THE INFLUENCE OF CABLE CAPACITANCE ON TRIPLEN HARMONICS PRODUCED BY SYNCHRONOUS GENERATOR

By

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12374

FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

MAY 2012

Universiti Teknologi PETRONAS

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

____

(Ir Mohd Faris Bin Abdullah)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

MAY 2012

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 in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Mohd Helmi Syazwan B. Abd Razak

ABSTRACT

Generator neutral earthing resistor (NER) at Universiti Teknologi PETRONAS (UTP) power plant becomes high temperature during parallel operation with utility grid of Tenaga Nasional Berhad (TNB). Due to increase in triplen harmonics current that flow through the generator NER, it has been observed that cable capacitance allows triplen harmonics current to flow back to the generator neutral. The main objective of this study is to investigate the influence of cable capacitance on the triplen harmonics behaviour. Lab scaled experiments have been conducted to vary all parameters related to cable capacitance under various load impedance conditions in both island and parallel mode. Cable capacitance which depends on cable length, size and number of parallel cable, combined with load impedance determines the third harmonic current magnitude. The triplen harmonic current is proportional to the cable capacitance value. The presence of cable capacitance that interact with generator inductance resulted to series harmonic resonance at 9th and 15th harmonic order that causes high 9th and 15th harmonic current flowing between generator and cable capacitor. The author hope by the end of this project, the findings will help the industry to understand better the characteristics of triplen harmonic flowing through cable capacitance.

ACKNOWLEDGEMENTS

There were many people's involved throughout completing this Final Year Project, which has contributed to give help, guidance, assistance, motivate, advice, supports, and also supervise. It is a good experience going through all the process to complete this project. I would like to express my appreciation and highest gratitude to the individual that have taken the time and effort to assist me in completing the project. Without the cooperation and some motivation of these individuals, no doubt I would have to face some problem throughout the project.

Special thanks go to my supervisor, Ir Mohd Faris B. Abdullah, without his guidance, assistance and motivation I would face a lot of obstacle. Also thanks to the Final Year Project Coordinator, Dr Zuhairi B. Baharudin for giving all of final year student all the information especially on timeline and guideline that required along the final year project.

Next, thanks to all lecturers and technicians from UTP who had provided untiring guidance and help throughout the period of the project.

To both my parent thank you so much for your understanding upon completing the Final Year Project course. Thank you also to my colleagues of UTP. All your guidance, support and assistance are very important in completing my project.

Finally, I would like to apologize if any party was inadvertently excluded from being mentioned above and I would like to thank all parties that were involved in making this project a success. Thank you.

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CHAPTER 1

1. INTRODUCTION

1.1 Background of study

Based on IEEE Standard Dictionary of Electrical and Electronic Terms, IEEE Standard 100, 1984, harmonic can be defined as "a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency". Triplen harmonic is the odd multiple of third harmonic (3^{rd}, 9^{th}, 15^{th}, etc.). Triplen harmonics currents are zero sequence and add up at neutral under balanced load. Triplen harmonics is undesirable in power system because it cause high temperature at NER and heating at neutral conductor. One of the triplen harmonics sources is synchronous generator. Synchronous generator produces triplen harmonics depending on its winding design. Triplen harmonics currents needs neutral to flow because it adds up at the neutral become higher currents. By referring to this research findings, the purpose of this study is to investigate the effect of cable capacitance towards the behaviour of triplen harmonics.

1.2 Problem Statement

Universiti Teknologi PETRONAS (UTP) get electricity supply from gas district cooling (GDC) plant located at the campus. Under normal condition, UTP will get supply only from GDC or in island mode but during emergency UTP power system will operating in parallel with utility grid. During parallel operation, generator neutral earth resistor (NER) temperature becomes high. The triplen harmonics current continuously flow through NER during island and parallel mode.

During island mode, triplen harmonics currents from the loads are blocked by the delta winding of 11/0.415 kV transformer. Therefore, generator is the only source of triplen harmonics currents. The only path for these triplen harmonics currents returning to generator neutral is through capacitance of underground cables. In this study, we will see whether the cable capacitance, which is the ability of two conductors separated by insulation to store charge, affects the properties of triplen harmonics in a power system.

1.3 Project Objectives

The objectives of this project are listed as below:

- To study the fundamental of triplen harmonics
- To study the influences of cable capacitance on the behaviour of triplen harmonics produced by synchronous generator under various load condition.

1.4 Scope of Study

The project begins with the study on relating topic such as cable capacitance, triplen harmonics and synchronous generator. All information regarding the topic will be gained by studying the published journals, articles, books and conference proceeding paper. By studying all these sources, it gives better understanding on the basic concept and theory of the project and also the latest update related to the topic. The lab experiment will be conducted to investigate the relationship between cable capacitance and triplen harmonics produced by synchronous generator. Based on the data collected at the lab experiments, the result will be analysed and discussed in order to come out with a conclusion that can relate the relationship between cable capacitance and triplen harmonics produced by synchronous generator.

1.5 Relevancy of Project

This project is related to the power quality problems that commonly faced by power utility and industries nowadays. The rapid increased in non-linear loads has make the impact of the harmonics is more significant. Furthermore in 3 phase 4 wires systems, triplen harmonics becomes major problem in the power system as it provide path for the triplen harmonics to flow through neutral conductor. This project is also applicable to wind farm and offshore plant as a long high voltage cable has an earth capacitance that form small impedance for harmonics current to flow. Besides, an island plant such as gas district cooling (GDC) can benefits from this project as it involve harmonics investigation during island mode and also during parallel operation with utility grid. As an electrical and electronics student, this study can help me understand better about the real problems happened in the power system and at the same time it can assist people in power industries understand more about the behaviour of triplen harmonics related to cable capacitance.

1.6 Feasibility of Project

This project will investigate the impact of cable capacitance on the behaviour of triplen harmonics generated by synchronous generator in order to help understand better the influence of cable capacitance on triplen harmonics. The project will be conducted in two phases which are Final Year Project 1 (FYP1) and Final Year Project 2 (FYP2). FYP1 will mainly be about understanding the fundamental theories and concept regarding to the project. All the reliable sources such as published works, journal papers and related books related to this project will be studied in order improve past experiment that have conducted and plan for future experiments. After that, the experiments also will be conducted in this phase. In FYP2 all the experiments will be completed and all the data from the experiment will be analysed. All data from lab experiments will be analysed to identify the relationship between cable capacitance and triplen harmonics behaviour. Based on the methodology and planning of the project milestones, the project will be able to be completed within the time given.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Triplen Harmonics

Ideally, currents and voltages are in perfect sinusoidal. But, the increased usage of non-linear load nowadays mainly have contributed to the distortion of the perfect sinusoidal as in Figure 1. The distorted sinusoidal is known as harmonics. Harmonics can be defined as “a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency” [1].

$$f_h = (h) \times (fundamental\ frequency)$$

Where h is an integer

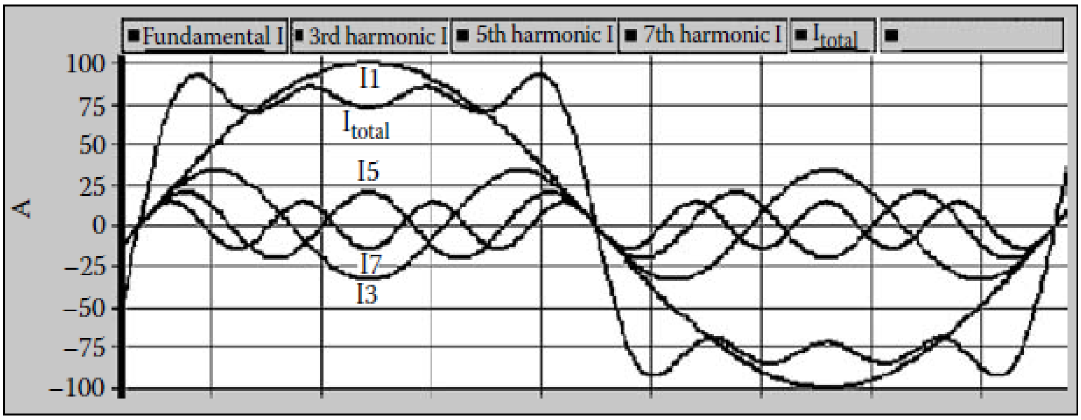


Figure 1: Sinusoidal waveform distorted by third, fifth and seventh harmonics

Harmonics of different order form positive sequence, negative sequence and zero sequence.

Positive sequence: 1, 4, 7, 10, 13,…

Negative sequence: 2, 5 8, 11, 14,…

Zero sequence: 3, 6, 9, 12, 15,…

Triplen harmonics currents and voltages are the odd multiple of third harmonic currents and voltages (3rd, 9th, 15th, etc.). Under balanced load, triplen harmonics currents are zero sequence because it have same magnitude and phase angle. Thus, triplen harmonics currents add up at the neutral become three times larger than phase currents value as shown in Figure 2 [2].

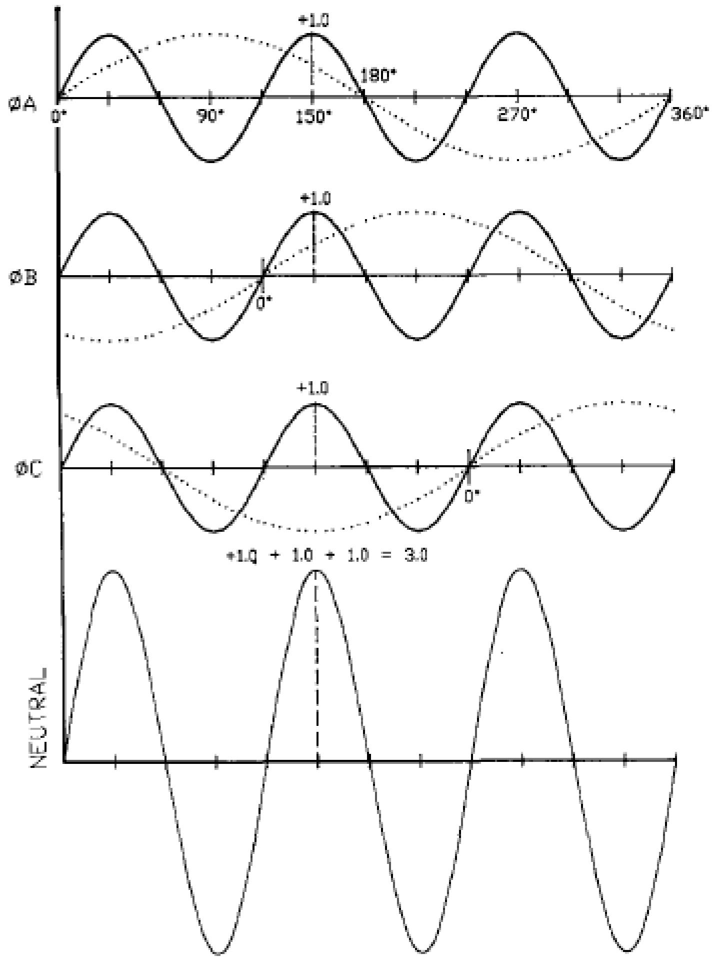


Figure 2: Triplen harmonics currents produce 3 times larger magnitude of phase currents [2]

The power systems mostly still can accommodate a certain level of triplen harmonics as long as it still within the limit but the system will experience problems as the triplen harmonics become a major component in the system. High temperature of neutral earthing resistor (NER) for generator caused by triplen harmonics has been reported in [3].

2.2 Triplen Harmonics in 3-Phases 4-Wires

The 3-phases 4-wires distribution system is the most common method of electric power distribution. On three phase power systems, neutral current is the vector sum of three line-to neutral currents. With balanced, three-phase, linear currents, which consist of sine waves spaced 120 electrical degrees apart, the sum at any instantaneous time is zero, and so there is no neutral current as in Figure 3.

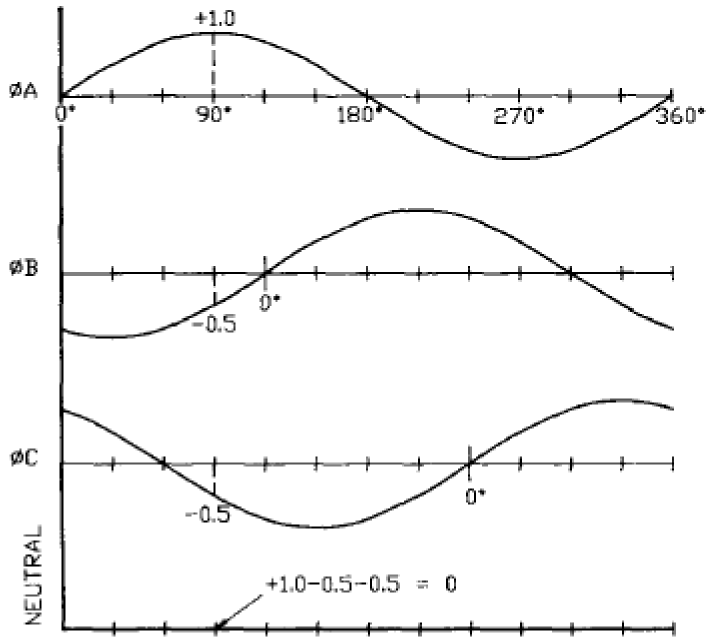


Figure 3: Balanced 3 phase loads result in zero neutral current [2]

In three-phase circuits, the triplen harmonic current add instead of cancel. Being three time the fundamental power frequency and spaced in time by 120 electrical degrees based on the fundamental frequency, the triplen harmonic currents are in phase with each other, and add in the neutral circuit. High neutral currents in power systems can cause overloaded power feeders, overloaded transformers, voltage distortion and common mode noise [6],[7],[8].

Triplen harmonics become major concern for this system as the neutral conductor becomes a path for current to flow. The resulting problems are overloading neutral conductor and high neutral currents. When harmonics current flow through neutral conductor, the ampacity of the power feeder will be reduced by the additional heat generated [2].

Theoretically, triplen harmonics currents add up at neutral become three times larger than phase currents. [2] proposes that high neutral currents should be considered in the design of all three phase computer power systems to accommodate neutral currents up to 1.73 times the phase current. Besides, [9] suggests that neutral conductor used is same or larger size compared to the phase conductor and separate neutral conductor is used for each line.

2.3 Triplen Harmonics Sources

Basically, any non-linear load generates triplen harmonics currents. Mostly the non-linear loads that generate triplen harmonics currents are single phase loads with power conversion circuit as published in [10] such as switched mode power supplies (SMPS), uninterruptible power supplies (UPS) and electronic fluorescent lighting ballasts. Besides, there are also three phase loads that contributed to triplen harmonics generation such as variable speed drives and large UPS units.

As reported in [3], at the islanded generator, the only source of triplen harmonics currents come from generator as the triplen harmonics from loads have been blocked by delta winding of the transformer. In this situation, cable capacitance has provides path for the triplen harmonics to flow.

2.4 Triplen Harmonics Generated By Synchronous Generator

Synchronous generator has been identified as one of the sources of triplen harmonics. A source of harmonic currents can be represented by synchronous machines on two counts which are the frequency conversion effect and the non-linear characteristic due to magnetic saturation [4]. Under the frequency conversion effect, a synchronous generator that feeding an unbalanced, three-phase load may experience the flow of a negative sequence current in the rotor, which in turn may induce a third-order harmonic current on the stator winding. In special cases when the generator feeds static converter equipment the machine can be important source of harmonic generation. The saturation of the stator's circuit represents another harmonic source.

Based on [5] if the magnetic flux of the field system is distributed perfectly sinusoidal around the air gap, the e.m.f. (electromotive force) generated in each full-pitched armature coil is

$$\text{e.m.f.} = 2\pi f\varphi.\sin\omega t \text{ [V per turn]}$$

However the flux is never exactly distributed in this way, particularly in salient pole machines. A non/sinusoidal field distribution can be expressed as a harmonic series:

$$F(x) = F_1 sin\left(\frac{2\pi x}{\lambda}\right) + F_3 sin\left(\frac{3 \times 2\pi x}{\lambda}\right) + F_5 sin\left(\frac{5 \times 2\pi x}{\lambda}\right) + \cdots$$

The machine can be consider to have 2p fundamental poles together with 6p, 10p, … 2np harmonic poles, all individually sinusoidal and all generating electromotive forces in an associate winding. The winding e.m.f. can be expressed as a harmonic series:

$$E(t) = E_1 sin\omega t + E_3 sin3\omega t + E_5 sin5\omega t + \cdots$$

The magnitude of the harmonic e.m.f.s is determined by the harmonic fluxes, the effective electrical phase spread of the winding, the coil span, and the method of interphase connection. The triplen harmonics in a three-phase machine are generally eliminated by phase connection, and it is usual to select the coil span to reduce 5^{th} and 7^{th} harmonic.

Study in [3] reveal that triplen harmonics currents produced by synchronous generator flow in reverse direction of the load flow. This situation can be observed when the synchronous generator is in parallel with utility grid. Triplen harmonics currents actually flow through zero sequence impedance of the electrical network.

When islanded generator is connected in parallel to the grid, higher triplen harmonics currents are observed. During parallel mode, as shown in Figure 4 utility grid act as short circuit to the triplen harmonics currents to return to generator neutral which cause overloading at generator neutral.

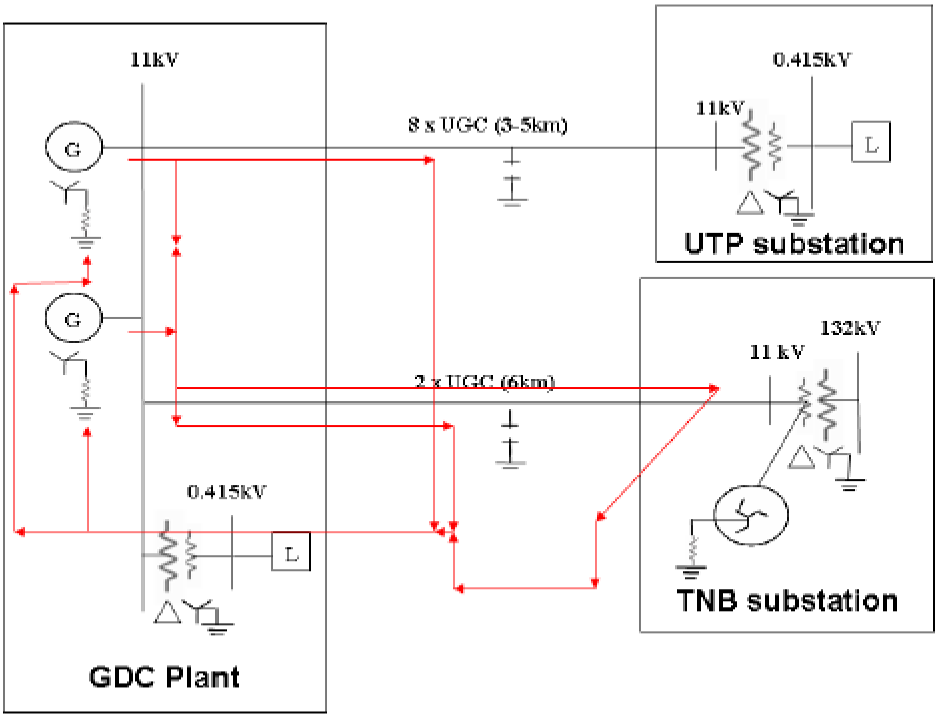


Figure 4: Triplen harmonics currents flow during parallel operation [3]

2.5 Cable Capacitance

Any two conductors separated by a distance can store a charge. So any two wires in a cable or harness can store a charge. The term "capacitance" describes the ability of two conductors to store a charge. Capacitance is affected by the distance between the conductors and the insulation around the conductors. As the conductors get closer together or have more surface area the capacitance will increase.

Capacitance of a transmission line is the result of the potential difference between the conductors. It causes them to be charged in the same manner as the plates of a capacitor when there is a potential difference between them. For longer lines of higher voltage, capacitance becomes increasingly important [11].

Investigation in [12] reveals that cable length and cable size influence the triplen harmonics currents magnitude. Increase cable length will increase the triplen harmonics current. The same situation happened with cable size. The larger the cable size, the higher triplen harmonics currents.

Based on [12], coupled pi model is the most suitable model as it takes cable capacitance into account. Besides, zero sequence effect also can be represented by this model.

CHAPTER 3

3. METHODOLOGY

3.1 Project Activities

In this project, the research methodologies are divided into five different stages as in Figure 5. The first stage is the preliminary research work on the project. The process continues with lab scaled experiment based on various loads that have been planned. Next will be the result analysis and discussion stage. The last stage is the final documentation that compiles all the research works and the outcomes of the project.

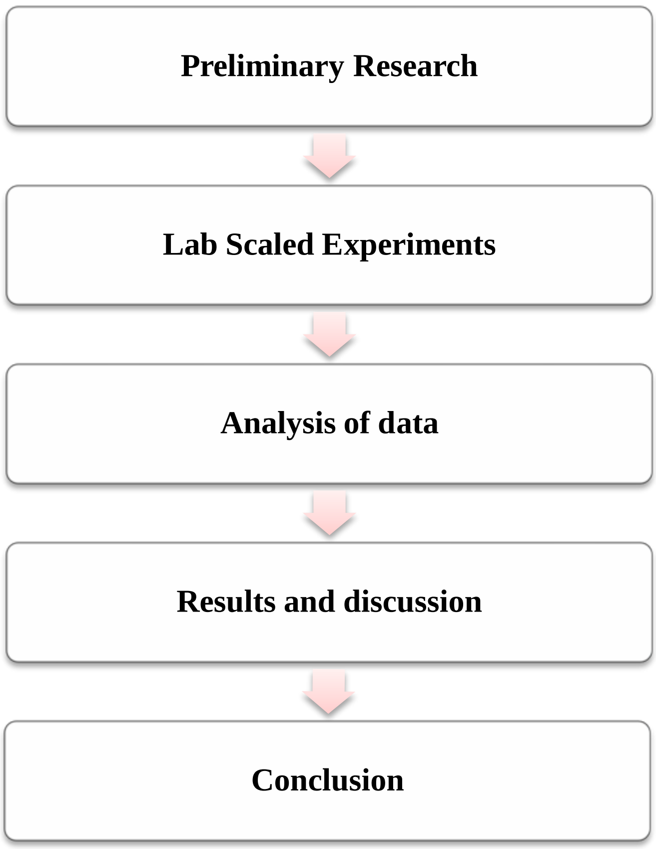


Figure 5: Project activities

3.1.1 Preliminary Research Work

This stage focusing more on data collection related to the project. All information from published journals, articles, technical papers and various books on related subject will be compiled at this stage. Apart from that, the research on the effects of triplen harmonics and the sources of triplen harmonics also been conducted using the same method. Great understanding particularly in power quality, load flow and triplen harmonics current are obtained from a thorough research pertaining to the project.

3.1.2 Lab Scaled Experiment

After all related information has been gathered and basic understanding gained, experiments can be carried out to investigate the influence of cable capacitance towards triplen harmonics behaviour.

During the experiment, synchronous generator and loads will be connected in 3 phase 4 wire system. Capacitor will be connected in parallel with the generator and load to act as a cable capacitance. The load and capacitor values will be increased and the value of triplen harmonics will be recorded. The purpose in doing this is to see whether triplen harmonics is affected by capacitor when we increase the value of capacitor. Due to generator’s reactive power limitation, the cable is only represented by its capacitance without resistance and inductance.

The measurement is done at three different measuring points. The first point is at the generator, the second point is at the load and the third point is at the capacitor. The purpose of this is to see how triplen harmonics behave at each point.

The planned experiments:

1. Single generator
    i. Single generator with cable capacitance connected to balanced resistive and inductive load

ii. Single generator with cable capacitance connected to balanced combined resistive and inductive load by varying load impedance magnitude with fixed angle (about 36 degree)

Figure 6 below is the circuit diagram for the single generator experiments

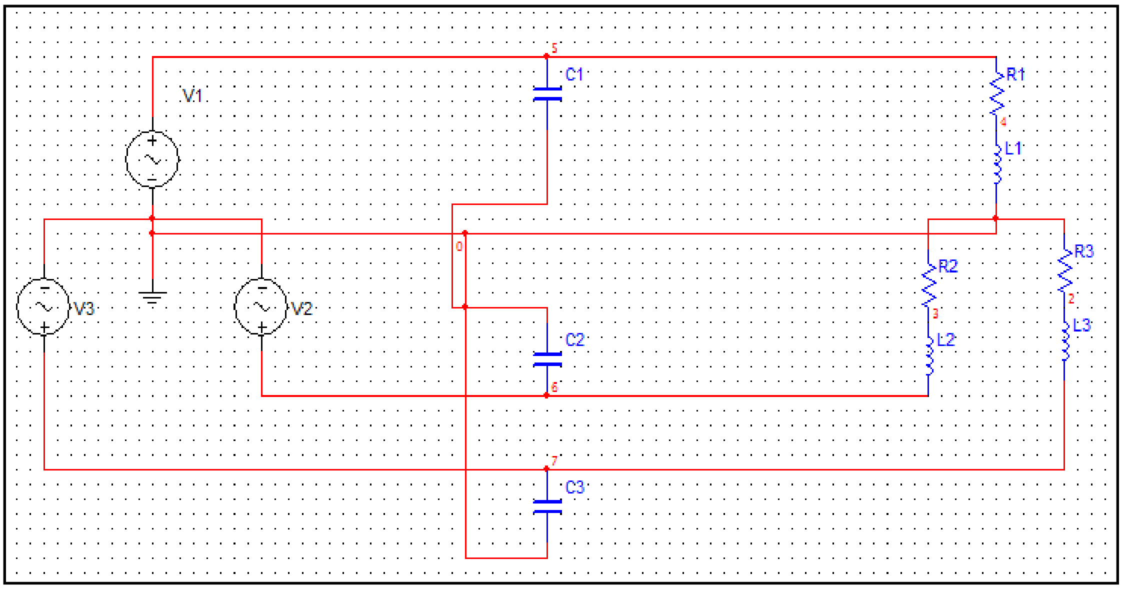


Figure 6: Single Synchronous generator with cable capacitance connected to balanced/unbalanced resistive and inductive load

2. Single generator parallel with grid

i. Single generator parallel with grid connected to balanced combined resistive and inductive load by varied load impedance magnitude with fixed angle (about 36 degree)

Figure 7 below is the circuit diagram for the single generator connected to the grid experiments

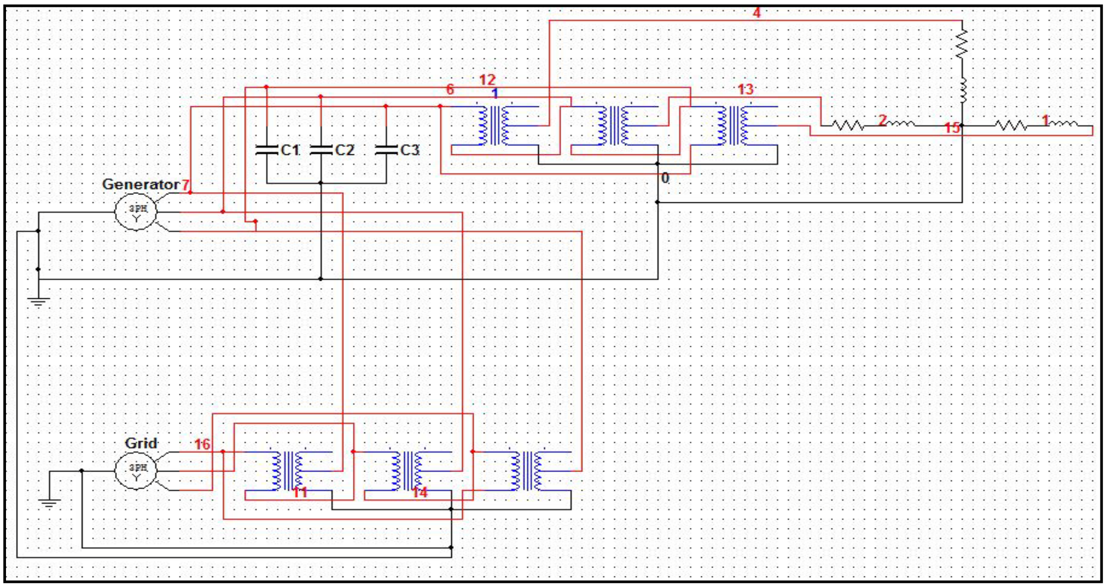


Figure 7: Single synchronous generator parallel to the grid with cable capacitance connected to balanced resistive and inductive load

3. Varying capacitor value

In this study, capacitor represents cable capacitance. The triplen harmonics current is analysed based on different capacitor value. The higher the capacitor value, the smaller the reactance.

Based on Tenaga Cable Industries Sdn. Bhd., cable capacitance value for three core 11 kV unarmoured cable 300 mm^2 copper conductor is 0.53 uF/km. Table 1 is equivalent distance for every value of capacitor.

Table 1: Equivalent distance for capacitor value

Capacitor (uF)	Distance (km)
0.66	1.30
1.33	2.60
1.99	3.80
2.65	5.10
3.31	6.40
3.98	7.70
4.64	8.90
6.60	12.45

4. Purely resistive and inductive load

Normally, loads are consists of combined resistive and reactive load. For purely resistive load, the load angle is 0 degree while for purely reactive load, the load angle is 90 degree. Table 2 is the resistive and inductive load impedance value used during the experiments.

Table 2: Resistive and Inductive load impedance value

Resistive load (Ω)	Inductive load (H)
686	2.5
766	3.8
800	5.1
880	7.6

5. Varying load impedance magnitude with fixed load angle

In real situation, the power factor is about 0.8 (36°) normally. During the experiment, the load angle is fixed to about 36° while the load magnitude is varied. Table 3 is load impedance for this case.

Table 3: Varying load magnitude

R+L	Load angle (degree)
240+j160	288 ∠ 34
320+j240	400 ∠ 37
480+j320	577 ∠ 34
686+j480	837 ∠ 35
960+j686	1180 ∠ 36
1200+j800	1442 ∠ 34

3.1.3 Results analysis and discussion

In the study of triplen harmonics currents, the third harmonic current is the main concern and significant as the higher number of harmonic become negligible due to impedance imposed by the network. Therefore, the measurement for third harmonic current is studied and presented here to characterize the general behaviour of triplen harmonics currents.

After completing all the previous stages of work, the data gained from lab scaled experiments will be analysed and discussed with the supervisor to come out with a conclusion.

3.1.4 Final Documentation

The research works, methods and outcomes of the project will be documented in a proper manner for future use. All of the documents required for the project will be done continuously starting at the early stage of the project until the last stage in order to keep the the project on track and ensuring the project to meet the necessary requirements.

3.2 Gantt Chart

The Gantt Charts shown below describe the timeline of the project. The schedule of the activities may change from time to time depending on the work progress. Table 4 and Table 5 below are the FYP 1 and FYP 2 Gantt chart respectively.

Table 4: FYP 1 Gantt chart

No	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection and Confirmation of Project Title														
2	Preliminary Research Work on Related Topics														
3	Lab Scaled Experiments														
4	Proposal Defence														
5	Preparing Interim Draft Report														
6	Preparing Interim Final Report														

Table 5: FYP 2 Gantt chart

No	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Collecting data at the site (GDC)																
2	Continue Lab Scaled Experiments																
3	Analysis Data																

4	Preparing Project Dissertation (Soft bound)																
5	Preparing Technical Paper																
6	Preparing Project Dissertation (Hard bound)																

3.3 Key Milestone

A key milestone is constructed to mark the end stage of a work or process of the project. It is an important element in order to monitor the progress and make sure that the project is on schedule. Table 6 and 7 below are the FYP 1 and FYP 2 milestone respectively.

Table 6: FYP 1 Key milestone

No	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Confirmation of Project Title		●												
2	Submission of Extended Proposal						●								
3	Proposal Defence									●					
4	Submission of Interim Draft Report													●	
5	Submission of Interim Final Report														●

Table 7: FYP 2 Key milestone

No	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Submission of Progress Report		●														
2	Pre-EDX						●										
3	Submission of Draft Report									●							
4	Submission of Dissertation (soft bound)													●			
5	Submission of Technical Paper													●			
6	Oral Presentation														●		
7	Submission of Project Dissertation (Hard Bound)															●	

3.4 Experimental Tools

The tools required for this project can be divided into two, tools used for lab experiment and tools used to harmonics measurement. The tools required for the lab scaled experiment is Lab – Volt 0.2 kW Electromechanical Training system. It is a modular program in electric power technology. The system consists of several modules, which can be grouped to form subsystems which deal with the different techniques associated with the generation and use of electrical energy. Symbols and diagrams specific to each module are clearly silk-screened on the faceplates. Standard colour coded safety 4 mm jacks are used to interconnect all system components. Figure 8, 9, 10, 11, 12, 13, 14, 15 and 16 are all equipments that will be used during the experiments.

Figure 8: Power supply

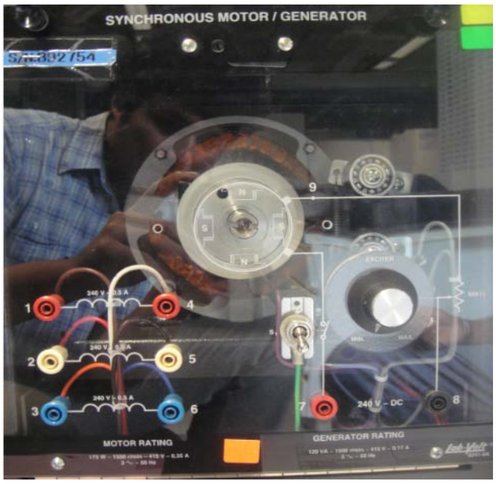


Figure 9: Synchronous generator

Figure 10: Prime mover

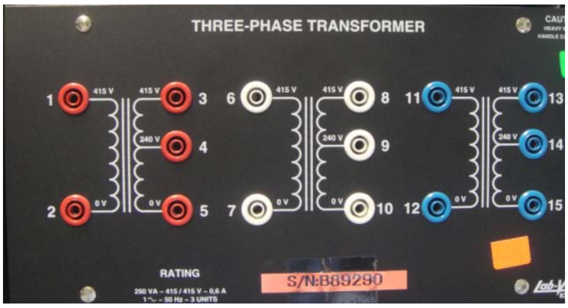


Figure 11: Three phase transformer

Figure 12: Synchronising module

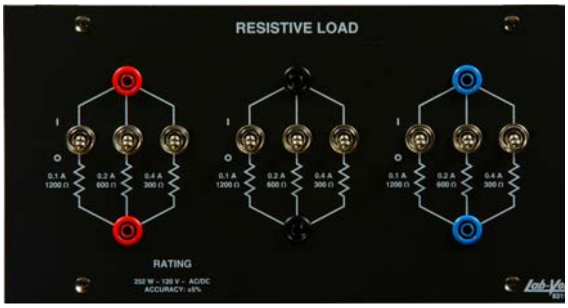


Figure 13: Resistive load

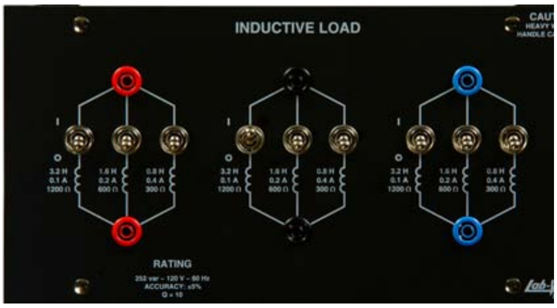


Figure 14: Inductive load

Figure 15: Capacitive load/ cable capacitance

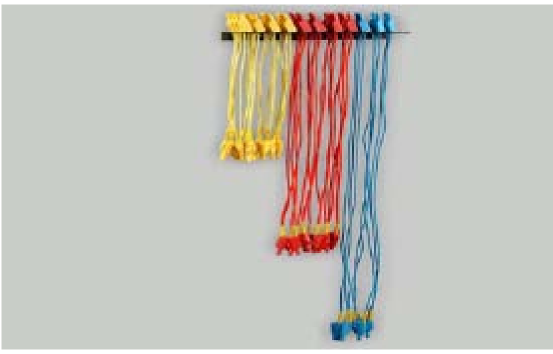


Figure 16: Connection leads

The tool required for measuring the harmonics distortion is Fluke Three Phase Power Quality Analyzer. It is an ideal tool to conduct energy consumption studies and electrical load analysis, and to perform power quality logging and analysis. It is a complete three phase troubleshooting tool that measures virtually every power system parameter such as voltage, current, frequency, power, energy consumption, power factor, unbalance, harmonics and inter-harmonics. The Fluke Three Phase Power Quality Analyzer as shown in Figure 17 will be used together with the Flukeview software to transfer the data measured during the lab scaled experiment into a computer.

Figure 17: Fluke power quality analyzer

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 Single generator with balanced resistive load

4.1.1 Balanced resistive load

The third harmonic voltage when the generator connected directly to the load without the capacitor as in Figure 18 is higher compared to the third harmonic voltage when the generator and the load connected to the capacitor shown in Figure 20.

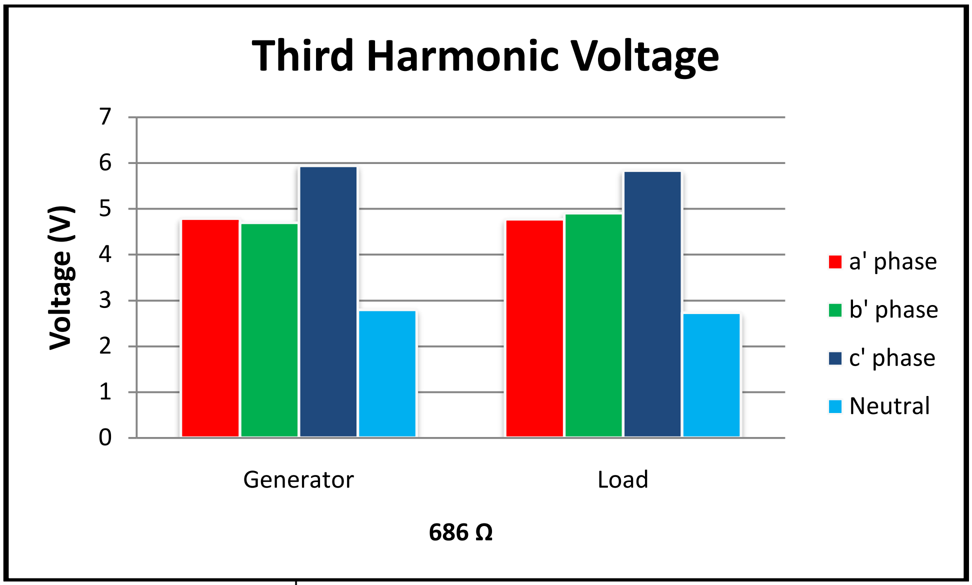


Figure 18: 3rd Harmonic Voltage for Balanced R (686Ω)

The third harmonic current in Figure 22 is lower compared to the third harmonic current when the generator directly connected to the load in Figure 19.

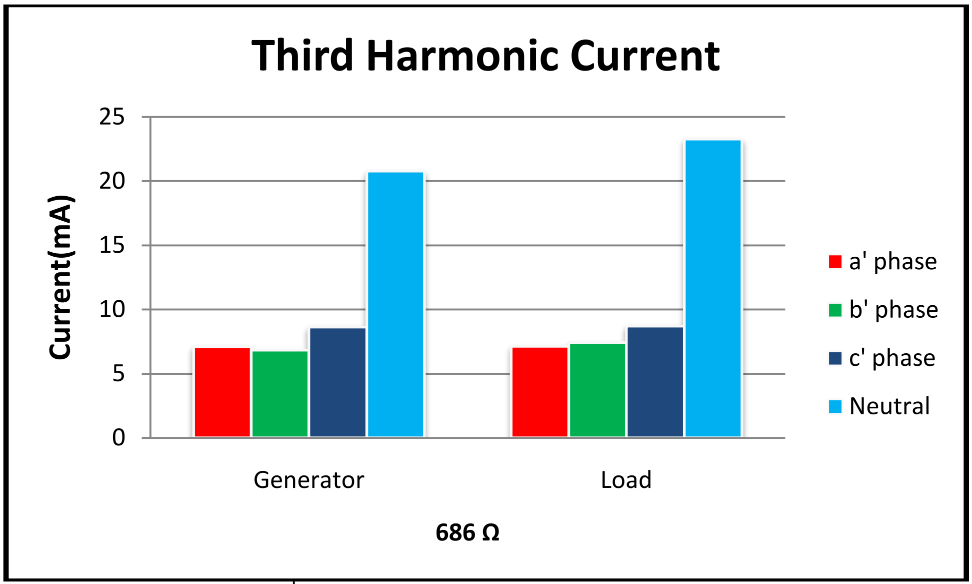


Figure 19: 3rd Harmonic Current for Balanced R (686 Ω)

4.1.2 Balanced resistive load with capacitor

The third harmonic voltage in Figure 20 has almost same magnitude at all terminals as all the terminals are in parallel. In Figure 21, the phase angle for all the terminals are almost the same. Other data can be referred in Appendix A.

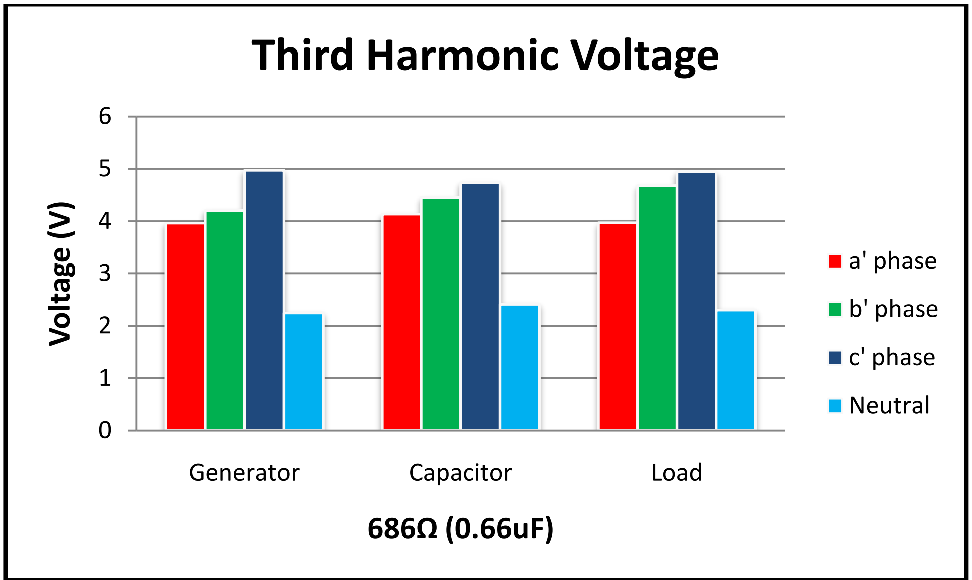


Figure 20: 3rd Harmonic Voltage for Balanced R (686 Ω) with C (0.66uF)

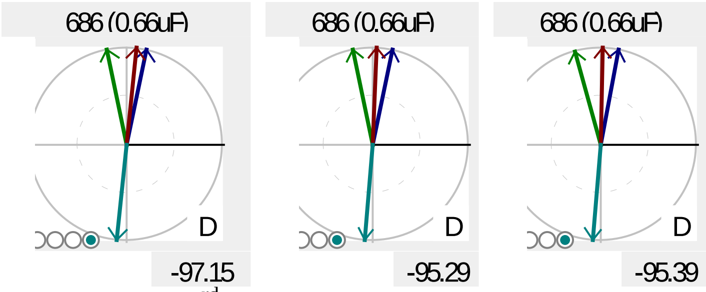


Figure 21: Phasor diagram 3rd Harmonic Voltage for Balanced R (686 Ω) with C (0.66uF)

From Figure 22, there is third harmonics current flow through the capacitor. At all the three points, the phase currents magnitude and phase angles are the almost the same. So, they add at the neutral become three times than the phase currents. Figure 23 is the phasor diagram for each terminal.

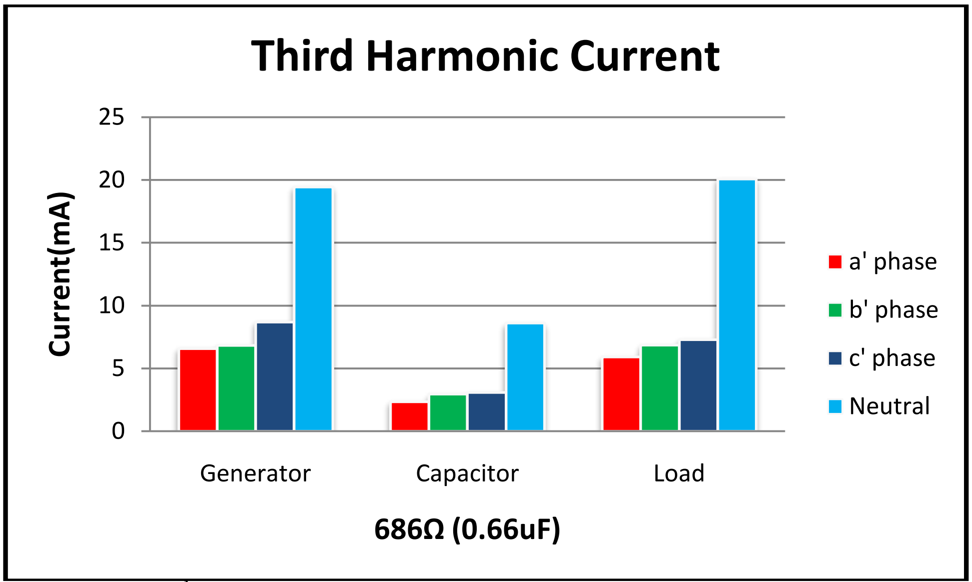


Figure 22: 3rd Harmonic Current for Balanced R (686 Ω) with C (0.66uF)

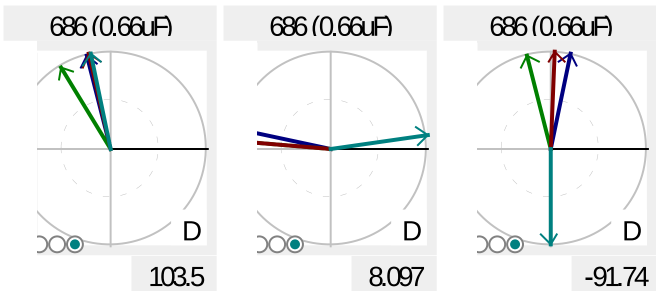


Figure 23: Phasor diagram 3rd Harmonic Current for Balanced R (686 Ω) with C (0.66uF)

4.1.3 Increasing capacitor value with fixed load

The capacitor is representing the cable capacitance in the real case. The capacitor value was increased to observe the effect of cable length towards the third harmonics current when the balanced load is fixed. The data collected at three points which are generator, capacitor and load.

At the generator terminal, the third harmonic current increase as the capacitor value increased as in Figure 24. From Figure 25, as the capacitor value increased, the current value also increased. The neutral current is three times than the phase currents. The higher capacitor value, the higher current is allowed to flow through it. Figure 26 show that the third harmonic current is dependent on the capacitor value.

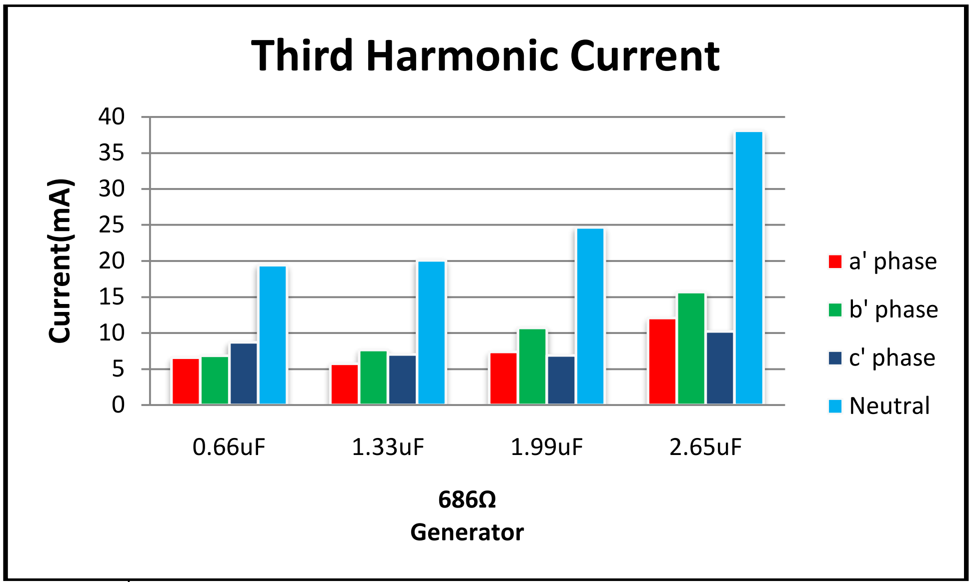


Figure 24: 3rd Harmonic Current increasing C with load fixed (686 Ω) at generator

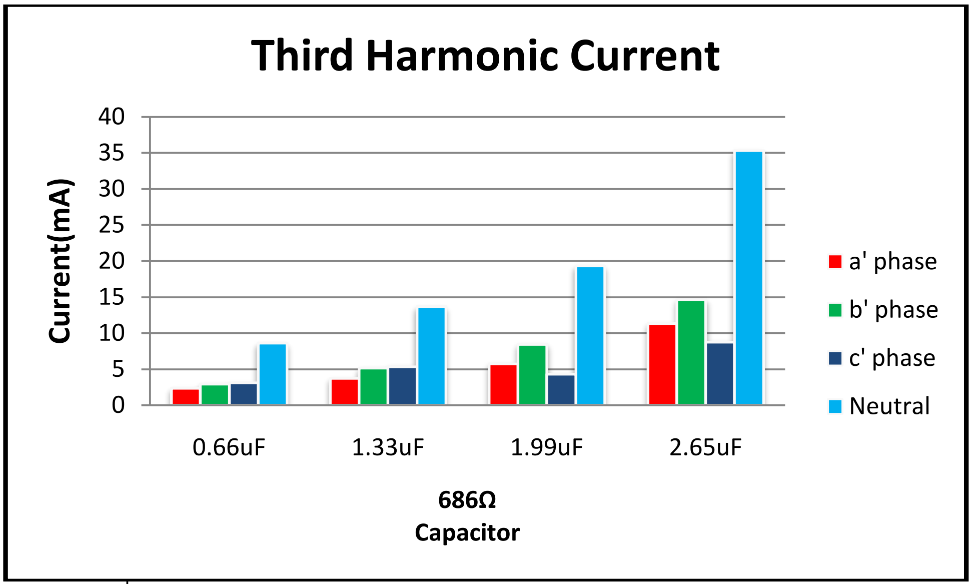


Figure 25: 3rd Harmonic Current increasing C with load fixed (686 Ω) at Capacitor

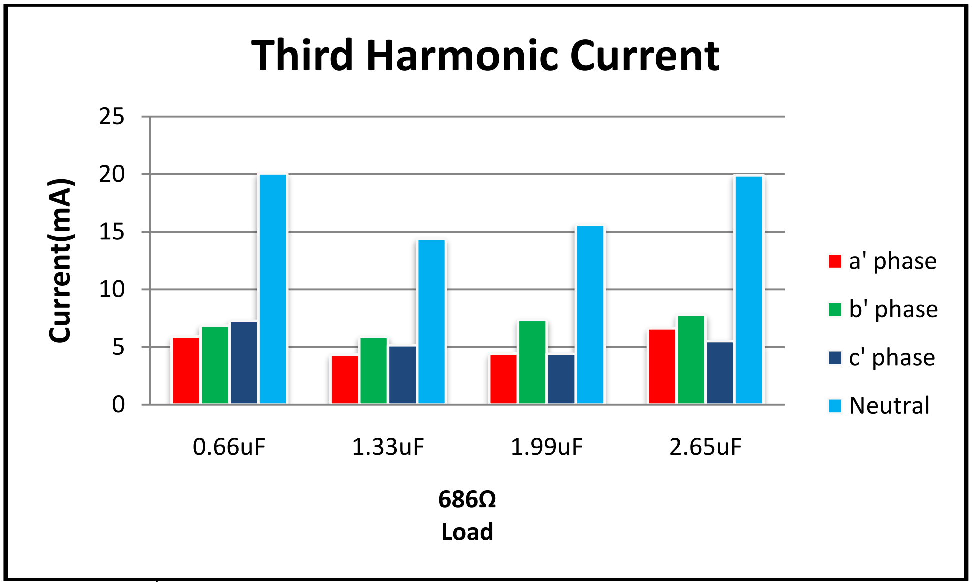


Figure 26: 3rd Harmonic Current increasing C with load fixed (686 Ω) at Load

4.1.4 Increasing load with fixed capacitor

During the experiment, the load is increased with the capacitor value is fixed to investigate the effect of varying load impedance towards third harmonics current behaviour. The load impedance varied between 686 ohm and 880 ohm.

In Figure 28, the third harmonic current at the capacitor terminal is not affected by the load impedance value. The capacitor current is almost the same for all load impedance. The neutral currents still three times than the phase currents but they are almost the same for every load impedance.

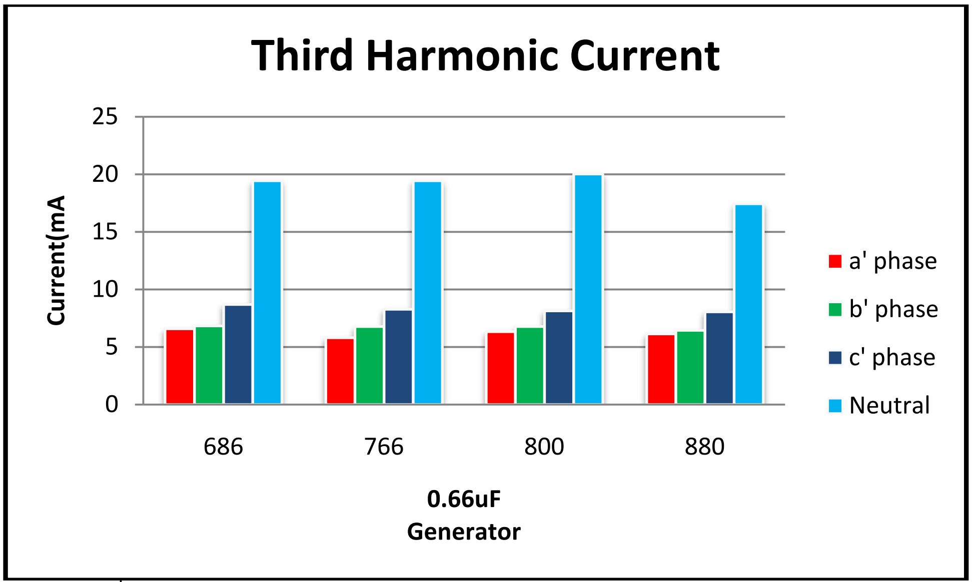


Figure 27: 3rd Harmonic Current increasing load with C fixed (0.66uF) at Generator

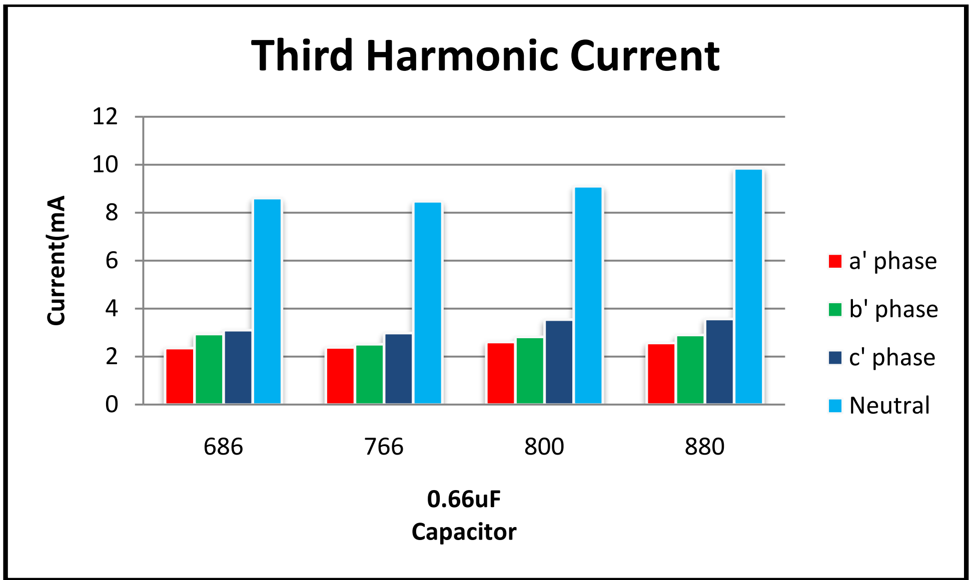


Figure 28: 3rd Harmonic Current increasing load with C fixed (0.66uF) at Capacitor

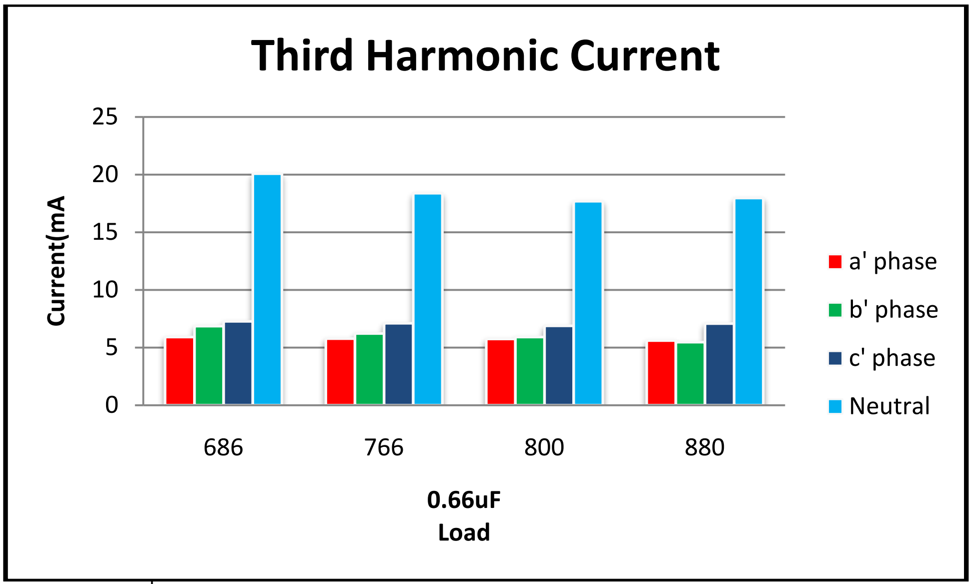


Figure 29: 3rd Harmonic Current increasing load with C fixed (0.66uF) at Load

4.2 Single generator with balanced inductive load

4.2.1 Balanced inductive load

The third harmonic voltage for a network without capacitor as in Figure 30 has almost same voltage with the network with the presence of capacitor. The third harmonic current at the generator and load are same when there is no capacitor between them as in Figure 31.

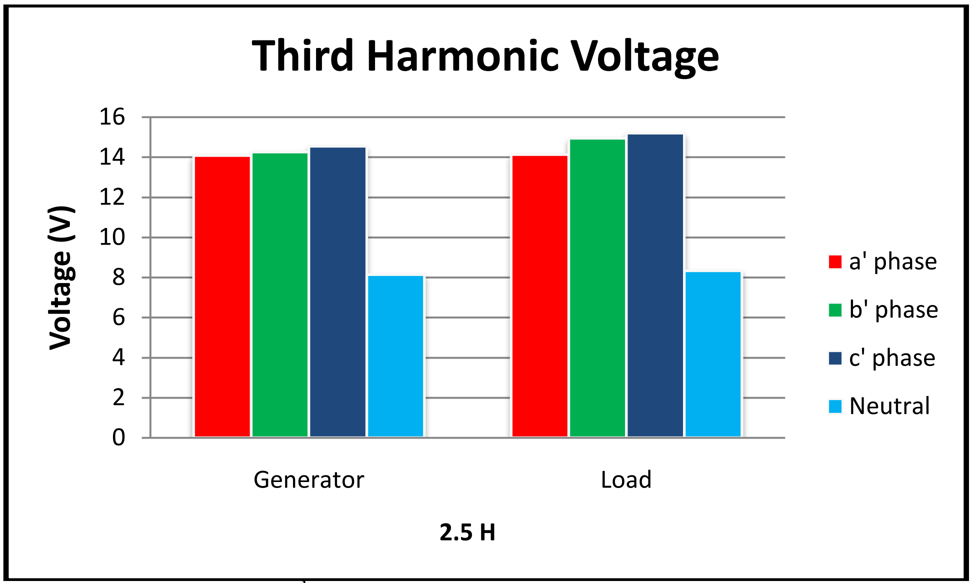


Figure 30: 3rd Harmonic Voltage for balanced L (2.5H)

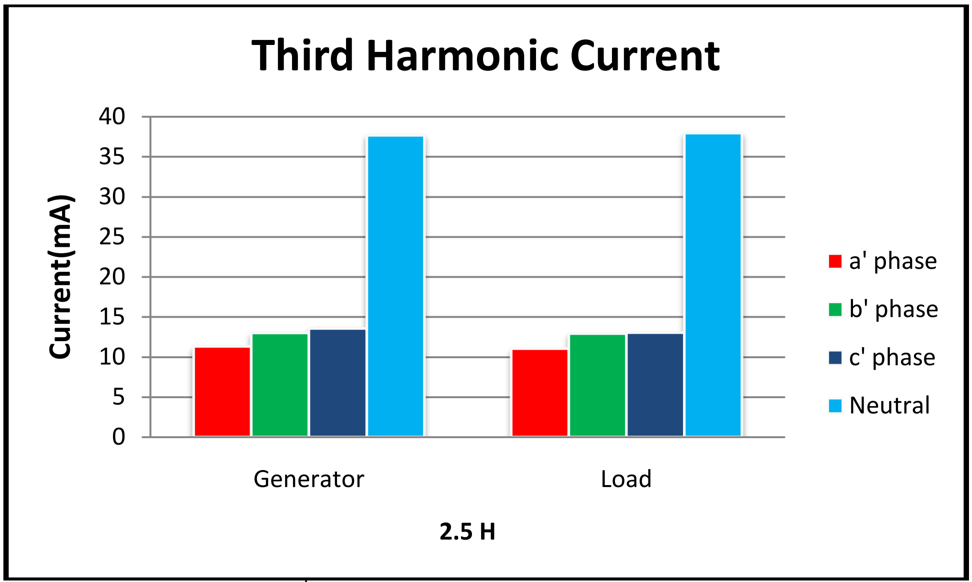


Figure 31: 3rd Harmonic Current for balanced L (2.5H)

4.2.2 Balanced inductive load with capacitor

From Figure 32, the third harmonics voltage magnitude for every point is almost the same. The voltage angles are also almost the same for the all points. The phasor diagram as in Figure 33 for all terminals are almost at the same angle.

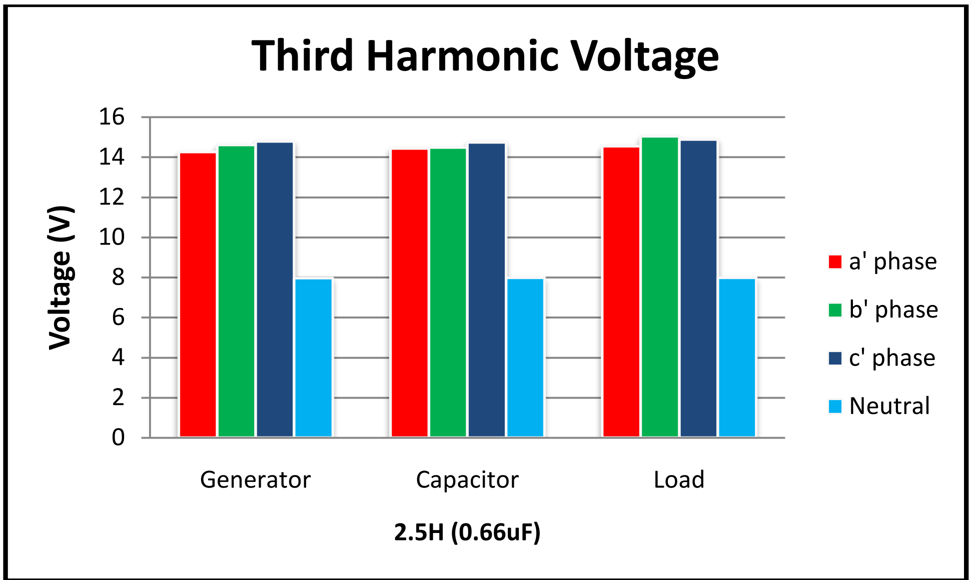


Figure 32: 3rd Harmonic Voltage for balanced L (2.5H) with C (0.66uF)

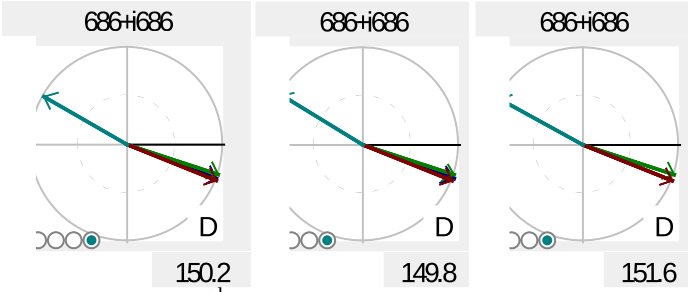


Figure 33: Phasor diagram 3rd Harmonic Voltage for balanced L (2.5H) with C (0.66uF)

From Figure 34, the neutral currents at all points are three times than the phase currents. The phase currents have same magnitude and angle. Thus, added at the neutral to become three times than the phase currents. Figure 35 is the phasor angle for third harmonic current at all terminals. Other data can be referred in Appendix B.

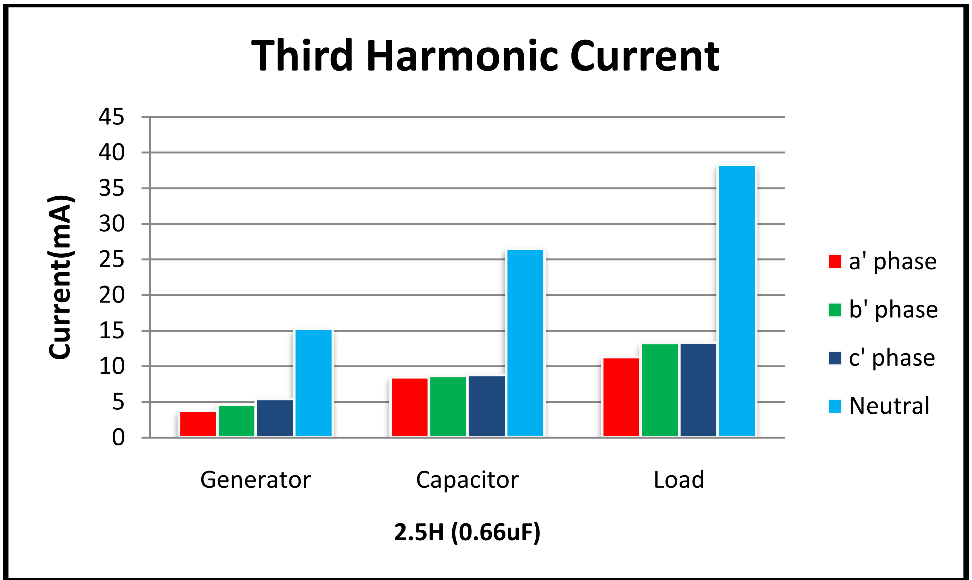


Figure 34: 3rd Harmonic Current for balanced L (2.5H) with C (0.66uF)

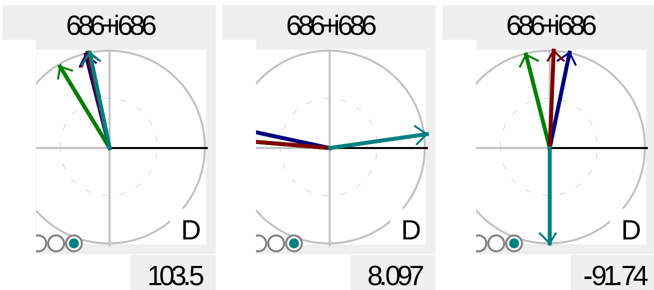


Figure 35: Phasor diagram 3rd Harmonic Current for balanced L (2.5H) with C (0.66uF)

4.2.3 Increasing capacitor value with fixed load

During the experiment, the capacitor value is increasing gradually from 0.66uF to 2.65uF while maintaining the load impedance at 2.5 H. The data collected at three points which are generator, capacitor and load.

From Figure 37, as the capacitor value increased, the current value also increased. The higher the capacitor value, the higher the current flow through the capacitor as the reactance become smaller. The third harmonics current measured at load are almost same for all capacitor value.

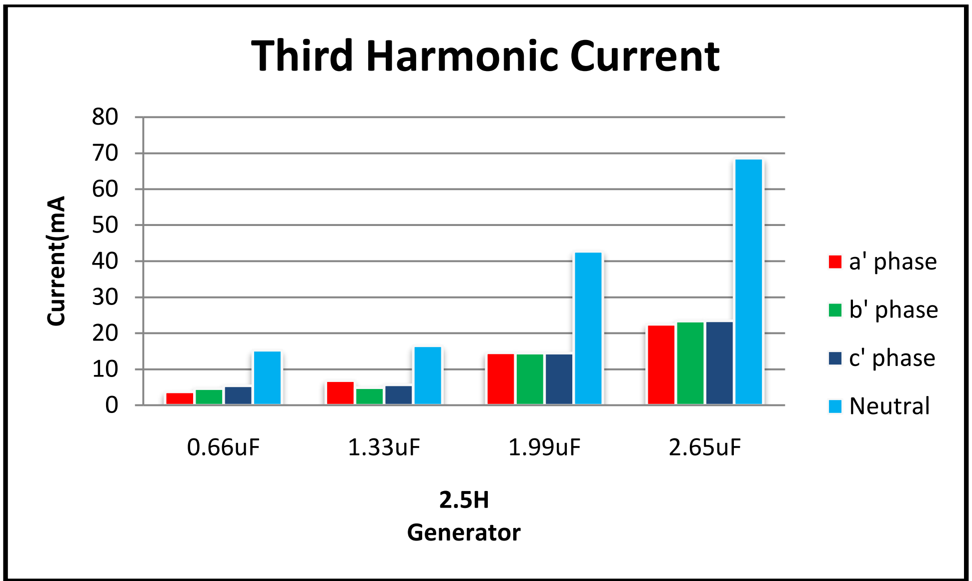


Figure 36: 3rd Harmonic Current increasing C with inductive load fixed (2.5H) at generator

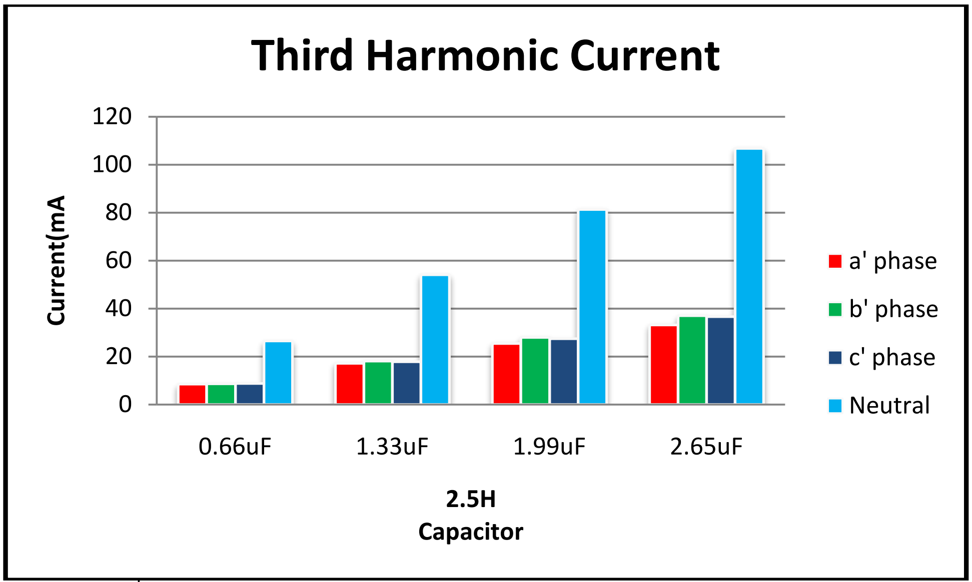


Figure 37: 3rd Harmonic Current increasing C with inductive load fixed (2.5H) at capacitor

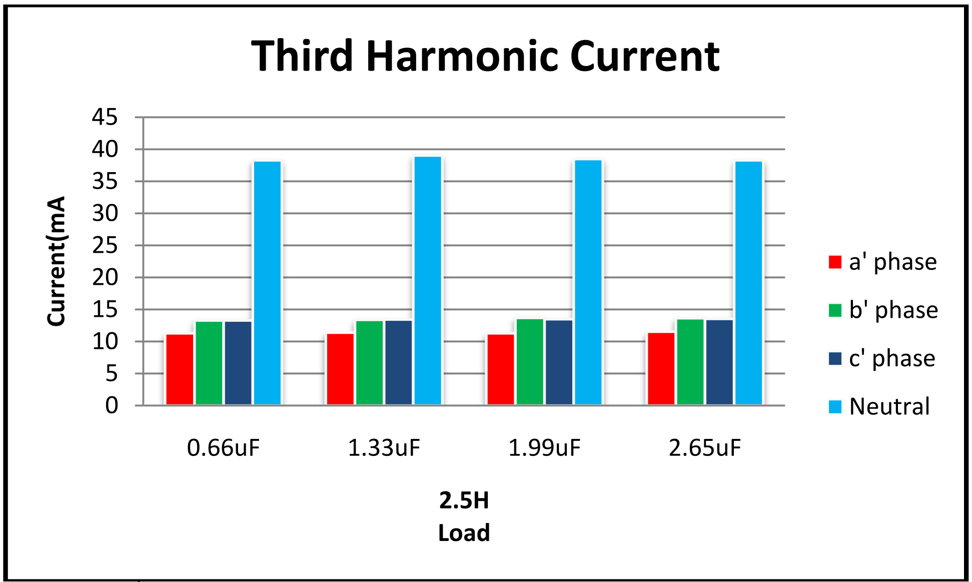


Figure 38: 3rd Harmonic Current increasing C with inductive load fixed (2.5H) at load

4.2.4 Increasing load with fixed capacitor

From Figure 40, the third harmonics current at capacitor terminal is almost the same for all load impedance. The third harmonics currents at the capacitor are not influenced by the load impedance. The third harmonics current at the load decreased as the load impedance are increased.

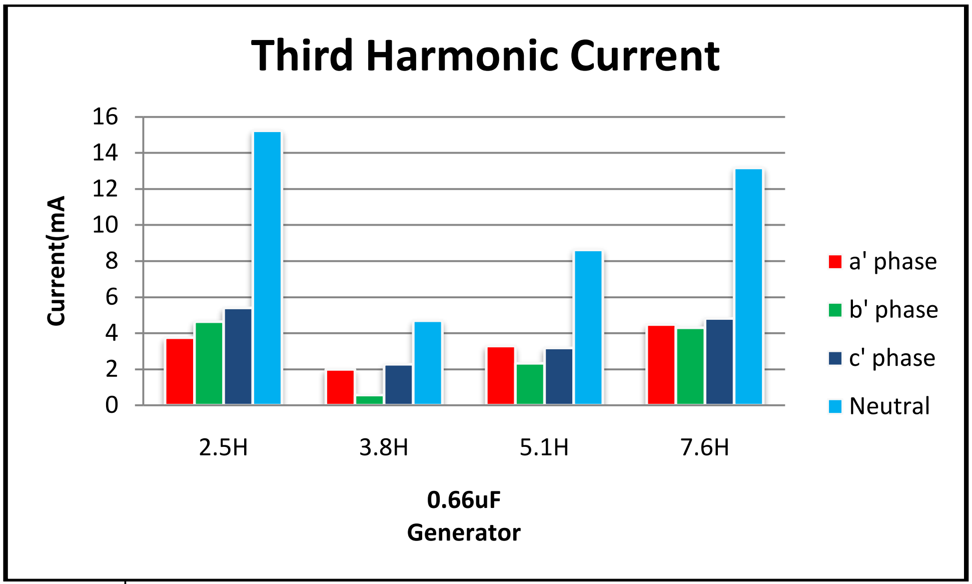


Figure 39: 3rd Harmonic Current increasing inductive load with C fixed (0.66uF) at generator

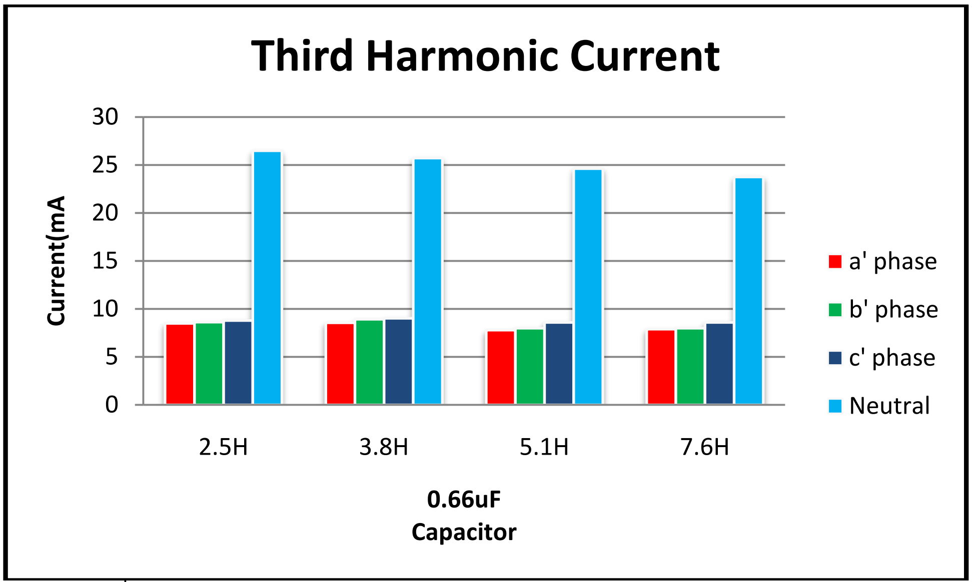


Figure 40: 3rd Harmonic Current increasing inductive load with C fixed (0.66uF) at Capacitor

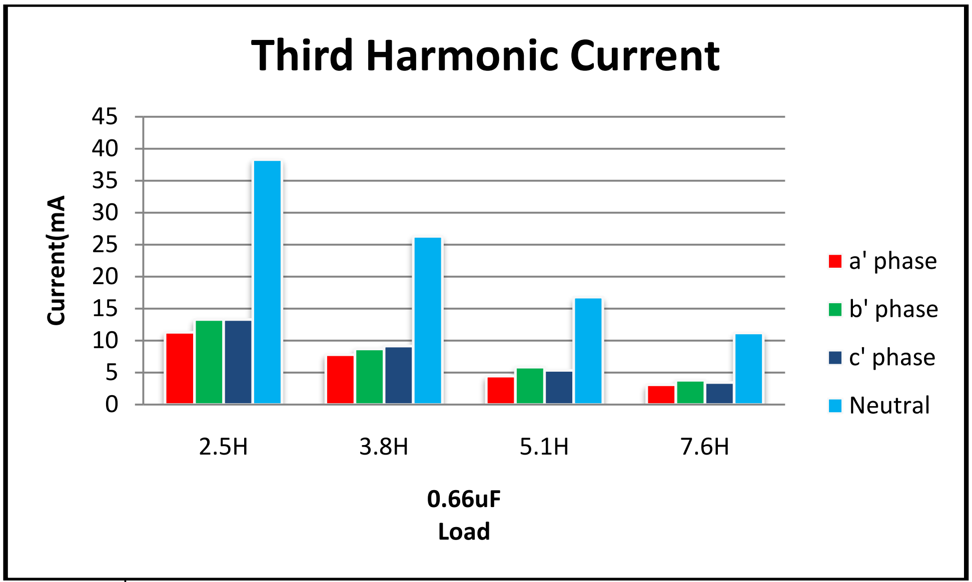


Figure 41: 3rd Harmonic Current increasing inductive load with C fixed (0.66uF) at load

4.3 Single generator combined balanced resistive and inductive load

4.3.1 Balanced resistive and inductive load with capacitor

The third harmonic voltages for all terminals are same as all terminals are in parallel. Figure 42 show third harmonic voltage at generator, capacitor and load terminals. The phasor angle for third harmonic voltage at phase is almost same at all terminals while neutral angle is opposite of phase angles as shown in Figure 43.

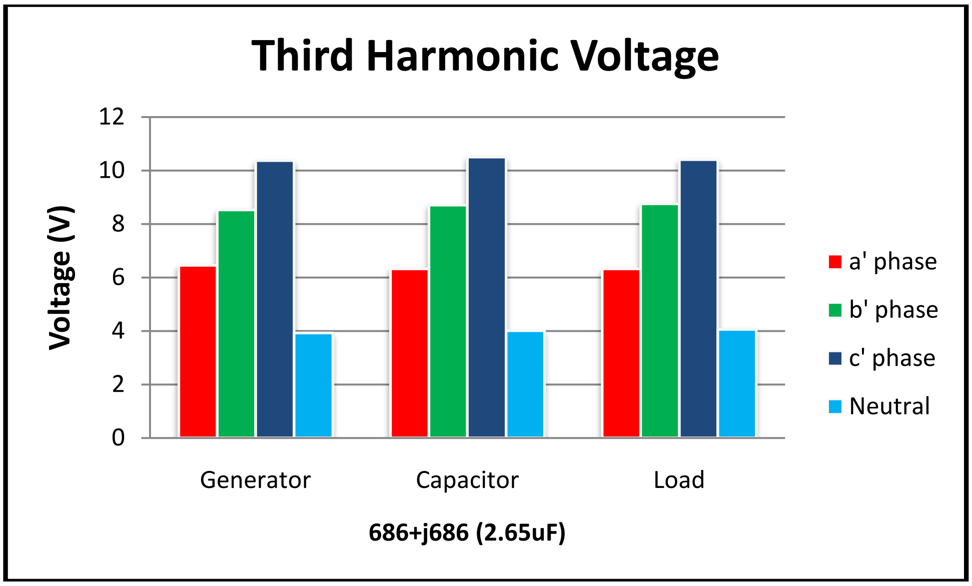


Figure 42: 3rd harmonic voltage for balanced R+L (686 Ω +j686 Ω) with C (0.66uF)

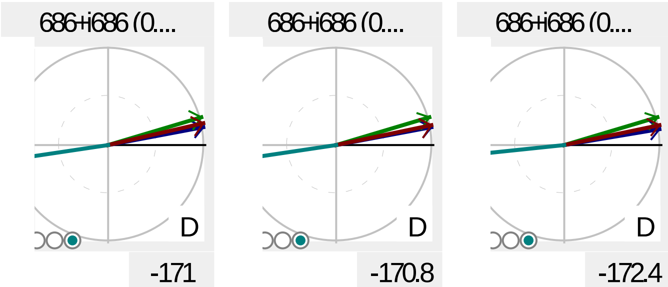


Figure 43: 3rd harmonic voltage angle for balanced R+L (686 Ω +j686 Ω) with C (0.66uF)

The third harmonic neutral current increased by about three times of the phase current as shown in Figure 44. The phasor angle for third harmonic current at phase is almost same at all terminals while neutral angle is opposite of phase angles as shown in Figure 45. The third harmonic current at generator terminal is the vector sum of third harmonic current flow through capacitor and load. Other results are put in the Appendix C as they have the same characteristic as presented here.

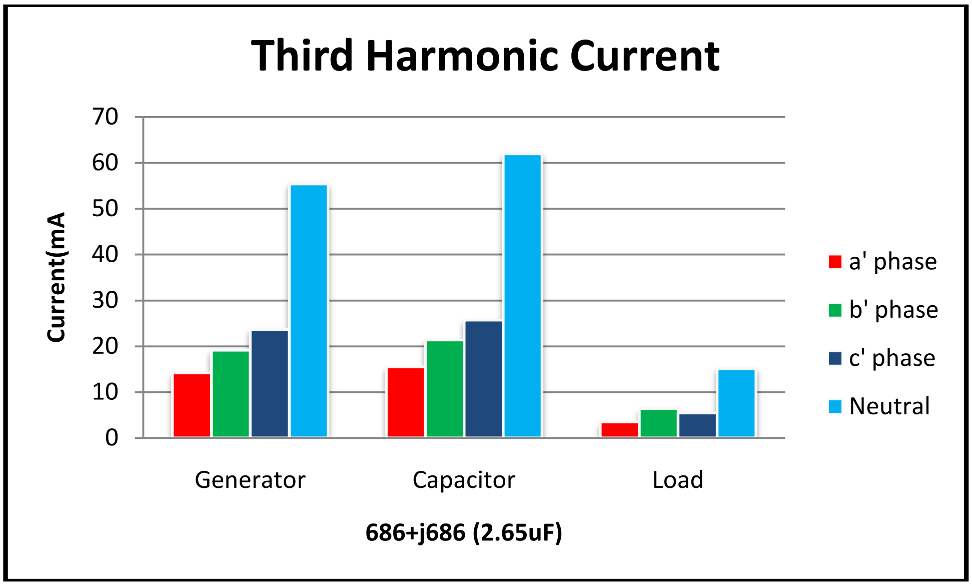


Figure 44: 3rd harmonic current for balanced R+L (686 Ω +j686 Ω) with C (0.66uF)

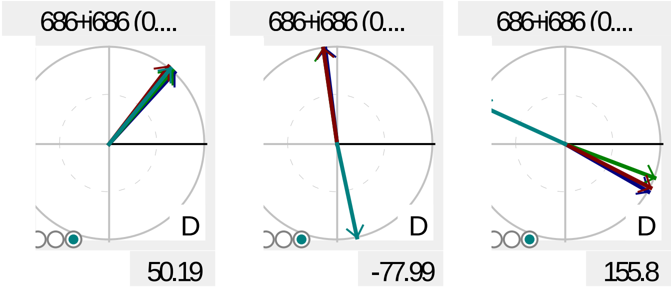


Figure 45: 3rd harmonic current angle for balanced R+L (686 Ω +j686 Ω) with C (0.66uF)

4.3.2 Increasing capacitor value with fixed load

When single generator is connected to balanced resistive and inductive load with capacitor, the data was collected at three different measurement points. The purpose of collecting data at three different points is to see how capacitor affects the triplen harmonics behaviour in a power system when the capacitor value is increased.

From Figure 47, we can observe that the magnitude of triplen harmonics at capacitor side increasing when the capacitor value is increased. As the capacitor value increase, the reactance (X_c) value will decrease. Thus, more current will flow through the capacitor. From Figure 48, the triplen harmonic current measured at the load decreased when the capacitor is increased. As reactance (X_c) value decreased, more current will flow through capacitor than flow through the load.

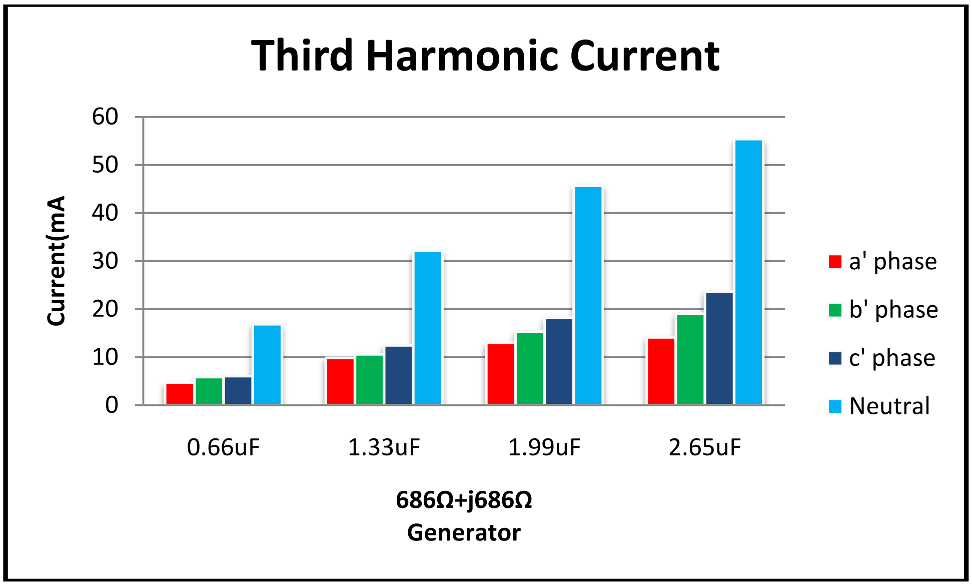


Figure 46: 3rd harmonic current measured at generator by increasing capacitor with fixed load

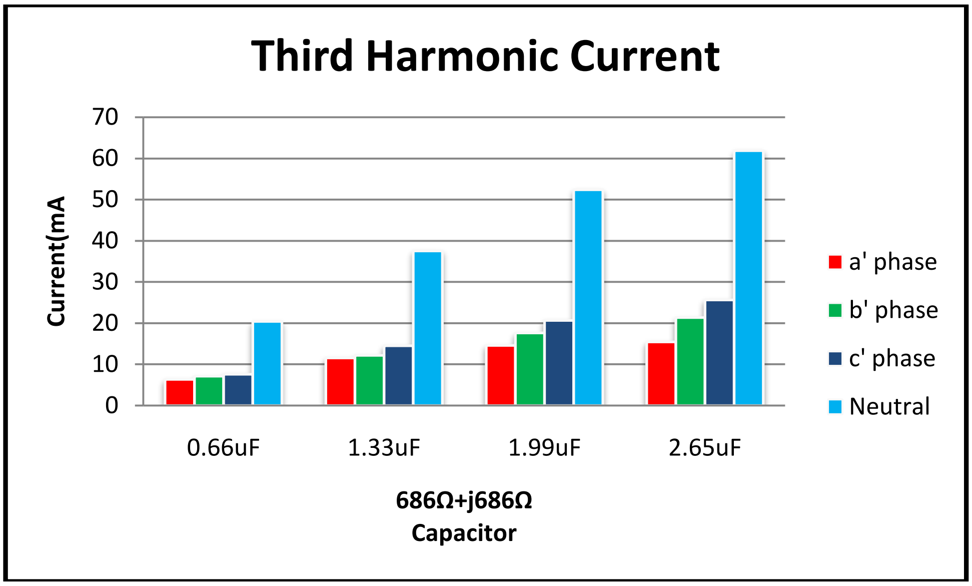


Figure 47: 3rd harmonic current measured at load by increasing capacitor with fixed load

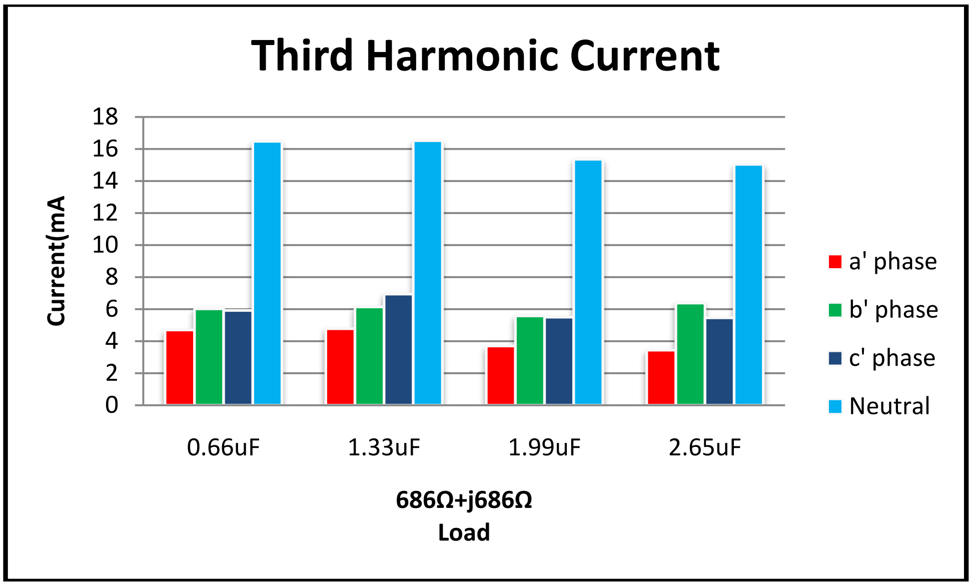


Figure 48: 3rd harmonic current measured at capacitor by increasing capacitor with fixed load

4.3.3 Varying load impedance magnitude with fixed load angle

The third harmonic voltage magnitude at generator, capacitor and load terminals are proportional to the load impedance magnitude as shown in Figure 49, 50 and 51 for 1.33µF cable capacitance. The bigger the load impedance phase angle magnitude, the bigger the voltage magnitude.

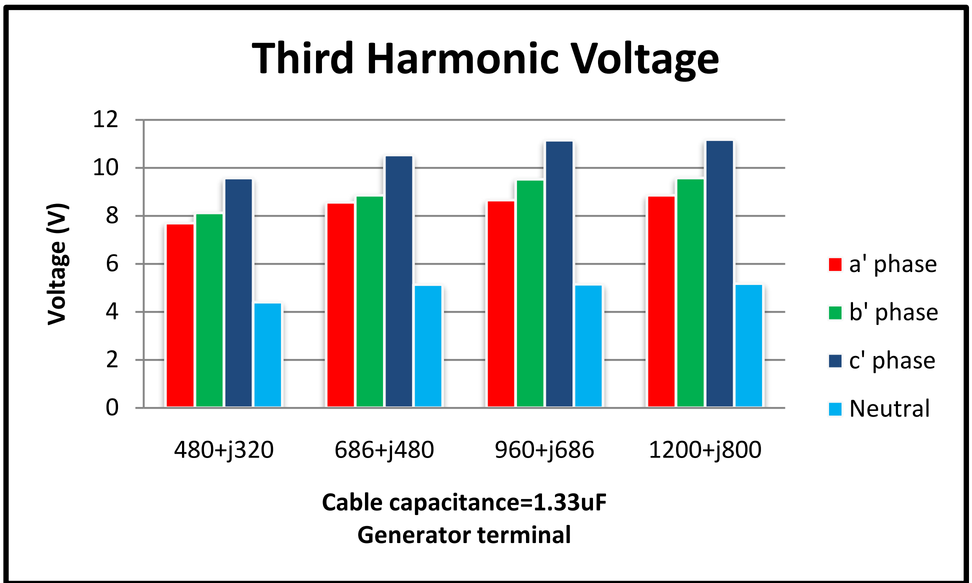


Figure 49: 3rd harmonic voltage at generator terminal for varying load impedance magnitude with fixed load angle

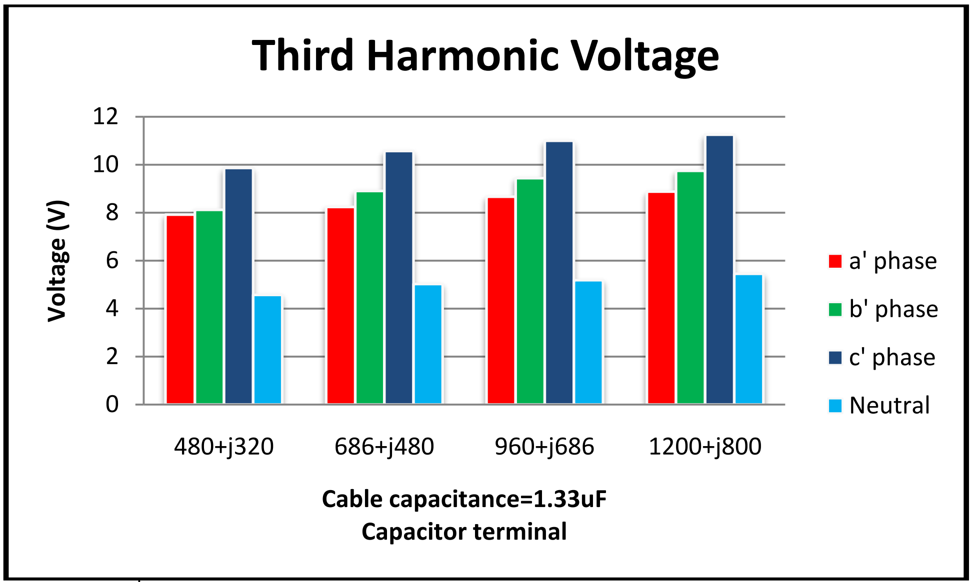


Figure 50: 3rd harmonic voltage at capacitor terminal for varying load impedance magnitude with fixed load angle

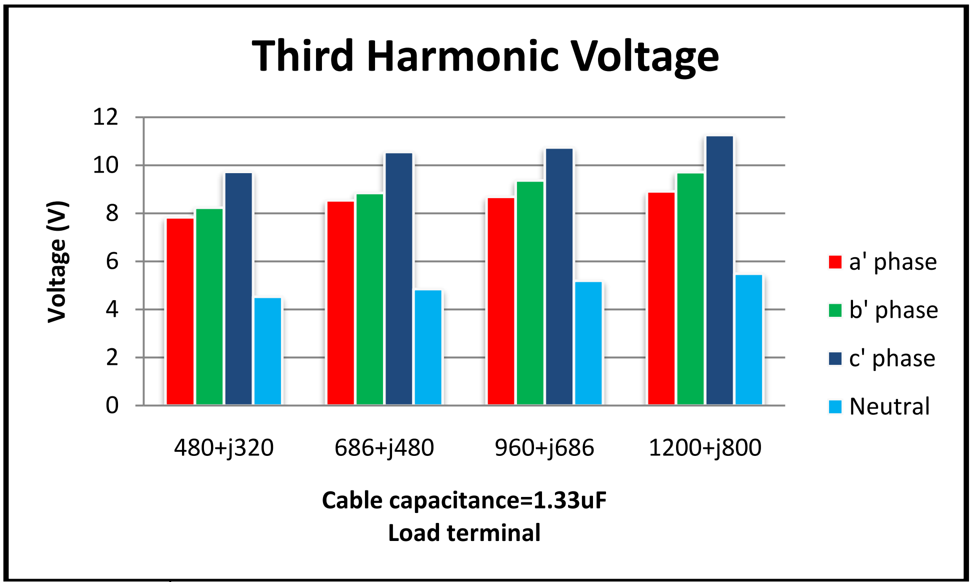


Figure 51: 3rd harmonic voltage at load terminal for varying load impedance magnitude with fixed load angle

The third harmonic current magnitude at generator terminal is the vector sum of third harmonic current flowing through capacitor and load. Therefore, the magnitude of third harmonic current at generator terminal depends on combined impedance of capacitor and load. Regardless of cable capacitance values, the magnitude of third harmonic current at cable capacitor terminal is proportional to the load impedance magnitude. Figure 52, 53 and 54 show the third harmonic current magnitude at generator, cable capacitor and load terminals for 1.33μF cable capacitance.

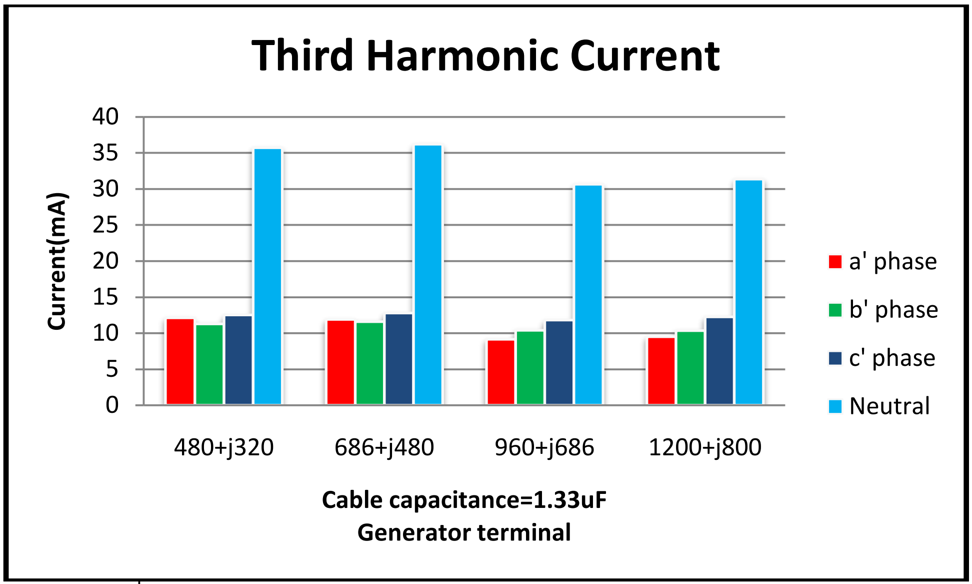


Figure 52: 3rd harmonic current at generator terminal for varying load impedance magnitude with fixed load angle

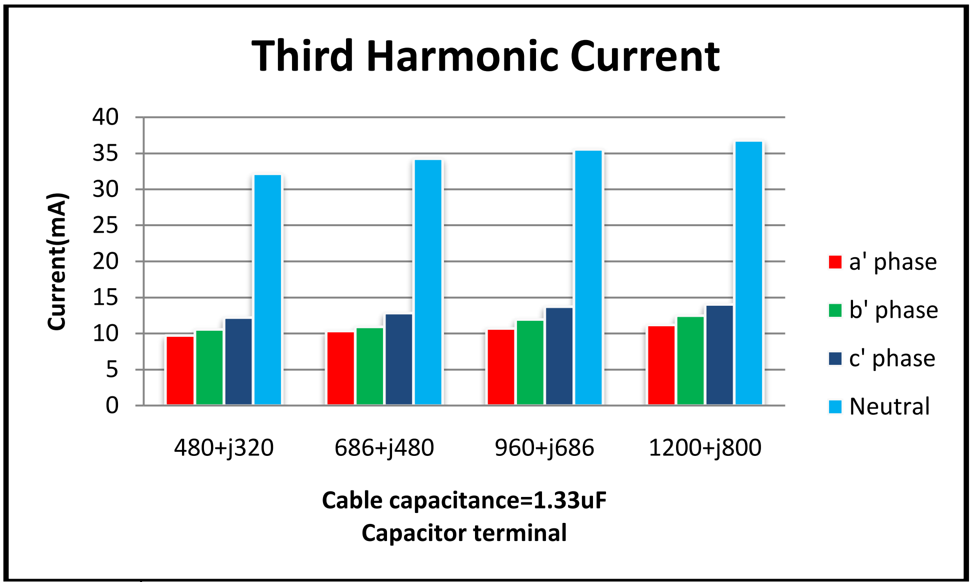


Figure 53: 3rd harmonic current at capacitor terminal for varying load impedance magnitude with fixed load angle

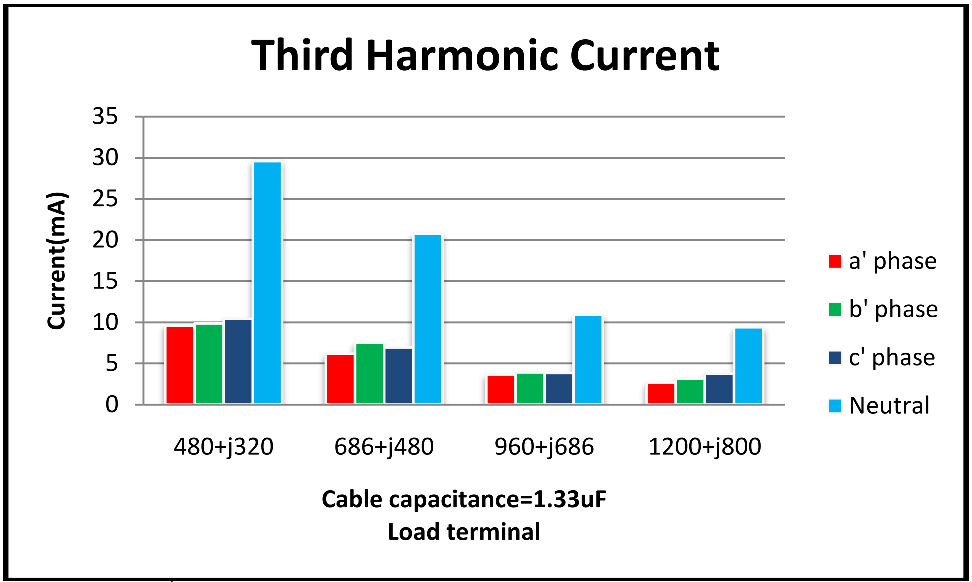
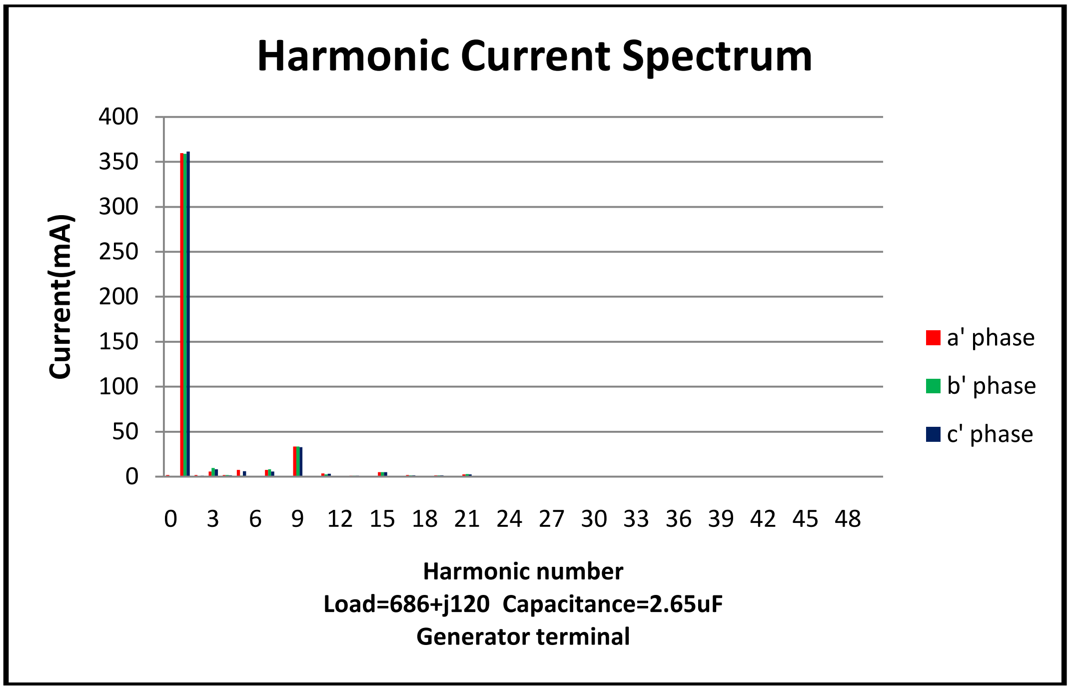
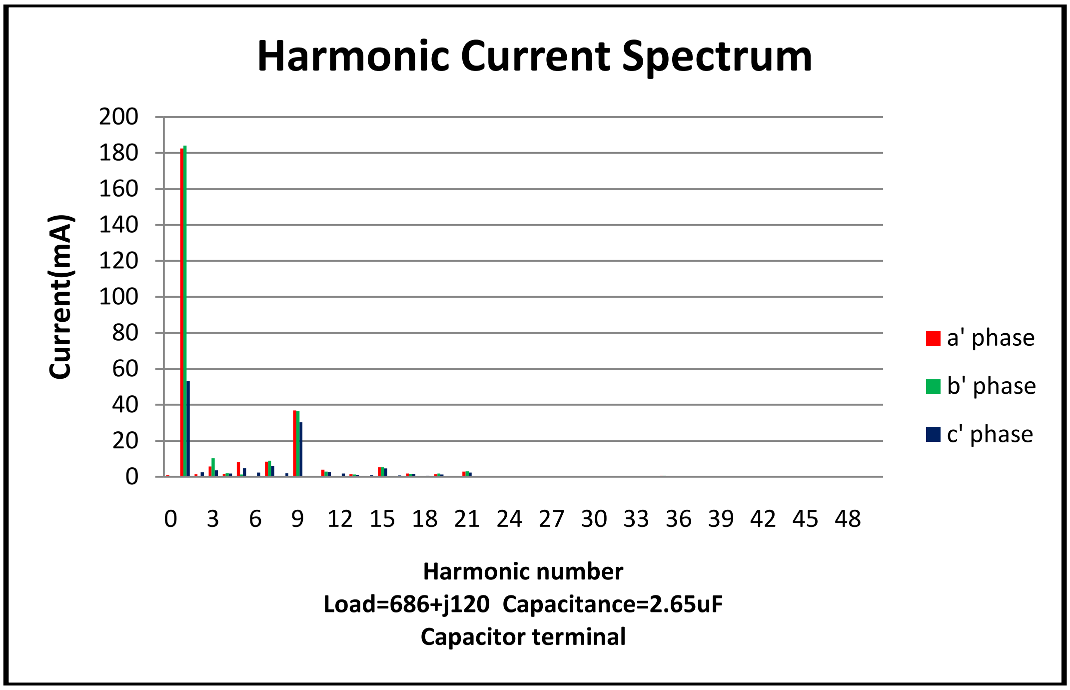


Figure 54: 3^{rd} harmonic current at load terminal for varying load impedance magnitude with fixed load angle

4.3.4 Resonance

The harmonic current spectrum when generator directly connected to a combined resistive and inductive load show that almost no current at other harmonic number except third harmonic. Harmonic series resonance is observed at 9^{th} and 15^{th} harmonic number as shown in Figure 55 and 56 respectively. Resonance at 9^{th} harmonic number occurred at higher capacitor value while resonance at 15^{th} harmonic number detected at lower capacitor value.


Harmonic Current Spectrum
Current(mA)
400
350
300
250
200
150
100
50
0
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48
a' phase
b' phase
c' phase
Harmonic number
Load=686+j120 Capacitance=2.65uF
Generator terminal


Harmonic Current Spectrum
Current(mA)
200
180
160
140
120
100
80
60
40
20
0
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48
a' phase
b' phase
c' phase
Harmonic number
Load=686+j120 Capacitance=2.65uF
Capacitor terminal

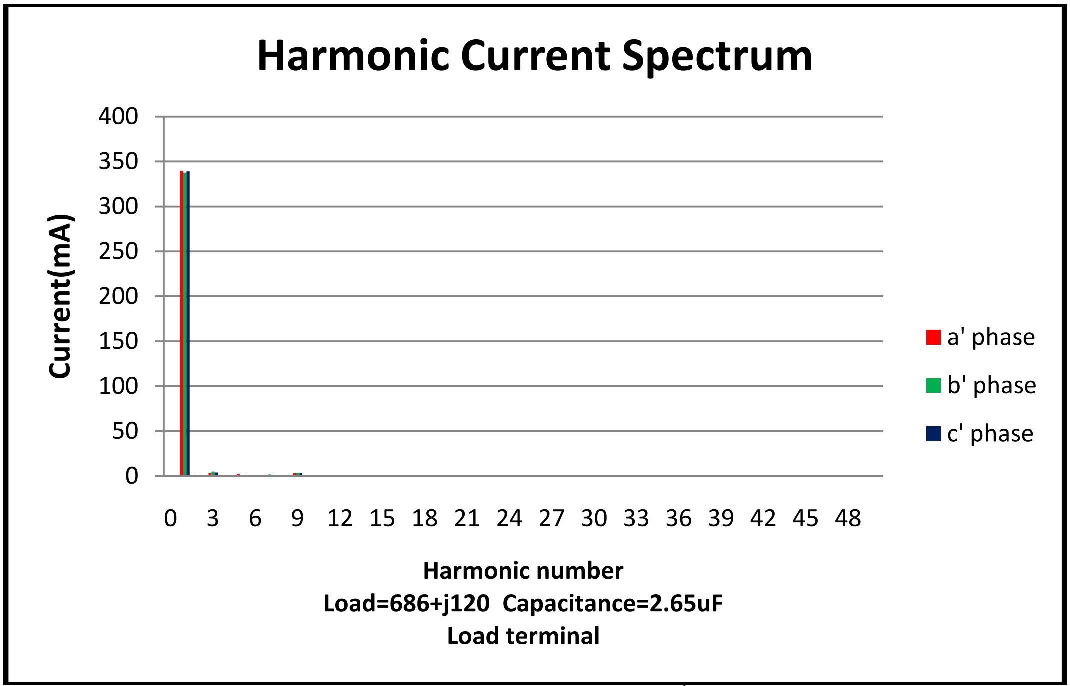
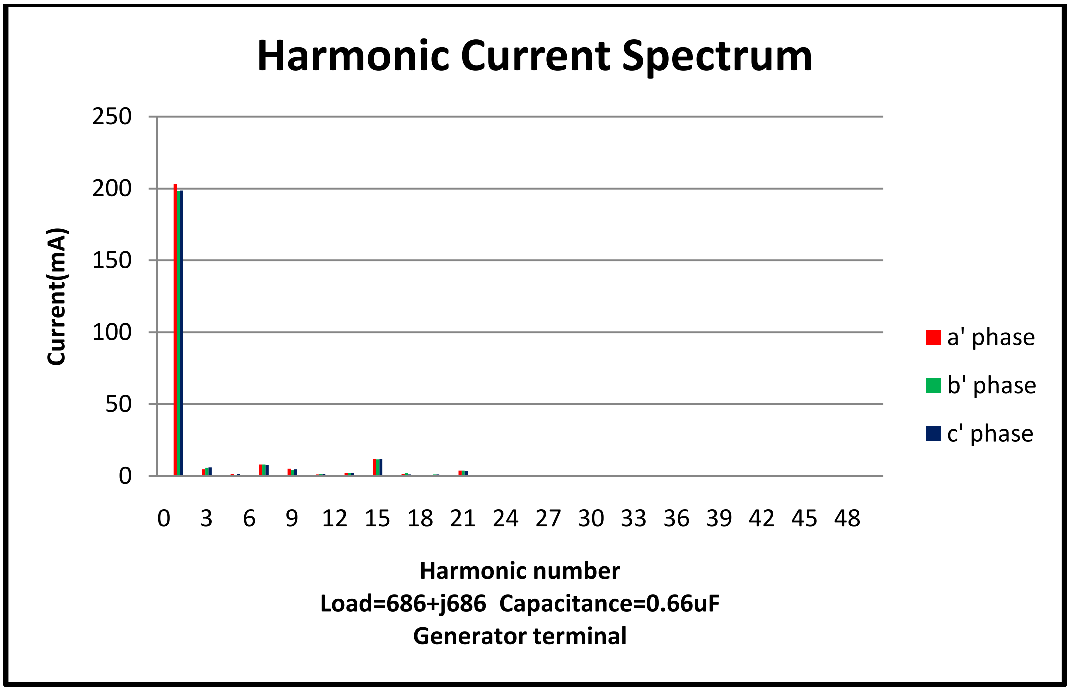
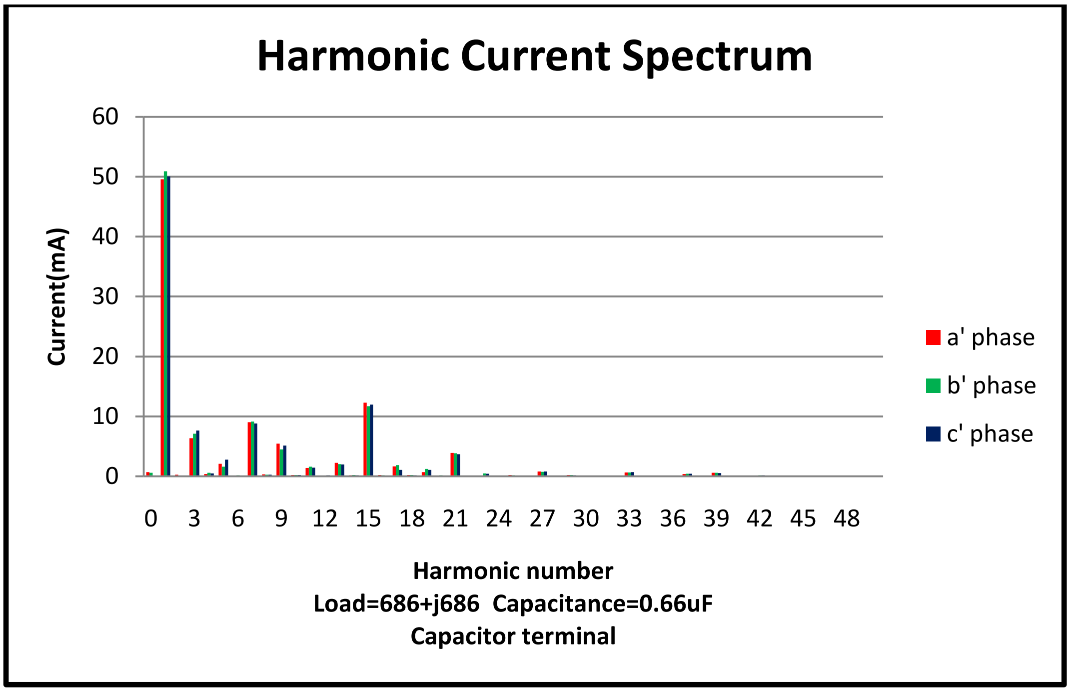


Figure 55: Harmonic current spectrum for 9th harmonic resonance





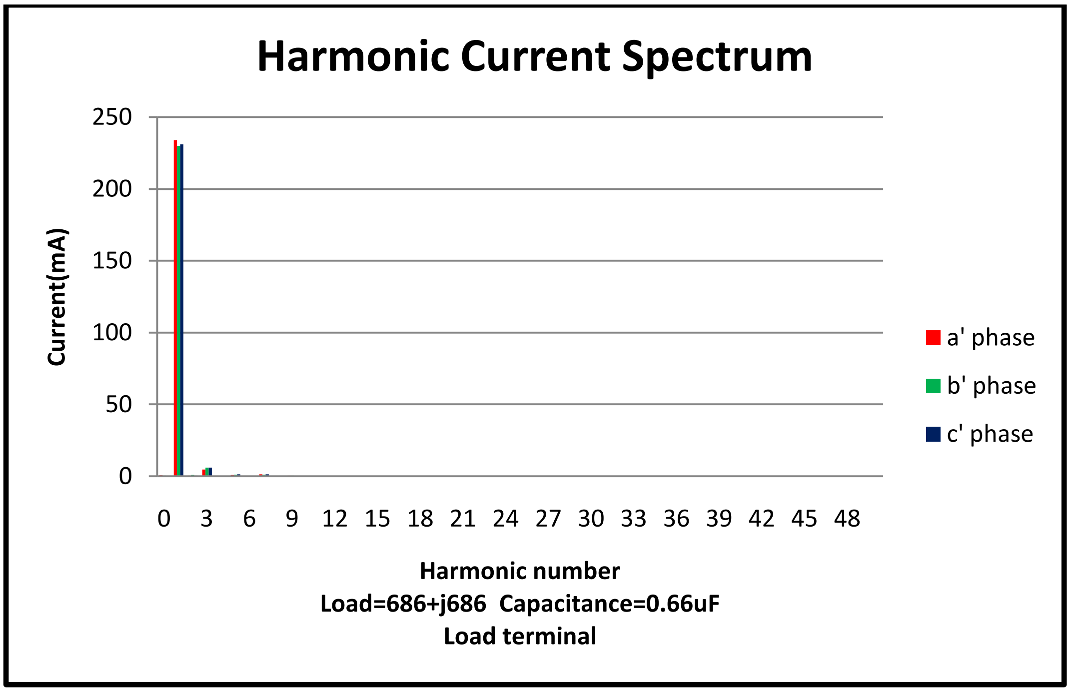


Figure 56: Harmonic current spectrum for 15^{th} harmonic resonance

The resonance occurred only at the generator and capacitor terminals. The resonance occurred at frequency where the inductive reactance and capacitive reactance both have same value but 180° out of phase. It cancels each other and left only the resistive component in the network. Hence, the current increases as the network impedance decrease.

4.4 Single generator parallel with grid connected to combined balanced resistive and inductive load with capacitor

4.4.1 Balanced resistive and inductive load

In parallel lab scaled experiments, the third harmonic voltage and current were taken at eight measuring points. Based on data in Figure 57 and 58, the third harmonic voltage before parallel are higher compared to during parallel at all terminals except at grid terminal.

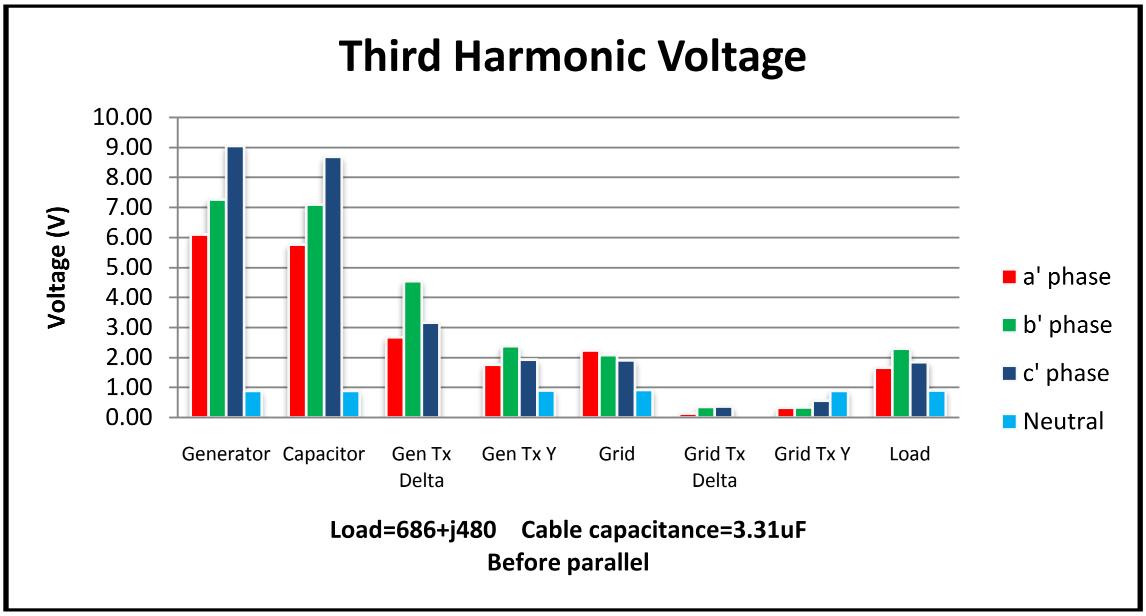


Figure 57: 3rd harmonic voltage before single generator parallel with grid connected to 686 Ω +j480 Ω with 3.31uF

In Figure 58, the third harmonic voltage has same value at all neutral points. The phasor angles for third harmonic voltage are almost in phase at all terminals except at delta winding transformer as shown in Figure 59.

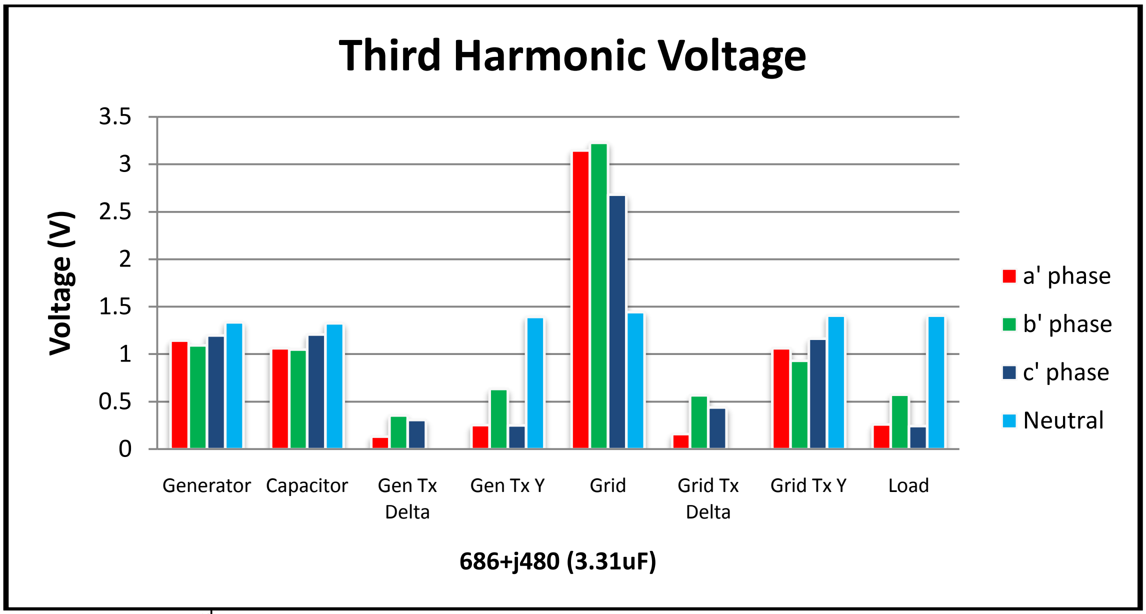


Figure 58: 3rd harmonic voltage single generator parallel with grid connected to 686 Ω +j480 Ω with 3.31uF

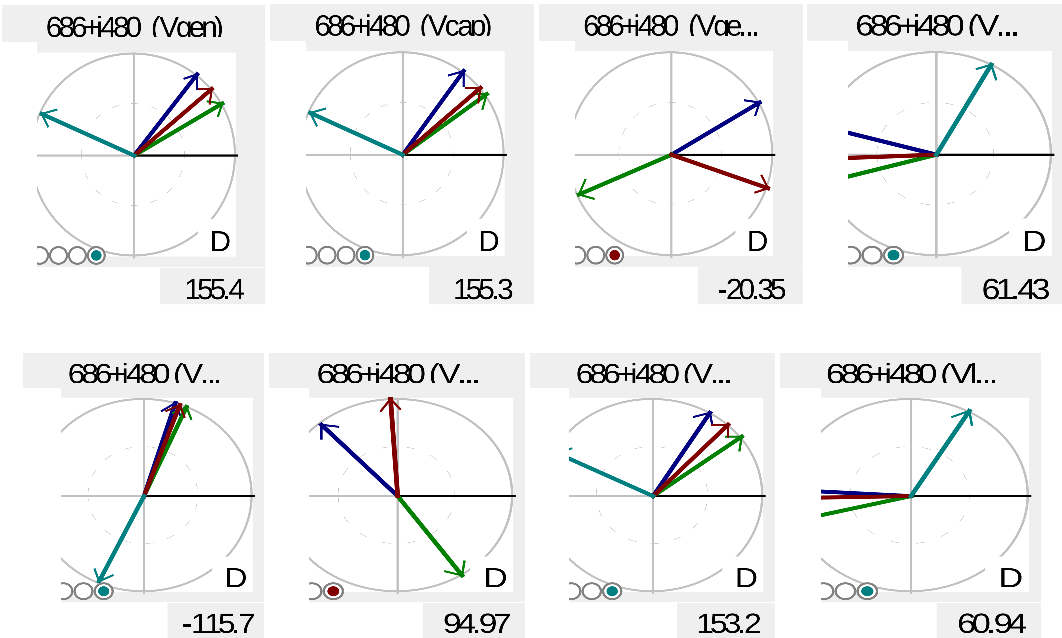


Figure 59: Phasor diagram for 3rd harmonic voltage single generator parallel with grid connected to 686+j480 with 3.31uF

Before parallel, the third harmonic voltage current at generator and capacitor are almost the same as in Figure 60. The capacitor is the only path for third harmonic current to return back to the generator as delta side of the transformer block the third harmonic current path to the load.

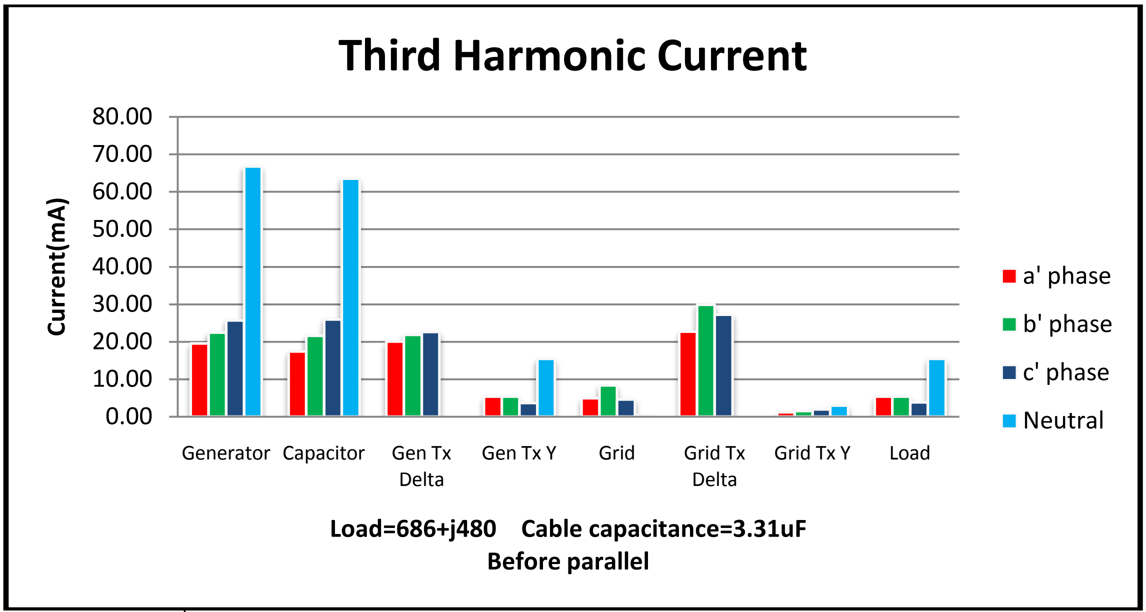


Figure 60: 3rd harmonic current before single generator parallel with grid connected to 686 Ω +j480 Ω with 3.31uF

The third harmonic current during parallel is shown in Figure 61. There is current flow through capacitor back to the generator but most of the current flow through transformer neutral at grid side as the transformer neutral has lower impedance compared to the capacitor. Other data can be referred at Appendix D.

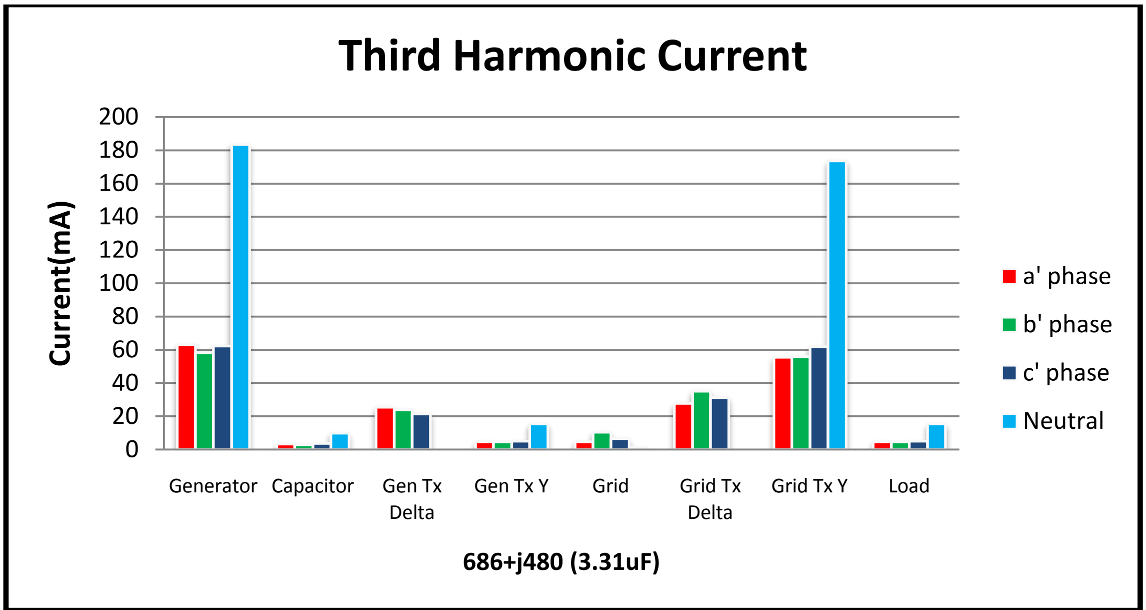


Figure 61: 3rd harmonic current single generator parallel with grid connected to 686 Ω +j480 Ω with 3.31uF

In Figure 62, the phasor angle for third harmonic current at all terminals except at the gird terminal are almost same. Thus, the neutral current is three times than phase current at the terminals.

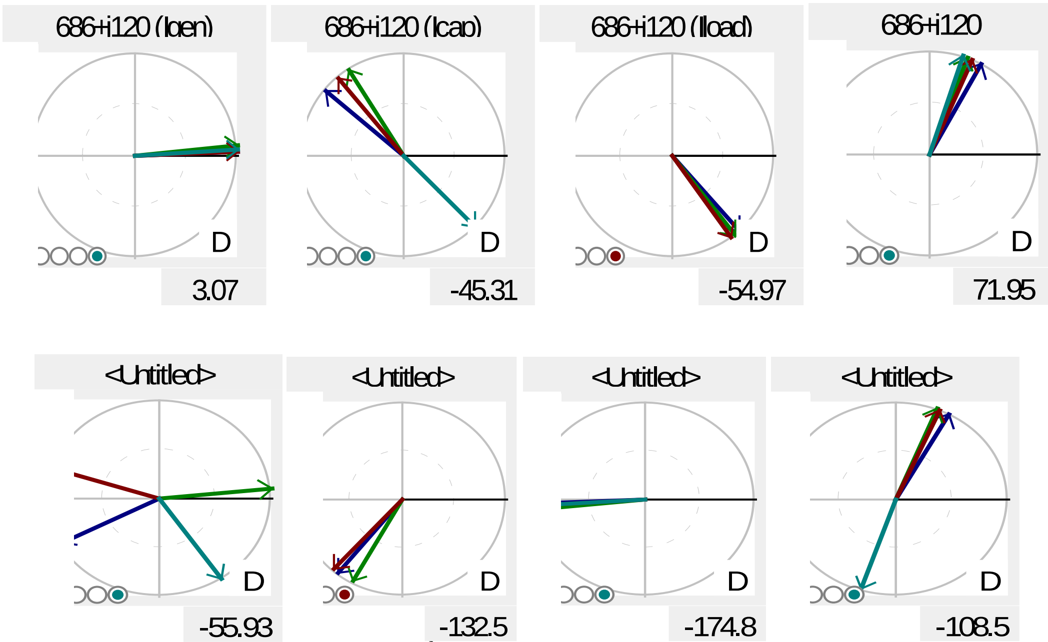


Figure 62: Phasor diagram for 3rd harmonic current single generator parallel with grid connected to 686+j480 with 3.31uF

4.4.2 Increasing capacitor value with fixed load

The third harmonic voltage at capacitor terminal decrease when the capacitor value increase as shown in Figure 63. The third harmonic current at capacitor terminal always increased with increase in capacitor value as shown in Figure 64. Theoretically, when the capacitor value increase the capacitive reactance will decrease. Thus, more current will flow through the capacitor.

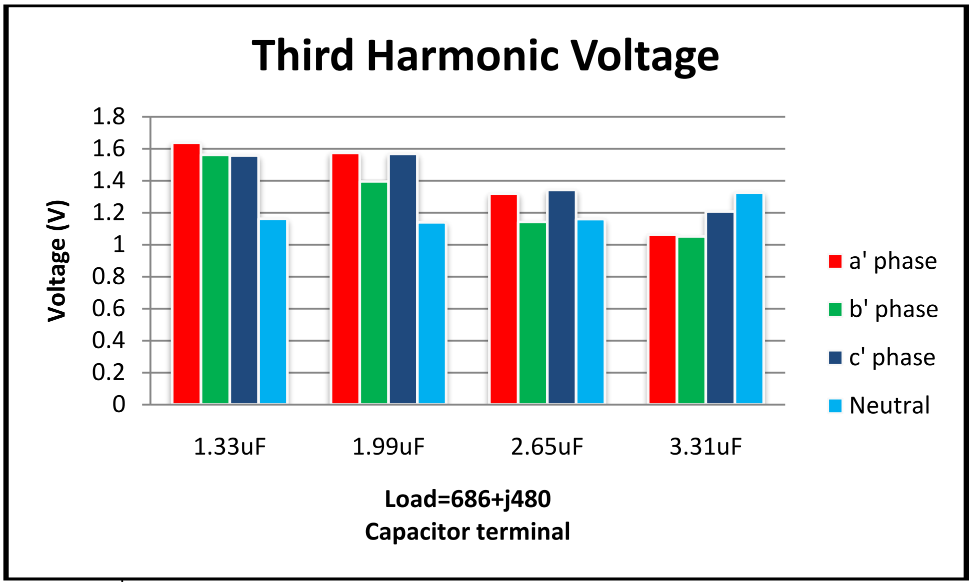


Figure 63: 3rd harmonic voltage at capacitor terminal when single generator parallel with grid increasing capacitor value with fixed load

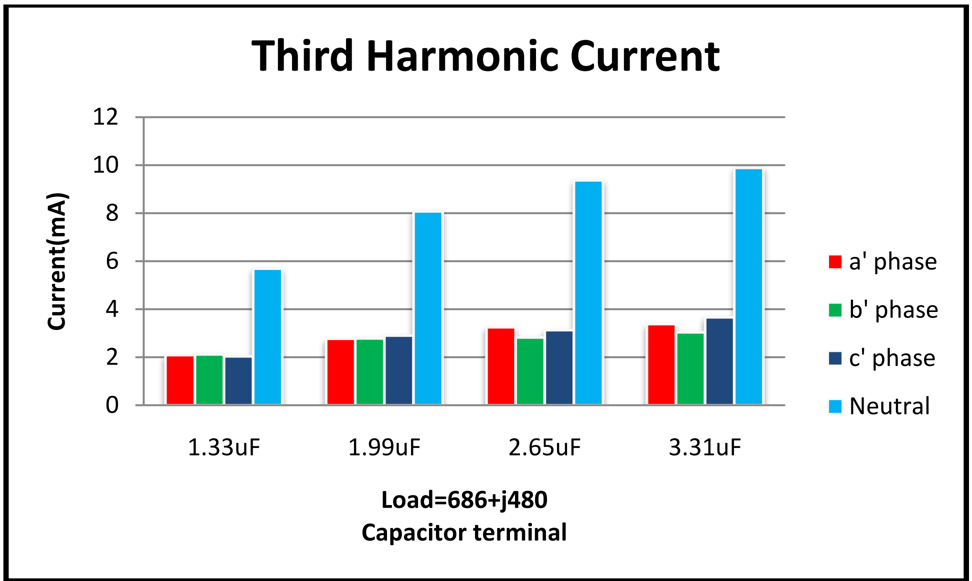


Figure 64: 3rd harmonic current at capacitor terminal when single generator parallel with grid increasing capacitor value with fixed load

CHAPTER 5

5. RECOMMENDATIONS AND CONCLUSION

5.1 Recommendations

The study on the effect of cable capacitance on the characteristics or behaviours of triplen harmonics produced by synchronous generator is very essential as this research can provide a very important input to mitigate the impact of harmonics in power system. How triplen harmonics affect the power system is a very important study that need to be done because the only way to reduce harmonics is by studying their sources, return path, how they circulate and their impact to line voltages and currents. Studying harmonics behaviour is not an easy task as it needs knowledge, proper software and high technology equipment. For further thorough analysis regarding the effect of cable capacitance on triplen harmonics produced by synchronous generator, it is recommended to do research that include more capacitor connected to the phase conductor. This is to make sure that the increasing trend of third harmonics currents flowing into capacitor is accurate.

5.2 Conclusion

The capacitor in the circuit represents the cable capacitance. The cable capacitance provides the earth path for third harmonic current to return to generator neutral. The higher the value of capacitor means that the longer the transmission line. From the experiment, the magnitude of the triplen harmonics current at capacitor side increase as the capacitor value is increased.

Since cable capacitance is in parallel connection with combined resistive and inductive load in single generator experiments, their net impedance decides the magnitude of third harmonic current at generator. The presence of cable capacitance and generator inductance creates series resonance at 9^{th} and 15^{th} harmonic number. In practice the cable capacitance value represent cable length, size and number of cable in parallel.

In parallel experiment, most of the current flow through the transformer neutral at grid as compared to the capacitor as it has lower impedance. The third harmonic current increase as the capacitor value is increased.

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APPENDICES

Appendix A: Single generator balanced resistive load with capacitor

1. Balanced R (686) with C

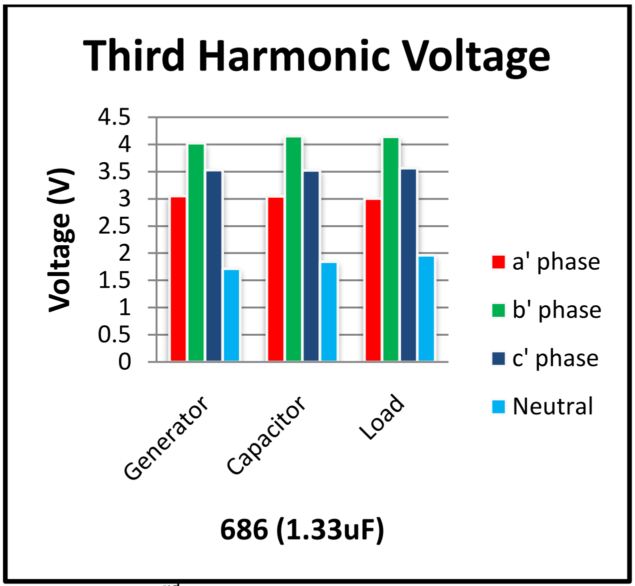


Figure 65: 3rd Harmonic Voltage for Balanced R (686 Ω) with C (1.33uF)

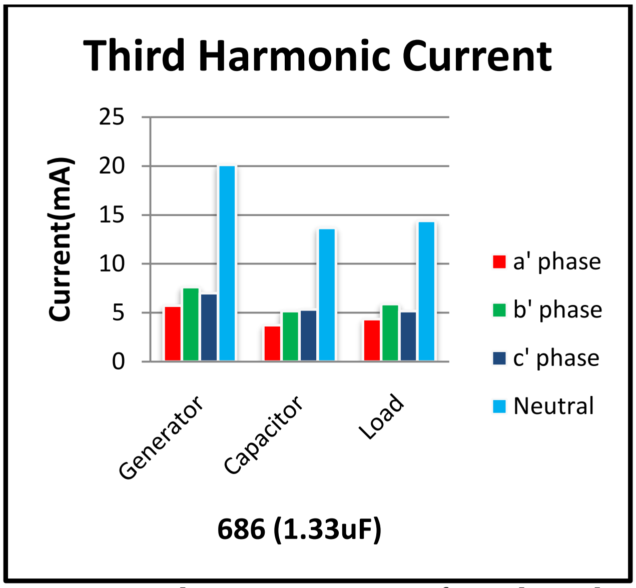


Figure 66: 3rd Harmonic Current for Balanced R (686 Ω) with C (1.33uF)

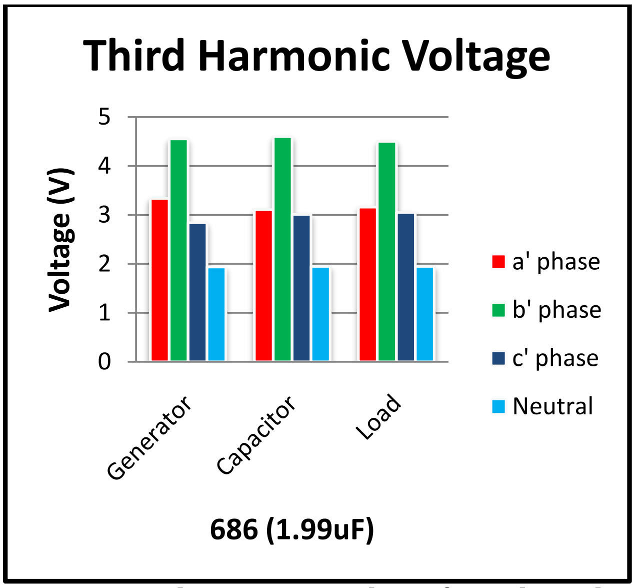


Figure 67: 3rd Harmonic Voltage for Balanced R (686 Ω) with C (1.99uF)

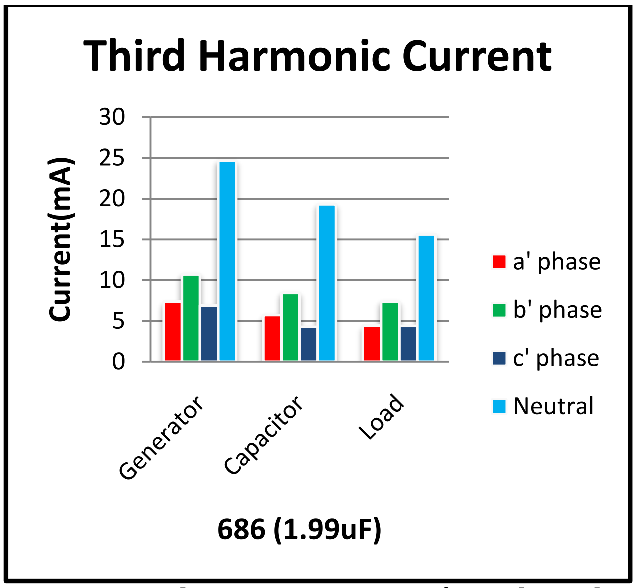


Figure 68: 3rd Harmonic Current for Balanced R (686 Ω) with C (1.99uF)

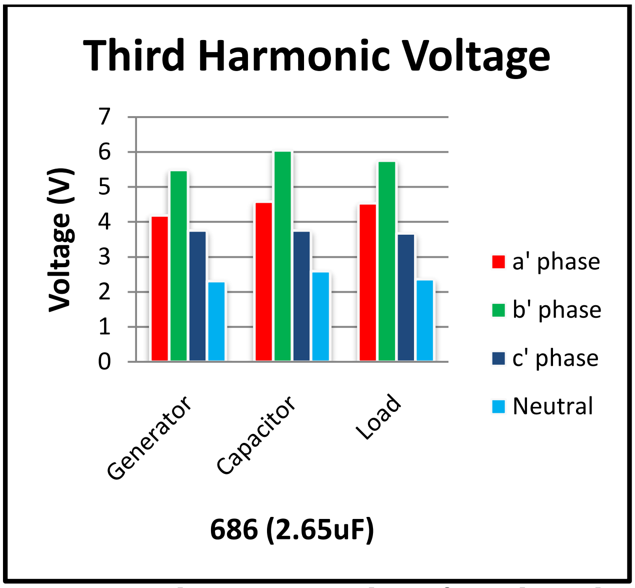


Figure 69: 3rd Harmonic Voltage for Balanced R (686 Ω) with C (2.65uF)

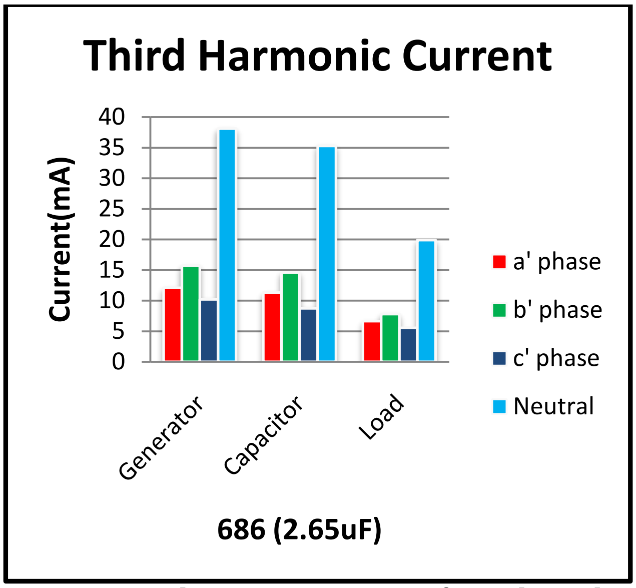


Figure 70: 3rd Harmonic Current for Balanced R (686 Ω) with C (2.65uF)

2. Balanced R (766) with C

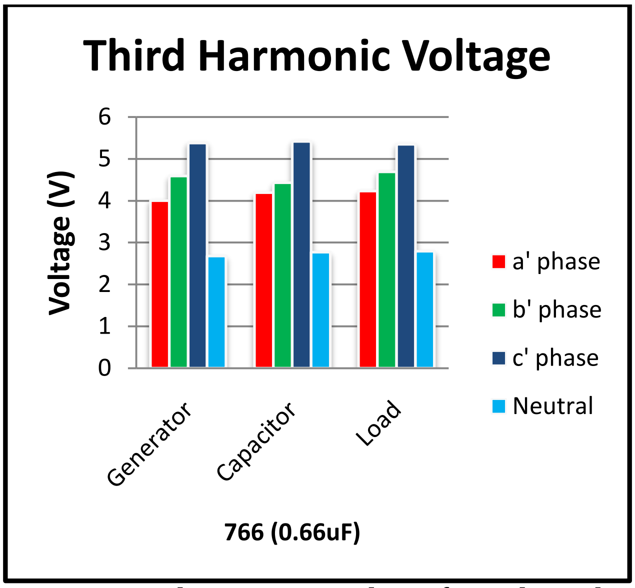


Figure 71: 3rd Harmonic Voltage for Balanced R (766 Ω) with C (0.66uF)

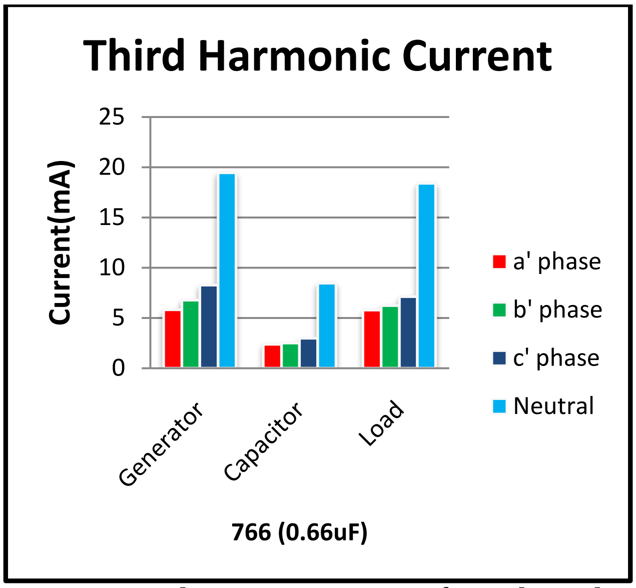


Figure 72: 3rd Harmonic Current for Balanced R (766 Ω) with C (0.66uF)

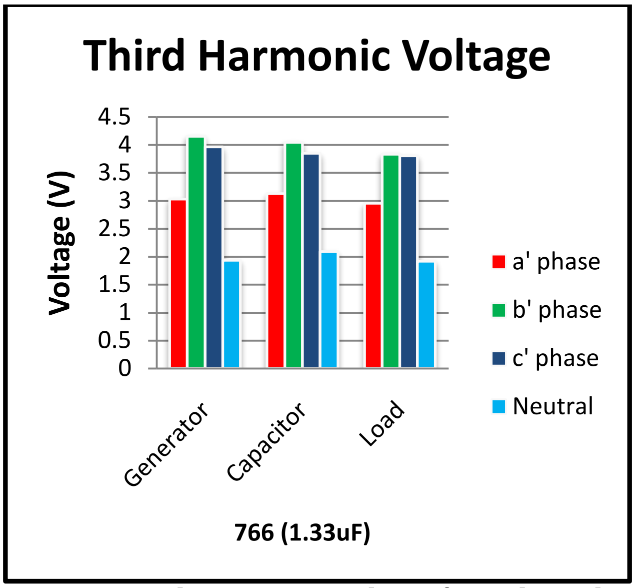


Figure 73: 3rd Harmonic Voltage for Balanced R (766 Ω) with C (1.33uF)

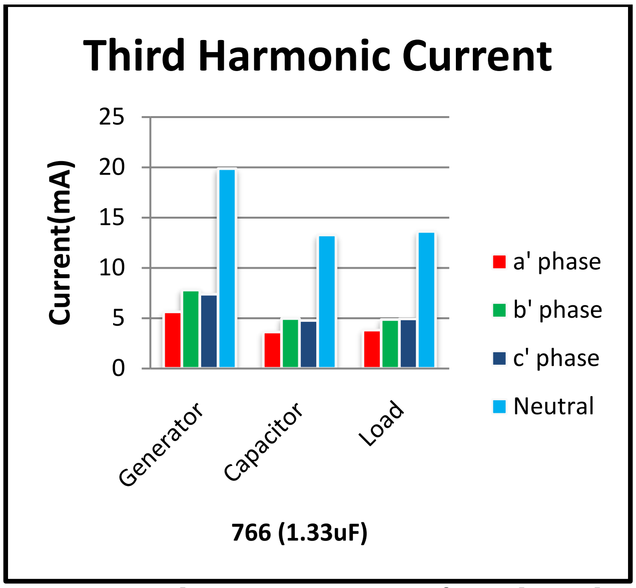


Figure 74: 3rd Harmonic Current for Balanced R (766 Ω) with C (1.33uF)

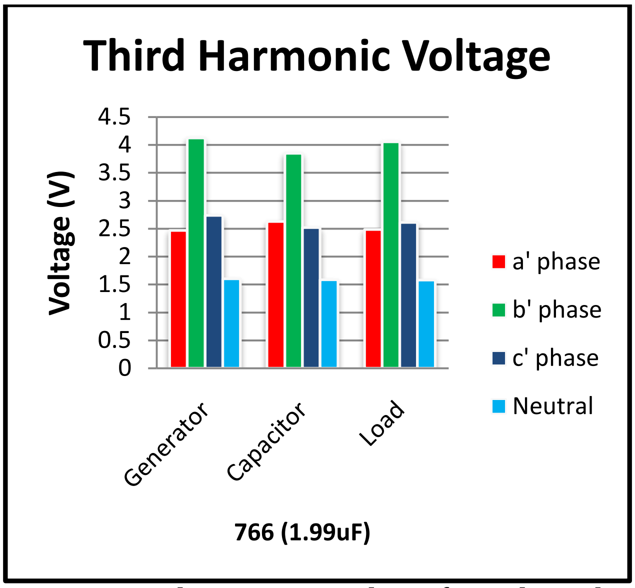


Figure 75: 3rd Harmonic Voltage for Balanced R (766 Ω) with C (1.99uF)

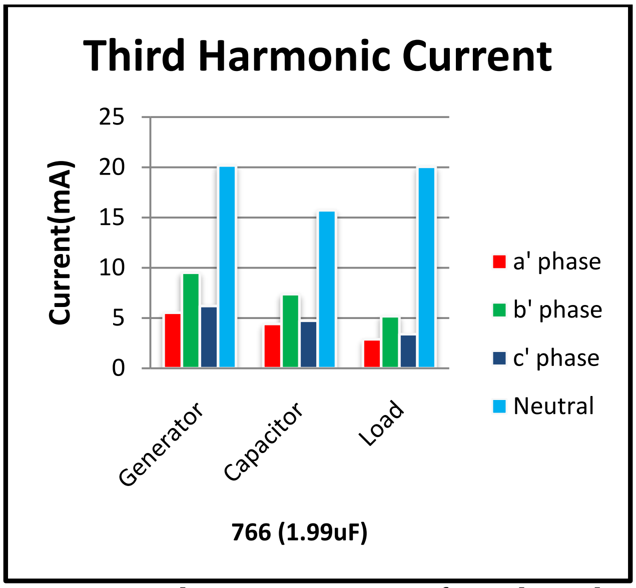


Figure 76: 3rd Harmonic Current for Balanced R (766 Ω) with C (1.99uF)

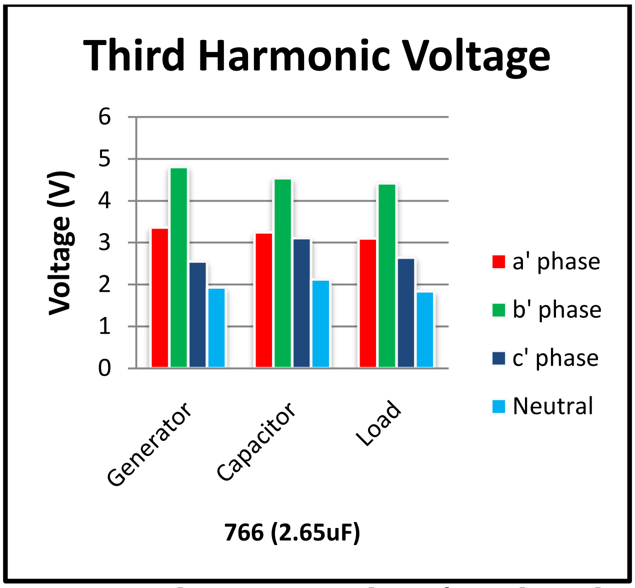


Figure 77: 3rd Harmonic Voltage for Balanced R (766 Ω) with C (2.65uF)

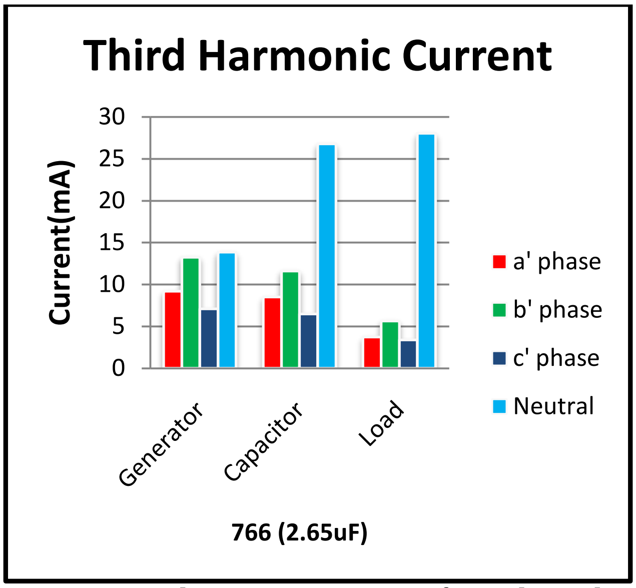


Figure 78: 3rd Harmonic Current for Balanced R (766 Ω) with C (2.65uF)

3. Balanced R (800) with C

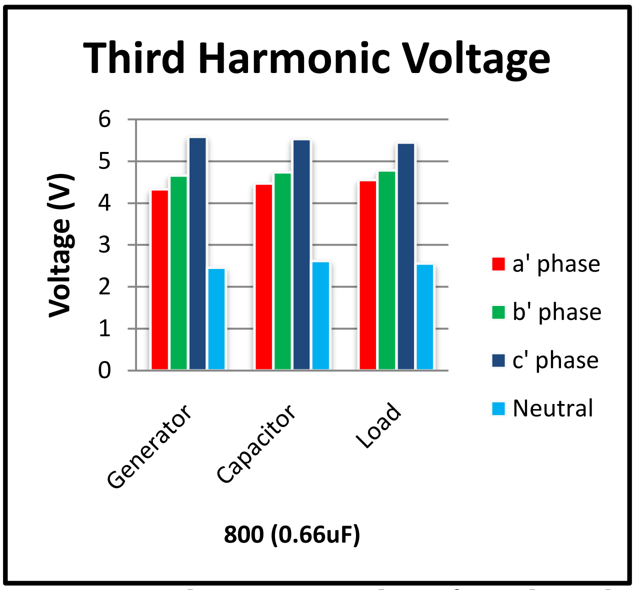


Figure 79: 3rd Harmonic Voltage for Balanced R (800 Ω) with C (0.66uF)

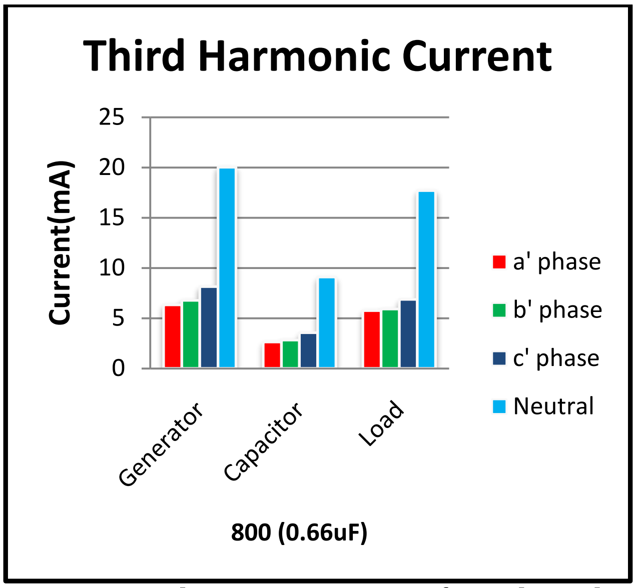


Figure 80: 3rd Harmonic Current for Balanced R (800 Ω) with C (0.66uF)

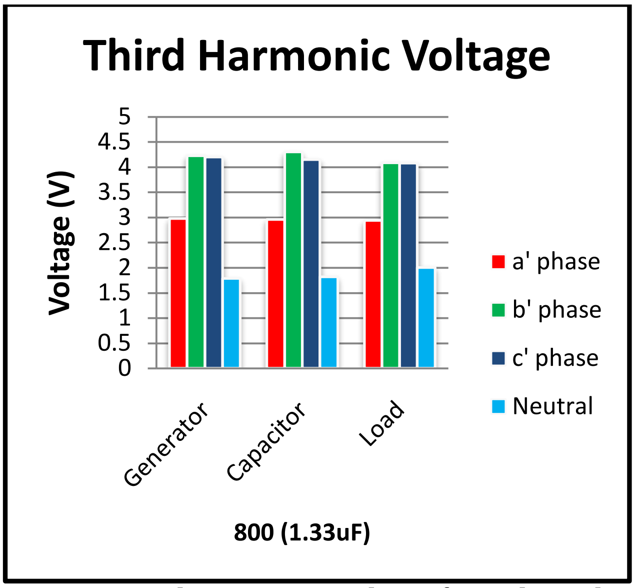


Figure 81: 3rd Harmonic Voltage for Balanced R (800 Ω) with C (1.33uF)

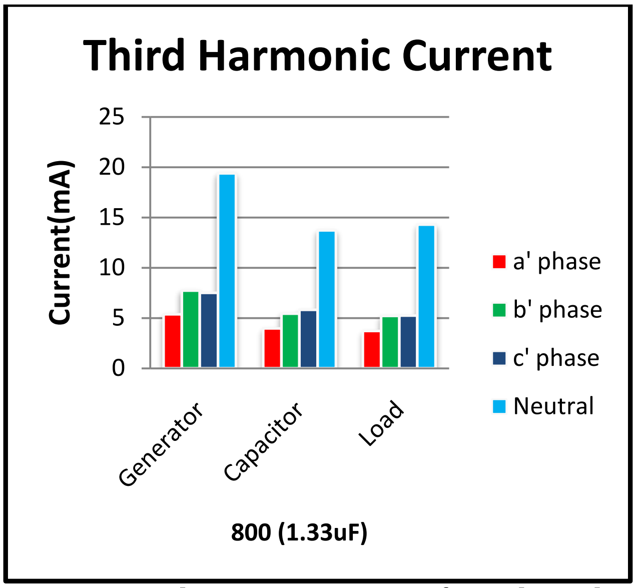


Figure 82: 3rd Harmonic Current for Balanced R (800 Ω) with C (1.33uF)

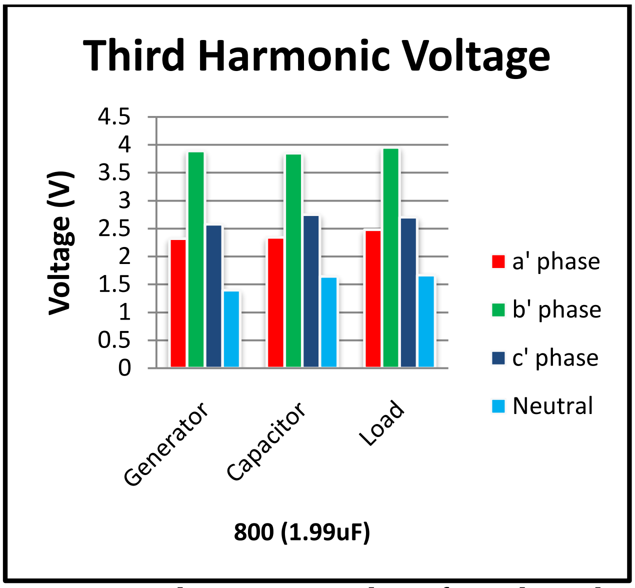


Figure 83: 3rd Harmonic Voltage for Balanced R (800 Ω) with C (1.99uF)

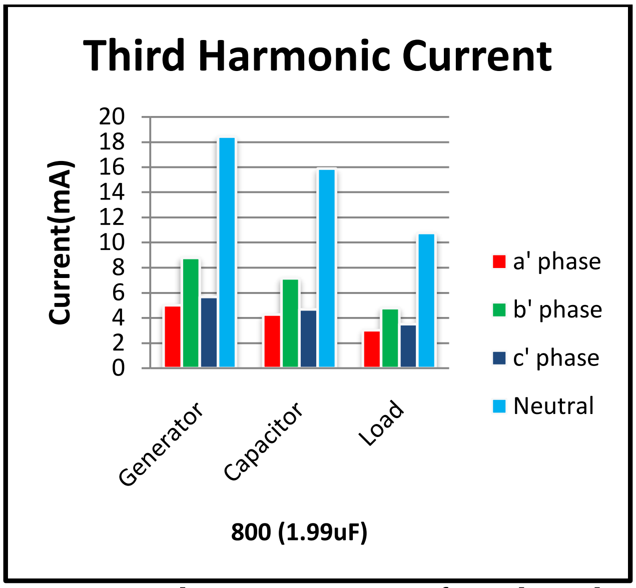


Figure 84: 3rd Harmonic Current for Balanced R (800 Ω) with C (1.99uF)

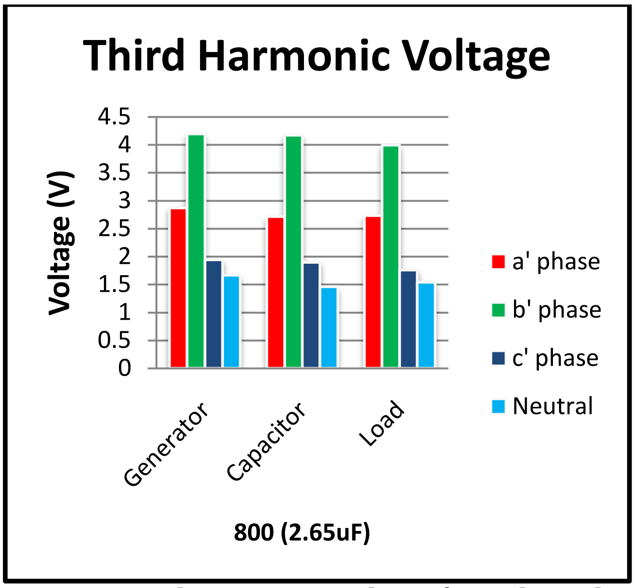


Figure 85: 3rd Harmonic Voltage for Balanced R (800 Ω) with C (2.65uF)

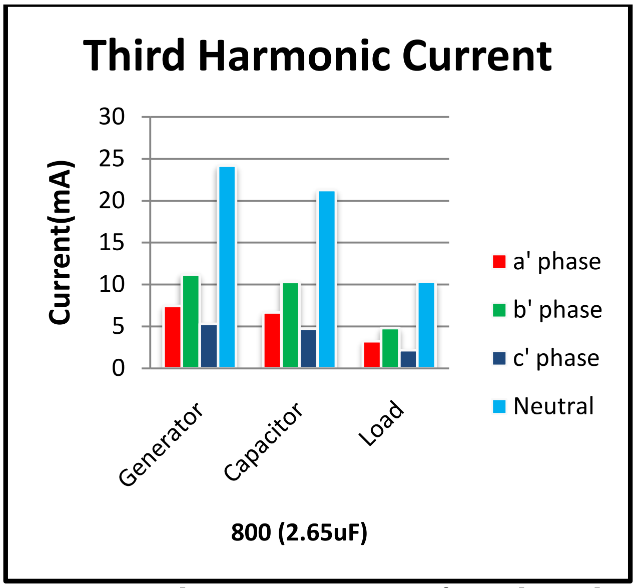


Figure 86: 3rd Harmonic Current for Balanced R (800 Ω) with C (2.65uF)

4. Balanced R (880) with C

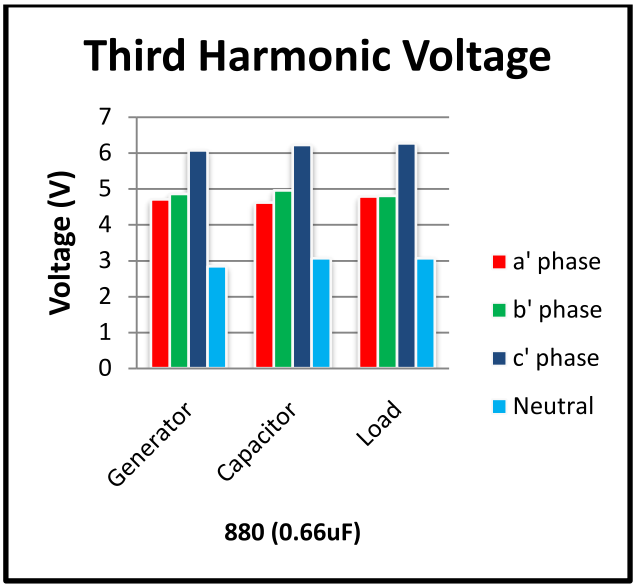


Figure 87: 3rd Harmonic Voltage for Balanced R (880 Ω) with C (0.66uF)

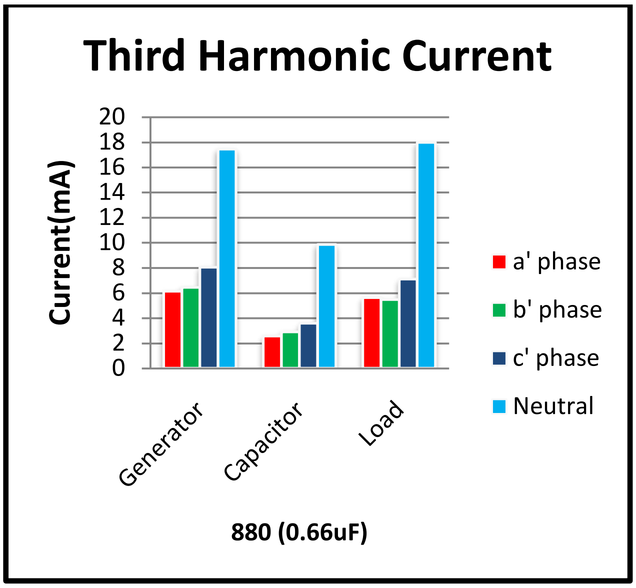


Figure 88: 3rd Harmonic Current for Balanced R (880 Ω) with C (0.66uF)

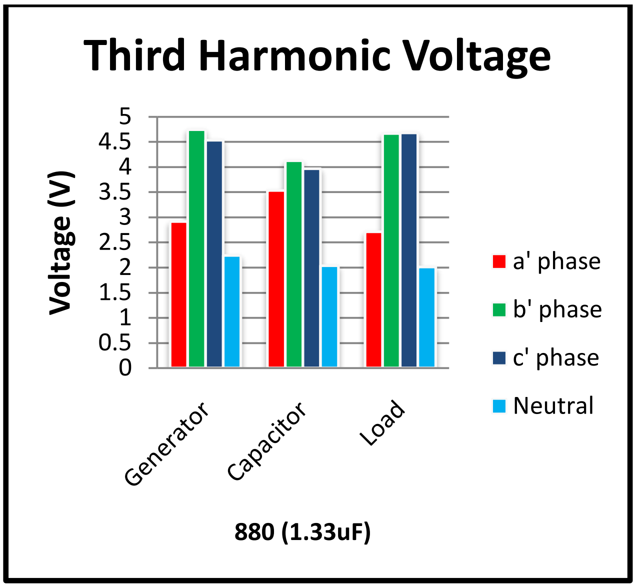


Figure 89: 3rd Harmonic Voltage for Balanced R (880 Ω) with C (1.33uF)

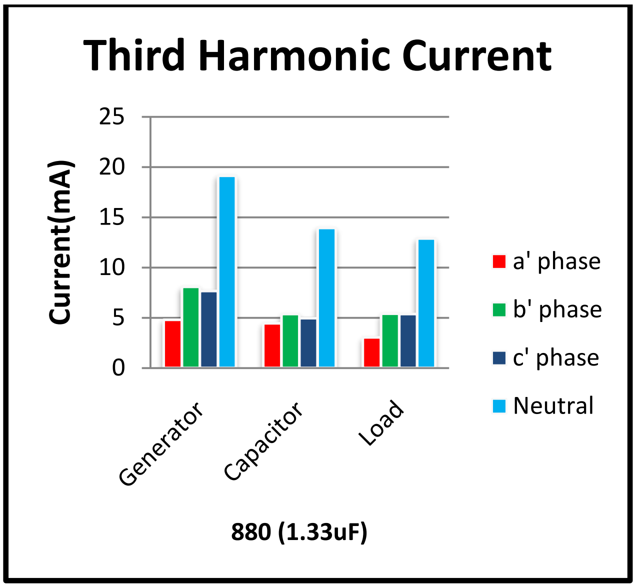


Figure 90: 3rd Harmonic Current for Balanced R (880 Ω) with C (1.33uF)

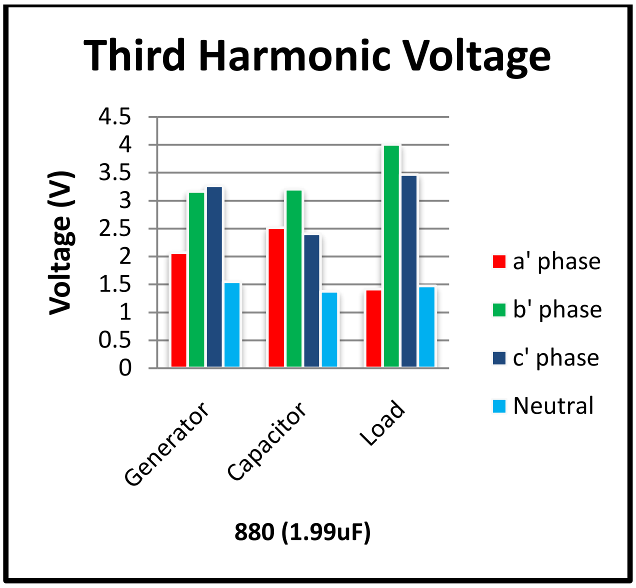


Figure 91: 3rd Harmonic Voltage for Balanced R (880 Ω) with C (1.99uF)

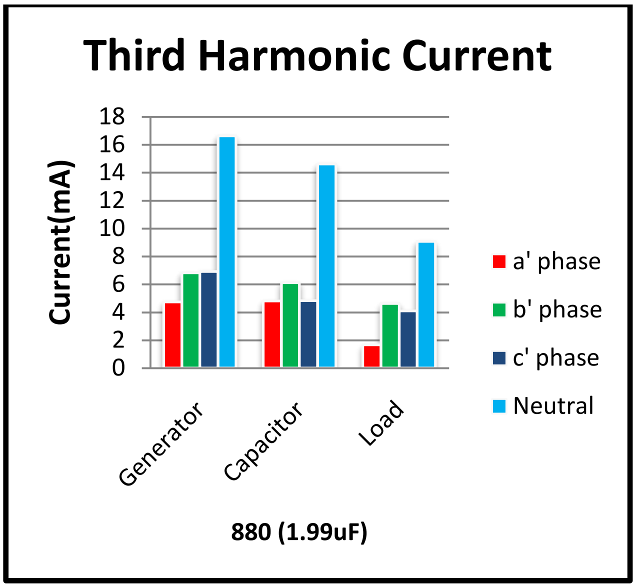


Figure 92: 3rd Harmonic Current for Balanced R (880 Ω) with C (1.99uF)

Appendix B: Single generator balanced inductive load with capacitor

1. Balanced L (2.5) with C

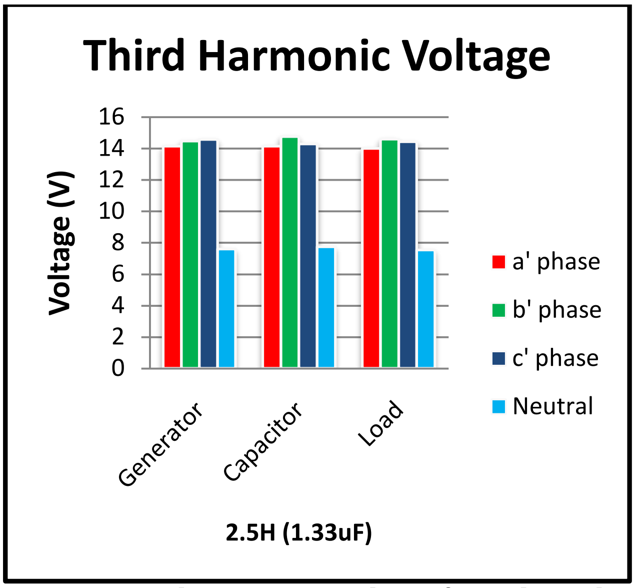


Figure 93: 3rd Harmonic Voltage for Balanced L (2.5H) with C (1.33uF)

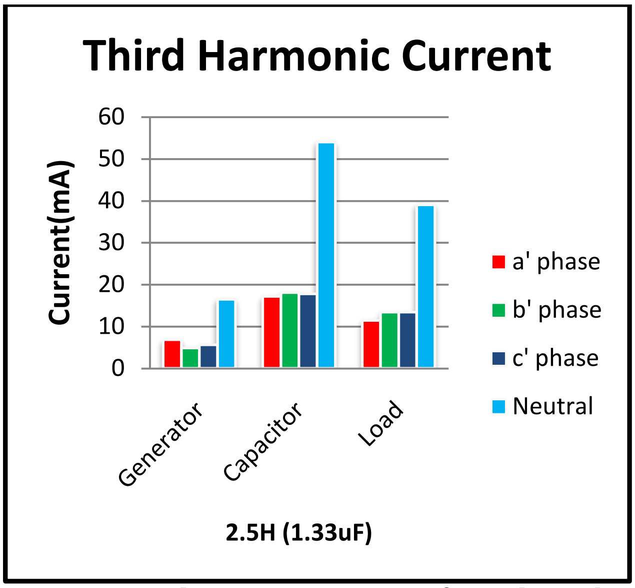


Figure 94: 3rd Harmonic Current for Balanced L (2.5H) with C (1.33uF)

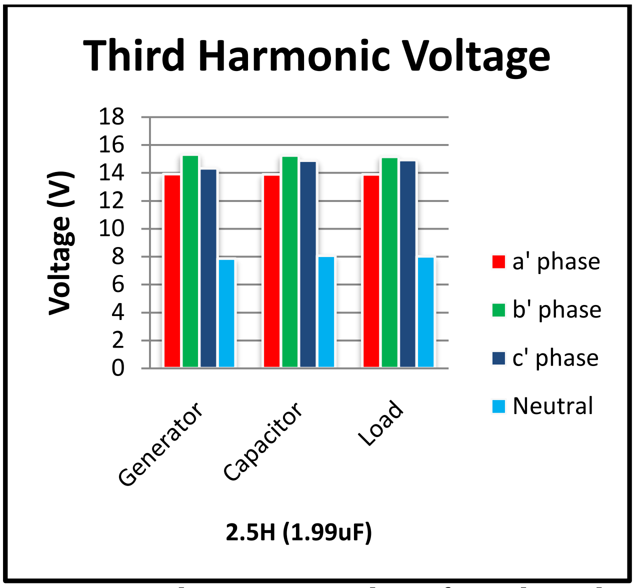


Figure 95: 3rd Harmonic Voltage for Balanced L (2.5H) with C (1.99uF)

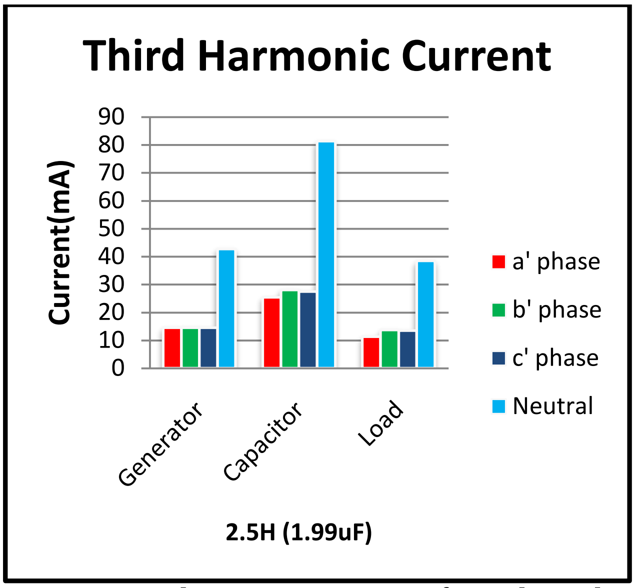


Figure 96: 3rd Harmonic Current for Balanced L (2.5H) with C (1.99uF)

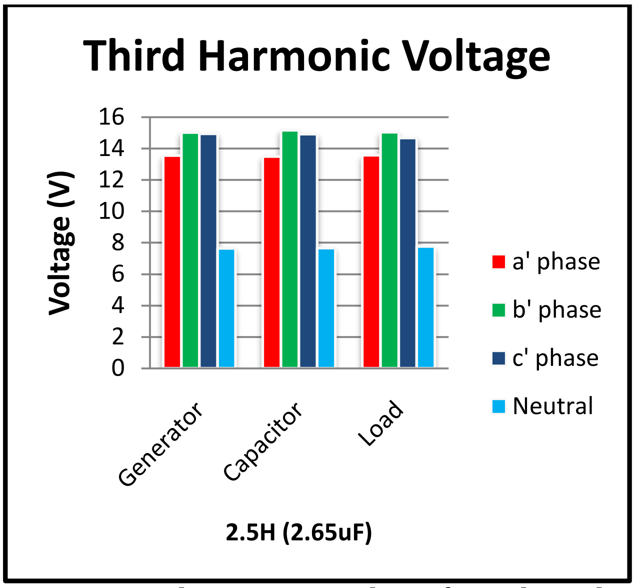


Figure 97: 3rd Harmonic Voltage for Balanced L (2.5H) with C (2.65uF)

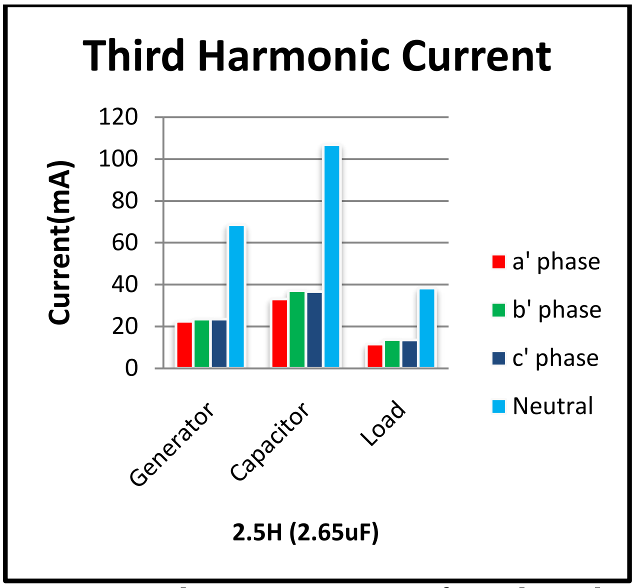


Figure 98: 3rd Harmonic Current for Balanced L (2.5H) with C (2.65uF)

2. Balanced L (3.8) with C

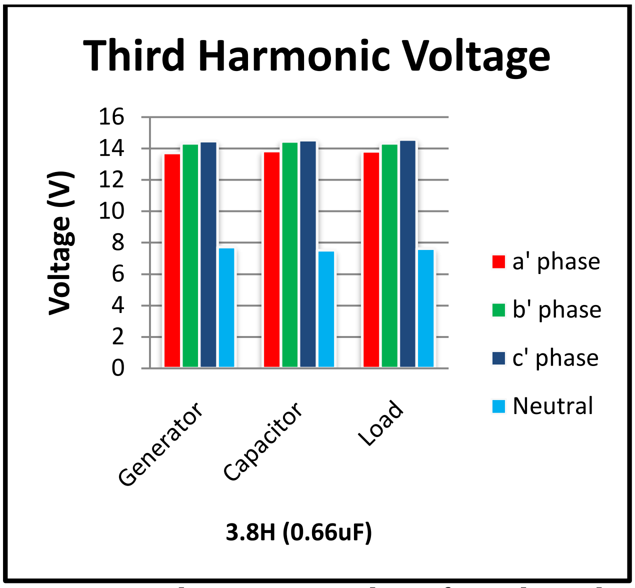


Figure 99: 3rd Harmonic Voltage for Balanced L (3.8H) with C (0.66uF)

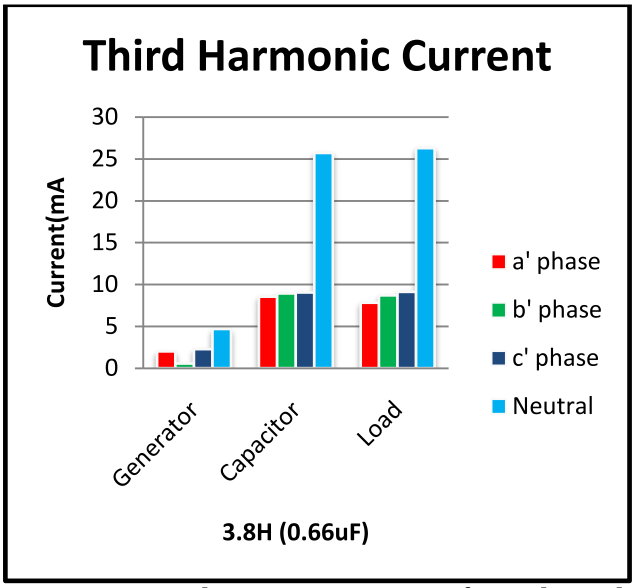


Figure 100: 3rd Harmonic Current for Balanced L (3.8H) with C (0.66uF)

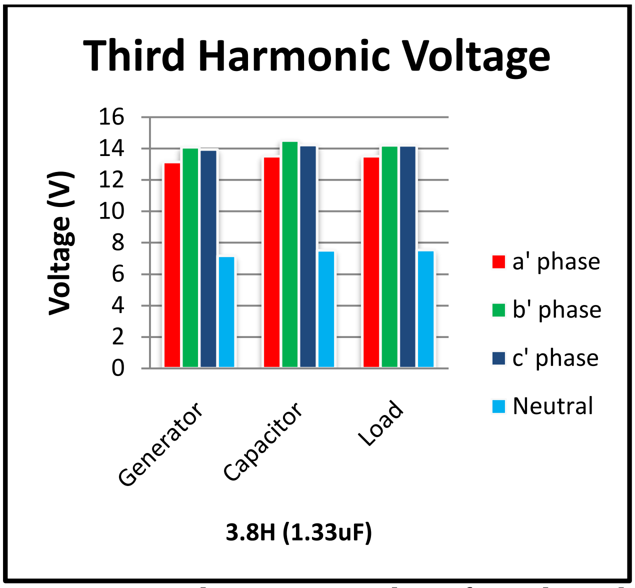


Figure 101: 3rd Harmonic Voltage for Balanced L (3.8H) with C (1.33uF)

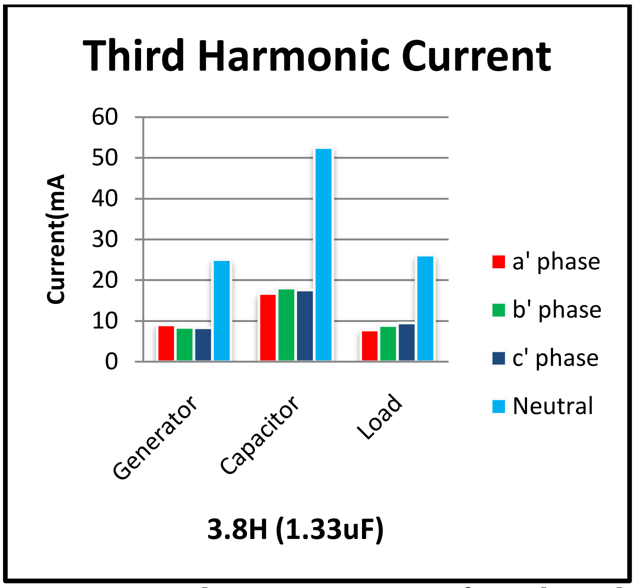


Figure 102: 3rd Harmonic Current for Balanced L (3.8H) with C (1.33uF)

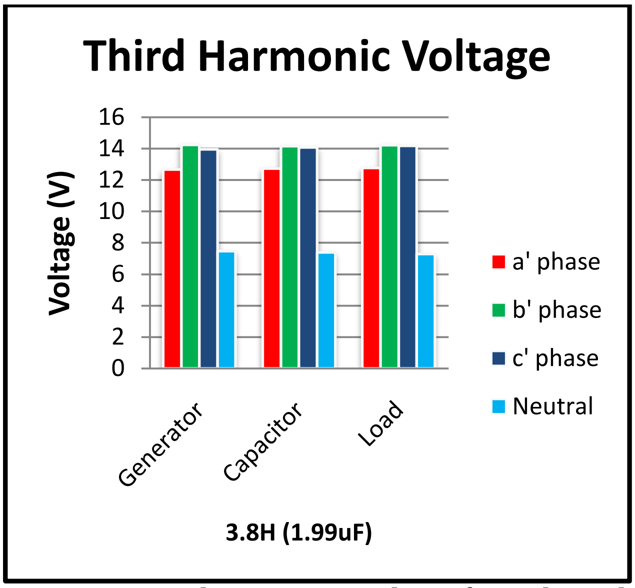


Figure 103: 3rd Harmonic Voltage for Balanced L (3.8H) with C (1.99uF)

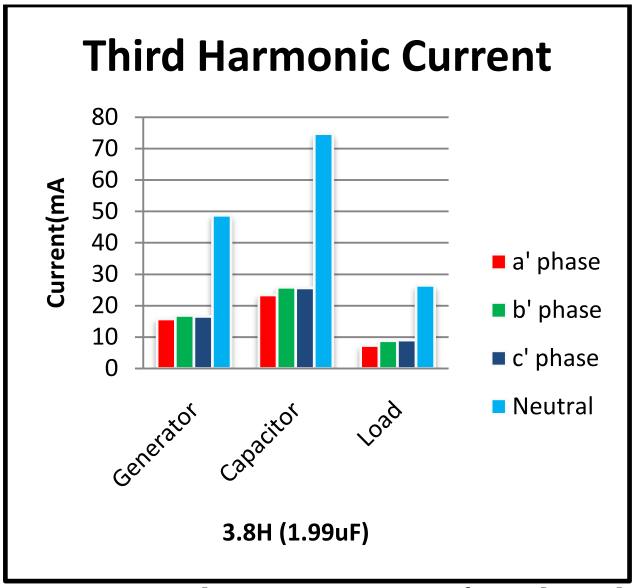


Figure 104: 3rd Harmonic Current for Balanced L (3.8H) with C (1.99uF)

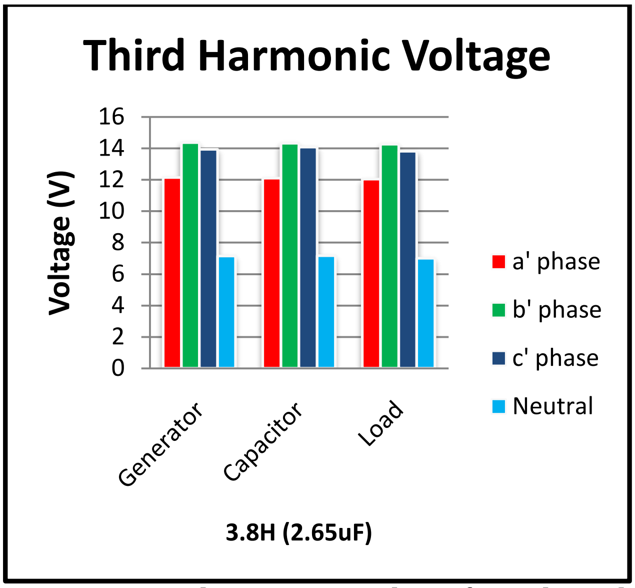


Figure 105: 3rd Harmonic Voltage for Balanced L (3.8H) with C (2.65uF)

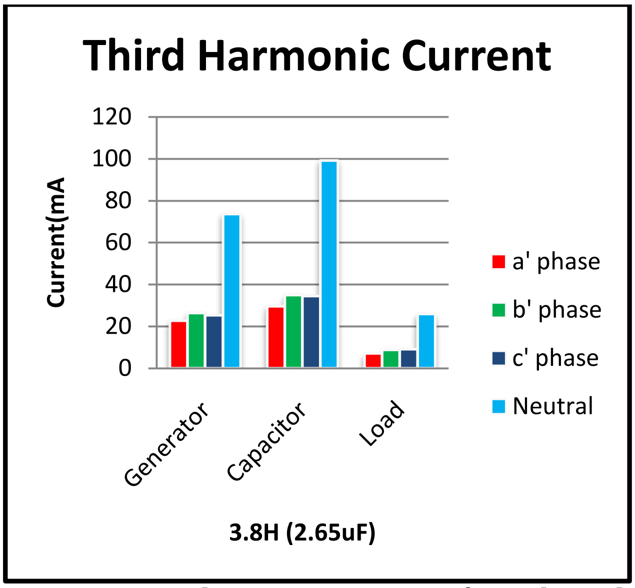


Figure 106: 3rd Harmonic Current for Balanced L (3.8H) with C (2.65uF)

3. Balanced L (5.1) with C

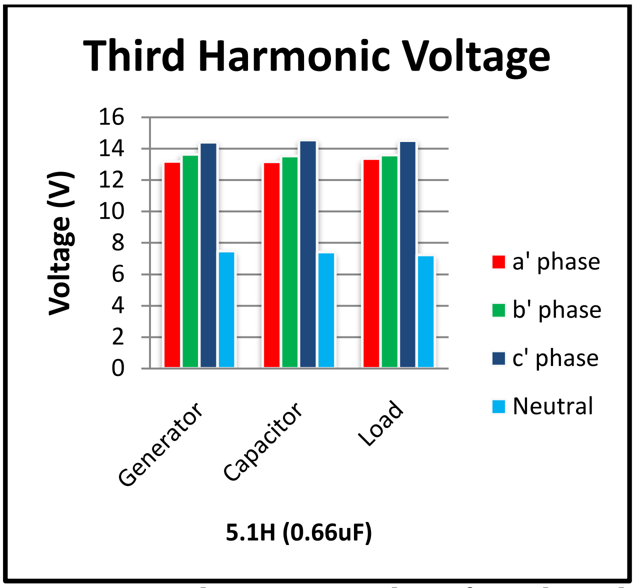


Figure 107: 3rd Harmonic Voltage for Balanced L (5.1H) with C (0.66uF)

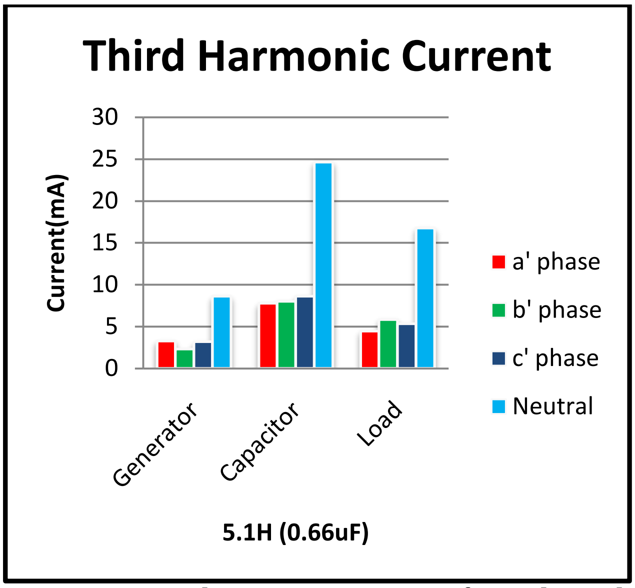


Figure 108: 3rd Harmonic Current for Balanced L (5.1H) with C (0.66uF)

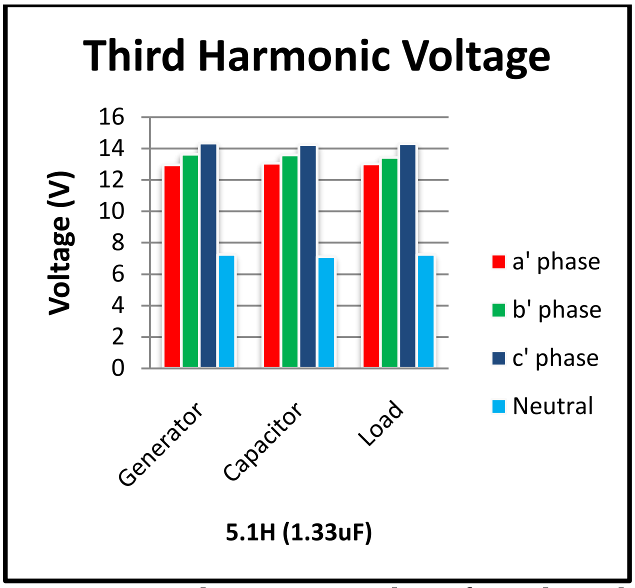


Figure 109: 3rd Harmonic Voltage for Balanced L (5.1H) with C (1.33uF)

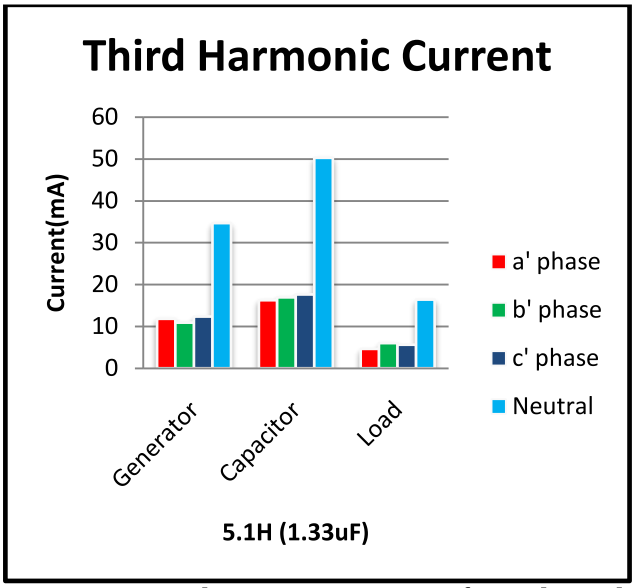


Figure 110: 3rd Harmonic Current for Balanced L (5.1H) with C (1.33uF)

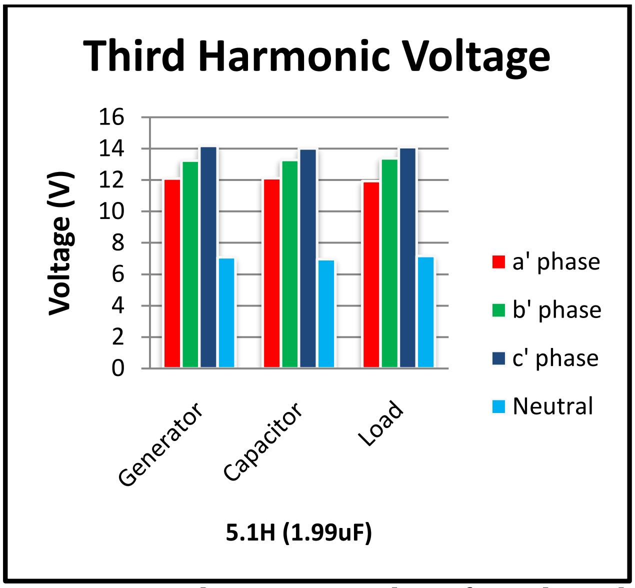


Figure 111: 3rd Harmonic Voltage for Balanced L (5.1H) with C (1.99uF)

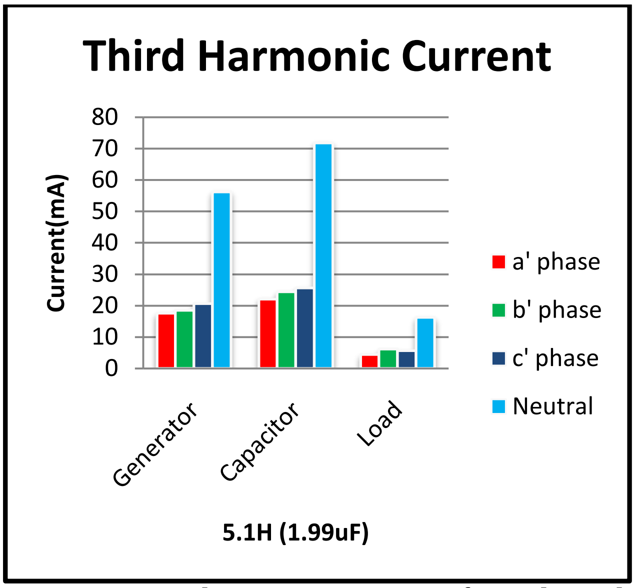


Figure 112: 3rd Harmonic Current for Balanced L (5.1H) with C (1.99uF)

4. **Balanced L (7.6) with C**

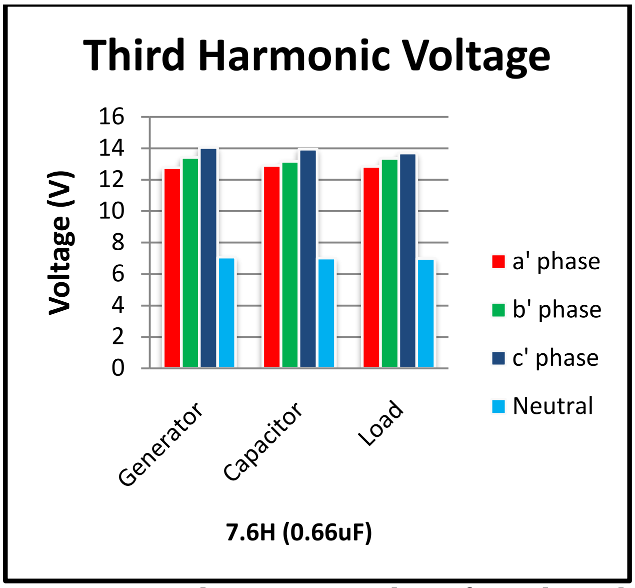


Figure 113: 3rd Harmonic Voltage for Balanced L (7.6H) with C (0.66uF)

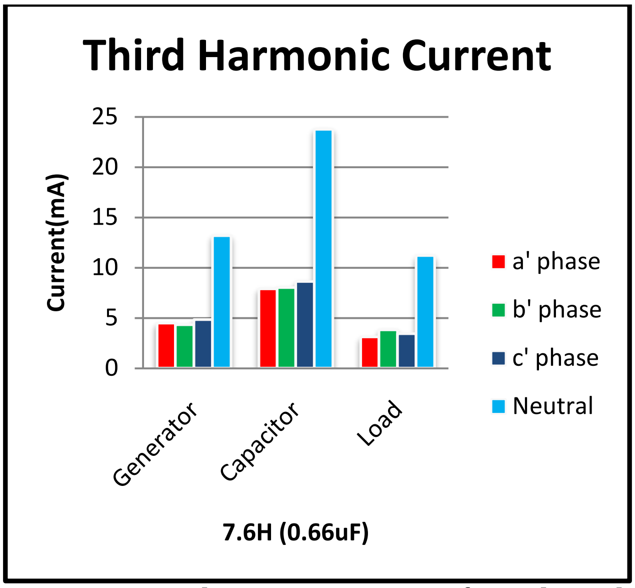


Figure 114: 3rd Harmonic Current for Balanced L (7.6H) with C (0.66uF)

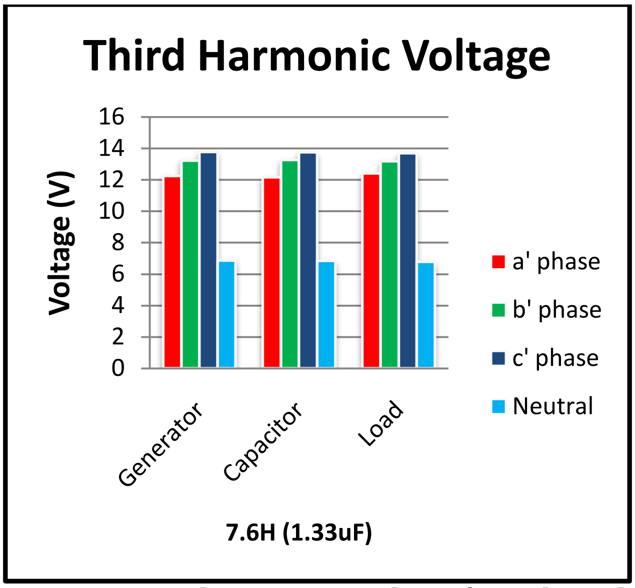


Figure 115: 3rd Harmonic Voltage for Balanced L (7.6H) with C (1.33uF)

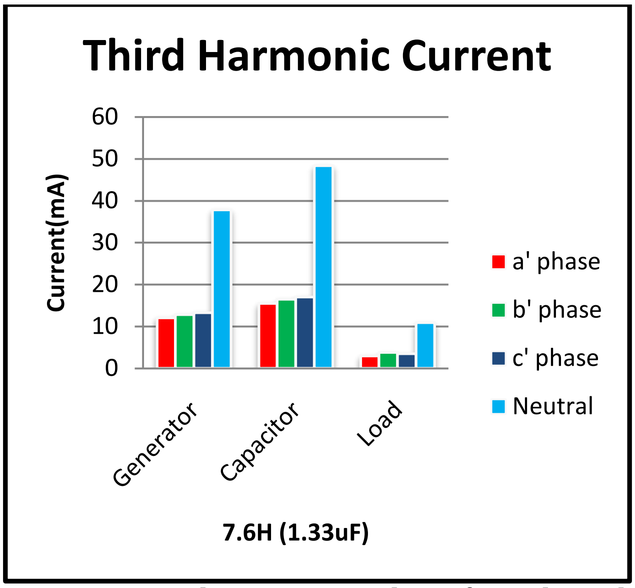


Figure 116: 3rd Harmonic Voltage for Balanced L (7.6H) with C (1.33uF)

Appendix C: Single generator balanced combined resistive and inductive load with capacitor

1. Balanced R+L (686+j120) with C

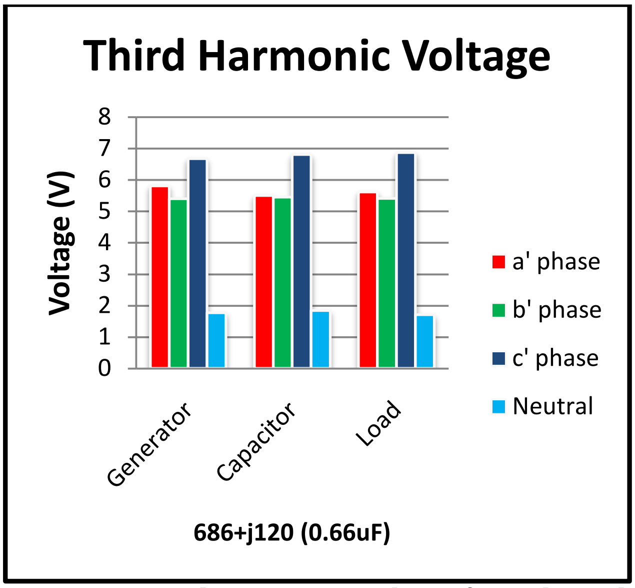


Figure 117: 3rd Harmonic Voltage for Balanced R+L (686+j120) with C (0.66uF)

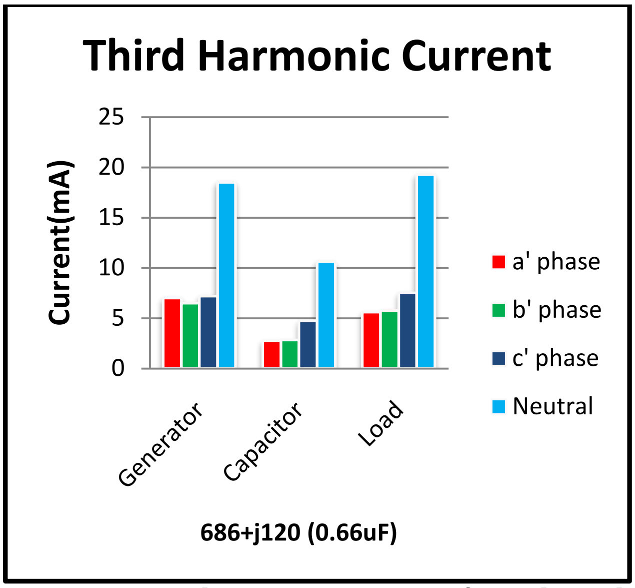


Figure 118: 3rd Harmonic Current for Balanced R+L (686+j120) with C (0.66uF)

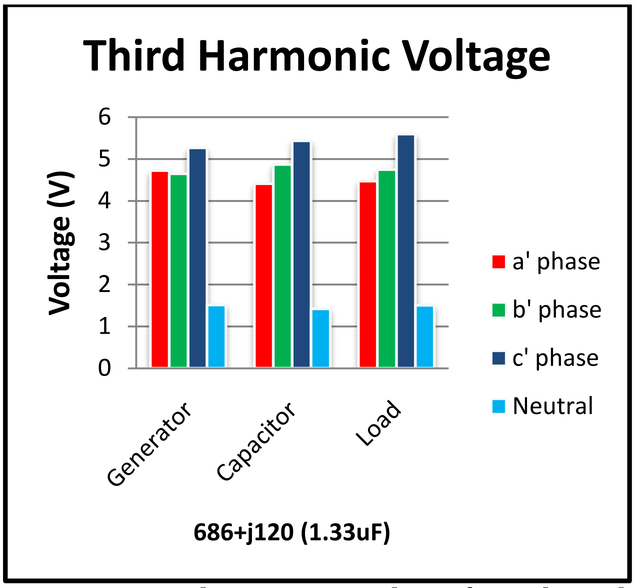


Figure 119: 3rd Harmonic Voltage for Balanced R+L (686+j120) with C (1.33uF)

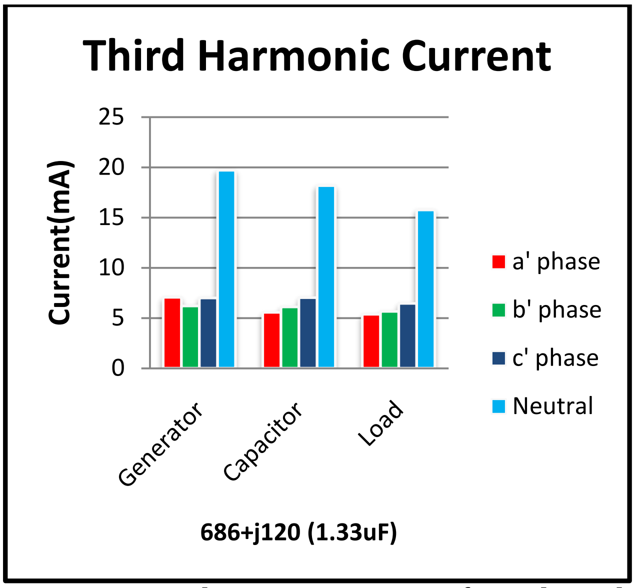


Figure 120: 3rd Harmonic Current for Balanced R+L (686+j120) with C (1.33uF)

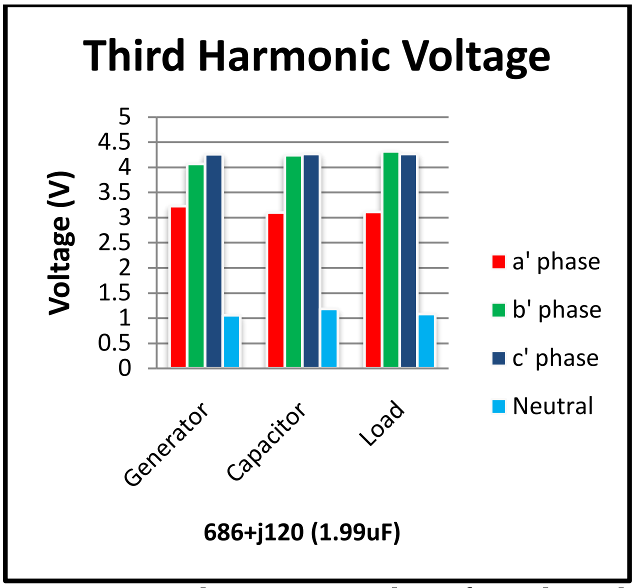


Figure 121: 3rd Harmonic Voltage for Balanced R+L (686+j120) with C (1.99uF)

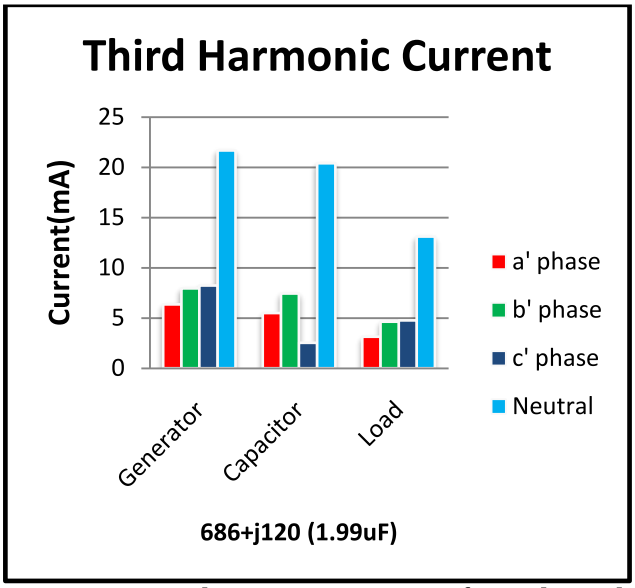


Figure 122: 3rd Harmonic Current for Balanced R+L (686+j120) with C (1.99uF)

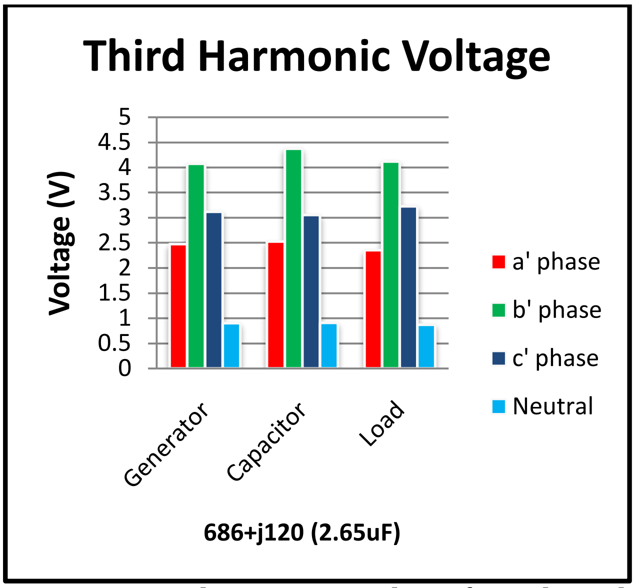


Figure 123: 3rd Harmonic Voltage for Balanced R+L (686+j120) with C (2.65uF)

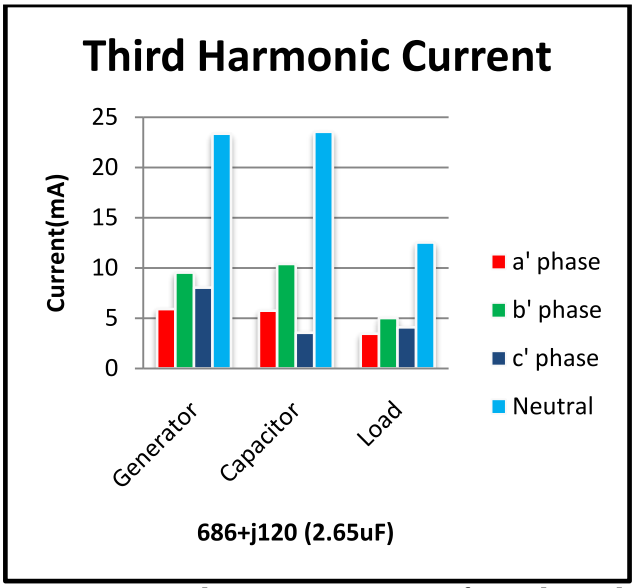


Figure 124: 3rd Harmonic Current for Balanced R+L (686+j120) with C (2.65uF)

2. **Balanced R+L (686+j240) with C**

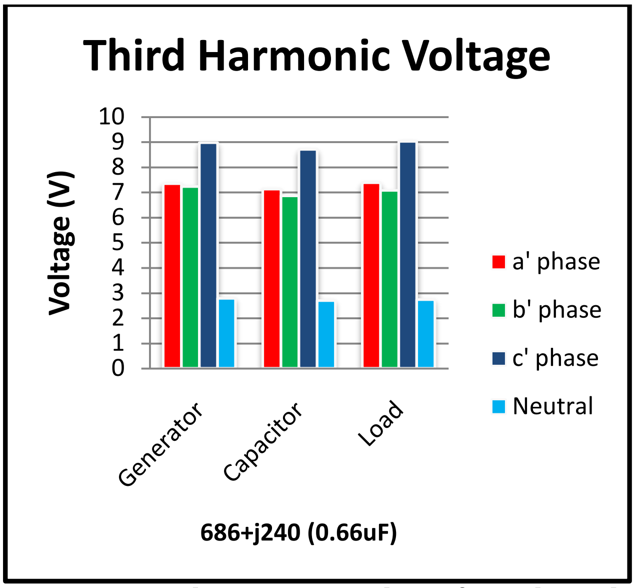


Figure 125: 3rd Harmonic Voltage for Balanced R+L (686+j240) with C (0.66uF)

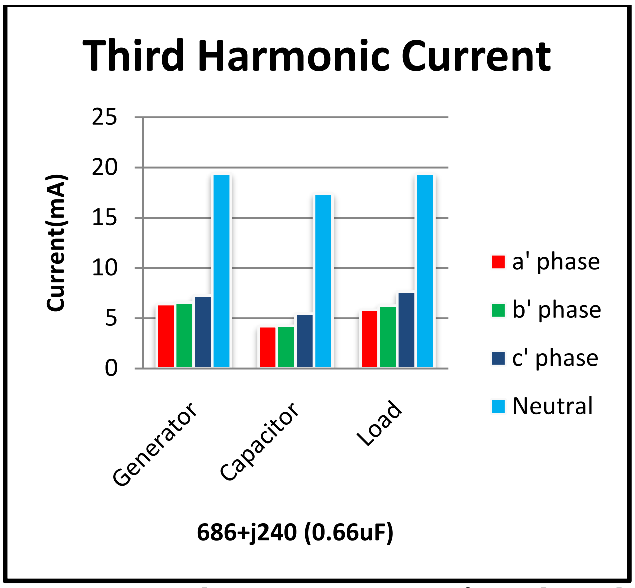


Figure 126: 3rd Harmonic Current for Balanced R+L (686+j240) with C (0.66uF)

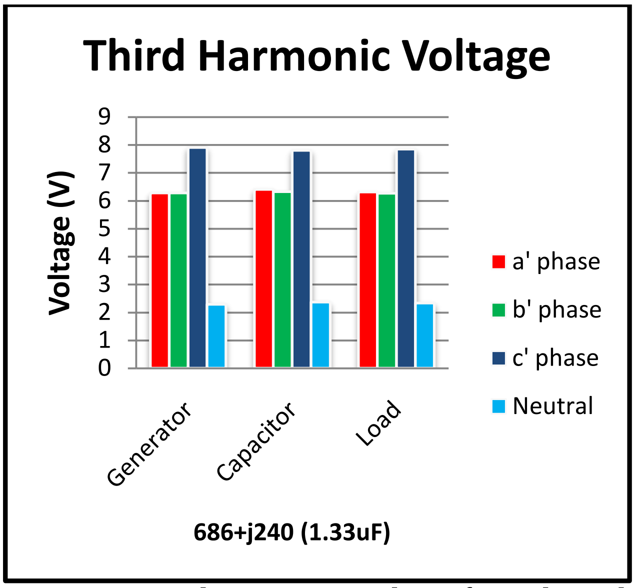


Figure 127: 3rd Harmonic Voltage for Balanced R+L (686+j240) with C (1.33uF)

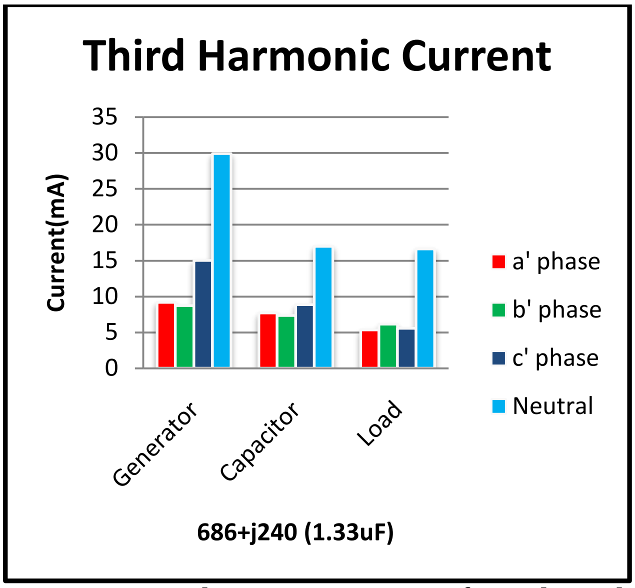


Figure 128: 3rd Harmonic Current for Balanced R+L (686+j240) with C (1.33uF)

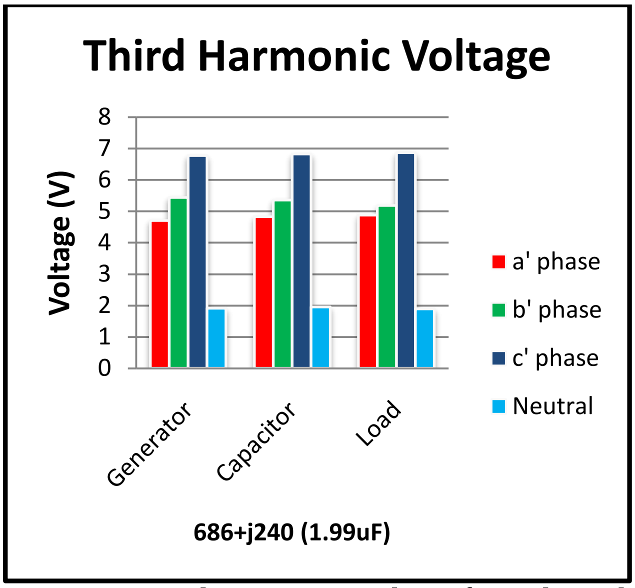


Figure 129: 3rd Harmonic Voltage for Balanced R+L (686+j240) with C (1.99uF)

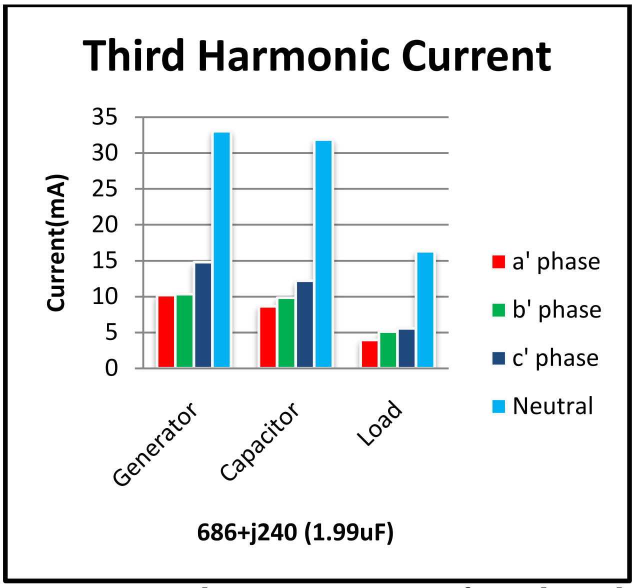


Figure 130: 3rd Harmonic Current for Balanced R+L (686+j240) with C (1.99uF)

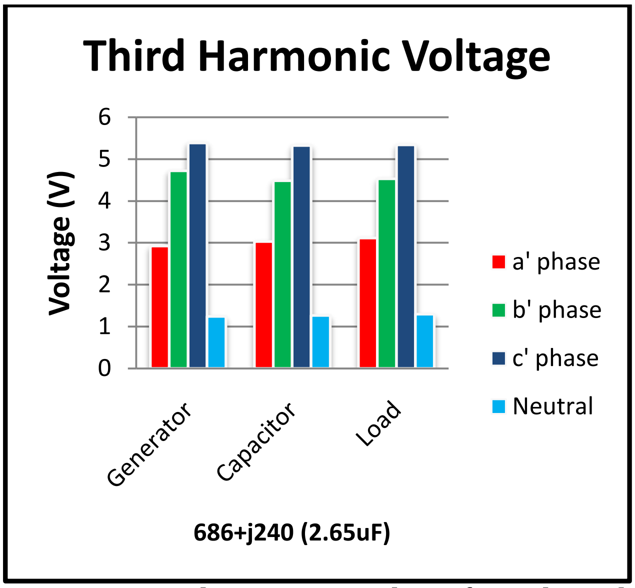


Figure 131: 3rd Harmonic Voltage for Balanced R+L (686+j240) with C (2.65uF)

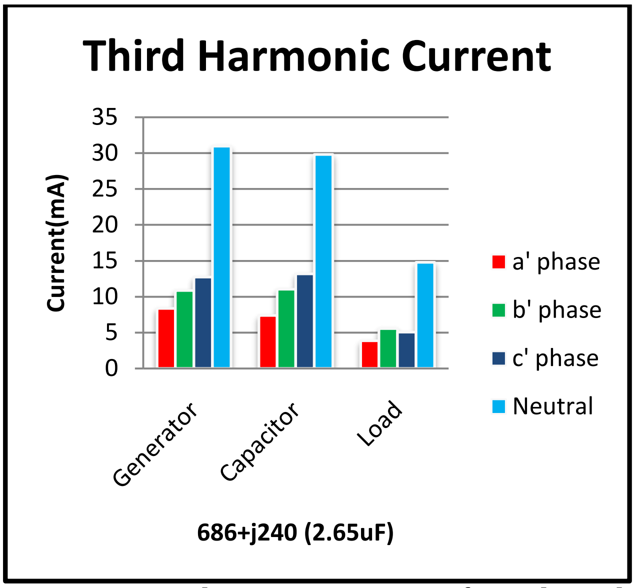


Figure 132: 3rd Harmonic Current for Balanced R+L (686+j240) with C (2.65uF)

3. Balanced R+L (686+j686) with C

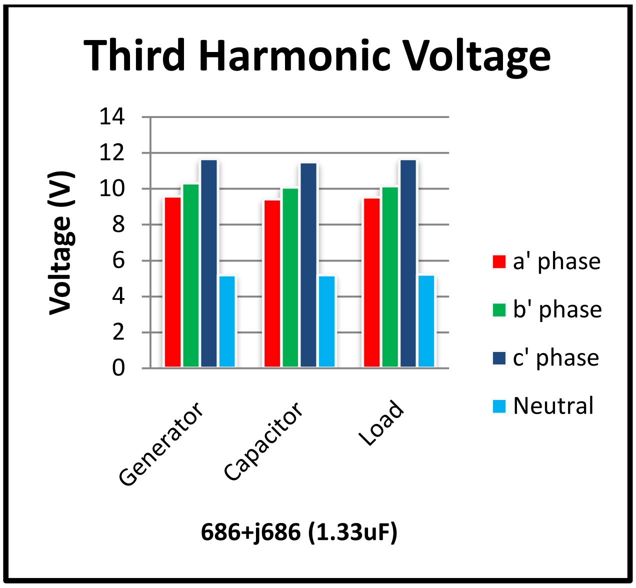


Figure 133: 3rd harmonic voltage for balanced R+L (686+j686) with C (1.33uF)

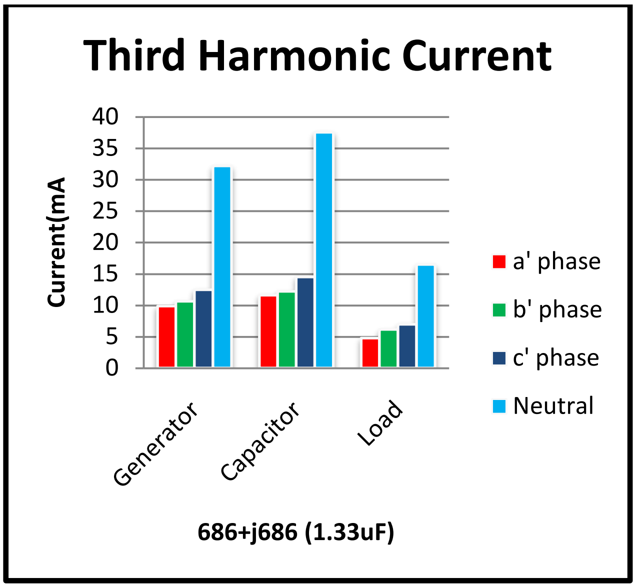


Figure 134: 3rd harmonic current for balanced R+L (686+j686) with C (1.33uF)

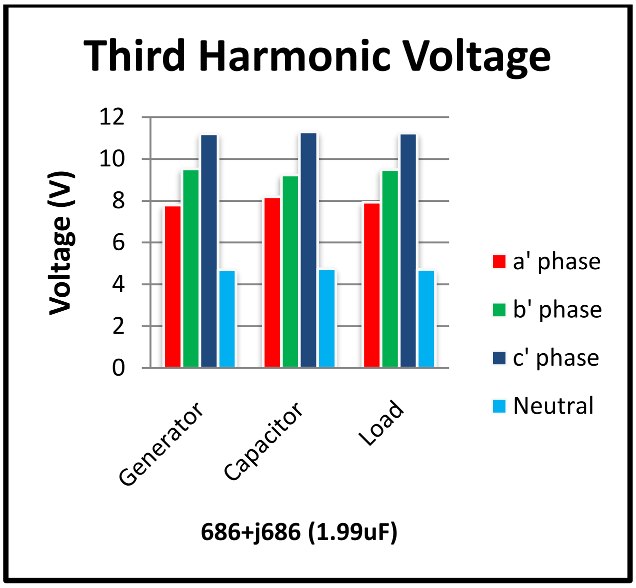


Figure 135: 3rd harmonic voltage for balanced R+L (686+j686) with C (1.99uF)

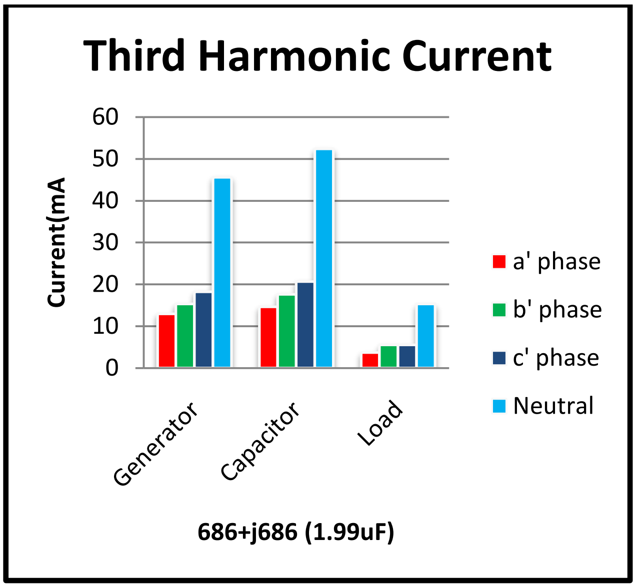


Figure 136: 3rd harmonic current for balanced R+L (686+j686) with C (1.99uF)

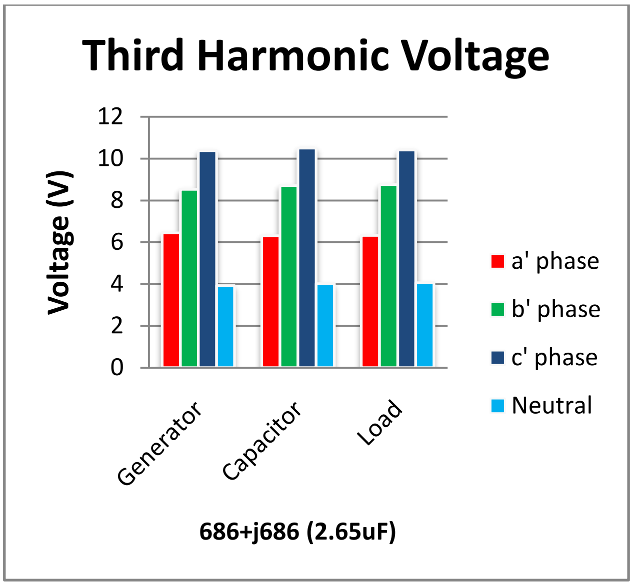


Figure 137: 3rd harmonic voltage for balanced R+L (686+j686) with C (2.65uF)

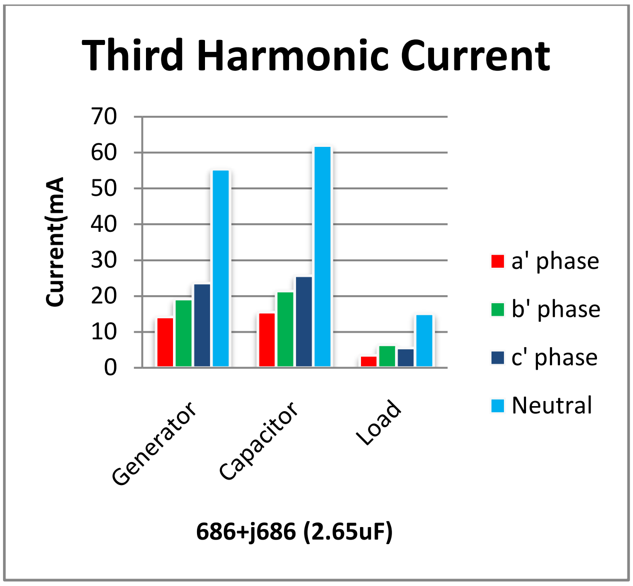


Figure 138: 3rd harmonic current for balanced R+L (686+j686) with C (2.65uF)

4. Balanced R+L (686+j1200) with C

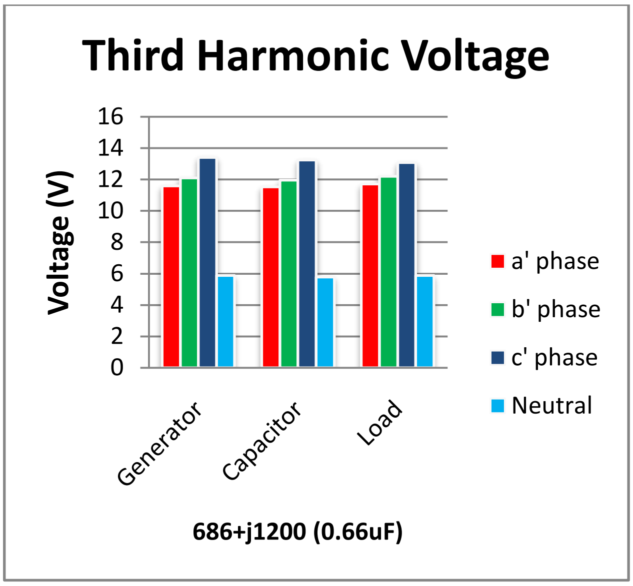


Figure 139: 3rd harmonic voltage for balanced R+L (686+j1200) with C (0.66uF)

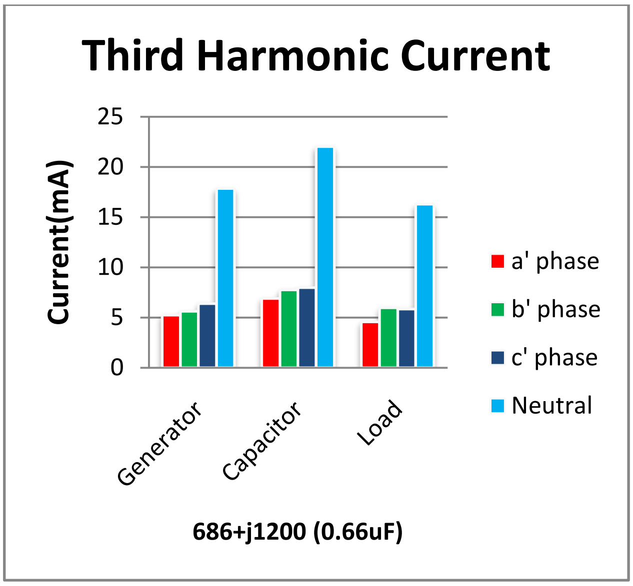


Figure 140: 3rd harmonic current for balanced R+L (686+j1200) with C (0.66uF)

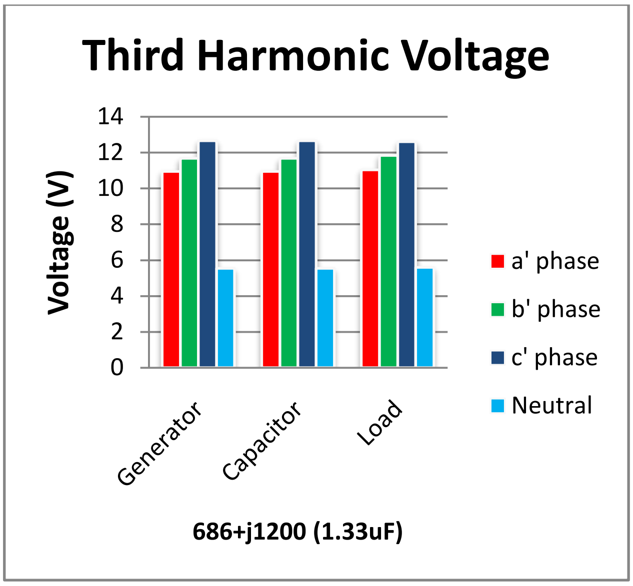


Figure 141: 3rd harmonic voltage for balanced R+L (686+j1200) with C (1.33uF)

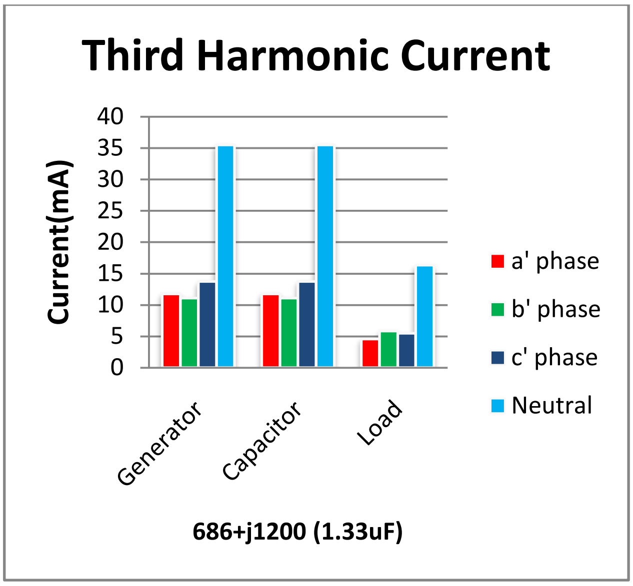


Figure 142: 3rd harmonic current for balanced R+L (686+j1200) with C (1.33uF)

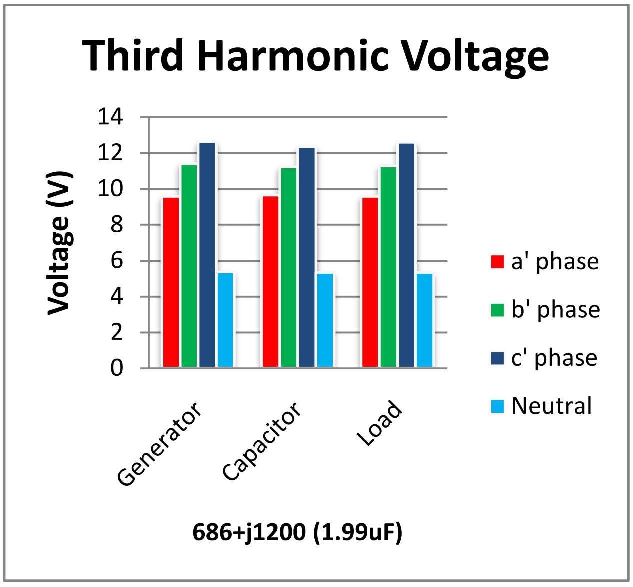


Figure 143: 3rd harmonic voltage for balanced R+L (686+j1200) with C (1.99uF)

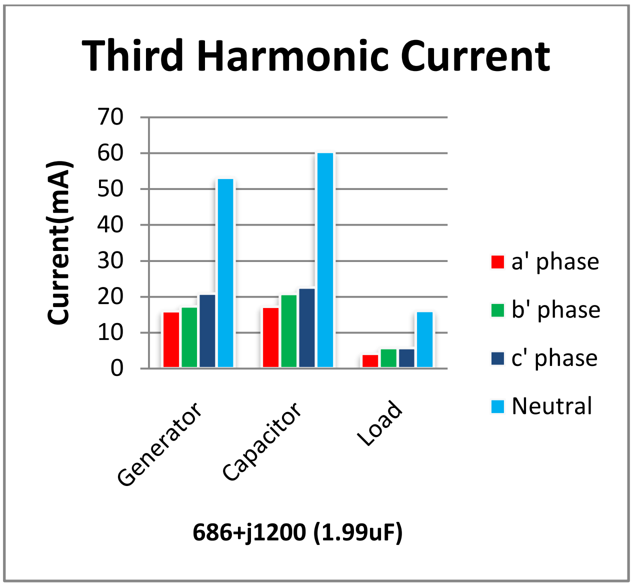


Figure 144: 3rd harmonic Current for balanced R+L (686+j1200) with C (1.99uF)

5. Balanced R+L (120+j960) with C

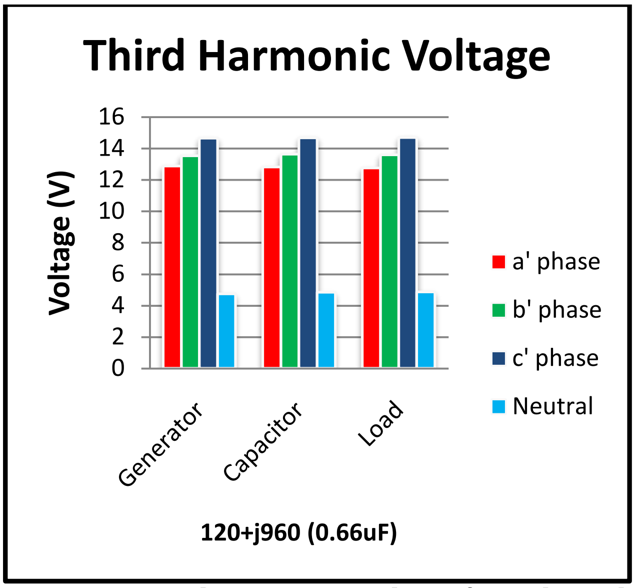


Figure 145: 3rd Harmonic Voltage for Balanced R+L (120+j960) with C (0.66uF)

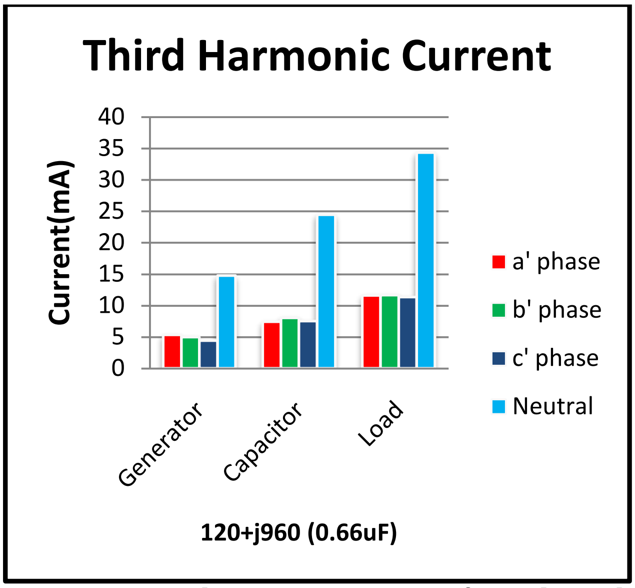


Figure 146: 3rd Harmonic Current for Balanced R+L (120+j960) with C (0.66uF)

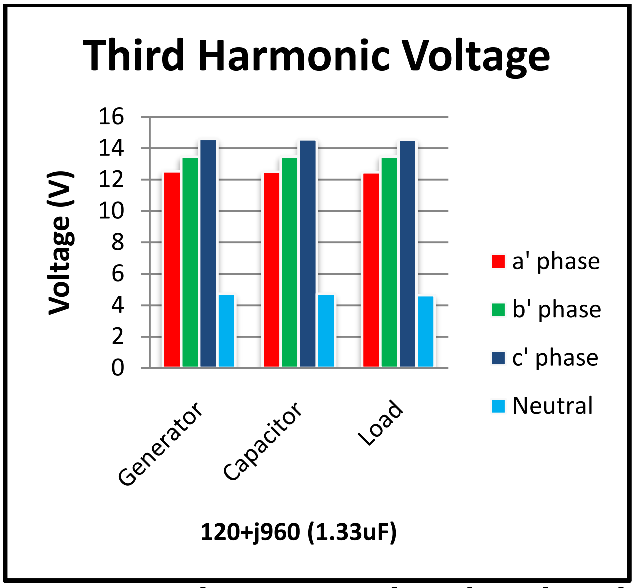


Figure 147: 3rd Harmonic Voltage for Balanced R+L (120+j960) with C (1.33uF)

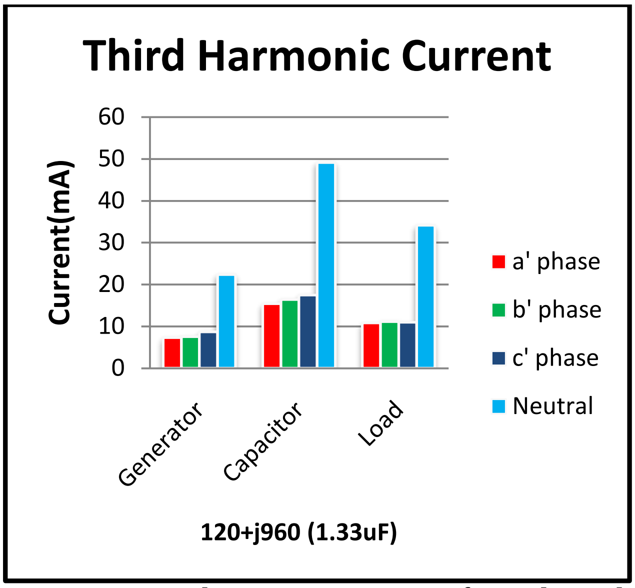


Figure 148: 3rd Harmonic Current for Balanced R+L (120+j960) with C (1.33uF)

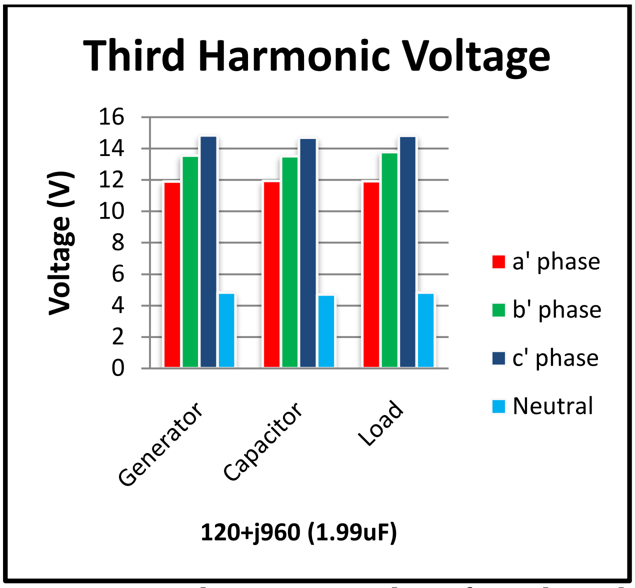


Figure 149: 3rd Harmonic Voltage for Balanced R+L (120+j960) with C (1.99uF)

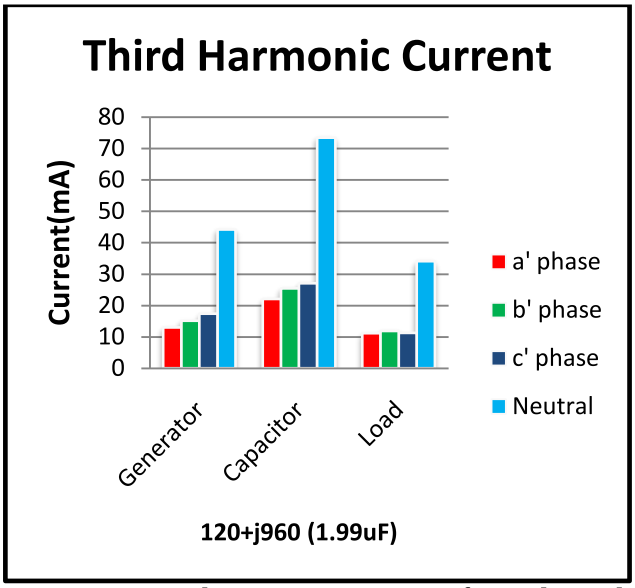


Figure 150: 3rd Harmonic Current for Balanced R+L (120+j960) with C (1.99uF)

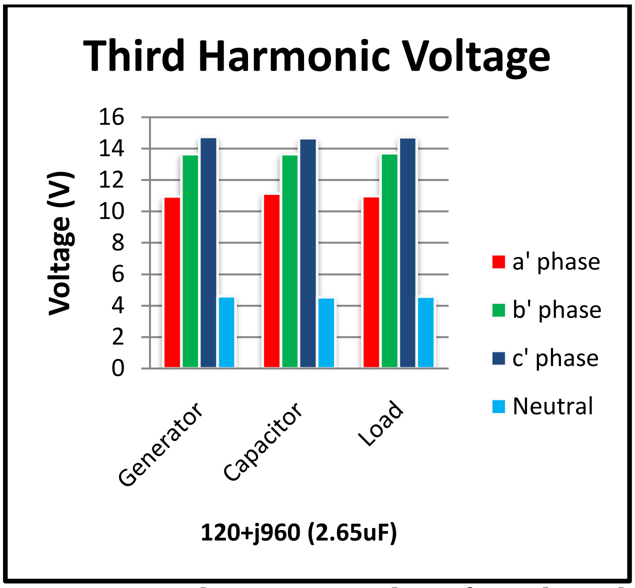


Figure 151: 3rd Harmonic Voltage for Balanced R+L (120+j960) with C (2.65uF)

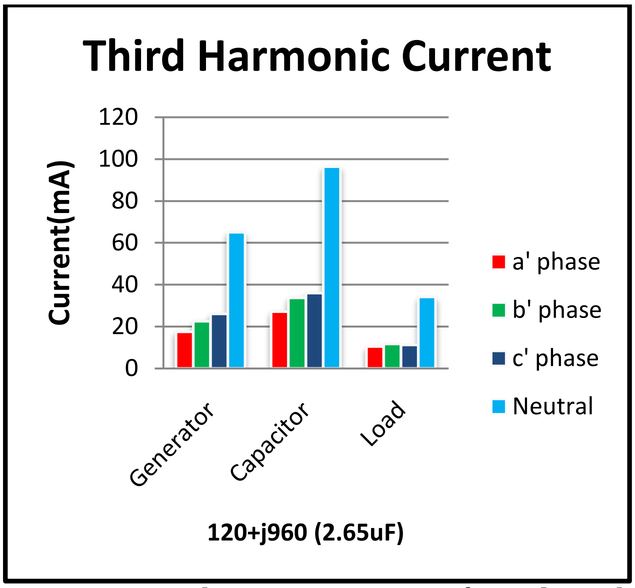
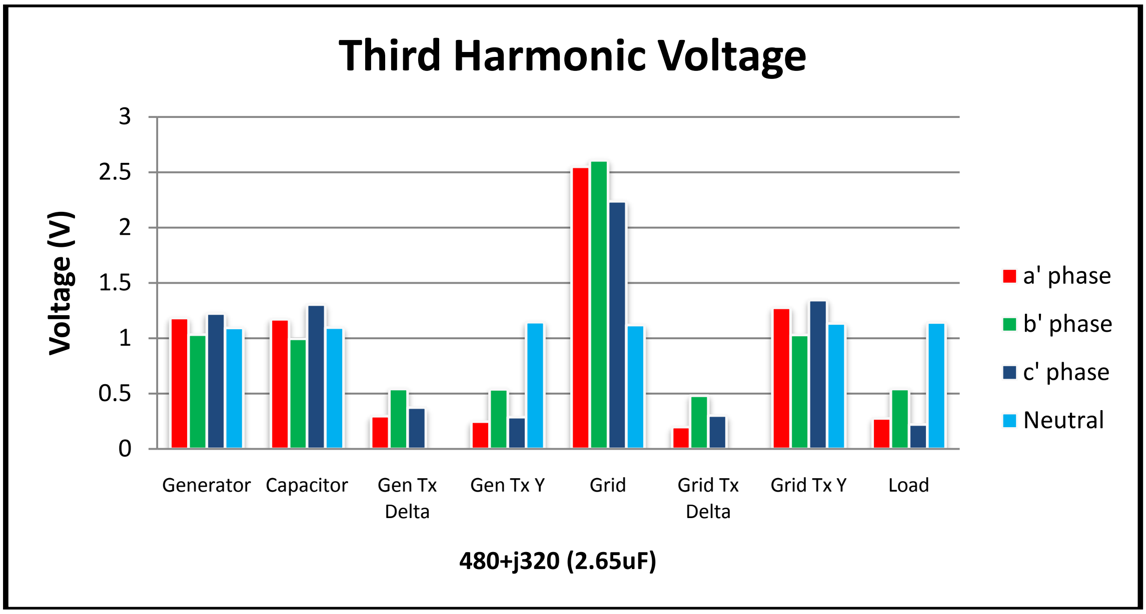


Figure 152: 3rd Harmonic Current for Balanced R+L (120+j960) with C (2.65uF)

Appendix D: Single generator parallel with grid connected to combined balanced resistive and inductive load with capacitor

1. 480+j320



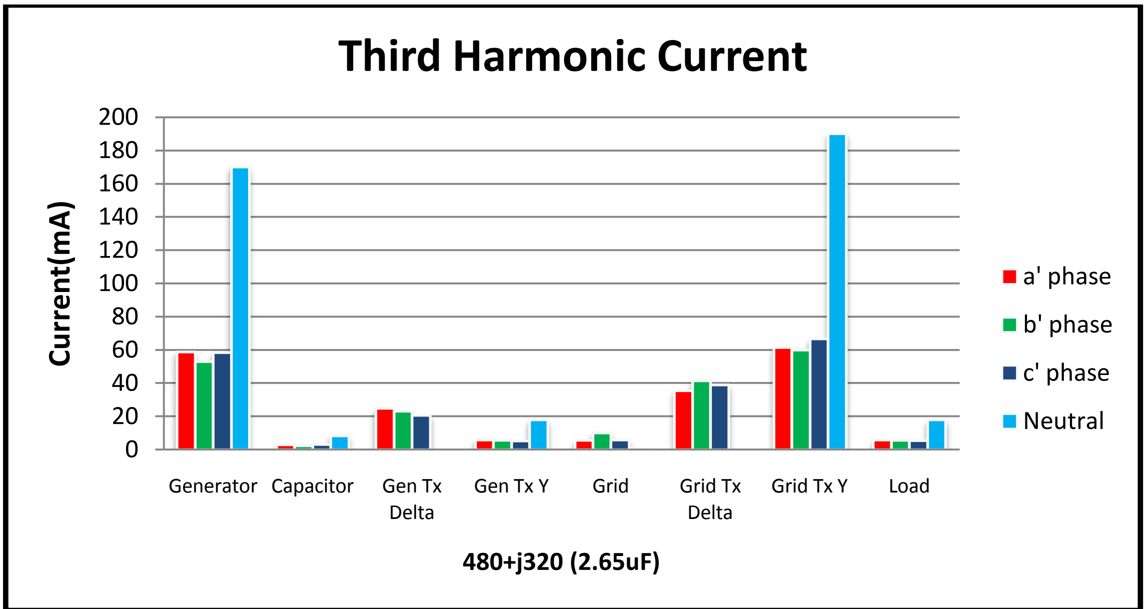
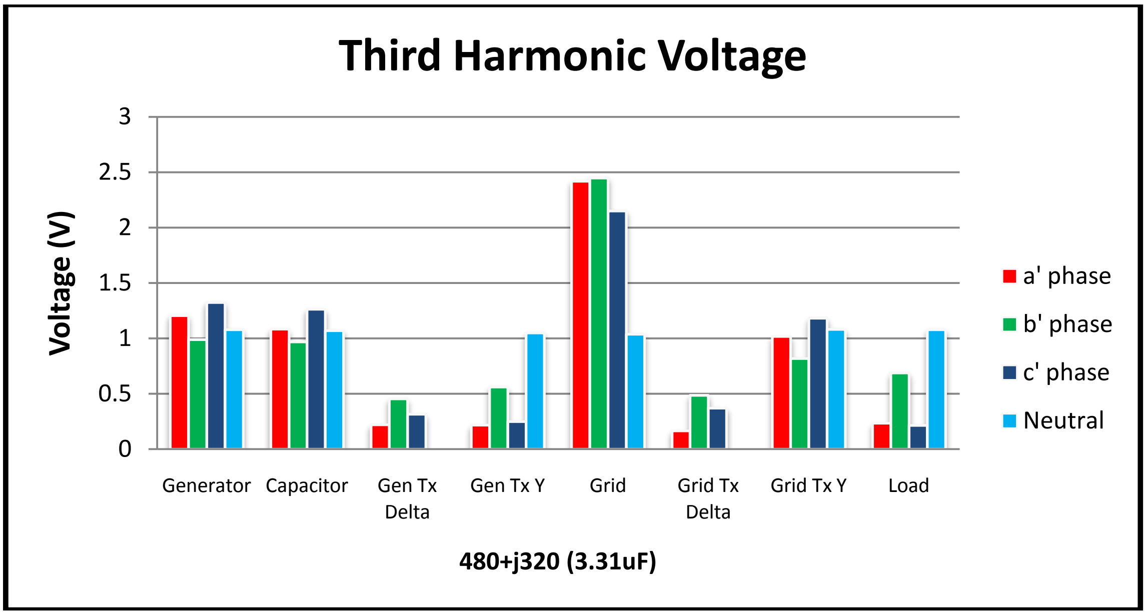


Figure 153: 3rd harmonic voltage and current for parallel 480+j320 with 2.65uF



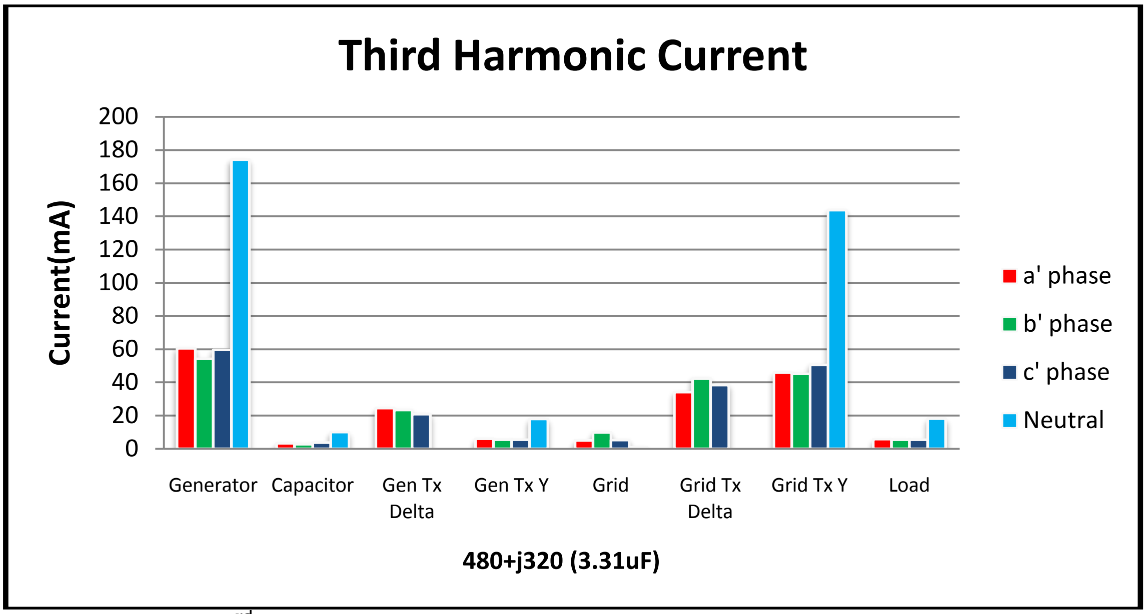
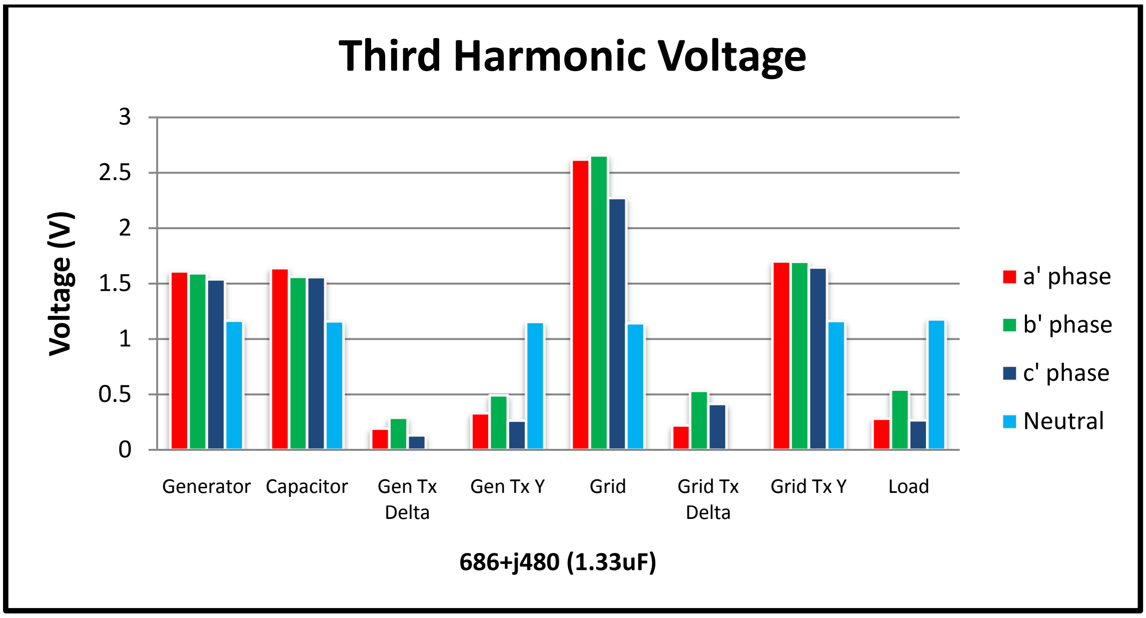


Figure 154: 3rd harmonic voltage and current for parallel 480+j320 with 3.31uF

2. 686+j480



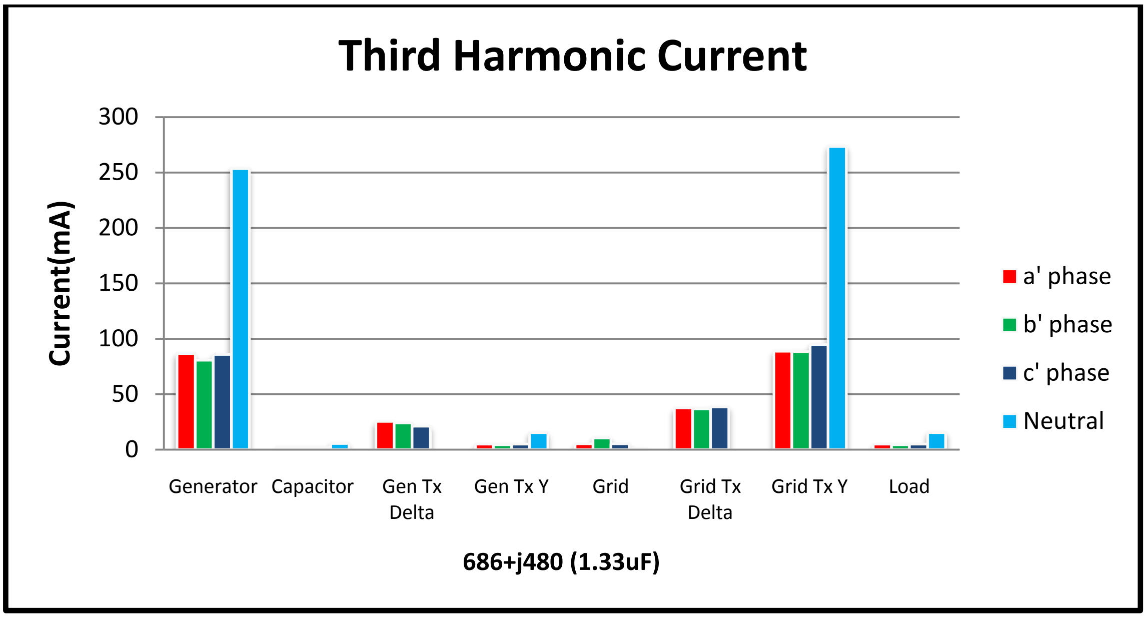
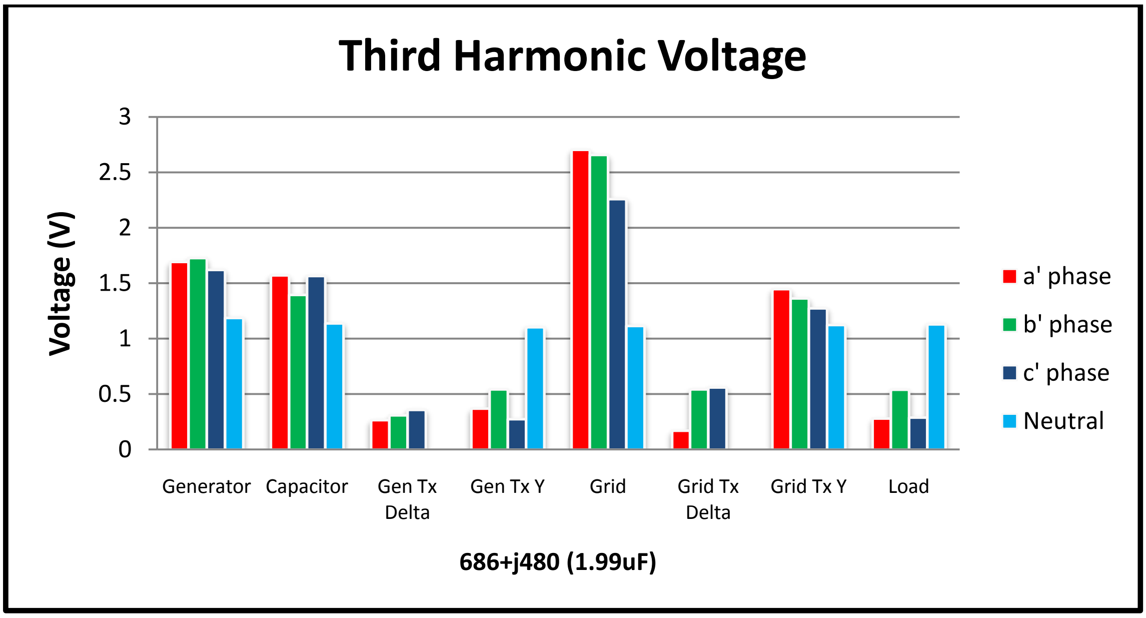


Figure 155: 3rd harmonic voltage and current for parallel 686+j480 with 1.33uF



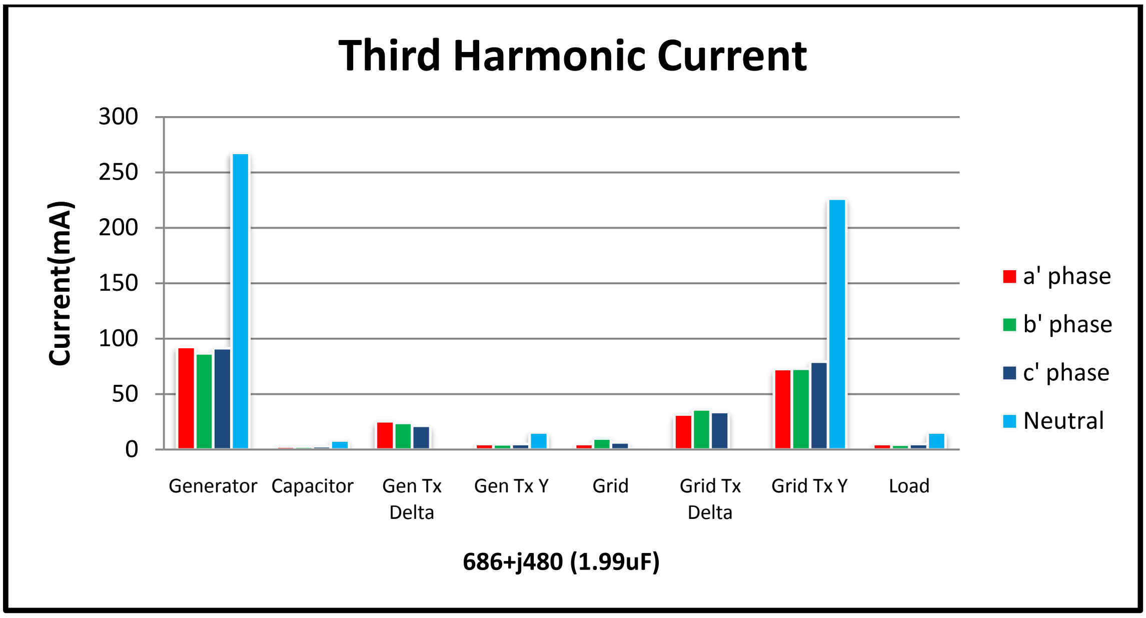
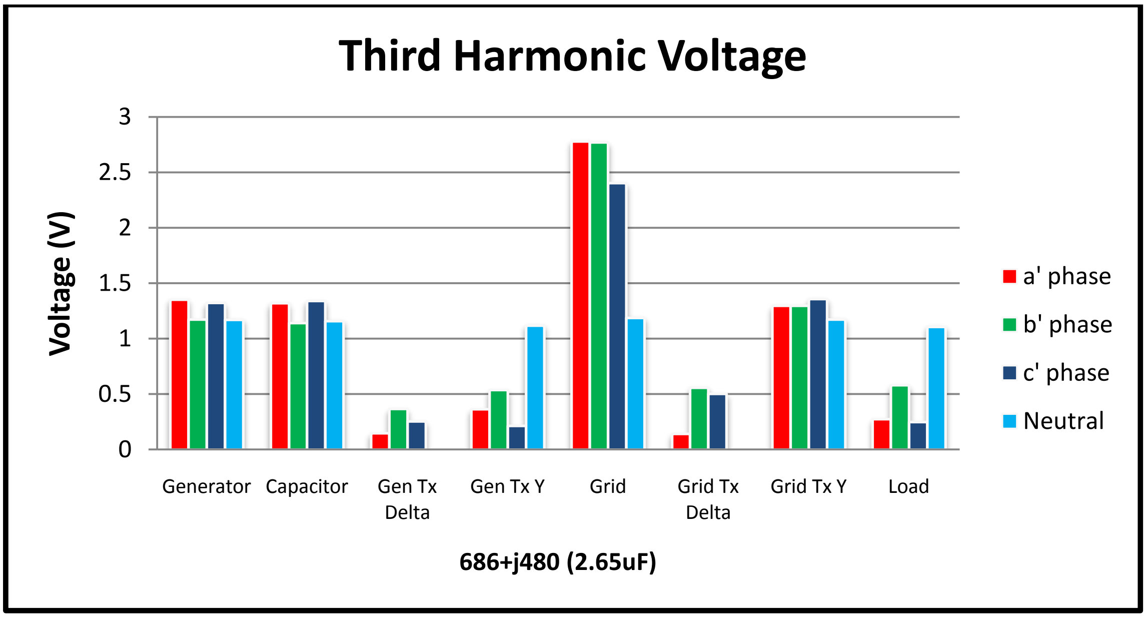


Figure 156: 3rd harmonic voltage and current for parallel 686+j480 with 1.99uF



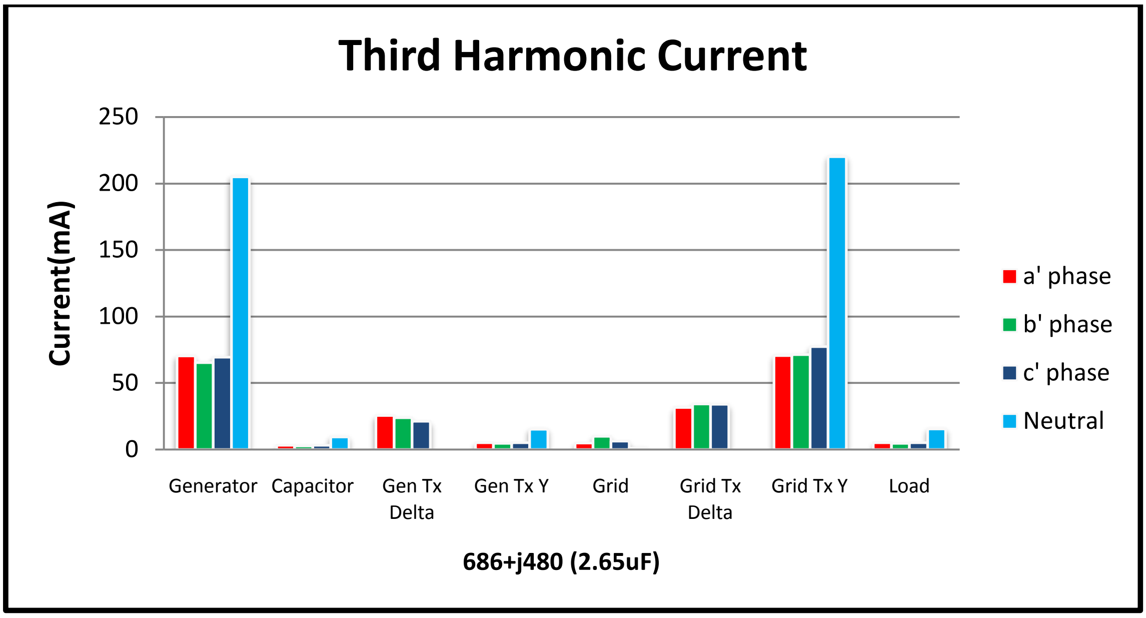
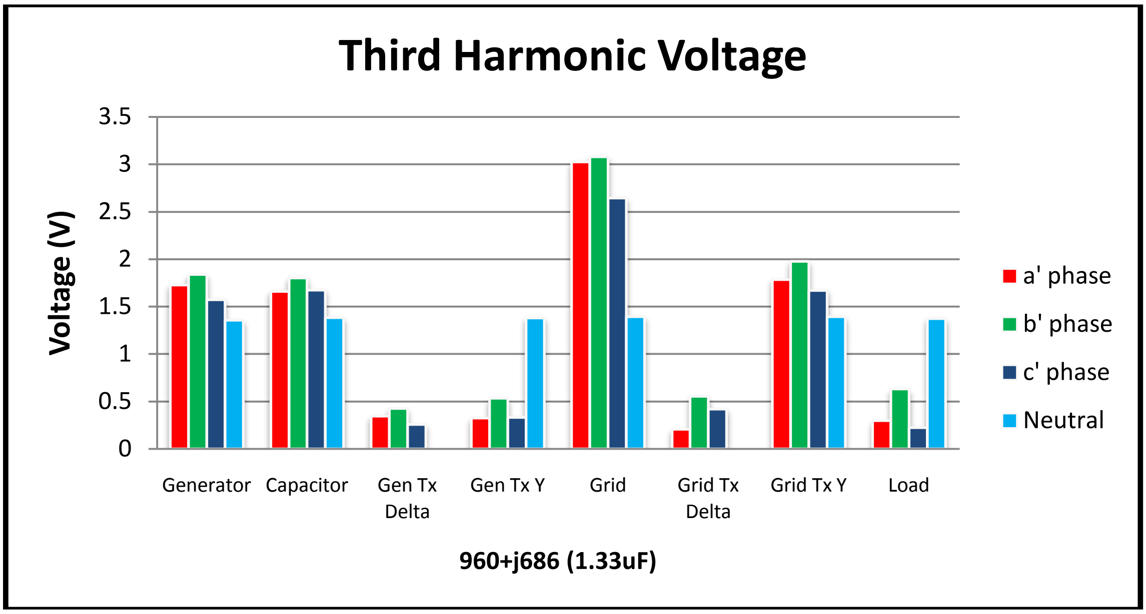


Figure 157: 3rd harmonic voltage and current for parallel 686+j480 with 2.65uF

3. 960+j686



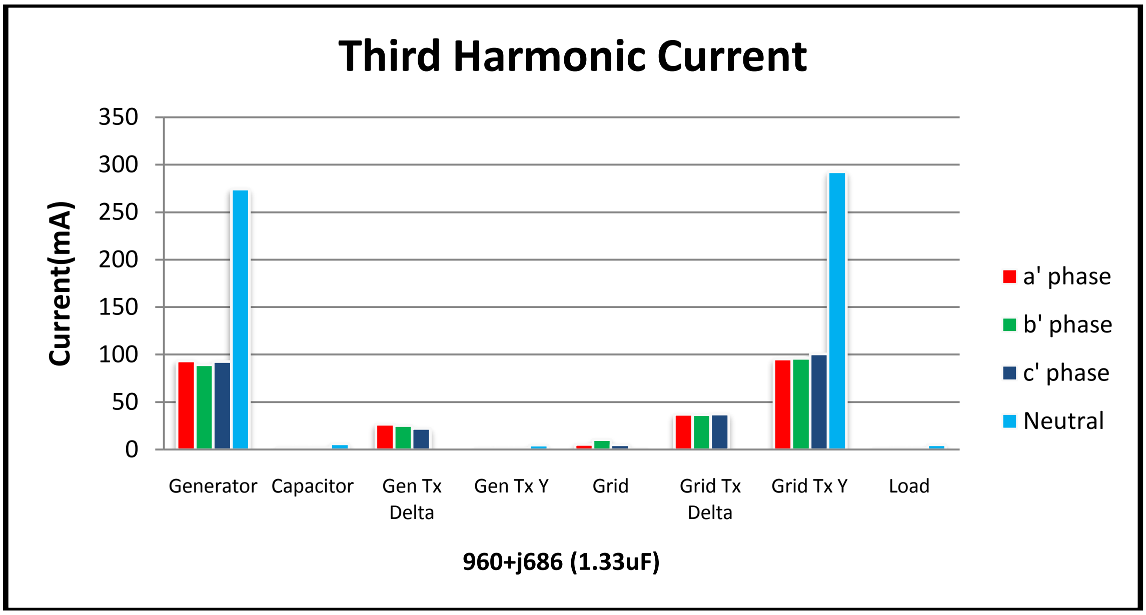
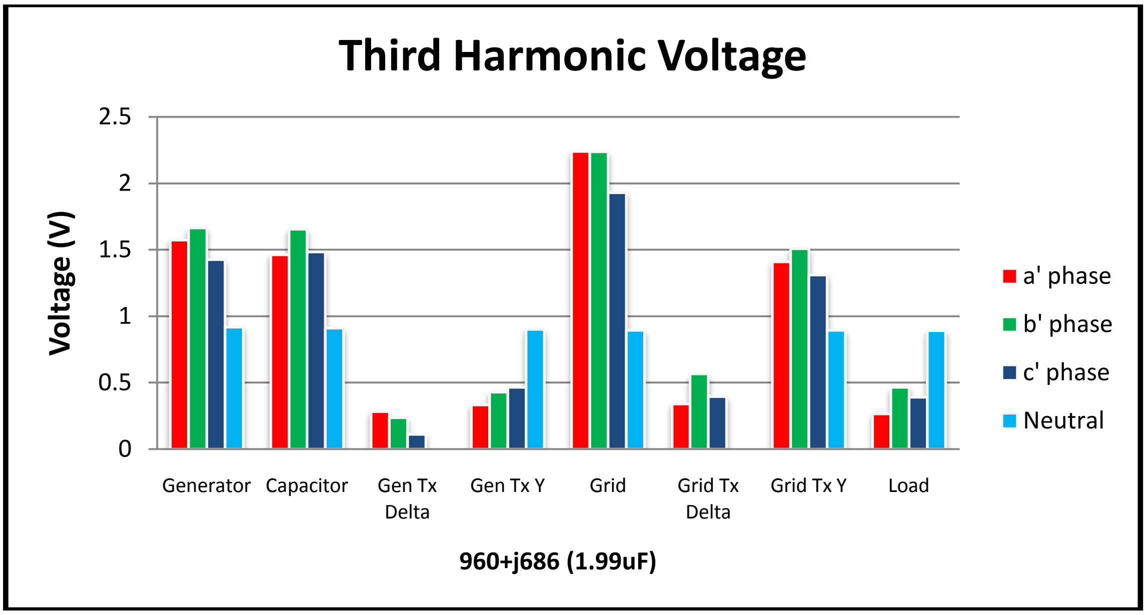


Figure 158: 3rd harmonic voltage and current for parallel 960+j686 with 1.33uF



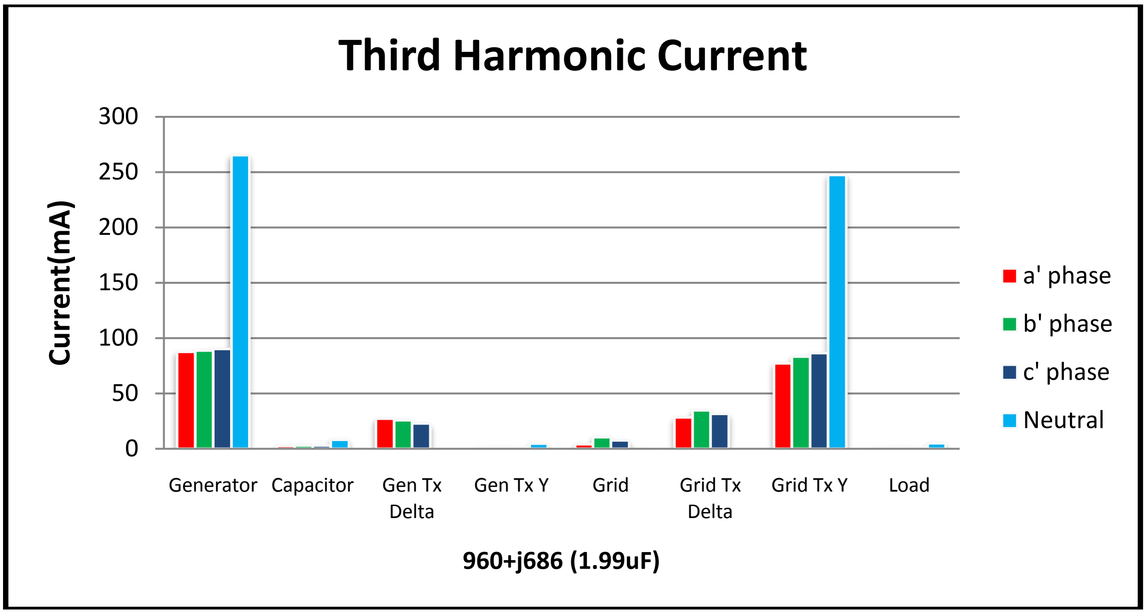
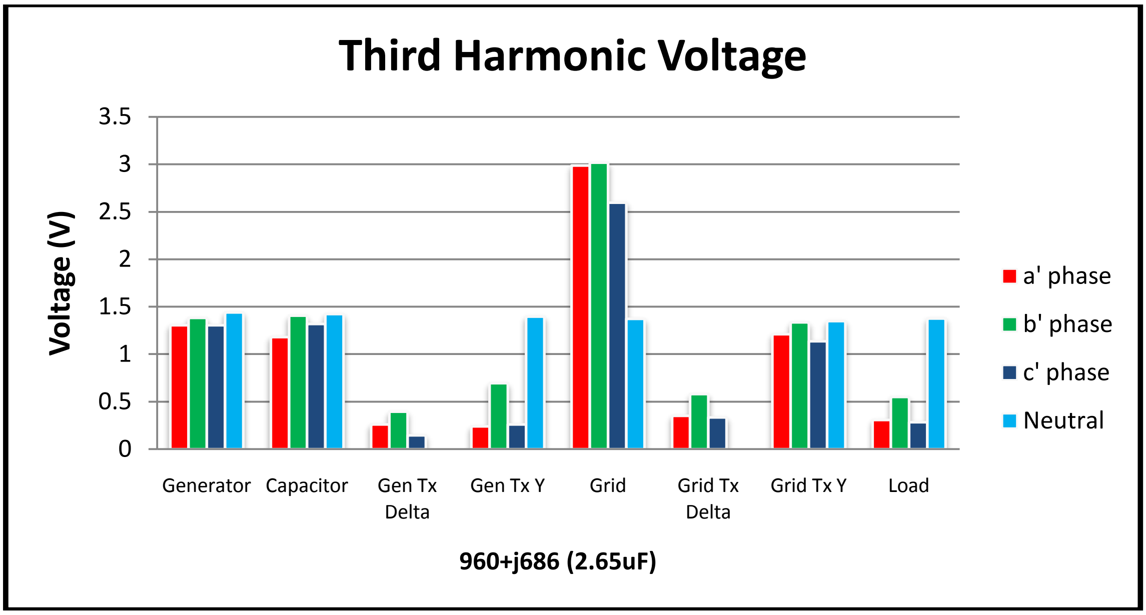


Figure 159: 3rd harmonic voltage and current for parallel 960+j686 with 1.99uF



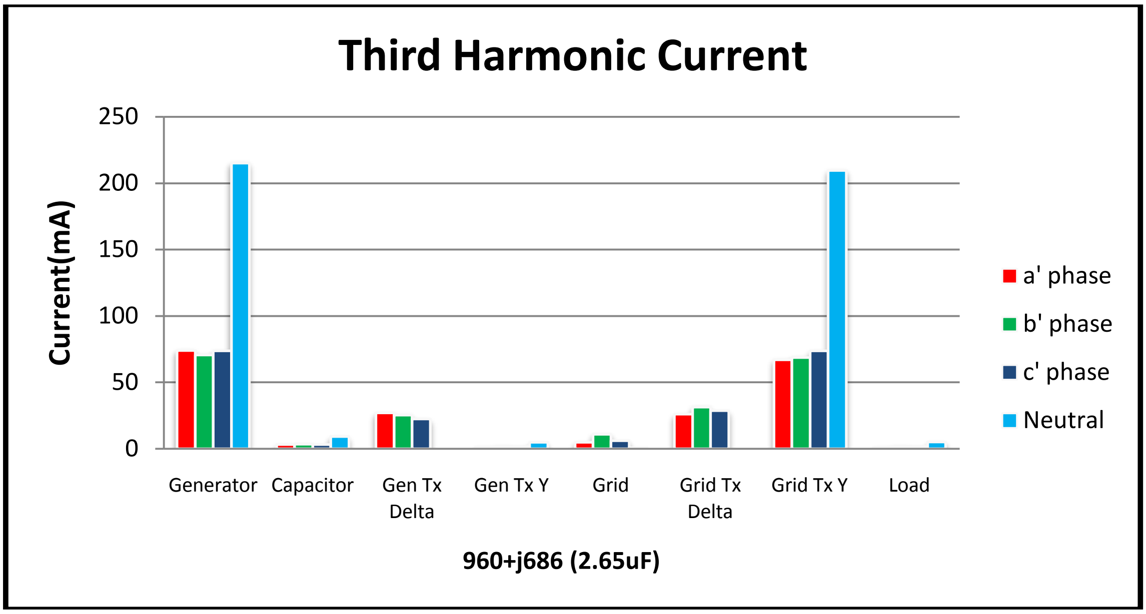
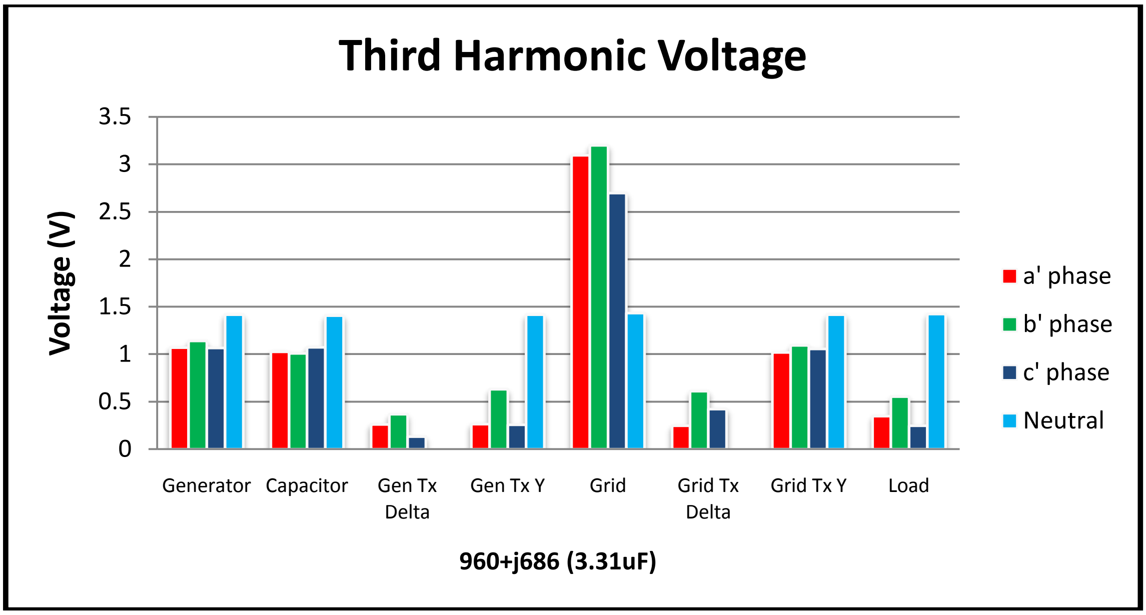


Figure 160: 3rd harmonic voltage and current for parallel 960+j686 with 2.65uF



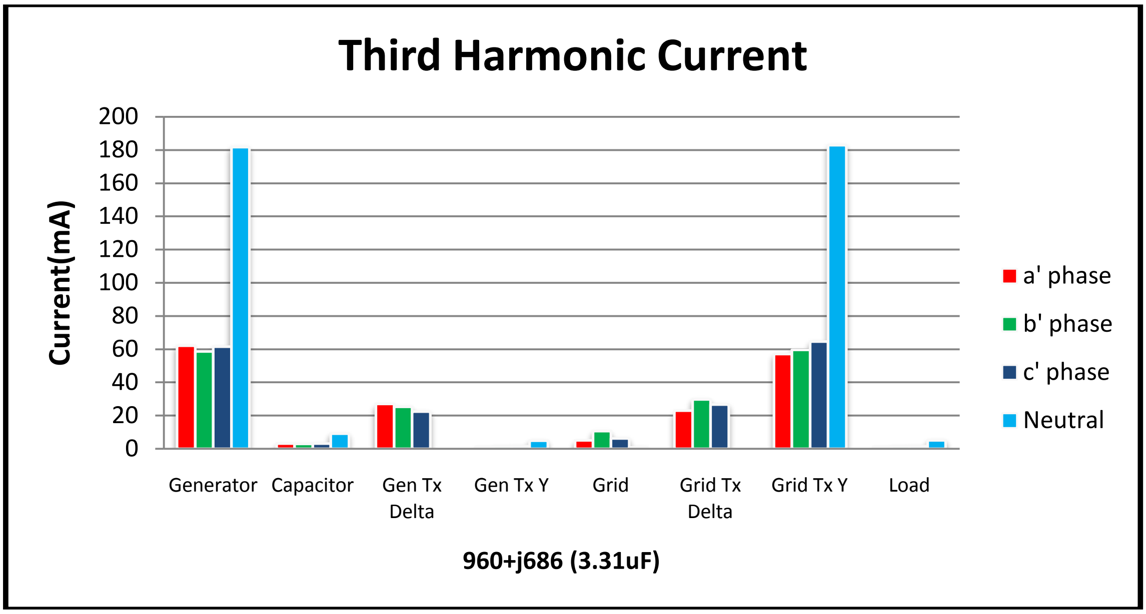
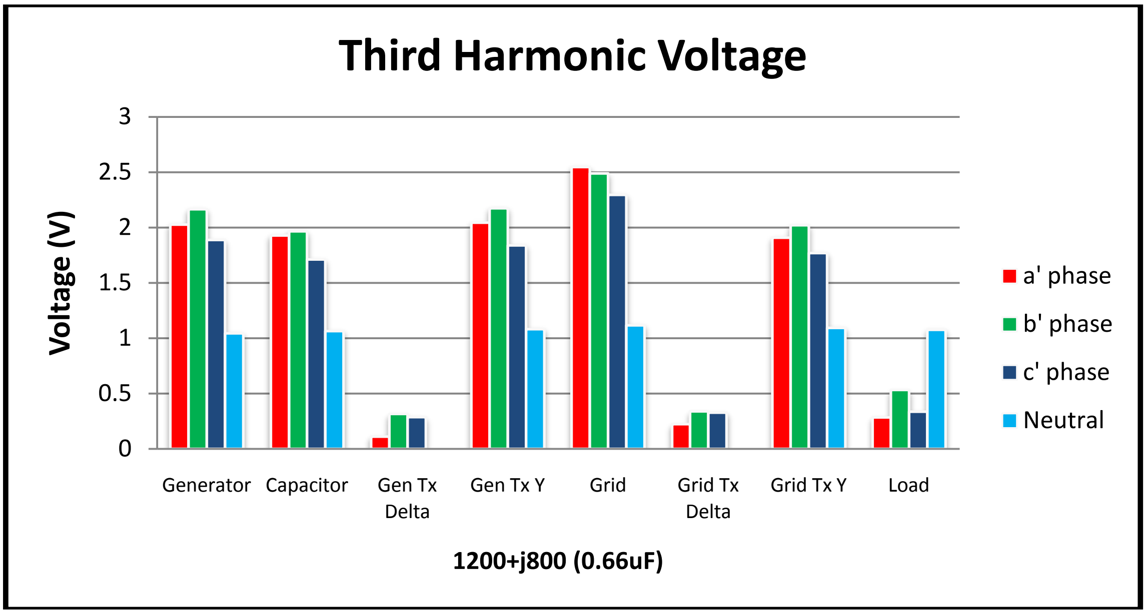


Figure 161: 3rd harmonic voltage and current for parallel 960+j686 with 3.31uF

4. 1200+j800



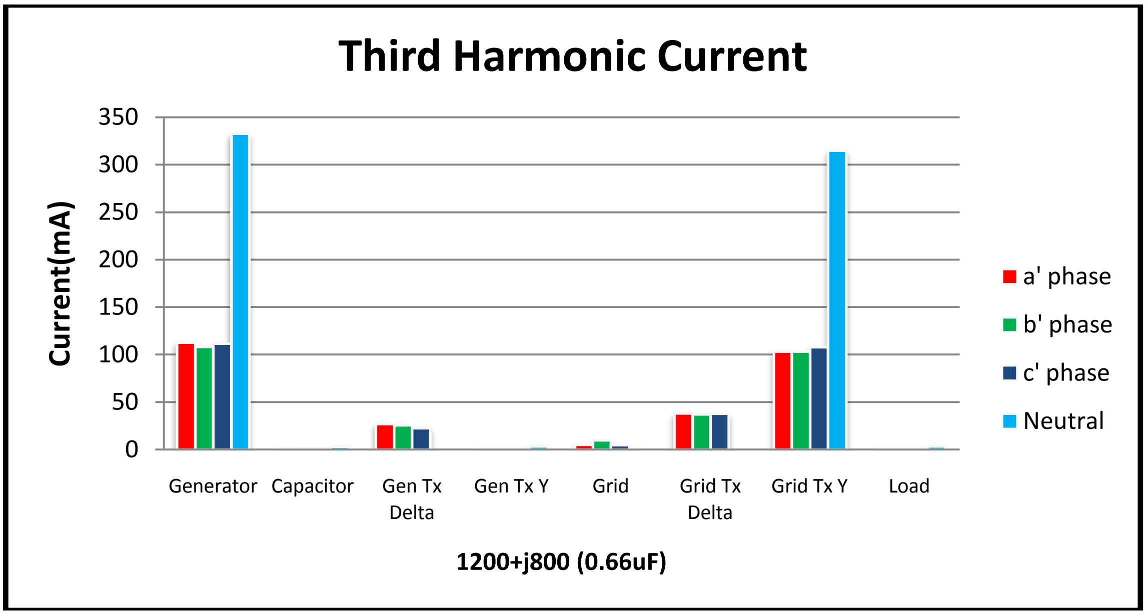
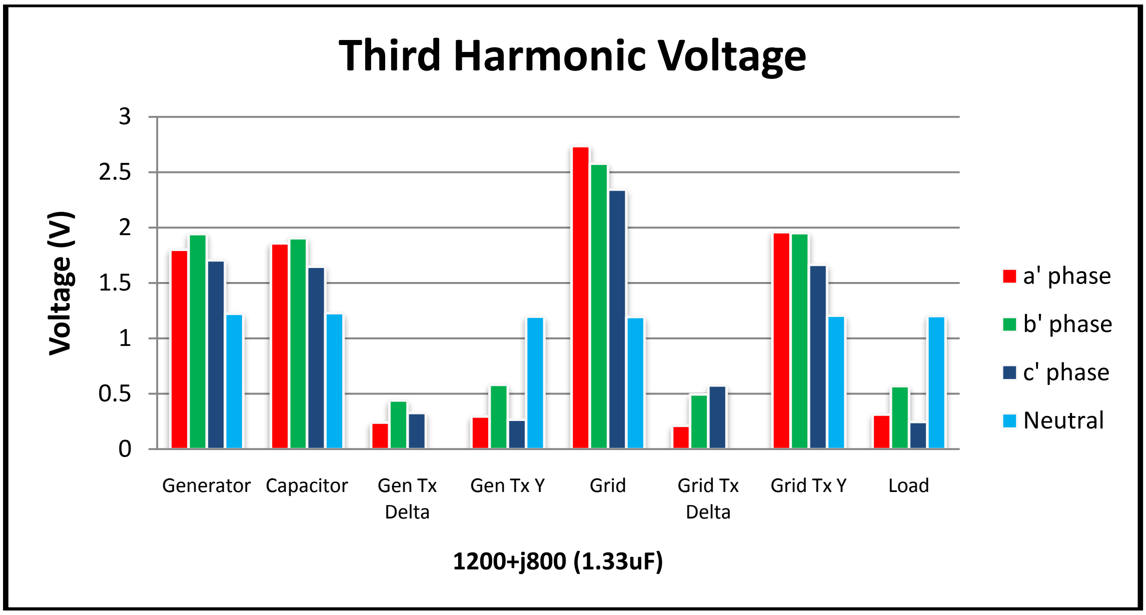


Figure 162: 3rd harmonic voltage and current for parallel 1200+j800 with 0.66uF



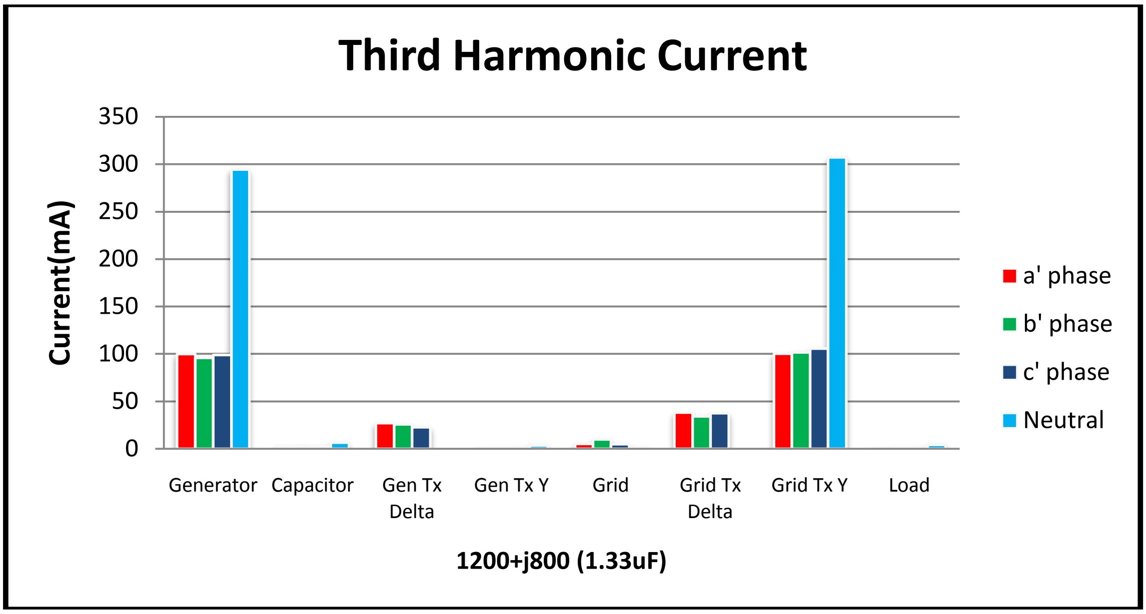
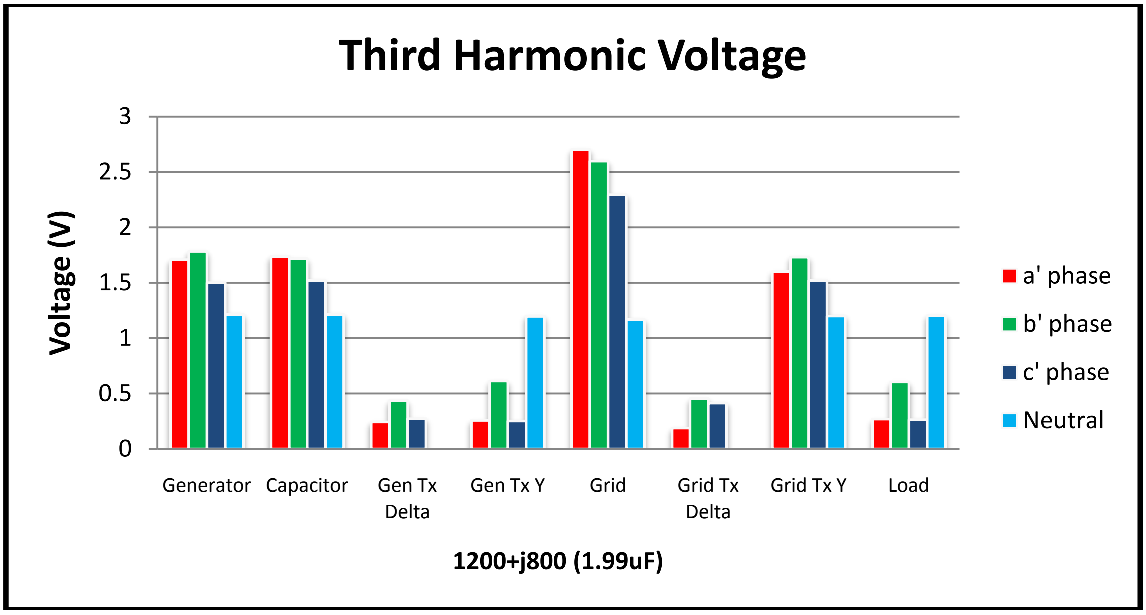


Figure 163: 3rd harmonic voltage and current for parallel 1200+j800 with 1.33uF



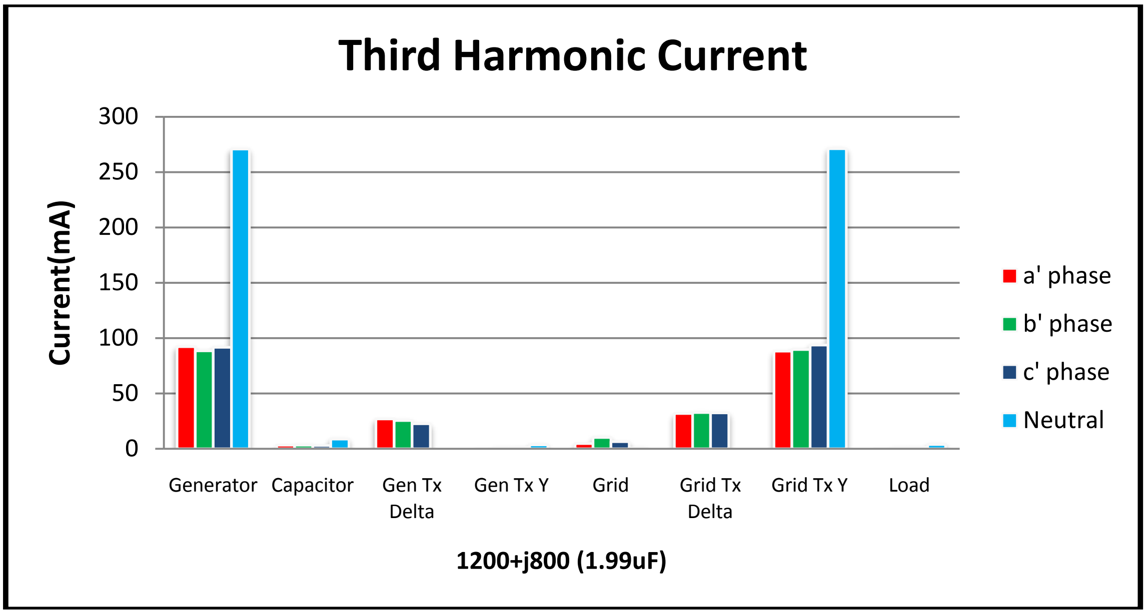
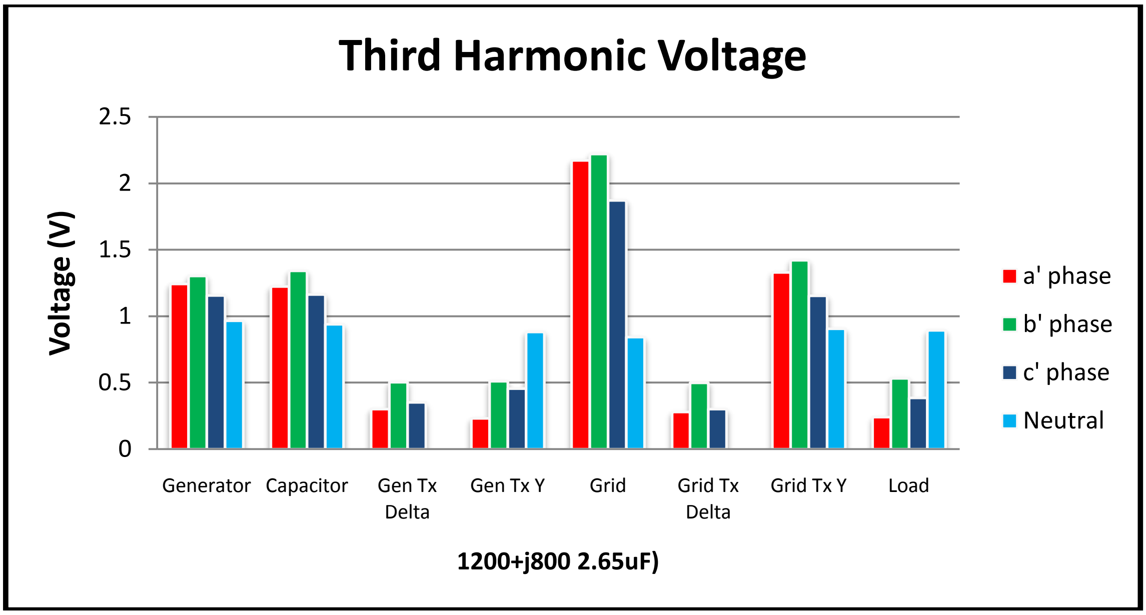


Figure 164: 3rd harmonic voltage and current for parallel 1200+j800 with 1.99uF



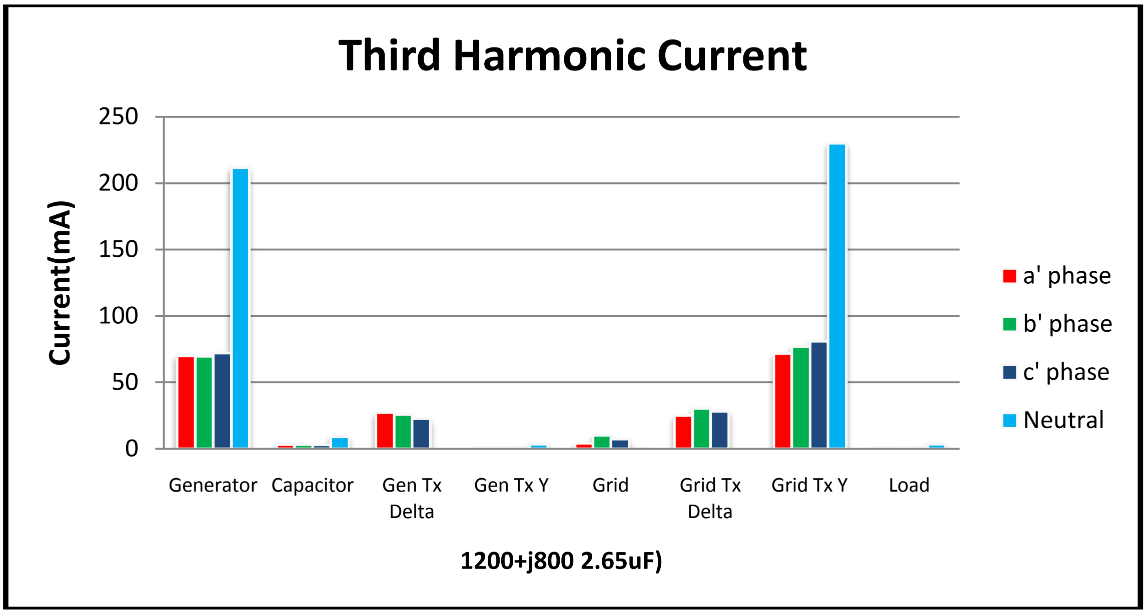


Figure 165: 3rd harmonic voltage and current for parallel 1200+j800 with 2.65uF