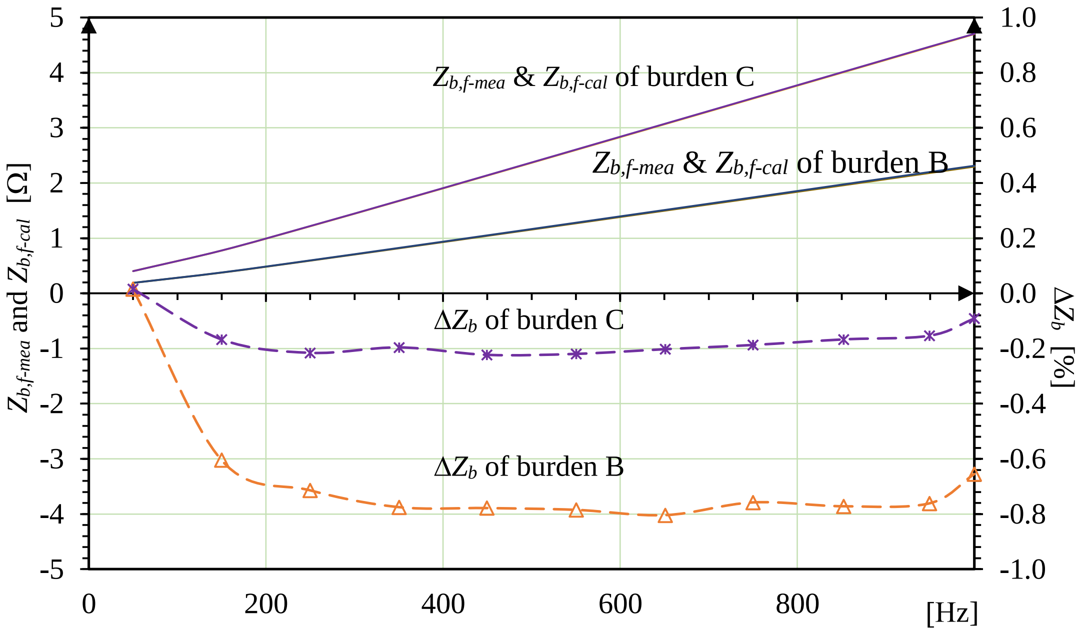


Figure 3-8: The comparison between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ for burden B and C.

In this illustration, the left vertical-axis was valid for the value of $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$, while the right vertical-axis was valid for ΔZ_b (dash line). The results indicated that there were small errors between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ for burden B, roughly 0.8%, and for burden C, roughly 0.3 %. From Figure 3-6 and Figure 3-8, we noted that almost value of $Z_{b,f\text{-}mea}$ was higher than the value of $Z_{b,f\text{-}cal}$.

3.3.3. Conclusion

The several burdens of CT under test are discussed. As mentioned previously, two power factors of burden i.e. 0.8 and 0.9 are taken in consideration for testing the ratio error of CT. Moreover, this work extended the study of the behavior of burden. The values of burden are examined not only at frequency of 50 Hz but also at other frequencies from 50 Hz to 1 kHz. Because of the characteristic of impedance at high frequency, the value of these burdens, excluding the resistive burden, dramatically increased with increasing frequency, as shown in Figure 3-6 and Figure 3-8. We notice that ΔZ_b is slightly high because of the method of measurement with the 4287A Precision LCR Meter. The higher error of measurement is occurred when the small value of resistance is measured, e.g. for burden A (Z_b=0.13 Ω, PF=0.8). Other cause of these errors can be the effect of the construction of each burden. When the burden is constructed in different method, the parasitic of components and other disturbance also varied, as shown in Figure 2-4. For example, the burden with power factor of 0.8 consisted only inductance connected in series because the resistive part of this burden, shall be the internal resistance of inductance. Unlikely, the burden with power factor of 0.9 consisted the resistance and the inductance connected in series and parallel. Therefore, the deviations of these two types burden were different.

From these results, the author expect that the increasing values of these burdens will reflect to increasing of the ratio error of CT when the CT is tested at frequency differs from rated frequency. Moreover, the error between $Z_{b,f\text{-}cal}$ and $Z_{b,f\text{-}mea}$ shall be considered because it may effect to the ratio error. From these error, the author carefully measured the value of burden in order to reduce the error of test on the ratio error of CT. The terminal point of measured component shall be fixed from one measurement to another, when the repeat or the verification of measurement is obligation. In addition, taking average value of all measurements is considered to get value close to the real value.

Finally, all experiments on the ratio error of CT in this study, the author separated the determination of output current of CT in two cases. First case based on the fix burden and otherwise based on the frequency dependence burden.

3.4. Preliminary test with single frequency current

As mentioned previously, there were several parameters which affect to accuracy of CT. Hence, the preliminary test of the influence of burden on the ratio error of CT was examined. The test circuit is shown in Figure 3-9.

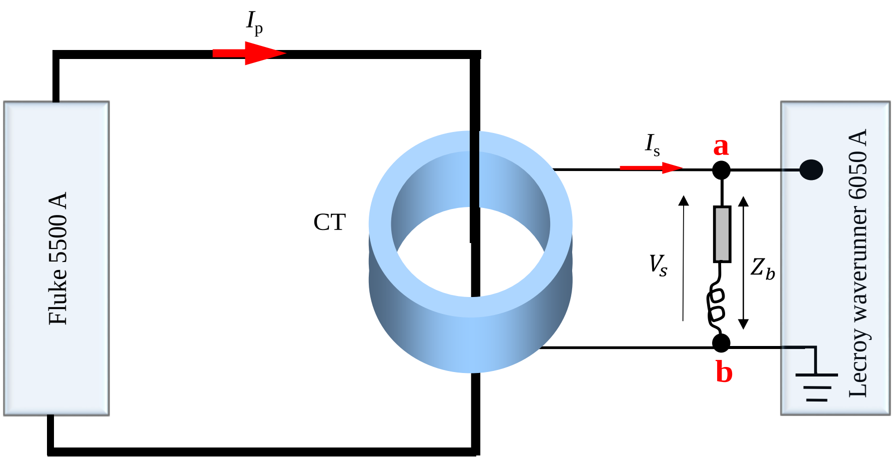


Figure 3-9: Test circuit by injected single frequency current.

The output current I_s of CT was simply equal to V_s divided by burden Z_b, as given in equation (3-3).

$$I_s = \frac{V_s}{Z_b} \tag{3-3}$$

As the results, the ratio errors were obtained by using equation (2-5). The full circuit test in laboratory was presented Figure 3-10. From one measurement to another, the connection was fixed to limits the tolerance of each measurement, as shown in Figure 3-11. Because the total of burden of CT was the burden across the points a and b in Figure 2-3, measuring the burden and the output signal of CT must be at the same points (a and b). A thorough description of the test equipment were as follow.

Figure 3-10: Real test circuit when single frequency current was injected to CT1 with standard burden B.

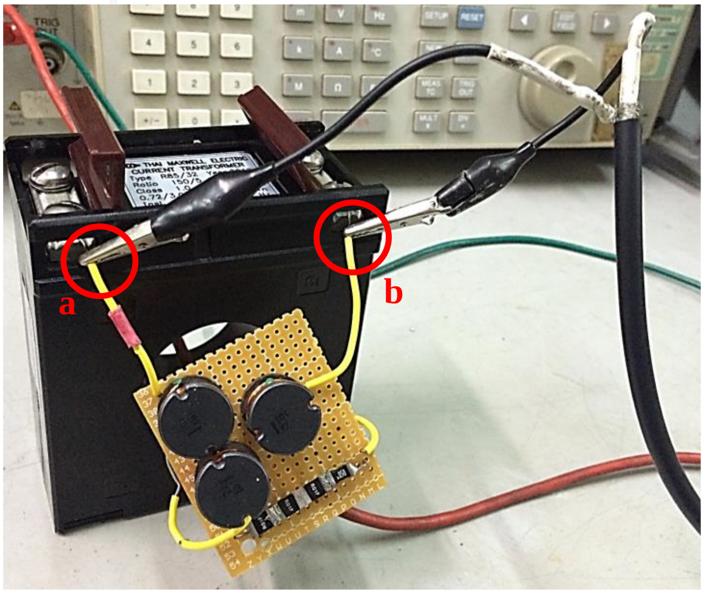


Figure 3-11: The connection between an oscilloscope and a burden, point a and b.

3.4.1. Current source

The Fluke Model 5500A Multi-Product Calibrator, as shown in Figure 3-12, was used as a high stability signal generator for exciting primary current I_p to CT. The Fluke 5500A can deliver test current up to 10A at various frequencies up to 1 kHz (for frequency up to 5 kHz, this calibrator can inject maximum test current of only 2 A). In order to insure that the output of this calibrator is correct, it was calibrated by the National Institute of Metrology, Thailand (NIMT). The results of calibration showed that the output current uncertainty, at 50 Hz up to 1 kHz, was ± 0.12 mA/A, with 95% confidence level.

Figure 3-12: Fluke Model 5500A Multi-Product Calibrator.

In this test, the current waveform was single frequency current which had the rms value of 10 A with adjustable frequency from 50 Hz to 1 kHz. Anyways, because of back Electromotive Force (e.m.f), we were not sure whether we can use the Fluke 5500A to inject a test current to 2-windings CT or not. This became the reason for using ring CT in this study. Some reasons that the test current of 10 A was used in experiment were:

- The amplitude of harmonic is usually not high.
- The current of 10 A is roughly 5 % of rated current.
- The calibrator has limit of current at high frequency.

3.4.2. Measuring the output current I_s

The LECROY WAVERUNNER 6050A, which is digital storage oscilloscopes (as shown in Figure 3-13), was connected to point a and b of the secondary side of CT, i.e. across Z_b, in order to get the output waveform V_s, as shown in Figure 3-9. Then, this work used this oscilloscope to analyze the output waveform by using its built-in Fast Fourier Transform (FFT). The purpose of this analysis was to explore whether the output waveform had a single frequency or not, if a single frequency current was injected to primary side of CT.

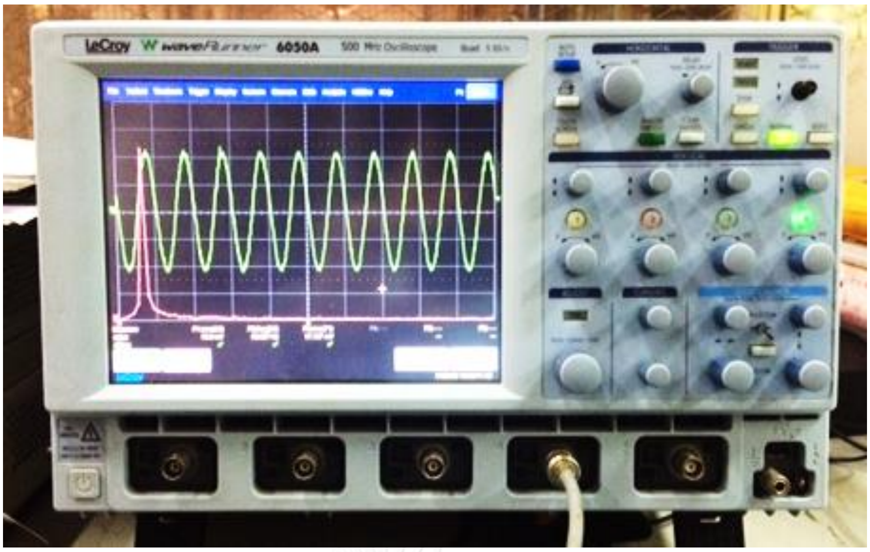


Figure 3-13: LECROY WAVERUNNER 6050A oscilloscope.

However, some cautions should be considered when use oscilloscope, as well as FFT analysis, to avoid the error in the measurement. In order to sight the cause of errors in implementation of oscilloscope, the following comments are given.

A. Increasing vertical resolution

The loss of data makes the error from one measurement to another always happen when use oscilloscope without care about vertical scale which views in display grid. Thus, choosing an appropriate Volts/div scale (fully display the waveform) is vital to get an accurate value. The variable gain is an effective way to increase vertical resolution by adjusting the gain in increment with the granularity.

B. Leakage and aliasing

In most case, the spurious signal position in the display grid will significantly change the spectrum. Leakage and aliasing effects, which make the pseudo-spectrum, must be clearly known in order to get correct acquisition data in frequency domain when using FFT.

Aliasing happened when the input signal contains a frequency component greater than the Nyquist frequency (half the sampling frequency). It is a simple way to check this problem by adjusting the sample rate, then observing whether the distribution of frequency changes or not.

Leakage is other reason that makes the frequencies fold back and spurious in the spectral domain (the spectra magnitudes are not correspond to the real values in the time domain). Leakage occur when the final replication of signal contain in the time grid is outside the observation window. We can avoid this error by ensuring that input signal appears in the display grid without discontinue at the edges. Other way can smooth the edges of the signal by using a window function.

C. Choosing a Window

The type of spectral window define the characteristic of signal. The window function defines the shape and the bandwidth of the filter to be used in the FFT procedure. In some experiments, it is essential to choose the window which is most suitable. Some types of window such as Rectangular, Hanning (Von Hann), Hamming, Flat Top and Blackman–Harris are built in LECROY scope. The highest frequency resolution, Rectangular windows, are useful to estimate the harmonic component in the signal. Flat Top and Blackman-Harris are alternative functions with less attenuation but provide maximum amplitude, especially Flat top gives excellent amplitude accuracy. For general purpose, Hamming and Von Hann are good application with continuous waveforms.

3.5. Test with harmonic current

From previous sections, the ratio error of CT was tested by injected single frequency current with various frequencies from 50 Hz up to 1 kHz. To test CT as the real practice, a harmonic current was created for testing on ratio error of CT.

3.5.1. Injecting primary current I_p

The test current was supplied by OMICRON CMC 353 Test device, as shown in Figure 3-14. This calibrator had capability to generate the harmonic voltage and current, transient and other distorted waveform. The software, which was completely flexible and adaptable for different testing applications, was used to control this device. Harmonic function, which was the one of those applications, can generate a signal sequence with definable harmonic combination up to 3 kHz, but it depended on the fundamental of voltage or current and the fundamental frequency (50 Hz or 60 Hz). For example if we want to create a harmonic signal with current of 10A and fundamental frequency of 50 Hz, the maximum harmonic order can be up to 19th.

Figure 3-14: OMICRON CMC 353 Device.

Therefore, this test used this device to create the current waveform with the combination of harmonic component up to 19th of the fundamental current of 10 A. The total harmonic distortion (THD) was equal to 9 %. In condition of injected current waveform, the harmonic current was focused on only the odd harmonic and the reason of this condition was discussed in section 2.1. The rms values of each harmonic components were based on the limit current distortion in IEEE Standard. 519, 2014 (Table 2-1). In addition, Table 3-6 presented the rms value of current and the percentage of fundamental current at each harmonic order and these currents were called *injected current* I_p in this study. The full test circuit was shown in Figure 3-15 and full test setup in laboratory was shown in Figure 3-16.

Table 3-6: Real values of harmonic current corresponding to IEEE standard 519, the current value of fundamental of 10A at 50 Hz.

Odd harmonic order of 10A, 50 Hz	rms value [A]	% of fundamental [%]
$3^{rd} – 9^{th}$	0.4	4
$11^{th} – 15^{th}$	0.2	2
17^{th} and 19^{th}	0.15	1.5
Total harmonic distortion = 9 %		

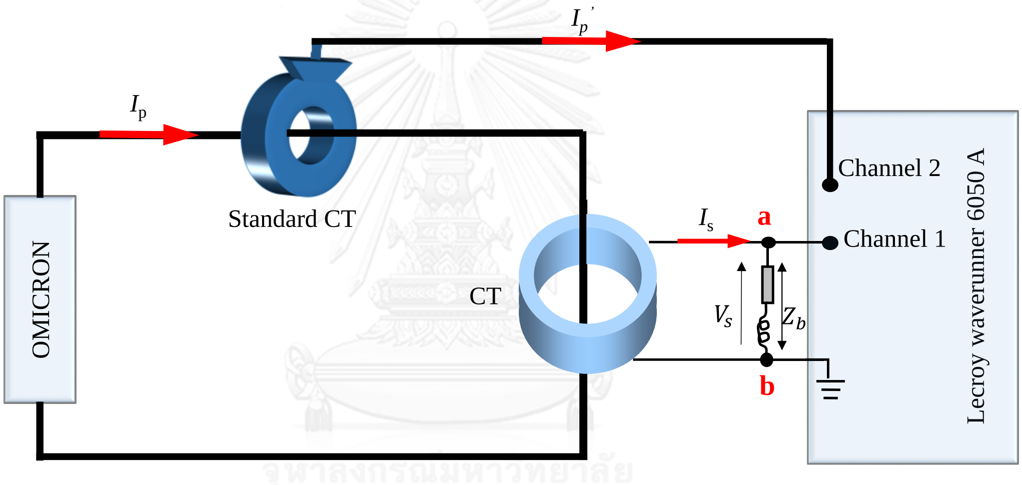


Figure 3-15: Test circuit by injected harmonic current.

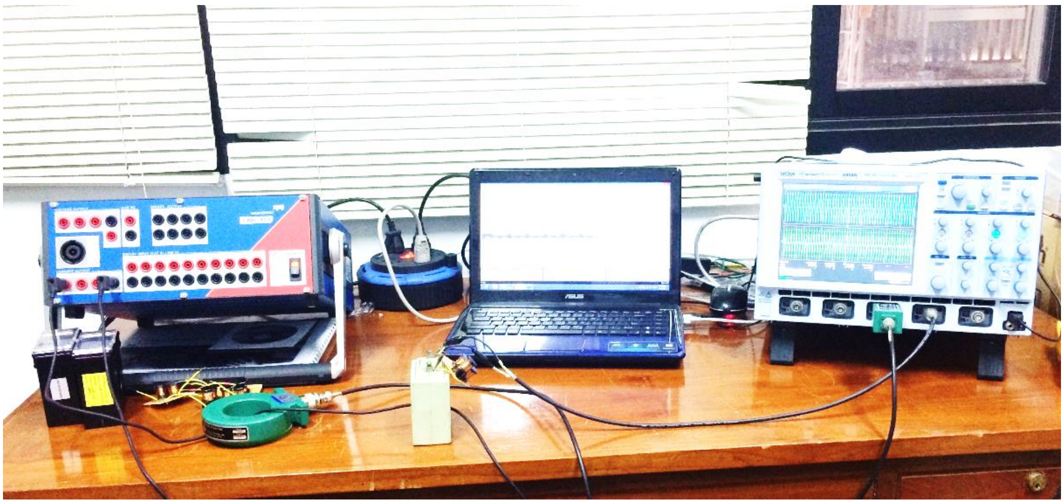


Figure 3-16: Real test circuit when harmonic current was injected to CT2 with standard burden C.

Moreover, this study used the standard CT whose sensitivity equals 0.1 Volt/Ampere (+1/-0%) to measure the primary current of CT. The verification of the accuracy of standard CT will conduct in section 3.6 before implementation into the test system.

3.5.2. Measuring the output current I_s

The same as the preliminary test, LECROY WAVERUNNER 6050A was used to measure and to analyze the signal in spectrum representation. In order to see all harmonic components clearly, FFT was used to analysis the waveform which measured by oscilloscope. The FFT transformed the waveform from time domain to frequency domain in order to get insight of the amplitude of signal. For example, the analysis of harmonic signal is easier in spectral representation than time domain to get magnitude and phase as well as power spectrum.

In addition, the output waveform can be inserted in to Mathlab to analyze this signal in frequency domain by using function fft(). Consequently, the output signal of standard CT and CT under test were connected to first and second channels of oscilloscope, respectively, as shown in Figure 3-15. Before the output currents of both CTs were calculated, the results of built in FFT analysis from oscilloscope were verified with the results of function fft() in Mathlab to confirm that the results from the measurement instrument were correct. The comparison of result built in FFT analysis from Oscilloscope and from Mathlab is shown in Figure 3-17. From this comparison, the error was lower than 1 %. It means that we can analyze the signal by using FFT both in oscilloscope and in Mathlab. Therefore, for next discussions, only FFT analysis in Mathlab is used.

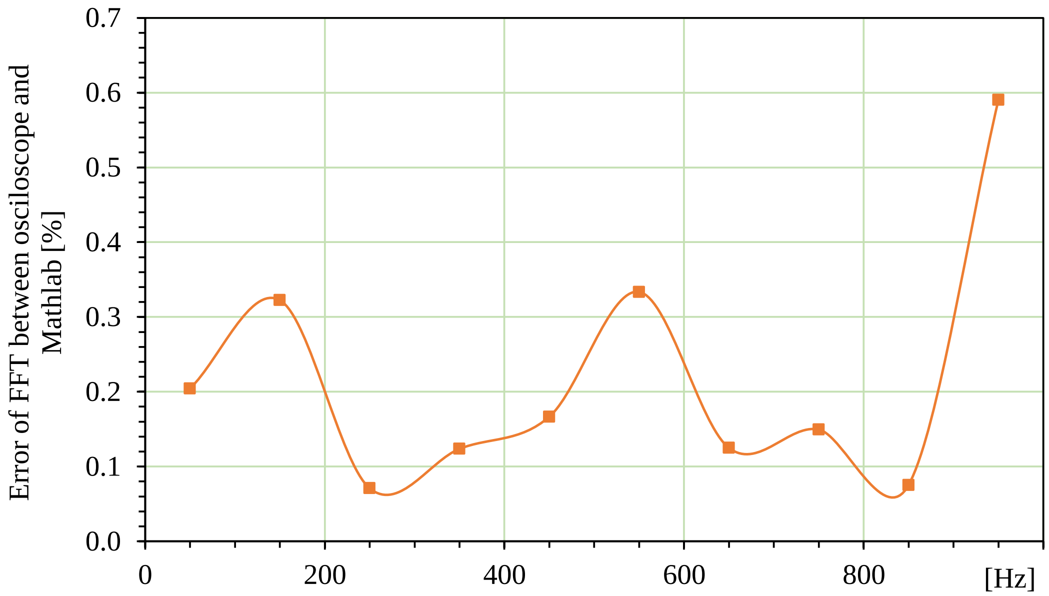


Figure 3-17: The error of FFT by using FFT function in Oscilloscope and in Mathlab.

In this test, after using FFT to transform signal to frequency domain, only the odd harmonic components were selected and another was deleted. The test results are not only analyzed in frequency domain but also in time domain. Hence, an equation (3-4) was used to transform the current signal to time domain.

$$i(t) = \sum_{h=1}^{n} A_h sin(2\pi f_1 ht) \quad (3\text{-}4)$$

Where *i(t)* is the current in time domain, A_h is the magnitude of harmonic component [A], f_1 is fundamental frequency [Hz], *h* is the harmonic order, *n* is the maximum harmonic order and *t* is the time [s].

3.6. Verification of the accuracy of standard CT

For measuring the harmonic current with accurate amplitude, the current monitor or the standard current transformer (standard CT) is used. This work used Pearson Current Monitor as standard CT. Because we were exactly not sure about the uncertain output of the calibrator CMC 353, as established in section 3.5, the standard CT was used to measure the output of this calibrator. In order to avoid incorrectly analyzing the ratio error of CT under test, the accuracy of this standard CT was very important. Therefore, it urged the author to establish the test on the accuracy of standard CT.

In this study, two tests on the ratio error of standard CT is conducted. The first test was done with single frequency current and other was worked with sinusoid current including harmonic. The specification of standard CT is given in Table 3-7.

Table 3-7: The specification of standard CT.

Pearson current monitor: Model 110A	
Classification	Wide band current monitor
Sensitivity	0.1 Volt/Ampere (+1/-0%)
Frequency range	1 Hz up to 20 MHz
Maximum current rms	65 A

3.6.1. Test with single frequency current

In the first test, the small single frequency currents such as 150 mA, 200 mA, 400 mA and 1 A over frequency range from 50 Hz to 1 kHz were generated by Fluke model 5500A and passed through the hold of standard CT. Then the test was repeated with a large current of 10 A (approximate 15 % of rated current). The output wave shape was displayed on LECROY WAVERUNNER 6050A. Thus, we can calculate output current of standard CT by using the sensitivity in volts per ampere of standard CT. The test setup was illustrated in Figure 3-18 and the real circuit test was shown in Figure 3-19.

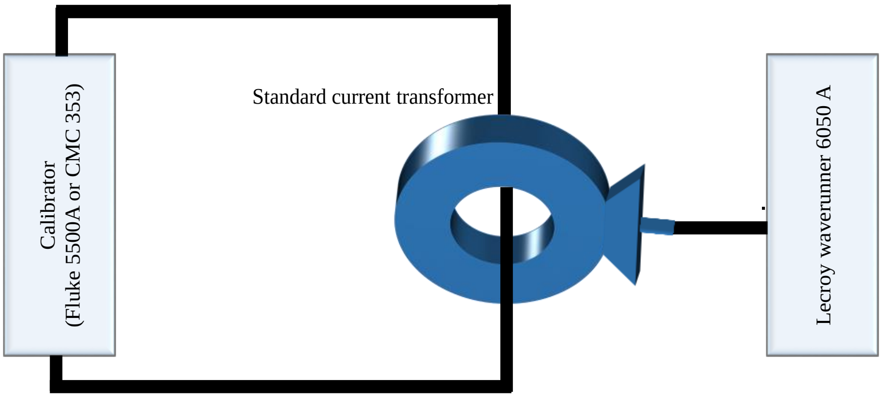


Figure 3-18: Test circuit of standard CT.

Figure 3-19: Real test circuit on the standard CT.

As the result of built in FFT from oscilloscope, the output current of standard CT had the same frequency as the injected current frequency, without any noticeable of other frequencies, Figure 3-20 gave the example of FFT analysis of output signal of standard CT when the small currents were injected. The results from measurements showed that the ratio error of standard CT was depended on the primary current and the test frequency, as shown in Figure 3-21. The ratio error of injected large current e.g.10 A (approximately 15 % of maximum rms current of standard CT), was better than the ratio error of small current, e.g. 1 A (approximately 1.5 % of maximum rms current of standard CT). For example at frequency of 50 Hz when we notice at the ratio error of current of 10 A, the error was within ±2 %; but, when we test CT at current of 150 mA, the error was approximately 8%. However, the ratio error of small current decreased around 3% when the test performed at 1 kHz.

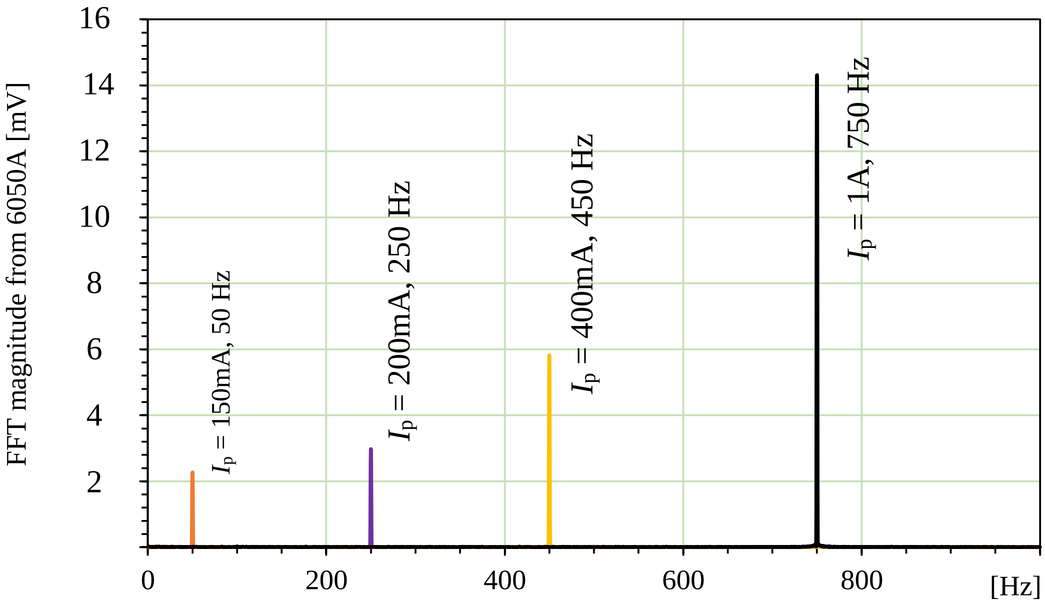


Figure 3-20: The example of FFT analysis when injected small currents.

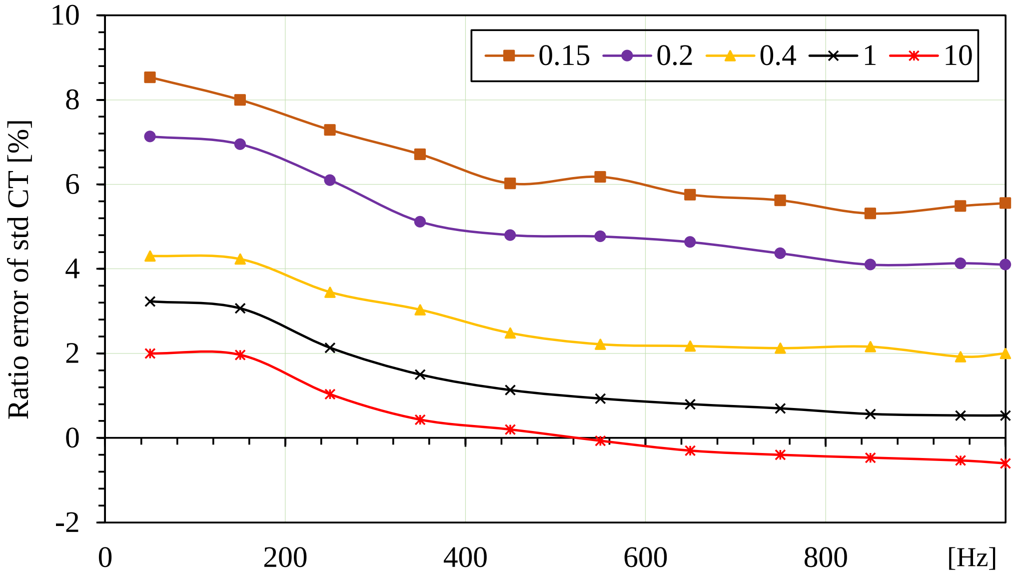


Figure 3-21: Ratio error of standard CT, by using single frequency current.

3.6.2. Test with harmonic current

In the first test, the Fluke Model 5500A was used to calibrate the CT with 95 % confidence level. However, in this test, the signal generator was CMC 353, which was the product of OMICRON, was used to generate harmonic current to test system. From the discussion in section 2.1, the author focused on only the odd harmonic current. In order to correspond to the limit current distortion in IEEE standard 519 in Table 2-1 and be easy to discuss in next section, the rms values of each harmonic components based on the Table 3-6. In this test, the built in FFT analysis in Oscilloscope was used to see the output waveform of standard CT in frequency domain. Then the output current was obtained and called *standard current* I_p'.

Moreover, the additional test on the accuracy of standard CT is examined. The author used the CMC 353 to injected single frequency current with adjustment of frequency. The rms values of each current were the same as each harmonic component. For example at frequency of 50 Hz, the rms current was equal to 10 A and at frequency of 550 Hz, the rms current was equal to 200 mA. The current of additional test is called *individual current*, I_p''. Figure 3-22 illustrated the rms value of current I_p, I_p' and I_p''. The I_p' and I_p'' were taken to compare with real value I_p and Figure 3-23 presented their errors.

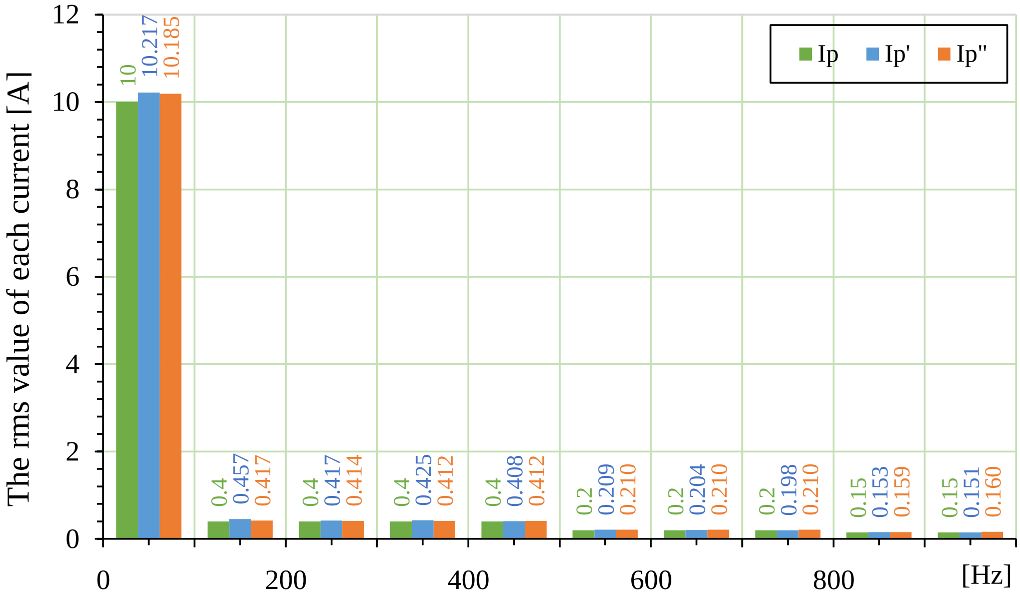


Figure 3-22: The rms value of each current measured (I_p, I_p' and I_p'').

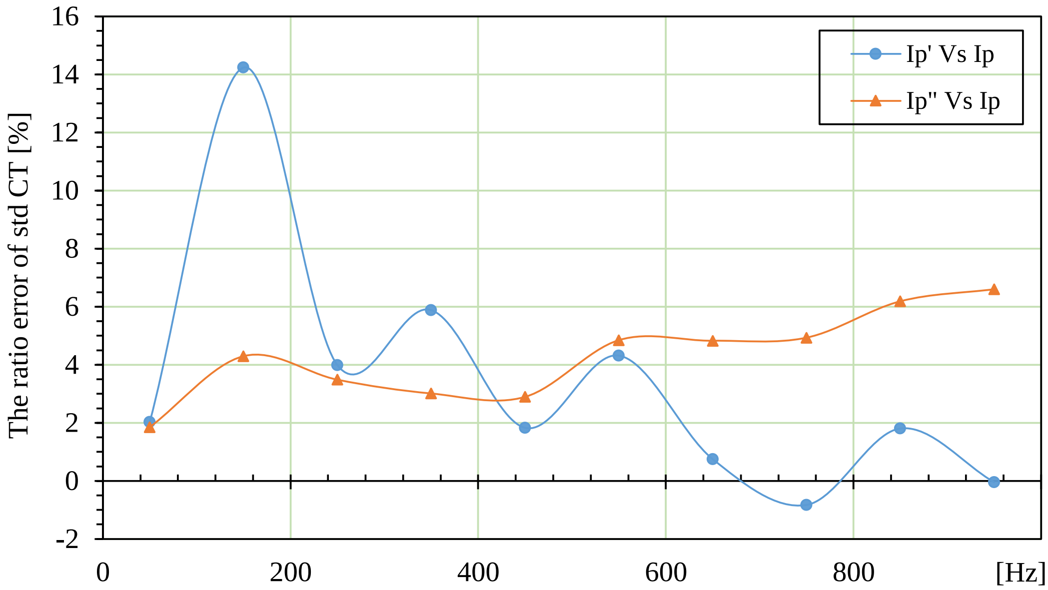


Figure 3-23: The error of real standard current compare to the real current.

At frequency of 50 Hz, the errors of both comparisons were the same, roughly equal to 2%, but the errors changed conversely at other frequencies. The errors of $I_p{}'$ were quite good at high frequency, for example at frequency above 550 Hz, the errors were accurate within ±1%. Unfortunately, at frequency of 150 Hz or at third harmonic order, the error was noticeable equal to 14 %. This high error may be come from the effect of third harmonic in system, as the section 2.1 presented the effect of each harmonic order.

Anyways, the error of $I_p{}''$ approximately increased 2 % at frequency of 550 Hz and this error increased to more than 2 % at frequency of 950 Hz. It means that the error was equal 6 % at frequency 950 Hz. From these errors, we notice that the tendency of the error of $I_p{}''$ was the similarly to the error which was shown in Figure 3-21. For example for the current of 200 mA at 550 Hz in Figure 3-21, the error was equal to 4.77 % while at the same frequency for the rms value of $I_p{}''$ of 200 mA, the error was equal to 5 %.

3.6.3. Conclusion

In order to make sure on the accuracy of standard CT and want to verify the characteristic of standard CT, the test on standard CT is carried out. From the results of analysis, we can conclude that the accuracy of standard CT will be more accurate at high frequency than at frequency of 50 Hz. The measurement of harmonic current will be better when we inject the full current waveform with combination of harmonic than when we inject the individual harmonic current although the rms values of each components are the same. But the drawback of this technique is the effect of third harmonic, as shown in Figure 3-23, the ratio error of $I_p{}'$ is better than the ratio error of $I_p{}''$ but there is high error at frequency of 150 Hz.

There are some reasons that make the high measurement error when we want to use standard CT to measure the small currents (smaller than 1% of rated current). When the current at primary side of standard CT is small e.g. 150 mA, obviously the current at secondary side of standard CT must be too small. Then measurement instrument like Oscilloscope do not have capability to gain signal in full display to get accurate data. Thus the loss of data will occur, as presented in section 3.4. Likely, the accuracy of CT always changes when we change the frequency of measurement and this accuracy is variable with the input current of CT, for example when the input current is small, the output of CT is not accurate.

Chapter 4 : Test results and discussion

This chapter discusses the test results of the influence of burden on the ratio error of CT over wide frequency range, for both power factor of burden based on IEC and IEEE standards. The analyses of the results from two cases of calculation of output current are provided. As mentioned in Chapter 3, there are two types of current source are used to inject current to CT for characterizing the ratio error. First type is the single frequency current which used in the preliminary test and second type is the harmonic current. In the last section, the correction of the ratio error is provided. Because of the similarity of tendency of the ratio error, in this chapter the author will present only the results and discussions on CT1 and the results of other CTs are shown in appendix.

4.1. Preliminary test on ratio error of CT

In this section, the single frequency current was injected to CT by using the Fluke 5500A. As mentioned in section 3.2, the burdens under test had power factor of 0.8 and 0.9 lagging according to IEC standard and IEEE standard, respectively. Therefore, in the following sub-sections, the author separated the standard burden in two parts.

4.1.1. Based on IEEE standard burden

In this section, the power factor of burden under test based on the IEEE standard burden, as discussed in detail in section 3.3.1. For CT1, the burden B was the standard burden which was Z_b = 0.210 Ω = (0.184 + j0.1) Ω. The FFT analyses of the output current from oscilloscope were shown in Figure 4-1, where the label “I_p = 60 Hz” and “I_p = 550 Hz” mean that the input current of CT had a frequency of 60 Hz and 550 Hz respectively.

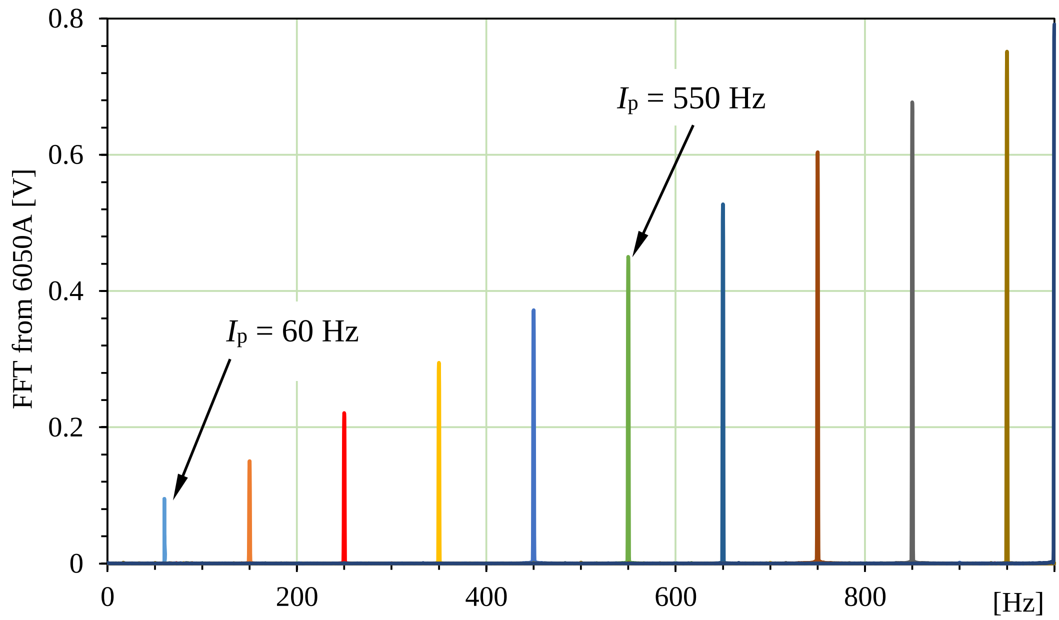


Figure 4-1: FFT analysis of CT1 based on IEEE standard burden, Z_b = (0.184 + j0.1).

Thus, it is clearly that the frequency of the output current has the same frequency as the input current. As we mentioned in section 3.3, in order to obtain the output current of CT, the author proposed two cases of burden (Z_b). The result and discussion of these two cases were following.

A. First case: Fix burden $Z_{b,fix}$

The test results of the ratio error and the ratio correction factor (*RCF*) of CT were shown in Figure 4-2 and Figure 4-3, respectively. In these figures, the left vertical-axis was valid for burden A-D while the right vertical-axis was valid for burden E and F. The test results were obtained by using fix burden $Z_{b,fix}$ at 60 Hz to calculate the output current I_s of CT at other frequencies.

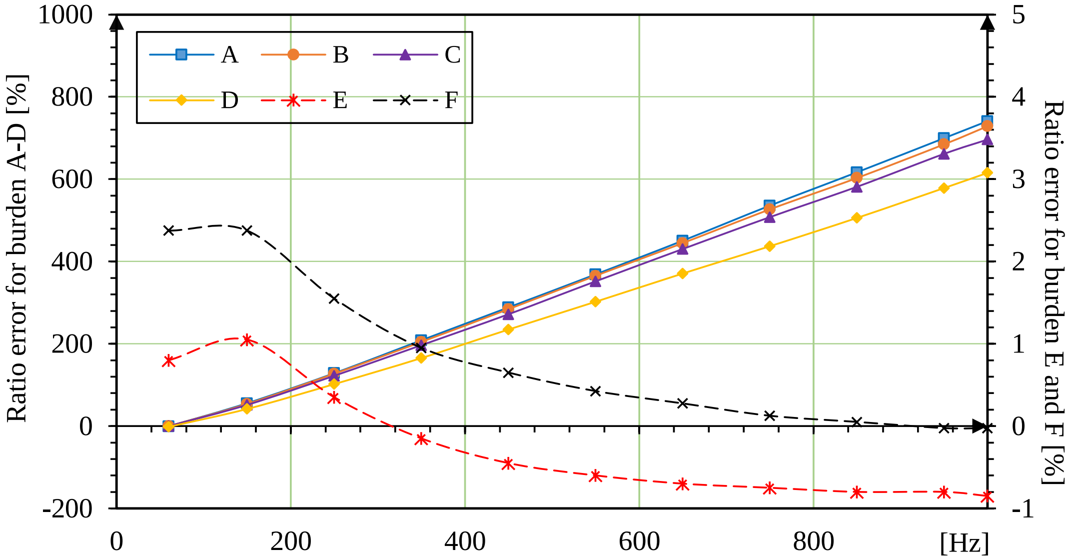


Figure 4-2: Ratio error of CT1, by using fix burden (burden B was standard burden).

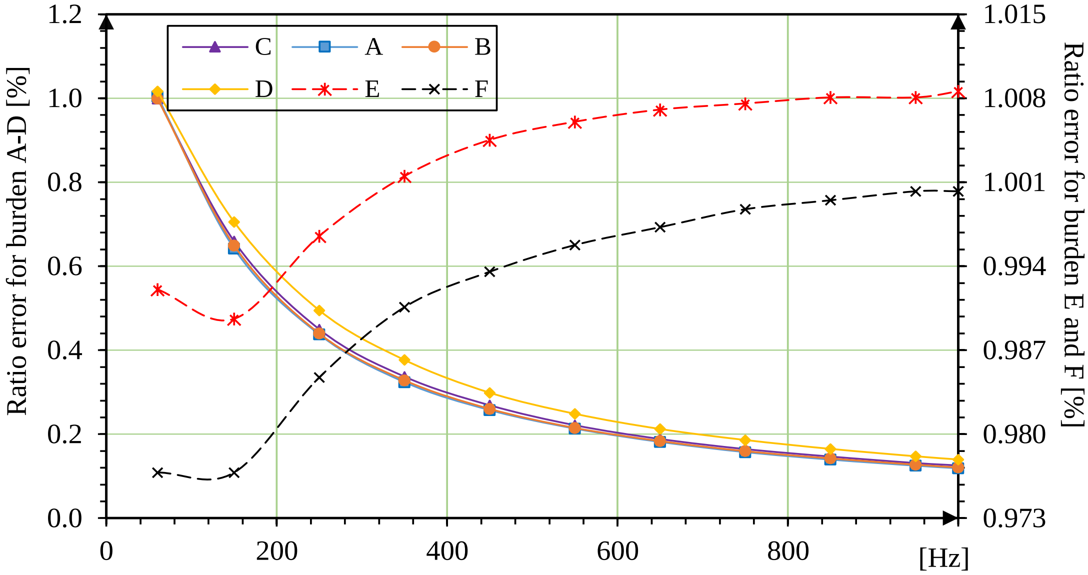


Figure 4-3: Ratio correction factor (RCF) of CT1, by using equation (2-7), (burden B was standard burden).

At frequency of 60Hz, the ratio errors were -0.45 %, 0.10 %, 0.07 %, -1.60 % for burden A-D respectively and the *RCF* of CT1 was equal to one for burden A-D. We can note that the *RCF* of standard burden B was acceptable according to IEEE standard [20].

On the other hand, at high frequency, the ratio error drastically increased with increasing frequency for burden A-D. These high errors come from the behavior of impedance increased with increasing frequency. We can also notice that the dependence of the ratio error on the frequency was reduced when the *L*/*R* ratio of the burden decreased, for example burden D.

For resistive burden, at frequency of 60 Hz, the ratio errors were 0.8 % and 2.38 % for burden E and F respectively. And above frequency of 250 Hz, the ratio error was practically within 1 %. At frequency of 1 kHz, the ratio errors were -0.85 % and -0.02 % for burden E and F respectively. These errors were acceptable for the current distortion limit which was shown in Table 2-1. Thus, if we want to use CT to measure harmonic current, the resistive burden should be advisable.

B. Second case: Frequency dependence burden, $Z_{b,f}$

The ratio error at high frequency was reduced when we use $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ to calculate I_s, as shown in Figure 4-4 and Figure 4-5 respectively. As the author expected in section 3.3.3, the deviation between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ in Figure 3-6 reflected in the ratio errors of CT in Figure 4-4 and Figure 4-5.

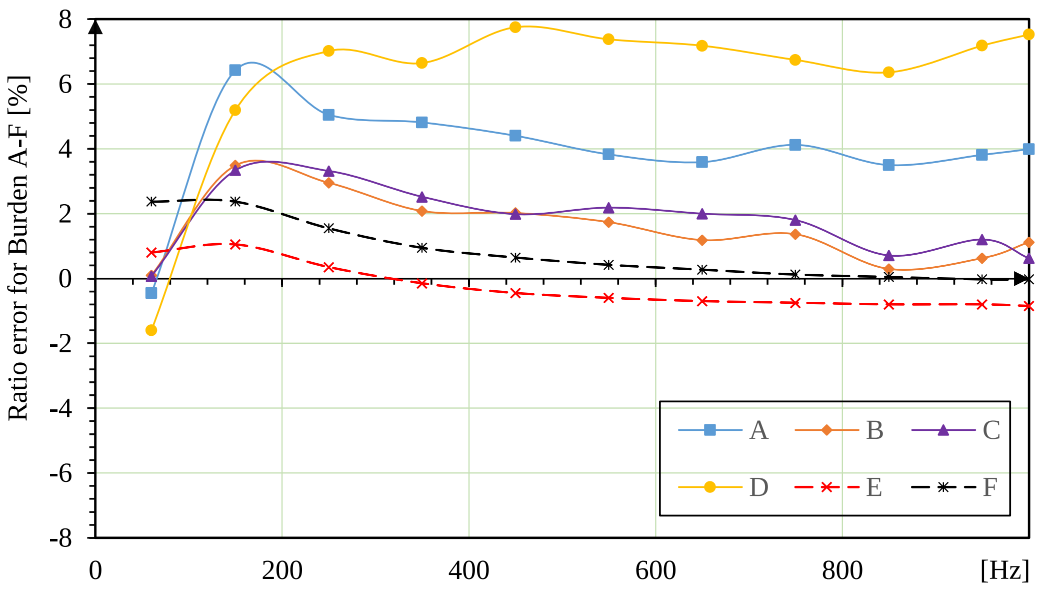


Figure 4-4: Ratio error was calculated by using $Z_{b,f\text{-}mea}$, B was standard burden. The test current was 10 A at various frequencies (60 Hz to 1 kHz).

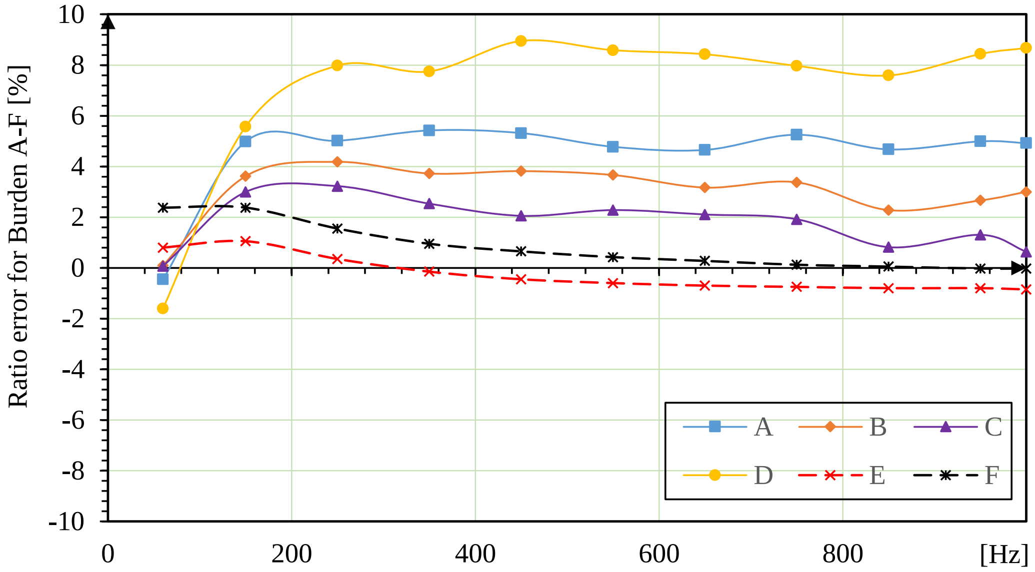


Figure 4-5: Ratio error was calculated by using $Z_{b,f\text{-}cal}$, B was standard burden. The test current was 10 A at various frequencies (60 Hz to 1 kHz).

For example, for standard burden B, the $Z_{b,f\text{-}mea}$ was higher than the $Z_{b,f\text{-}cal}$ about 2 % (see Figure 3-6), hence the ratio error of CT1 by using $Z_{b,f\text{-}mea}$ was lower than the ratio error of CT1 by using $Z_{b,f\text{-}cal}$, about 2 %. This was also true for burden C i.e. the deviation between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ was lower than 1% while the ratio error of CT1 by using $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ was lower than 1% too.

Here, we can assume that the using of $Z_{b,f\text{-}mea}$ or $Z_{b,f\text{-}cal}$, in the calculation of I_s, result was practically the same ratio error. Of course, the method to measure $Z_{b,f\text{-}mea}$ should be considered, when a small value of impedance is measured, e.g. for burden A (Z_b=0.122 Ω).

When $Z_{b,f\text{-}cal}$ was used in the calculation, in Figure 4-5 except at frequency of 60 Hz, the ratio errors for burden A were equal to 5 %. For standard burden B and burden C, the ratio errors were approximately equal to 4 % and 2 %, respectively. The ratio error was high, equal to 8 % for burden D.

In addition, the current of 2 A (1 % of rated current) at frequency 50 Hz up to 5 kHz was injected to CT to observe the frequency response of CT at higher frequency than 1 kHz. The result of this test was shown in Figure 4-6.

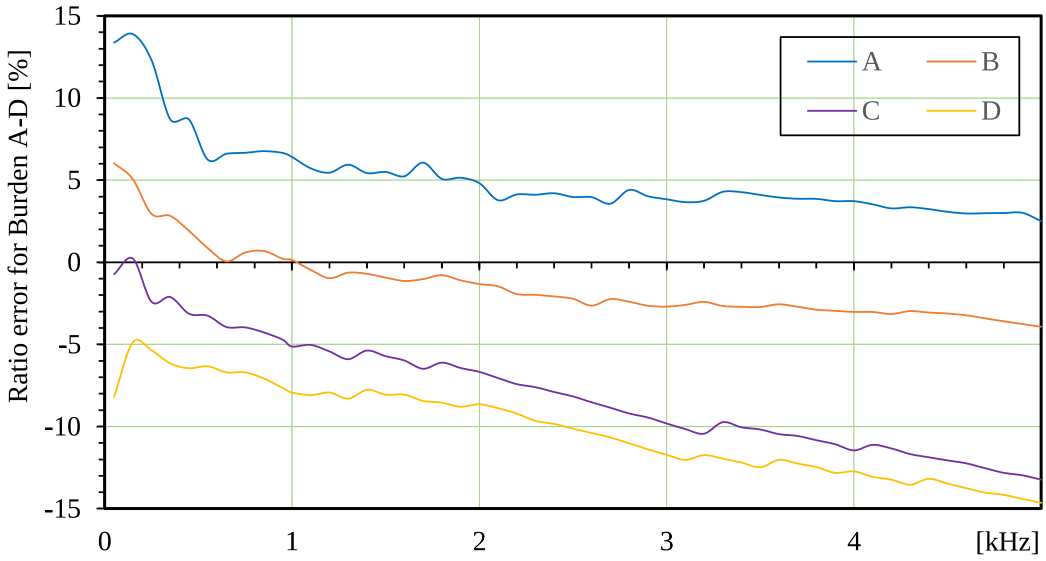


Figure 4-6: Ratio error was calculated by using $Z_{b,f\text{-}cal}$. The test current was 2 A at various frequencies (50 Hz to 5 kHz).

In this case, the ratio error was different from previous case (10A, 50 Hz to 1 kHz) for burden A and D at 60 Hz because the test current was very low compared to rated current (only 1 % of rated current). However, the tendency of the ratio error did not change. It means that the ratio error sloped down when the frequency was increased. Therefore, at high frequency, the effect of inductance of burden on frequency response of CT was reduced. This shows that the burden is strongly effect to frequency response of CT.

4.1.2. Based on IEC standard burden

In this section, the power factor of burden are based on the IEC standard burden, as discussed in detail in section 3.3.2. For CT1, the burden B was the standard burden which was Z_b = 0.190 Ω = (0.152 + j0.114) Ω. As we mentioned in section 3.3, in order to obtain the ratio error of CT, the output current was calculated with the method described in previous chapter. Similarity in previous section, the FFT analyses of the output current from oscilloscope were shown in Figure 4-7, where the label "I_p = 50 Hz" and "I_p = 550 Hz" mean that the input current of CT had a frequency of 50 Hz and 550 Hz respectively. Thus, it is clearly that the frequency of the output current has the same frequency as the input current. The result and discussion of these two cases were following.

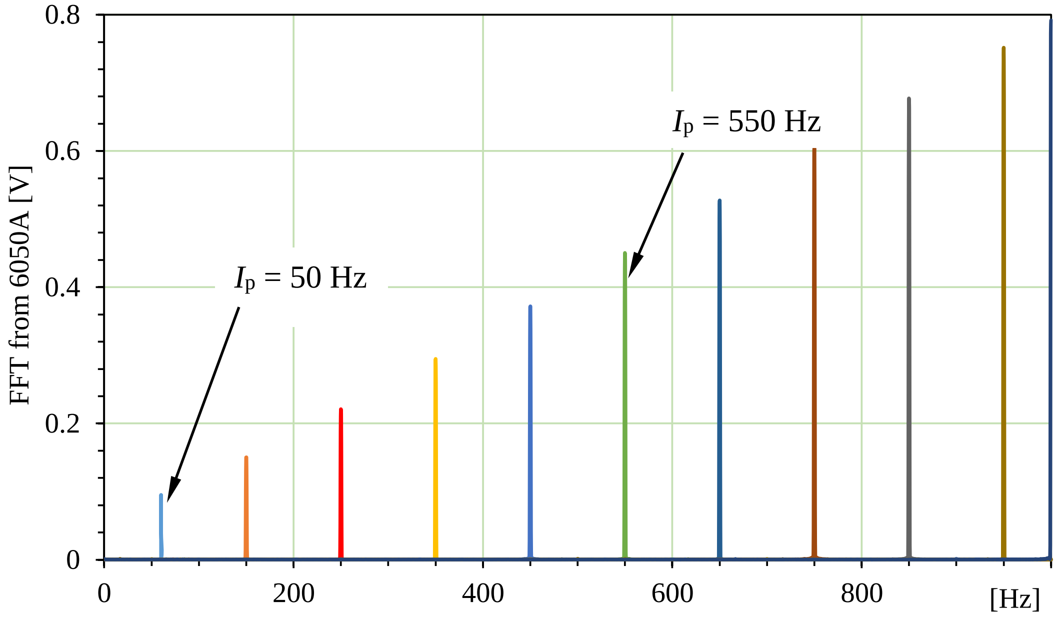


Figure 4-7: FFT analysis of CT1 based on IEC standard burden, Z_b = (0.152 + j0.114) Ω.

A. First case: Fix burden $Z_{b,fix}$

The results of the ratio error of CT1 based on IEC standard burden, at frequency up to 1 kHz, were illustrated in Figure 4-8. The left vertical-axis was valid for burden A to D while the right vertical-axis was valid for burden E and F. The ratio error in this case was obtained by using fix burden $Z_{b,fix}$ in

Table 3-4 to calculate I_s of CT at other frequencies. The test results showed that the frequency response of CT1 did not flat, especially for the burden A-D.

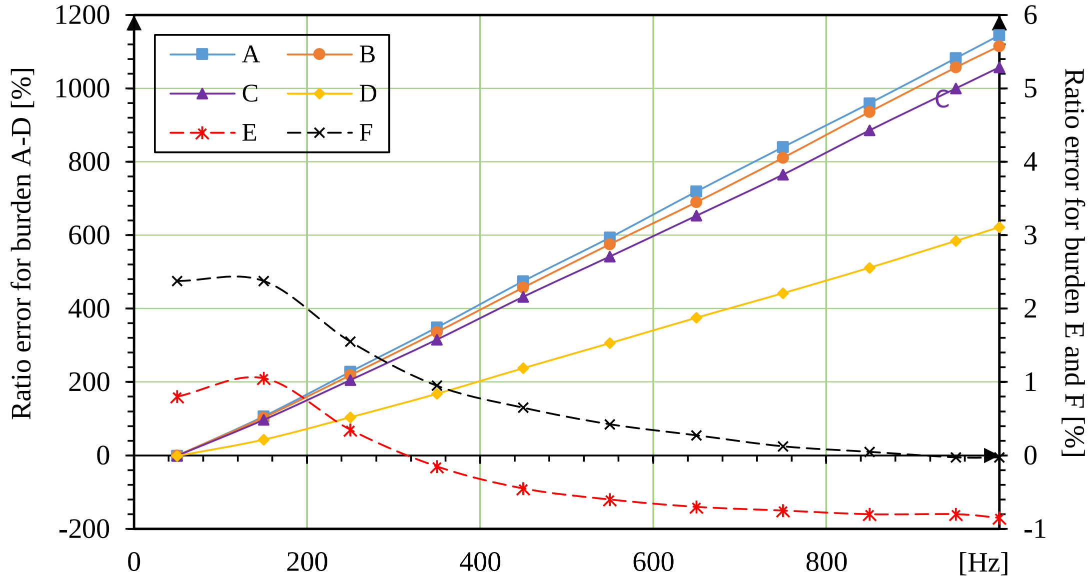


Figure 4-8: Ratio error of CT1, by using fix burden (B was standard burden).

At frequency of 50Hz, the ratio errors were -1.05 %, -0.13 %, -0.89 % and -1.57 % for burden A-D respectively. From Figure 4-8, the ratio error was acceptable to declared class in Table 2-4 for all burdens. Thus, there were not noticeable error at frequency of 50 Hz when used the burdens with power factor according to IEC standard although the values of burdens were slight difference from the standard burden. For instance, burden B was the standard burden for CT1; but, burden A was lower and burden C and burden D were higher than burden B.

Furthermore, at high frequency, the ratio error was drastically increased with increased frequency for burden A-D. Likely, the dependence of ratio error on the frequency was reduced when the *L*/*R* ratio of the burden decreased, for example burden D.

Moreover, Figure 4-8 indicated a significant influence of the burden on the ratio error of CT1. The pure resistive burden did not affect to the ratio error of CT with increased frequency. At frequency of 50 Hz, the ratio errors were 2.38 % and 0.80 % for burden E and F respectively. On the other hand, above frequency of 250 Hz, the ratio error was virtually within ±2%. At frequency of 1 kHz, the ratio errors were -0.02 % and -0.85% for burden E and F, respectively. Although a small resistive burden e.g. burden F leaded higher error than a large resistive burden e.g. burden E, for this type of burden, the ratio error conformed to limits of the ratio error of IEC standard and were acceptable for the current distortion limit which was shown in Table 2-1. Thus, in order to simplify the experiment, many tests in previous studies used the resistive burden to evaluate the accuracy of CT when harmonic current was injected. However, this idea had drawback in real performance of CT, as shown in Figure 2-3.

B. Second case: Frequency dependence burden, $Z_{b,f}$

In Figure 4-8, the ratio error was high at high frequency because burden A to burden D increased with increased frequency. Hence, in this case the burden $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ were used to calculate I_s. As the results, the ratio error of CT1 at high frequency was reduced, as shown Figure 4-9 and Figure 4-10.

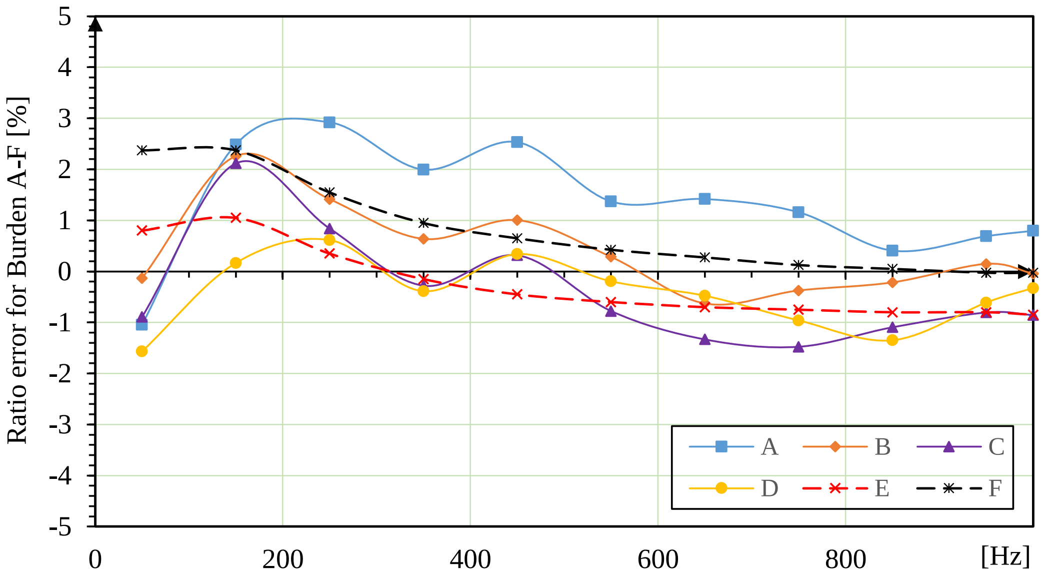


Figure 4-9: Ratio error of CT1, by using $Z_{b,f\text{-}mea}$ (B was standard burden).

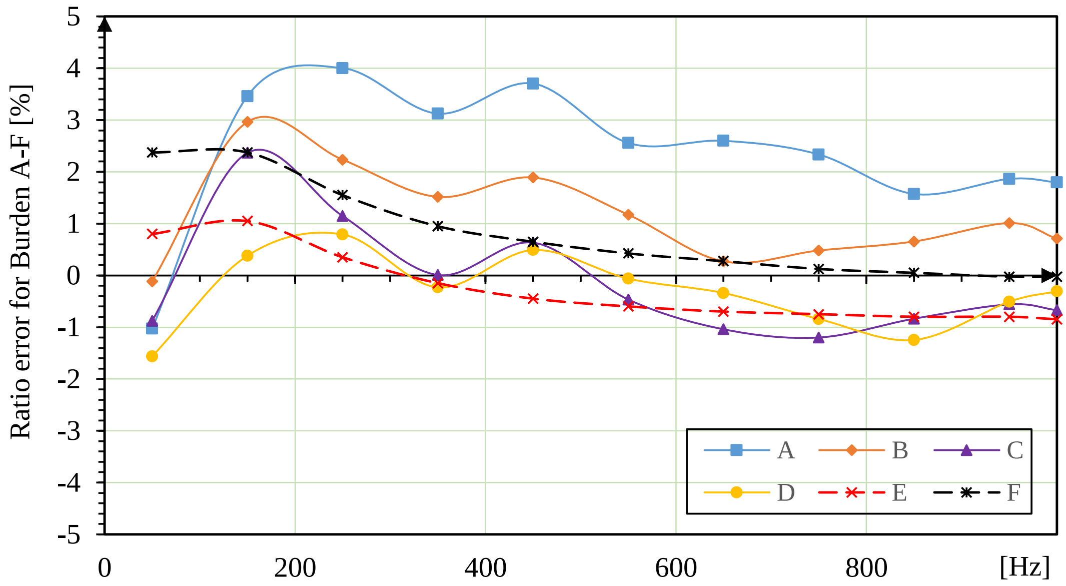


Figure 4-10: Ratio error of CT1, by using $Z_{b,f\text{-}cal}$ (B was standard burden).

Obviously, the deviation between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ in Figure 3-8 made the ratio errors in Figure 4-9 and Figure 4-10 were slightly different. From comparisons in Figure 3-8, the errors between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ were approximately 1 % and for some burdens were lower than 1%. Here, we can assume that the using of $Z_{b,f\text{-}mea}$ or $Z_{b,f\text{-}cal}$, in the calculation of I_s, result practically the same ratio error.

When $Z_{b,f\text{-}cal}$ was used in the calculation, in Figure 4-10, the ratio errors for standard burden B, burden C and burden D were approximately equal ±1% for all frequency under test, except at 150 Hz for burden B and C. For burden A, the ratio errors were 3% at frequency from 150 Hz to 650 Hz and were practically within ±2 % for other frequencies. From the analysis of results, the frequency responses of CT1 for burden B-D were similar to the frequency response for resistive burden.

In this part, when the power factor of burden corresponded to IEC standard and the output currents I_s were calculated by using $Z_{b,f}$, the ratio error was comparable to resistive burden. Exception for burden A because the ratio error was slightly high. It may be the effect of parasitic of burden and come from the value of burden A was small i.e. Z_b=0.13 ohm. One can observe the strong interaction between the burden and the ratio error. Therefore, we need to know the exact value of burden.

4.1.3. Conclusion

The characterization of the ring-CT performance has been examined by injected single frequency current with various frequencies. The analysis shows that if the fix value of Z_b at frequency of 50 Hz is used in the calculation of I_s of CT, the ratio error of CT drastically increase with increased frequency. The small ratio error of CT can be achieved by using frequency dependence burden $Z_{b,f}$. This method was used to reduce the effect of burden at high frequency but the ratio errors were not well like the resistive burden. It may be the effect of parasitic of burden and come from the value of burden was small e.g. burden A. Therefore, to obtain an accurate current measurement by using

CT, the burden shall be known exactly. The value of burden shall also be measured with great care as a small error of burden may cause a high ratio error of CT.

In addition, the acceptable ratio error obtained by using resistive burden could be questionable or unreliable at high frequency, because the power factor of burden shall correspond to IEC 61869-2. One more thing, in practice, we use wires to connect the secondary side of CT and measuring device and the wire impedance Z_w is also a part of burden of CT. Therefore, as the burden of CT was not defined, there will have the error measurement when the CT is used to measure higher harmonic current.

By generally analyzing, the ratio error shall be equal or more accurate when using the burden based on the IEEE standard burden. Conversely, it became a question from this test results when using the burden according to IEC standard burden, the ratio errors were more accurate than using the burden according to IEEE standard burden. However, when we look at nameplate of CT1, the manufacturer recommended the application of CT1 according to IEC standard. This point can respond to the question above. Therefore, in the next test, the author will focus on only the burden based on IEC standard burden and the author still keep the discussion on two cases of the frequency dependence burden.

4.2. Test on ratio error of CT by injected harmonic current

From previous section, the ratio error of CT was tested by injected single frequency current of various frequencies from 50 Hz up to 1 kHz. The tests based on the power factor of 0.8 and 0.9 lagging of burden correspond to IEC and IEEE standards respectively. The author discussed two cases of burdens which were used to calculate the output current I_s of CT after obtained the output data from oscilloscope. In the first case, the ratio errors were so high dramatically increased with increased frequency, except at frequency of 50 Hz. Because of the behavior of impedance, the values of burden with certain of power factor increased when they were implemented at high frequency. This was the reason why the ratio errors at high frequency in first case were so high. Conversely, in second case, the test results showed that the ratio errors at high frequency range from the first case were reduced by replacing the $Z_{b,fix}$ with $Z_{b,f}$.

This section underlined the fact that the burden influences to the accuracy of CT. This time, the CTs were injected by the harmonic current, as shown in test procedure in section 3.5. The results and discussions were as following sub-section.

4.2.1. The primary current

In order to evaluate the accuracy of CT with real waveform including harmonic components, the exact knowledge of the primary current was very important. In the preliminary test, the Fluke Model 5500A was used to calibrate the CT with 95 % confidence level. Anyways, in this section, the signal generator was CMC 353. Because unknown data to insure about its accuracy, the author used the standard CT to measure the current waveform I_p which generated from CMC 353. The output current I_p' of standard CT from oscilloscope and the difference between I_p' and I_p in time domain were shown in Figure 4-11.

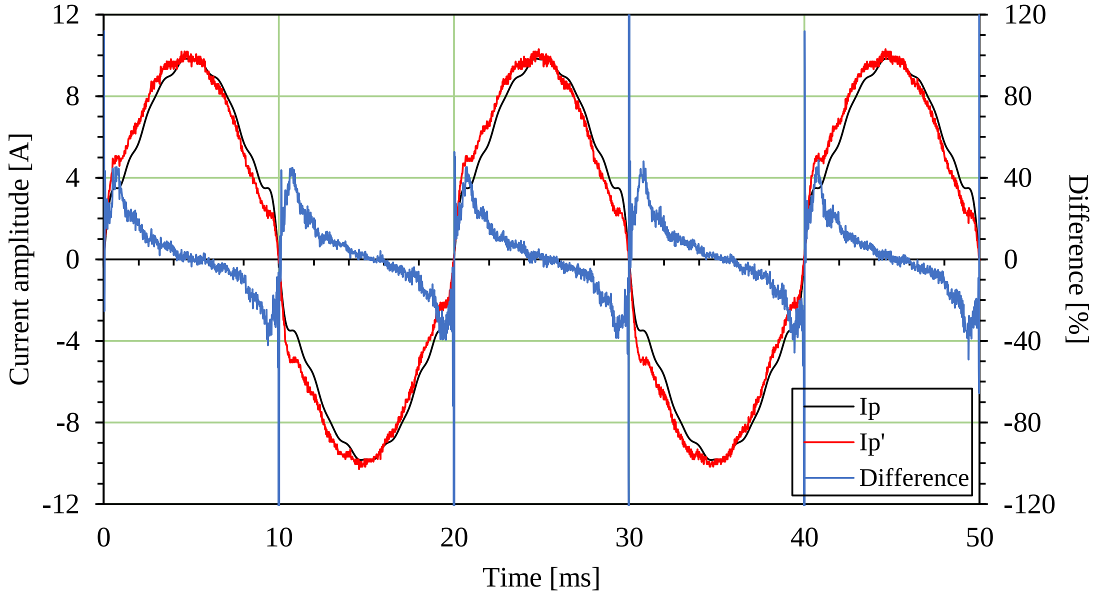


Figure 4-11: The waveform of injected current, the output of standard CT from oscilloscope and thier difference in time domain.

The left vertical axis in this figure was valid for the current I_p and $I_p{}'$ and the right vertical axis was valid for the difference between I_p and $I_p{}'$. The current waveform I_p was constructed by using equation (3-4), where the amplitude of each harmonic currents was shown in Table 3-6. From this illustration, because of the noise of $I_p{}'$, there were high error when we made comparison of $I_p{}'$ with I_p. Thus, in order to eliminate the noise and to see magnitude of current clearly, the FFT was used to analyze the waveform of $I_p{}'$. The rms values of $I_p{}'$ in frequency domain were presented in Figure 4-12.

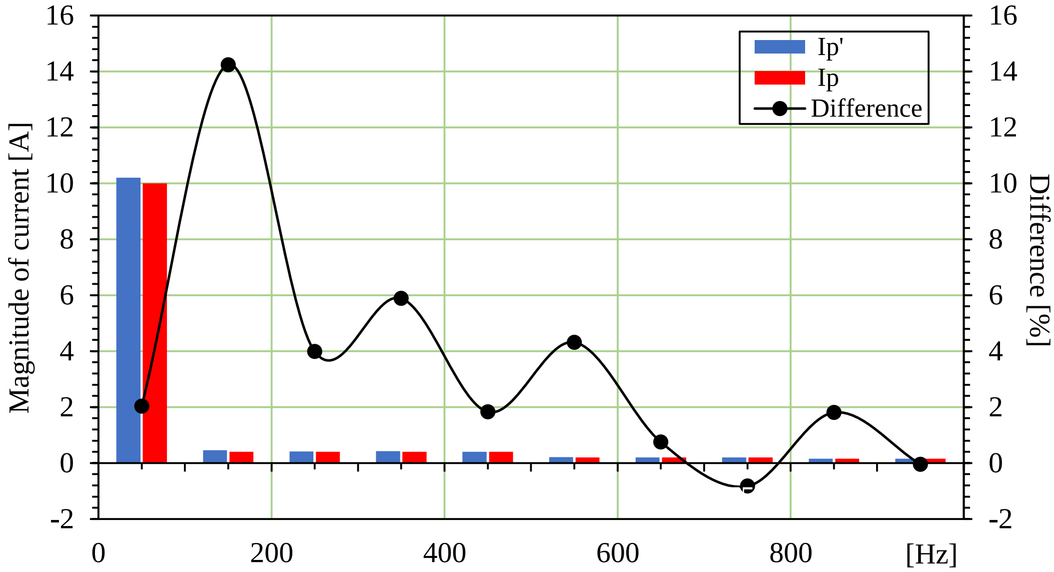


Figure 4-12: The rms value of current $I_p{}'$, I_p and the difference between them.

In this figure, the left vertical-axis was valid for the rms values of $I_p{}'$ and I_p while the right vertical-axis was valid for the difference between $I_p{}'$ and I_p. At frequency of 50 Hz, the difference was equal 2 % and at above frequency of 550 Hz, the differences were practical within ± 1 %. Nevertheless, the difference was so high, approximately 14 % at frequency of 150 Hz. This standard CT was practically accurate within ± 1 % to measure small current at high harmonic order e.g. 13th to 19th order.

After selecting only the magnitude of odd harmonic, the equation (3-4) was used to transform the current waveform to time domain. Then, the calculation of the difference was done in time domain. The current $I_p{}'$ and the difference between $I_p{}'$ and I_p were shown in Figure 4-13.

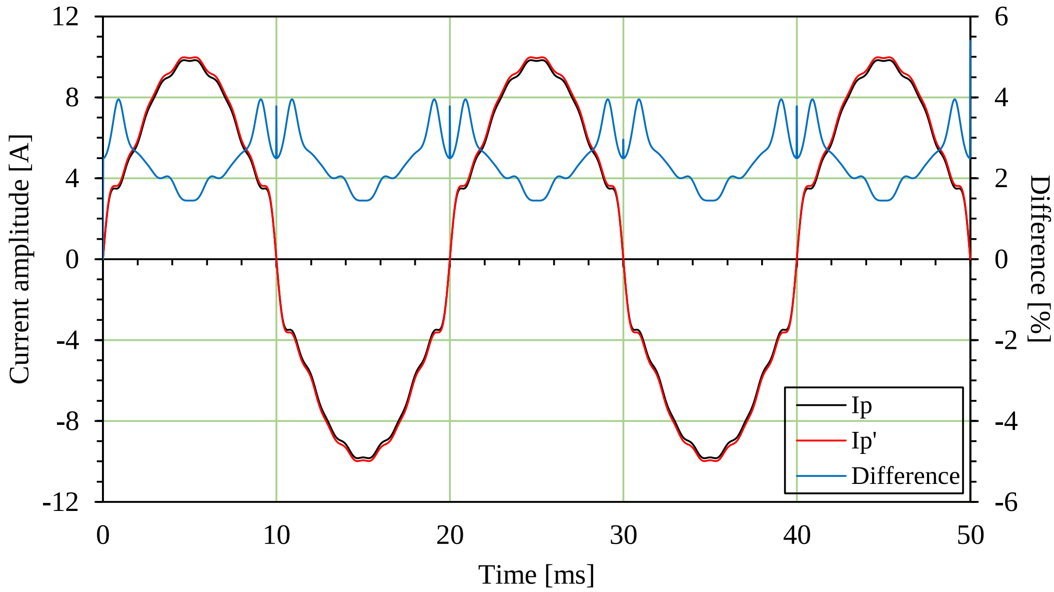


Figure 4-13: The reconstruction of waveform of $I_p{}'$.

By helping from FFT function to analyze the output waveform of standard CT, the difference was reduced. In Figure 4-13, the ratio error was between 1.5% and 4%. By analyzing the result in both frequency and time domains, we can assume that the injected current from CMC 353 was applicable. Therefore, the real current I_p is used in the discussion on the secondary current of CT under test in next section.

4.2.2. The secondary current

As we mentioned in the preliminary test, the author proposed two cases of burden (Z_b) in order to obtain the output current I_s of CT. The result and discussion of these tests are following.

A. First case: Fix burden, $Z_{b,fix}$

In this case, by using the oscilloscope to measure the output of CT under test, the Figure 4-14 illustrated the output waveform of CT1 with burden B and the ratio error in time domain.

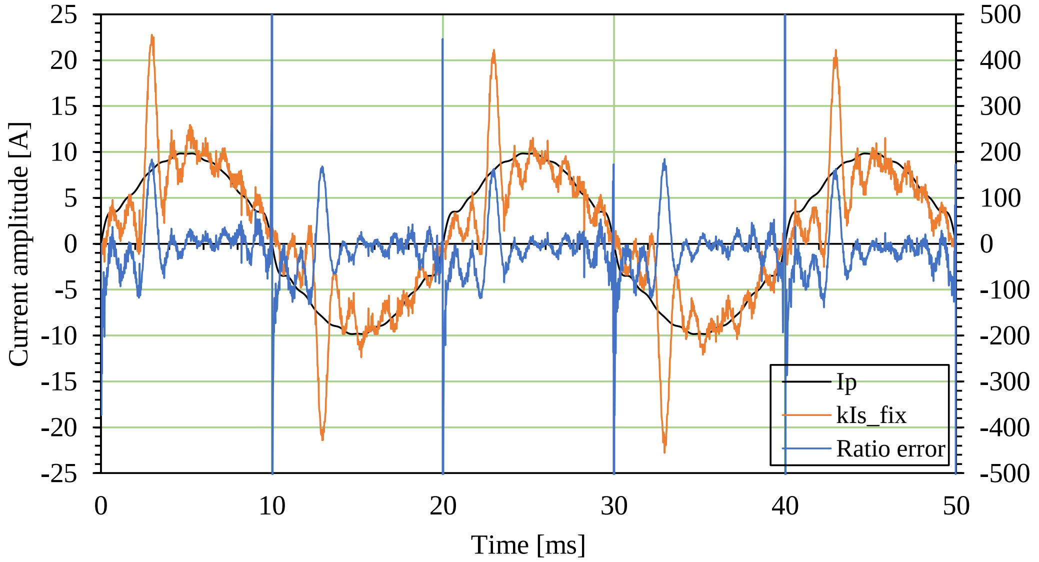


Figure 4-14: The output waveform of CT1 with standard burden B and the ratio error.

In this figure, the left vertical axis was valid for the amplitude while the right vertical axis was valid for the percentage of the error. Because of the presence of noise in waveform, the author used the FFT to analyze the waveform in frequency domain. In this process, we extracted the noise and kept only odd harmonic components to analyze. After obtained the results from FFT analysis, the fix burden $Z_{b,fix}$ was used to calculate the output current I_s of CT. Then, by multiplying with ratio k, the measured current $kI_{s\text{-}fix}$ was obtained, as shown in Figure 4-15.

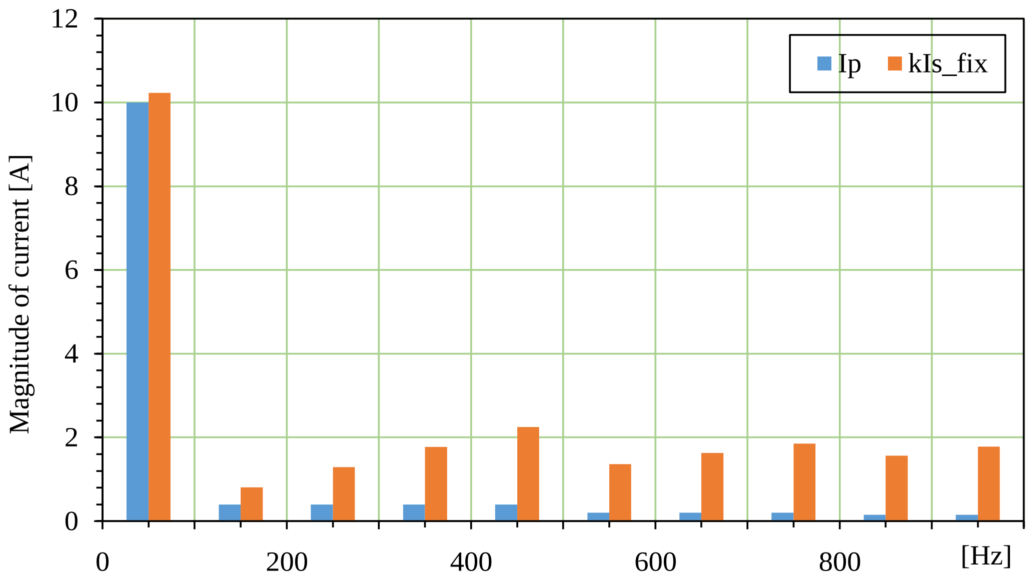


Figure 4-15: The rms value of Ip and $kI_{s,fix}$, by using $Z_{b,fix}$ of CT1, standard burden B.

Because of the impedance increased with increased frequency, from this figure, we noticed that the current $kI_{s\text{-}fix}$ were significantly higher than the current I_p, except at frequency of 50 Hz. The THD of I_p was 9 %; but, the THD of $kI_{s,fix}$ was 48 %. Thus the ratio error between $kI_{s,fix}$ and I_p in frequency domain was illustrated in Figure 4-16.

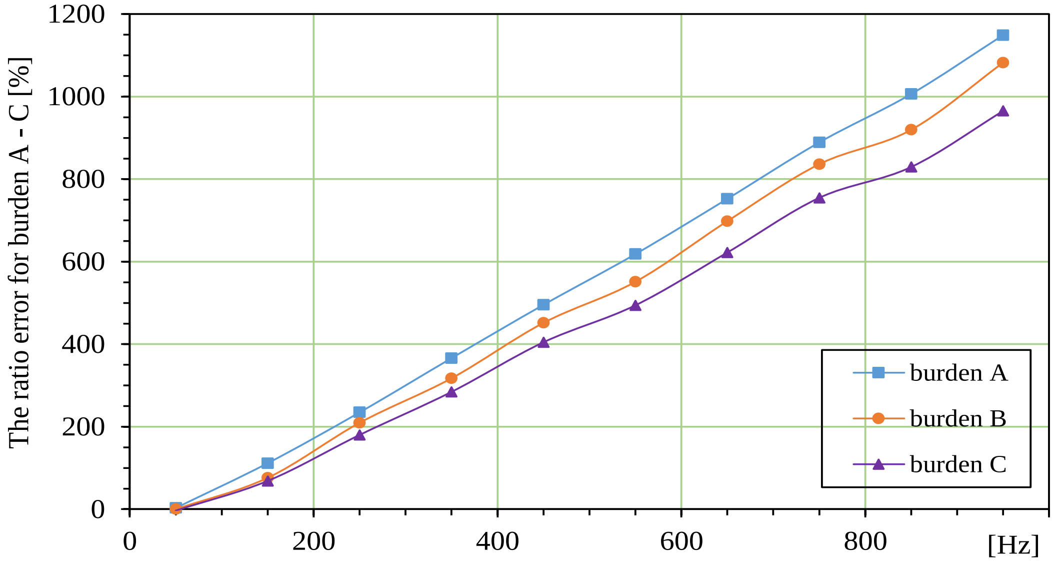


Figure 4-16: The ratio errors of CT1 for burden A to C, by using fix burden (burden B was standard burden).

As the result in the preliminary test, at frequency of 50 Hz, the ratio errors, were 2 %, 1.9 % and -2 % for burden A to C respectively, were well compliant with the IEC standard. Since the IEC standard provided the information of CT at only frequency of 50 Hz, the ratio error of CT1 increased with increased frequency.

After using FFT to select only odd harmonic current, the reconstruction of the current $kI_{s,fix}$ to time domain by using equation (3-4) was shown in Figure 4-17.

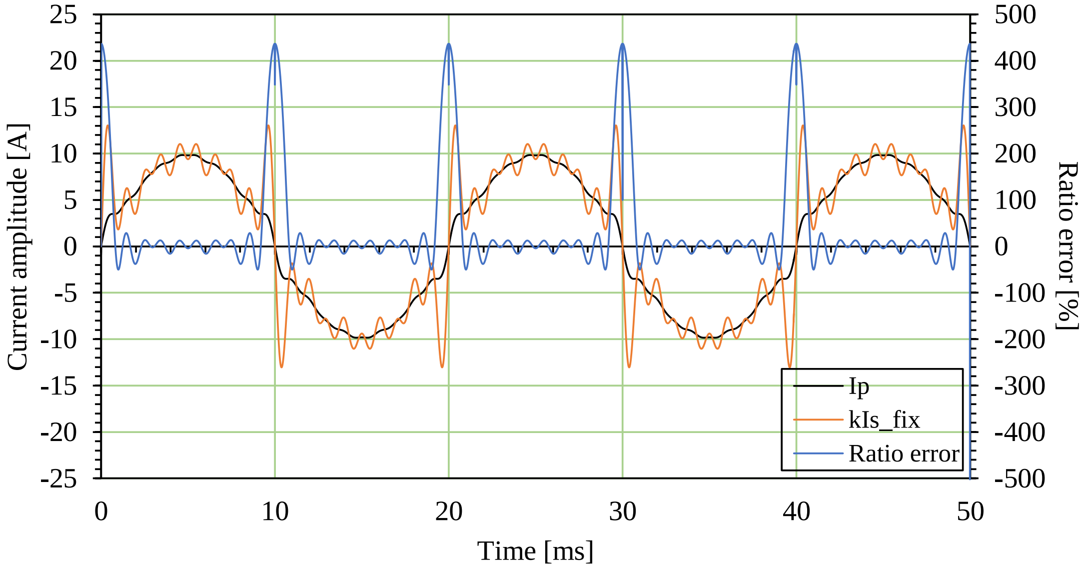


Figure 4-17: The reconstruction of the current waveform $kI_{s,fix}$ and the ratio error.

This figure presented clearly about the distortion of output current of CT when the primary current was harmonic current. Although some points of the ratio error were lower than 10 %, the maximum of ratio error was so high, approximately 430 %. Therefore, in next section, the $Z_{b,f}$ is used to reduce the effect of burden at high frequency.

B. Second case: Frequency dependence burden, $Z_{b,f}$

As we mentioned in previous chapter, the frequency dependence burden $Z_{b,f}$ was the variable burden whose values depended on the frequency of the primary current. In the second case in preliminary test as well as in this test, $Z_{b,f}$ was used to calculate the output current I_s of CT under test after getting acquisition data from oscilloscope. The discussion in section 3.3.2 mentioned that there were the deviation between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$, but the deviation of ratio error by using these burdens was small. From this reason, only frequency dependence burden from calculation $Z_{b,f\text{-}cal}$ was used in this section.

The rms values of measured current $kI_{s,f}$ were shown in Figure 4-18 and the THD in this case was roughly equal 9 % after the $Z_{b,f}$ was used. The ratio error of $kI_{s,f}$ in frequency domain was presented in Figure 4-19.

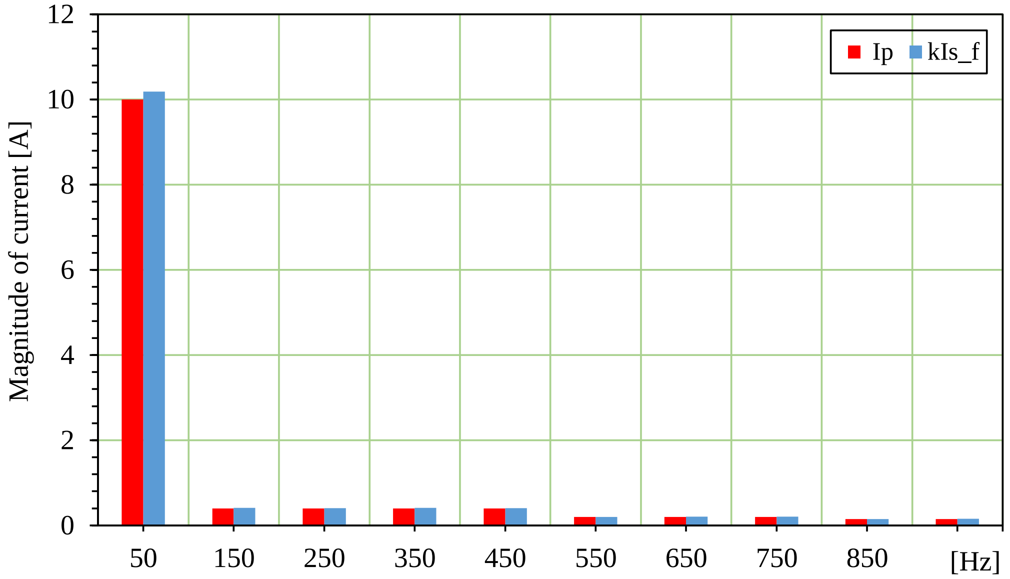


Figure 4-18: The rms value of current I_p and $kI_{s,f}$ of CT1 for standard burden B.

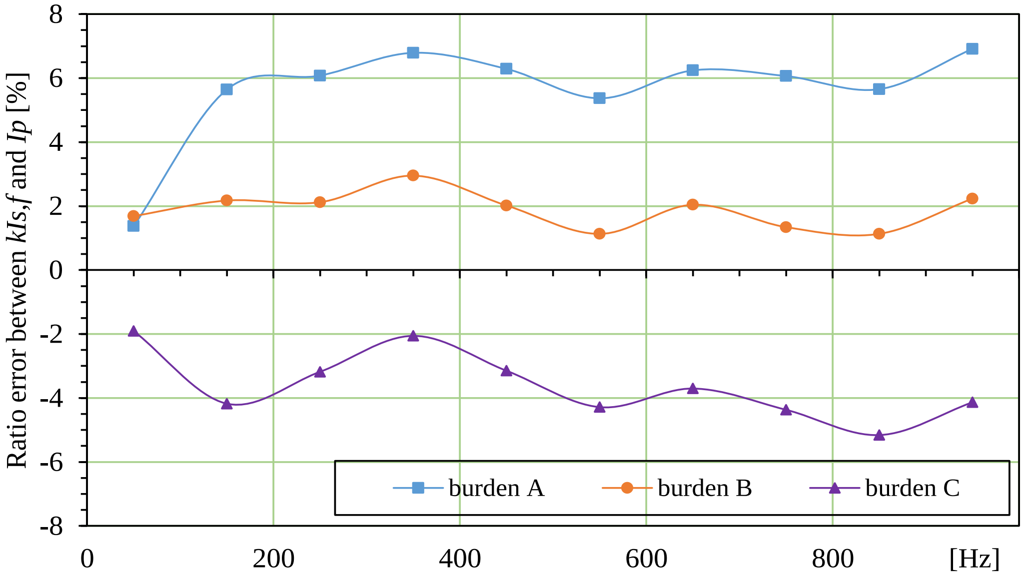


Figure 4-19: The ratio error of CT1 when draw a comparison between $kI_{s,f}$ and I_p.

The ratio error at frequency of 50 Hz was practical within ± 2 % and corresponded to the limits of ratio error of the IEC standard. Since burden B was the standard burden of CT1, the ratio error was approximately equal 2 % over the frequency up to 1 kHz. On the other hand, at frequency above 150 Hz, the ratio error for burden A was about 6 % and for burden C was about -4 %. Although the ratio error at frequency of 50 Hz increased 2 % in Figure 4-19, the ratio error was smoother than the ratio error in Figure 4-10 and conformed to limits of ratio error in Table 2-4.

Anyways, the discussion of $kI_{s,f}$ in time domain was preferable. Hence the reconstruction of the current waveform $kI_{s,f}$ by using equation (3-4) and the calculation of the ratio error in time domain were done. Figure 4-20 showed the current waveform $kI_{s,f}$ of CT1 for standard burden B and Figure 4-21 presented the ratio error for burden A to burden C in time domain.

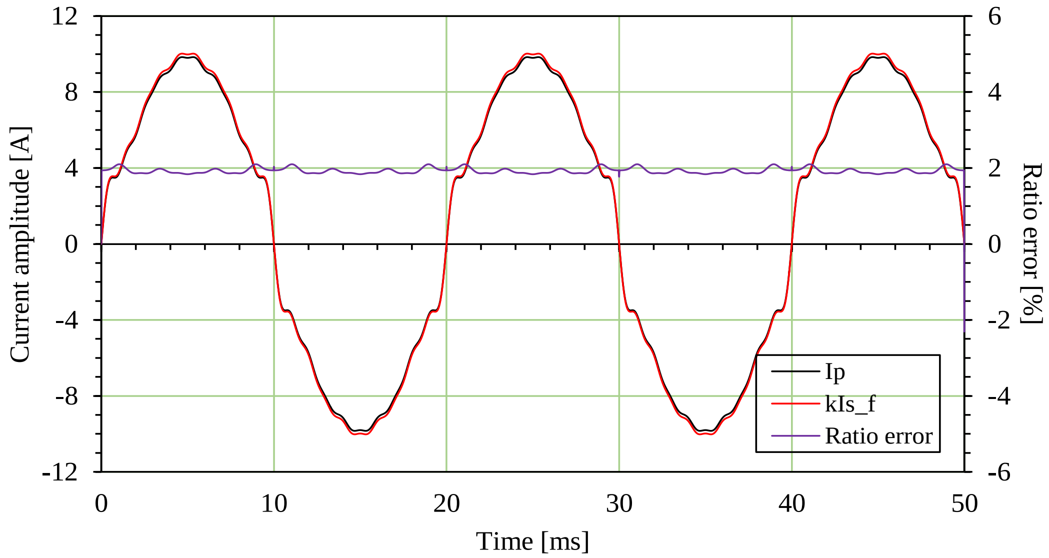


Figure 4-20: The reconstruction waveform of $kI_{s,f}$ for CT1 with standard burden B.

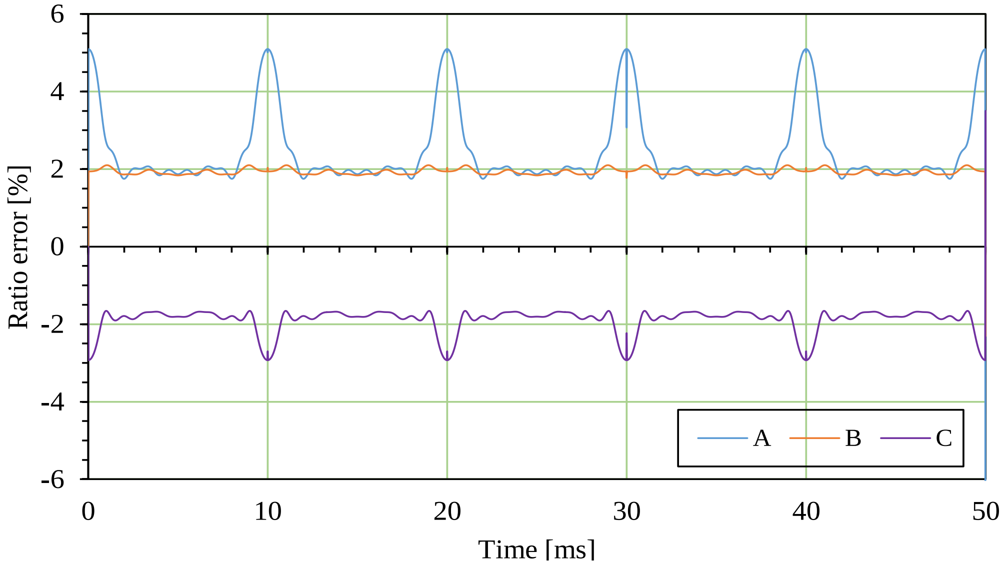


Figure 4-21: The ratio error of CT1 for burden A to C in time domain, by using $Z_{b,f}$.

We can note that for burden A and C, the maximum ratio errors were 5% and -3%, respectively, and the ratio error was approximately equal to 2% for standard burden B.

4.2.3. Conclusion

The additional test on the ring CTs by injected harmonic current is conducted. The test results show that the frequency response of CT is indistinguishable from the preliminary test. At frequency of 50 Hz, the ratio errors of CT corresponded closely to the limits of ratio error which provided in IEC 61869-2. Since the behavior of impedance varied according to the frequency test, the ratio error was unacceptable when the CT was implemented over wide frequency range.

However, the ratio error at high frequency was significantly reduced when the output current I_s was calculated by using the frequency dependence burden $Z_{b,f}$. Moreover, the ratio error of small current was reduced because the loss of data from oscilloscope was reduced when CT was injected by harmonic current.

Therefore, we can assume that the ratio error of CT under test was acceptable accord to IEC 61869-2-2012 [19]. Notably for standard burden B, the ratio error was accurate for all test frequencies. Although the ratio error for standard burden B was acceptable as IEC standard declared, the correction of the ratio error is needed when CT is implemented at high frequency.

4.3. The correction of the ratio error of CT

The main factor, which leaded to low accuracy of CT in this investigation, was the burden. As mentioned in section 3.2, the value of burden dramatically increased with increasing test frequency, because of the nature of impedance. Consequently, the calculation of I_s by using $Z_{b,fix}$ was replaced by using $Z_{b,f}$, as the results, the high ratio error at high frequency or high harmonic was alleviated. Especially, when the burden was a standard burden as IEC standard declared, the ratio errors of CT at all frequencies under test were acceptable. A case in point was standard burden B of CT1; the ratio error was practical within 2 %.

From the test results in Figure 4-19, although the ratio error for standard burden (burden B for CT1) was acceptable with IEC standard, it was significant for other burden i.e. burden A and C. Moreover, in real application, the value of burden was not exactly equal to the standard burden, for example burden A and C. Thus, this work proposed a method for correcting the ratio error by using the ratio error from preliminary test be as the correction factor (*CF*). The current after correction $kI_{s,f\text{-}cor}$ was

$$kI_{s,f-cor} = (1 - |CF|)\, kI_{s,f} \tag{4-1}$$

From the testing CT with single frequency current, we got the ratio error at each frequencies or the correction factor (*CF*), as shown in Table 4-1.

Table 4-1: The correction factor (CF) from the preliminary test (test current at 10A with frequency from 50Hz to 1kHz).

Frequency [Hz]	**Ratio error / Correction factor (CF) [%]**		
	Burden A	**Burden B**	**Burden C**
50	-1.028	-0.113	-0.876
150	3.462	2.964	2.368
250	4.002	2.235	1.148
350	3.124	1.516	0.007
450	3.706	1.891	0.633
550	2.557	1.172	-0.465
650	2.600	0.271	-1.040
750	2.336	0.481	-1.199
850	1.573	0.656	-0.837
950	1.864	1.011	-0.559
1000	1.799	0.710	-0.671

After making correction on $kI_{s,f}$ by using equation (4-1), the ratio error was calculated in frequency domain and was shown in Figure 4-22.

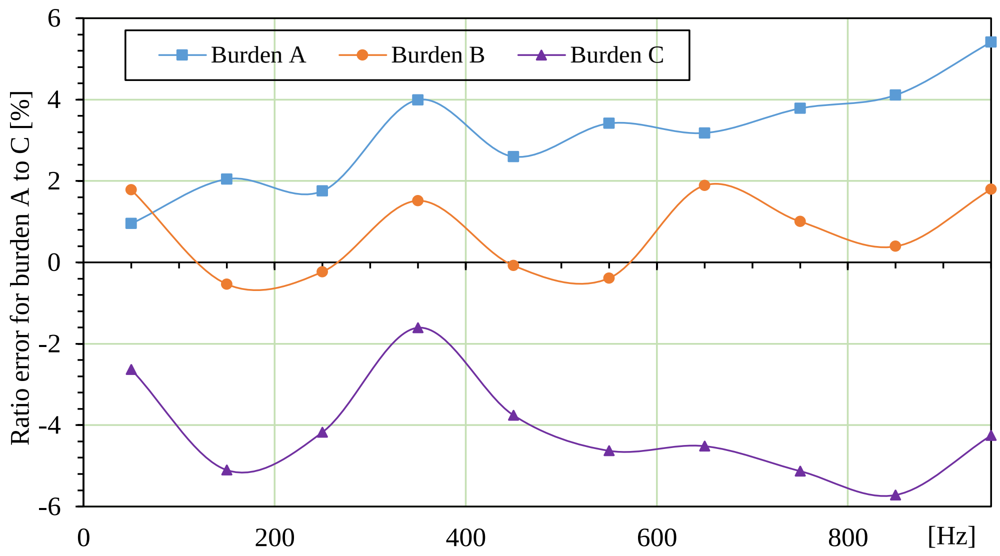


Figure 4-22: The ratio error after correcting CT1 for burden A to C.

For burden A, the corrected ratio error was lower than 4%, except at frequency of 1 kHz. For standard burden B, the corrected ratio error was fluctuated between -1% and 2%. Unfortunately, for burden C, the ratio error was increased because the ratio error for this burden before correction was negative.

Anyways, the analysis of the result of correction shall be discussed in time domain. By using the magnitude of each harmonic components, the current waveform $kI_{s,f\text{-}cor}$ was reconstructed and the ratio error was calculated in time domain, for example for CT1 with standard burden B was shown in Figure 4-23. The uncorrected and corrected ratio error were illustrated in Figure 4-24.

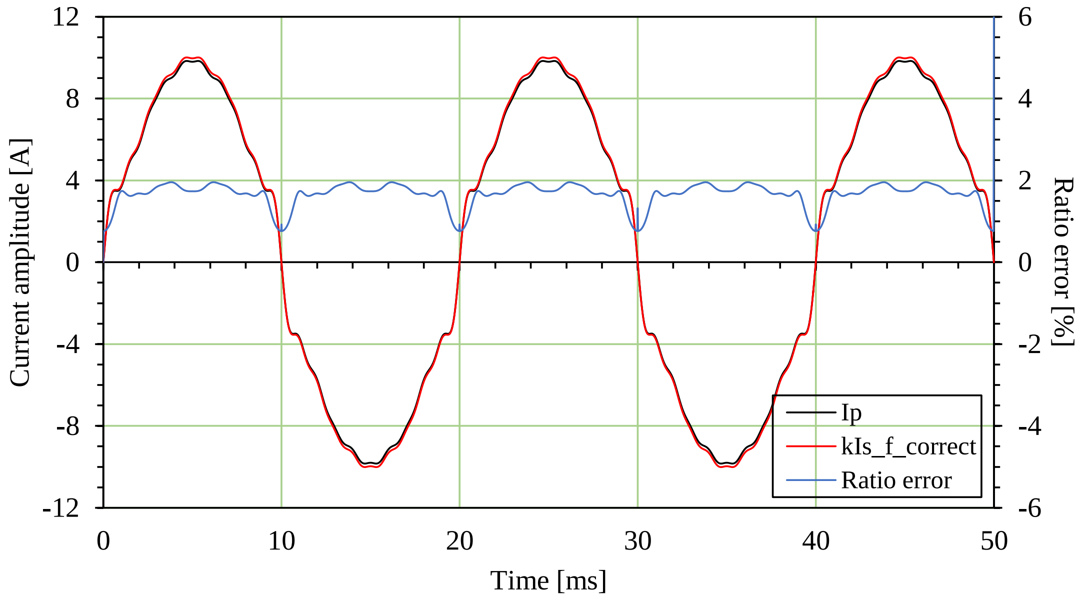


Figure 4-23: The current waveform $kI_{s,f\text{-}cor}$ and the ratio error of CT1 for standard burden B in time domain.

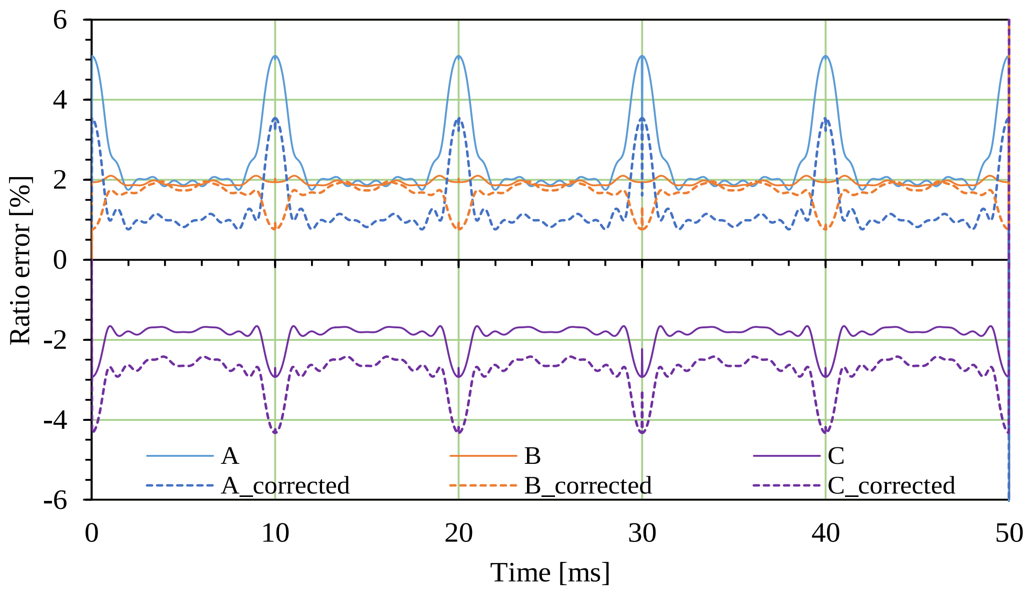


Figure 4-24: The ratio error of CT1 for burden A to C after correction in time domain.

As we can see in time domain, the ratio error for burden A was reduced approximately 1.5%; hence, the maximum corrected ratio error was equal to 3.5%. Anyways, for standard burden B, the ratio error was slightly decreased after correction. The maximum corrected ratio error for this burden was still approximately equal to 2%. Nevertheless, as the analyzing result in frequency domain, the ratio error was approximately increased 1.5% after correction. It was the drawback of this correction method when the measured current kI_s was lower than the real current I_p.

Chapter 5 : Conclusion

The tests on the ratio error of three CTs over wide frequency range are investigated. This work pointed out the fact that the burden strongly influence to the accuracy of CT at high frequency, although it can neglect the effect at rated frequency in some cases. Therefore, several burdens according to IEC and IEEE standards, including the resistive burden, were tested with CTs, but the standard burden was the main point. In addition, this work can be called the real application of CT because both the primary current and the burden conform to the practical recommended in standard. In order to make a definite conclusion, the test was done with the both single frequency current and harmonic current. The conclusion of this thesis will be presented in the following sections.

5.1. The frequency response of CT under investigation

At rated frequency and with the burden according to IEC standard, the ratio error of CT was compliant with the limit of ratio error specified in IEC standard, because the application of these CTs are based on IEC standard. Unfortunately, the ratio error increased with increasing frequency when the value of burden was fixed in determination of output current I_s. Although the primary current was practical within the limits of current distortion in IEEE standard, but when CT was implemented, the error of measurement was significant. For instance the odd harmonic current I_p = 10.04 A with THD = 9 %, but the measured current $I_{p,fix}$ = 11.35 A with THD = 48 %. Hence, the measurement error = 1.31 A or 13 %.

However, the ratio error at high frequency was reduced when the frequency dependence burden was used in calculation of output current I_s. As the limit of ratio error was declared in Table 2-4, the CT could be used with burden for 25 % to 100 % of rated burden. Although the approximate burdens in this range, for instance burden A, were not effect to ratio error at rated frequency, the influence of these burden appeared when CT was used at high frequency. It means that when the primary current of CT have the presence of harmonic, the burden of CT shall be the standard burden in order to reduce the ratio error at high frequency. By way of illustration, for burden B, the ratio error of CT1 was practically within 2% for all frequencies under test.

5.2. The correction of the ratio error of CT

Although the ratio error corresponded to IEC standard when the standard burden is used, a more accurate of application of CT and the improvement the ratio error for other burden are needed. Thus this work proposed the correction on the ratio error by using the ratio error from preliminary test to compensated the output current of CT; as result, the ratio error is more accurate. This correction has a slightly effect to ratio error for standard burden and has bad effect to ratio error of CT when the output current of CT multiplies by the ratio of CT is lower than the primary current, $kI_{s,f} < I_p$, burden C is a case in point.

5.3. Recommendation

From the test analysis, we can notice that the variable value of burden strongly influences to the calculation of the ratio error. Although the deviation of burden is small, it seem to accentuate its negative impact on the ratio error of CT. For instance when Z_b = 0.190 Ω hence ratio error = - 0.13 %, when Z_b = 1 % of 190 Ω = 0.192 Ω hence ratio error = -1.04%. Thus, the burden increases only 1 %, but the ratio error grows 700 %. Of course, the method to measure burden shall be considered, when a small value of resistance is measured, e.g. for burden A (Z_b=0.13 Ω). Therefore, to obtain an accurate high frequency current measurement by using CT, the burden shall be known exactly as shown in Figure 2-3, i.e. the sum impedance of Z_w and Z_{in} must be equal to Z_b. The value of burden shall also be measured with great care as the error of the measured burden may result in the ratio error of CT.

Moreover, choosing the primary current to inject to CT in experiment is also important. As IEC standard provided the limits of current error, the injected current shall be at least equal to 5 % of rated current. If the primary current is too small, it will make the voltage distortion at secondary side of CT. As the results, there are loss of data in measurement, especially when we use oscilloscope to measure. Therefore, this thesis provided the guideline to avoid some of these problems.

5.4. Future work

This thesis provided a clear and a precise description of test on the ratio error of CT. All provided information might make other researcher to replicate the findings in this work. However, the further research on the accuracy of CT over wide frequency range is required. As shown in Figure 3-8, the ΔZ_b seems to decrease at 1 kHz, this might be the effect of stray capacitance of our burden. Due to the limits of the frequency of 1 kHz in this study, the experiment on the ratio error of CT at higher frequency up to 2.5 kHz (50^{th} harmonic, see Table 2-1) might be explored.

Because the capability of calibrator is within limit, increasing the primary current of CT up 100 % of rated current might be needed in further test. Although the correction method is well practical, the ratio error of 2 % is slightly high. If it is possible, the adding more compensation on the performance of CT over wide frequency range shall be taken in consideration.

In addition, from the results of the correction ratio error, the ratio error was slightly decreased, especially for burden B. Although the ratio error was approximately decreased 1.5% for burden A, the ratio error for this burden still higher than the limits of the ratio error from IEC standard. When the secondary current of CT was smaller than the primary current, this correction method did not make the ratio error to be low but it made the ratio error after correction increase, for example burden C. This become the drawback of this correction which is needed to improve to make the ratio error be more accurate.

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APPENDIX

Appendix A: Frequency analysis

To detect an underlying component of sinusoidal waveform which combines with the noise or harmonic components, the signal in time domain is transformed to frequency domain. As mentioned in [37], Fourier series is used to separately analyze the harmonic waveform in individual harmonic. Hence, the Fourier series representation of a periodic signal $x(t)$, of period T_0, is an equivalent representation that uses sinusoids rather than complex exponentials or is given by an infinite sum of weighted sinusoids or complex exponentials with frequencies multiples of the fundamental frequency of signal $\Omega_0 = \frac{2\pi}{T_0}\ rad/sec$ as the basis functions. Equation (A-1) gives the formula of the Fourier series in complex exponential form.

$$x(t) = \sum_{k=-\infty}^{\infty} X_k e^{jk\Omega_0 t} \qquad \text{(A-1)}$$

where the Fourier coefficients X_k are obtained according to

$$X_k = \frac{1}{T_0}\int_{t_n}^{t_0+T_0} x(t)e^{-jk\Omega_0 t}\, dt \qquad \text{(A-2)}$$

for $k = 0,\ \pm 1,\ \pm 2, \ldots$

A periodic signal $x(t)$ of period T_0 is represented in the frequency domain by each spectra as follow:

- Magnitude line spectrum: $|X_k|$
- Phase line spectrum: $\angle X_k$
- Power line spectrum: $|X_k|^2$

A.1. Selection of Sampling Frequency

The most important thing, that should be considered in frequency analysis, is the selection of sampling frequency. The choice of sampling frequency is arbitrary. The signal such as harmonic contains various frequency components should be detected to be real insight into the magnitude of signal. If the value of the sampling period is large, the advantage is data compression. Unfortunately, the risk of losing some information will show in the analog signal. Alternatively, if the sampling frequency f_s of the detected frequency f is too low, e.g. $f_s <= 2f$, a lower erroneous frequency will be observed.

Due to the overlap, signals cannot recover the original continuous-time signal from the discrete signal. It means that the sampled signal does not share the same information with the original continuous-time signal. The phenomenon is called the *aliasing*. However, if the choice of sampling period is correct, the information in the analog signal and in the discrete signal will be equal after sampling. Thus, the reconstruction of the original signal can be done from the samples.

In order to choose a roughly value for the sampling period, Shannon Sampling Theorem stated that: "*The measured signal must not contain frequencies above half of the sampling rate*". The frequency equals to half of the sampling frequency is the highest detectable frequency, is called *the Nyquist or folding frequency*. Thus, the sampling period depends on the maximum frequency present in the analog signal. Moreover, using a low pass filter with the cut-off frequency less than half of the sampling rate is the most effective way of avoiding the aliasing.

Without frequency aliasing, let Ω_{max} is the maximum frequency in $x(t)$ can be sampled uniformly by using a sampling frequency. The Nyquist sampling condition is given by equation:

$$\Omega_s = \frac{2\pi}{T_s} \geq 2\Omega_{max} \tag{A-3}$$

Where T_s is periodic of period (sampling period) with $x(t)$.

On the other hand, equivalently when the sampling rate f_s (sample/sec) or the sampling period T_s (sec/sample) are given by equation:

$$f_s = \frac{1}{T_s} \geq \frac{\Omega_{max}}{\pi} \tag{A-4}$$

Where $T_s \leq \frac{T0}{2}$ where T_0 is period.

A.2. Fast Fourier Transform

The Fast Fourier Transform (FFT) is an algorithm that has been developed to compute the discrete Fourier series in a remarkably economical trend. By utilizing the results of previous computations to reduce the number of operations, the time of operation is faster than the discrete Fourier transform (DFT). In particular, to make transformation, FFT used the periodicity and symmetry of trigonometric functions with approximately $n\,log2n$ operations. For instance given $n = 50$ samples, the FFT is about 10 times faster than the DFT and for $n = 1000$, it is about 100 times faster.

The FFT should take the sampled signal for one period and calculate the magnitude and phase of the signal, except the frequency components at f=0 and f=f_s /2 (the Nyquist frequency), which are both real. The number of FFT elements equal to the size of the time sample. Then, the half of these complex numbers corresponds to negative frequencies and otherwise are complex conjugates for the positive frequencies of the first half and do not carry any new information. An algorithm of FFT is presented in Figure A-1.

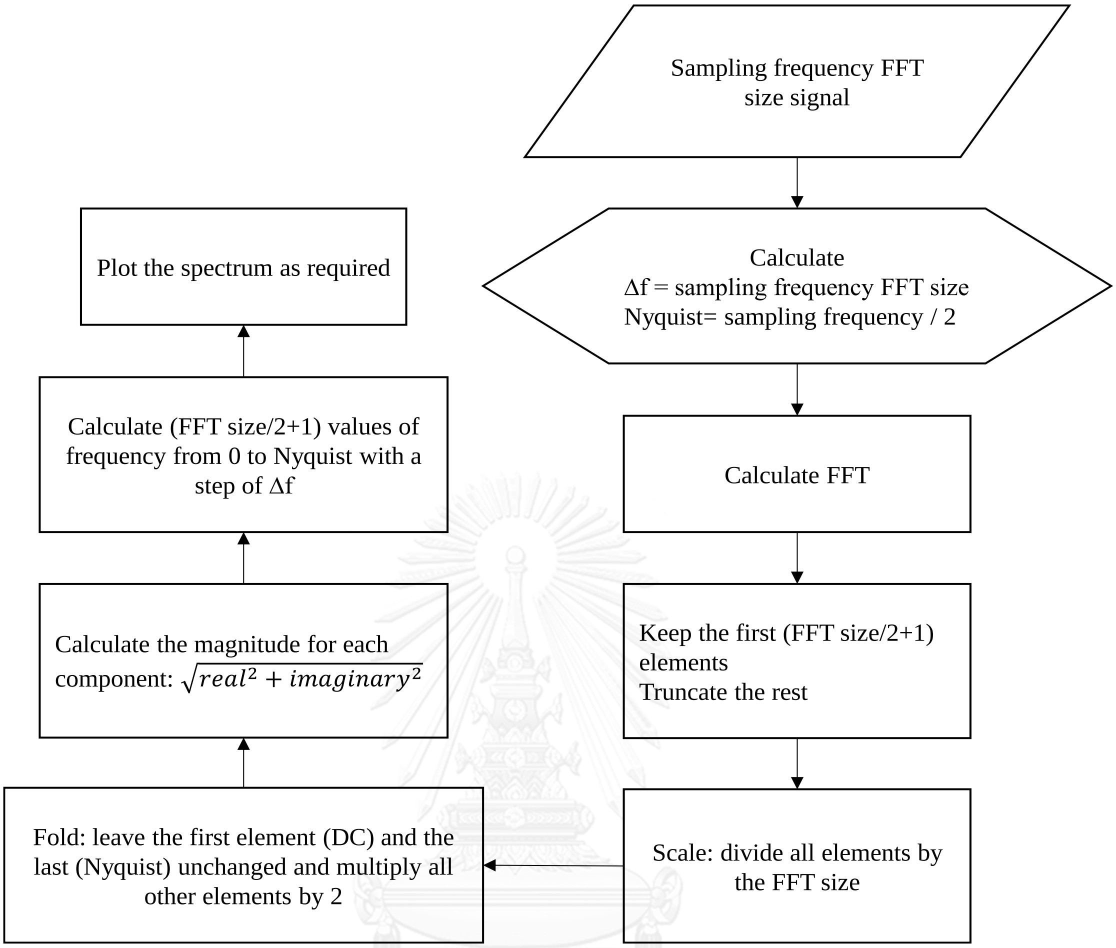

Figure A-1: The flow chart of FFT algorithm.

Commonly, implementations of FFT algorithm are available in MS Excel and in Matlab. Figure A-2(a) showed the 81-time domain samples used as the input to the FFT and Figure A-2(b) showed the frequency spectrum generated from the FFT by using Mathlab. In this case, the length of the sample is 40 ms and hence the frequency resolution, Δf, will equal 50Hz and the Nyquist frequency is 1 kHz. It is clear that frequency resolution is increased by increasing the sampling time domain.

Moreover, the inverse fast Fourier transform (IFFT), is used to reconstruct a time domain signal based on the magnitude and phase of signal in frequency domain, can be performed by removing the fundamental from the input signal.

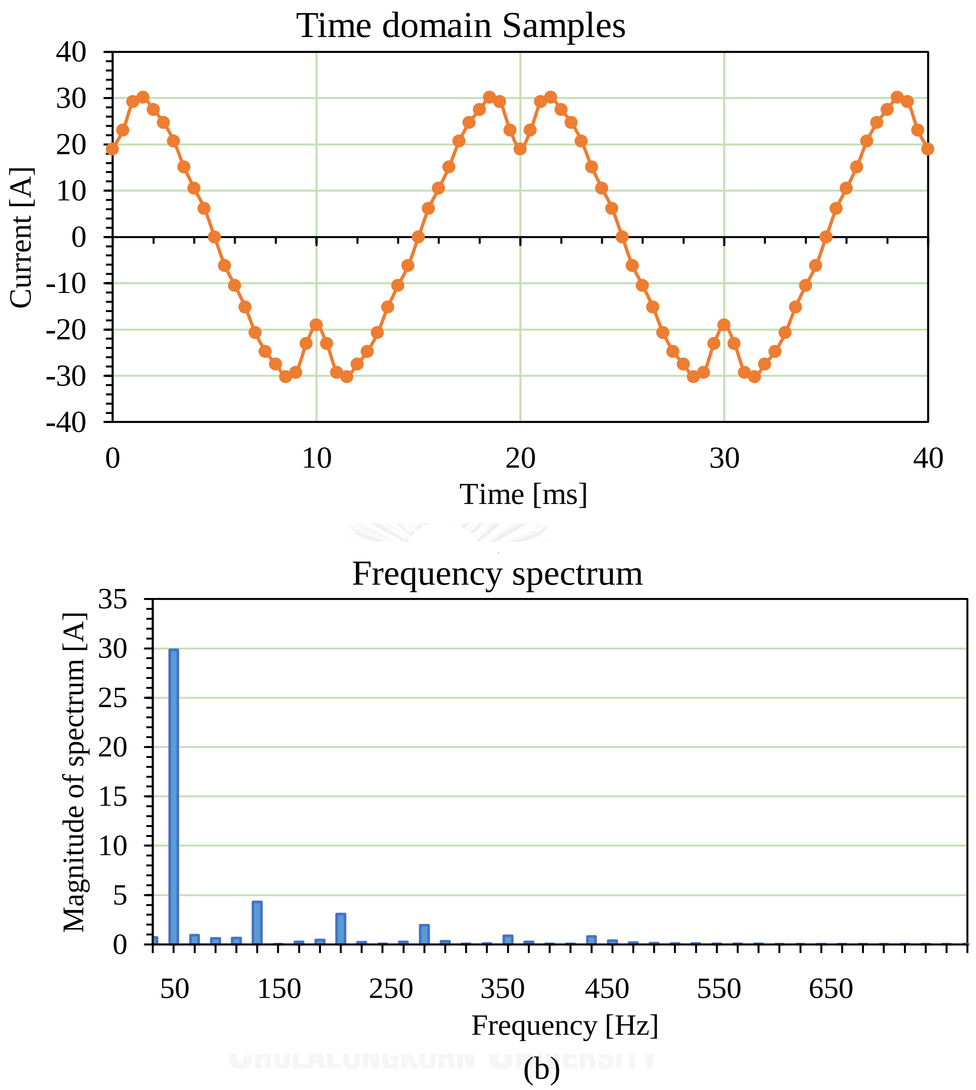

Figure A-2: The sinusoid current (a) in time domain (b) in frequency domain by using FFT.

A.3. General problems on frequency analysis

FFT has become popular tool for analyzing signal in frequency domain. A case in point is analysis of harmonic waveform. However, some cautions must be taken with FFT. In most instances, incorrect positioning of the signal within the frequency will significantly change the spectrum, especially obtained the magnitude of signal with incorrect frequency. The leakage and aliasing should be taken to considered, because both of these are cause of the spectrum distortion and make the incorrect amplitude signal when using FFT. As previously discussed, an effective way to alleviate these effects is to maximize the sampling time domain, because of the relationship of length of time domain, sampling rate and frequency resolution. In addition, in order to avoid spectral leakage, which would lead to an incorrect generated signal, the FFT must be calculated over a complete mains cycle.

Moreover, the problem with doing the FFT in Mathlab gives the correlation between the results returned and the actual value we want. In order to interpret the results of FFT correctly, one must understand how FFT returns the results of the transform. For practical reasons, the presentation of the spectrum for positive frequencies only is preferred. However, to compensate the effect of ignoring the negative frequencies, all positive frequency components must multiply by 2. Besides the showing the processing of FFT, Figure A-1 showed the folding the FFT spectrum and the calculation of magnitude of signal in frequency domain.

Appendix B: The results of test based on injected single frequency current

B.1. Based on IEEE standard

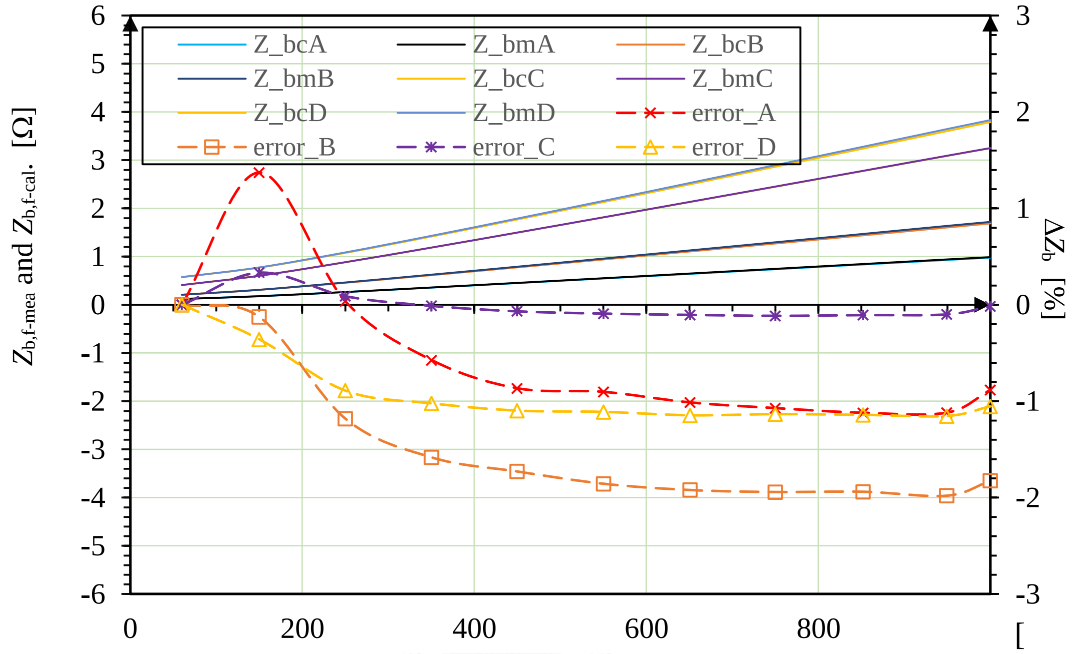

Figure B-1: The comparison between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ for burden A to D.

B.1.1. For CT 2

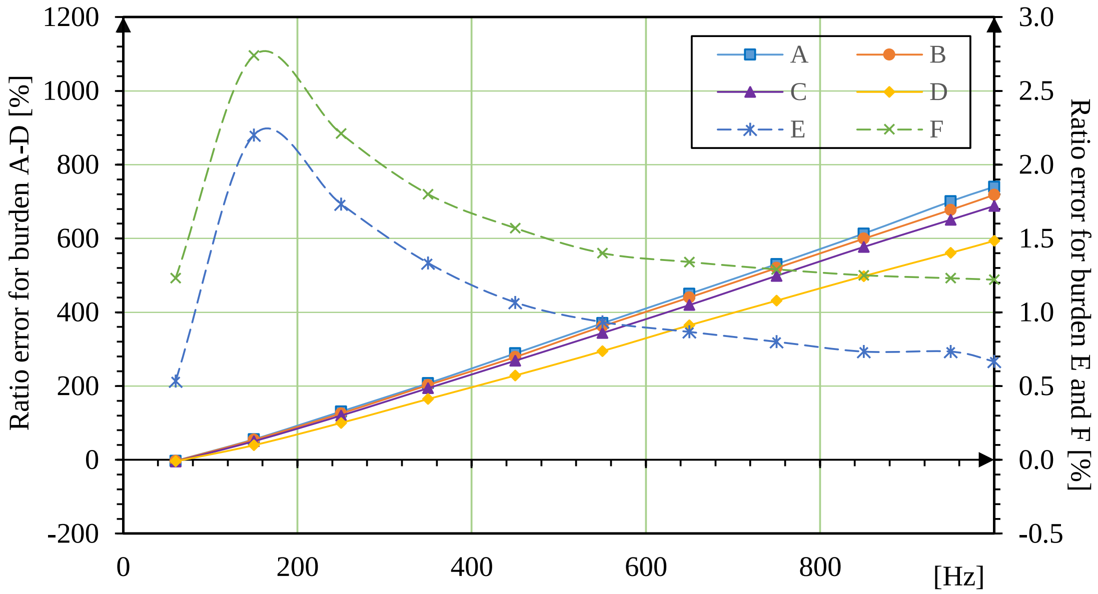

Figure B-2: The ratio error of CT2 for burden A to burden F, by using $Z_{b,fix}$.

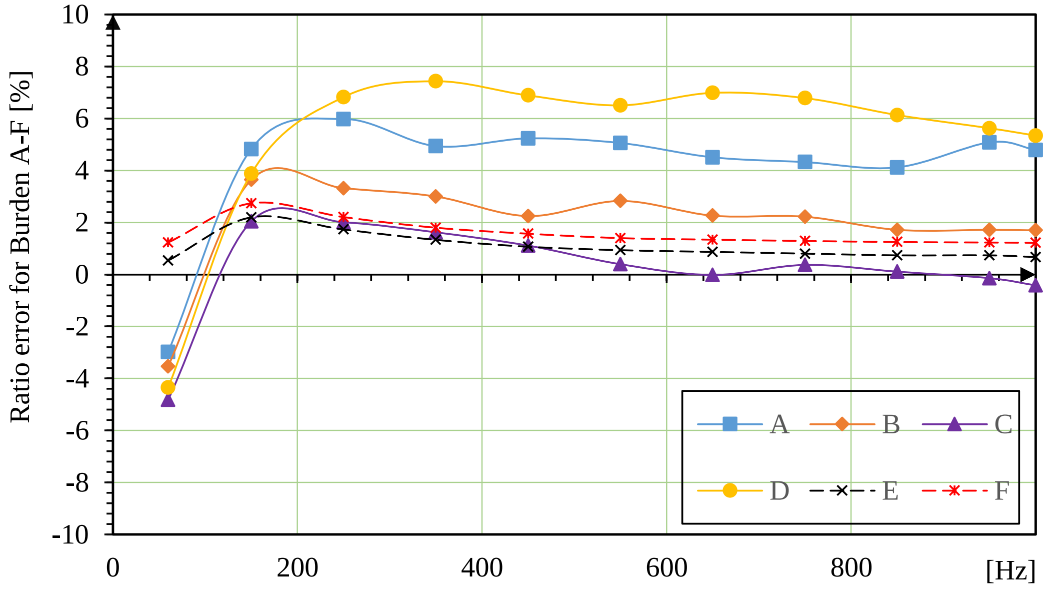

Figure B-3: The ratio error of CT2 for burden A to burden F, by using $Z_{b,f\text{-}cal}$.

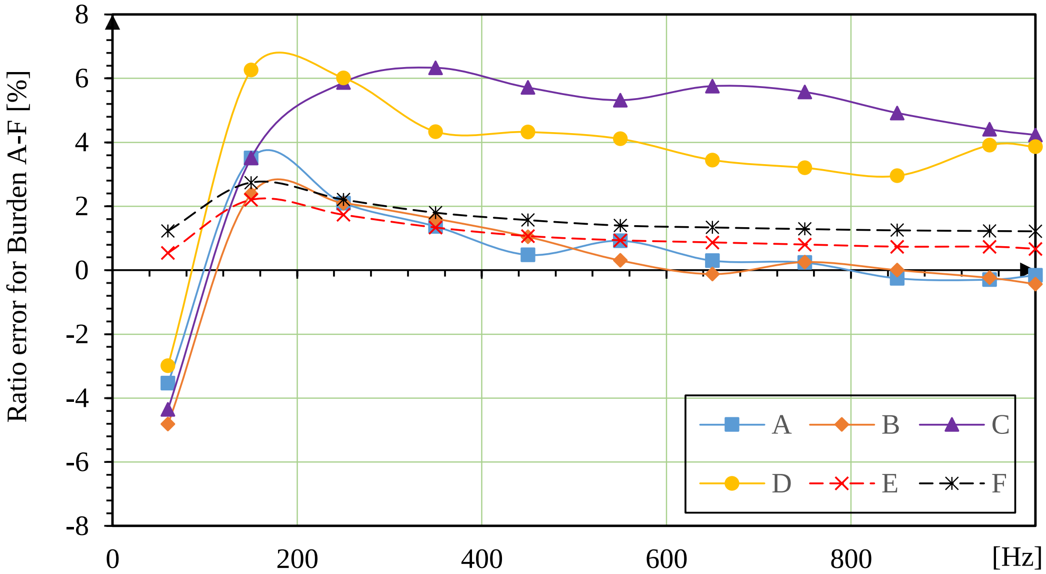

Figure B-4: The ratio error of CT3 for burden A to burden F, by using $Z_{b,f\text{-}mea}$.

B.1.2. For CT 3

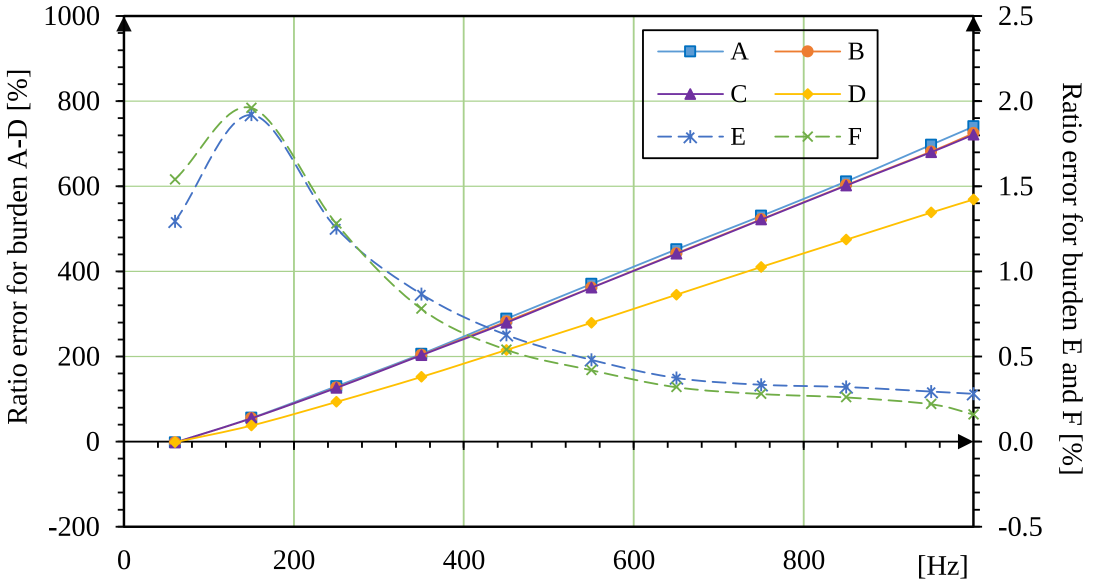

Figure B-5: The ratio error of CT3 for burden A to burden F, by using $Z_{b,fix}$.

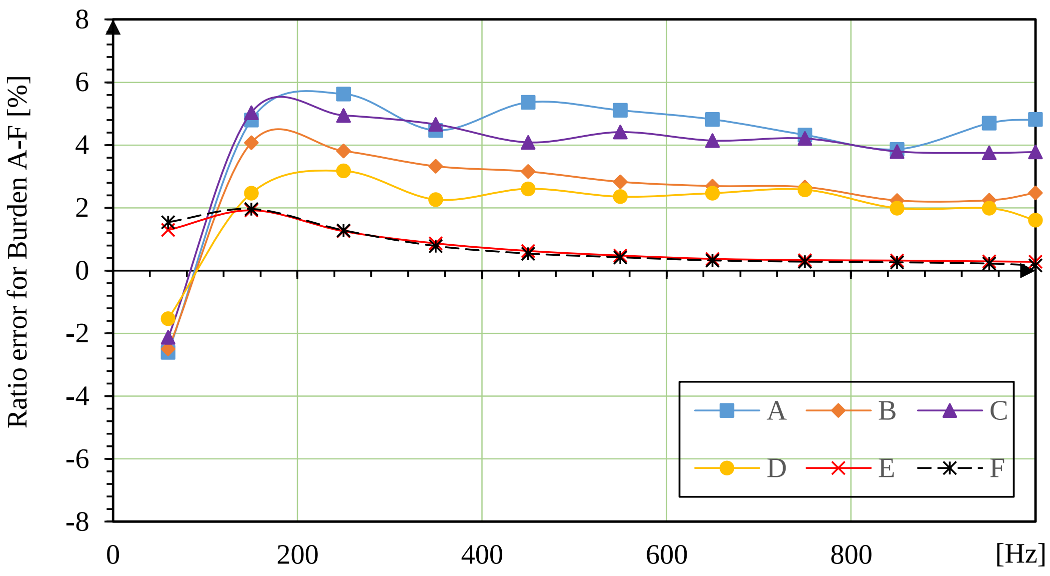

Figure B-6: The ratio error of CT3 for burden A to burden F, by using $Z_{b,f\text{-}cal}$.

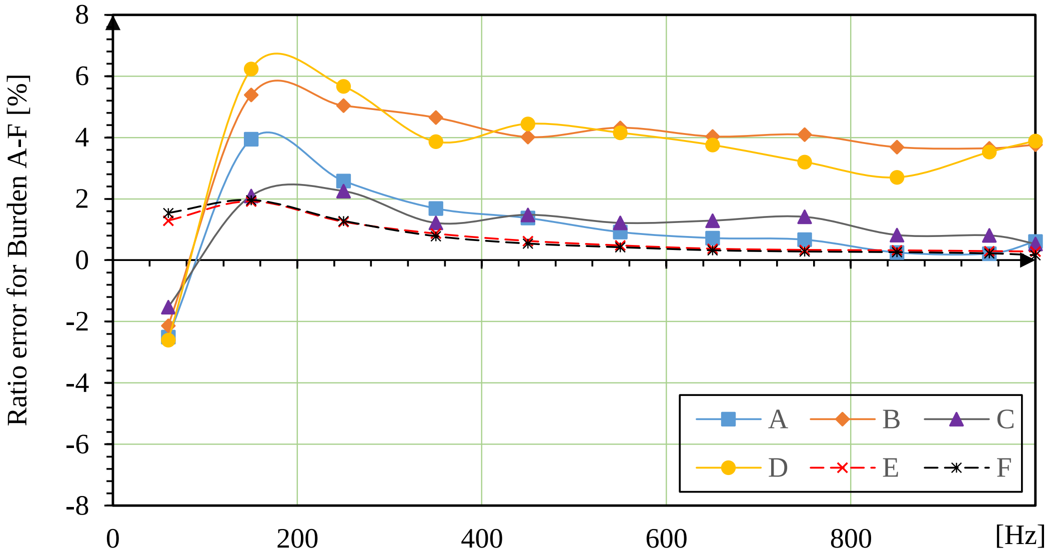

Figure B-7: The ratio error of CT3 for burden A to burden F, by using $Z_{b,f\text{-}mea}$.

B.2. Based on IEC standard

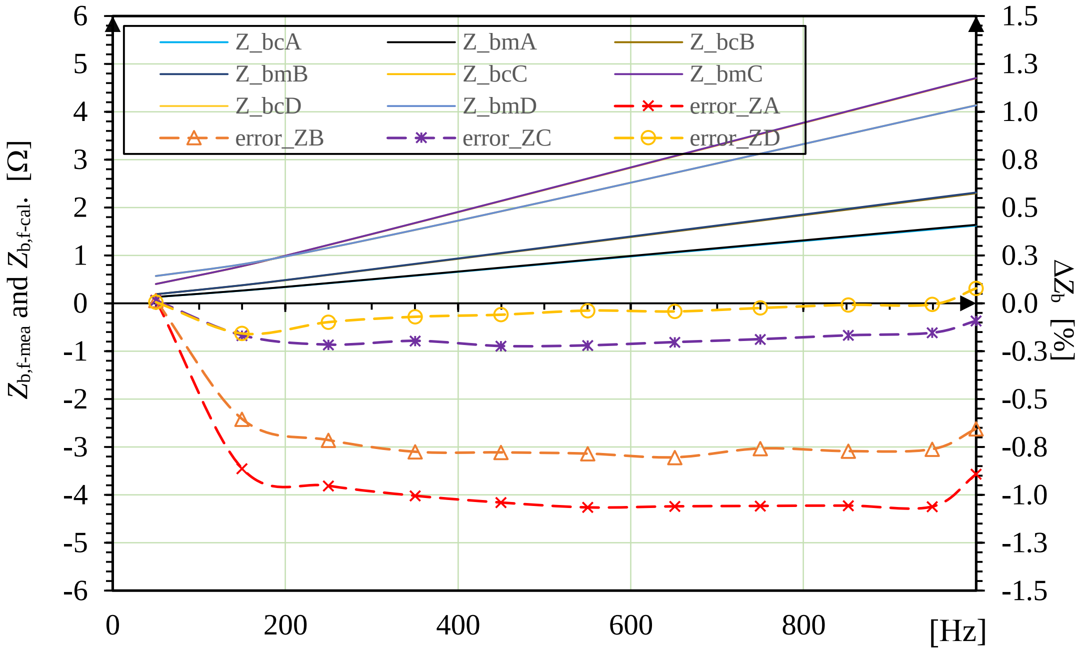

Figure B-8: The comparison between $Z_{b,f\text{-}mea}$ and $Z_{b,f\text{-}cal}$ for burden A to D.

B.2.1. For CT2

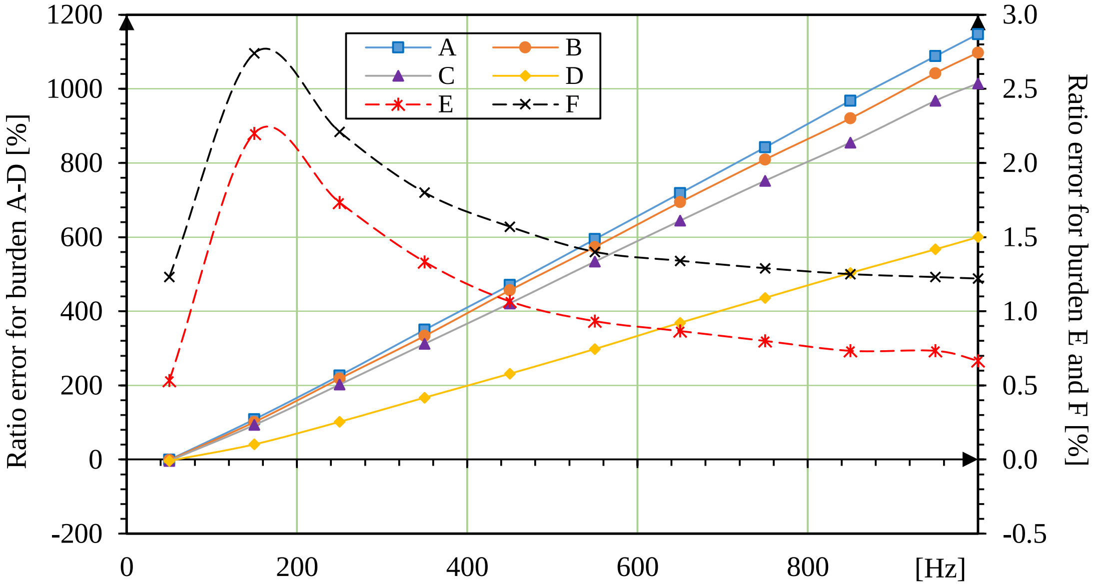

Figure B-9: The ratio error of CT2 for burden A to burden F, by using $Z_{b,fix}$.

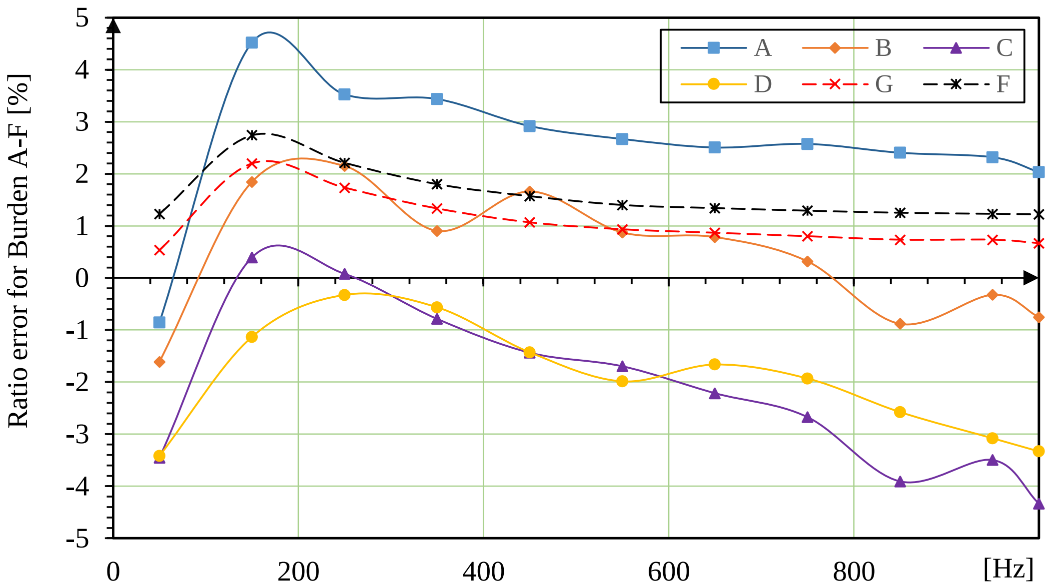

Figure B-10: The ratio error of CT2 for burden A to burden F, by using $Z_{b,f\text{-}cal}$.

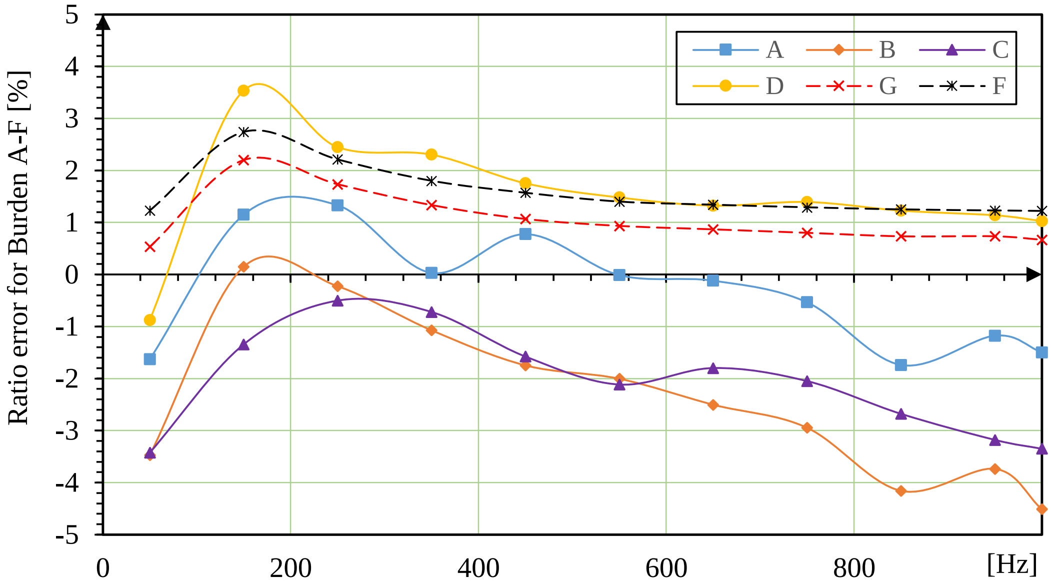

Figure B-11: The ratio error of CT2 for burden A to burden F, by using $Z_{b,f\text{-}mea}$.

B.2.2. For CT3

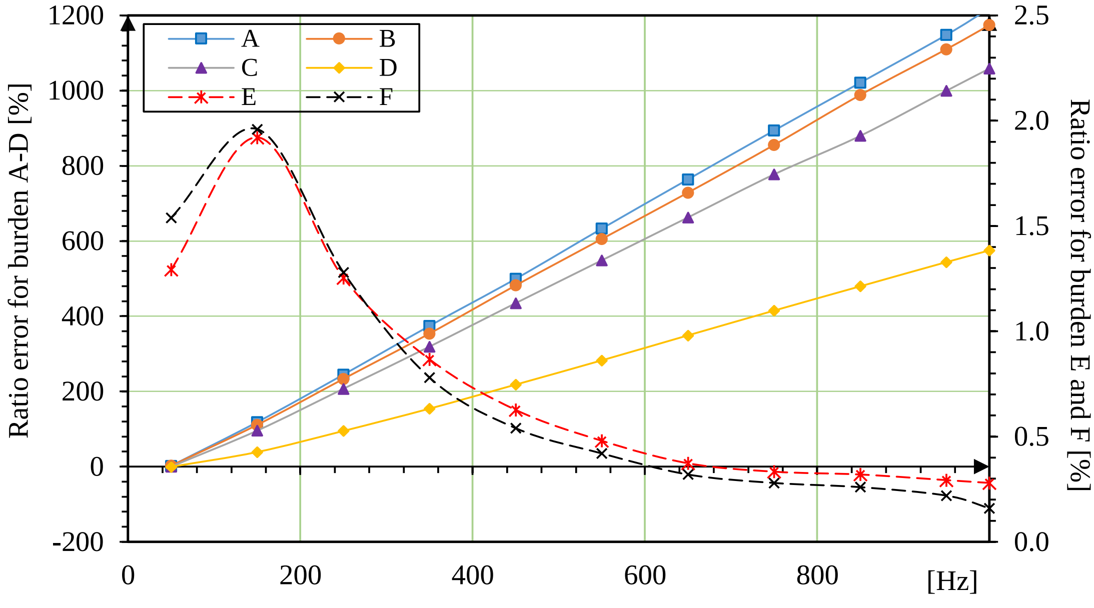

Figure B-12: The ratio error of CT2 for burden A to burden F, by using $Z_{b,fix}$.

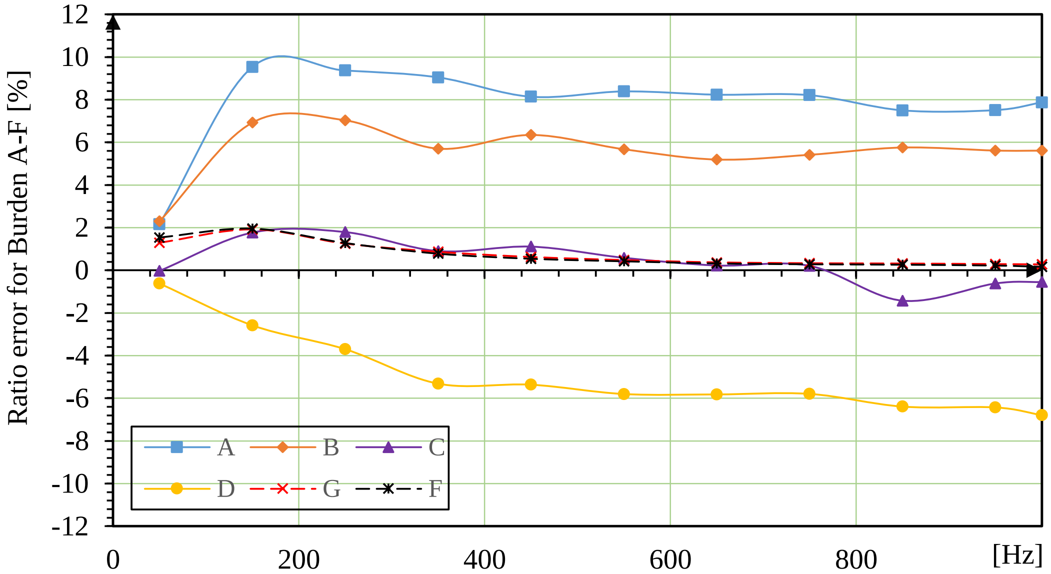

Figure B-13: The ratio error of CT3 for burden A to burden F, by using $Z_{b,f\text{-}cal}$.

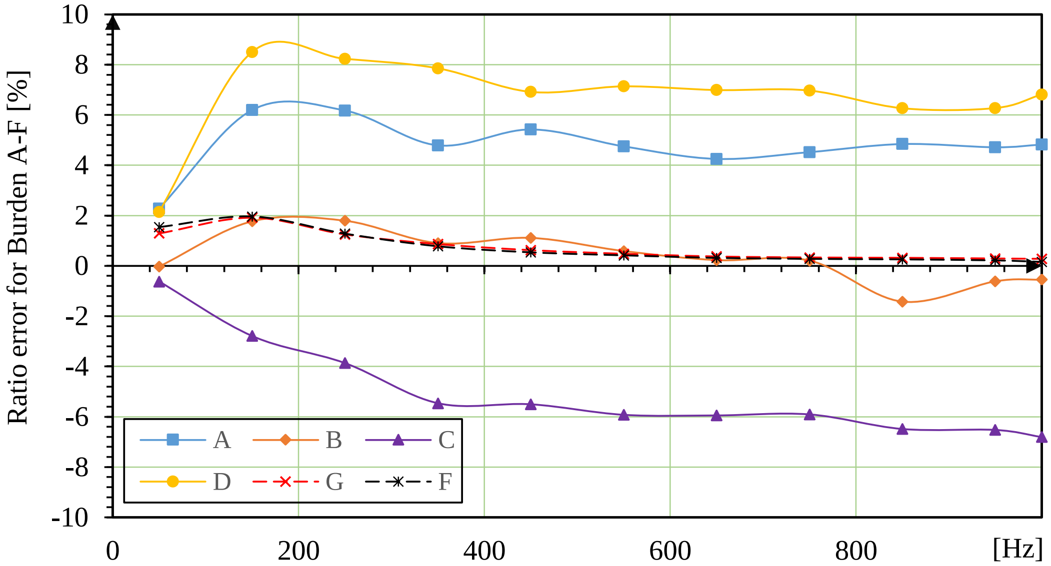

Figure B-14: The ratio error of CT3 for burden A to burden F, by using $Z_{b,f\text{-}mea}$.

Appendix C: The results of test based on injected harmonic current

C.1. For CT2

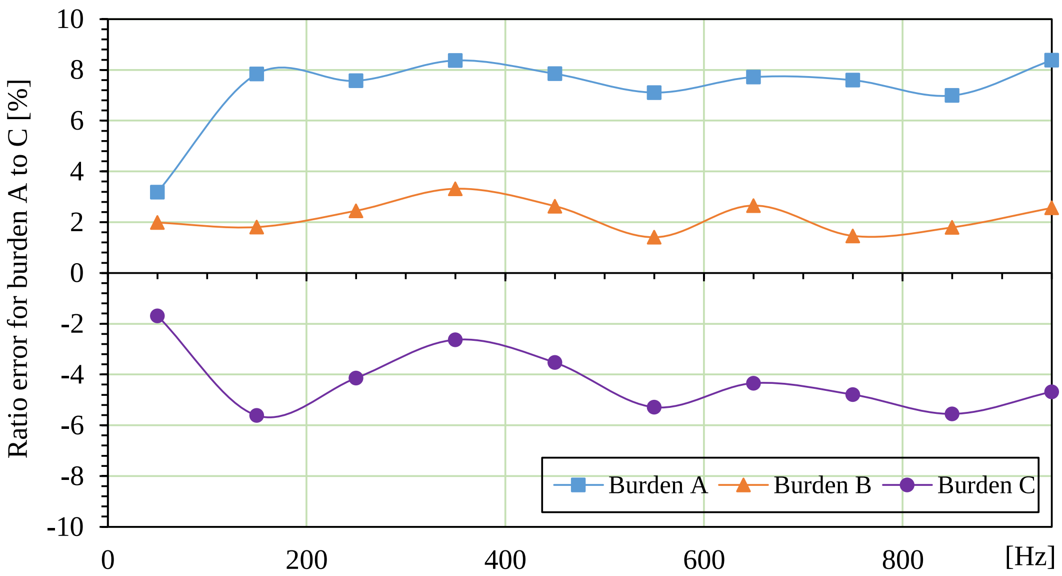

Figure C-1: The ratio error of CT2 for burden A to C in frequency domain.

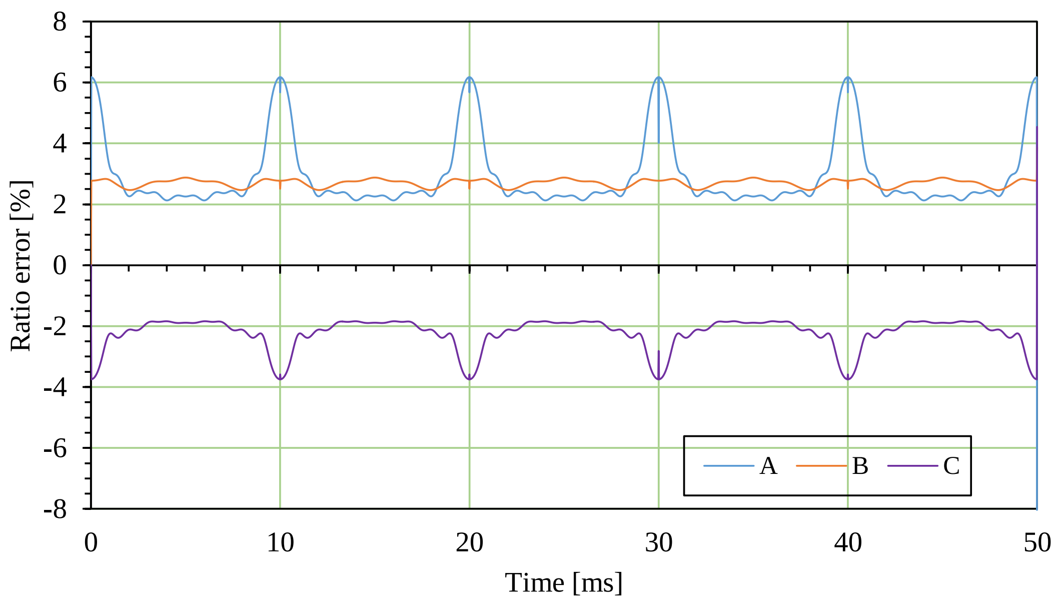

Figure C-2: The ratio error of CT2 for burden A to C in time domain.

C.2. For CT3

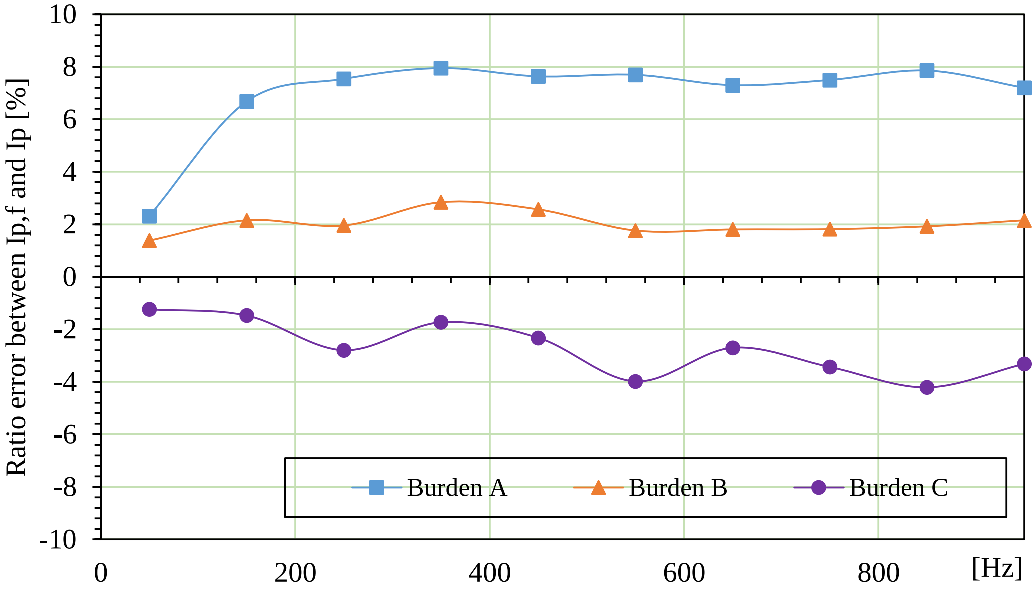

Figure C-3: The ratio error of CT3 for burden A to C in frequency domain.

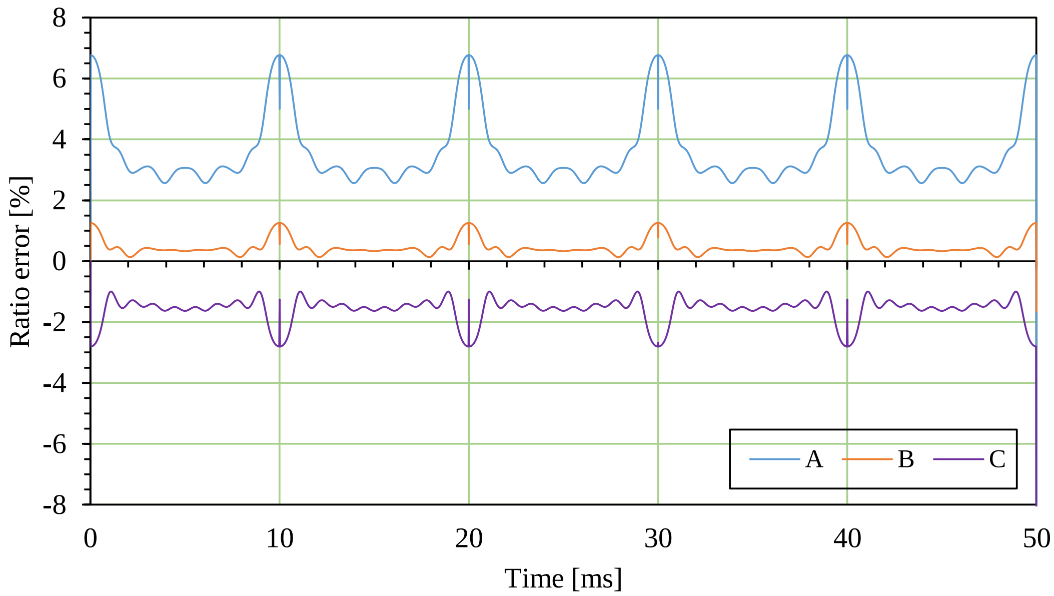

Figure C-4: The ratio error of CT3 for burden A to C in time domain.

Appendix D: The results of correction ratio error

D.1. For CT2

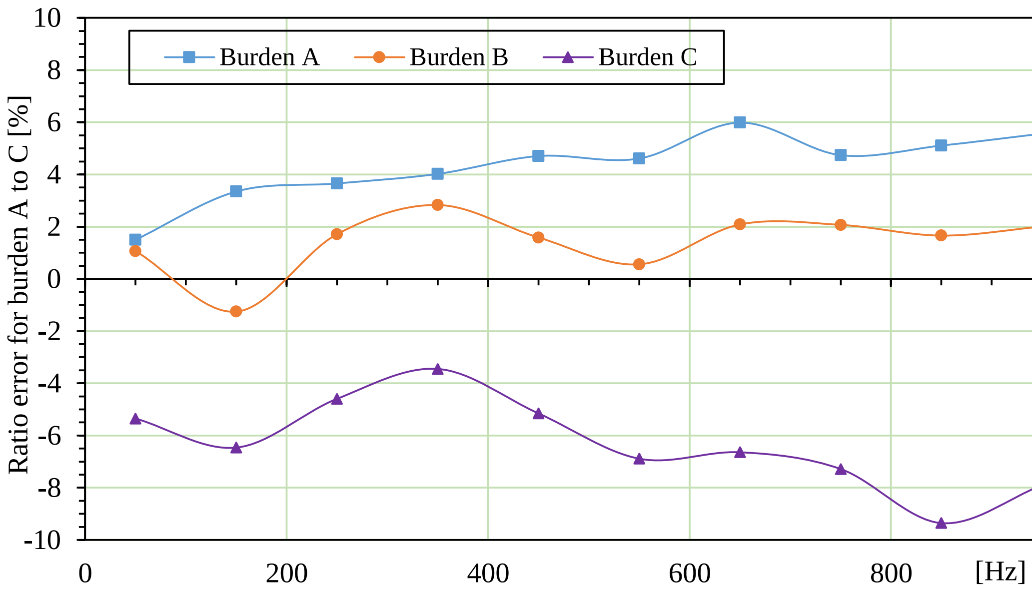

Figure D-1: The correction of the ratio error of CT2 for burden A to C in frequency domain.

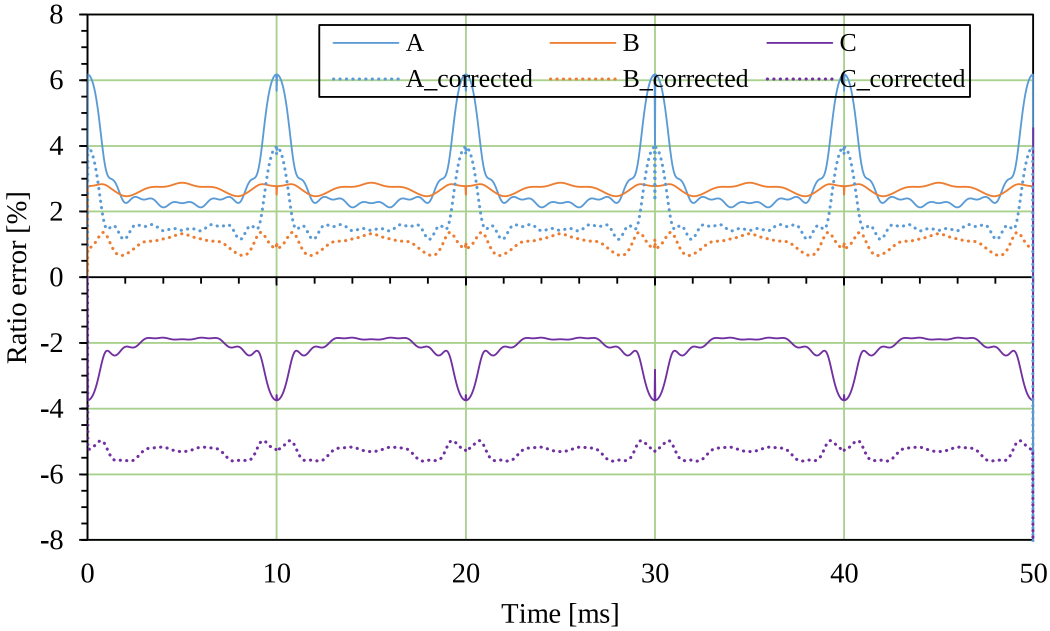

Figure D-2: The correction of the ratio error of CT2 for burden A to C in time domain.

D.2. For CT3

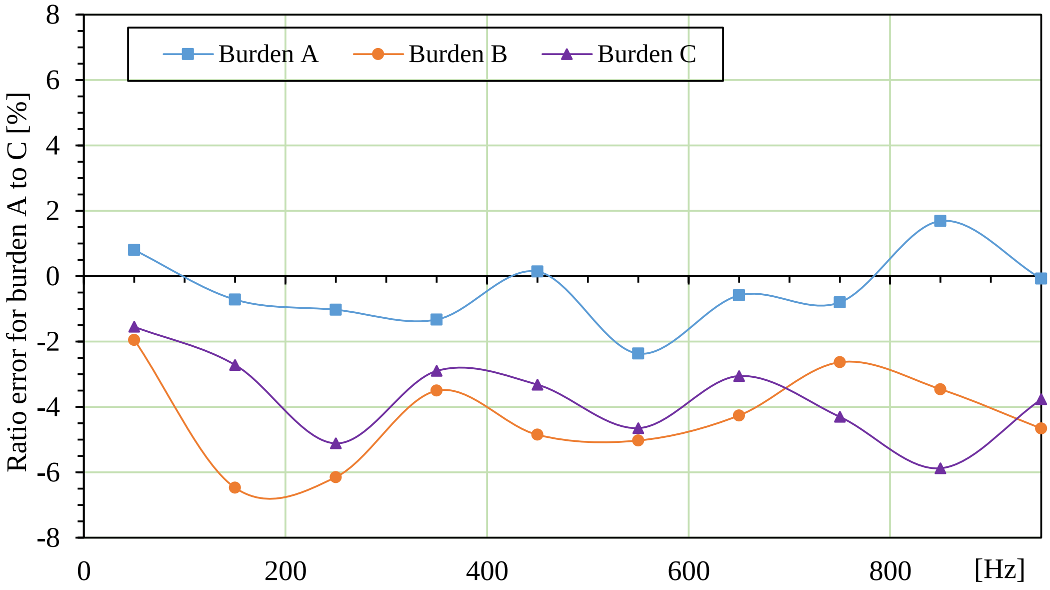

Figure D-3: The correction of the ratio error of CT3 for burden A to C in frequency domain.

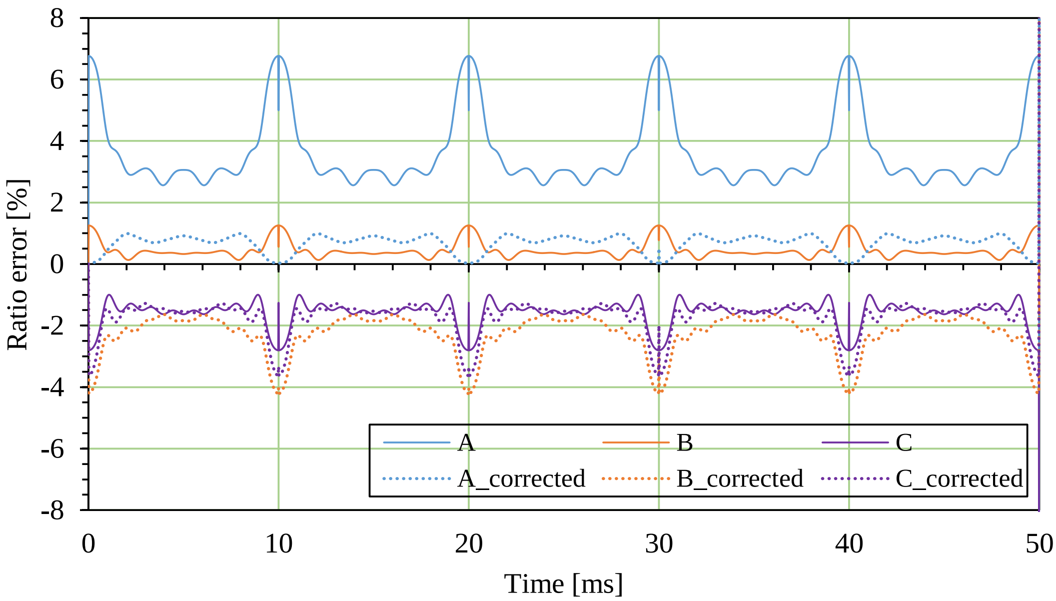

Figure D-4: The correction of the ratio error of CT3 for burden A to C in time domain.

VITA

Oudom Siv was born in Phnom Penh, Cambodia in 1989. He graduated from high school in 2008 and continued his bachelor's degree at Institute of Technology of Cambodia. After he received his bachelor's degree in electrical engineering in 2013, he got a scholarship to study Master's degree at Chulalongkorn University in Bangkok, Thailand. His field of study is High voltage engineering and his thesis title is Influence of Burden on the Accuracy of Current Transformer at High Frequency.