The Study of Third Harmonic Characteristics from Salient Pole Synchronous Generator under Unbalanced Load

By

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Dissertation submitted in partial fulfilment of
the requirements for the
BACHELOR OF ENGINEERING (Hons)
(ELECTRICAL AND ELECTRONICS)

January 2015

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CERTIFICATION OF APPROVAL

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Approved by,

____

(Ir. Mohd Faris Abdullah)
UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SERI ISKANDAR, PERAK

January 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified the references and acknowledgements, and that the original work contained herein have not been undertaken r done by unspecified sources or persons.

MOHAMMAD MUNZIR MOHAMMAD HUSNI

ACKNOWLEDGEMENT

Firstly, Alhamdulillah to Allah s.w.t. for without His help, I would not be able to complete my Final Year Project Report.

Next, I would like to thank Ir. Mohd Faris Abdullah, my supervisor for this project, for guiding me throughout the course of this project. His inputs and comments were vital for me to accomplish this project.

On top of that, my sincerest gratitude goes to the laboratory technicians such as Mr. Zuraimi and Mrs. Noralyza, as well as Research Officers such as Mr. Sayyid Haziq Hasmoro and Ms. Iylia for assisting me to conduct the experimental part of this project.

Also, my thanks go out to Department of Electrical and Electronics Engineering, Universiti Teknologi PETRONAS especially the FYP Committee, who have provided us with the proper guidelines in order to accomplish our project.

Finally, I would like to that other parties that were unmentioned above in helping me in whatever way possible. Thank you.

ABSTRACT

A non-linear load draws non-sinusoidal current that consists of frequencies that are multiples of the fundamental frequency. This is the basis of harmonics and it creates distortions when interacting with power systems. In medium voltage systems, loads are always balanced due to the presence of power transformers of delta-wye winding configuration, by which the triplen harmonics currents only circulate at the delta winding of transformer, unable to reach the load. However, in low voltage systems, loads remain unbalanced. Generators are found to be a source of third harmonics and factors influencing the production include slot skew, distribution factor and pitch factor. The objective of this project is to study the characteristics of third harmonics characteristics when unbalanced load is introduced into the system. In order to obtain the relevant data for analysis purposes, lab-scale experiments are conducted by using the equipments that are readily available in the laboratory. The scope of the lab experiments include performing experiments using balanced load as reference value, and unbalanced load, which are relevant with the project's objectives. Upon investigation, at fundamental frequency, when load impedance increases, voltages for all forms of loads at generator and load side showed minimal fluctuations and current magnitude decreases. Meanwhile, at third harmonics frequency, the neutral current carries the highest current magnitude. As load impedance increases, the magnitude of current decreases. Also, voltage differences when load impedance increased are minimal. Analysis for the result was conducted using per-phase and symmetrical component method, with the former method being a better method for analysis. Cross-coupling phenomenon was also discovered for resistive loads.

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List of Abbreviations

AC – Alternating current

Hz – Hertz

UTP – Universiti Teknologi PETRONAS

GDC – Gas District Cooling

GTG – Gas turbine generator

NER – Neutral earthing resistor

DC – Direct current

PCC – Point of common coupling

VA – volt amperes

CHAPTER 1: INTRODUCTION

1.1 Background

By taking a common AC power system for example, the current that flows has a sinusoidal variation at frequencies of usually 50 or 60 Hz. Whenever a load is applied to the system, the load draws current. If the load is a linear load, the current drawn is sinusoidal and with the same frequency to the system's voltage. One example of linear loads includes fluorescent lamps.

However, if the system is connected to a non-linear load, the current drawn may not necessarily be sinusoidal. Non-linear loads include computers and variable speed drives. The load can be considered to be non-linear when its impedances vary with the applied voltage. The current waveform and waveform complexity that is drawn by the load depends on the load characteristics such as its type. The non-linear loads then produce frequencies that are multiples of the fundamental frequencies of 50 or 60 Hz. This phenomenon is called as harmonics. Harmonic currents can create voltage distortions by means of interaction with the power system's impedances. Voltage distortions will then affect the power system and the loads that are connected to it.

Studies have found that apart from non-linear loads, generators are also another source of the production of third harmonics. The production is influenced by several factors, namely slot skew, pitch factor as well as distribution factor.

Meanwhile, currents that are viewed as multiple values of the fundamental frequency are known as harmonics currents. Usually, the harmonics are odd numbers, e.g. 3^{rd}, 7^{th}, 9^{th} order and so on, because under symmetry waveforms, the even harmonics do not exist. In addition to that, harmonics currents that have the frequency of multiples of 3 are called triplen harmonics currents. Such examples include 3^{rd}, 9^{th} and 15^{th} harmonics etc.

1.2 Problem Statement

Tracing back its origins from synchronous generators, third harmonics current flows at a continuous basis. Then, it flows back to its neutral point via neutral or ground path. Loads remain unbalanced when it comes to low voltage systems. Hence, a study regarding third harmonic current characteristics from salient pole synchronous generator during unbalanced load is necessary to be done. Other harmonic levels such as 5^{th}, 7^{th} and etc. are not considered in the study since the current contribution of third harmonics make up the majority of total harmonic distortion in the system.

1.3 Objectives/Scope of Project

The objectives of this project:

1. To study the characteristics of third harmonic voltage & current from salient pole synchronous generator during balanced load condition
2. To study the characteristics of third harmonic voltage & current from salient pole synchronous generator during unbalanced load condition.

The project also aims to compare the best method for result analysis, either by using per-phase method or symmetrical component method.

The scope of the project involves only steady-state studies when synchronous generator operating at normal operation without saturation.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

Universiti Teknologi PETRONAS (UTP) has pursued innovation by making use of the abundance of natural gas in Malaysia by generating its own electricity. The Gas District Cooling (GDC) plant supplies electricity as well as chilled water for the air conditioning system of the academic and Chancellor Complex. GDC houses two units of gas turbine generators (GTG) that are able to produce electricity up to 4.2 MW for each unit. Meanwhile, a precaution that was exercised by this medium voltage network in case of emergencies such as power trip is that the network is connected to the national utility network. On a normal daily basis, the plant runs in island mode. As mentioned, in the case of emergencies or maintenance works, the network can be connected in parallel to the utility network in order to add on electricity to meet user demands [1].

Both GTG units are connected to ground by means of using neutral earthing resistors (NER) rated at 31.75 Ω, 200 Amps for 10 seconds. These NERs are grounded individually for both GTG units. The specifications of both NERs are according to IEEE 32-1972 standards. It specifies that during a specific short time period, the temperature rise should not go beyond 760 ^{0}C and they are not designed to withstand continuous current flows of any values [2].

It has been reported that there has been cases of the NER being overheated. Upon inspection, it was found that the cause was third harmonics currents flowing through the NER. Some reported cases also found that this cause have made NER fail to function [3]. Besides that, during parallel resonance mode, damage can be inflicted to the wye connected power capacitors due to high third harmonics currents [4].

2.2 Third/Triplen Harmonics

With the increase of the harmonics order, the subsequent effect would be a reduction of the third harmonic current's magnitude. This constitutes that the third harmonics current makes up a large portion of triplen harmonics current, with its magnitude affected by both third harmonic zero sequence impedance and voltage [5].

Under balanced conditions, third harmonics currents at the neutral is equal to three times the phase triplen harmonics currents due to all third harmonics currents for all phases being added up at the neutral. As such, triplen harmonics currents rise rapidly as an islanded generator is connected to the grid. This resulted from the utility power supply acting as a source of short circuit or low zero sequence impedance [6]. In contrast of zero sequence inductive reactance clamping down third harmonics current, zero sequence capacitive reactance offers lesser zero sequence impedance. When this comes into effect, generators in islanded mode which have system capacitances directly connected to them will provide a zero sequence path for the triplen harmonics currents to return to the neutral point of the generator [7].

Studies have shown that there are several ways to limit the effects of triplen harmonics currents. Firstly, triplen harmonics currents production can be restricted by identifying the source, whether from the generator or non-linear load. As discussed in [5], [6], using armature winding pitch of 2/3 for the generator will result in the production of smaller magnitude of triplen harmonics currents. Meanwhile, triplen harmonics currents production by non-linear loads can be halted by harmonics suppression method [8], [9]. Another method discussed is by using the correct method of grounding for the system, which will increase the network's zero sequence impedance [5]. Finally, triplen harmonics currents can be shunted to earth, which stops the propagation into the network by using a zig-zag transformer [5].

2.3 Salient pole generators

When a DC current is applied to the rotor winding of a synchronous generator, the resultant effect would be a rotor magnetic field. Then, a prime mover turns the rotor, which in turn creates a magnetic field in the generator. When this magnetic field is cut, there will be three phase voltages induced at the 3 phase armature windings of the stator.

To put it simply, the rotor of a generator is actually a large electromagnet that has two forms of construction, salient and non-salient pole. When the surface of the rotor has some poles sticking out from it, it is a salient pole. Salient poles are usually used when two or more poles are used. This increase in number of poles means that the machine is not used in high-speed applications. Meanwhile, if the poles are in alignment with the rotor surface, the pole is considered to be a non-salient pole. Non-salient poles are commonly used in machines with two or four pole configurations at the rotor. As opposed to salient poles, non-salient poles are used for machines with high-speed applications [10].

Generally, generators are constructed in a wye-formation while they are connected to either wye or delta formation loads. The reason that generators are not winded in a delta formation is that when there exists any unbalance in the voltages at the phase windings, a net voltage occurs which in turn creates a circulating current at the delta windings. Besides that, generators commonly have the wye configured windings due to the lesser phase voltages, meaning that less insulation is required for the windings [11].

Generators are found to be one of the main sources of the production of third harmonics currents. Another source comes from non-balanced loads and switched electronic devices such as iron-core reactor and static power converter respectively [12]. Factors affecting the triplen harmonics currents produced by synchronous generators are their winding design, which can be further broken down into their slot skew, and distribution and pitch factors. Apart from that, only third harmonics currents are being taken into consideration since higher impedance impedes higher triplen harmonics frequencies [13].

Third harmonics voltage produced at no-load conditions are due to the generator's salient pole shape and concentrated field winding. Meanwhile, those two factors added with direct-axis and quadrature-axis armature reactance produced third harmonics voltage at balanced load condition. Finally, at unbalanced load, third harmonics voltage is produced by the resultant of backward field mmf to all of the above factors [14].

2.4 Unbalanced load

In power systems, symmetry and balance are two different concepts that should not be wrongly understood. Symmetrical loads occur when the load's voltage or current phase vectors are separated by 0° or 120° between two phases. Meanwhile, balanced loads occur when the current or voltage vector addition of all phases of the loads add up to zero. Since this project studies about unbalanced loads, it can be defined as loads with current vector addition of all phases that does not sum up to zero. The main cause for an unbalanced load in a power system is the overloading of single phase loads within one phase in a three-phase system.

Unbalanced loads occur when multiple single phase loads are connected not in uniform among all phases. This can cause equipment heating and also efficiency drop. In small scale system, this could happen when rural power systems are connected to generators driven by wind turbines via long distribution lines. Meanwhile, in industrial applications, unbalanced loads occur when a heavy demand of single phase loads such as plant lighting have to be catered to by large plant facilities. Although the plant's incomer supply is balanced, the single-phase demands that are not distributed evenly among all phases can result in unbalanced conditions. Finally, unbalanced conditions can occur when there are transformers using unsymmetrical windings or transmission impedances. Examples include open wye and delta, and so on [15]. When weak power systems due to unbalanced load problems are connected to wind turbines, the continuous operation will be hazardous to the generator. At the point of common coupling (PCC), the effect of unbalanced load will be unbalanced voltage due to unbalanced voltage along transmission lines. With respect to the unbalanced voltages, when the magnitude is small, this constitutes a large magnitude of negative-sequence currents coming from an inductive generator's low sequence impedance. The large magnitude of current results in overheating or creation of hot spots at a certain location in an equipment winding, which can cause equipment breakdown. Moreover, a pulsating torque will occur due to unbalanced voltages in the system, which in turn creates mechanical vibration, speed pulsation and acoustic noise [16].

A study by [16] shows that copper losses at involved phases will increase rapidly when one or more phases conduct higher current compared to other phases. The losses created hot spots, due to the winding temperature of the involved phase to be higher than the rated current. These hot spots will in turn deteriorate the life expectancy of the machine's insulation material. Meanwhile, unbalanced voltages have a long time delay in terms of detection, as opposed to other faults such as short-circuit condition. However, this phenomenon only affects users using three phase induction motors and will be insignificant for customers using single phase loads [16].

2.5 Resultant effects of third harmonics in the system

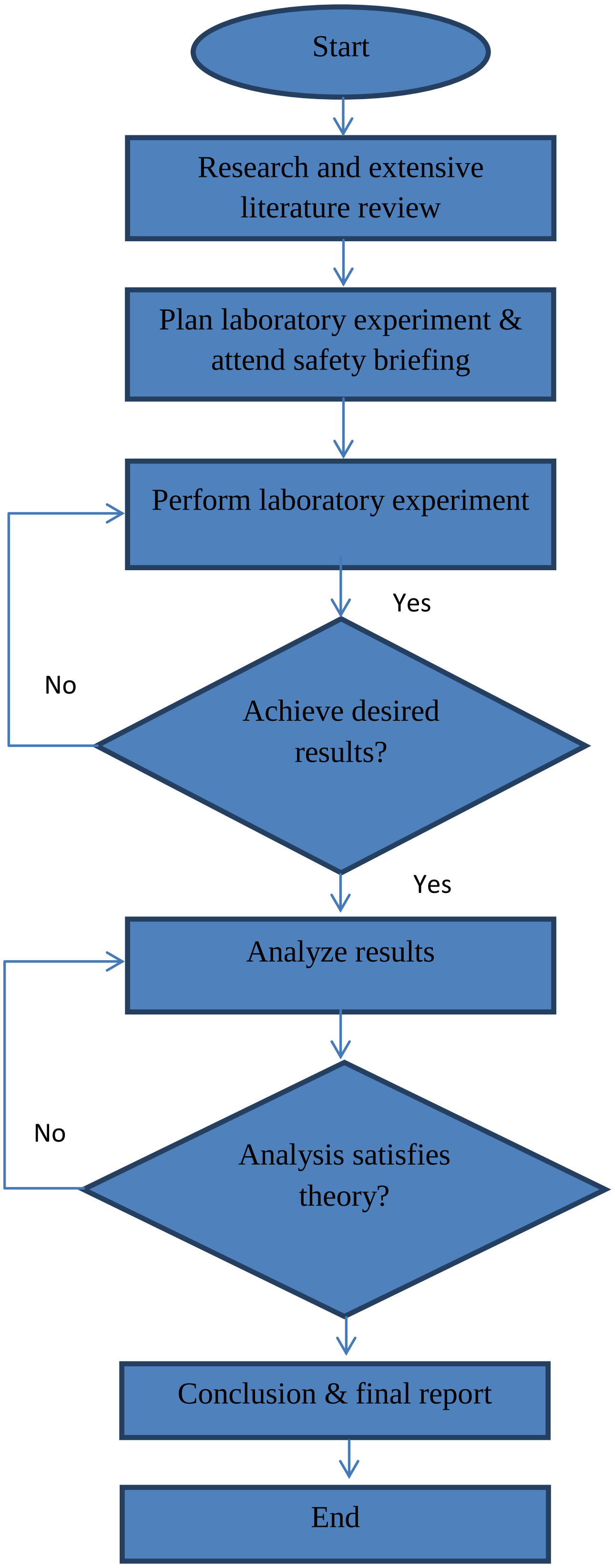
Based on the results when the generator is connected directly to the load, it is found that when impedance of the load increases, the third harmonic voltage increases while current decreases. The same can be said when the load is connected to the generator via a transformer of varied winding configurations [17].

Meanwhile, as cable length increases, third harmonic current also rises in proportion up until the cable length of 40 km. Beyond that length, the current magnitude drops due to low capacitive reactance and also high inductive reactance as the cable gets longer. Cable size affects the third harmonic current minimally since the cables have lower impedances as the increase in size. Adding on to that, as NER values increase, third harmonic current decreases in magnitude [18]. It is found in [18] that third harmonics current is inversely proportional to the balanced resistive, inductive and also the combination of both load impedances. This also means that generator NER resistance has an inversely proportional relationship to the magnitude of third harmonics current.

A study conducted by [17] found that when delta windings are used for the secondary winding of the transformer, the third harmonics current will only circulate inside the windings. They do not escape the windings, thus unable to reach the load. However, star windings will have induced voltage inside the windings and this enables the third harmonics current to reach the load and circulate around it [17]. Another finding from the study done by [19] showed that when the load impedance phase angle increases, third harmonic voltage magnitude and third harmonic current at cable capacitor terminal rises in proportion. Meanwhile, zig-zag transformers effectively limit the flow of third harmonic current to the load to a very small amount due to it providing the smallest value of impedance to ground. However, usage of zig-zag transformer poses another problem whereby the third harmonic current circulates between the generator and the zig-zag transformer, causing heating [19].

CHAPTER 3: METHODOLOGY

3.1 Project Flow Chart



3.2 Research Methodology

The project's main aim is to study the effect of third harmonics current under unbalanced load. Therefore, in order to have a solid background of the knowledge regarding the subject matter, research must be done based on different types of reading materials. These include textbooks, past journals and research papers from previous researchers.

Also, in order to observe third harmonic current and voltage characteristic during balanced load (as base value) and also unbalanced load, lab experiments may need to be carried out. The result will then be analyzed and compared to previous studies.

This lab-scale experiment shall use a generator with the rating of 120 VA. Five different set of load impedances (resistance, inductance, combination of both) will be used along the experiment as loads for each phase. To start off the experiment, a base data should be obtained. This data use balanced load at all phases and will be the reference point for the whole experiment to see the changes in characteristics of the third harmonic voltage and current.

The ratings of the generator are:

Table 1: Generator ratings

Power (VA)	120
Voltage (V)	240
Full load current (A)	0.17

The loads for the generator are shown in Tables 2 to 4.

Table 2: Generator load (resistance only)

Case study	Phase ‘a’ (Ω)	Phase ‘b’ (Ω)	Phase ‘c’ (Ω)
1	960	960	960
2	960	960	1600
3	960	1600	2400
4	1600	2400	3600
5	2400	3600	4800

Table 3: Generator load (inductive reactance only)

Case study	Phase ‘a’ (Ω)	Phase ‘b’ (Ω)	Phase ‘c’ (Ω)
1	j660	j660	j660
2	j660	j660	j1200
3	j660	j1200	j1600
4	j1200	j1600	j2400
5	j1600	j2400	j3600

Table 4: Generator load (combination of resistance and inductive reactance components)

Case study	Phase ‘a’ (Ω)	Phase ‘b’ (Ω)	Phase ‘c’ (Ω)
1	960+ j660	960+ j660	960+ j660
2	960+ j660	960+ j660	1600+ j1200
3	960+ j660	1600+ j1200	2400+ j1600
4	1600+ j1200	2400+ j1600	3600+ j2400
5	2400+ j1600	3600+ j2400	4800+ j3600

The load values for the combination of resistive and inductive loads are calculated as below:

$P = 3\,V\,I\cos\theta\;(phase\ line)$ (3.1)

The generator's ratings are as follows:

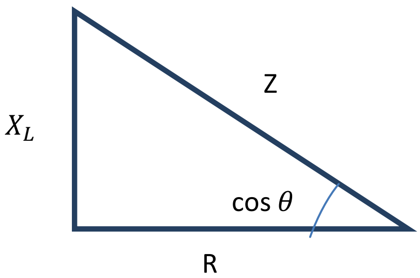
- Voltage = 240 V
- Current = 0.17 A
- Power = 120 VA

$$120\ VA = 3(240)(0.17)(cos\theta)$$

$$\frac{120\ VA}{(3)(240)(0.17)} = cos\theta$$

$$cos\theta = 0.9804\ (power\ factor\ for\ generator)$$

From the above calculations, the values of resistance and impedance can then be found by using the power factor triangle below.



36° = cos 0.8

Cos 36° = $\frac{R}{Z}$

Sin 36° = $\frac{X_L}{Z}$

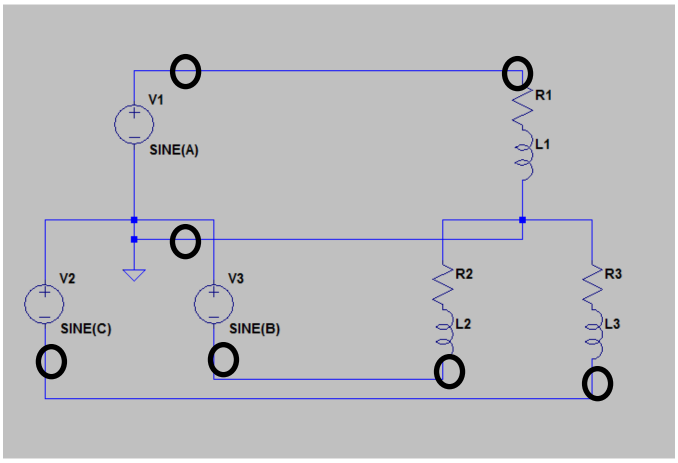


Figure 1: LTSpice schematic of generator directly connected to load

The data then will be further analyzed to see and understand the characteristic of third harmonic current under balanced and unbalanced load. Fluke 434/435 Three Phase Power Quality Analyzer will be used as the measuring tools to measure the third harmonic voltage and current in the electrical power system during balanced and unbalanced load. The equipment is equipped with a clamp meter which helps users to easily measure the current value simply by clamping it to the cable.

3.3 Tools

1. Hardware:
    a. Lab-Volt Electromechanical System (EMS) Workstation

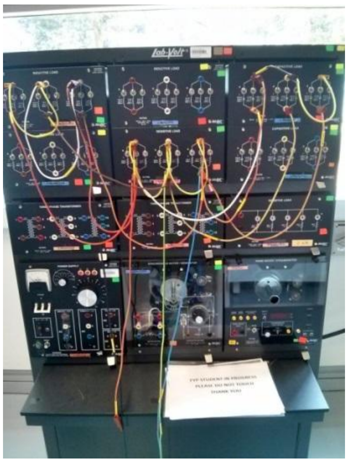


Figure 2: Lab-Volt Electromechanical System (EMS) workstation

    b. Cables

c. Multimeter

d. Fluke View 435 Power Quality Analyzer and clamp meter

Figure 3: Fluke PQ Analyzer

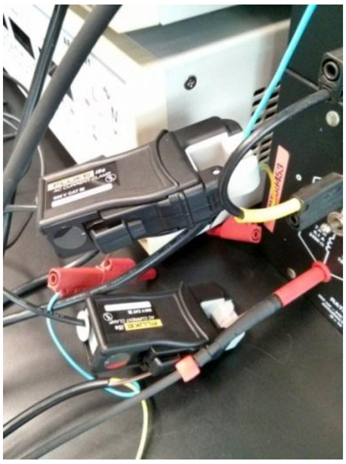


Figure 4: Clamp meter

e. Desktop computer

2. Software:

   a. Microsoft Excel

   b. Fluke View Power Quality Analyzer Software

3.4 Method of Analysis

After collecting data from experiments, those data need to be analyzed in order to verify the behavior of third harmonics current and voltage behavior under unbalanced load. In order to perform this verification, the recorded values are used with a proposed mathematical model so that the theoretical/calculated values at the end tallies with the recorded values.

3.4.1 Per-phase analysis

To perform this analysis, the steps below are taken.

a. Data from Fluke 435 Analyzer are extracted and transferred to Excel spreadsheet.
b. In the spreadsheet, data for voltages and currents are extracted and then transformed from polar form to rectangular complex form (for ease of calculations in spreadsheet).
c. Next, per-phase analysis is conducted by calculating the value of current phase-by-phase using the formula:

$$I_{abc(calc)} = \frac{V_{abc}}{Z_{abc}} \qquad (3.2)$$

d. Finally, comparison is done by computing the percentage error between the calculated value ($\boldsymbol{I_{abc(calc)}}$) and the recorded value ($\boldsymbol{I_{abc(rec)}}$). The formula for percentage error is as follows:

$$Percentage\ error\ (\%) = \left|\frac{Recorded\ value - Theoretical\ value}{Theoretical\ value}\right| \times 100\% \qquad (3.3)$$

3.4.2 Symmetrical component analysis

For this method, the following steps are taken:

1) Data from Fluke 435 Analyzer are extracted and transferred to Excel spreadsheet.

2) In the spreadsheet, data for voltages and currents are extracted and then transformed from polar form to rectangular complex form (for ease of calculations in spreadsheet).
3) Both voltages and currents are in phase form. The data are then converted to symmetrical form using the formulas below:

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) \tag{3.4}$$

$$V_1 = \frac{1}{3}(V_a + aV_b + a^2V_c) \tag{3.5}$$

$$V_2 = \frac{1}{3}(V_a + a^2V_b + aV_c) \tag{3.6}$$

$$I_0 = \frac{1}{3}(I_a + I_b + I_c) \tag{3.7}$$

$$I_1 = \frac{1}{3}(I_a + aI_b + a^2I_c) \tag{3.8}$$

$$I_2 = \frac{1}{3}(I_a + a^2I_b + aI_c) \tag{3.9}$$

4) Since the experiment involves with unbalanced impedances at all phases, the impedances need to be converted from phase to symmetrical form. However, in the case of impedances, two kinds of formulas are found. According to [20], the conventional formula is as follows:

$$Z_{mn012} = AZ^{-1}A \tag{3.10}$$

However, in another paper by [21], it was explained that the impedances can be transformed to symmetrical components via the following formula:

$$Z_0 = \frac{1}{3}(Z_a + Z_b + Z_c) \tag{3.11}$$

$$Z_1 = \frac{1}{3}(Z_a + aZ_b + a^2Z_c) \tag{3.12}$$

$$Z_2 = \frac{1}{3}(Z_a + a^2Z_b + aZ_c) \tag{3.13}$$

Therefore, in this part of the analysis, both formulas will be used and the accuracy of the results will then be compared in order to choose the best method for analysis.

5) After all three components (voltages, currents, & impedances) have been transformed to symmetrical components; terminal voltages can then be computed. In typical applications, only positive sequence networks will have terminal voltage flowing in the system. Meanwhile, for both negative and zero sequences, both do not have voltage supplies in the system. However, in [21], a

formula was presented in order to calculate the terminal voltages, as can be referred to below:

$$E_0 = I_0Z_0 + I_1Z_2 + I_2Z_1 \quad (3.14)$$

$$E_1 = I_0Z_1 + I_1Z_0 + I_2Z_2 \quad (3.15)$$

$$E_2 = I_0Z_2 + I_1Z_1 + I_2Z_2 \quad (3.16)$$

In the calculation method above, it can be seen that under unbalanced load condition, there is cross-coupling occurring between positive, negative and zero sequences. In this analysis, this set of equations will be used to compute the terminal voltages.

6) After obtaining the terminal voltages in symmetrical form, they are converted back to phase form in order to compare the value with phase voltages $\boldsymbol{V_a}$, $\boldsymbol{V_b}$ and $\boldsymbol{V_c}$. The set of equations used for transformation are:

$$E_a = (E_0 + E_1 + E_2) \quad (3.17)$$

$$E_b = (E_0 + a^2E_1 + aE_2) \quad (3.18)$$

$$E_c = (E_0 + aE_1 + a^2E_2) \quad (3.19)$$

Next, comparison is done by computing the percentage error between the calculated value ($\boldsymbol{E_{abc}}$) and the recorded value ($\boldsymbol{V_{abc}}$). The formula for percentage error is as follows:

$$Percentage\ error\ (\%) = \left|\frac{Recorded\ value - Theoretical\ value}{Theoretical\ value}\right| \times 100\% \quad (3.20)$$

3.5 Gantt chart

Table 5: Gantt chart for FYP 1

No	Activities/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Title														
2	Research on Third Harmonic Current and Unbalanced Load														
3	Extended Proposal Submission														
4	Proposal Defense														
5	Familiarizing with Lab Equipments														
6	Conducting Lab Experiments														
7	Draft Report Submission														
8	Interim Report Submission														

Table 6: Gantt chart for FYP 2

No	Activities/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Continuation of Progress from FYP 1																
2	Progress Report Submission																
3	Draft Report Submission																
4	Final Report																
5	Technical Paper																
6	Viva																
7	Final Report (Hard Cover)																

CHAPTER 4: PROJECT RESULTS & DISCUSSIONS

4.1 Resistive loads

Figures 5 and 6 shows the experiment results for balanced resistive loads of 960 Ω loads at all phases. This is used as a base reading for our unbalanced load study. For both diagrams, the readings above are for fundamental frequency and the bottom part of the diagram are results for third harmonics. The order or phases from top to bottom are; Phase A, Phase B, Phase C and Neutral phase.

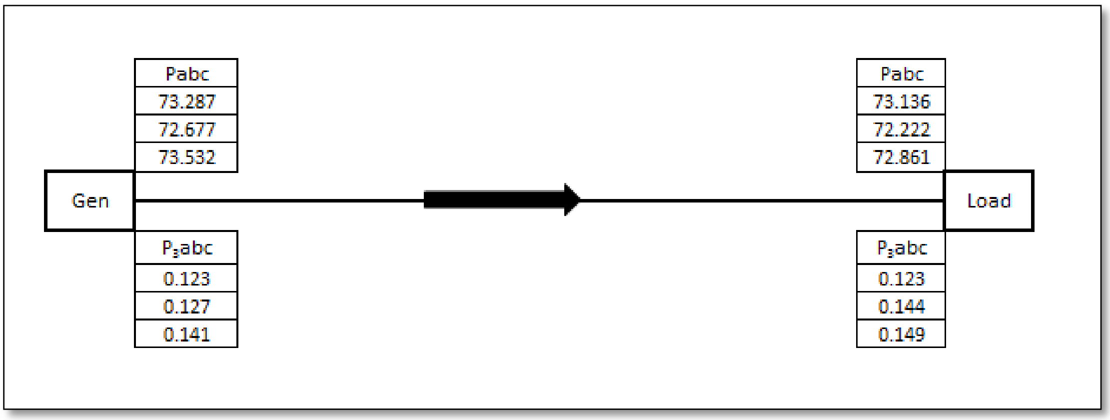


Figure 5: Power diagram for 960 Ω loads at all phases

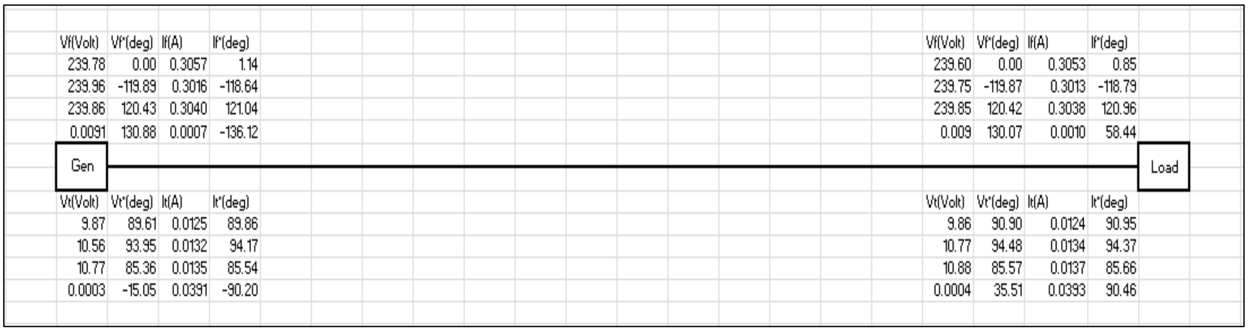


Figure 6: Voltage and current diagram for 960 Ω loads at all phases

Referring to the power diagram, it can be seen that power at all phases are close to each other since all the loads are still balanced. Further observation shows that power measured at the generator side and also the load side does not have too much difference. This means little amount of losses since this is a small-scale experiment and no long cables were used, which would constitute in losses.

Meanwhile, when looking at the voltage and current diagram, at the fundamental frequency, voltage and current are separated by roughly 120° apart between phases. Looking at the third harmonics section, it is proven that third harmonics exist in the system since the current magnitude at the neutral is three times the magnitude of phase current, or summation of all phase currents.

Figures 7 and 8 shows the experiment results for unbalanced resistive loads of 960 Ω, 1600 Ω and 2400 Ω at phases R, Y and B respectively. By looking at the power diagram, powers at the phases reduce as the loads increase. The transmission of power also has not much difference between generator side and load side.

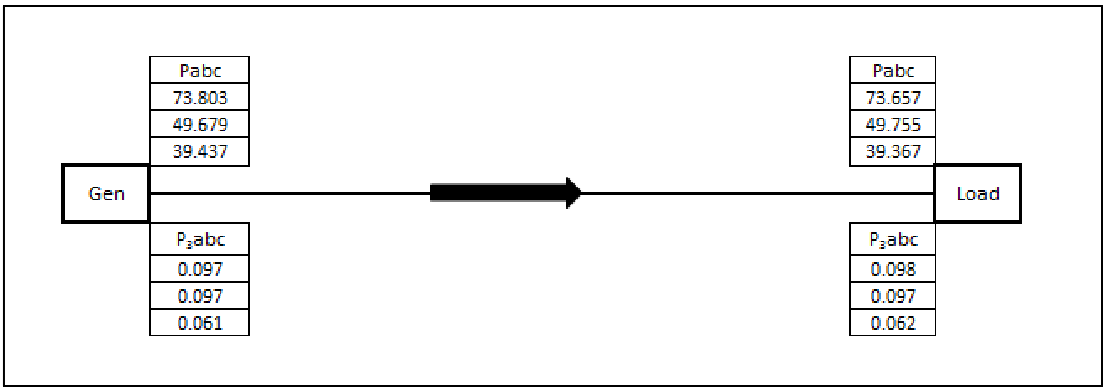


Figure 7: Power diagram for 960 Ω / 1600 Ω / 2400 Ω at phases R, Y and B respectively

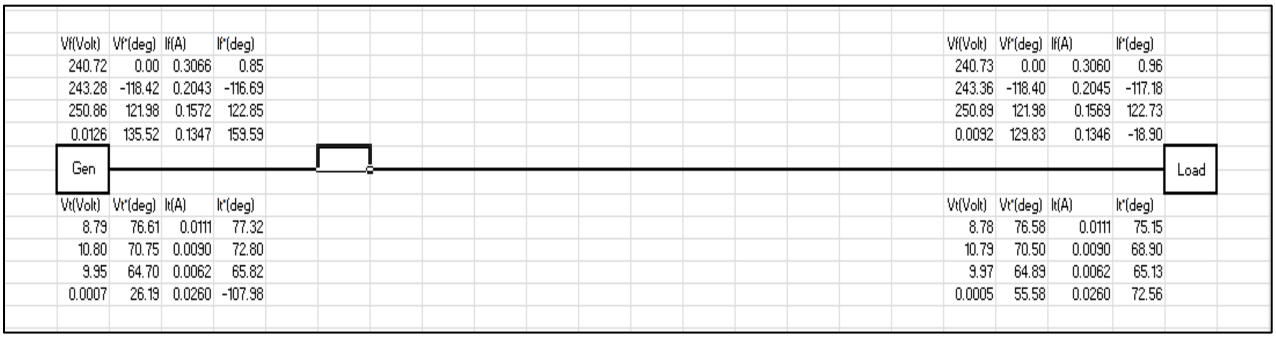


Figure 8: Voltage and current diagram for 960 Ω / 1600 Ω / 2400 Ω at phases R, Y and B respectively

Meanwhile, similar characteristics with balanced loads can be found at the voltage and current diagram. At the fundamental frequency, voltage and current are separated by roughly 120° apart between phases. Third harmonics current characteristics have also been recorded at the neutral. The voltage and current magnitudes also experience drops as the loads were increased.

Figures 9 and 10 shows the results of voltage and current readings for purely resistive loads when measured from the load side at fundamental frequency. Observing the voltage graphs, it can be seen that for all load variations, the voltages does not have much difference between each other. Voltage readings at the neutral are very small, explaining the absence in the bar chart.

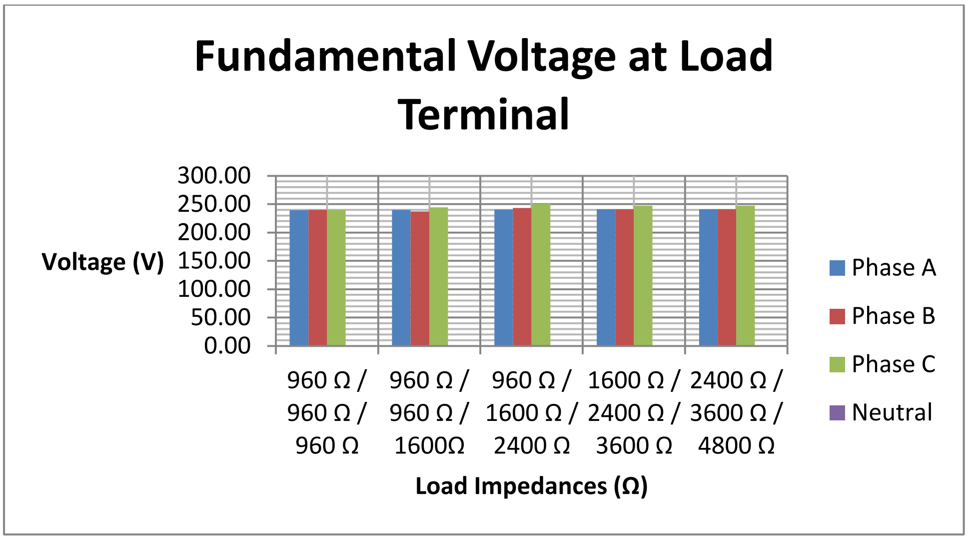


Figure 9: Fundamental voltage at load terminal

Meanwhile, when observing the current behavior, as the load impedance increases, the value of current drops. At balanced loads, there is no current flowing through the neutral phase. Only when unbalanced load has started to be introduced, then the magnitude of current is present in the neutral phase.

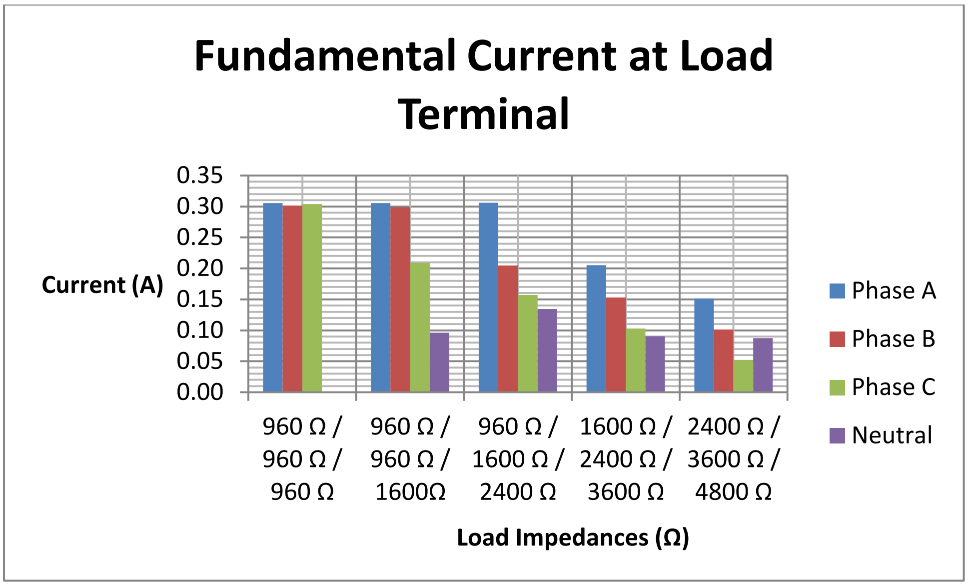


Figure 10: Fundamental current at load terminal

Next, Figures 11 and 12 shows the results of voltage and current readings for purely resistive loads when measured from the load side at third harmonics frequency. Observing the voltage graphs, it can be seen that for all load variations, the voltages does not have much difference between each other. Voltage readings at the neutral are very small, explaining the absence in the bar chart.

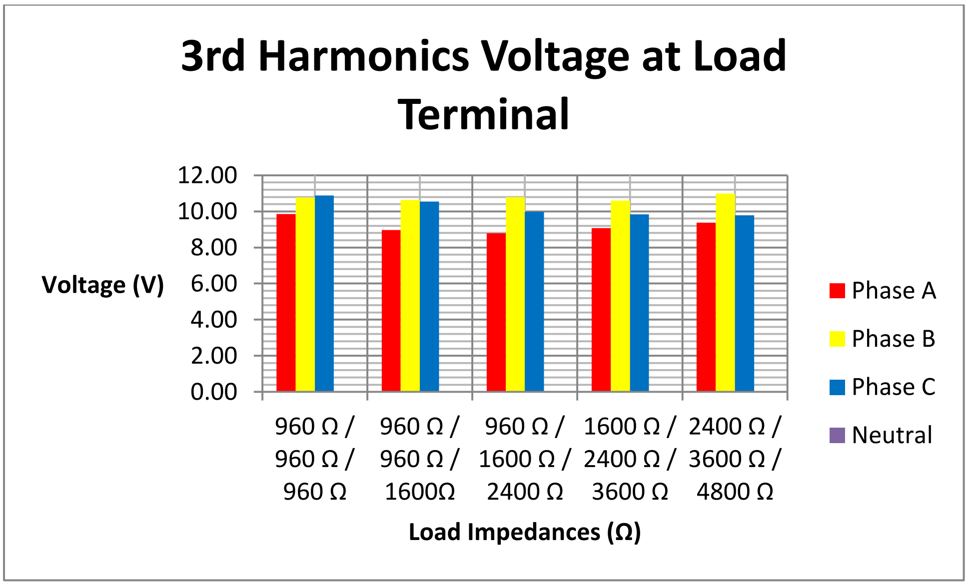


Figure 11: Third harmonics voltage at load terminal

Meanwhile, when observing the current behavior, the current at neutral phase is highest, proving that third harmonics current for all phases add up at the neutral. As load impedance is increased, the current at the neutral drops.

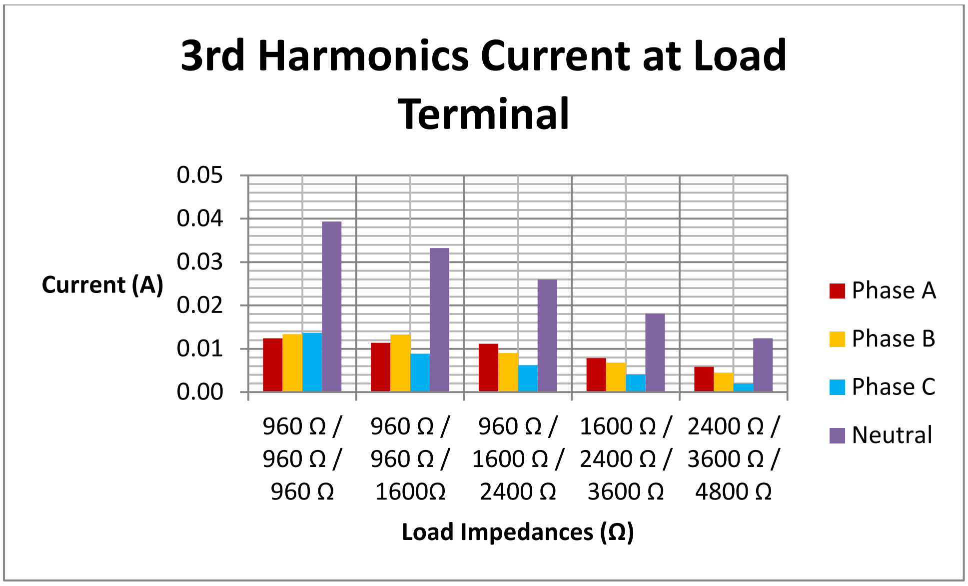


Figure 12: Third harmonics current at load terminal

4.2 Inductive loads

Figures 13 and 14 shows the experiment results for balanced inductive loads for j660 Ω loads at all phases. Referring to the power diagram, it can be seen that power at all phases are close to each other since all the loads are still balanced. Further observation shows that power measured at the generator side and also the load side does not have too much difference, meaning minimal losses. A major difference in the readings of power at the generator and load side is that the readings became very small, estimated to be 10% of the power readings from balanced resistive loads.

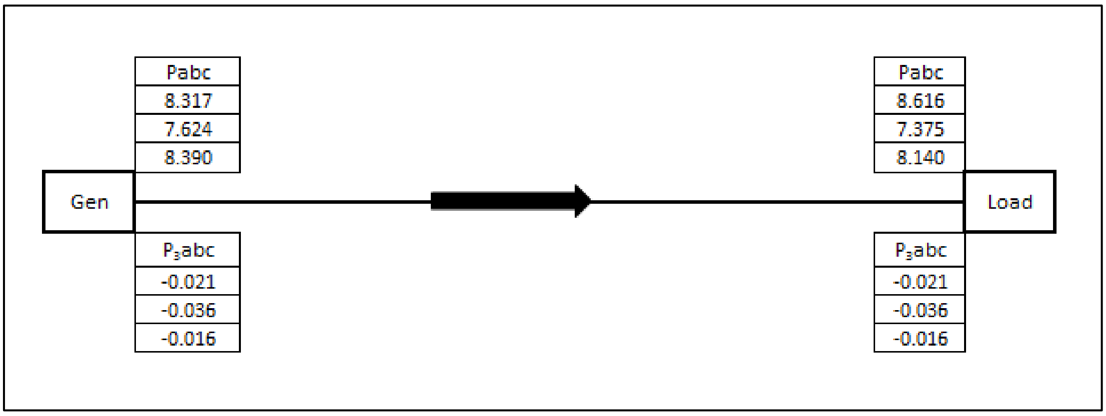


Figure 13: Power diagram for j660 Ω loads at all phases

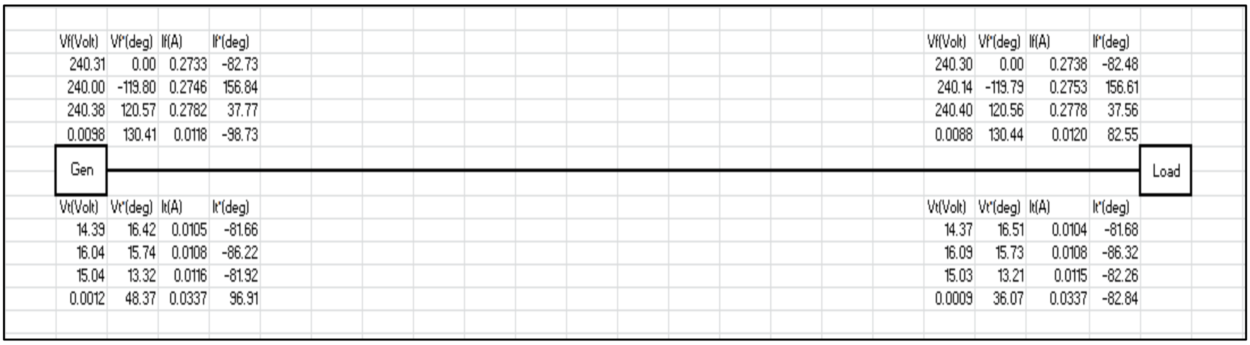


Figure 14: Voltage and current diagram for j660 Ω loads at all phases

Meanwhile, when looking at the voltage and current diagram, at the fundamental frequency, a characteristic of using reactive loads can be seen. The phase angles for voltages at all phases leads the phase angles for currents at all phases. Looking at the third harmonics section, we can observe that the third harmonics current characteristics have also been recorded at the neutral.

Figures 15 and 16 show the experiment results for unbalanced inductive loads of j660 Ω, j1200 Ω and j1600 Ω at phases R, Y and B respectively. By looking at the power diagram, power at the phases reduces as the loads increase. The transmission of power also has not much difference between generator side and load side.

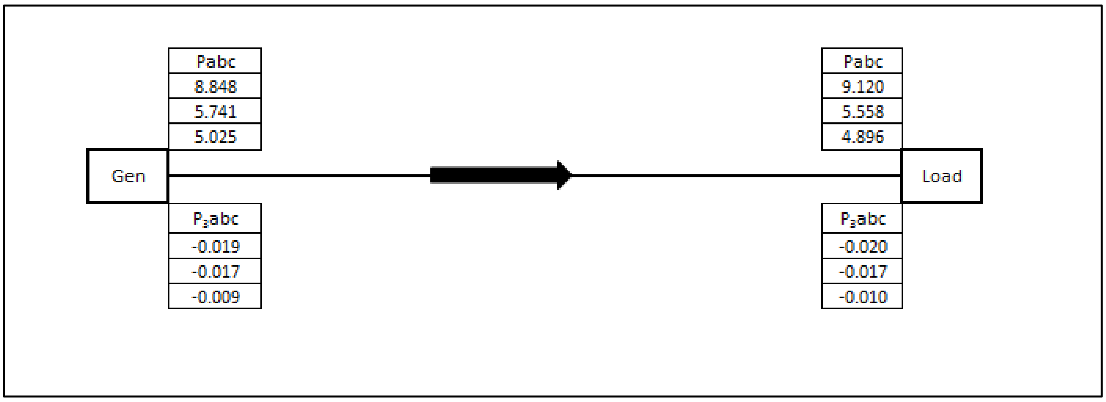


Figure 15: Power diagram for j660 Ω / j1200 Ω / j1600 Ω at phases R, Y and B respectively

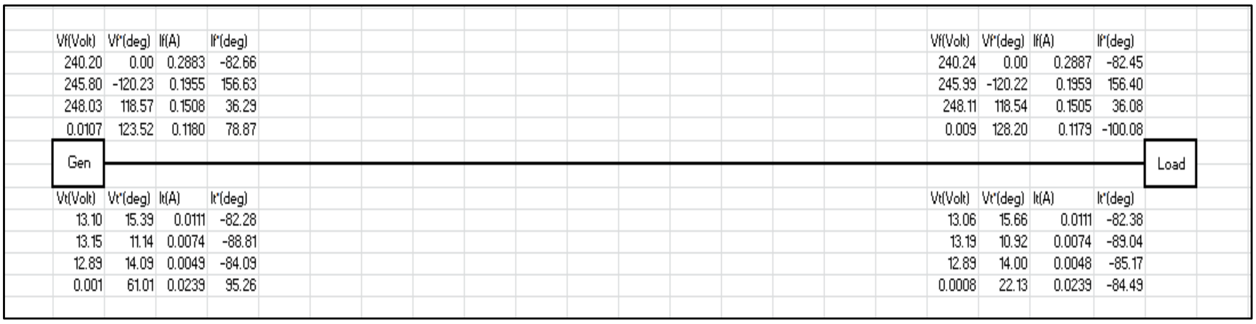


Figure 16: Voltage and current diagram for j660 Ω / j1200 Ω / j1600 Ω at phases R, Y and B respectively

Meanwhile, similar characteristics with balanced inductive loads can be found at the voltage and current diagram. At the fundamental frequency, the phase angles for voltages at all phases leads the phase angles for currents at all phases. Third harmonics current characteristics have also been recorded at the neutral. The voltage and current magnitudes also experience drops as the loads were increased.

Figures 17 and 18 displays the results of voltage and current readings for purely inductive loads when measured from the load side at fundamental frequency. As similar as before, for all load variations, the voltages do not have much difference between each other. Voltage readings at the neutral are very small, explaining why it is barely visible inside the bar chart.

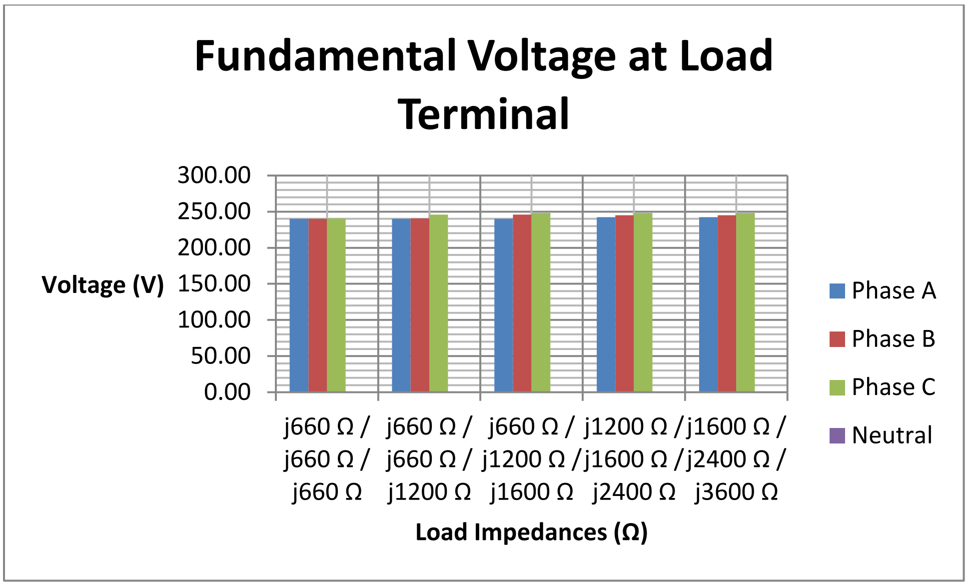


Figure 17: Fundamental voltage at load terminal

Meanwhile, the same characteristics can be seen when observing the current behavior. The load impedance increases, as the value of current drops. A difference in the previous part is that current at the neutral phase is already present even when at balanced inductive load.

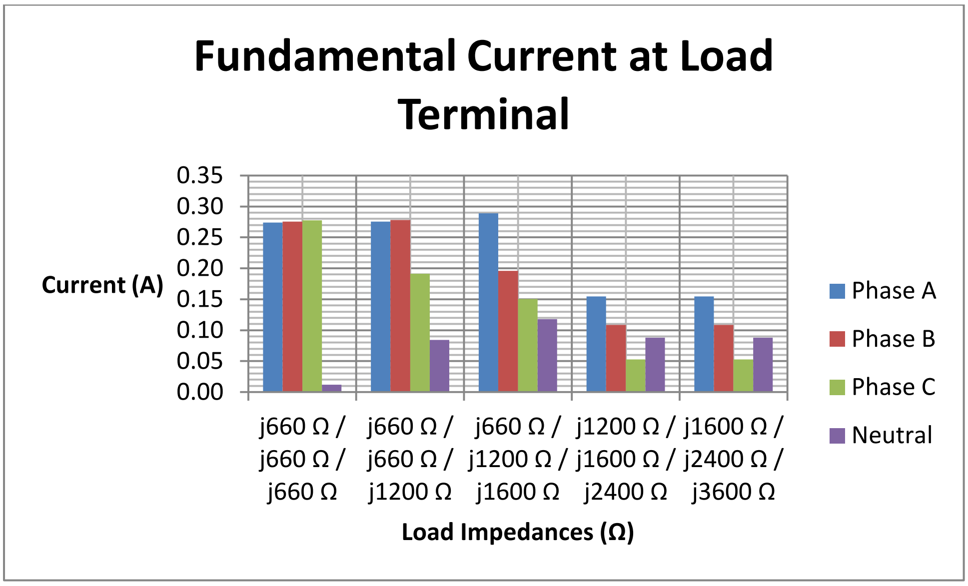


Figure 18: Fundamental current at load terminal

Then, Figures 19 and 20 shows the results of voltage and current readings for purely inductive loads when measured from the load side at third harmonics frequency. As similar as before, for all load variations, the voltages do not have much difference between each other. Voltage readings at the neutral are very small, explaining why it is barely visible inside the bar chart.

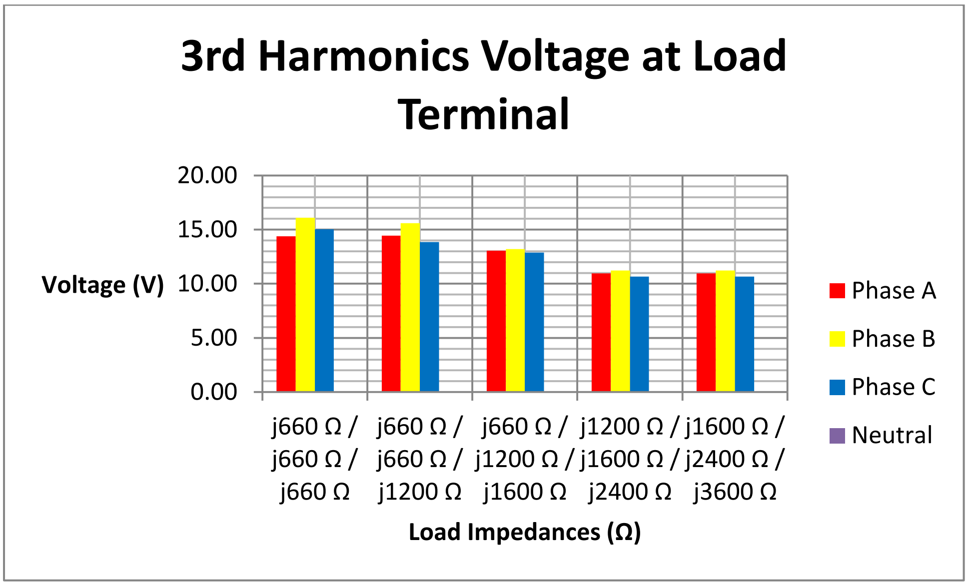


Figure 19: 3rd Harmonics voltage at load terminal

The same characteristics as seen with purely resistive loads can be seen when observing the current behavior. At the neutral phase, the current reading is highest as compared to other phases. Third harmonics current for all phases has been added up at the neutral. The current at the neutral drops as load impedance is increased.

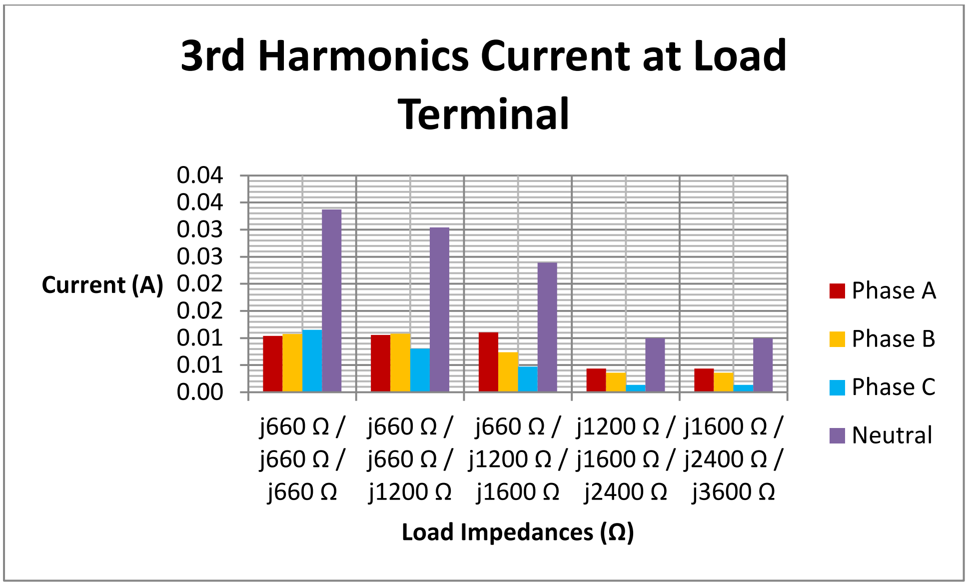


Figure 20: Third harmonics current at load terminal

4.3 Resistive and inductive loads

Figures 21 and 22 shows the experiment results for balanced combination of resistive and inductive loads of 960+j660 Ω loads at all phases. Referring to the power diagram, it can be seen that power at all phases are close to each other since all the loads are still balanced. Further observation shows that power measured at the generator side and also the load side does not have too much difference, meaning minimal losses. The magnitude of power at the generator and load side measured is between the readings of purely resistive and purely inductive loads.

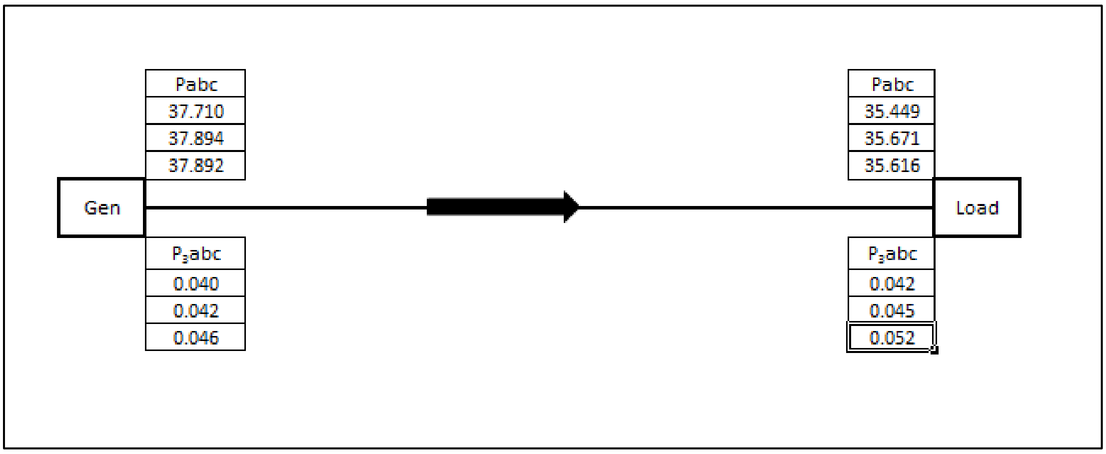


Figure 21: Power diagram for 960+j660 Ω loads at all phases

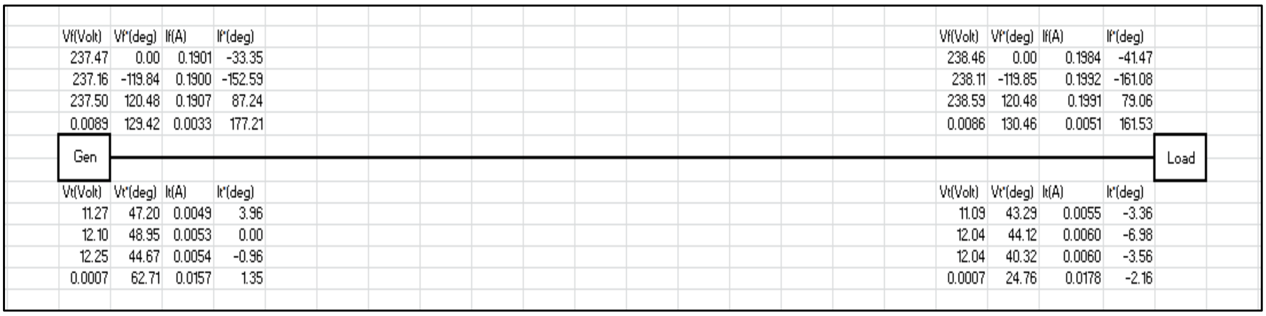


Figure 22: Voltage and current diagram for 960+j660 Ω loads at all phases

Meanwhile, when looking at the voltage and current diagram, the phase angles for voltages at all phases lead the phase angles for currents at all phases. Looking at the third harmonics section, we can observe that the third harmonics current characteristics have also been recorded at the neutral.

Figures 23 and 24 shows the experiment results for unbalanced combination of resistive and inductive loads of 960+j660 Ω, 1600+j1200 Ω and 2400+j1600 Ω at phases R, Y and B respectively. By looking at the power diagram, powers at the phases reduce as the loads increase. The transmission of power also has not much difference between generator side and load side.

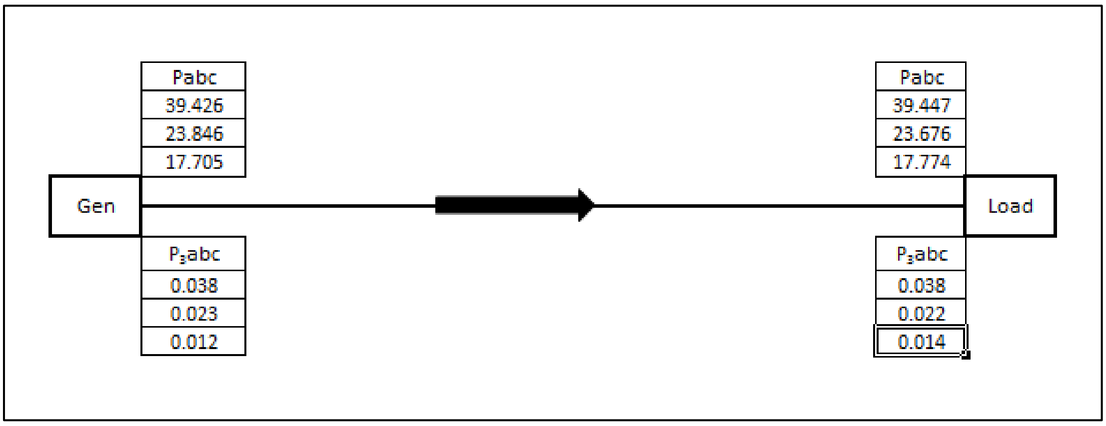


Figure 23: Power diagram for 960+j660 Ω / 1600+j1200 Ω / 2400+j1600 Ω at phases R, Y and B respectively

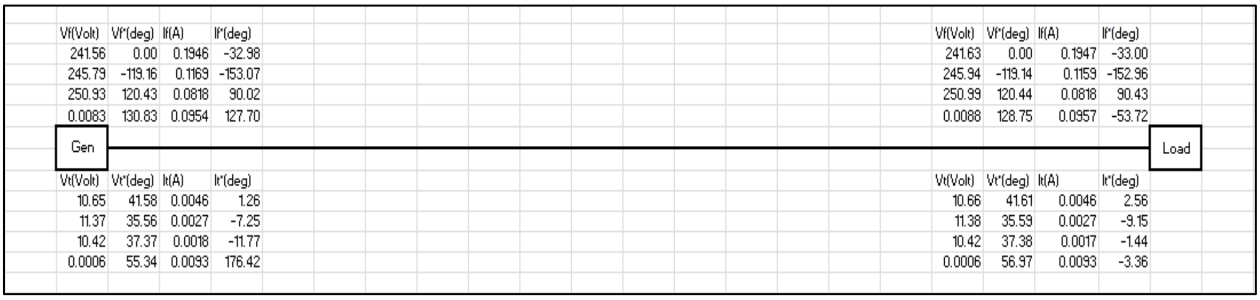


Figure 24: Voltage and current diagram for 960+j660Ω / 1600+j1200Ω / 2400+j1600Ω at phases R, Y and B respectively

Meanwhile, similar characteristics with balanced inductive loads can be found at the voltage and current diagram. At the fundamental frequency, the phase angles for voltages at all phases leads the phase angles for currents at all phases. Third harmonics current characteristics have also been recorded at the neutral. The voltage and current magnitudes also experience drops as the loads were increased.

Figures 25 and 26 shows the results of voltage and current readings for resistive and inductive loads when measured from the load side at fundamental frequency. As similar as before, for all load variations, the voltages do not have much difference between each other. Voltage readings at the neutral are very small, explaining why it is barely visible inside the bar chart.

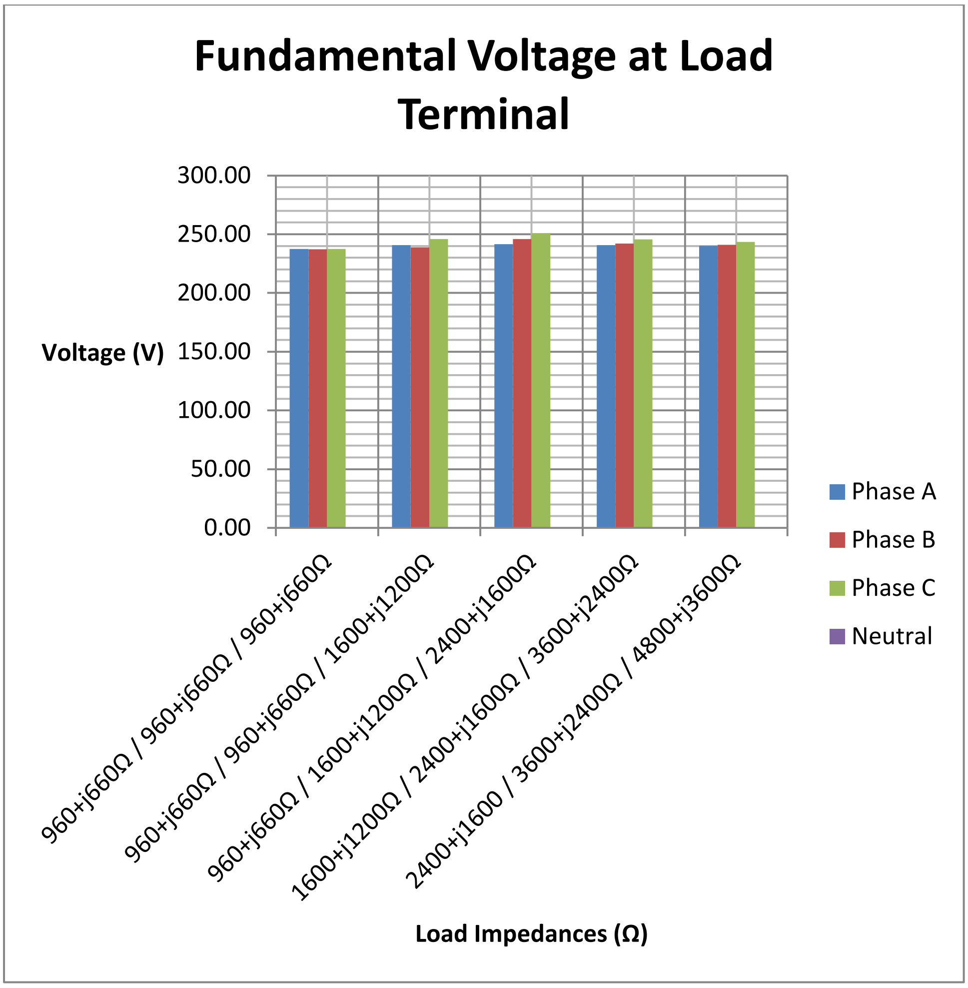


Figure 25: Fundamental voltage at load terminal

Meanwhile, the same characteristics can be seen with inductive load experiment when observing the current behavior. The load impedance increases when the value of current drops. The current at the neutral phase is already present even when at balanced resistive and inductive load.

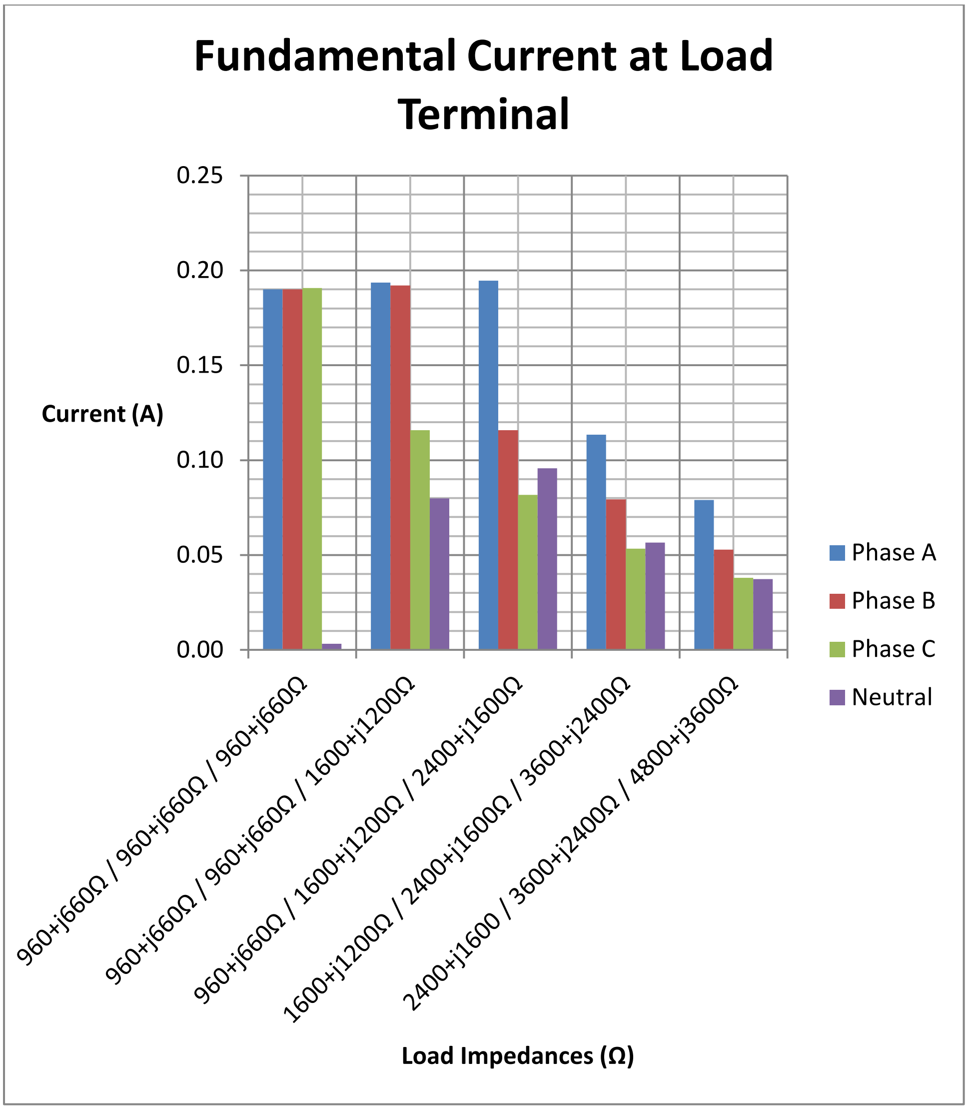


Figure 26: Fundamental current at load terminal

Finally, Figures 27 and 28 shows the results of voltage and current readings for resistive and inductive loads when measured from the load side at third harmonics frequency. As similar as before, for all load variations, the voltages do not have much difference between each other. Voltage readings at the neutral are very small, explaining why it is barely visible inside the bar chart.

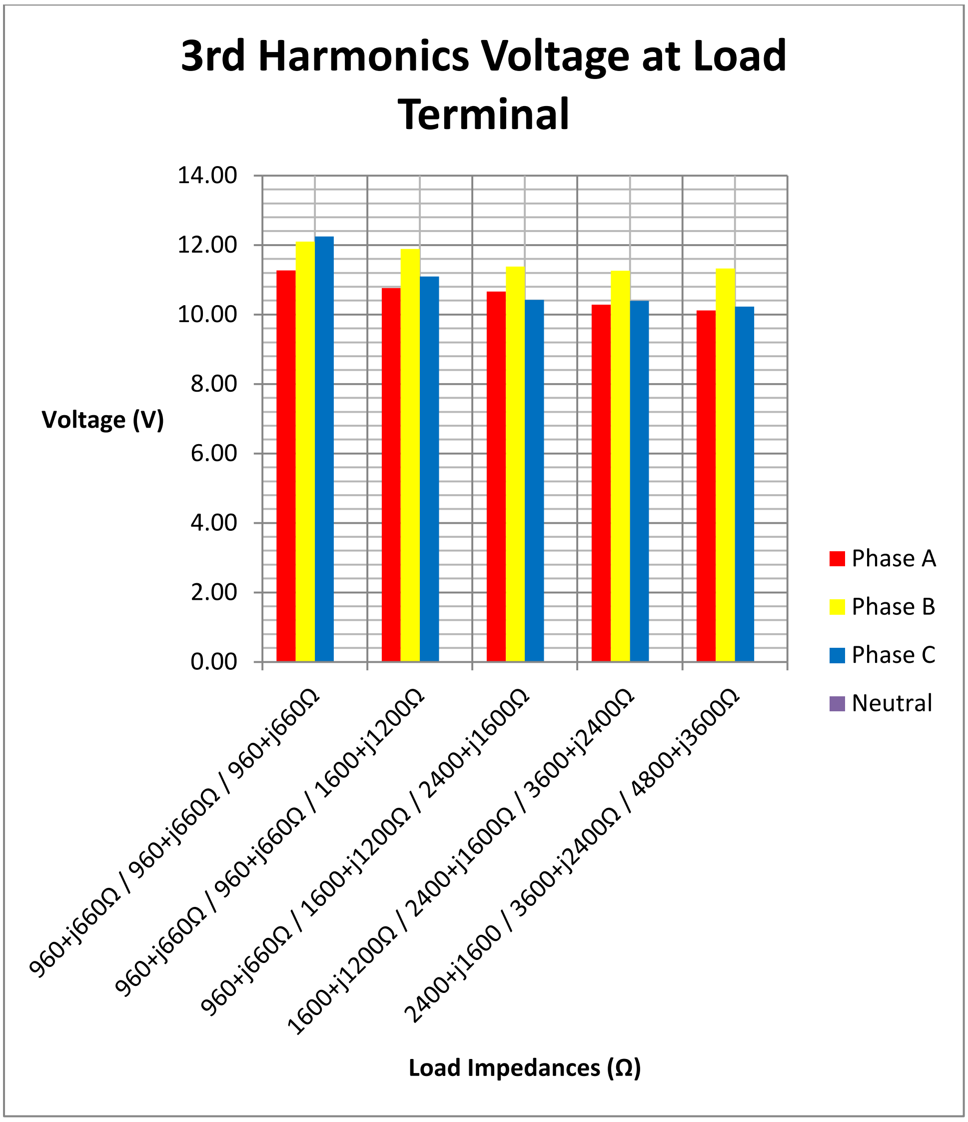


Figure 27: Third harmonics voltage at load terminal

The same characteristics as seen with purely resistive loads can be seen when observing the current behavior. At the neutral phase, the current reading is highest as compared to other phases. Third harmonics current for all phases has been added up at the neutral. The current at the neutral drops as load impedance is increased.

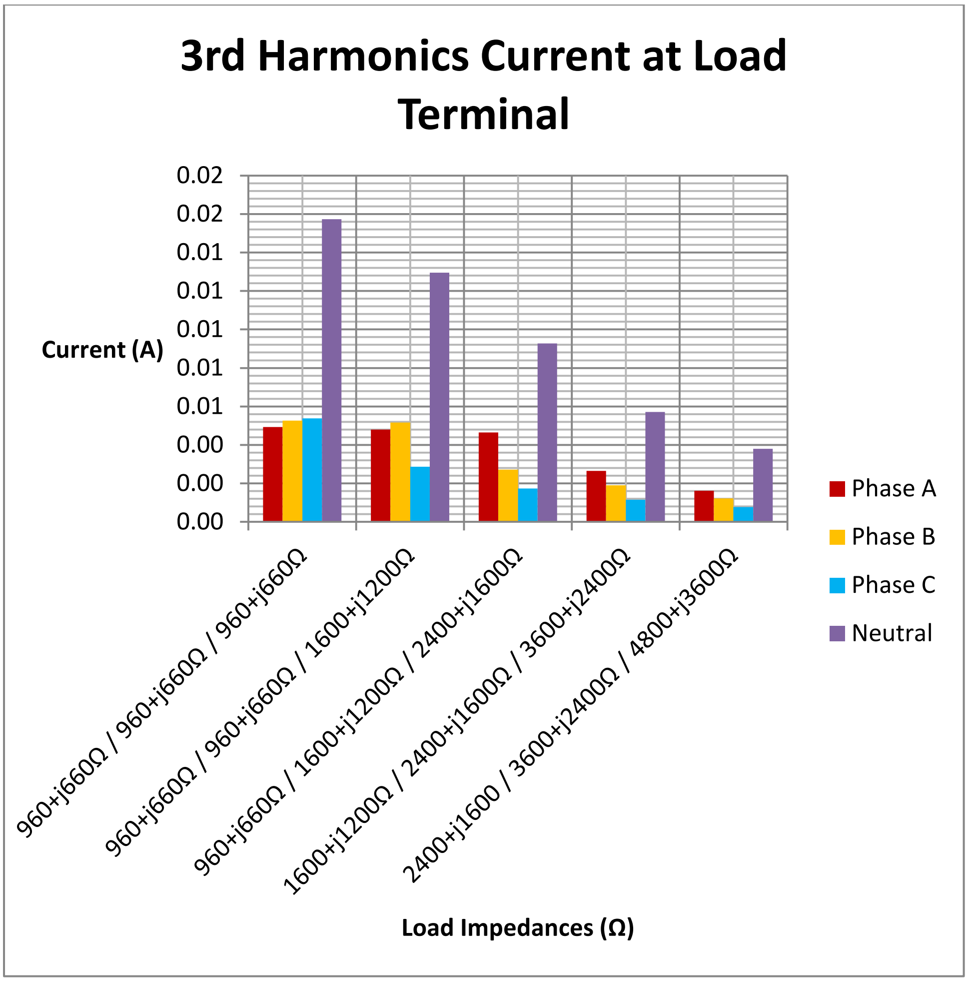


Figure 28: Third harmonics current at load terminal

4.4 Results of Analysis

4.4.1 Analysis Using Per-Phase Method

4.4.1.1 Resistive loads

The results for the computed results of per-phase analysis for resistive loads are contained in Table 7 and 8. Complete results can be referred to at the Appendices section.

Table 7: Percentage difference for resistive loads at fundamental frequency

		Load impedances (Ω)				
		960/960/960	**960/960/ 1600**	**960/1600/ 2400**	**1600/2400/ 3600**	**2400/3600/ 4800**
Percentage diff.	**Ia**	1.82	1.86	1.77	2.43	2.67
	Ib	2.63	2.51	3.19	3.48	3.54
	Ic	1.22	1.85	2.26	2.81	2.67

Table 8: Percentage difference for resistive loads at third harmonics frequency

		Load impedances (Ω)				
		960/960/960	**960/960/ 1600**	**960/1600/ 2400**	**1600/2400/ 3600**	**2400/3600/ 4800**
Percentage diff.	**Ia**	1.28	0.97	1.42	2.71	6.48
	Ib	5.37	5.25	6.10	5.37	10.03
	Ic	1.14	3.90	3.06	3.51	17.21

As can be observed from the percentage difference values, the calculated values are close to the actual values of current from the experiment. The range of errors for fundamental frequency is low, at less than 4 %. Meanwhile, the highest value of error for third harmonics frequency is at approximately 17 %. Therefore, it is proven that this method is suitable for analysis of third harmonics for resistive loads.

4.4.1.2 Inductive loads

Meanwhile, the results for the computed results of per-phase analysis for inductive loads are contained in Tables 9 and 10. Complete results can be referred to at the Appendices section.

Table 9: Percentage difference for inductive loads at fundamental frequency

		Load Impedances (Ω)				
		j660/j660/ j660	**j660/j660/ j1200**	**j660/j1200/ j1800**	**j1200/j1800/ j2400**	**j1800/j2400/ j3600**
Percentage diff.	**Ia**	13.69	13.68	13.35	12.31	14.70
	Ib	12.33	12.56	12.18	15.82	16.87
	Ic	13.07	13.22	14.23	14.43	26.52

Table 10: Percentage difference for inductive loads at third harmonics frequency

		Load Impedances (Ω)				
		j660/j660/ j660	**j660/j660/ j1200**	**j660/j1200/ j1800**	**j1200/j1800/ j2400**	**j1800/j2400/ j3600**
Percentage diff.	**Ia**	42.77	42.10	36.39	22.26	35.70
	Ib	45.92	43.14	28.79	33.17	17.98
	Ic	38.99	25.02	39.42	32.34	49.91

In the case of inductive loads, the calculated values are not as close to the actual values of current from the experiment, with the percentage error values calculated for fundamental frequency in the range of 12 % - 23 %. Meanwhile, the range of value of error for third harmonics frequency is around 22 % - 50 %. As per the end of this inductive load analysis, the per-phase method yields a high percentage error. Therefore, this method shall be compared with the symmetrical component method to validate the best method for analysis.

4.4.1.3 RL loads

Finally, the results for the computed results of per-phase analysis for inductive loads are contained in Tables 11 and 12. Complete results can be referred to at the Appendices section.

Table 11: Percentage difference for resistive and inductive loads at fundamental frequency

		Load Impedances (Ω)				
		960+j660/ 960+j660/ 960+j660	**960+j660/ 960+j660/ 1600+j1200**	**960+j660/ 1600+j1200/ 2400+j1800**	**1600+j1200/ 2400+j1800/ 3600+j2400**	**2400+j1800/ 3600+j2400/ 4800+j3600**
Percentage diff.	**Ia**	7.88	7.77	7.73	7.13	8.08
	Ib	6.98	7.10	7.15	8.54	8.68
	Ic	7.56	7.42	7.68	7.49	9.44

Table 12: Percentage difference for resistive and inductive loads at third harmonics frequency

		Load Impedances (Ω)				
		960+j660/ 960+j660/ 960+j660	**960+j660/ 960+j660/ 1600+j1200**	**960+j660/ 1600+j1200/ 2400+j1800**	**1600+j1200/ 2400+j1800/ 3600+j2400**	**2400+j1800/ 3600+j2400/ 4800+j3600**
Percentage diff.	**Ia**	48.40	49.88	50.92	49.42	52.12
	Ib	49.54	54.44	51.41	54.78	47.38
	Ic	50.87	52.43	50.35	56.46	51.77

For RL loads at fundamental frequency, the per-phase analysis returns a low percentage error, which ranges from 6 % to 10 %. However, the same cannot be said at third harmonics frequency because a high rate of error is returned, at around 47 % to 56 %. Therefore, as similarly as for the analysis for inductive loads, this result will be compared to analysis using symmetrical component method.

4.4.2 Analysis Using Symmetrical Components

4.4.2.1 Resistive loads

In the first part of the analysis, two sets of equations will be used to compute the symmetrical components of the impedances, Z_{012}. Firstly, Equation (3.10) shall be used.

Tables 13 and 14 show the computed results of percentage difference for resistive loads at fundamental frequency and third harmonics. For full results of the computations step by step, Appendices can be referred to. As can be observed above, the percentage difference is very high, with the highest at around 1343 %. This means that applying transformation equation (3.10) is incompatible with Equations (3.14) to (3.16) and Equations (3.17) to (3.19) in order to make the comparison between the theoretical values and recorded values.

Table 13: Percentage difference for resistive loads at fundamental frequency using Equation (3.10)

		Load Impedances (Ω)				
		960/960/ 960	**960/960/ 1600**	**960/1600/ 2400**	**1600/2400/ 3600**	**2400/3600/ 4800**
Percentage diff.	**Ea-Va**	807.97	1008.89	1460.87	1343.53	1268.29
	Eb-Vb	100.00	267.68	327.20	309.18	268.51
	Ec-Vc	100.00	191.49	247.87	234.92	223.11

Table 14: Percentage difference for resistive loads at third harmonics using Equation (3.10)

		Load Impedances (Ω)				
		960/960/ 960	**960/960/ 1600**	**960/1600/ 2400**	**1600/2400/ 3600**	**2400/3600/ 4800**
Percentage diff.	**Ea-Va**	88.96	90.81	93.50	93.13	92.43
	Eb-Vb	1.74E+16	134.85	139.52	137.68	156.63
	Ec-Vc	1.78E+16	159.26	159.38	160.55	171.58

Meanwhile, the results in Tables 15 and 16 shows the results of percentage difference when Equations (3.11) to (3.13) are used. As we refer to the Table 15, it can be observed that the percentage error is significantly lower as Equations (3.11) to (3.13) are used, with the highest value at around 1.78E+16 %. If the same equation is used for third harmonics analysis, the results are as follows:

Table 15: Percentage difference for resistive loads at fundamental frequency using Equations (3.11) to (3.13)

		Load Impedances (Ω)				
		960/960/ 960	**960/960/ 1600**	**960/1600/ 2400**	**1600/2400/ 3600**	**2400/3600/ 4800**
Percentage diff.	**Ea-Va**	1.71	1.76	1.68	2.32	2.55
	Eb-Vb	2.54	2.43	3.07	3.37	3.42
	Ec-Vc	1.09	1.69	2.09	2.67	2.57

Table 16: Percentage difference for resistive loads at third harmonics using Equations (3.11) to (3.13)

		Load Impedances (Ω)				
		960/960/ 960	**960/960/ 1600**	**960/1600/ 2400**	**1600/2400/ 3600**	**2400/3600/ 4800**
Percentage diff.	**Ea-Va**	1.16	1.16	1.52	2.48	6.70
	Eb-Vb	5.22	5.50	6.65	5.17	10.51
	Ec-Vc	1.05	4.11	3.35	3.39	18.44

In Tables 15 and 16, the percentage difference is at an acceptable level, at around 1 % to 18.5 %. This proves that by using Equations (3.11) to (3.13), we are able to obtain calculated results that are close to the actual/measured results from the experiment that can verify the experimental results. Therefore, for resistive loads, Equations (3.11) to (3.13), as well as Equations (3.17) to (3.19) can be used altogether to prove the validity of the recorded readings from the experiment.

4.4.2.2 Inductive loads

Similar methods are applied with regards to inductive loads. Under fundamental frequency and third harmonics, the results by using Equation (3.10) are displayed in Tables 17 and 18. For full results for this part, Appendices can be referred to. As can be observed above, the percentage difference is also very high, a similar case when using resistive loads. The highest value recorded was around 1526 %.This again means that applying transformation Equation (3.10) is incompatible with Equations (3.14) to (3.16) and Equations (3.17) to (3.19) for experimental results validation purposes.

Table 17: Percentage difference for inductive loads at fundamental frequency using Equation (3.10)

		Load Impedances (Ω)				
		j660/j660/ j660	**j660/j660/ j1200**	**j660/j1200/ j1800**	**j1200/ j1800/ j2400**	**j1800/ j2400/ j3600**
Percentage diff.	**Ea-Va**	775.75	1017.35	1526.72	663.19	1397.16
	Eb-Vb	100.00	314.21	345.44	297.60	303.15
	Ec-Vc	100.00	201.01	275.10	222.90	183.16

Table 18: Percentage difference for inductive loads at third harmonics using Equation (3.10)

		Load Impedances (Ω)				
		j660/j660/ j660	**j660/j660/ j1200**	**j660/j1200/ j1800**	**j1200/ j1800/ j2400**	**j1800/ j2400/ j3600**
Percentage diff.	**Ea-Va**	420.36	573.20	968.94	556.08	860.81
	Eb-Vb	100.00	203.40	265.91	241.26	246.49
	Ec-Vc	100.00	179.74	211.21	140.40	154.58

Meanwhile, as compared to the results when using Equations (3.11) to (3.13), the results are displayed in Table 19 and 20.

Table 19: Percentage difference for inductive loads at fundamental frequency using Equations (3.11) to (3.13)

		Load Impedances (Ω)				
		j660/j660/ j660	**j660/j660/ j1200**	**j660/j1200/ j1800**	**j1200/ j1800/ j2400**	**j1800/ j2400/ j3600**
Percentage diff.	**Ea-Va**	129.57	129.73	188.63	133.65	132.36
	Eb-Vb	131.49	131.65	114.10	134.76	136.21
	Ec-Vc	130.97	134.64	127.65	133.19	116.70

Analysis for third harmonics components yields the following results:

Table 20: Percentage difference for inductive loads at third harmonics using Equations (3.11) to (3.13)

		Load Impedances (Ω)				
		j660/j660/ j660	**j660/j660/ j1200**	**j660/j1200/ j1800**	**j1200/ j1800/ j2400**	**j1800/ j2400/ j3600**
Percentage diff.	**Ea-Va**	119.98	121.41	123.44	144.81	126.09
	Eb-Vb	121.78	120.71	130.71	135.93	135.68
	Ec-Vc	120.55	130.71	125.57	136.95	109.01

Based on Tables 19 and 20, it can be seen that although the percentage difference is still very high, but by using Equations (3.11) to (3.13), the values are much lesser as compared to using Equations (3.10). The range of values was around 100 % to 135 %. Therefore, to conclude this part, both equations are unable to provide results that are as close to the recorded values of voltages and currents. Both sets of equations returned values with high error percentages, which does not able to validate the experimental results. A more suitable set of equations should be used in order to prove the validity of the experimental results.

4.4.2.3 RL loads

Finally, for resistive and inductive loads, the similar methods are applied. By using Equation (3.10) at fundamental frequency, the results are tabled in Tables 21 and 22.

Table 21: Percentage difference for RL loads at fundamental frequency using Equation (3.10)

		Load Impedances (Ω)				
		960+j660/ 960+j660/ 960+j660	**960+j660/ 960+j660/ 1600+j1200**	**960+j660/ 1600+j1200/ 2400+j1800**	**1600+j1200/ 2400+j1800/ 3600+j2400**	**2400+j1800/ 3600+j2400/ 4800+j3600**
Percentage diff.	**Ea-Va**	734.47	935.80	1375.35	1217.11	1213.00
	Eb-Vb	100.00	276.00	314.99	280.58	283.45
	Ec-Vc	100.00	183.63	244.53	229.46	198.98

Table 22: Percentage difference for RL loads at third harmonics using equation (3.10)

		Load Impedances (Ω)				
		960+j660/ 960+j660/ 960+j660	**960+j660/ 960+j660/ 1600+j1200**	**960+j660/ 1600+j1200/ 2400+j1800**	**1600+j1200/ 2400+j1800/ 3600+j2400**	**2400+j1800/ 3600+j2400/ 4800+j3600**
Percentage diff.	**Ea-Va**	371.13	469.07	685.26	610.42	569.02
	Eb-Vb	100.00	170.88	207.53	181.41	194.44
	Ec-Vc	100.00	135.63	173.50	156.12	157.15

The behavior of the results shows a similar trait with results when using resistive or inductive loads. The percentage errors returned are also very high, with the highest reading at around 685 %. This also means that Equation (3.10) is unable to provide us with an output of low percentage difference for verification purposes. When Equations (3.11) to (3.13) are used, the results are as displayed in Tables 23 and 24.

Table 23: Percentage difference for RL loads at fundamental frequency using Equations (3.11) to (3.13)

		Load Impedances (Ω)				
		960+j660/ 960+j660/ 960+j660	**960+j660/ 960+j660/ 1600+j1200**	**960+j660/ 1600+j1200/ 2400+j1800**	**1600+j1200/ 2400+j1800/ 3600+j2400**	**2400+j1800/ 3600+j2400/ 4800+j3600**
Percentage difference	**Ea-Va**	54.45	54.32	54.34	56.90	50.67
	Eb-Vb	53.78	53.63	56.04	49.55	49.11
	Ec-Vc	54.14	55.85	50.76	50.99	54.76

Table 24: Percentage difference for RL loads at third harmonics using Equations (3.11) to (3.13)

		Load Impedances (Ω)				
		960+j660/ 960+j660/ 960+j660	**960+j660/ 960+j660/ 1600+j1200**	**960+j660/ 1600+j1200/ 2400+j1800**	**1600+j1200/ 2400+j1800/ 3600+j2400**	**2400+j1800/ 3600+j2400/ 4800+j3600**
Percentage diff.	**Ea-Va**	48.50	49.97	51.01	49.52	52.21
	Eb-Vb	49.63	54.52	51.50	54.87	47.47
	Ec-Vc	50.96	52.52	50.44	56.54	51.85

Full calculations can be referred at Appendices. From Tables 23 and 24, it can be observed that the percentage difference drops to values around 45 % to 55 % percentage difference. Although they are still high, they are still lower as compared to using Equation (3.10). In conclusion, a better set of equations are also needed in this part to properly analyze and verify the experimental results.

4.5 Comparison of Analysis

After all three methods of analysis have been performed; the outputs are compared in order to select the best method for analyzing third harmonics characteristics under unbalanced load.

4.5.1 Analysis of Results

As can be observed in the previous sections, when resistive loads are used, percentage errors recorded by any method are small. In comparison, whenever an inductive load is used, the percentage errors dramatically increased.

To explain this phenomenon, the experiment is re-conducted to find out if there are any errors during the experiment. However, latter results are still similar to the previous results. Meanwhile, after analyzing the results again, it was found that actually, the inductive load connected to the system records a different value in the analyzer as compared to its actual value. In theory, for zero sequence networks, the load reactance is triple its actual value. For third harmonics frequency, the inductance value is higher than its actual value but not close to three times. This explains why the calculated values as well as the percentage error recorded become very high.

Table 25: Actual values of inductance during experiment at third harmonics frequency

Actual Load Impedance				Measured Load Impedance				% Difference			
Ra	Xa	Rc	Xc	R	X	Absolute	Angle	R	X	Absolute	Angle
0.00	660.00	660	90.00	-119.47	1128.20	1134.51	96.04	#DIV/0!	71%	72%	7%
0.00	840.00	840	90.00	-128.96	1233.41	1240.13	95.97	#DIV/0!	47%	48%	7%
0.00	1153.33	1153	90.00	-166.19	1502.54	1511.70	96.31	#DIV/0!	30%	31%	7%
0.00	1733.33	1733	90.00	-403.54	1975.65	2016.45	101.54	#DIV/0!	14%	16%	13%
0.00	2533.33	2533	90.00	-268.29	3298.42	3309.32	94.65	#DIV/0!	30%	31%	5%
Average								#DIV/0!	38%	40%	8%

4.5.2 Recommendation and Comments

After reviewing results from both analyses, several conclusions can be made.

1) Per-phase method and symmetrical component method are both suitable to analyze resistive loads.
2) Percentage error yielded from per-phase method is lower than that of symmetrical component method for analyzing inductive and RL loads. A more suitable method of analysis for both loads would be the per-phase method.
3) As can be seen previously, per-phase method is much easier to be used since it directly uses its phase values without the need for transforming the results to symmetrical components. It also yielded a more accurate result, proven by the lower percentage error calculated.
4) Cross-coupling phenomenon does exist in the system after analyzing using symmetrical component. However, the analysis returns a high error but that was due to the behavior of the inductive load.

To conclude, the author would recommend the use of per-phase analysis for analyzing third harmonics characteristics under unbalanced load. This is due to the easier calculations to be performed, as well as returning a lower percentage error. Although symmetrical component can be used to analyze third harmonics characteristics under unbalanced load, the method needs to be refined further with more proof in order to reduce the error rate returned.

CHAPTER 5: CONCLUSION

To conclude, the characteristics of third harmonics under unbalanced load have been recorded. As such, in general, it can be observed that as load impedance at the phase increases, the phase currents reduce while neutral current increases. Minimal fluctuations were observed for the voltage as the load is varied and at third harmonics frequency, the neutral phase carries the largest magnitude of current. In terms of result validation, comparison was made between per-phase method and symmetrical component method. Therefore, it was found that per-phase method is more suitable to analyze this case since the error percentages returned were lower as compared to symmetrical component method. Apart from that, cross-coupling phenomenon was proven to exist in the system when applying symmetrical component theory. However, the analysis needs to be refined further for inductive loads, since its behavior during the experiment does not tally with theory, which is any impedance value should be three times its value in zero component.

As a recommendation, this study can be furthered by including a wider scope (e.g. transformer, cable capacitances etc.) to dig deeper about third harmonic characteristics under unbalanced load.

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APPENDICES

1. Resistive load analysis (fundamental) using per-phase analysis

	Impedance values
60-1600	960-1600-2400
240.5476	
024-206.353773043254j	-115.477318324445-213.31537
816+208.488200017519j	-132.574620405501+212.25111
.00408084691647454j	0.251991299556608+0.00395917283431
.219793756810799j	-0.0698437158011524-0.137562358112
+0.13112381932385j	-0.0574406860257049+0.089273806594
960.00	
960.00	
1600.00	
0.250570416666667	0.2500186
275-0.214951846920056j	-0.0721733239527781-0.13332210
51+0.130305125010949j	-0.0552394251689588+0.088437962
1.86	
2.51	
1.85	

2. Resistive load analysis (third harmonics) using per-phase analysis

	Impedance values
60-1600	960-1600-2400
202+8.30262979612877j	3.9188985211384+7.9041798
627+9.61554765637608j	5.87071718629592+8.9541545
931+8.96793751908499j	5.57847206007528+7.7067250
+0.00857857023043819j	0.00416511671398295+0.0081321720
+0.00989426203187183j	0.00358524180048723+0.0051971970
+0.00556022702699037j	0.00227267120185582+0.003101484
960.00	
960.00	
1600.00	
7+0.0086485727043008j	0.00408218595951917+0.008233520
5+0.0100161954753918j	0.00366919824143495+0.005596346
+0.00560496094942812j	0.0023243633583647+0.003211135
0.97	
5.25	
3.90	

3. Inductive load analysis (fundamental) using per-phase analysis

	Impedance values
60/j1200	j660/j1200/j1600
212.5905	
393-186.877857860355j	-117.346963011477-197.84004
662+191.731194193473j	-107.693153157401+205.32458
16-0.311317005690812j	0.0437334867413548-0.32614530
38+0.116900074123114j	-0.17918855243648+0.079359793
54+0.113337620593872j	0.121464866613644+0.086750445
660j	
660j	
1200j	
-0.322106818181818j	-0.33639075
86+0.154506331839288j	-0.164866707194346+0.097789135
7+0.0901346200551667j	0.128327863569039+0.067308220
13.68	
12.56	
13.22	

4. Inductive load analysis (third harmonics) using per-phase analysis

Impedance values	
60/j1200	j660/j1200/j1600
723+4.34806619537867j	12.5262898618682+2.9627908
816+3.00453345421974j	12.1648112993438+1.8190898
167+3.22131247314951j	12.0600973836057+3.0624040
44-0.0120835874021661j	0.001809349728474-0.012407720
63-0.0124814243131542j	0.00020633332565759-0.00749306
1-0.00774693214409344j	0.00046924416283132-0.0048334054
660j	
660j	
1200j	
08-0.0199537072101095j	0.004489076974809-0.0189792276
45-0.0212706609236085j	0.00151590824816205-0.0101373427
2-0.00997980975843058j	0.00191400251064643-0.0075375608
42.10	
43.14	
25.02	

5. RL load analysis (fundamental) using per-phase analysis

Impedance values	
j660/1600+j1200	960+j660/1600+j1200/2400+j16
240.3036	
1657-207.813227757171j	-119.182053060454-213.52587
5975+210.765316017569j	-126.534620206979+215.262
562-0.103109466742115j	0.161805097932052-0.10322606
63-0.0921687689074277j	-0.103625236184935-0.05293805
52+0.116575235726396j	-0.000426774451004118+0.082441525
960+660j	
960+660j	16
1600+1200j	24
159-0.116858514588859j	0.170021503094607-0.11688978
29-0.0902116622428146j	-0.111730582741495-0.049655732
707+0.122114691904953j	0.00489621314521759+0.086428457
7.77	
7.10	
7.42	

6. RL load analysis (third harmonics) using per-phase analysis

Impedance values	
660/1600+j1200	960+j660/1600+j1200/2400+j16
509+7.77707480046596j	7.85254683708056+7.0157483
526+8.02348926735236j	9.13175728768483+6.4403069
447+6.85561138040124j	8.09630451346227+6.197999
0.000457827351833686j	0.00447230056368418+0.00014906211
000087544317460397 9j	0.00271977384858252+0.000042952826
0.000260314851083595j	0.00175030166608508+0.0001345155
960+660j	
960+660j	16
1600+1200j	24
+0.00207527459127274j	0.00896613532907823+0.001143853
+0.00162946441093983j	0.00558479500299685-0.00016340440
0.000266390905642155j	0.00352739551133442+0.00023090294
49.88	
54.44	
52.43	

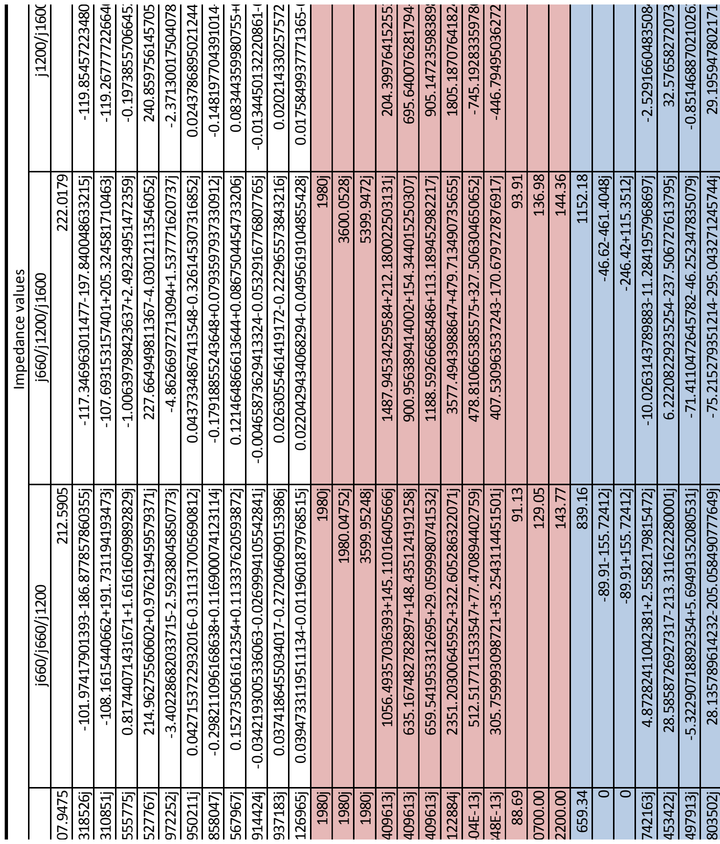
7. Resistive load analysis (fundamental) using Equation (3.10) and Equations (3.11) to (3.13)

Impedance values			
50-960	960-960-1600	960-1600-2400	1600-2400-3600
240.348	240.5476	240.0179	2
08437-208.249925094131j	-116.79927390024-206.353773043254j	-115.477318324445-213.315370664082j	-117.338122996568-211.31376
38901+207.212104834507j	-128.957040056816+208.488200017519j	-132.574620405501+212.251110794119j	-128.789470751884+210.537126
9243-0.345594146454792j	-1.73450174769965+0.710764182430248j	-2.67533489707202-0.354398536697679j	-1.72390561823452-0.258620476
1085+0.916464285544735j	240.652075581169+3.15065019748595j	243.950619288489+5.10768504787961j	242.869343574613+3.43162700
3855-0.570870139089996j	1.38947856653036-3.86141437991609j	-1.49740229141739-4.7532865111816j	-0.435688656378833-3.17300652
62+0.00385444435057174j	0.252813066126821+0.00408084691647454j	0.251991299556608+0.00395917283431268j	0.152673541855923+0.00301960075
7038-0.222247475628382j	-0.117774846971479-0.219793756810799j	-0.0698437158011524-0.137562358112014j	-0.0472012948627258-0.091123190
8316+0.216521222441079j	-0.0833074752704479+0.13112381932385j	-0.0574406860257049+0.0892738065940194j	-0.0376784731007823+0.0587565501
7-0.00062331234263151 3j	0.0172263377136697-0.028168167159968j	0.0415273969440071-0.0147616831016661j	0.0225753267061742-0.00977256410
81+0.00498384981652815j	0.21886386644407+0.00618283489836308j	0.170520515162119+0.00578168746098821j	0.108194790558058+0.00364840033
2-0.000509947567675379j	0.016470048902954 6+0.0260620983311628j	0.0396913961509258+0.0129352093021563j	0.021750751049835+0.00914074492
2880	2880	2880	
2880	2880.05632	4800.0704	72
2880	4799.94368	7199.9296	107
93566+11.0896989299173j	1147.58075356761+23.6132488853004j	1537.85610352046+61.2040106446046j	1433.4615852849+58.308359
93566+11.0896989299173j	758.996065302659+61.7772608276064j	976.208770539259+38.9267381139489j	916.785545376539+45.8679079
93566+11.0896989299173j	760.459453450664-42.339860018376j	1231.81603280521-41.2771694757552j	1127.22866689929-35.398217
93807+33.2690967897519j	2667.03627232093+43.0506496945308j	3745.88090686493+58.8535792827983j	3477.47579756073+68.778050
-6.82121026329696E-13j	478.01842084357+15.1618426168575j	503.300285820909+283.735115447822j	481.830943395159+235.317257
-6.82121026329696E-13j	297.687567538327+12.6272543445125j	364.387117875542-158.976662796801j	341.078014898812-129.170229
8.90E+01	9.10E+01	9.36E+01	9
3.52E+16	1.33E+02	1.37E+02	1
3.53E+16	1.58E+02	1.56E+02	1
959.04	1172.16	1651.68	
0	-106.56-184.56192j	-346.32-230.7024j	-466.2-34
0	-106.56+184.56192j	-346.32+230.7024j	-466.2+34
7458-0.597781469077326j	-1.2162029775805 4+0.9005726583516j	-2.560283484246-0.681020686604199j	-1.54632905245056-0.78043367 5
25738+4.77971132804316j	242.943940812061+7.33211233388266j	247.127892508228+9.75847216244549j	246.609539818886+9.2425782 9
0744-0.489060115303395j	0.4876472608481-4.32290326088542j	-3.1395428331388-5.2842433659371j	-1.27385485323019-3.6404412
01258+3.69286974366244j	242.215385095329+3.90978173134884j	241.428066190843+3.79320810990419j	243.789355913205+4.8217033 1
71939-212.918743780177j	-112.838753508966-210.571182093497j	-111.527466674211-219.649734090482j	-113.057476569442-218.248521
33776+207.432529629283j	-133.025240519104+209.363118337203j	-137.58144996937+213.813463920766j	-135.370866501115+211.085517
1.71E+00	1.75E+00	1.68E+00	2
2.52E+00	2.42E+00	3.03E+00	3

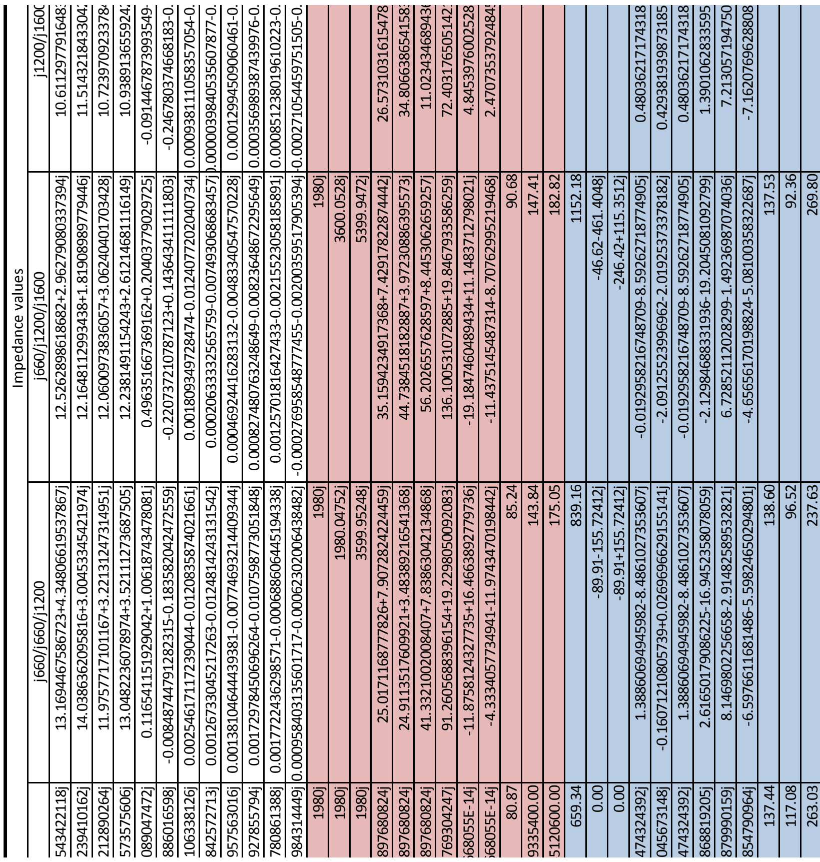
8. Resistive load analysis (Third harmonics) using Equation (3.10) and Equations (3.11) to (3.13)

Impedance values			
…0	960-960-1600	960-1600-2400	1600-2400-3600
…+8.84273441786583j	2.89530360946202+8.30262979612877j	3.9188985211384+7.90417981919207j	6.34288081689403+6.71803067263775j
…7+9.56521542331314j	3.1491250397627+9.61554765637608j	5.87071718629592+8.95415458156881j	7.97108359374444+7.22427510450967j
…25+9.6395074300329j	4.60964574320931+8.96793751908499j	5.57847206007528+7.70672503362222j	7.52817203279524+6.19326603149587j
…3+9.33980327131356j	3.54780677268052+8.9530762855394j	5.1175732265807+8.18016479164957j	7.27343143566342+6.70514541227822j
…-0.713736744866594j	-0.514455749585717-0.750556599021915j	-0.961028040159444-0.0576675111290912j	-0.765767084250721+0.130809564966857j
…+0.207825157001005j	-0.14094271724227+0.091807479815138j	-0.241565563803975-0.226221641147603j	-0.171126415335572-0.124642335279954j
…00925303452166181j	0.00296170382422156+0.00857857023043819j	0.00416511671398295+0.00813217207168809j	0.00411562014194991+0.00423954116786914j
…0.0100275711942888j	0.00274027706684186+0.00989426203187183j	0.00358524180048723+0.00519719700453235j	0.00354285842114886+0.00291565212945159j
…0.0100609878993409j	0.00263953584973699+0.00556022702699037j	0.00227267120185582+0.0031014844718359j	0.00217530942419937+0.00167609094471195j
…00977075067389207j	0.00277772507468654+0.00800300874333703j	0.00333766889553656+0.00547147423150275j	0.00327465139977028+0.00294081765259688j
…00621955089206853j	-0.0011593318237823+0.00031254300914163j	-0.000192716037887732+0.00170479931814895j	.0000609643856859909+0.00104161303169449j
…00949859024549283j	0.00134034886949311+0.000254439907729092j	0.00101599873962014+0.000947766349964469j	0.00077588873635169+0.000252870942409894j
2880	2880	2880	4800
2880	2880.05632	4800.0704	7200.1056
2880	4799.94368	7199.9296	10799.8944
…7+26.6220906829637j	6.29540098709901+25.2816552865835j	13.1018099900506+32.5816260621098j	21.9632164820496+27.1859329689521j
…7+26.6220906829637j	11.094728089199+25.170537003635j	22.7811428803028+37.9971345362628j	32.2499813515742+28.9049196760305j
…7+26.6220906829637j	13.854187715098+40.0469196415753j	26.0320068970088+50.3069531079192j	39.5291052635976+40.4740244438062j
…5+79.8662720488911j	31.244316791396+90.4991119317938j	61.9149597673622+120.885713706292j	93.7423030972214+96.5648770887888j
…79616346638068E-14j	-19.0620042795058-4.93738099999308j	-21.9650677816596-8.75516952151378j	-23.9451715544301-1.19981778315401j
…9737991503207E-14j	6.70389044940681-9.71676507205017j	-0.644462015550801-14.3856659984486j	-3.9074820966425-13.8072603987785j
88.96	90.82	93.50	93.14
…466826025772100.00	134.85	139.53	137.68
…856610822656800.00	159.27	159.39	160.56
959.04	1172.16	1651.68	2530.8
0	-106.56-184.56192j	-346.32-230.7024j	-466.2-346.0536j
0	-106.56+184.56192j	-346.32+230.7024j	-466.2+346.0536j
…3+9.37054072628945j	3.22592542719897+8.85904316083034j	5.05299237347663+7.83963461642081j	7.62439979757621+6.59173074118919j

9. Inductive load analysis (fundamental) using Equation (3.10) and Equations (3.11) to (3.13)



10. Inductive load analysis (Third harmonics) using Equation (3.10) and Equations (3.11) to (3.13)



11. Combination load analysis (fundamental) using Equation (3.10) and Equations (3.11) to (3.13)

Impedance values			
660/960+j660	960+j660/960+j660/1600+j1200	960+j660/1600+j1200/2400+j1600	1600+j1200/2400+j1600/3600+j24(
239.5914	240.3036	240.3679	2:
0071-207.506892022058j	-116.76580401657-207.813227757171j	-119.182053060454-213.525871724377j	-119.279404451297-209.746344!
2129+206.768596495265j	-126.02855165975+210.765316017569j	-126.534620206979+215.2622386656j	-124.112042444747+210.999277:
213-0.245852410422068j	-0.829421640214563+0.983045390712534j	-1.78114149805519+0.578210191427259j	-1.15156291638265+0.41722660:
764+0.729803238638303j	241.155202316779+2.17964994448869j	244.607394497068+1.83121351286696j	241.756245758412+1.1850131:
3107-0.48395082821652j	-0.262484276564749-3.16269533520127j	-2.69872089901301-2.40942370429416j	-0.911316142028934-1.60223977
109-0.102835340560571j	0.161750059414662-0.103109466742115j	0.161805097932052-0.103226067491496j	0.093362529634908-0.0638357487
84-0.0905643205717916j	-0.16925958553163-0.0921687689074277j	-0.103625236184935-0.052938053111693j	-0.0686966159435952-0.0413693456
599+0.191917196237971j	0.00558197212238552+0.116575235726396j	-0.000426774451004118+0.0824415253672861j	-0.000143831117335127+0.053862067
-0.000493660809832413j	-0.000641875480195969-0.0262080989744079j	0.0192317780696056-0.0245496242135557j	0.00816585349713457-0.017097227
946-0.102370939661961j	0.141312270986014-0.0888195878636324j	0.110246249464868-0.069046774603132j	0.0700143014041008-0.043106457
+0.000132095251783403j	0.0209179138494287+0.012021329562667j	0.0321652652996462-0.00952644260731697j	0.0150890122040378-0.00356822761
959.04	1172.16	1651.68	
0	-106.56-184.56192j	-346.32-230.7024j	-466.2-34
0	-106.56+184.56192j	-346.32+230.7024j	-466.2+34
475-0.473440463061677j	0.571764075827992-0.316249178997253j	-3.8237291510091+4.67682370455561j	-5.32667595646185-2.50283185
5457-98.1778259734071j	156.424280179035-98.6199098482488j	160.825817204299-99.2581666707567j	161.669016380249-97.063803
184+0.126684630270355j	-2.02639205080757+0.14894214587242j	-1.9797044936555-4.31758687307639j	-7.26090372271859-2.3663903
9253-98.5245818061984j	154.969652204055-98.7872168813736j	155.022383559634-98.8989298392775j	149.081436701069-101.93302
8733-86.7600124170617j	-162.161005815195-88.2990474788527j	-165.465327611122-84.5248813139565j	-164.538692081228-99.081045
5836+183.864272834075j	8.90664583862324+186.137516823235j	-1.0282434015397+197.4542822669j	-0.52277248922617+193.50557
71.35	71.03	71.04	
69.43	69.24	73.76	
70.55	73.61	64.20	
2880+1980j	2880+1980j	2880+1980j	480(
2880+1980j	2880.05632+1980.04752j	4800.0704+3600.0528j	7200.1056+540
2880+1980j	4799.94368+3599.95248j	7199.9296+5399.9472j	10799.8944+719
2737+22.1797470856989j	1084.52263840999+81.6787720901002j	1459.30118303709+135.637070929529j	1295.16849594946+41.674309
2737+22.1797470856989j	690.015361462841+80.2513391641047j	917.945577019381+75.9293732342278j	831.023623311032+36.238292
2737+22.1797470856989j	710.562607920396-28.069625356481j	1160.2942361508+28.8090307656892j	1033.44988158028-20.951711
3211+66.5392412570967j	2485.10060779323+133.860485897724j	3537.54099620727+240.375474929446j	3159.64200084077+56.960890
-2.27373675443232E-13j	478.039608993199+73.3818306185302j	460.987493029754+293.141807737379j	412.45828741618+209.332158

12. Combination load analysis (Third harmonics) using Equation (3.10) and Equations (3.11) to (3.13)

Impedance values			
60/960+j660	960+j660/960+j660/1600+j1200	960+j660/1600+j1200/2400+j1600	1600+j1200/2400+j1600/3600+j2
205+7.89520411590895j	7.04458959571509+7.77707480046596j	7.85254683708056+7.01574834095096j	8.52260985429311+5.6012237
955+8.52112174491673j	8.31975848201626+8.02348926735236j	9.13175728768483+6.44030695974306j	9.7631830876658+5.4604666
7729+7.9125487906692j	8.25284548839447+6.85561138040124j	8.09630451346227+6.1979998887456j	9.08053872174183+4.8385808
9186+8.1015152589478j	7.86452545751989+7.54450642425713j	8.35184267652983+6.54480037808339j	9.11298844401233+5.2947903
71-0.238840525295277j	-0.75028051498346+0.131691885978865j	-0.323450221663271+0.530567907388069j	-0.478788775987472+0.34727572
38+0.024634178140516j	-0.0766999364170701+0.0930994154295124j	-0.183698164623057-0.0666356928614463j	-0.120112423586056-0.046443511
0.000595472369664061j	0.0045734074013441+0.000457827351833686j	0.00447230056368418+0.000149062117005575j	0.0025924310908111+0.000025550687
0.000196966057680428j	.00461038690740857+0.0000875443174603979j	0.00271977384858252+0.0000429528268643428j	0.00175460858896588-0.000070466134
0.000251532706118583j	0.00254534128325247+0.000260314851083595j	0.00175030166608508+0.00013451550865535j	.00104891424055214+0.000023790372
0000489422107530617j	0.0039058021521377+0.000268293611285767j	0.00297781123409114+0.000108734640690914j	0.0017968526554696-7.03464959715
+0.00037515454423597j	0.000381339141847713+0.00069005168360093j	0.000771413177564203+0.000299663656143076j	.000423674504983453+0.00021978661
0.000170780142305365j	.000281692699957331-0.000500975770404844j	0.00071860385146515-0.000259485241945419j	.000369311499267239-0.00018722683
960+660j	960+660j	960+660j	16
960+660j	960+660j	1600+1200j	24
960+660j	1600+1200j	2400+1600j	36
959.04+659.34j	1172.16+839.16j	1651.68+1152.18j	2530.8
7.57154339225963E-14j	49.16412-274.47192j	-230.9688-477.1224j	-235.4976-6
3.78577169612981E-14j	-262.28412+94.65192j	-461.6712-15.7175999999999j	-696.9024-
184+3.36879987159733j	4.06409525793735+3.3452340876513j	4.15189883626245+3.1771695362334j	4.04524960631448+2.7921094
79+0.241179934746066j	0.107125902638518+0.228073683168612j	-0.0428776965199881+0.0463626854044231j	0.0217292658083091+0.35093433
5+0.0659272206800445j	-0.091088629296878-0.122257096494628j	0.0776205441103881-0.134900758471625j	0.0420197072531276+0.0024541770
932+3.67590702702344j	4.08013253127899+3.45105067432528j	4.18664168385285+3.0886314631662j	4.10899857937592+3.1454979
9927+3.3580798147532j	4.3594630764549+3.12067200965825j	4.29150155486391+3.32579004915291j	4.3151589324774+2.6329867
592+3.07241277301535j	3.75269016607816+3.46397957897036j	3.97755327007059+3.1170870963811j	3.71159130709013+2.597843
48.50	49.98	51.02	
49.64	54.53	51.51	
50.96	52.52	50.45	
2880+1980j	2880+1980j	2880+1980j	48
2880+1980j	2880.05632+1980.04752j	4800.0704+3600.0528j	7200.1056+54
2880+1980j	4799.94368+3599.95248j	7199.9296+5399.9472j	10799.8944+71
293+11.0387598400112j	11.8669886545322+12.3061123669563j	16.6802640642256+13.8728340432888j	15.3135219232629+12.505258