The Influence of Transformer Winding Configuration on Triplen Harmonic Produced by Synchronous Generator

By

Mohd Aizuddin Firdaus bin Mohmad Hamim
14067

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

May 2012

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

The Influence of Transformer Winding Configuration on Triplen Harmonic Produced by Synchronous Generator

By

Mohd Aizuddin Firdaus bin Mohmad Hamim

A project dissertation submitted to

Electrical and Electronics Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirements for the

BACHELOR OF ENGINEERING (Hons)

(ELECTRICAL AND ELECTRONICS ENGINEERING)

Approved by:

____

Ir Mohd Faris bin Abdullah

Project Supervisor

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.

____

Mohd Aizuddin Firdaus bin Mohmad Hamim

ACKNOWLEDGEMENT

At a very first, I would like to express my gratitude to God for giving me the strength to complete this project. Then, I would like to thanks to my parents, Mr Mohmad Hamim and Mrs Wan Azian for their support, encouragement, quiet patience and unwavering love were undeniably the bedrock upon which the past 23 years of my life have been built and all my family members who give me support and advise when I am in problem.

I would also like to thank my supervisor, Ir Mohd Faris Abdullah for giving the guidance and sharing his knowledge throughout the project. Not to forget the two technicians, Mrs Suhaili and Mr Zuraimi of the Power Systems Lab for their assistance and guidance in helping me in the laboratory.

My appreciation also goes to Universiti Teknologi PETRONAS especially Electrical and Electronics Engineering Department, by providing me the good facility and equipment for me to accomplish my project. I would also like to thank JPA for sponsoring my studies in Universiti Teknologi PETRONAS.

Last but not least, I offer my regards to those who support me especially Helmi, Anai and Izuddin for their help, discussions and information sharing. These friends and lab mates also provided for some much needed humour and entertainment in what could have otherwise been a somewhat stressful laboratory environment. Additionally, I would also thank all my friends for their support and guidance throughout the study period of time.

ABSTRACT

The existence of triplen harmonics in equipment has been recognized dated back in the 19thcentury. Even though many discovery has been made regarding the behavior of triplen harmonics in electrical equipment, many scope still needed to be studied and researched. Thus, the objective of this paper focuses on the characteristics of triplen harmonics produced by synchronous generator flowing through various transformer winding configurations subjected to several of load conditions. The scope of experiment for this study covers on the laboratory experiments using lab-scaled salient pole synchronous generator that connects directly to the transformer and load. The transformer has four winding configurations and the load can vary in different resistance and inductance connections in a circuit. Since the third harmonic voltage produced by generator are in phase or zero sequence in nature, the third harmonic current depend on transformer winding configuration, the load impedance magnitude and phase angle. In conclusion, this study provides a very important knowledge regarding the third harmonic flowing through transformer. Different kinds of transformer winding configuration have their own characteristic. Third harmonic voltage and current magnitude alone may not give correct indication to their severity because they are vector quantity and rely on zero sequence network, load impedance magnitude and phase angle.

TABLE OF CONTANTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Universiti Teknologi PETRONAS (UTP) campus has been operating its own power plant since last 10 years covering the area of 4 square kilometers (990 acres). The electricity is supplied by two gas turbine units at the gas district cooling (GDC) plant located inside campus and UTP medium voltage network also interconnected to utility grid. Each generator capable to produce 4.2 MW and maximum demand for overall activities in UTP is 7.9 MW. Power system in this campus operates in island mode during normal operation. However, during emergency or maintenance for one of the generators, the system will be connected in parallel to the utility grid of Tenaga Nasional Berhad (TNB) as shown in Figure 1 in order to top-up the generation shortage. Recent study revealed that on both condition of island mode and parallel operation, triplen harmonics propagates through neutral earthing resistor (NER). It is observed that significant increase of temperature especially in parallel condition where each generator is grounded separately through 31.75Ω NER rated at 200 Amps for 10 seconds.

With the increase of temperature as one of the effects of triplen harmonic current propagation, it clearly shows that the existence will produce more disadvantages. Series of studies need to be conducted in order to understand the behavior of triplen harmonics produced by synchronous generator flowing through transformer under various load conditions, so at the end they can be eliminate or reduce. Therefore, many power system units having similarity with GDC is facing the occurrence of triplen harmonics in the distribution system.

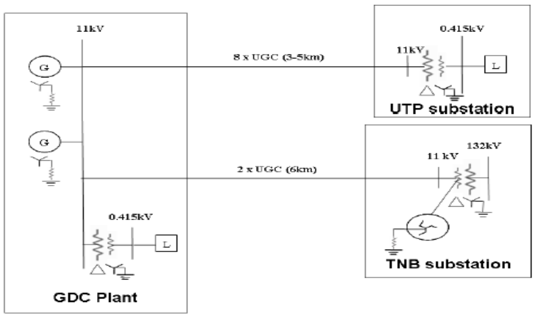


Figure 1: Simplified UTP medium voltage network [1]

1.2 Problem Statement

Recent study revealed that synchronous generator produced its own triplen harmonic. These triplen harmonic produced by the generator has caused the temperature of the generator neutral earthing resistor high. In addition, suitability of winding configuration for transformer due to numerous transformers available in the power system area needs to be studied.

1.3 Objective of Study

The objectives of this project are:

- To study on the characteristics triplen harmonic produced by synchronous generator directly connected to load.
- To identify the characteristics of triplen harmonic produce by synchronous generator for island mode and parallel with grid when flowing through various connection of transformer winding configurations under different loads.

1.4 Scope of Study

The scope of study mainly begins with understanding the theory of triplen harmonic covering the characteristics, behavior and factor of existing. Besides, the connection between generator and step down transformer winding configuration and end with loads being mainly focus for this study regarding on triplen harmonic. Laboratory experiments using a lab-scaled synchronous generator are being the practical mode to analyze relationship between transformer winding configurations with theory of triplen harmonic.

1.5 Relevance of the Project

Triplen harmonic study is very important because their existing is a major cause of increasing heat at neutral earthing resistor. This problem eventually occurs mostly at all power generation system that used island mode. In addition, all platforms are generating power using their own generator, so it can also be considered as island mode. Hence, this triplen harmonic problem will occur at the platform. Besides, most of PETRONAS plant also will have this problem as well as they are also generating their own power system.

1.6 Project Feasibility

The project is planned and scheduled to be done within 2 semesters. For that kind of purpose, all activities need to be planned and scheduled systematically. The approach planned to use is by running the lab-scaled experiment. All the data is collected and being examine. Then, data will be analyzed to identify the characteristics of triplen harmonic produced by generator when flowing through transformer. This investigation will revolve on the effects of triplen harmonic towards transformer, generator and load.

CHAPTER 2

LITERATURE REVIEW

2.1 Triplen Harmonic

Harmonic by definition is a steady state distortion of the fundamental frequency and for Malaysia it is standardize with 50 Hz. Harmonic distortion of current occurs when sinusoidal voltage is applied to a non-linear load. This distortion occurs in integer multiples of the fundamental frequency. Hence, the 2nd harmonic has a frequency as,

$$f = 2 \times 50 = 100 \text{ Hz}$$

and so on. In distribution system, harmonic currents are a result of voltage distortion generated indirectly when flowing through system. Besides, normally harmonic currents exist or widely found are coming from odd-order harmonics such as 3rd, 5th, 7th, etc. as shown in Figure 2 and even-order harmonics basically not exist due to cancel out between positive and negative sequence. Secondly, more often than not, the sources of the harmonic currents in distribution system are switched electronics device and non-linear load [1].

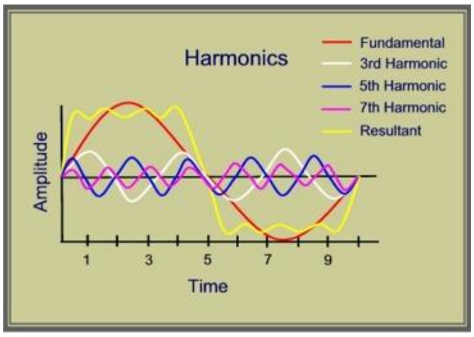


Figure 2: Waveform of harmonics [1]

While triplen harmonic are defined as the odd multiples of the 3rd harmonic such as 3rd, 9th, 15th, etc. Balance triplen harmonic are more likely being concern because they are zero sequence harmonic, unlike the fundamental, which is positive sequence. Hence, the magnitude of these currents on the 3 phases are additive in the neutral [1] as shown in Figure 3. These currents can also circulate in the transformer causing significant overheating.

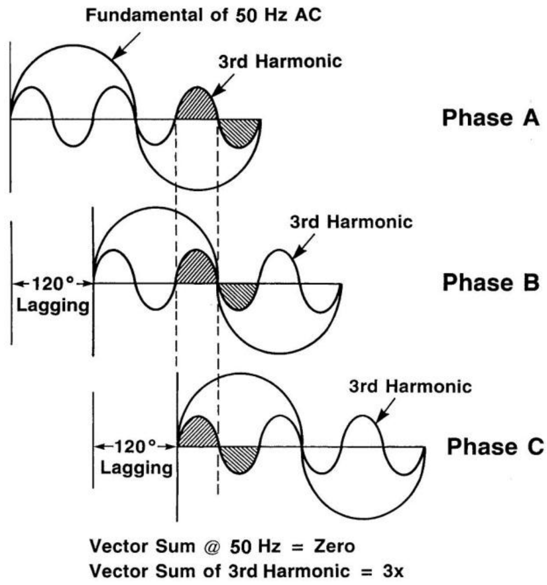


Figure 3: 3rd harmonic waveform characteristic [1]

Transformers in power system are usually used delta-star winding configuration because it reduces the quantity of triplen harmonic when delta connection is trapping triplen harmonic from flowing through secondary side which is star connection.

2.2 Harmonic Analysis by Mathematics

Generally, harmonic analysis is a process of calculating magnitudes and phases of fundamental and higher order harmonics of the periodic waveform. Based on IEEE Standard 519-1992 1993, harmonic is basically derived from mathematical modeling term of analyzing currents and voltages occur during operation period. Generally, distorted waveform will cause the harmonic where it can be transform into frequency spectrum [3] as shown in Figure 4.

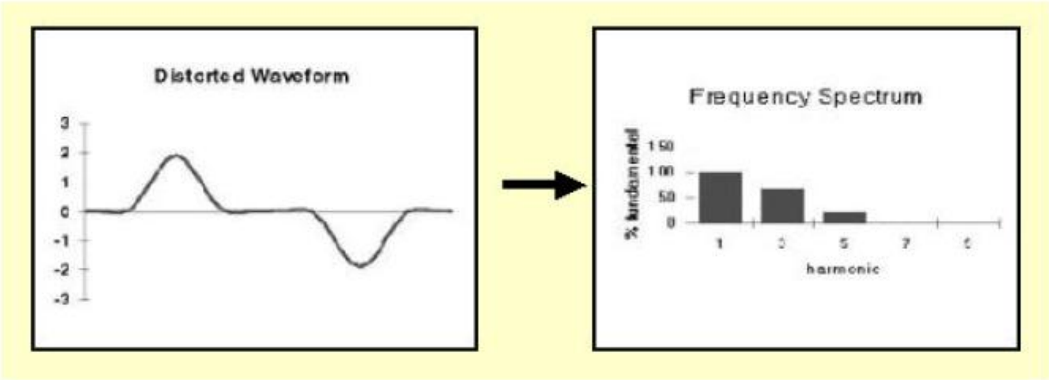


Figure 4: Relationship of Distorted Waveform with Frequency Spectrum [3]

With fundamental frequency of 50 Hz in Malaysia, frequency spectrum can be expressed as a mathematical equation where it is stated as,

fh= h x 50 Hz

where:
h is the harmonic order

In harmonic analysis, process of deriving magnitudes of voltages and currents is important to be analyzed as a major mathematical calculation as well. Another series of harmonic analysis commonly applied in electrical power system by using mathematical equation is known as Fourier analysis. Fourier series equation is used as a medium or platform to expand the voltage or current waveform representation from frequency component into frequency spectrum and sum it up together with harmonics components [4]. The Fourier Series equation is given as:

$$V_t = \alpha_0 + \sum V_h \sin(h \times 2\pi f t + \theta_h)$$

where:
α_0 is the peak voltage level
f is the fundamental frequency of 50Hz
t is running time
h is the harmonic order
θ_h is the phase angle of harmonics

Apart from that, Total Harmonic Distortion (THD) can also be used to measure the harmonic distortion in percentage of the system voltage to fundamental voltage on a power system [4]. The total harmonic distortion (THD) of a signal is the ratio of the sum of the all harmonic frequencies above the fundamental frequency. The THD is usually expressed in percentage and measurements for calculating the THD are made at the output of a device under specified conditions.
The THD is defined by the following formula:

$$\%THD = \frac{\sqrt{H_2^2 + H_3^2 + \ldots + H_N^2}}{\sqrt{H_1^2 + H_2^2 + H_3^2 + \ldots + H_N^2}} \times 100$$

where N is referred to the harmonic level and 1 is used only for fundamental level.

2.3 Triplen Harmonics Current Problem in Three Phase System

In three phase power systems, neutral current is the vector sum of three line-to neutral currents. During three-phase balanced condition, linear currents which consist of sine waveforms spaced 120 electrical degrees apart. Thus, the sum at any time is zero and no neutral current.

There are certain situations where balanced single-phase loads can produce neutral currents. Generally, nonlinear load have phase currents which are not sinusoidal waveform. The vector sum of balanced, nonsinusoidal and three phase currents does not necessarily equal to zero. The triplen harmonic currents are in phase with each other and add in the neutral circuit. Small neutral current may not cause problems at the power distribution system but high neutral can cause overload in power feeders, transformers, voltage distortion and also noise [5].

2.4 Harmonic Produced by Salient Pole Synchronous Generator

Synchronous machine is an ac rotating machine of speed under steady state condition that is proportional to the frequency of current. Basically, salient is projecting toward a line, surface or level. In this case, salient may refer to field winding configuration of synchronous generator. For a salient pole machine, the windings are wrapped around "teeth" (typically of the rotor). Publication studies state that synchronous generator produce triplen harmonics based on the winding such as pitch and distribution factor, and slot skew [6]. For no load condition, salient pole shape and field winding synchronous also caused third harmonic voltage [7].

2.5 Transformer Winding Configurations

The three phase transformer primary and secondary windings are mainly connected in the following ways,

- Star-Star
- Star-Delta
- Delta-Star
- Delta - Delta

For star-star connection, the advantages of applying this configuration are more economical than other connection, better economic fusing than delta connected primary winding [8]. While, the disadvantages are the distributed generation witness the same imbalance phase as the utility. Secondly, in terms of harmonic, star to star connection will just pass zero sequence harmonic currents. This type of direct flow may feed into any fault thus resulting in an increase in fault damage.

For star-delta configuration, the advantage is the triplen harmonic from primary winding side which is delta connection does not allow to flow through secondary winding connection by trapping the harmonic [9]. On the other hand, excessive current may occur at the primary side due to the high temperature increased.

For delta-star transformer winding configuration, the advantage of this connection is triplen harmonic cannot be flowing at secondary side after blocked by delta connection at the primary side. Unfortunately, triplen harmonic current that exist in the primary side are contributing to generator heating that could cause to equipment failure [10].

Lastly is the delta-delta transformer winding configuration. This connection is preferred because of the inherent reliability of the delta configuration. The disadvantage of delta to delta connection could lead to overvoltage and overcurrent resulting in equipment failure [10].

CHAPTER 3

METHODOLOGY

In this chapter, the process of the experiment is being explained in detail to give full information how the lab is conducted with all the equipment and tools needed. Besides single line circuit diagram is also attached.

3.1 Research Methodology

Flowchart is one of the visual aid used to illustrate in detail the sequence of the project conducted. Figure 5 is explained the detail activity regarding this project in sequence.

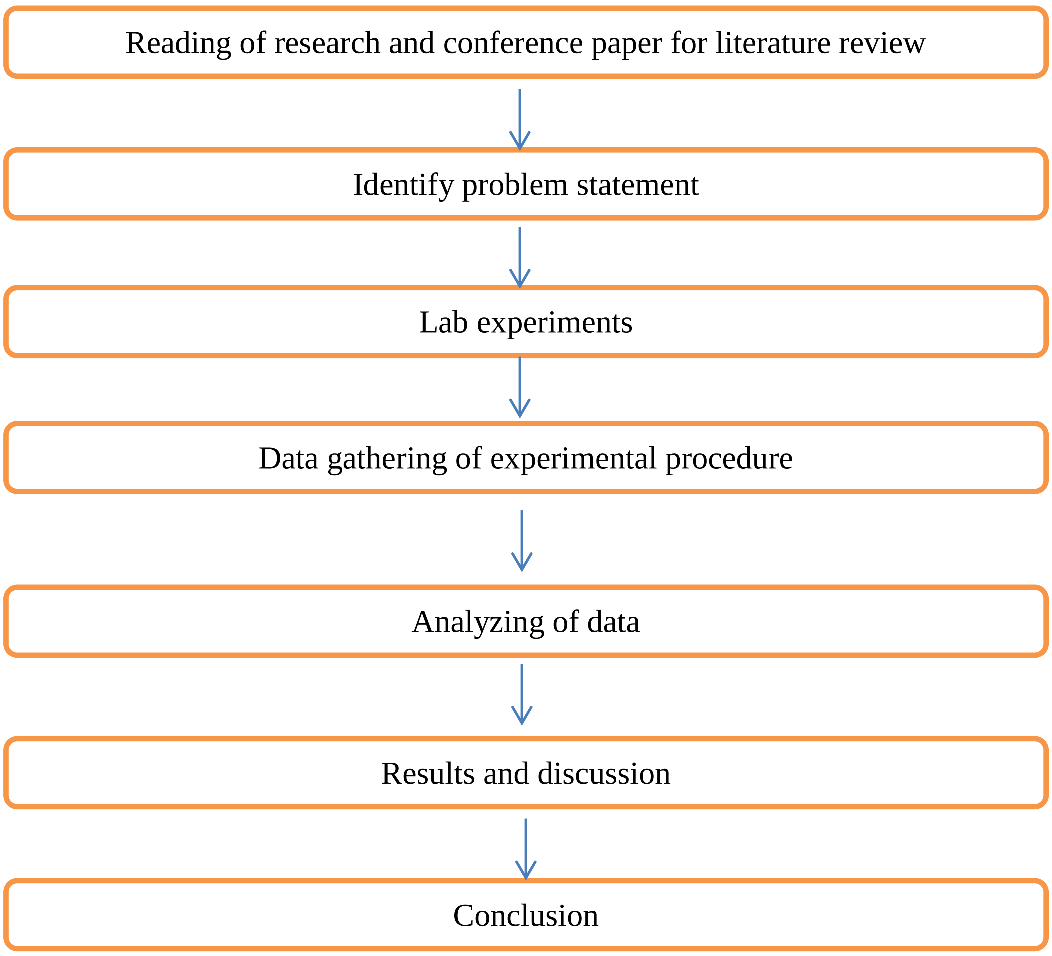


Figure 5: Flow chart of the research methodology

3.2 Project Activities

All the activities are divided into 3 parts which are literature review, lab experiment and analyze data. Figure 6 will explained more detail for the respective parts.

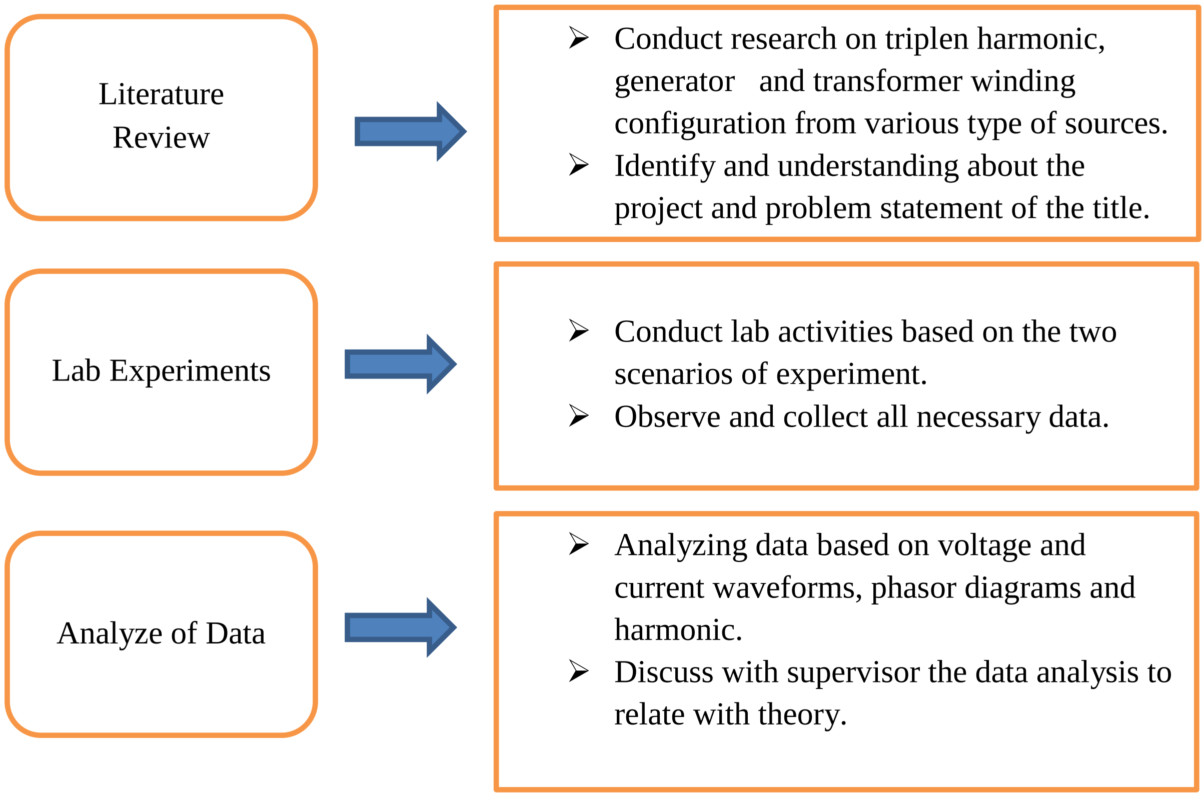


Figure 6: Detail of the project activities

3.3 Key Milestone

Key milestone or also known as progress achieve target is ideally important to be identified early. By having this target, all the progress works have to be followed based on the schedule. Figure 7 shows the entire important key milestone for both semesters.

- FYP 1

WEEK 6

Submission of Extended Proposal Defense

WEEK 13

Submission of Interim Draft Report

WEEK 14

Submission of Interim Report

- FYP 2

WEEK 8

Submission of Progress Report

WEEK 11

Poster Presentation for Pre-Sedex

WEEK 13

Submission of Draft Report

WEEK 14

Submission of Final Report and Technical Paper

WEEK 15

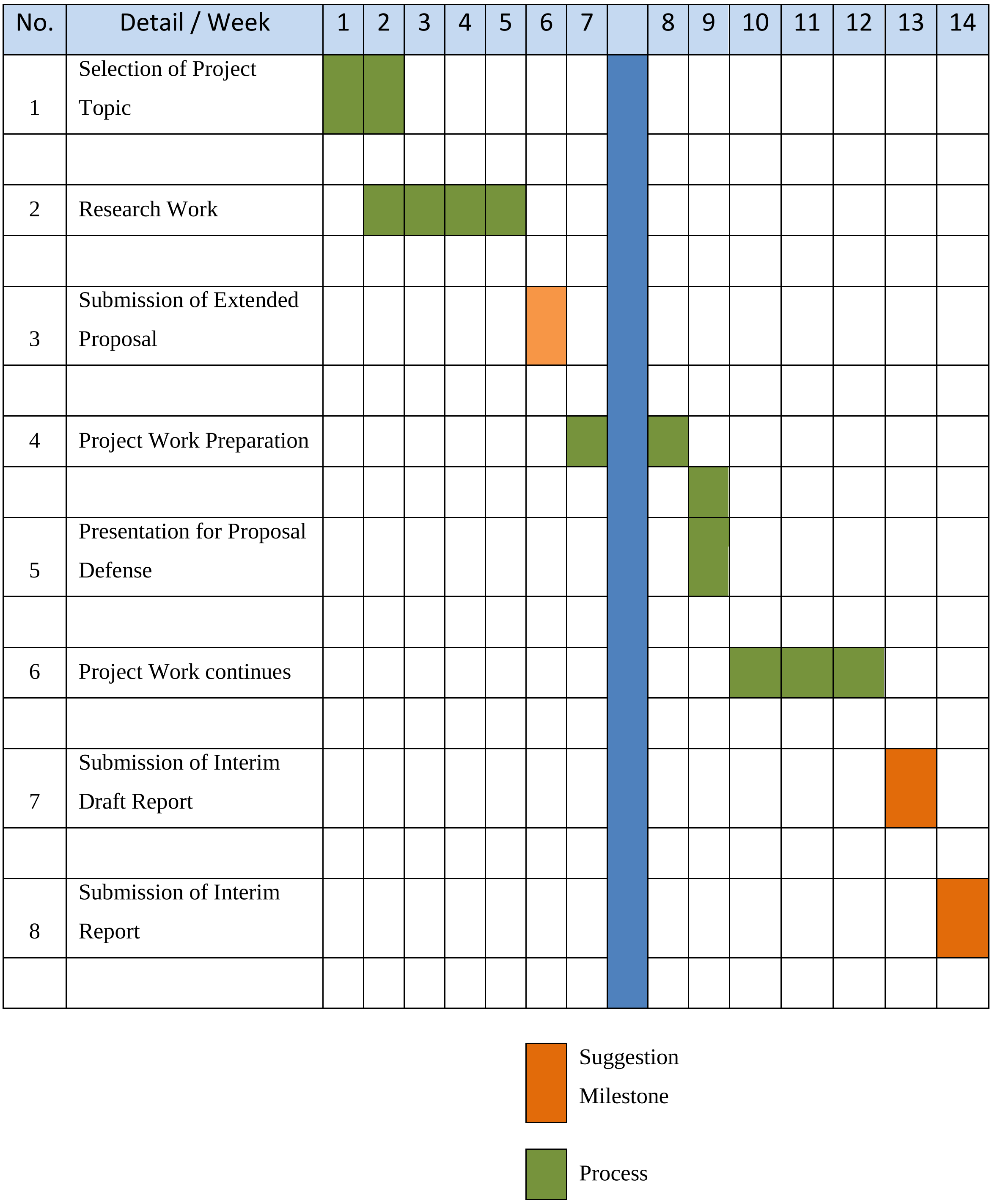
VIVA

Figure 7: Key milestone for FYP 1 and 2

3.4 Gantt Chart

Timeline or scheduling is a backbone of the project. Good or bad project basically depend on the timeline. Figure 8 is the timeline for FYP 1 and 2 explained in detail.

Timeline for FYP 1



Timeline for FYP 2

No.	Detail / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continues																
2	Submission of Progress Report																
3	Project Work Continues																
4	Pre-Sedex																
5	Submission of Draft Report																
6	Submission of Final Report and Technical Paper																
7	VIVA																

Figure 8: Timeline for FYP 1 and 2

3.5 Tools and Equipment Required

In order to conduct the experiment without any obstacle; tools and equipment required need to be prepared. Figure 9 are the list of the tools and equipment needed.

Equipment

- Synchronous Generator
- DC Motor
- Transformers
- Power Supply
- Resistive loads
- Inductive loads

Tools

- Fluke Power Meter
- Digital Multimeter

Figure 9: List of tools and equipment needed

3.6 Experimental Scenario

This project will be divided into two experimental scenarios which are:

- Scenario 1: Single Generator Operation
- Scenario 2: Generator Parallel with Grid

For every scenario, there are four transformer winding configuration which will be applied to the transformer in order to identify or determine the effect on triplen harmonic produced by synchronous generator. The winding configurations that will be used are:

- Delta-Star
- Star-Delta
- Delta-Delta
- Star-Star

Besides applying the entire winding configuration, for the scenario 1 there are two kind of load (combination of resistive and inductive) that will be applied which are:

- Vary the load spectrum
- Vary the load magnitude

For vary the load spectrum, combination of resistive and inductive will be calculated to get the different impedance angle. The combination will cover from small impedance to the large impedance. This combination of impedance is used for research purpose where it is not calculated based on real power factor condition. Table 1 is the list of 5 combination impedance with varying the spectrum.

Table 1: List of impedance for vary load spectrum

Impedance	Load magnitude	Load spectrum
686+j686	970.15	45
686+j1200	1382.24	60.25
686+j4800	4848.77	81.87
1200+j686	1382.24	29.76
4800+j686	4848.77	8.13

For vary the load magnitude, combination of the load is different with vary the load spectrum. This is to demonstrate the real condition applied in the circuit. Different combination need to be calculated with the load angle or spectrum between 32° to 37°. This angle eventually corresponds to 0.8 to 0.85 power factor based on real case condition. Table 2 is the list of load combination with the load magnitude and angle.

Table 2: List of impedance for vary load magnitude

Impedance	Load magnitude	Load angle
960+j660	1165	34.51
1600+j1194	1996.4	36.7
2400+j1602	2885.6	33.72
3600+j2388	4320	33.56
4800+j3581	5988.6	36.7

Meanwhile, for the scenario 2 which is the generator parallel with the utility grid, the combination as in table 2 will be used. These experiments also try to implement real case condition with power factor between 0.8-0.85. In this experiment also, the entire transformer winding also being applied for all combination impedances. For the utility grid side, there will be one fix transformer with delta-star connection applied for all experiment.

Figure 10 to 13 are the circuit diagram for the experiment in scenario 1. Even though in scenario 1 there are two kind of condition, the connections still the same because the different is only at the load.

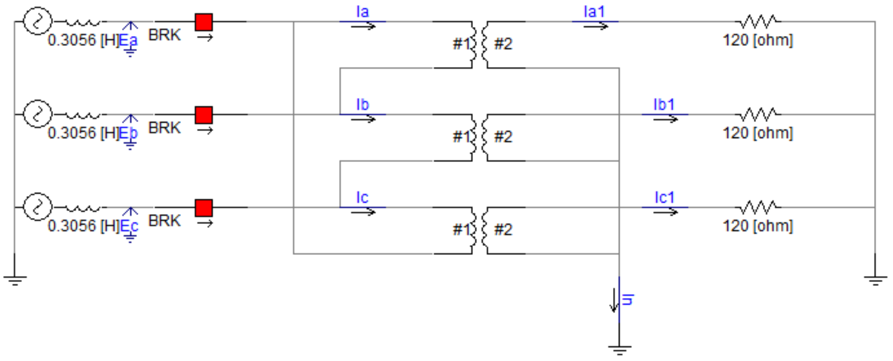


Figure 10: Circuit diagram of delta-star transformer with load for scenario 1

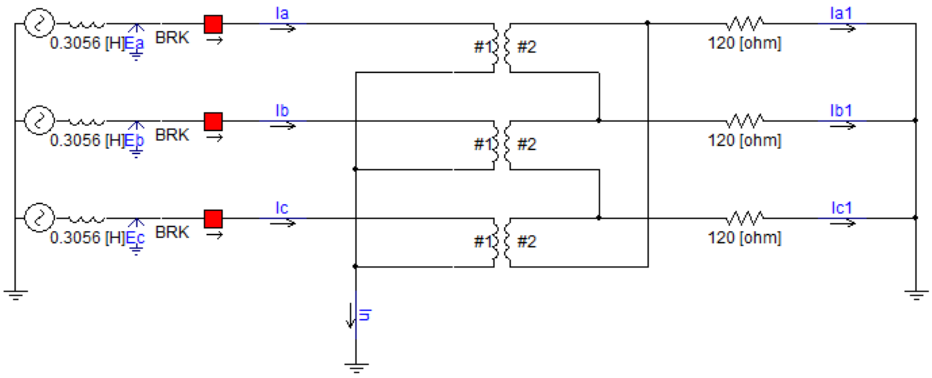


Figure 11: Circuit diagram of star-delta transformer with load for scenario 1

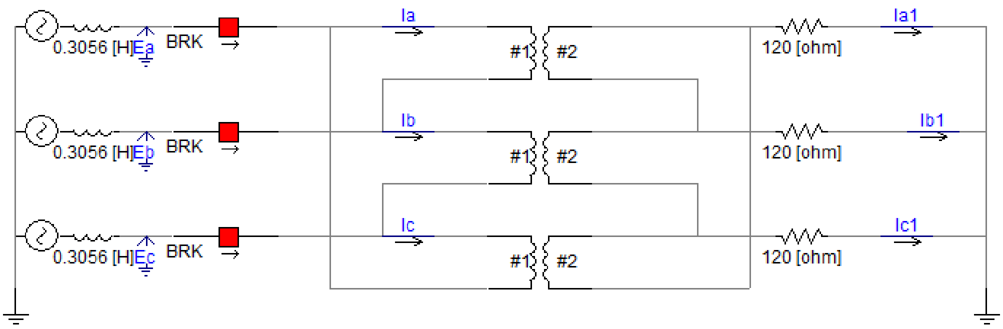


Figure 12: Circuit diagram of delta-delta transformer with load for scenario 1

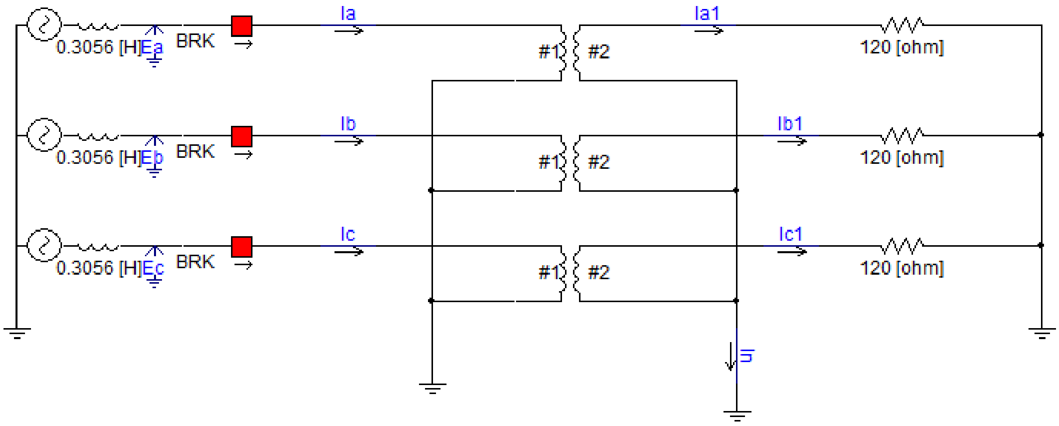


Figure 13: Circuit diagram of star-star transformer with load for scenario 1

CHAPTER 4

RESULT AND DISCUSSION

In this chapter, result from the experiment is being discussed. Third harmonic current is of concern, therefore, third harmonic presented here to characterize general behaviour of triplen harmonic. This chapter will be divided into 4 parts which allocate for every experiment. All the 4 parts are base data, island mode varying load spectrum, island mode varying load magnitude and generator parallel with grid varying load magnitude.

4.1 Base data

4.1.1 Generator Load Direct Connection

This experiment serves as the base data of generator voltage and current characteristic under balanced resistive, inductive and combined resistive and inductive load. Appendix A and B show the result for generator voltage and current characteristics for resistive and inductive load. Generator and load are connected in star with common neutral connection but no neutral impedance. Third harmonic neutral currents and voltages measurement at generator terminal is deemed the same as load terminal since negligible impedance between them.

4.1.1.1 Resistive and Inductive Load

The third harmonic voltage magnitude increase when the resistive or inductive components of the impedance increase, meanwhile, third harmonic current magnitude decreases when the resistive or inductive components of the impedance increase as shown in Figure 14. All third harmonic voltages are in phase and all third harmonic currents are almost in phase as shown in Figure 15 and Figure 16 respectively.

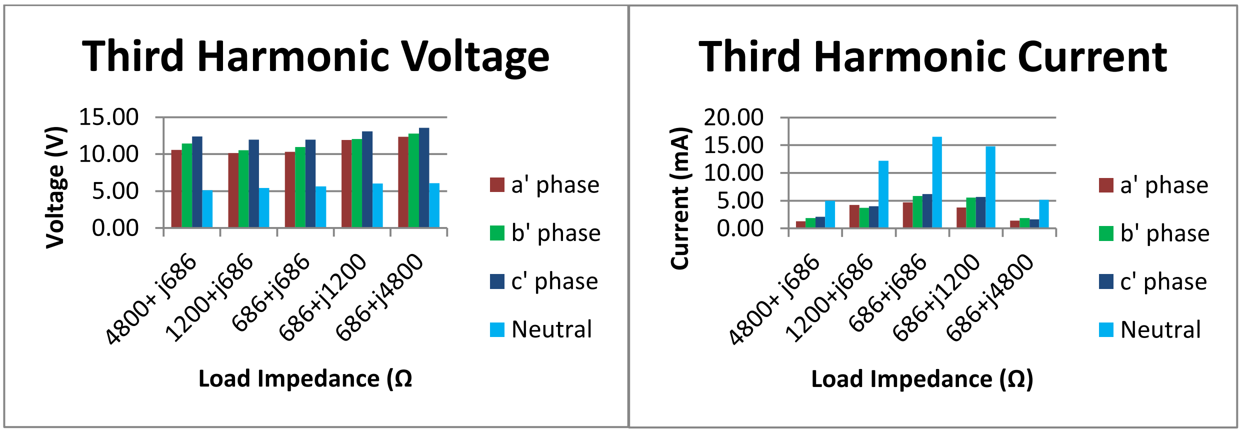


Figure 14: Third harmonic voltage and current graph for R+L

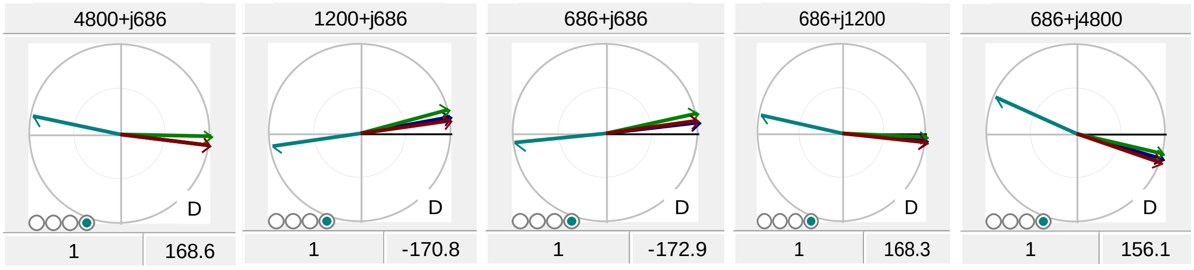


Figure 15: Phasor diagram for voltage R+L

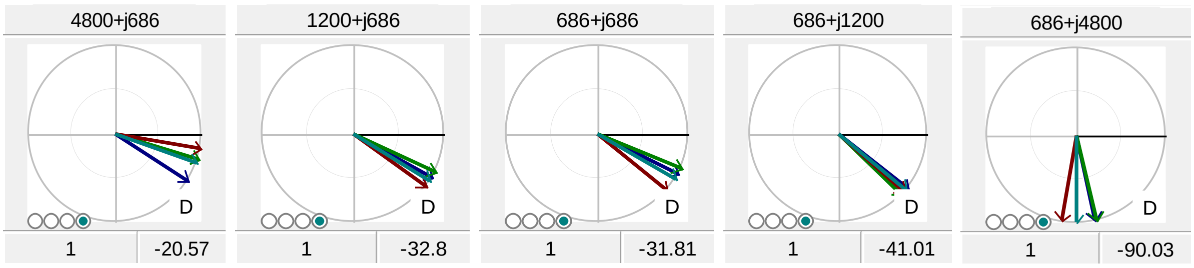


Figure 16: Phasor diagram for current R+L

Being in phase, third harmonic current added at neutral causing neutral current almost three times the phase current. The third harmonic current lag the third harmonic voltage similar to current lag voltage at fundamental frequency for combined resistive and inductive load. However, the lagging angle is more than fundamental frequency impedance phase angle due to the influence of resistive and inductive component of the impedance seen by third harmonic voltage.

4.2 Single Generator Operation

In this experiment, transformer is connected between the generator and load. Generator and load are connected in star with no neutral impedance. Common neutral connection is made for generator, transformer (only at star side) and load. The transformer winding configurations are varied for star-star, star-delta, delta-delta and delta-star. Third harmonic phase/neutral currents and voltages measurements are taken at generator, transformer primary, transformer secondary and load terminals. There are two kind of load that are being used to be analyzed which are varying load spectrum and load magnitude.

4.2.1 Varying Load Spectrum

For result and discussion, only result for 686+j686 Ω load is presented here but overall characteristic is deduced taking into account all load impedance used in experiment. Detail results are shown in the Appendix C, D, E and F.

4.2.1.1 Star-Star Transformer Winding Configuration

At load terminal, the third harmonic neutral voltage magnitude increase when the resistive or inductive components of the impedance increase. The third harmonic neutral current magnitude decrease when the resistive or inductive components of the impedance increase as shown in Figure 17. Slightly decrease in the third harmonic voltage magnitude from generator to load while the third harmonic current magnitude at transformer secondary and load reduced from the transformer primary and generator as shown in Figure 18. All the third harmonic voltages and currents are almost in phase as shown in Figure 19 and Figure 20.

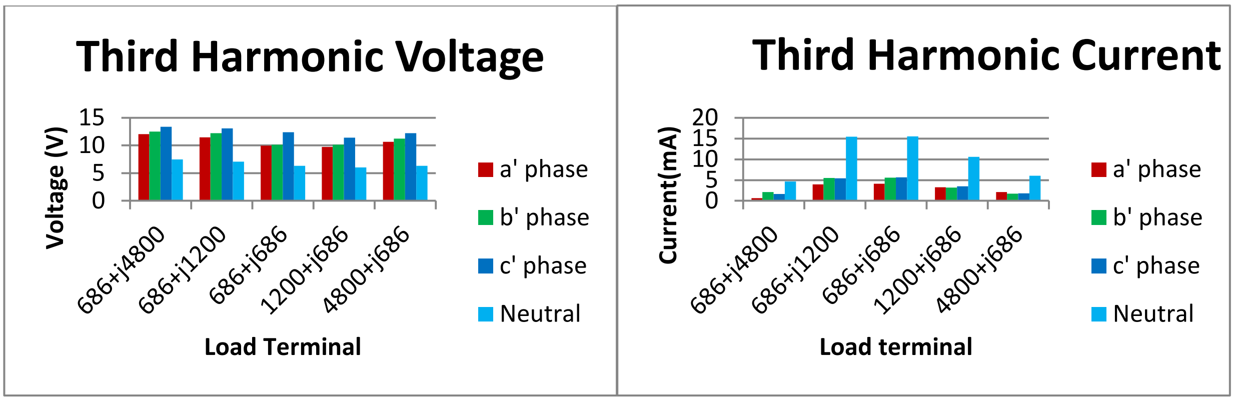


Figure 17: Third harmonic voltage and current graph at load terminal

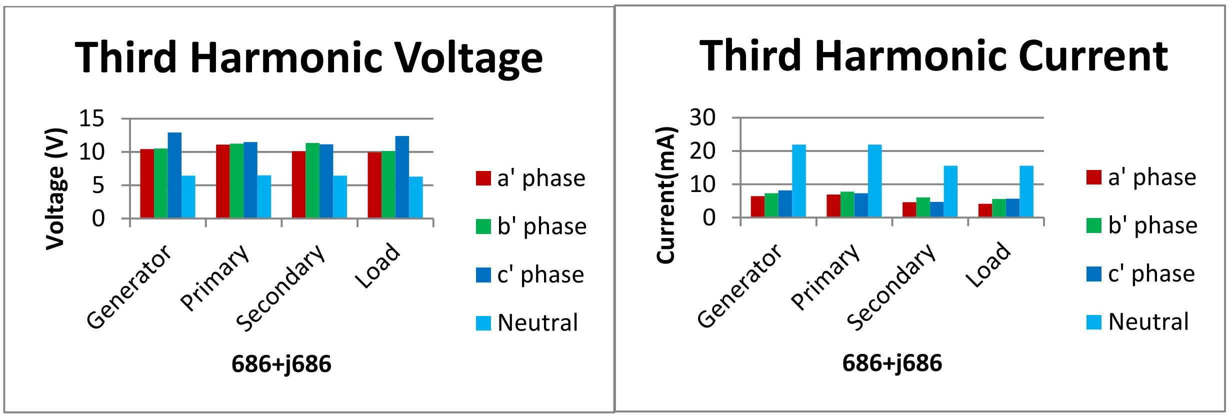


Figure 18: Third harmonic voltage and current graph for 686+j686 (star-star)

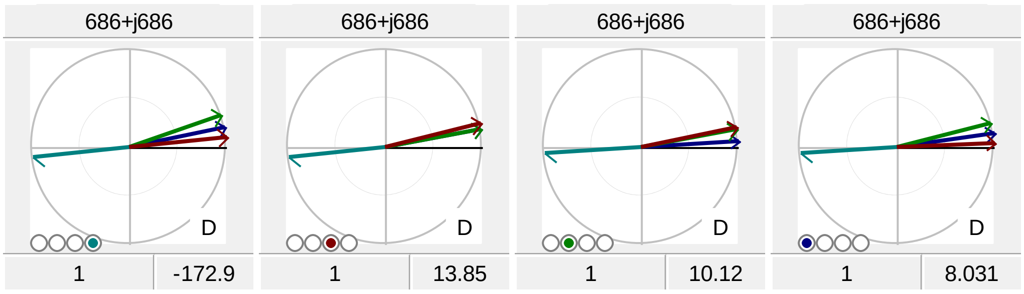


Figure 19: Phasor diagram for voltage 686+j686

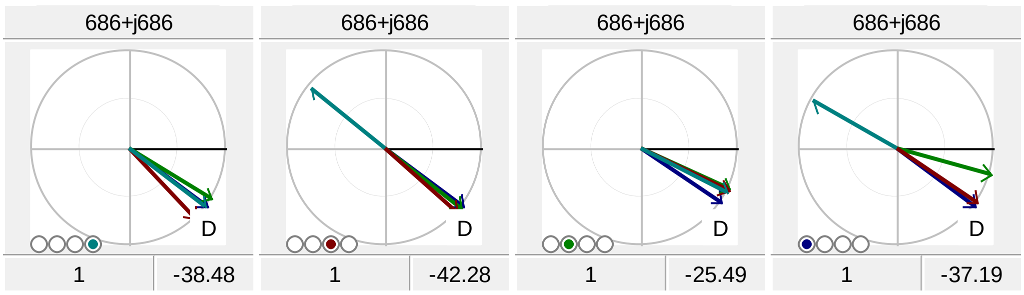


Figure 20: Phasor diagram for current 686+j686

Transformer secondary and load third harmonic voltage and current magnitude decrease slightly due to transformer impedance. The third harmonic current from the generator circulates around transformer primary as shown by the opposite direction of neutral current. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around load as shown by the opposite direction of neutral current. Based on the result also, it shows that this configuration will harm generator, transformer and load as well. It just looks like the third harmonic current is passing through this winding configuration.

4.2.1.2 Star-Delta Transformer Winding Configuration

At load terminal, the third harmonic neutral voltage magnitude increase when the resistive or inductive components of the impedance increase. The third harmonic neutral current magnitude decrease when the resistive or inductive components of the impedance increase as shown in Figure 21. The third harmonic voltage magnitude at generator is almost equal to the transformer primary while low third harmonic voltage magnitude at transformer secondary but highest at load as shown in Figure 22. The third harmonic current magnitude at transformer primary is almost equal to generator while small third harmonic current magnitude at transformer secondary and none at load as also shown in Figure 22. The third harmonic voltages are almost in phase at generator, transformer primary and load but not in phase at transformer secondary as shown in Figure 23. The third harmonic currents are almost in phase at generator, transformer primary and transformer secondary but not in phase at load as shown in Figure 24.

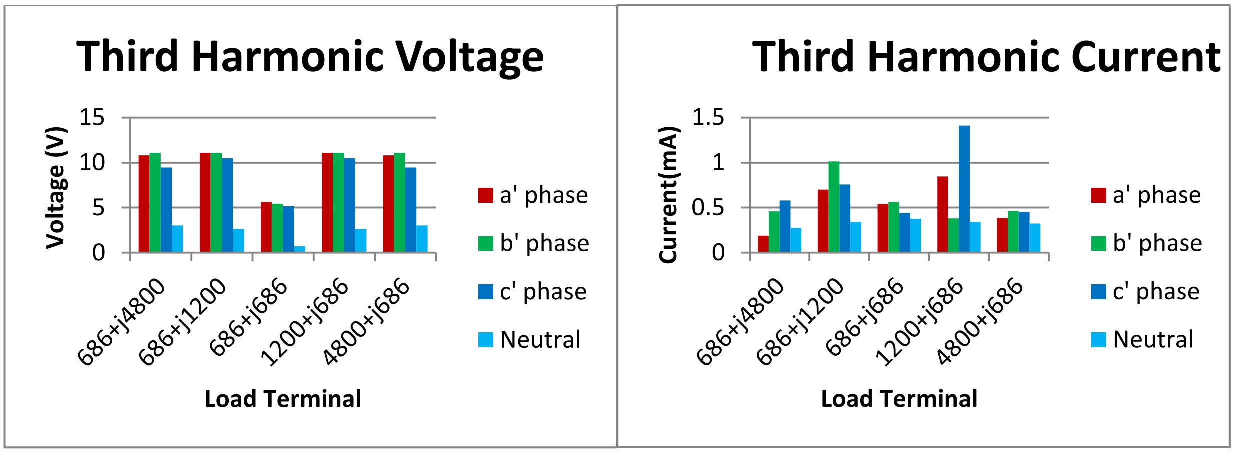


Figure 21: Third harmonic voltage and current graph at load terminal

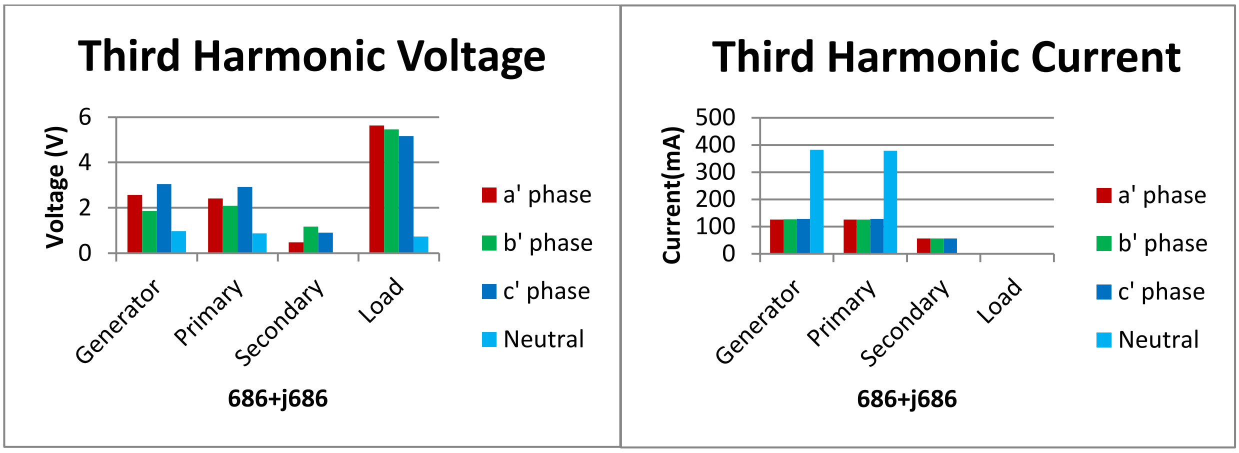


Figure 22: Third harmonic voltage and current for 686+j686 (star-delta)

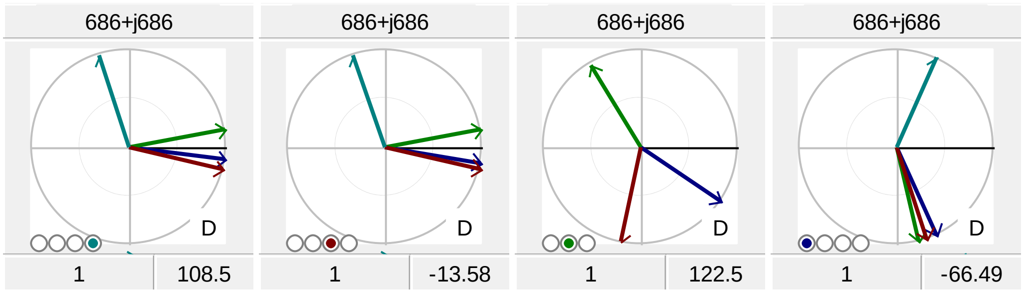


Figure 23: Phasor diagram for voltage 686+j686

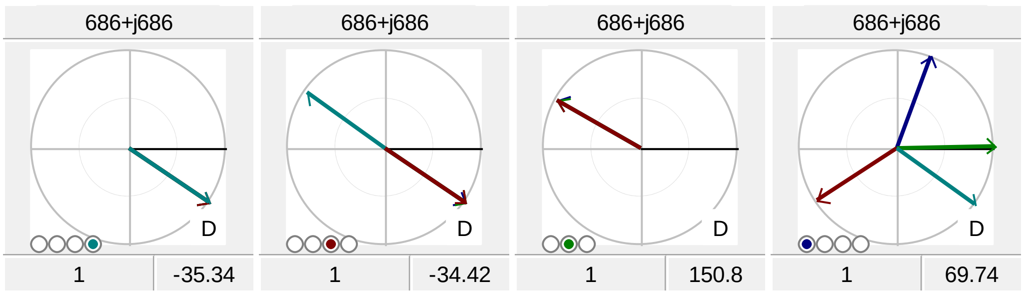


Figure 24: Phasor diagram for current 686+j686

The third harmonic current from the generator circulates around transformer primary as shown by the opposite direction of neutral current. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around delta winding preventing it from entering the load. Based on the result also, it shows that this configuration might harm or damage the generator. It will happen when third harmonic current cannot pass through delta winding and flowing back to the generator caused high temperature. Besides, the voltage and current transformation magnitude do not agree to transformer turn ratio which is 1:1.73 due to incompatible phase voltage and current angle.

4.2.1.3 Delta-Star Transformer Winding Configuration

At load terminal, the third harmonic neutral voltage magnitude increase when the resistive or inductive components of the impedance increase. The third harmonic neutral current magnitude decrease when the resistive or inductive components of the impedance increase as shown in Figure 25. The third harmonic voltage magnitude at transformer secondary is almost equal to load. Low third harmonic voltage magnitude at transformer primary but highest at generator as shown in Figure 26. The third harmonic current magnitude at transformer secondary is almost equal to load. Small third harmonic current magnitude occurred at generator but highest occurred at transformer primary as also shown in Figure 26. The third harmonic voltages are almost in phase at generator but not in phase at transformer primary, secondary and load as shown in Figure 27. The third harmonic currents are almost in phase at transformer primary, secondary and load but not in phase at generator as shown in Figure 28.

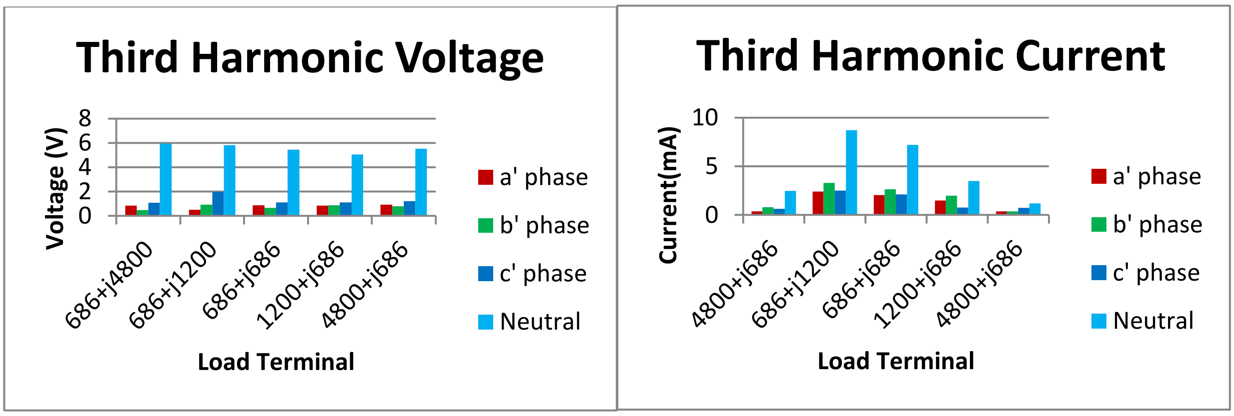


Figure 25: Third harmonic voltage and current graph at load terminal

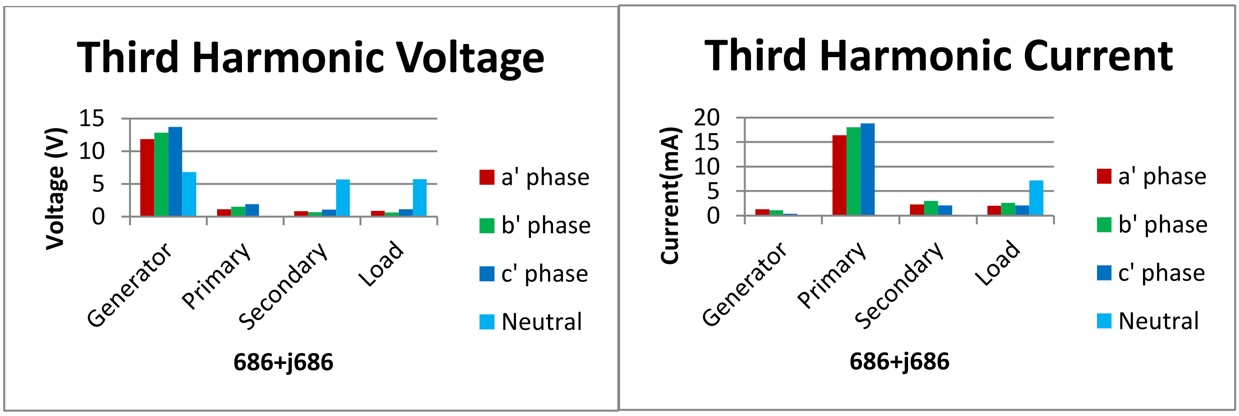


Figure 26: Third harmonic voltage and current for 686+j686 (delta-star)

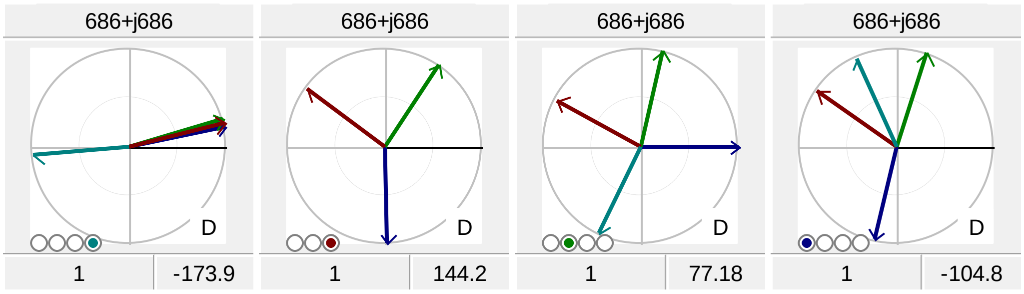


Figure 27: Phasor diagram for voltage 686+j686

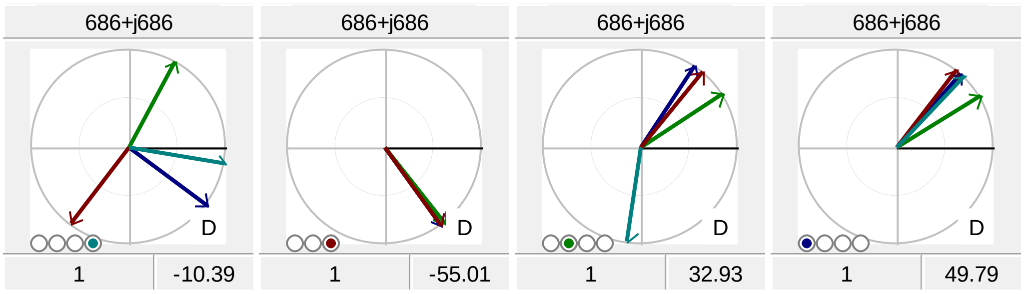


Figure 28: Phasor diagram for current 686+j686

The third harmonic current from the generator circulates around transformer primary. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around load. Based on the result also, it shows that this configuration will secure generator and transformer but a few third harmonic still can pass through to the load. It happen because the delta winding only blocked in phase while pass the third harmonic current in line. Besides, the voltage and current transformation magnitude do not agree to transformer turn ratio which is 1.73:1 due to incompatible phase voltage and current angle.

4.2.1.4 Delta-Delta Transformer Winding Configuration

At load terminal, the third harmonic neutral voltage magnitude increase when the resistive or inductive components of the impedance increase. The third harmonic neutral current magnitude decrease when the resistive or inductive components of the impedance increase as shown in Figure 29. Small third harmonic voltage magnitude at transformer primary that is almost equal to transformer secondary. Higher third harmonic voltage magnitude at generator as compared to load as shown in figure 30. The third harmonic current magnitude at transformer primary is almost equal to transformer secondary. Small third harmonic current magnitude occurred at generator and almost zero at load as also shown in Figure 30. The third harmonic voltages are almost in phase at generator and load but not in phase at transformer primary and secondary as shown in Figure 31. The third harmonic currents are almost in phase at transformer primary and secondary but not in phase at generator and load as shown in Figure 32.

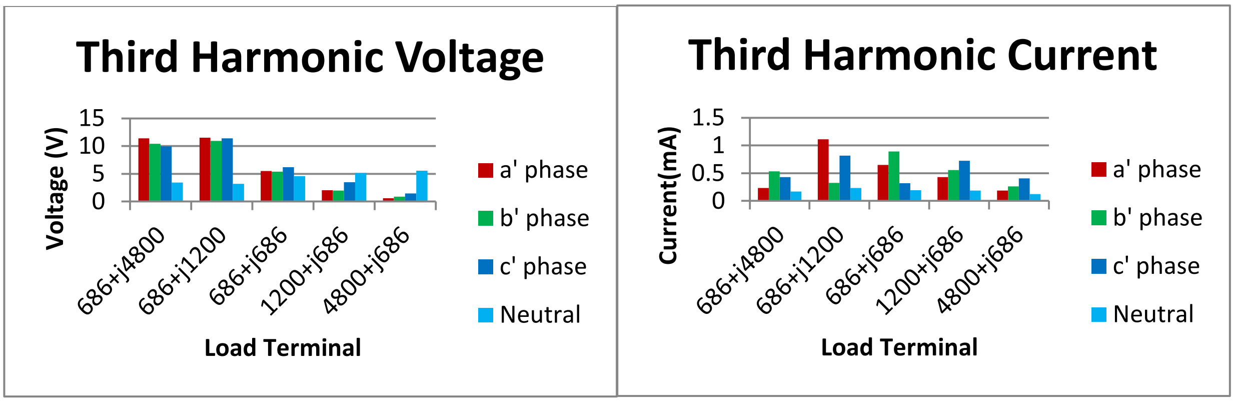


Figure 29: Third harmonic voltage and current graph at load terminal

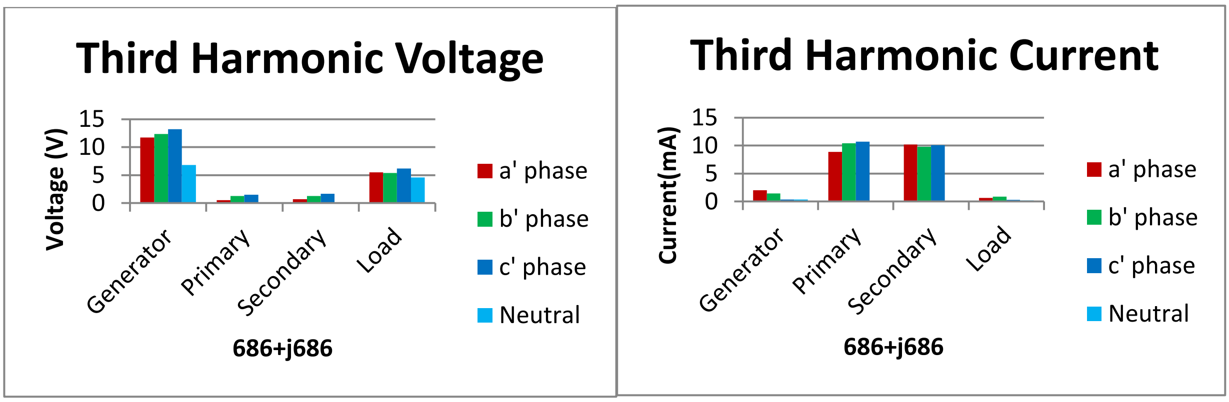


Figure 30: Third harmonic voltage and current graph for 686+j686 (delta-delta)

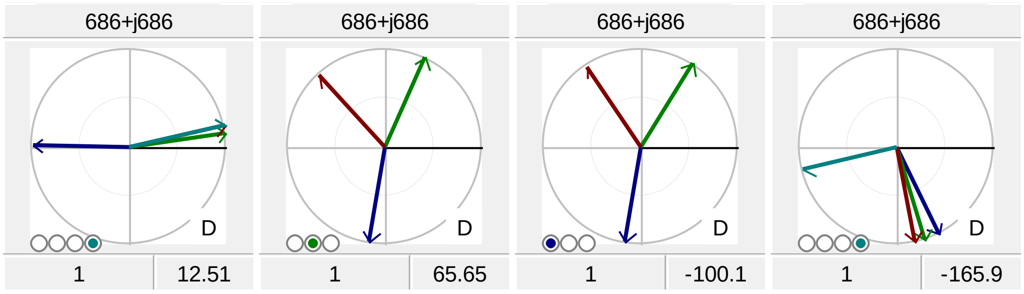


Figure 31: Phasor diagram for voltage 686+j686

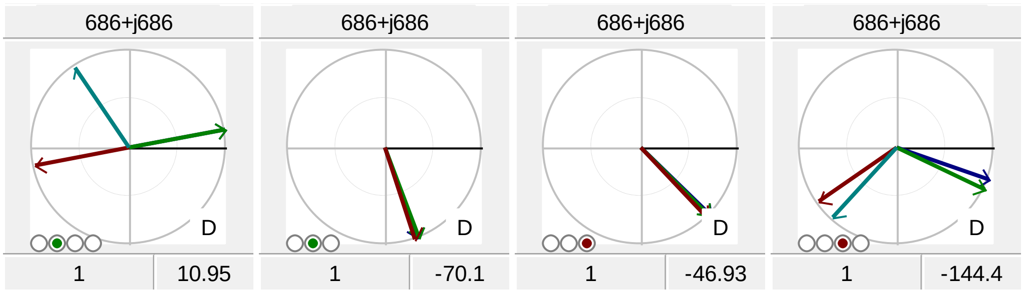


Figure 32: Phasor diagram for current 686+j686

The third harmonic currents from generator circulate around transformer primary and secondary delta windings preventing them from entering the load. Based on the result also, it shows that this configuration might harm or damage the transformer and secure the generator and load. By trapping the third harmonic current will cause higher temperature occur in the transformer.

4.2.2 Varying Load Magnitude

For result and discussion, only result for 960+j660 Ω load is presented here but overall characteristic is deduced taking into account all load impedance used in experiment. Detail results are shown in the Appendix G, H, I and J.

4.2.2.1 Star-Star Transformer Winding Configuration

Slightly decrease in the third harmonic voltage magnitude from generator to load while the third harmonic current magnitude at transformer secondary and load reduced from the transformer primary and generator as shown in Figure 33. All the third harmonic voltages and currents are almost in phase as shown in Figure 34 and Figure 35.

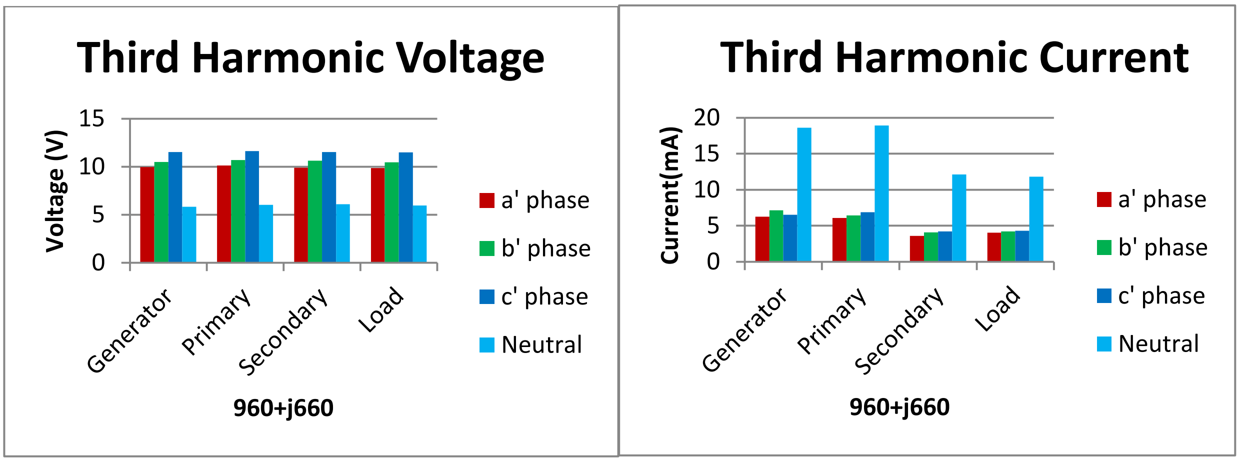


Figure 33: Third harmonic voltage and current graph for 960+j660 (star-star)

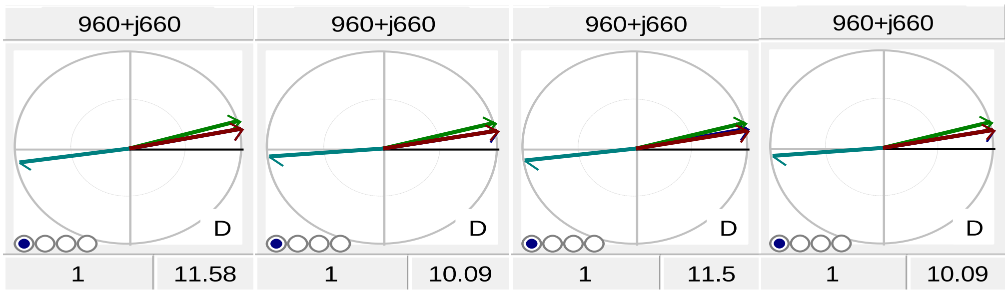


Figure 34: Phasor diagram for voltage 960+j660

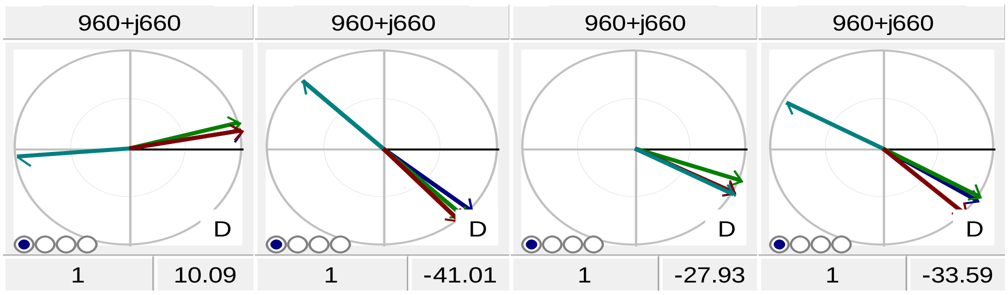


Figure 35: Phasor diagram for current 960+j660

The third harmonic voltage and current magnitude decrease slightly due to transformer impedance. The third harmonic current from the generator circulates around transformer primary as shown by the opposite direction of neutral current. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around load as shown by the opposite direction of neutral current. Based on the result also, it shows that this configuration might harm generator, transformer and load as well. It just looks like the third harmonic current is passing through this winding configuration.

4.2.2.2 Star-Delta Transformer Winding Configuration

The third harmonic voltage magnitude at generator is almost equal to the transformer primary while low third harmonic voltage magnitude at transformer secondary but highest at load as shown in Figure 36. The third harmonic current magnitude at transformer primary is almost equal to generator while small third harmonic current magnitude at transformer secondary and none at load as also shown in Figure 36. The third harmonic voltages are not in phase at generator, both transformer and load as shown in Figure 37. The third harmonic currents are almost in phase at generator, transformer primary and transformer secondary but not in phase at load as shown in Figure 38.

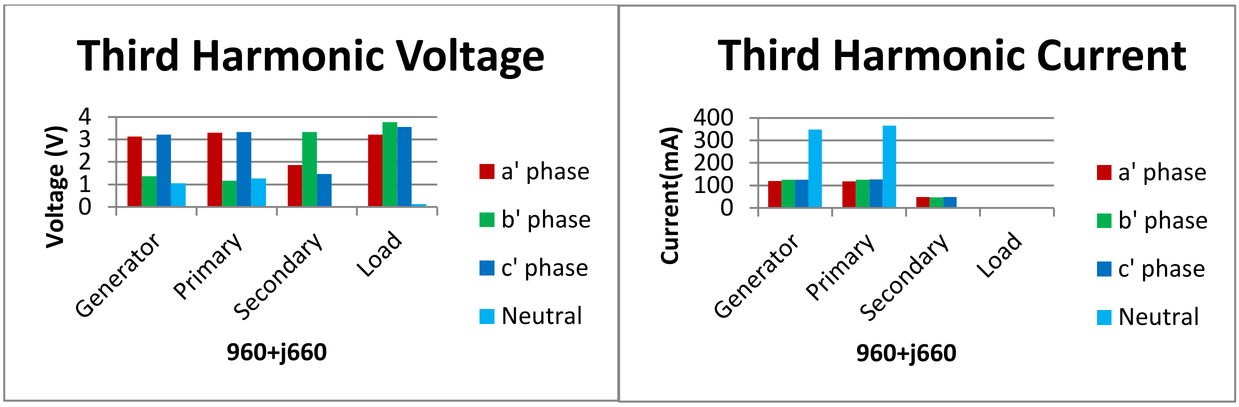


Figure 36: Third harmonic voltage and current graph for 960+j660 (star-delta)

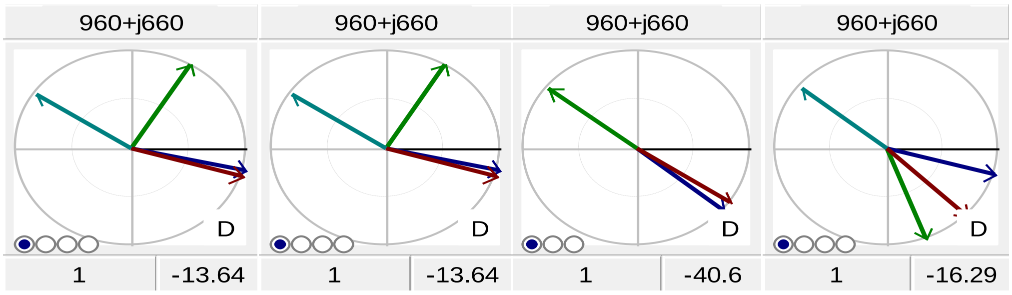


Figure 37: Phasor diagram for voltage 960+j660

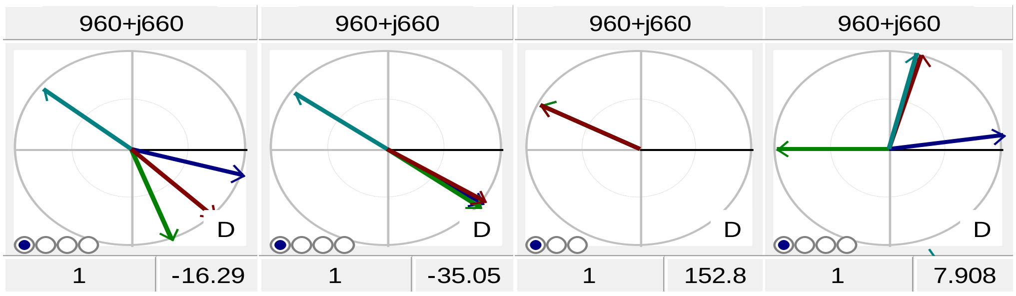


Figure 38: Phasor diagram for current 960+j660

The third harmonic current from the generator circulates around transformer primary as shown by the opposite direction of neutral current. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around delta winding preventing it from entering the load. Based on the result also, it shows that this configuration might harm or damage the generator. It will happen when third harmonic current cannot pass through delta winding and flowing back to the generator caused high temperature. Besides, the voltage and current transformation magnitude do not agree to transformer turn ratio which is 1:1.73 due to incompatible phase voltage and current angle.

4.2.2.3 Delta-Star Transformer Winding Configuration

The third harmonic voltage magnitude at transformer secondary is almost equal to load. Low third harmonic voltage magnitude at transformer primary but highest at generator as shown in Figure 39. The third harmonic current magnitude at transformer secondary is almost equal to load. Small third harmonic current magnitude occurred at generator but highest occurred at transformer primary as also shown in Figure 39. The third harmonic voltages are almost in phase at generator but not in phase at transformer primary, secondary and load as shown in Figure 40. The third harmonic currents are almost in phase at transformer primary, secondary and load but not in phase at generator as shown in Figure 41.

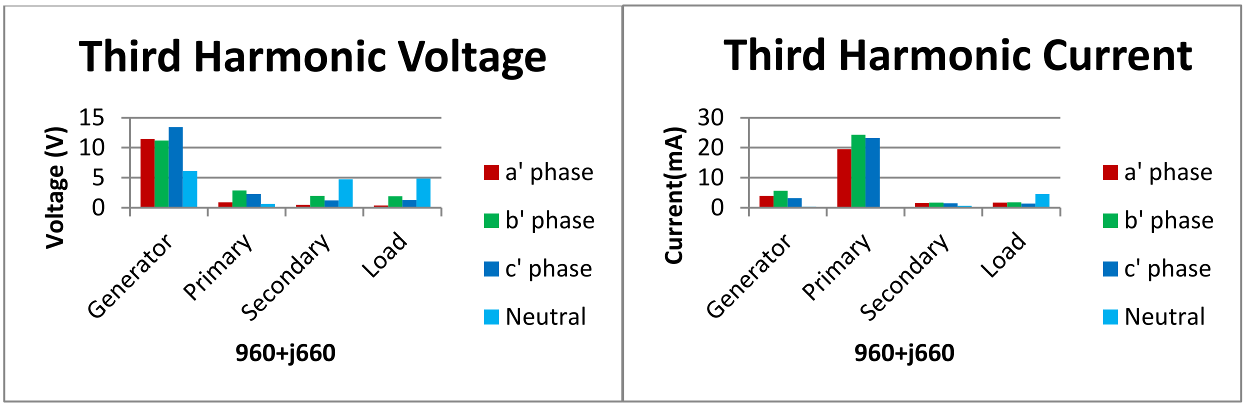


Figure 39: Third harmonic voltage and current graph for 960+j660 (delta-star)

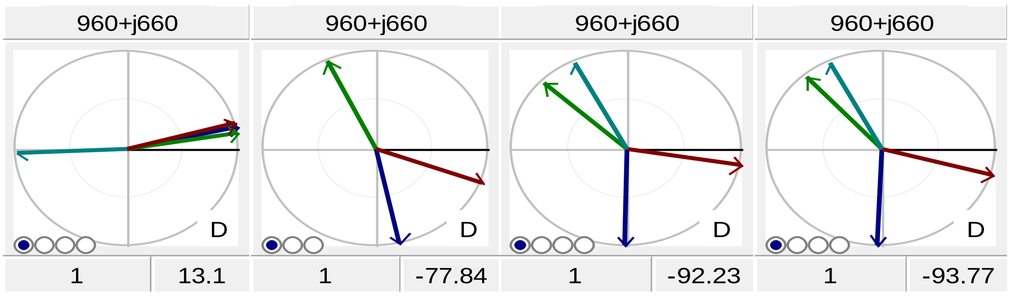


Figure 40: Phasor diagram for voltage 960+j660

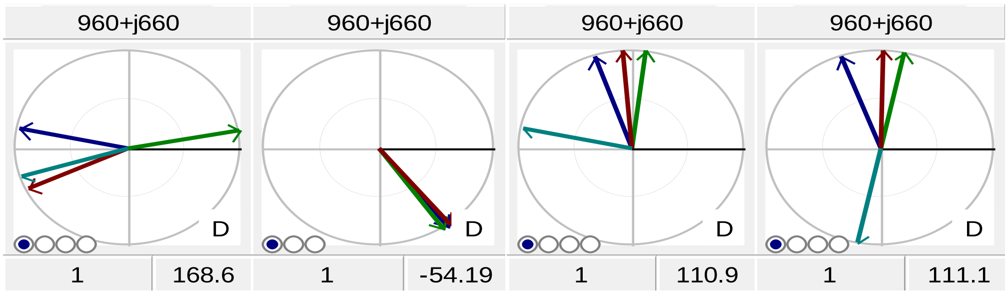


Figure 41: Phasor diagram for current 960+j660

The third harmonic current from the generator circulates around transformer primary. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around load. Based on the result also, it shows that this configuration will secure generator and transformer but a few third harmonic still can pass through to the load. It happen because the delta winding only blocked in phase while pass the third harmonic current in line. Besides, the voltage and current transformation magnitude do not agree to transformer turn ratio which is 1.73:1 due to incompatible phase voltage and current angle.

4.2.2.4 Delta-Delta Transformer Winding Configuration

Small third harmonic voltage magnitude at transformer primary that is almost equal to transformer secondary. Higher third harmonic voltage magnitude at generator as compared to load as shown in Figure 42. The third harmonic current magnitude at transformer primary is almost equal to transformer secondary. Small third harmonic current magnitude occurred at generator and almost zero at load as also shown in Figure 42. The third harmonic voltages are almost in phase at generator and load but not in phase at transformer primary and secondary as shown in Figure 43. The third harmonic currents are almost in phase at transformer primary and secondary but not in phase at generator and load as shown in Figure 44.

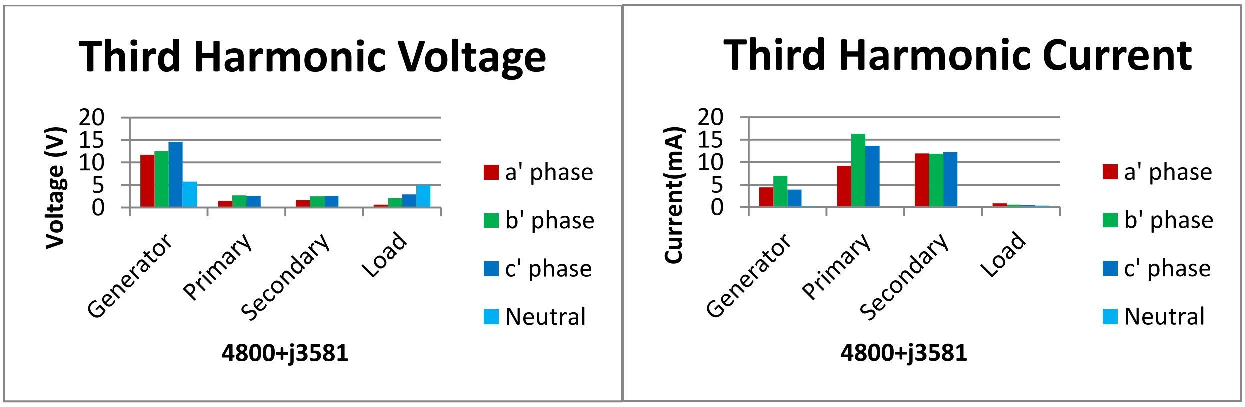


Figure 42: Third harmonic voltage and current graph for 960+j660 (delta-delta)

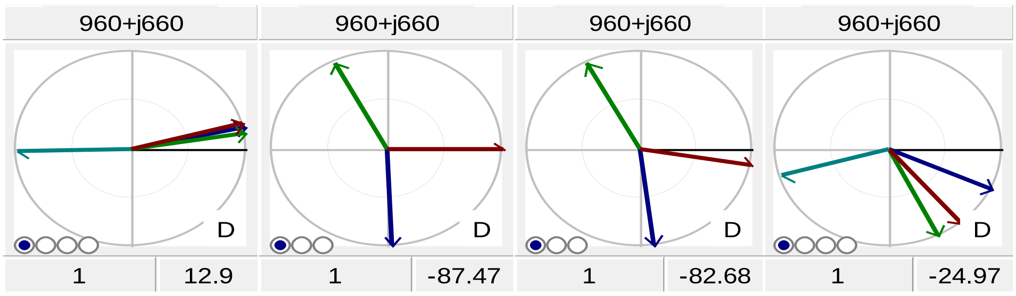


Figure 43: Phasor diagram for voltage 960+j660

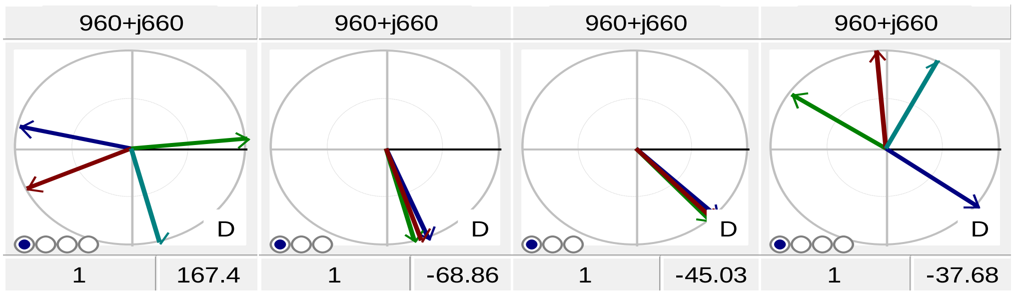


Figure 44: Phasor diagram for current 960+j660

The third harmonic currents from generator circulate around transformer primary and secondary delta windings preventing them from entering the load. Based on the result also, it shows that this configuration will harm or damage the transformer and secure the generator and load. By trapping the third harmonic current will cause higher temperature occur in the transformer.

4.3 Generator Parallel with Grid

In this experiment, transformer is used in two different connections. From grid, there will be a single delta-star transformer before parallel with the generator. This transformer winding is permanently used for all experiment. The other transformer is connected between parallel power source and load. Grid, generator and load are connected in star with no neutral impedance. Common neutral connection is made for grid, generator, transformer (only at star side) and load. The transformer winding configurations are varied for star-star, star-delta, delta-delta and delta-star. Third harmonic phase or neutral currents and voltages measurements are taken at grid, grid transformer (both winding), generator, transformer after parallel (both winding) and load terminals. There is only one experiment that is being used to be analyzed which is varying load magnitude.

4.3.1 Varying Load Spectrum

For result and discussion, only result for 4800+j3581Ω load is presented here but overall characteristic is deduced taking into account all load impedance used in experiment.

4.3.1.1 Star-Star Transformer Winding Configuration

The third harmonic voltage magnitude slightly decrease from generator to load and large decrease from grid to grid transformer primary but increase back at grid transformer secondary while the third harmonic current magnitude is almost zero at grid, generator transformer and load as shown in Figure 45. All the third harmonic voltages are not in phase as shown in Figure 46 while third harmonic currents are almost in phase at grid transformer and generator as shown in Figure 47.

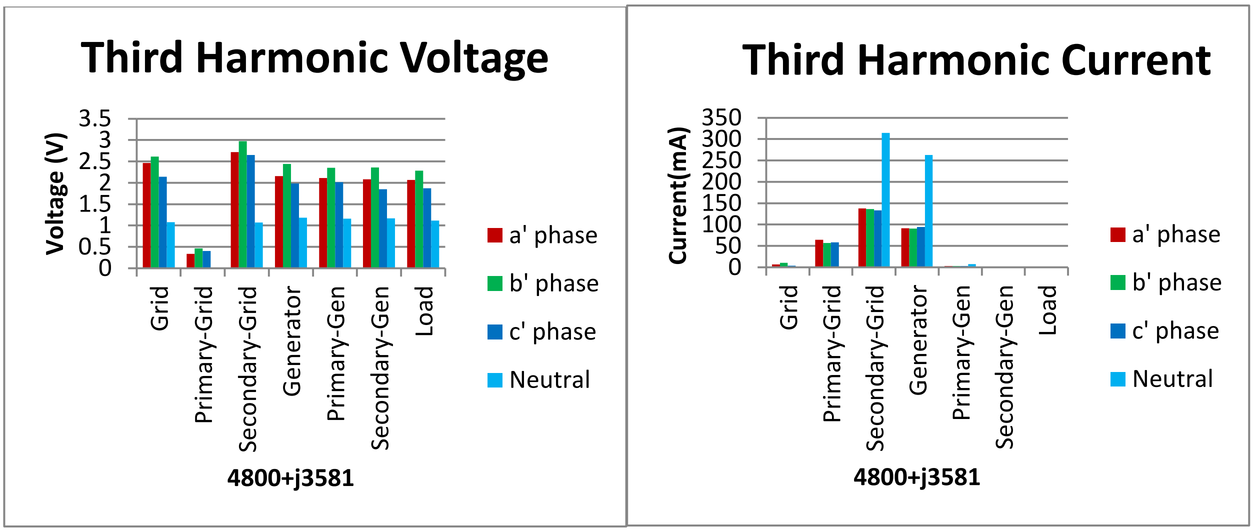


Figure 45: Third harmonic voltage and current graph for 4800+j3581 (star-star)

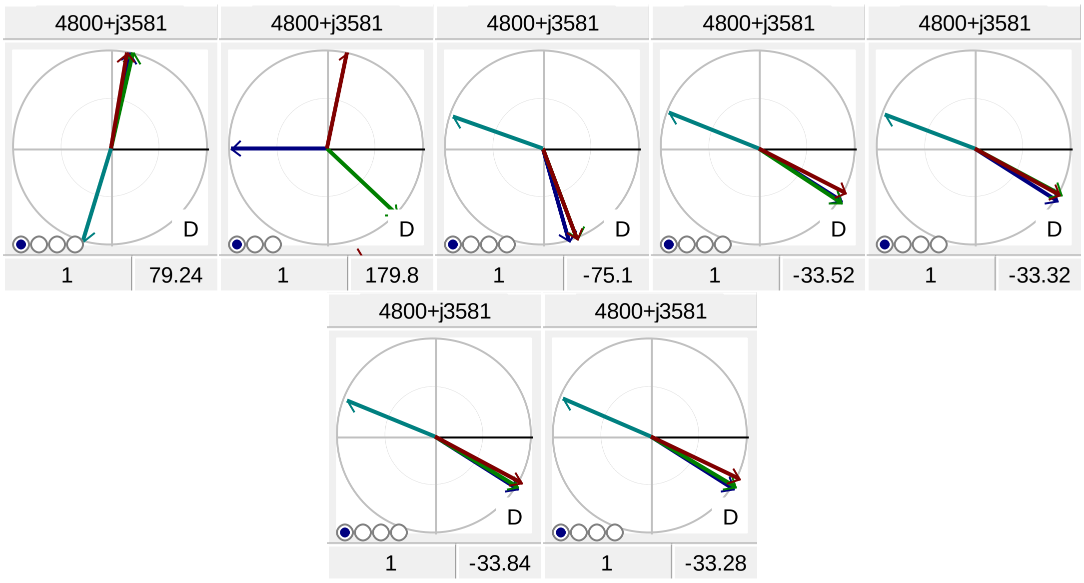


Figure 46: Phasor diagram for voltage 4800+j3581

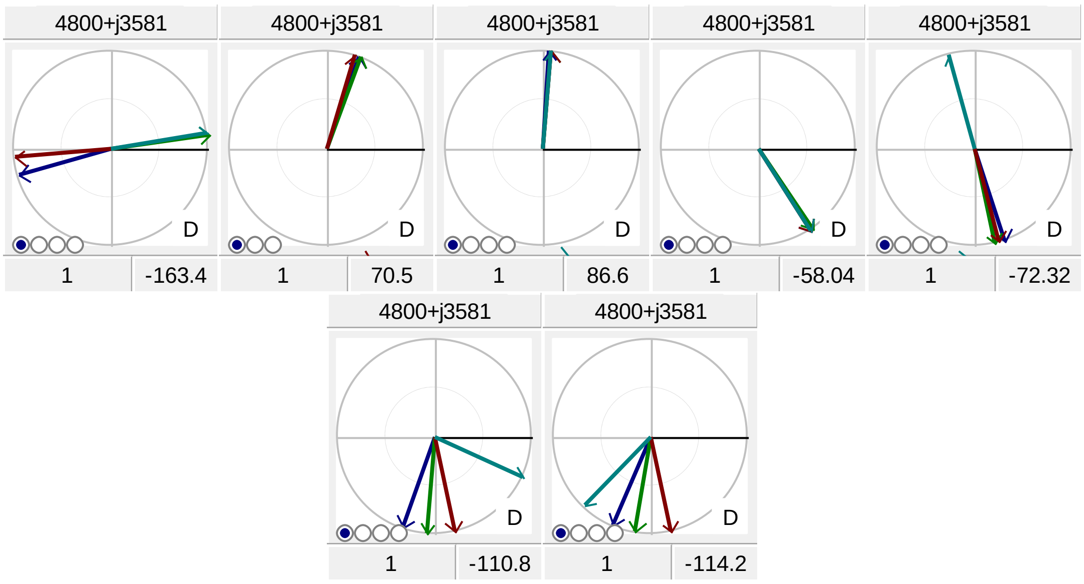


Figure 47: Phasor diagram for current 4800+j3581

The third harmonic voltage decreased slightly from generator to load due to transformer impedance. The third harmonic current from the generator circulates around grid transformer secondary as shown by the opposite direction of neutral current. Based on the result also, it shows that this configuration might harm generator, because lower impedance at the grid transformer secondary creating the third harmonic current to flow and return back to the generator.

4.3.1.2 Star-Delta Transformer Winding Configuration

The third harmonic voltage magnitude at grid is the highest and lowest at generator transformer secondary while almost equal at the grid transformer secondary, generator and generator transformer primary as shown in Figure 48. The third harmonic current magnitude at load and grid is almost zero while large third harmonic current magnitude at grid transformer secondary, generator and generator transformer primary and small at grid transformer primary and generator transformer secondary as also shown in Figure 48. All the third harmonic voltages are not in phase as shown in Figure 49. The third harmonic currents are almost in phase at grid transformer secondary, generator, generator transformer primary and secondary but not in phase at grid and load as shown in Figure 50.

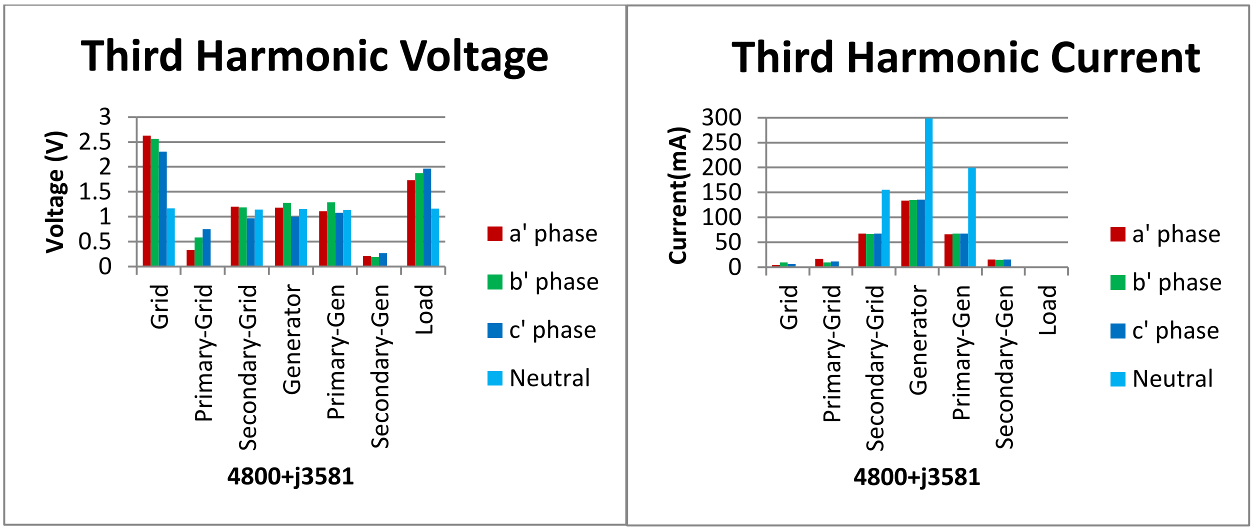


Figure 48: Third harmonic voltage and current graph for 4800+j3581 (star-delta)

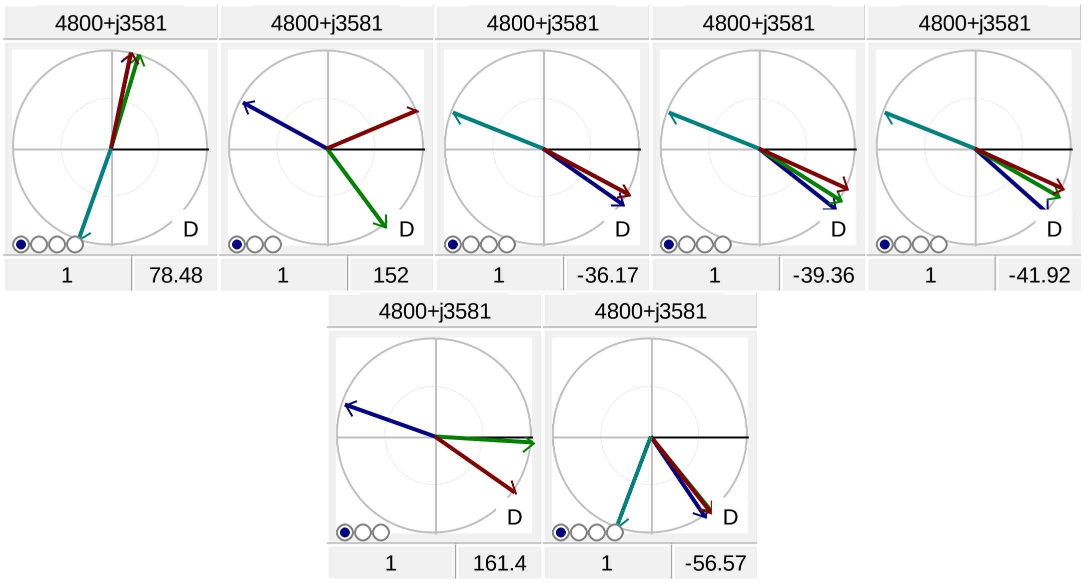


Figure 49: Phasor diagram for voltage 4800+j3581

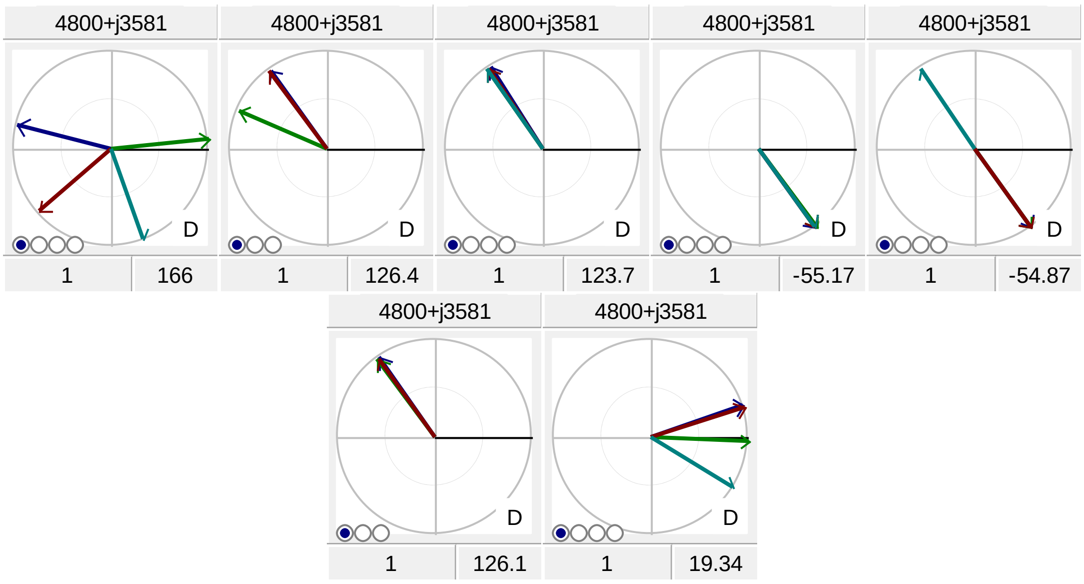


Figure 50: Phasor diagram for current 4800+j3581

The third harmonic current from the generator circulates around generator transformer primary and grid transformer secondary as shown by the opposite direction of neutral current. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around delta winding preventing it from entering the load. Based on the result also, it shows that this configuration might harm or damage the generator. It will happen when third harmonic current cannot pass through delta winding and flowing back to the generator caused high temperature.

4.3.1.3 Delta-Star Transformer Winding Configuration

The third harmonic voltage magnitude is high at grid and almost equal to grid transformer secondary and generator. While, third harmonic voltage magnitude is low at grid transformer primary and almost equal to generator transformer primary and secondary and also load as shown in Figure 51. The third harmonic current magnitude at grid transformer secondary is almost equal to generator. Small third harmonic current magnitude occurred at grid transformer primary and generator transformer primary but none at generator transformer secondary and load as also shown in Figure 51. The third harmonic voltages are almost in phase at grid, grid transformer secondary and generator but not in phase at grid transformer primary, generator transformer primary and secondary and also load as shown in Figure 52. The third harmonic currents are almost in phase at grid transformer secondary and generator but not in phase at other measuring point as shown in Figure 53.

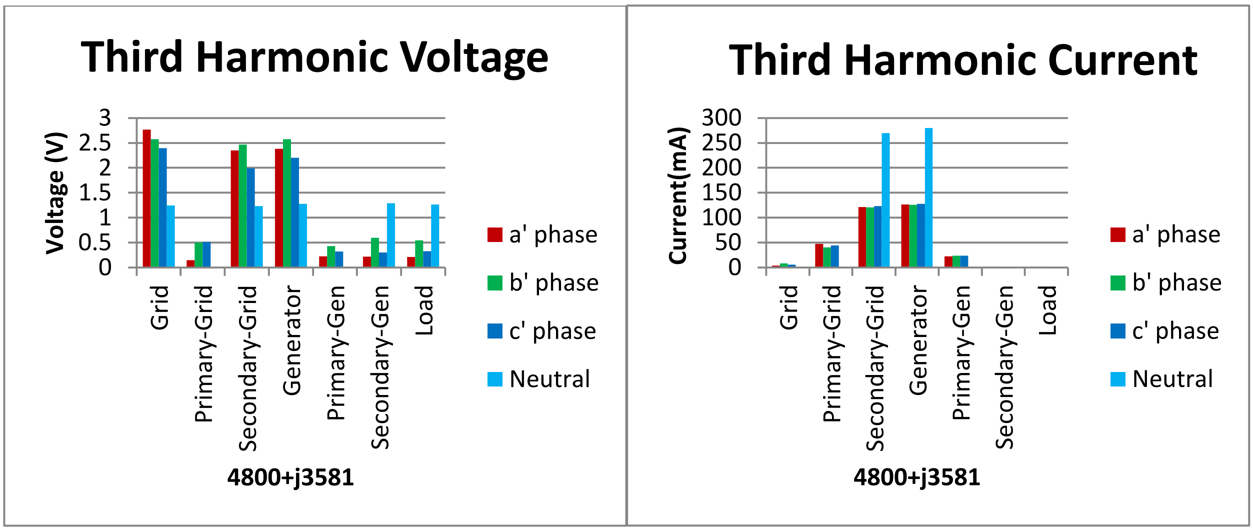


Figure 51: Third harmonic voltage and current graph for 4800+j3581 (delta-star)

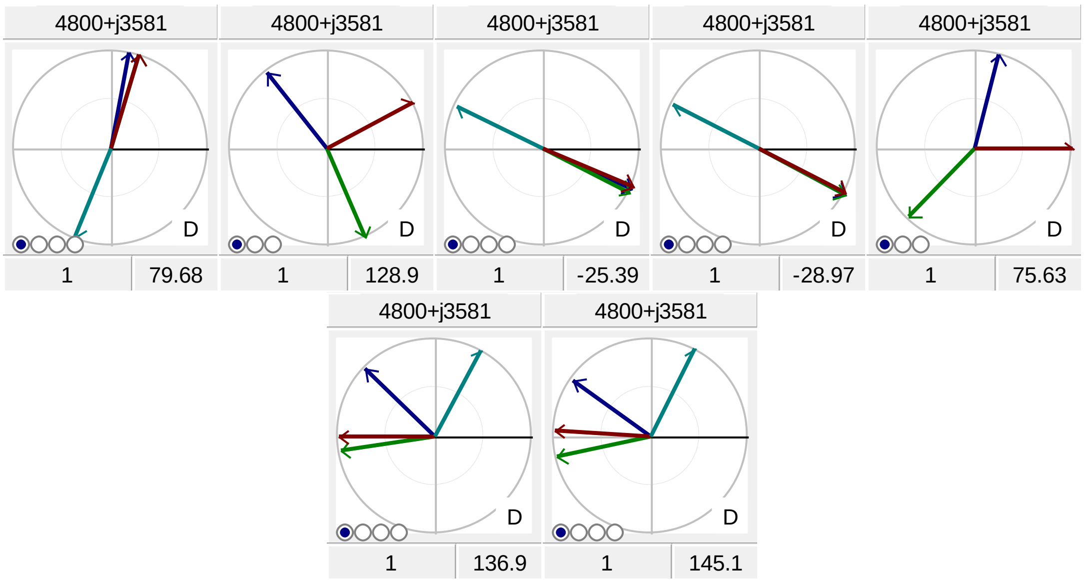


Figure 52: Phasor diagram for voltage 4800+j3581

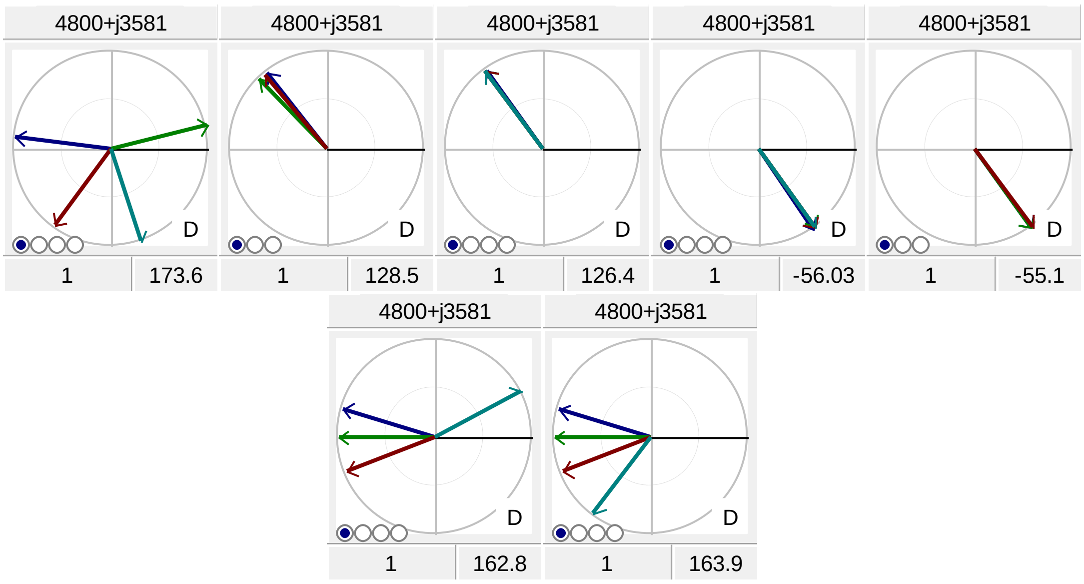


Figure 53: Phasor diagram for current 4800+j3581

The third harmonic current from the generator circulates around grid transformer secondary. The third harmonic voltage induced at transformer secondary causes the third harmonic trap or block from pass through. Based on the result also, it shows that this configuration will secure load but may harm the generator as third harmonic current circulate between generator and grid transformer secondary as this path is the lowest impedance that can be passed through.

4.3.1.4 Delta-Delta Transformer Winding Configuration

Small third harmonic voltage magnitude occurred at grid transformer primary and almost equal to generator transformer primary and secondary. Higher third harmonic voltage magnitude occurred at grid, grid transformer secondary, generator and load as shown in Figure 54. The third harmonic current magnitude at grid transformer secondary is almost equal to generator. Small third harmonic current magnitude occurred at grid transformer primary and generator transformer and almost zero at grid and load as also shown in Figure 54. The third harmonic voltages are almost in phase at grid, grid transformer secondary, generator and load but not in phase at grid transformer primary and generator transformer as shown in Figure 55. The third harmonic currents are almost in phase all terminal except at grid as shown in Figure 56.

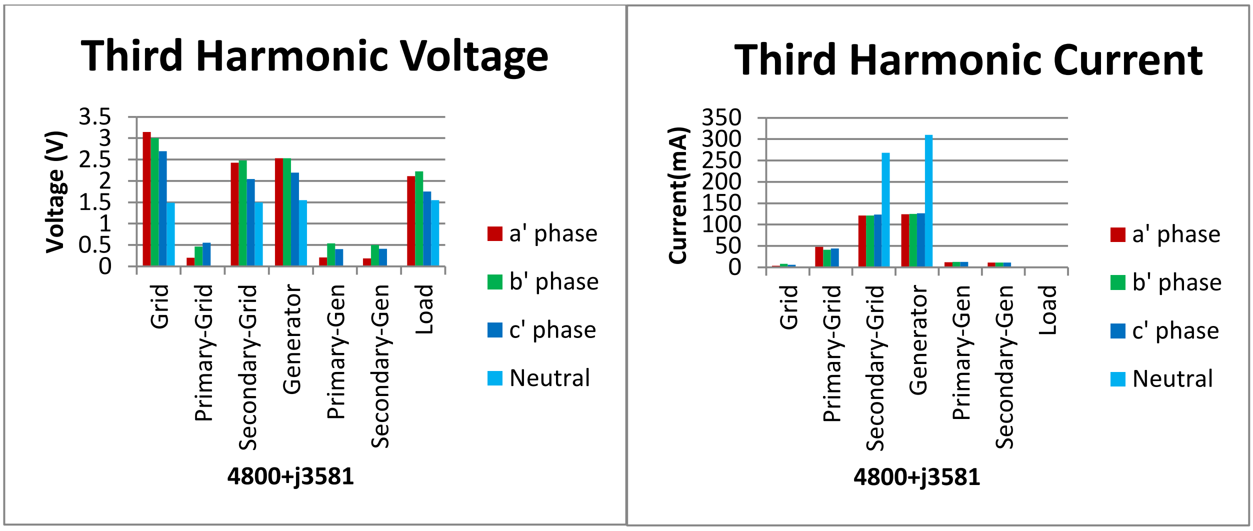


Figure 54: Third harmonic voltage and current graph for 4800+j3581 (delta-delta)

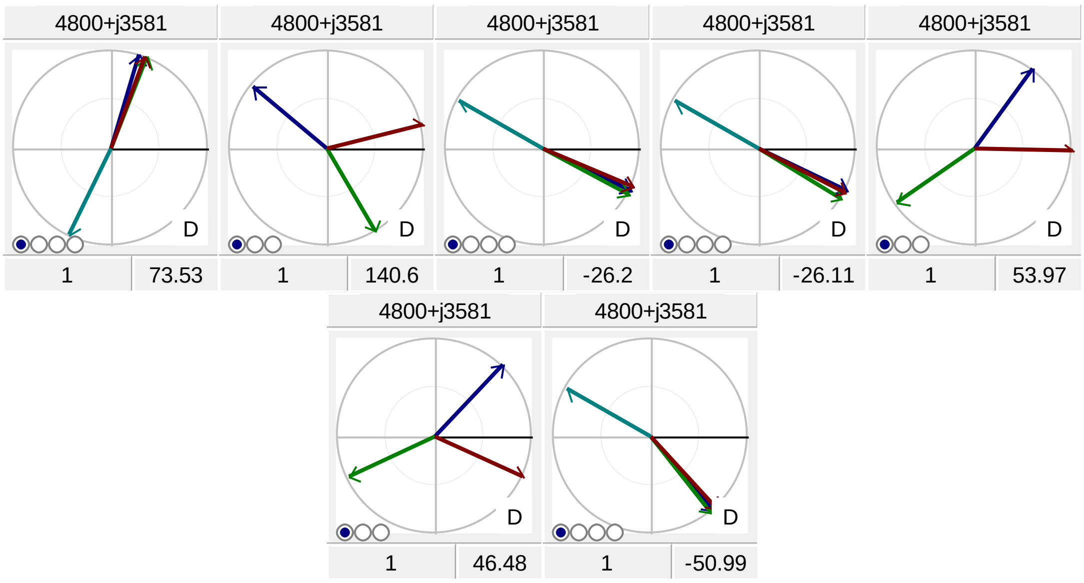


Figure 55: Phasor diagram for voltage 4800+j3581

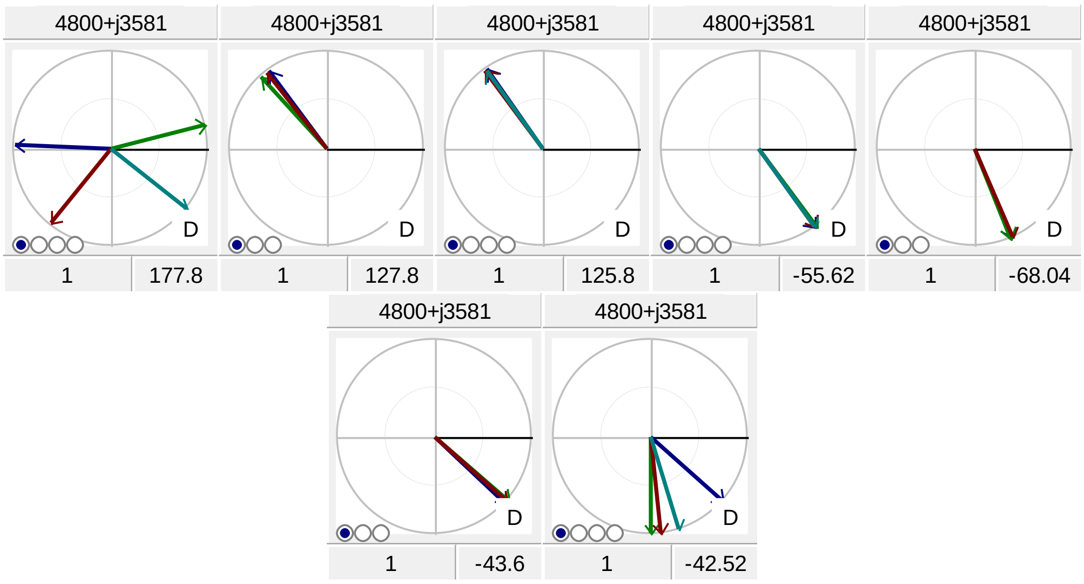


Figure 56: Phasor diagram for current 4800+j3581

The third harmonic current from the generator circulates around grid transformer secondary. The third harmonic voltage induced at transformer secondary causes the third harmonic current trap or block from pass through. Based on the result also, it shows that this configuration will secure load but may harm the generator as third harmonic current circulate between generator and grid transformer secondary as this path is the lowest impedance that can be passed through.

Based on the overall result, during island mode operation it shows that highest third harmonic currents exist when star-delta winding configuration is applied in the circuit. Meanwhile, the lowest third harmonic currents exist when delta-star winding configuration is applied. Every winding configuration can only protect some equipment and others need to be sacrificed. Meanwhile, when generator parallel with grid the third harmonic currents intend to pass through grid transformer secondary as it is the lowest impedance path. This happened at every transformer winding configuration.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Theoretically, under balanced load, third harmonic current are inversely proportional to load impedance, in other words, the higher the impedance, the lower the third harmonic currents. Theory also states that balanced triplen harmonic are zero sequence because their phase has same magnitude and angle. Triplen harmonic add up at the neutral and equivalent to three times the phase current.

When generator connected directly to a combined resistive and inductive load, the third harmonic current and voltage depend on load impedance magnitude and phase angle. Inductive component of the impedance has higher magnitude impact on the third harmonic voltage and current as compared to resistive component for identical impedance magnitude.

Since the third harmonic voltage produced by generator are in phase or zero sequence in nature, the transformer star winding provide the return path for third harmonic current. Transformer delta winding trap or provide path for third harmonic current to circulate in them. This is similar to zero sequence circuit for transformer used in symmetrical component analysis. Apart from transformer winding type, the load impedance magnitude and phase angle also influenced the third harmonic current and voltage.

The other experiment was conducted to study the behavior of the synchronous generator when paralleling with grid. Third harmonic current seen to pass through grid transformer secondary star winding rather than going through load because the former has lower impedance. Every transformer winding configuration behaves the same situation with different load impedance.

The recommendation is the study on third harmonic voltage and current propagation from generator should be done by performing harmonic measurement and analysis at all parts of the network. Third harmonic voltage and current magnitude alone may not give correct indication to their severity because they are vector quantity and rely on zero sequence network, load impedance magnitude and phase angle.

REFERENCES

[1] M.F. Abdullah, N.H. Hamid, Z.B. Baharudin, M.F.I. Khamis, N.S.R. Hashim, "Investigation on High Neutral Earthing Resistor Temperature When Islanded Generator Connected to Utility Grid,"

[2] "Harmonics, Triplen Harmonics, Adjustable Speed Drive, Power Quality", Hershey Energy Systems, Pittsford, New York 2001.

[3] Power System Harmonics, Jos Arrillaga and Neville R. Watson, Second Edition, John Willey and Sons Limited, 2003.

[4] Rosli Omar, Azhar Ahmad, and MarizanSulaiman, "Triplen Harmonics Mitigation 3 Phase Four-Wire Electrical Distribution System Using Wye Zig-Zig Transformers," Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS), 2004.

[5] L.W. Pierce, "Transformer Design and Application Considerations for Nonsinusoidal Load Currents," IEEE Trans. Ind. Appl., Vol. 25, No.4, 1996.

[6] Paul G. Cardinal, "Generator pitch and associated concerns when paralleling generators," Industry Applications Society Annual Meeting, 2009.

[7] G. Angst and J.L. Oldenkamp, "Third-Harmonic Voltage Generation in Salient Pole Synchronous Machines," Transactions of the American Institute of Electrical Engineers, Vol. 75, Issue: 3, pp. 434-441, June 1956.

[8] Power Quality in Power Systems and Electrical Machines,Ewald F Fuchs and Mohammad A.S Masoum, First Edition, Elsevier Academic Press, 2008.

[9] R.F. Arritt, R.C. Dugan, "Distributed Generation Interconnection Transformer and Grounding Selection," IEEE.

[10] “Application Notes: Harmonics”, Controlled Power Company, Troy, Michigan 1999.

[11] T.M. Gruzs, “Power System Problems from High Harmonic Neutral Currents,” Computer Technology Rev., Winter 1998.

[12] IEEE Std 519, “IEEE Recommended Practices and Requirements for Harmonics Control in Electrical Power Systems,” IEEE, New York, 1992 1993.

[13] M.F. Abdullah, N.H. Hamid, Z. Baharudin, M.F.I. Khamis, M.H.M. Nasir, “Characteristics of Triplen Harmonics Currents Produced by Salient Pole Synchronous Generator,”

[14] Mohamad Hisham B Mohamad Nasir, “Characteristics of Triplen Harmonics in Low Voltage Network,” Electrical & Electronic Engineering, Universiti Teknonlogi PETRONAS, May 2011.

[15] M.F. Abdullah, N.H. Hamid, Z. Baharudin, M.F.I. Khamis, “Triplen Harmonics Currents Propagation Through Medium Voltage Disitribution Network,” Electrical & Electronic Engineering, Universiti Teknonlogi PETRONAS.

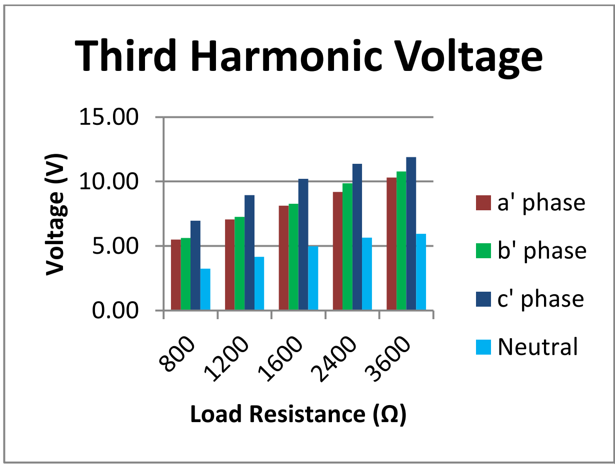
[16] Gianfranco Chicco, PetruPostolache, Cornel Toader, “Triplen Harmonics: Myths and Reality,” Department of Electrical Engineering, Polytechnic Torino, Italy, January 2010.

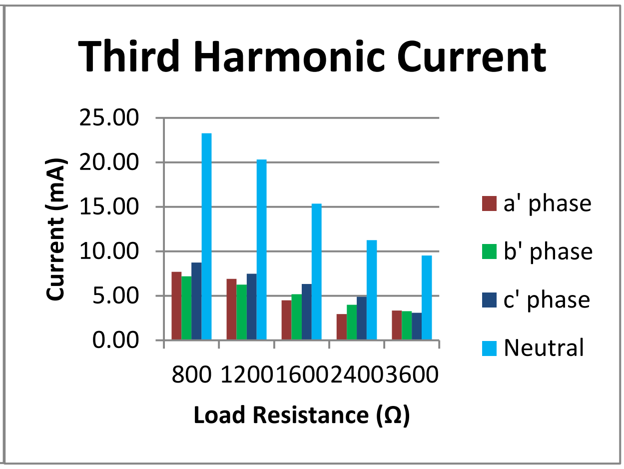
[17] Kus Vaclav, SkalaBuchmil, “Generator Overloading Owing to Neutral Wire Current”, University of West Bohemia in Pilsen, Czech Republic, 2011 IEEE.

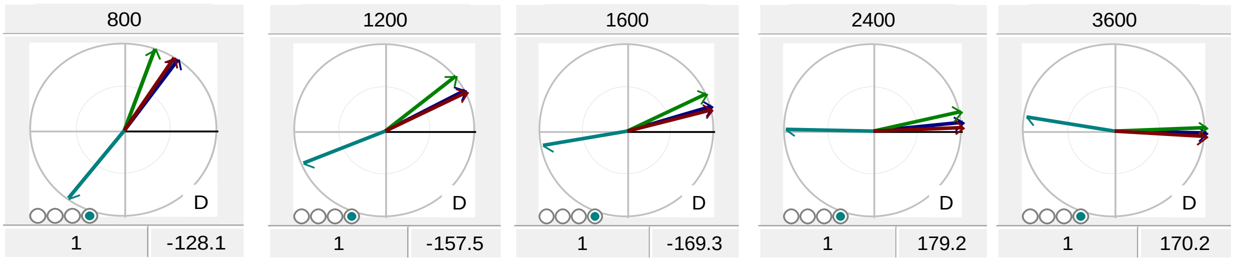
APPENDICES

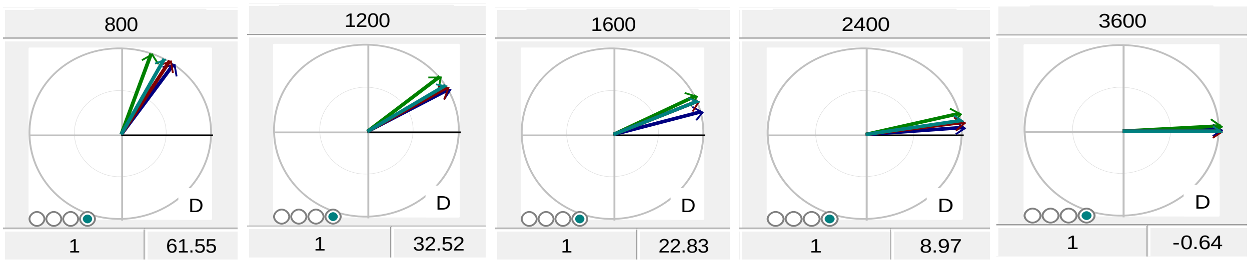
Appendix A

Resistive load



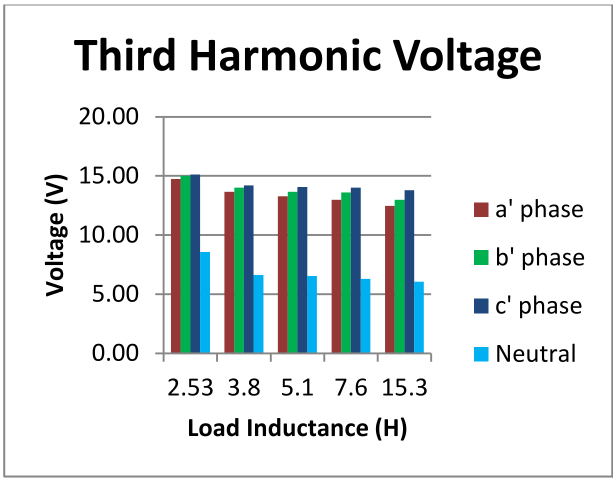


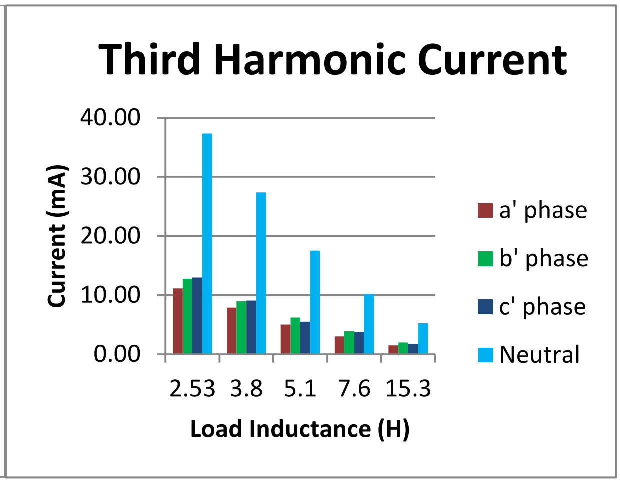


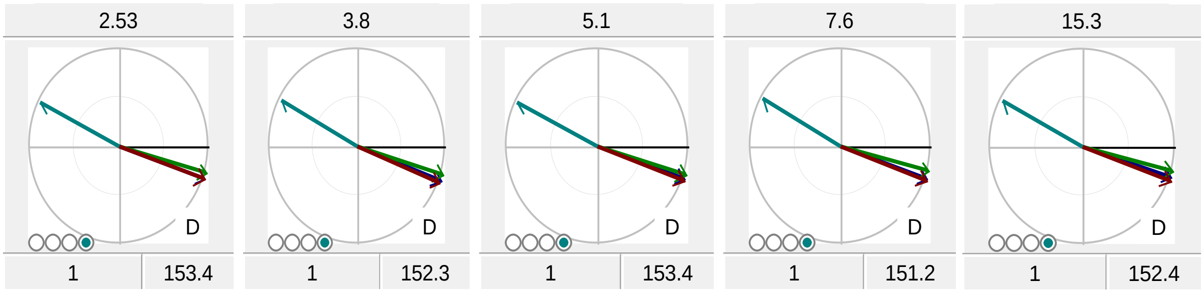


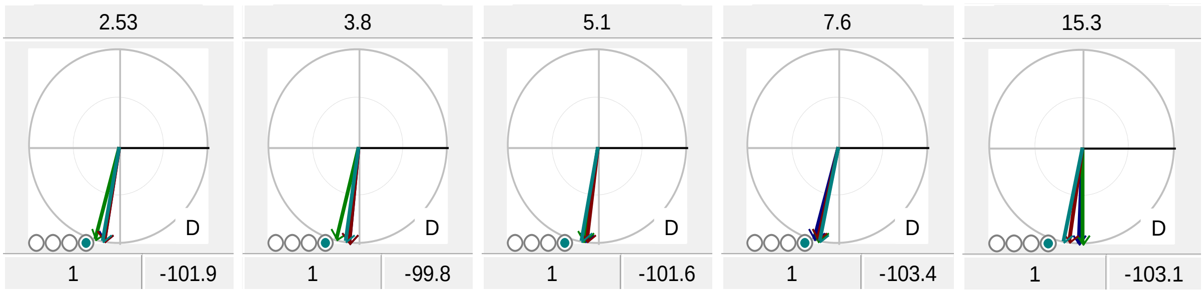
Appendix B

Inductive load



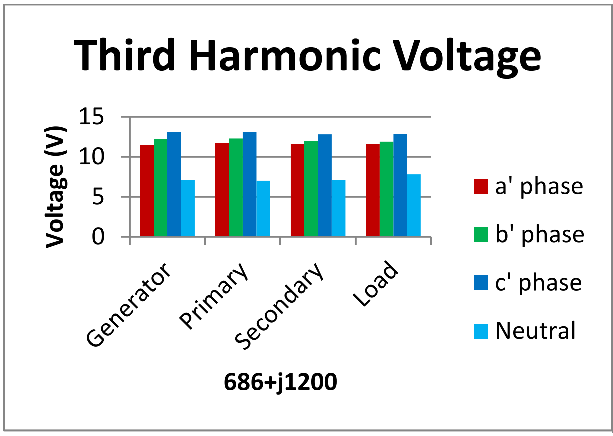


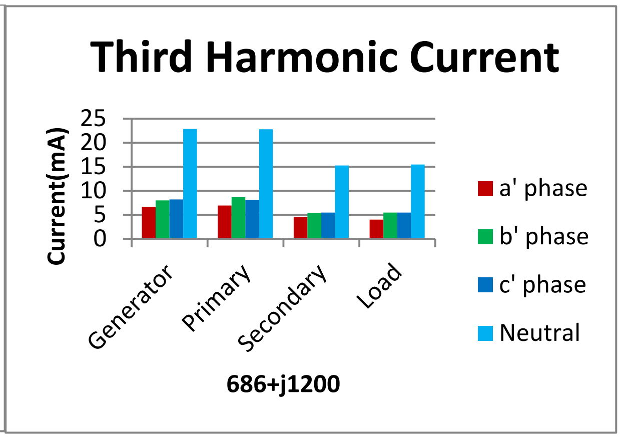


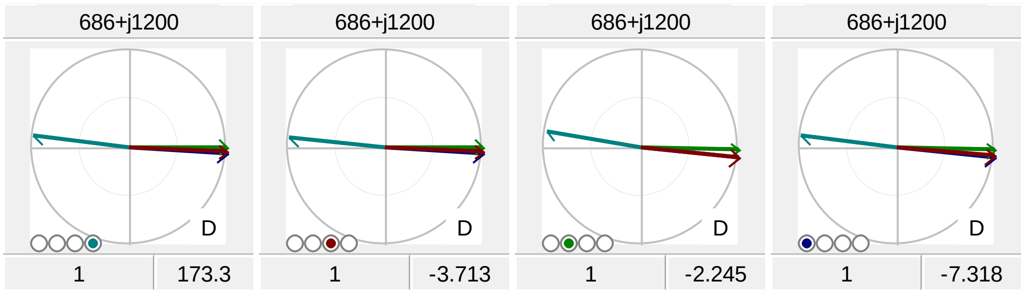


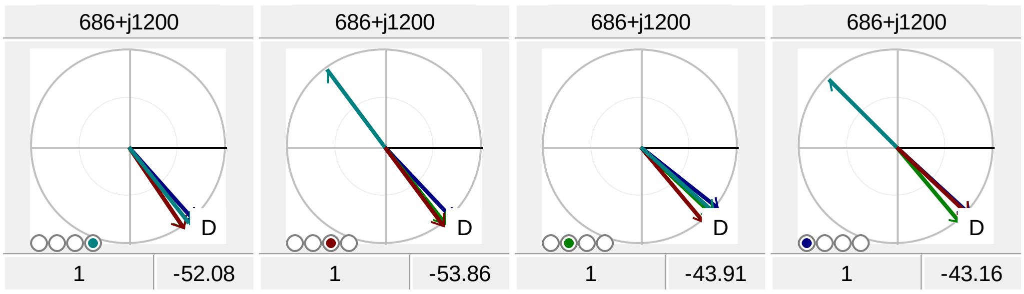
Appendix C

686 + j1200

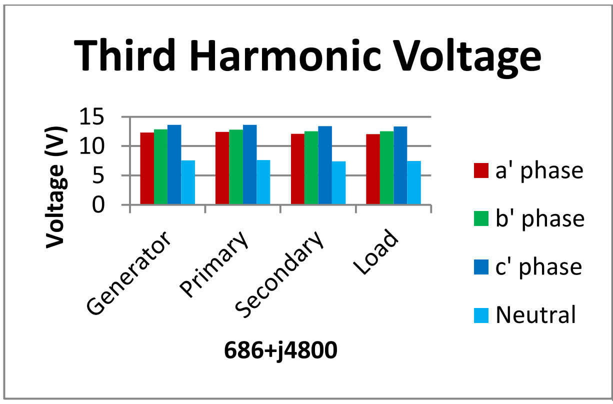


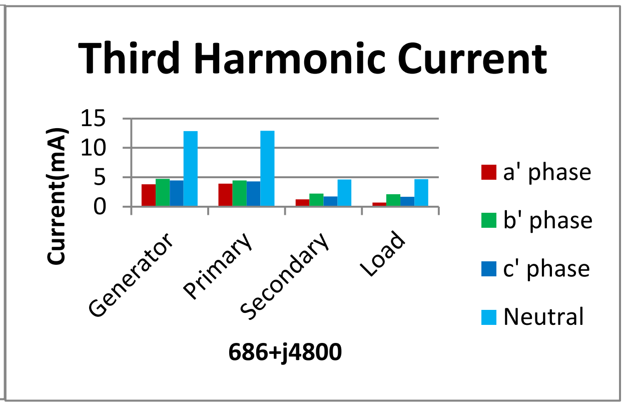


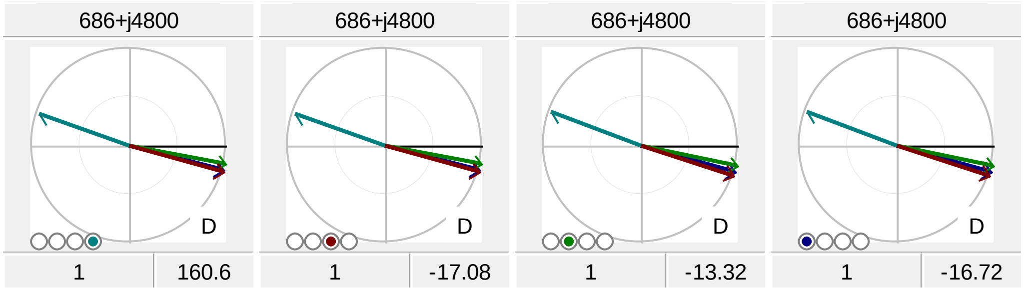


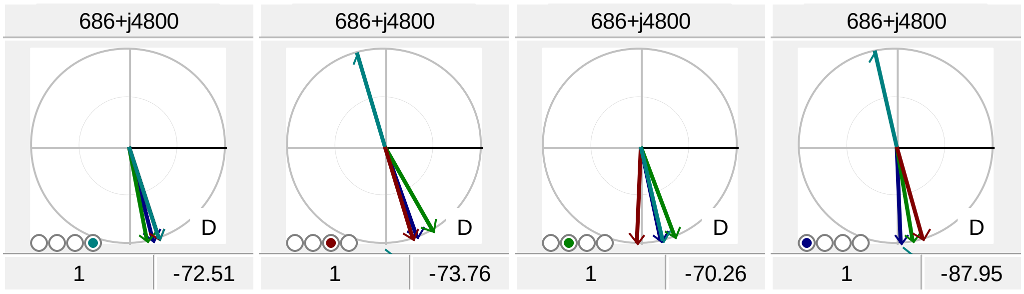


686 + j4800

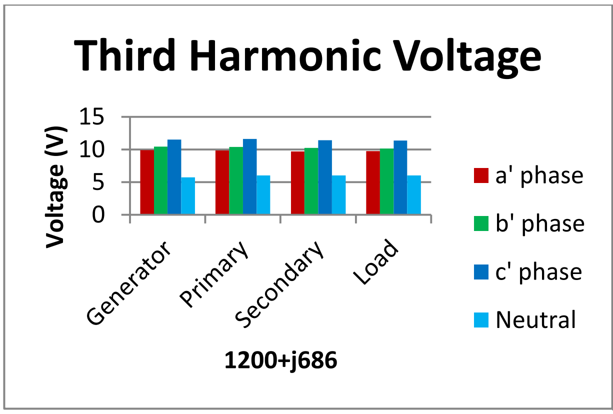

Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
686+j4800
a' phase
b' phase
c' phase
Neutral

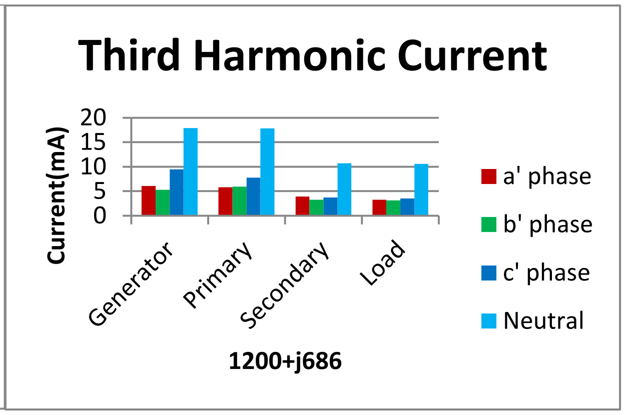

Third Harmonic Current
Current(mA)
15
10
5
0
Generator
Primary
Secondary
Load
686+j4800
a' phase
b' phase
c' phase
Neutral

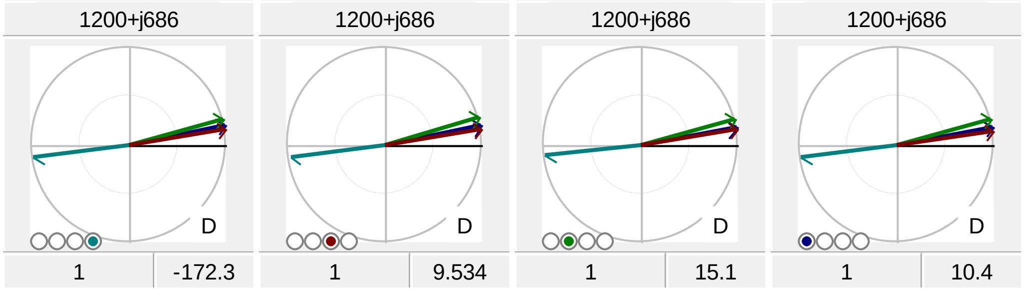

686+j4800
D
1
160.6
686+j4800
D
1
-17.08
686+j4800
D
1
-13.32
686+j4800
D
1
-16.72

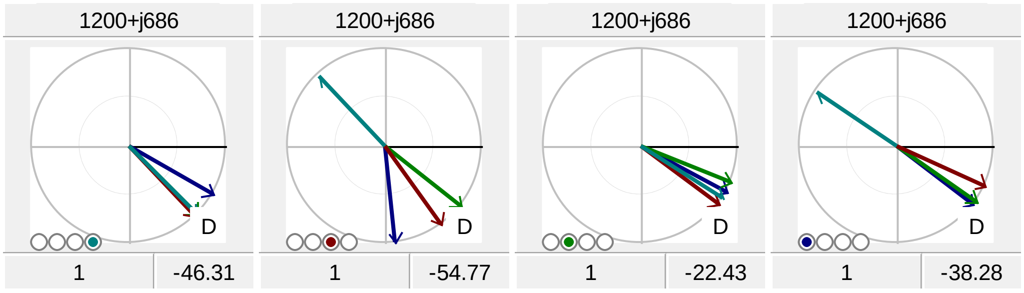

686+j4800
D
1
-72.51
686+j4800
D
1
-73.76
686+j4800
D
1
-70.26
686+j4800
D
1
-87.95

1200 + j686

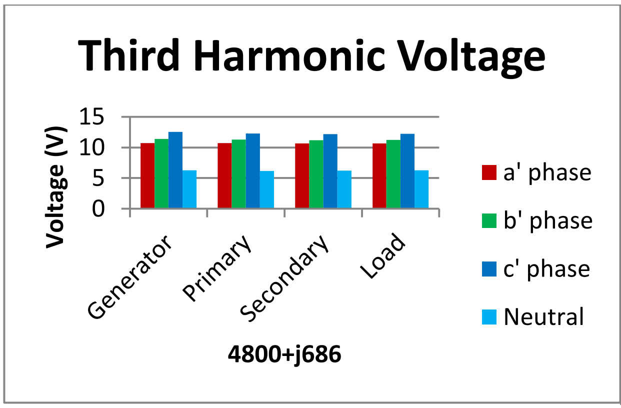

Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
1200+j686
a' phase
b' phase
c' phase
Neutral


Third Harmonic Current
Current(mA)
20
15
10
5
0
Generator
Primary
Secondary
Load
1200+j686
a' phase
b' phase
c' phase
Neutral

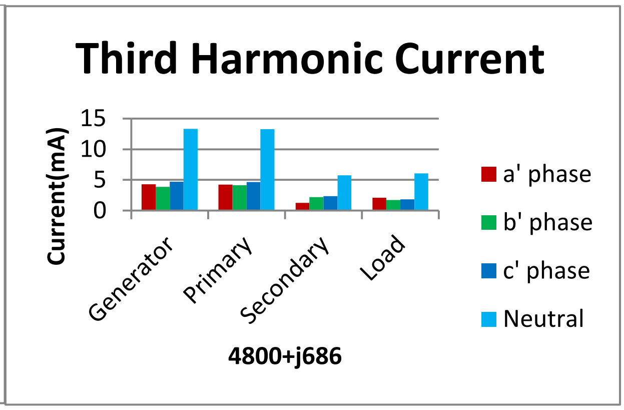

1200+j686
D
1
-172.3
1200+j686
D
1
9.534
1200+j686
D
1
15.1
1200+j686
D
1
10.4


1200+j686
D
1
-46.31
1200+j686
D
1
-54.77
1200+j686
D
1
-22.43
1200+j686
D
1
-38.28

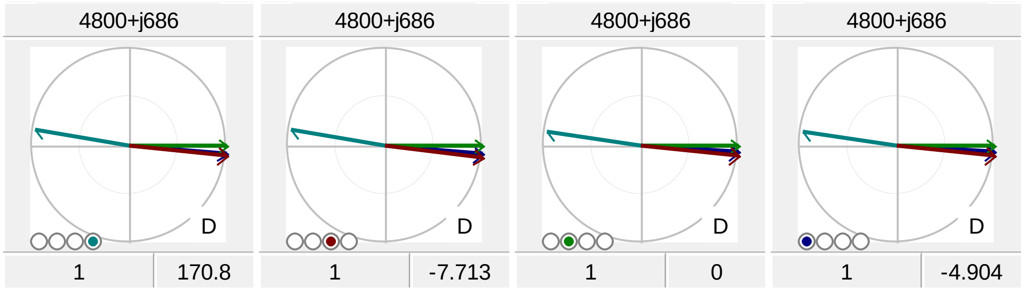
4800 + j686



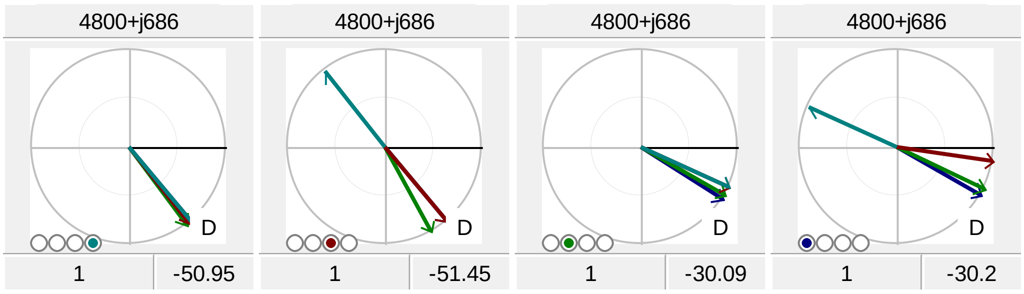
Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
4800+j686
a' phase
b' phase
c' phase
Neutral



Third Harmonic Current
Current(mA)
15
10
5
0
Generator
Primary
Secondary
Load
4800+j686
a' phase
b' phase
c' phase
Neutral



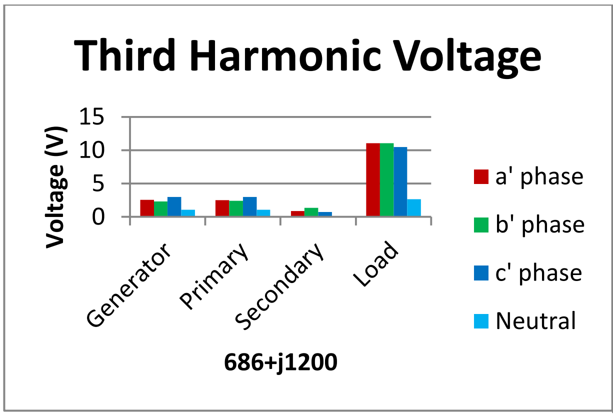
4800+j686
D
1
170.8
4800+j686
D
1
-7.713
4800+j686
D
1
0
4800+j686
D
1
-4.904

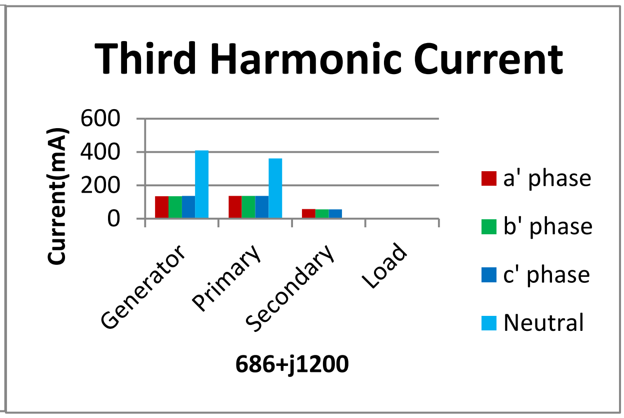


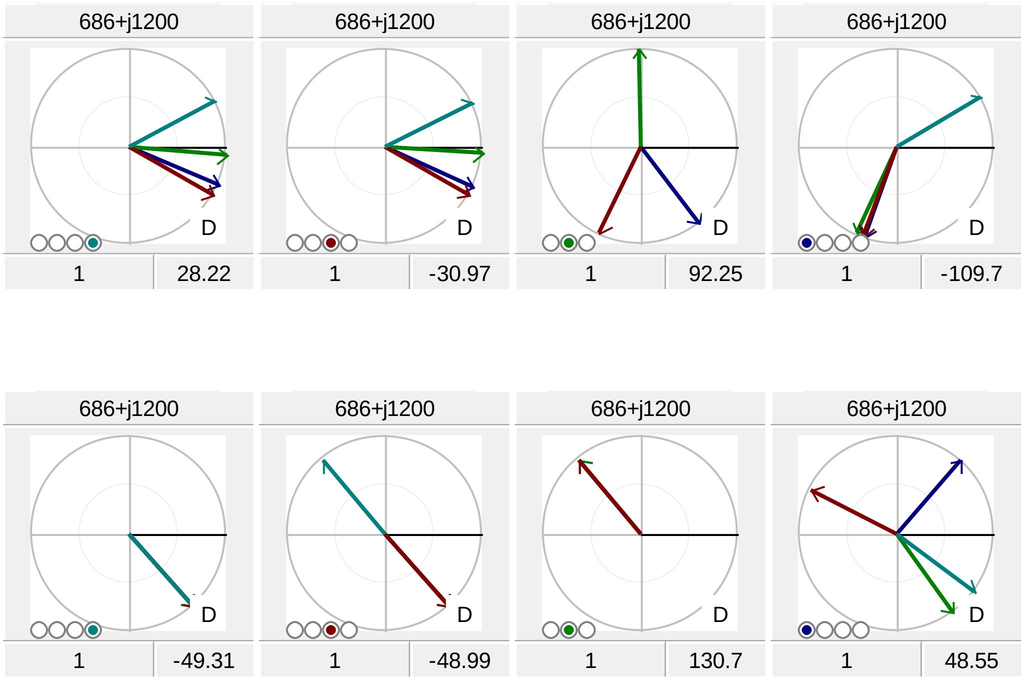
4800+j686
D
1
-50.95
4800+j686
D
1
-51.45
4800+j686
D
1
-30.09
4800+j686
D
1
-30.2

Appendix D

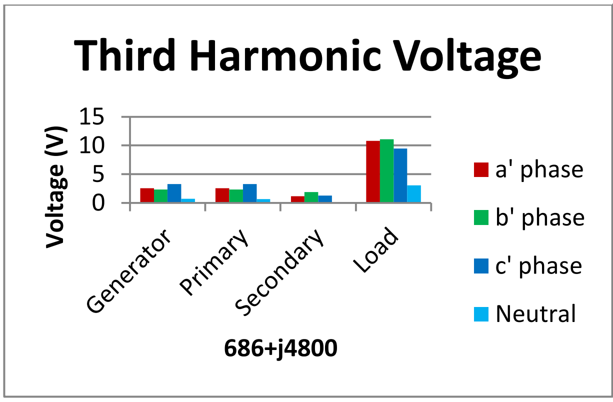
686 + j1200

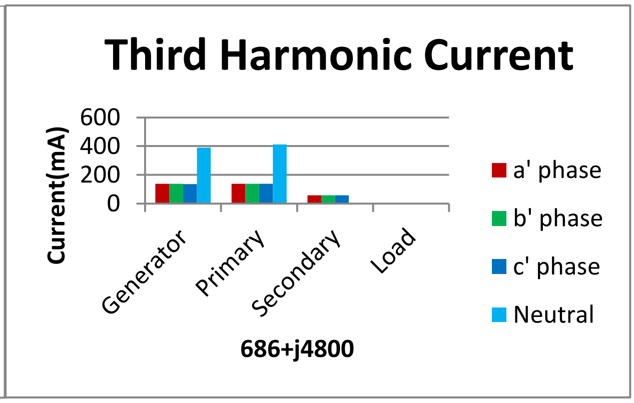


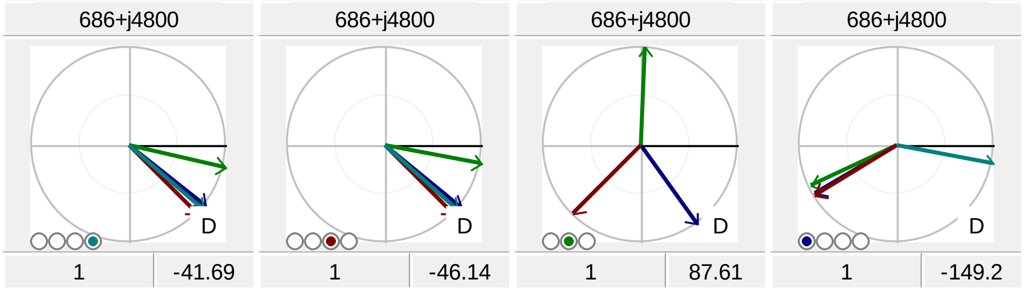


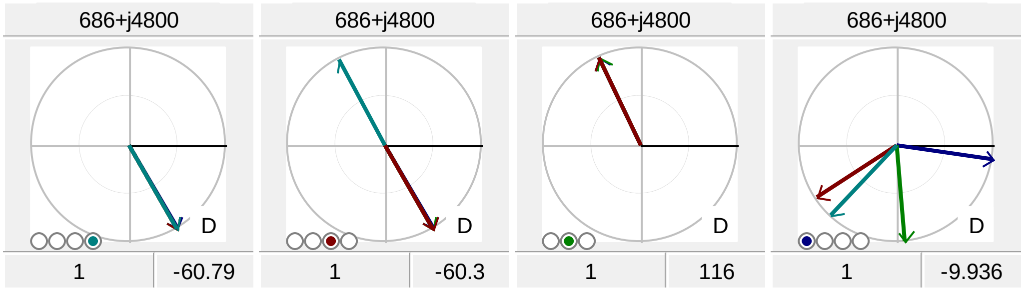


686 + j4800

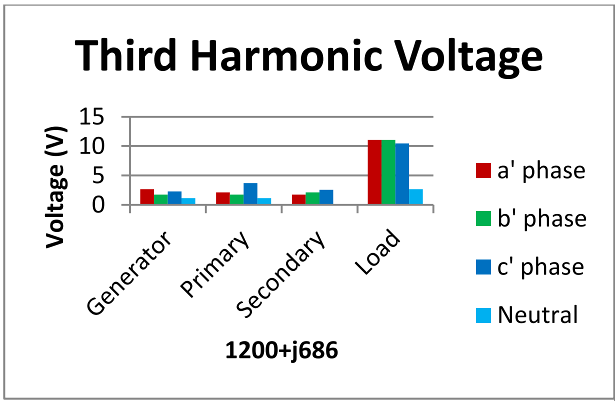

Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
686+j4800
a' phase
b' phase
c' phase
Neutral


Third Harmonic Current
Current(mA)
600
400
200
0
Generator
Primary
Secondary
Load
686+j4800
a' phase
b' phase
c' phase
Neutral

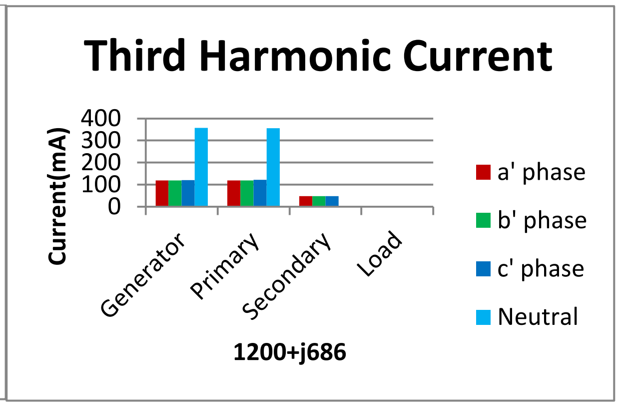

686+j4800
D
1
-41.69
686+j4800
D
1
-46.14
686+j4800
D
1
87.61
686+j4800
D
1
-149.2


686+j4800
D
1
-60.79
686+j4800
D
1
-60.3
686+j4800
D
1
116
686+j4800
D
1
-9.936

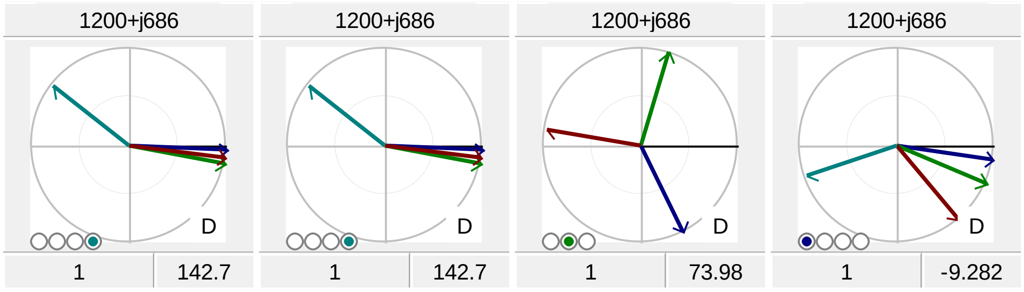
1200 + j686



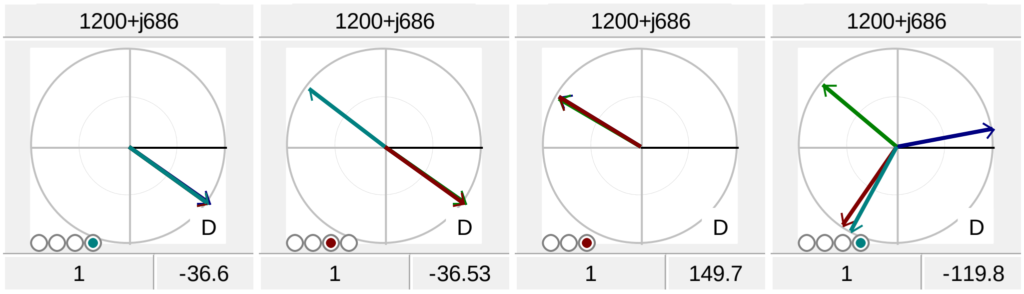
Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
1200+j686



Third Harmonic Current
Current(mA)
400
300
200
100
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
1200+j686

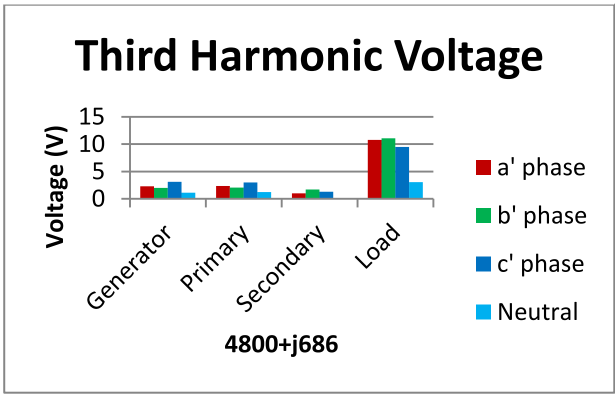


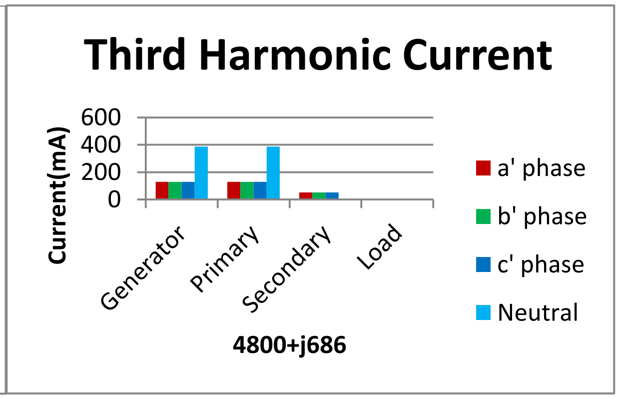
1200+j686
D
1
142.7
1200+j686
D
1
142.7
1200+j686
D
1
73.98
1200+j686
D
1
-9.282

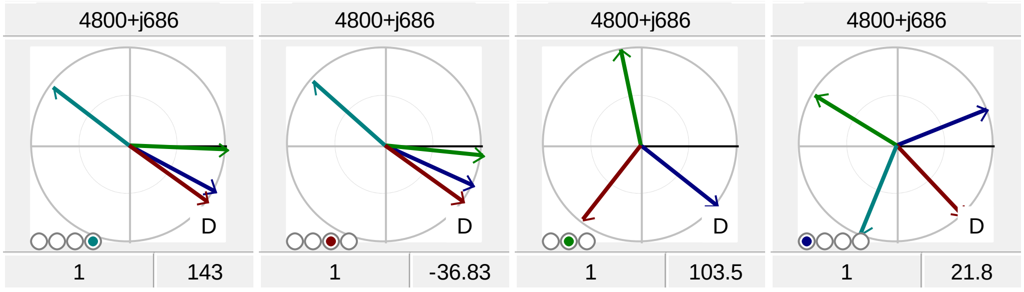


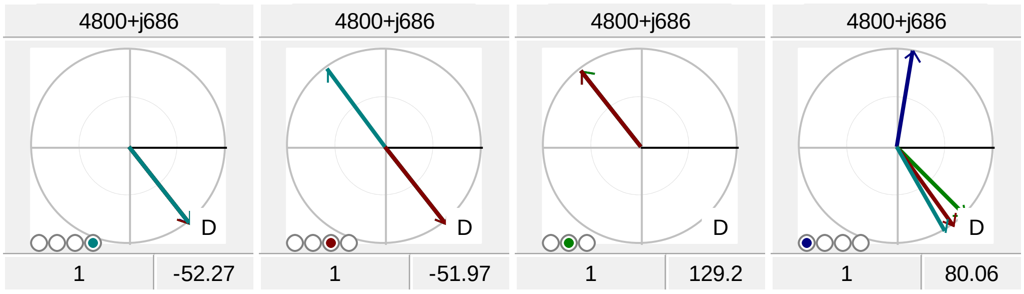
1200+j686
D
1
-36.6
1200+j686
D
1
-36.53
1200+j686
D
1
149.7
1200+j686
D
1
-119.8

4800 + j686


Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
4800+j686
a' phase
b' phase
c' phase
Neutral

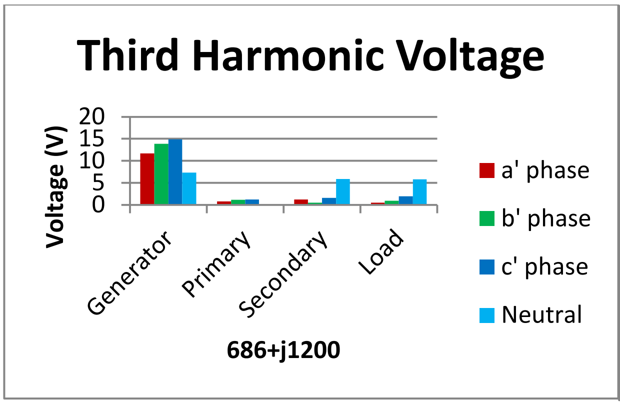

Third Harmonic Current
Current(mA)
600
400
200
0
Generator
Primary
Secondary
Load
4800+j686
a' phase
b' phase
c' phase
Neutral

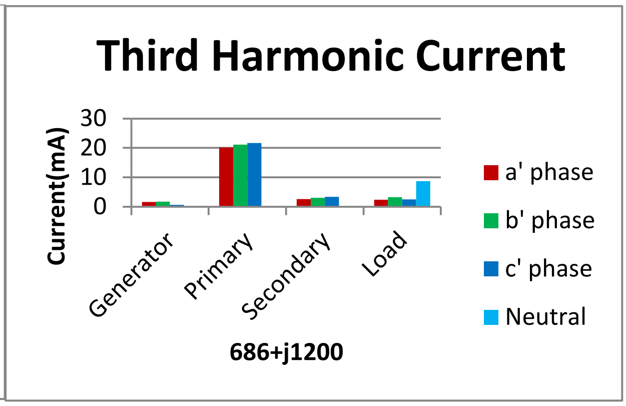

4800+j686
D
1
143
4800+j686
D
1
-36.83
4800+j686
D
1
103.5
4800+j686
D
1
21.8

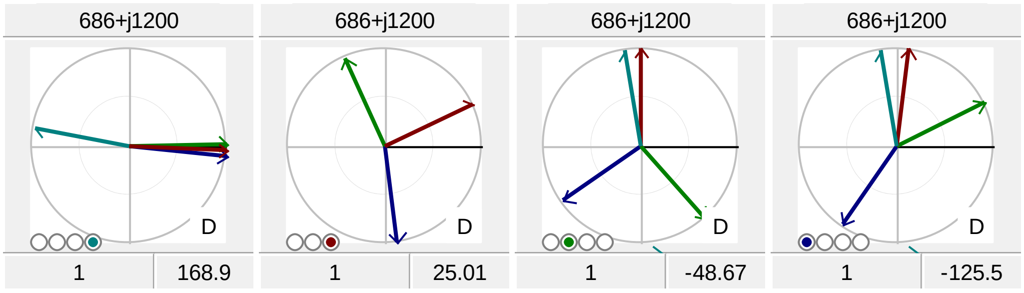

4800+j686
D
1
-52.27
4800+j686
D
1
-51.97
4800+j686
D
1
129.2
4800+j686
D
1
80.06

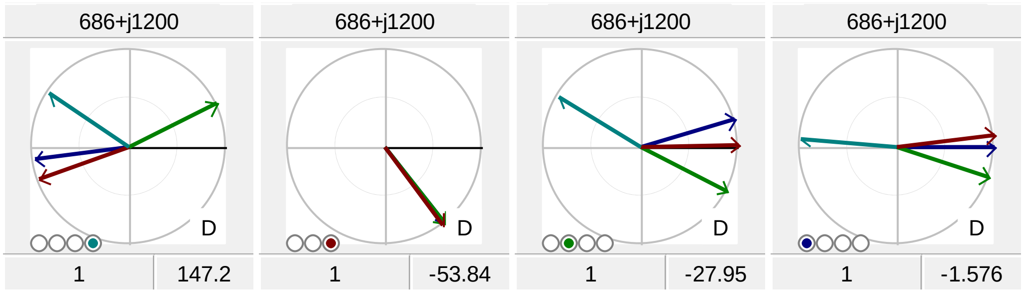
Appendix E

686 + j1200

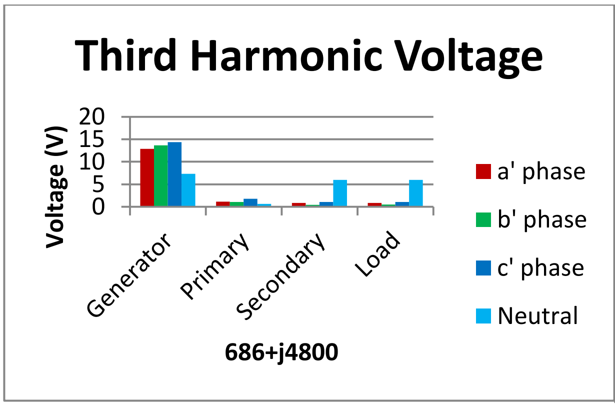


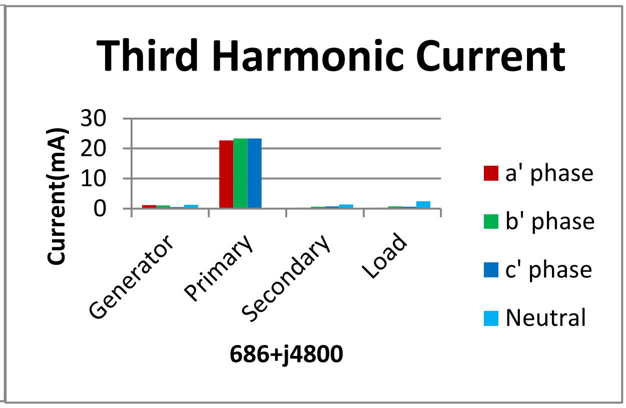


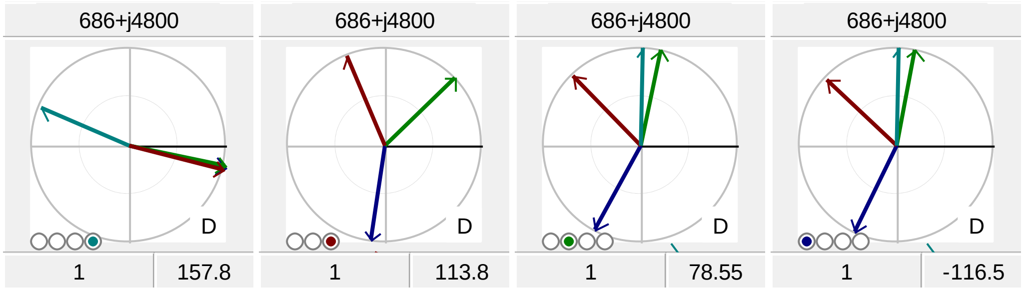


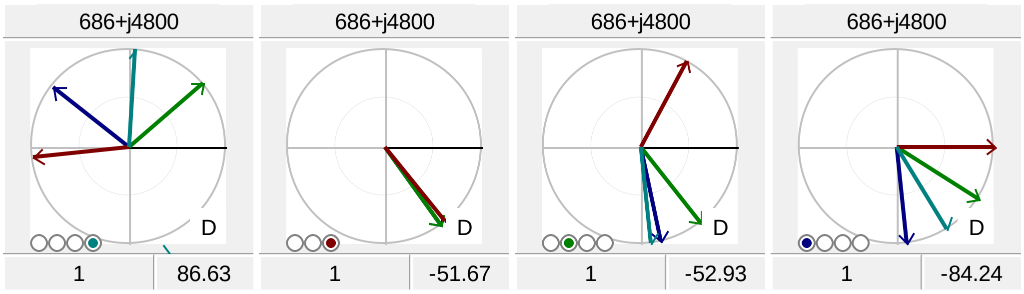


686 + j4800

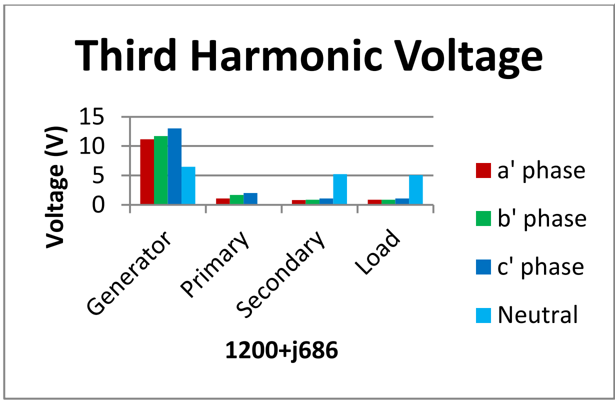

Third Harmonic Voltage
Voltage (V)
20
15
10
5
0
Generator
Primary
Secondary
Load
686+j4800
a' phase
b' phase
c' phase
Neutral

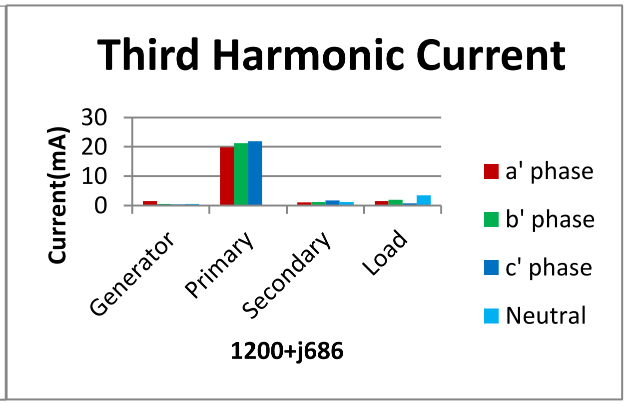

Third Harmonic Current
Current(mA)
30
20
10
0
Generator
Primary
Secondary
Load
686+j4800
a' phase
b' phase
c' phase
Neutral

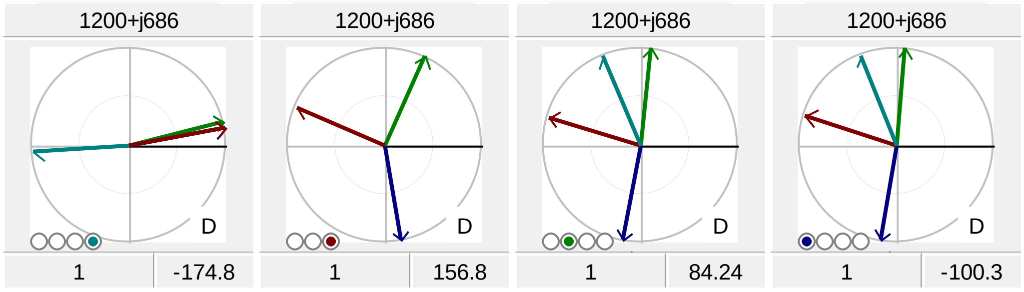

686+j4800
D
1
157.8
686+j4800
D
1
113.8
686+j4800
D
1
78.55
686+j4800
D
1
-116.5

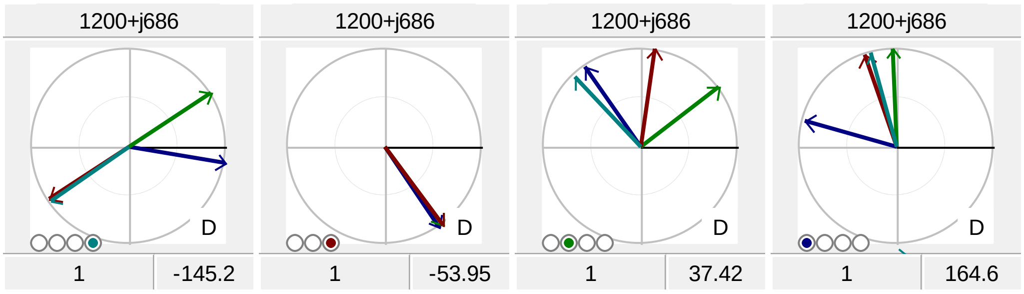

686+j4800
D
1
86.63
686+j4800
D
1
-51.67
686+j4800
D
1
-52.93
686+j4800
D
1
-84.24

1200 + j686

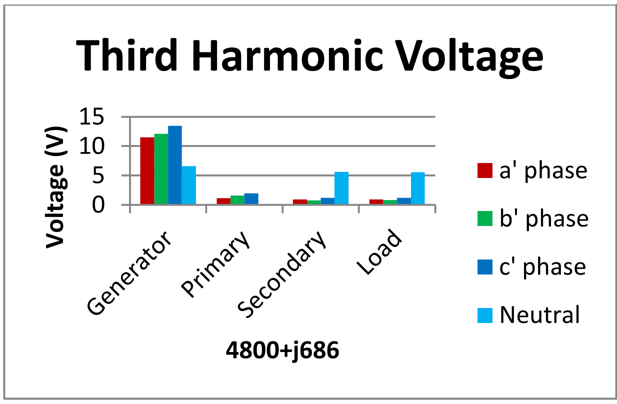

Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
1200+j686


Third Harmonic Current
Current(mA)
30
20
10
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
1200+j686

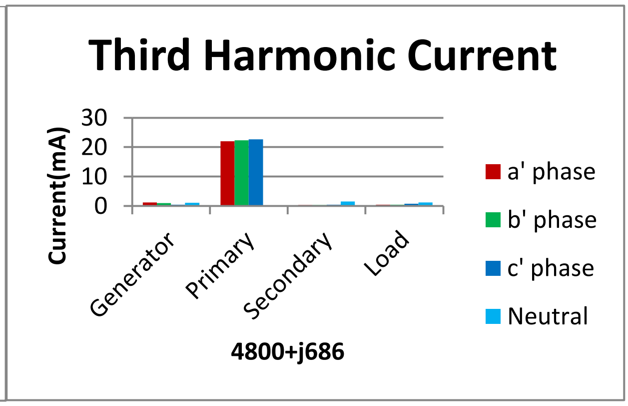

1200+j686
D
1
-174.8
1200+j686
D
1
156.8
1200+j686
D
1
84.24
1200+j686
D
1
-100.3


1200+j686
D
1
-145.2
1200+j686
D
1
-53.95
1200+j686
D
1
37.42
1200+j686
D
1
164.6

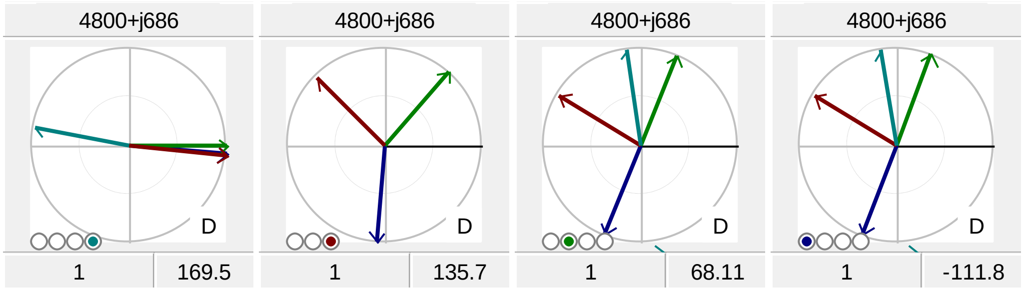
4800 + j686



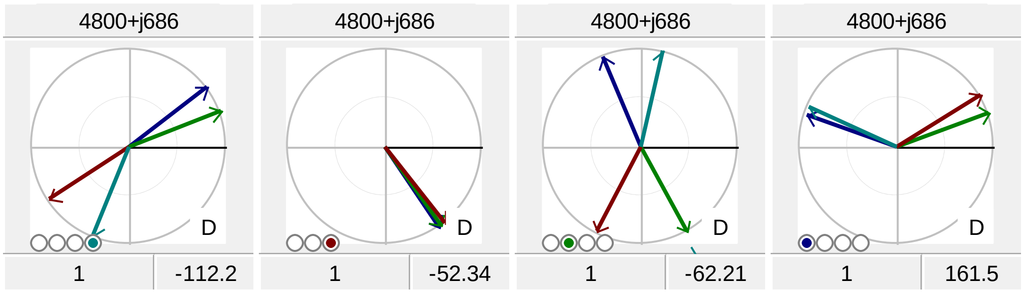
Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
4800+j686
a' phase
b' phase
c' phase
Neutral



Third Harmonic Current
Current(mA)
30
20
10
0
Generator
Primary
Secondary
Load
4800+j686
a' phase
b' phase
c' phase
Neutral



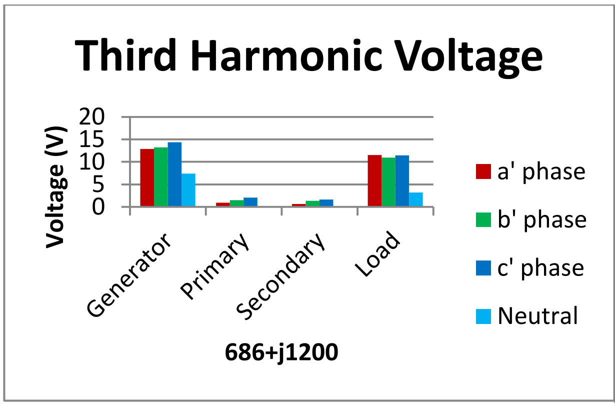
4800+j686
D
1
169.5
4800+j686
D
1
135.7
4800+j686
D
1
68.11
4800+j686
D
1
-111.8

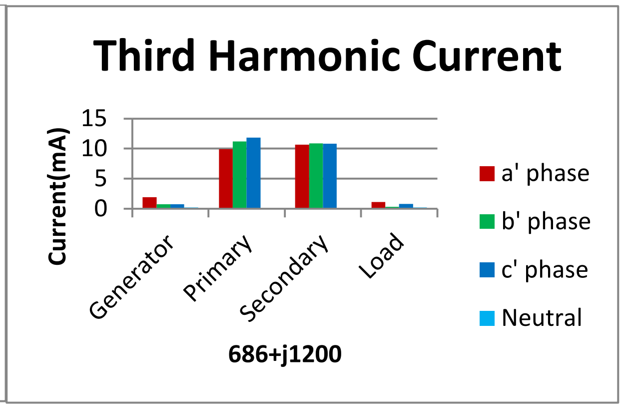


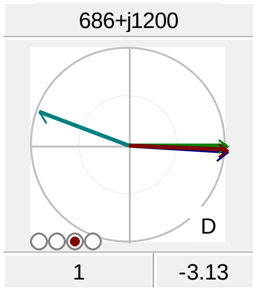
4800+j686
D
1
-112.2
4800+j686
D
1
-52.34
4800+j686
D
1
-62.21
4800+j686
D
1
161.5

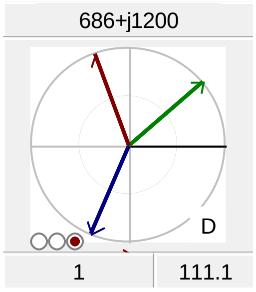
Appendix F

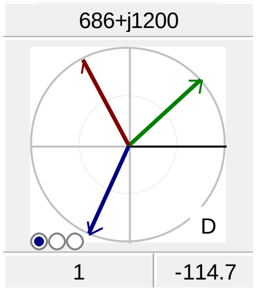
686 + j1200

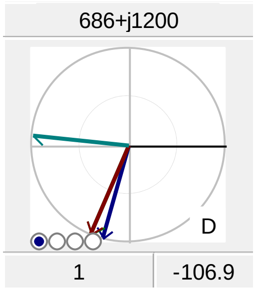


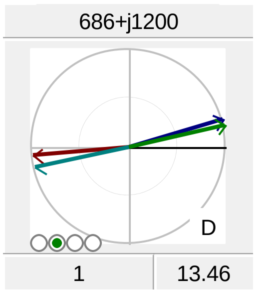


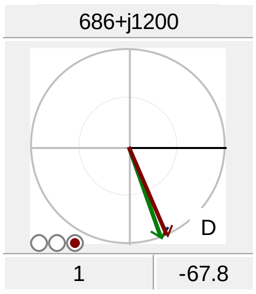


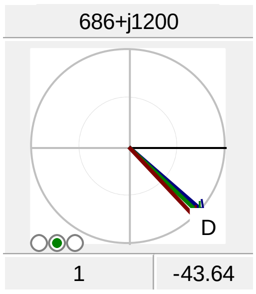


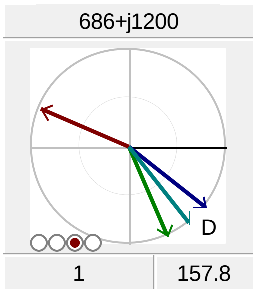




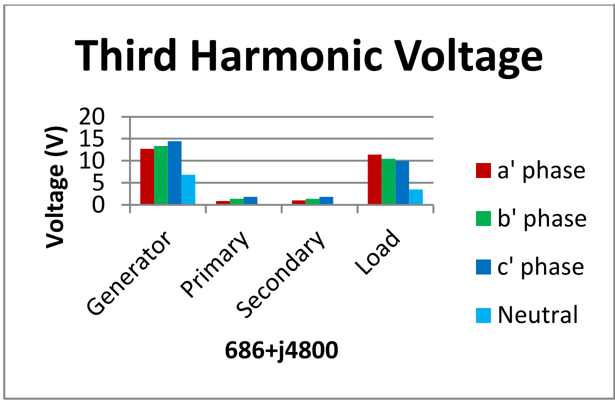


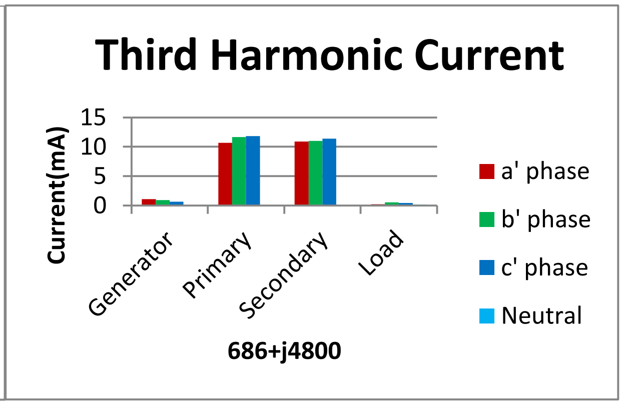


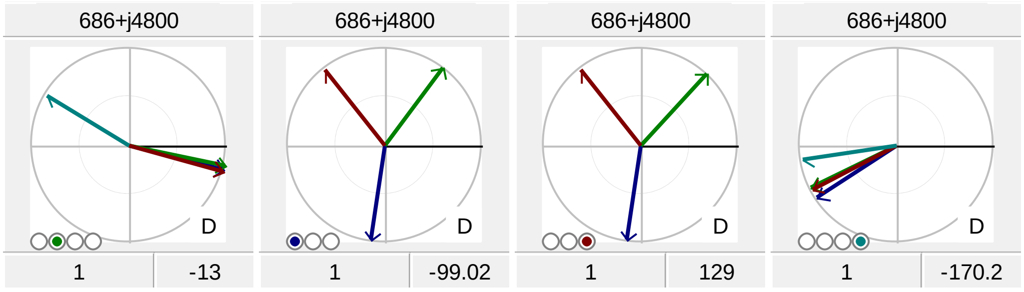


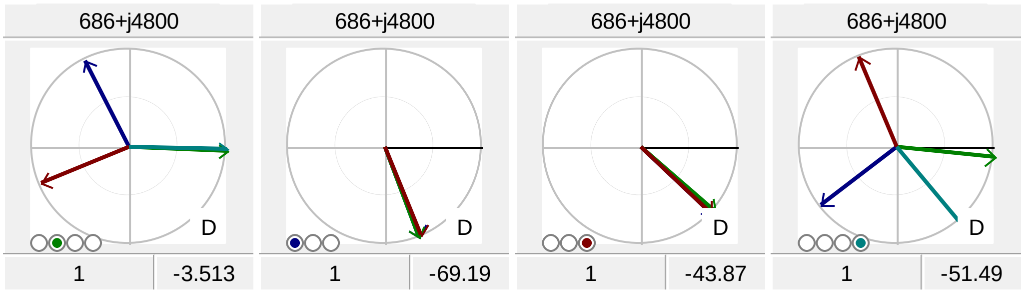


686 + j4800

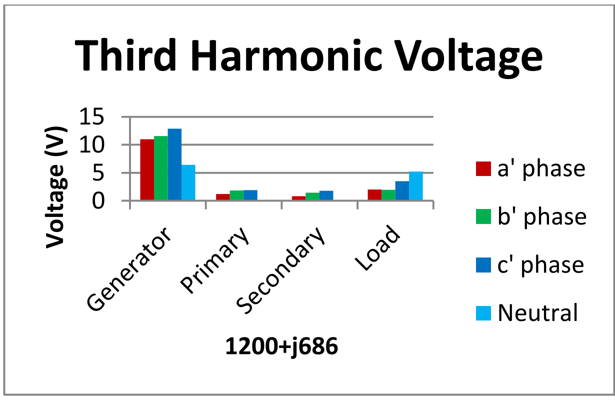

Third Harmonic Voltage
Voltage (V)
20
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
686+j4800

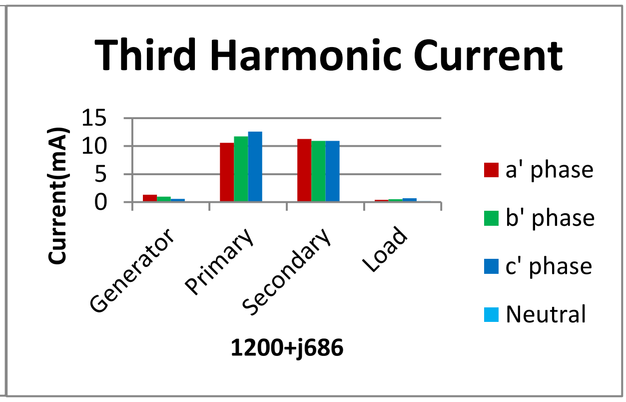

Third Harmonic Current
Current(mA)
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
686+j4800

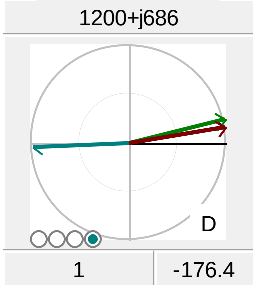

686+j4800
D
1
-13
686+j4800
D
1
-99.02
686+j4800
D
1
129
686+j4800
D
1
-170.2

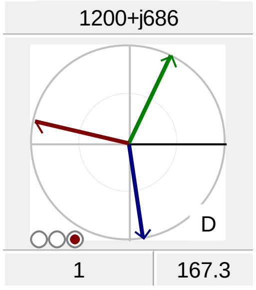

686+j4800
D
1
-3.513
686+j4800
D
1
-69.19
686+j4800
D
1
-43.87
686+j4800
D
1
-51.49

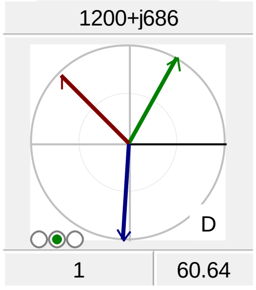
1200 + j686

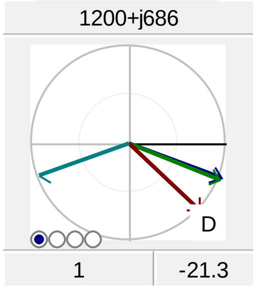

Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
1200+j686
a' phase
b' phase
c' phase
Neutral

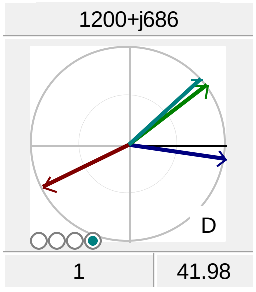

Third Harmonic Current
Current(mA)
15
10
5
0
Generator
Primary
Secondary
Load
1200+j686
a' phase
b' phase
c' phase
Neutral

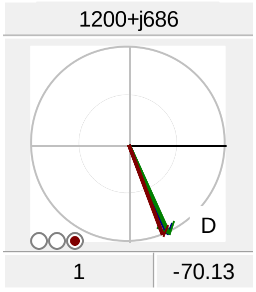

1200+j686
D
1
-176.4

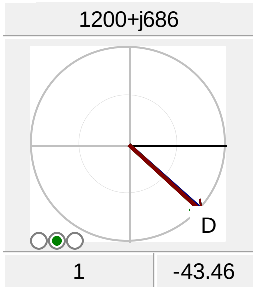

1200+j686
D
1
167.3

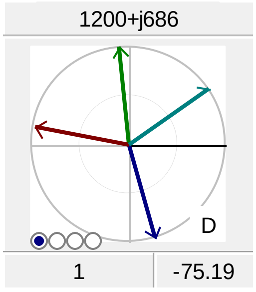

1200+j686
D
1
60.64


1200+j686
D
1
-21.3

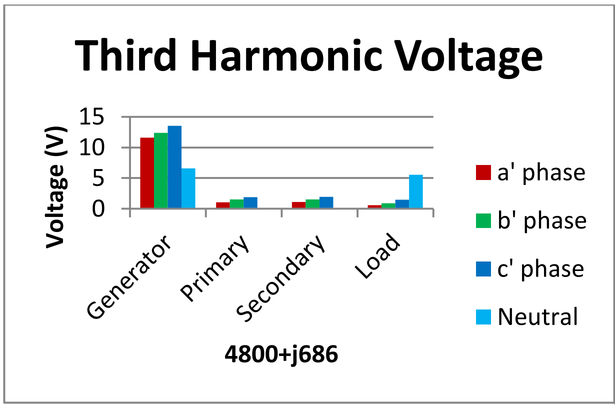

1200+j686
D
1
41.98

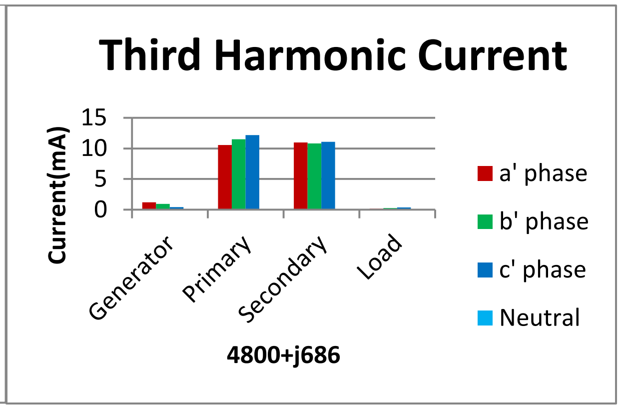

1200+j686
D
1
-70.13

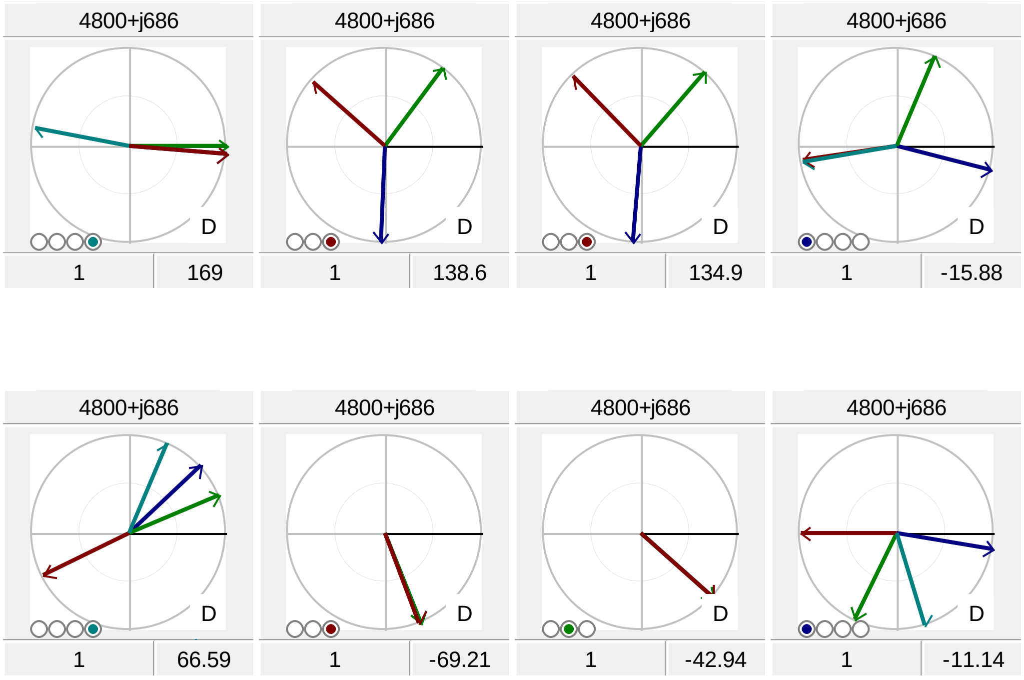

1200+j686
D
1
-43.46


1200+j686
D
1
-75.19

4800 + j686

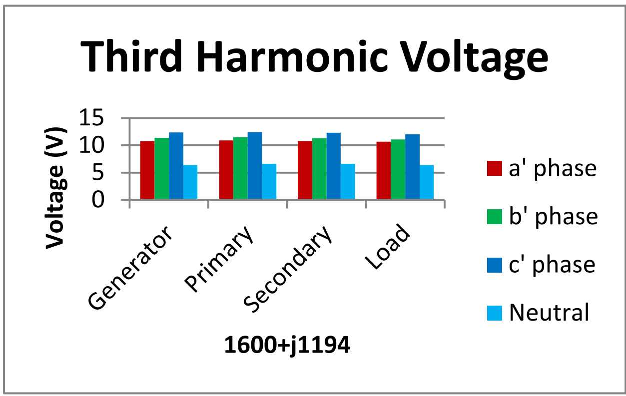

Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
4800+j686

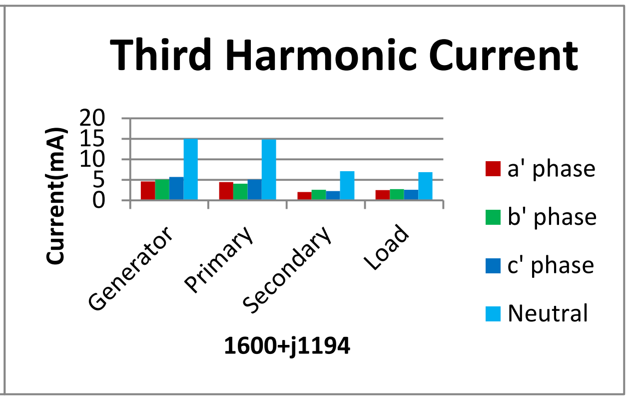

Third Harmonic Current
Current(mA)
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
4800+j686

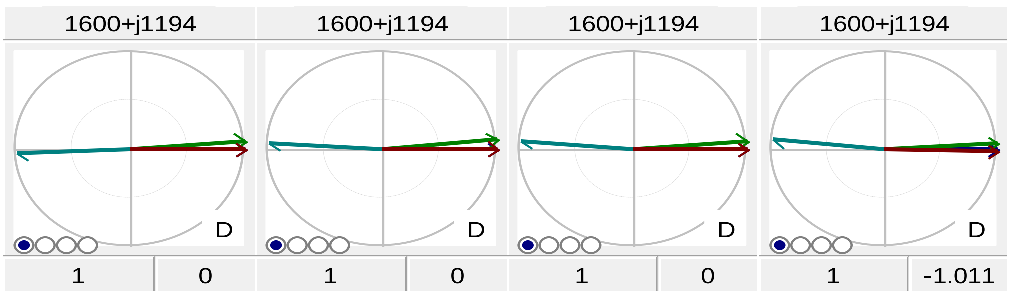

4800+j686
D
1
169
4800+j686
D
1
138.6
4800+j686
D
1
134.9
4800+j686
D
1
-15.88
4800+j686
D
1
66.59
4800+j686
D
1
-69.21
4800+j686
D
1
-42.94
4800+j686
D
1
-11.14

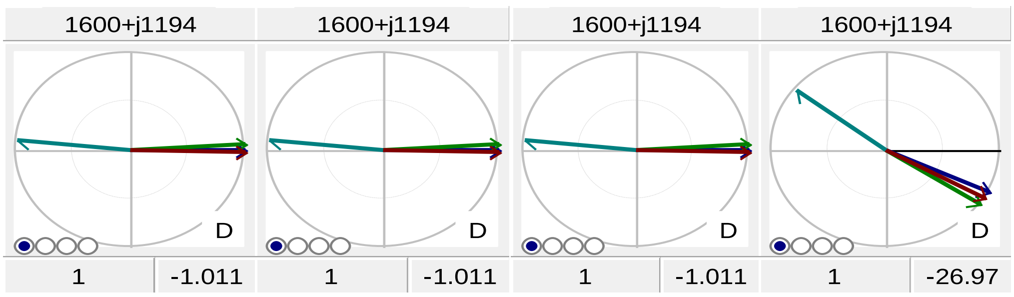
Appendix G

1600+j1194

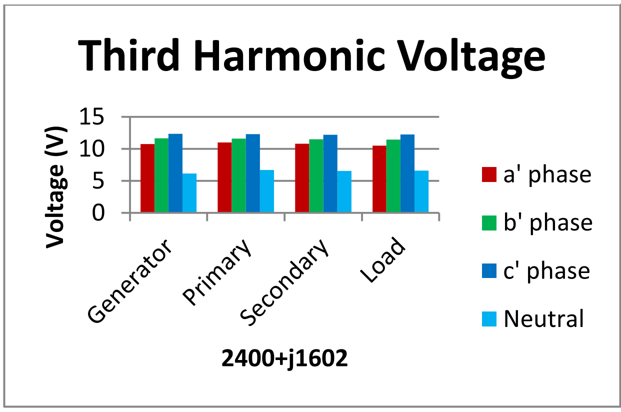


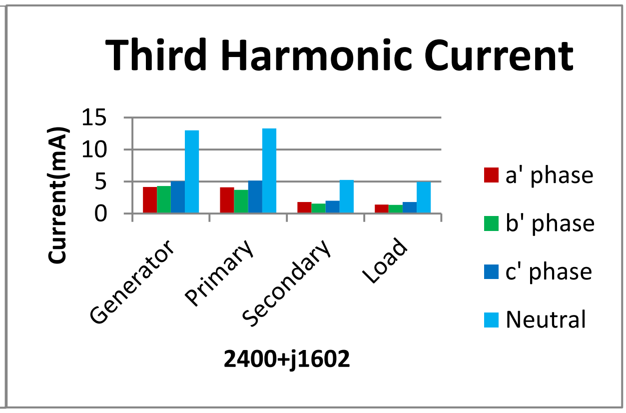


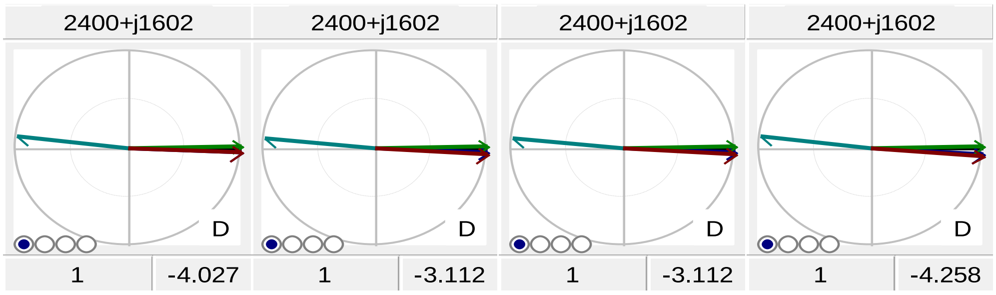


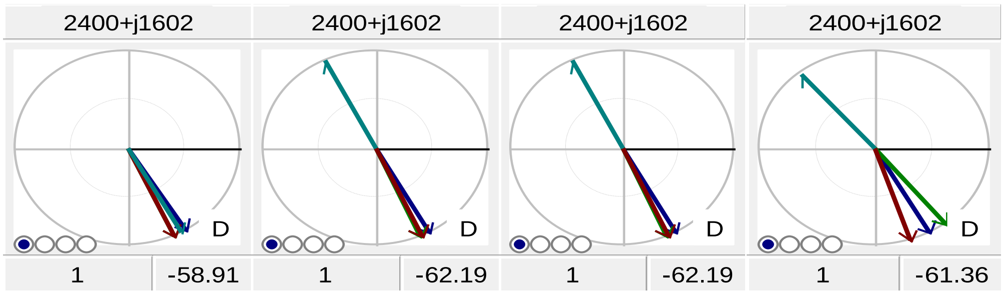


2400+j1602

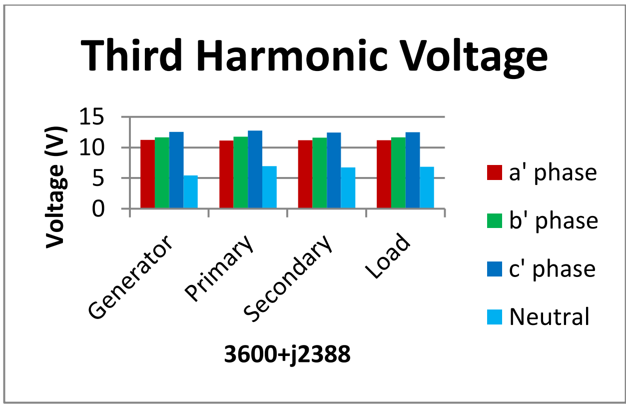

Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
2400+j1602


Third Harmonic Current
Current(mA)
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
2400+j1602

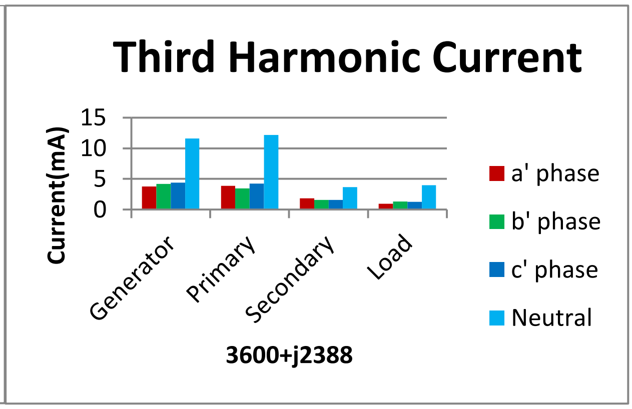

2400+j1602
2400+j1602
2400+j1602
2400+j1602
D
D
D
D
1
-4.027
1
-3.112
1
-3.112
1
-4.258


2400+j1602
2400+j1602
2400+j1602
2400+j1602
D
D
D
D
1
-58.91
1
-62.19
1
-62.19
1
-61.36

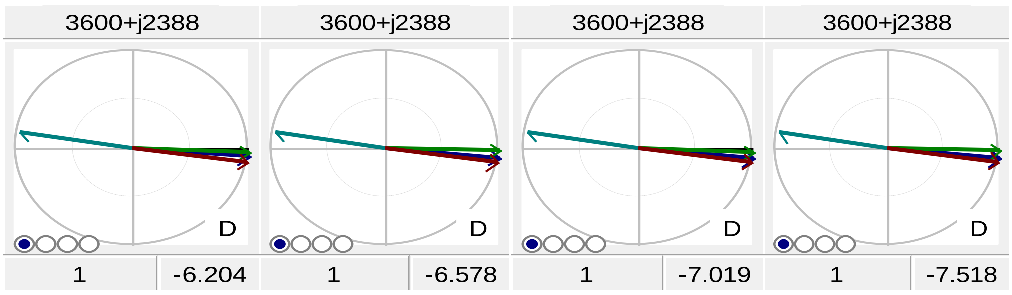
3600+j2388



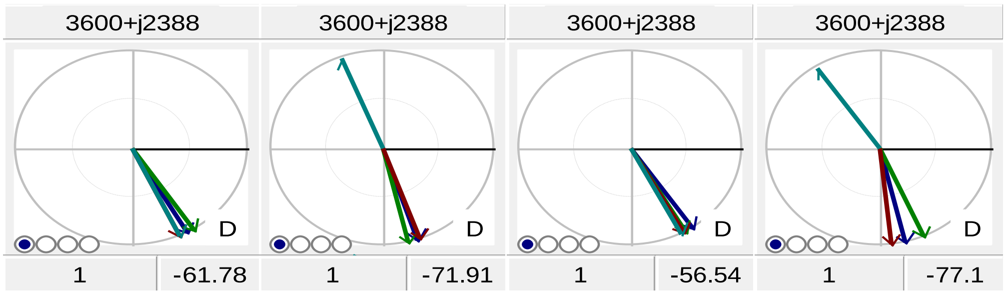
Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
3600+j2388
a' phase
b' phase
c' phase
Neutral



Third Harmonic Current
Current(mA)
15
10
5
0
Generator
Primary
Secondary
Load
3600+j2388
a' phase
b' phase
c' phase
Neutral

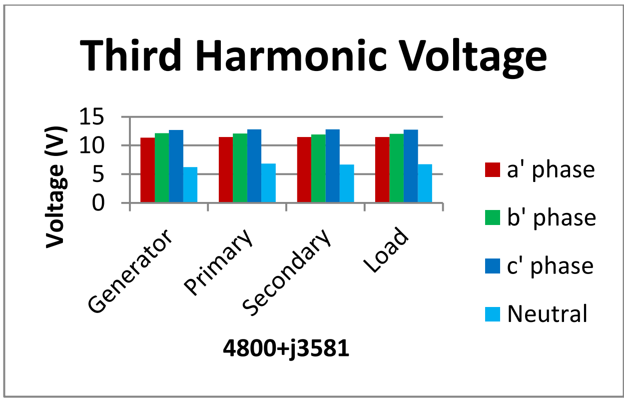


3600+j2388
3600+j2388
3600+j2388
3600+j2388
D
D
D
D
1
-6.204
1
-6.578
1
-7.019
1
-7.518

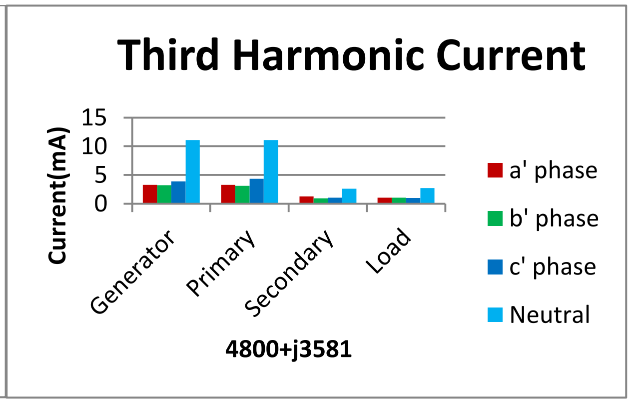


3600+j2388
3600+j2388
3600+j2388
3600+j2388
D
D
D
D
1
-61.78
1
-71.91
1
-56.54
1
-77.1

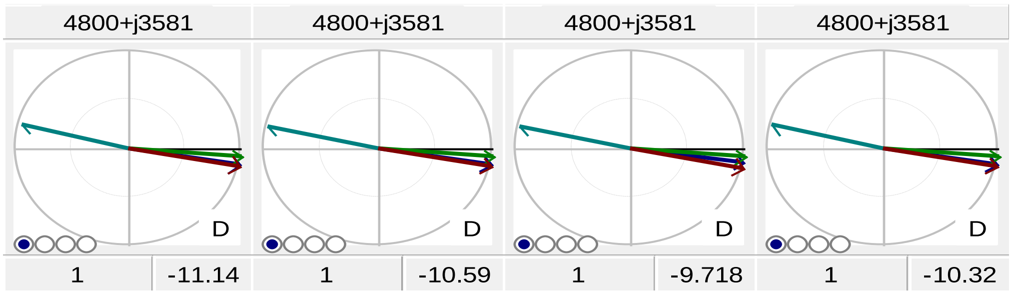
4800+j3581



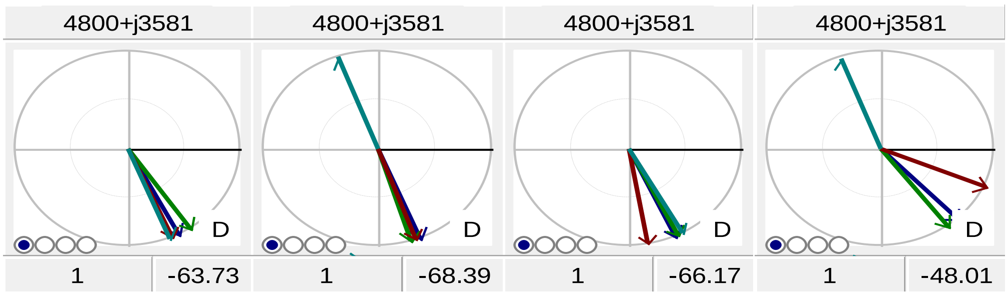
Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
4800+j3581
a' phase
b' phase
c' phase
Neutral



Third Harmonic Current
Current(mA)
15
10
5
0
Generator
Primary
Secondary
Load
4800+j3581
a' phase
b' phase
c' phase
Neutral



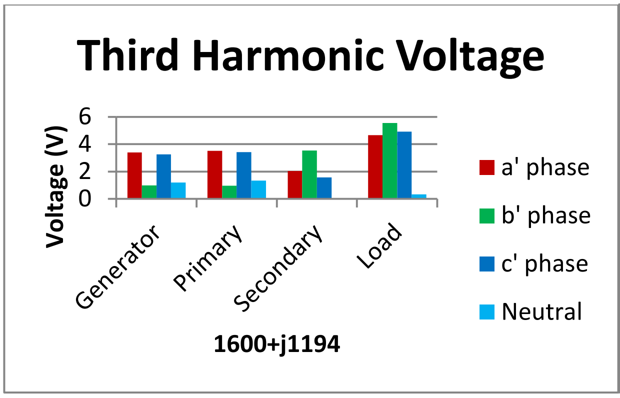
4800+j3581
4800+j3581
4800+j3581
4800+j3581
D
D
D
D
1
-11.14
1
-10.59
1
-9.718
1
-10.32

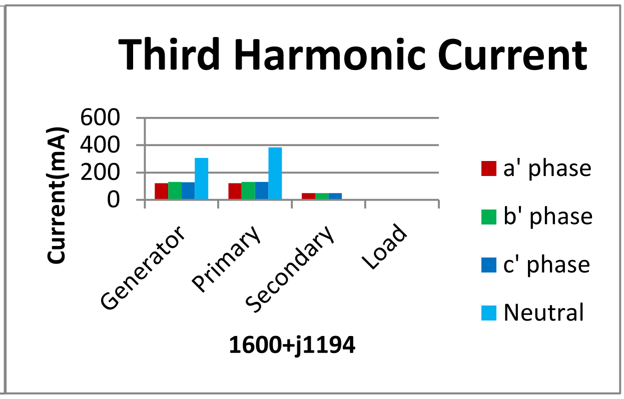


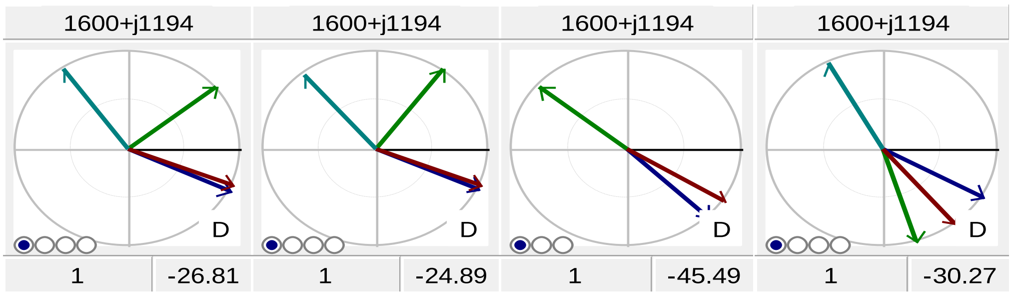
4800+j3581
4800+j3581
4800+j3581
4800+j3581
D
D
D
D
1
-63.73
1
-68.39
1
-66.17
1
-48.01

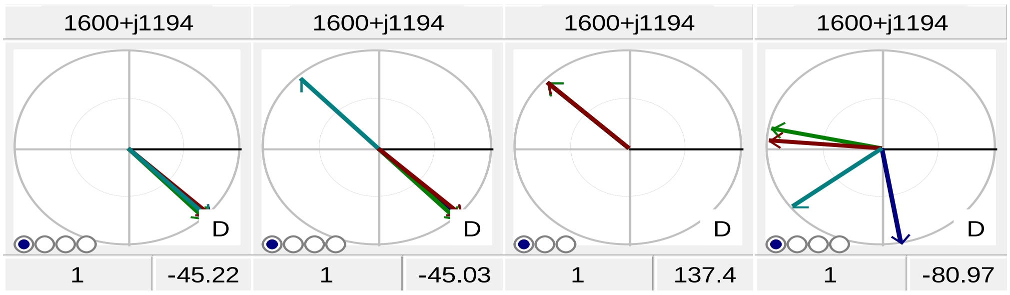
Appendix H

1600+j1194

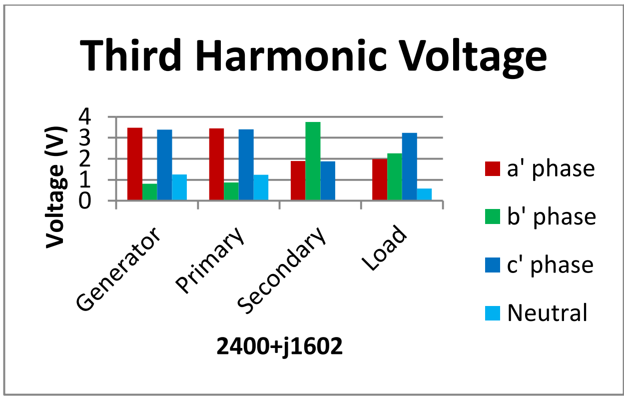


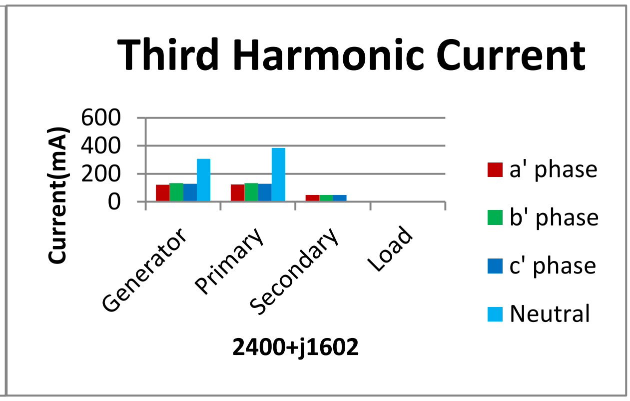


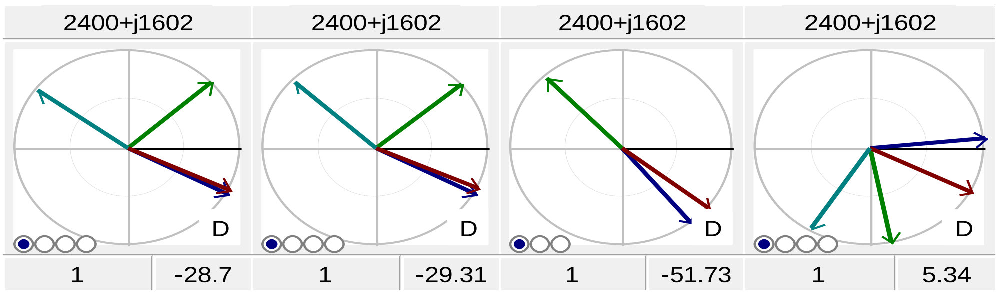


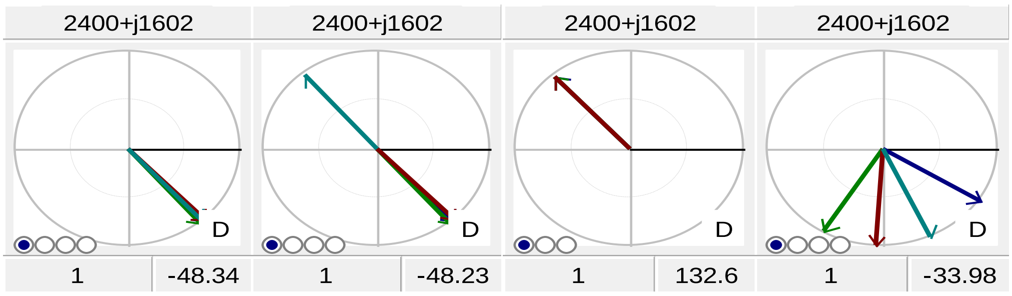


2400+j1602

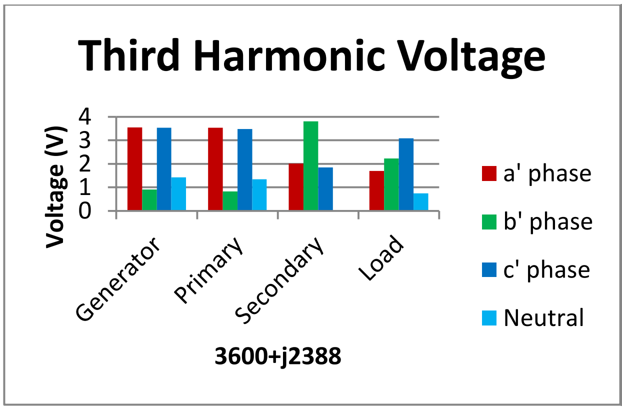

Third Harmonic Voltage
Voltage (V)
4
3
2
1
0
Generator
Primary
Secondary
Load
2400+j1602
a' phase
b' phase
c' phase
Neutral

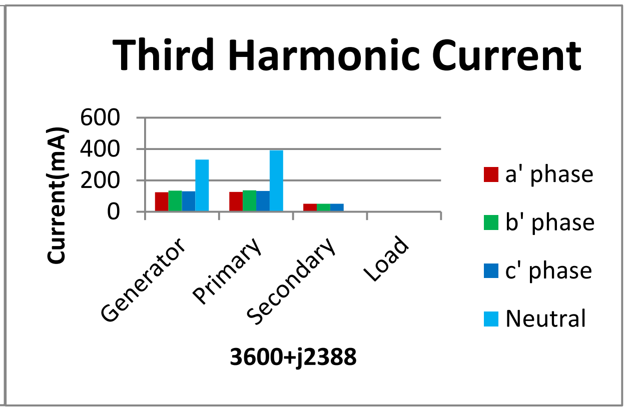

Third Harmonic Current
Current(mA)
600
400
200
0
Generator
Primary
Secondary
Load
2400+j1602
a' phase
b' phase
c' phase
Neutral

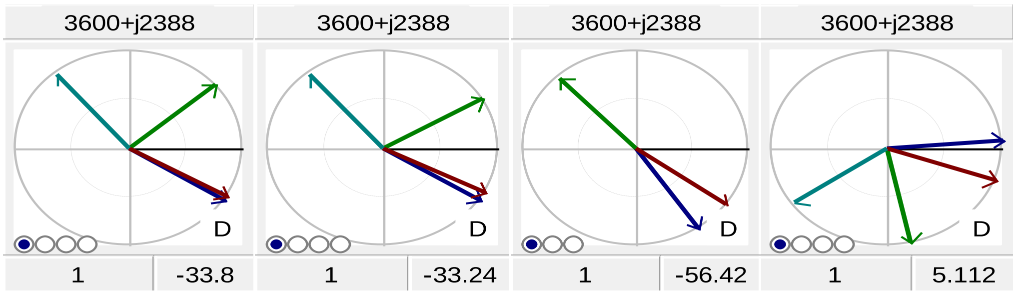

2400+j1602
2400+j1602
2400+j1602
2400+j1602
D
D
D
D
1
-28.7
1
-29.31
1
-51.73
1
5.34

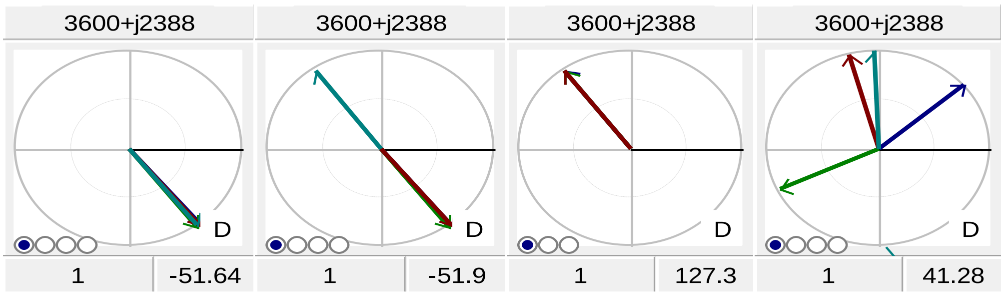

2400+j1602
2400+j1602
2400+j1602
2400+j1602
D
D
D
D
1
-48.34
1
-48.23
1
132.6
1
-33.98

3600+j2388

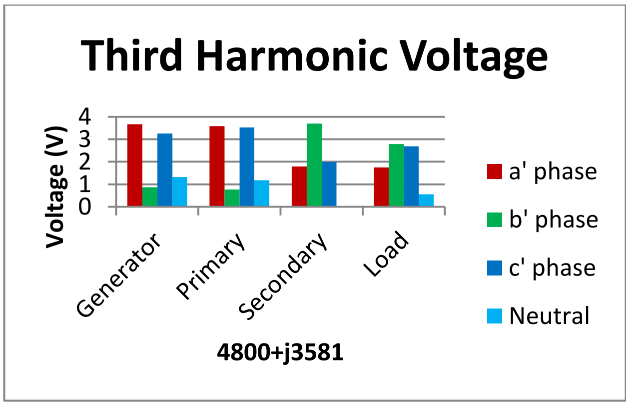

Third Harmonic Voltage
Voltage (V)
4
3
2
1
0
Generator
Primary
Secondary
Load
3600+j2388
a' phase
b' phase
c' phase
Neutral

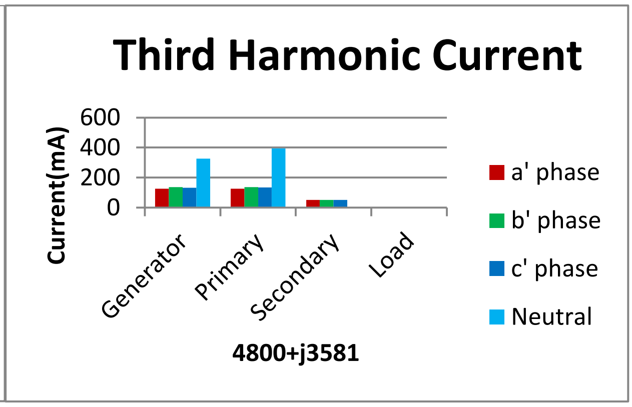

Third Harmonic Current
Current(mA)
600
400
200
0
Generator
Primary
Secondary
Load
3600+j2388
a' phase
b' phase
c' phase
Neutral

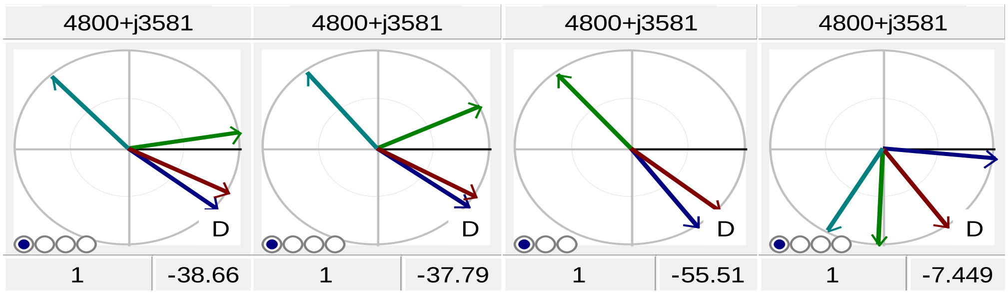

3600+j2388
3600+j2388
3600+j2388
3600+j2388
D
D
D
D
1
-33.8
1
-33.24
1
-56.42
1
5.112

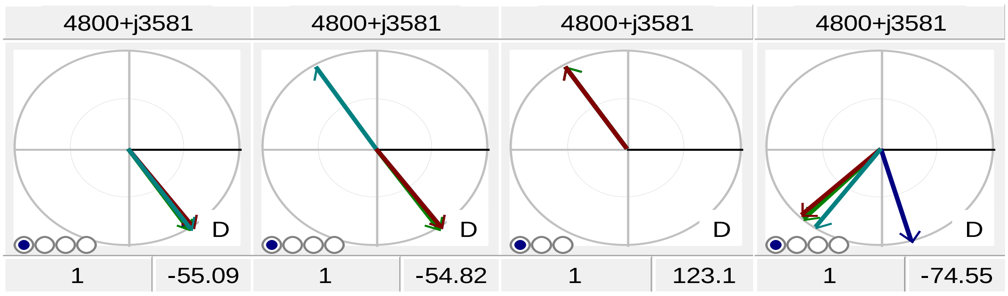

3600+j2388
3600+j2388
3600+j2388
3600+j2388
D
D
D
D
1
-51.64
1
-51.9
1
127.3
1
41.28

4800+j3581


Third Harmonic Voltage
Voltage (V)
4
3
2
1
0
Generator
Primary
Secondary
Load
4800+j3581
a' phase
b' phase
c' phase
Neutral

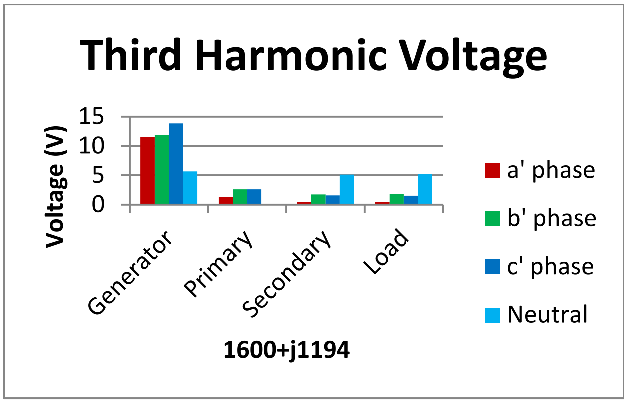

Third Harmonic Current
Current(mA)
600
400
200
0
Generator
Primary
Secondary
Load
4800+j3581
a' phase
b' phase
c' phase
Neutral

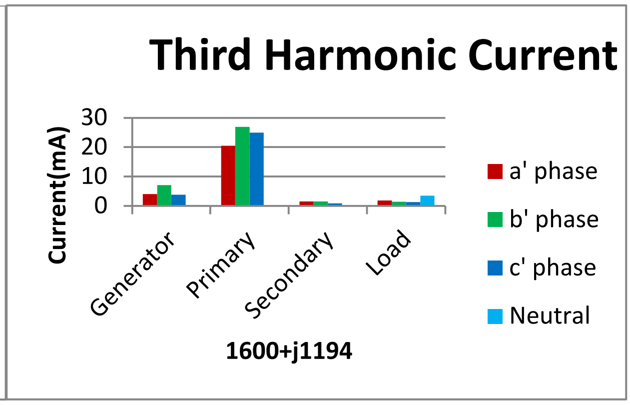

4800+j3581
4800+j3581
4800+j3581
4800+j3581
D
D
D
D
1
-38.66
1
-37.79
1
-55.51
1
-7.449

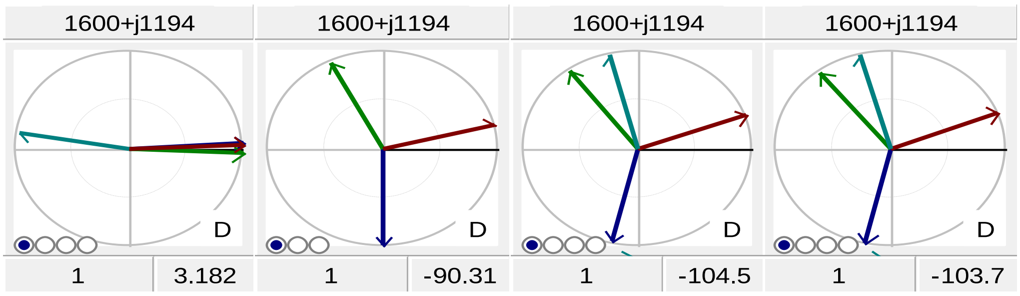

4800+j3581
4800+j3581
4800+j3581
4800+j3581
D
D
D
D
1
-55.09
1
-54.82
1
123.1
1
-74.55

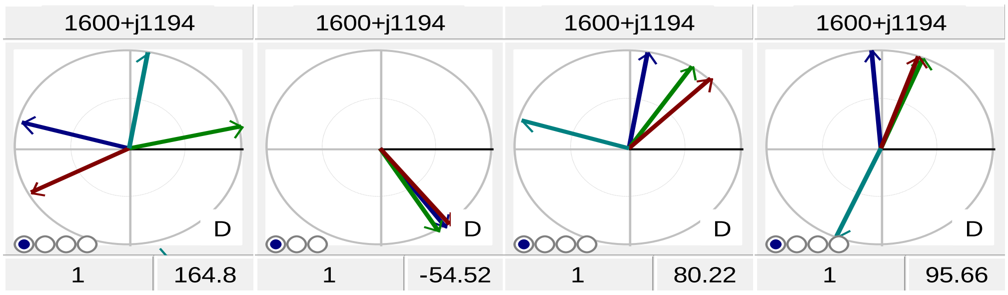
Appendix I

1600+j1194

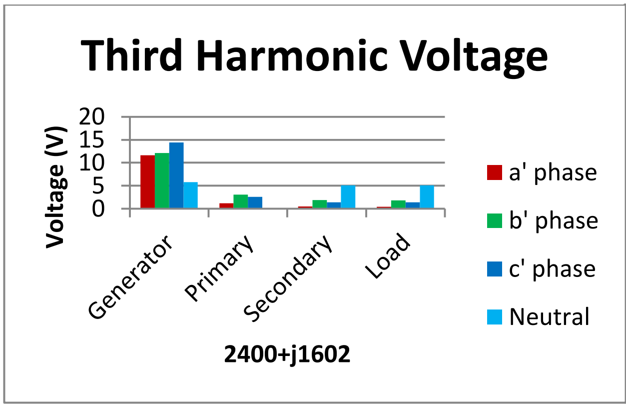


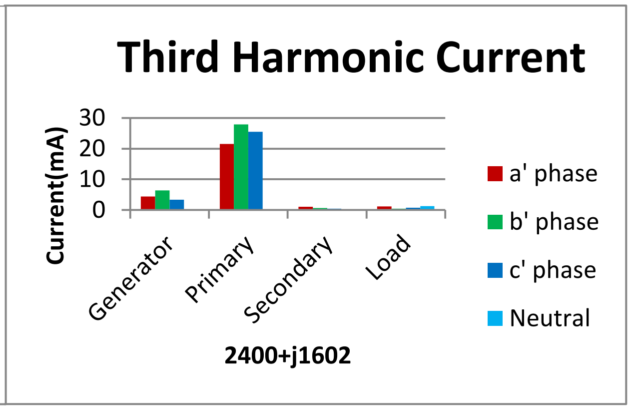


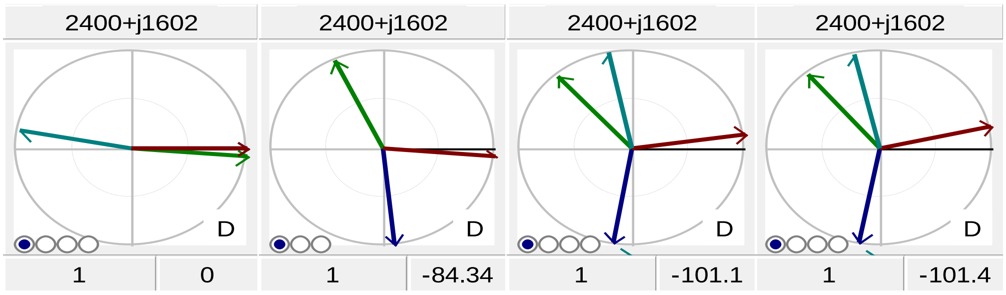


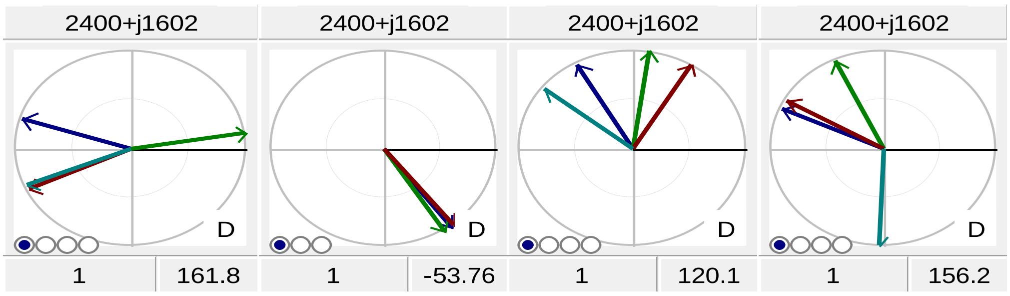


2400+j1602

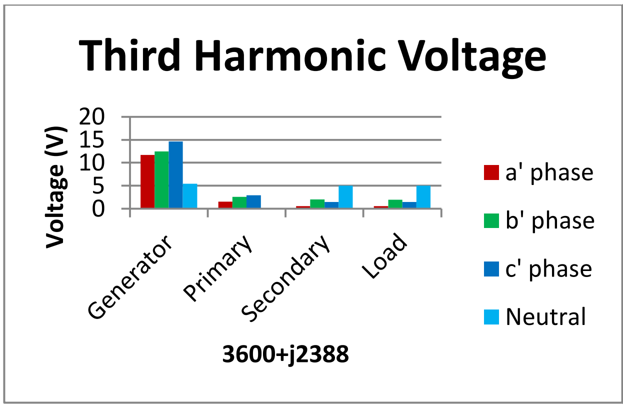

Third Harmonic Voltage
Voltage (V)
20
15
10
5
0
Generator
Primary
Secondary
Load
2400+j1602
a' phase
b' phase
c' phase
Neutral


Third Harmonic Current
Current(mA)
30
20
10
0
Generator
Primary
Secondary
Load
2400+j1602
a' phase
b' phase
c' phase
Neutral

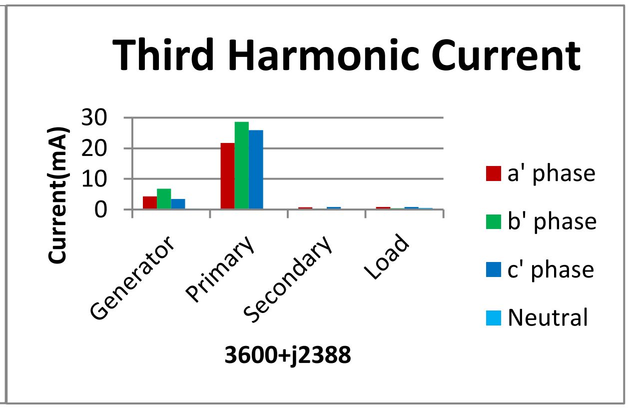

2400+j1602
2400+j1602
2400+j1602
2400+j1602
D
D
D
D
1
0
1
-84.34
1
-101.1
1
-101.4


2400+j1602
2400+j1602
2400+j1602
2400+j1602
D
D
D
D
1
161.8
1
-53.76
1
120.1
1
156.2

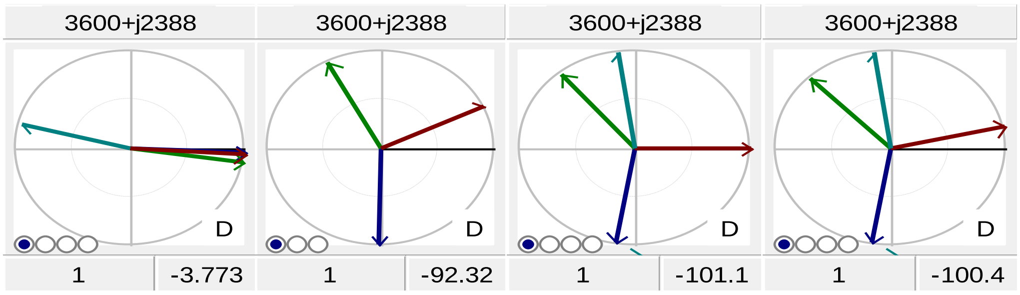
3600+j2388



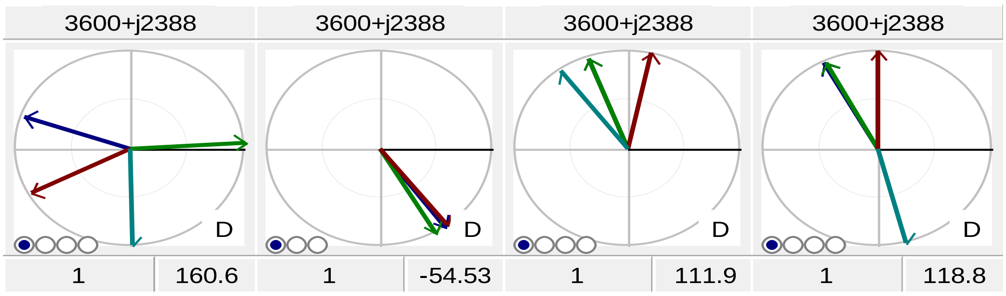
Third Harmonic Voltage
Voltage (V)
20
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
3600+j2388



Third Harmonic Current
Current(mA)
30
20
10
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
3600+j2388

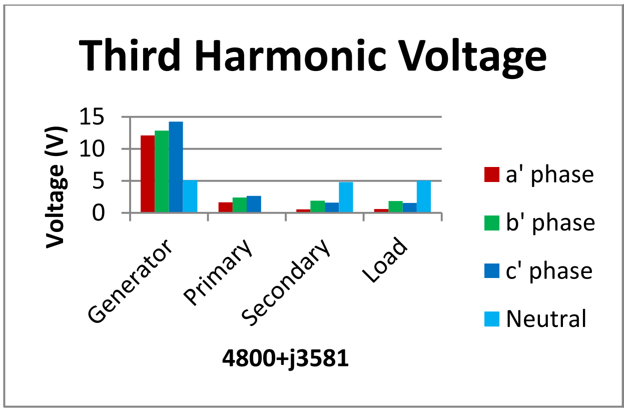


3600+j2388
3600+j2388
3600+j2388
3600+j2388
D
D
D
D
1
-3.773
1
-92.32
1
-101.1
1
-100.4

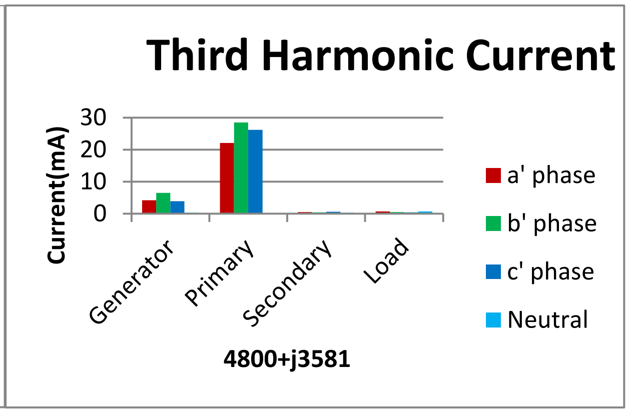


3600+j2388
3600+j2388
3600+j2388
3600+j2388
D
D
D
D
1
160.6
1
-54.53
1
111.9
1
118.8

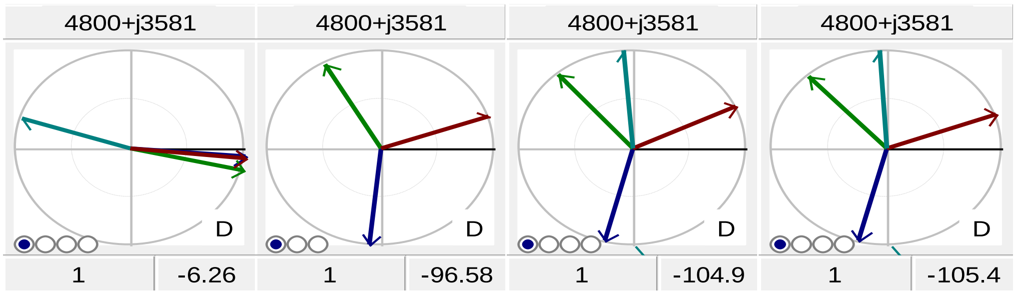
4800+j3581



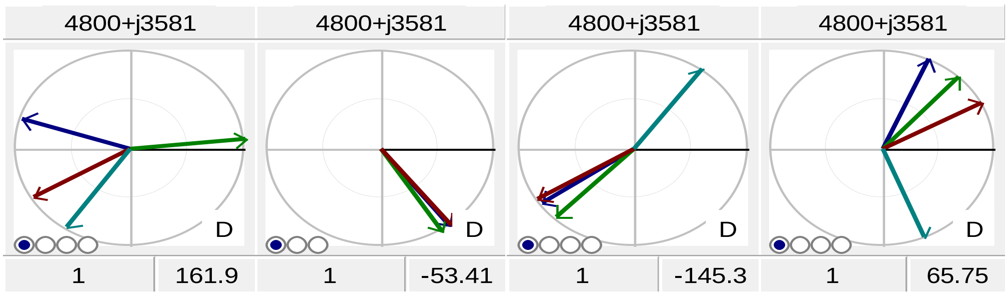
Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
4800+j3581



Third Harmonic Current
Current(mA)
30
20
10
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
4800+j3581



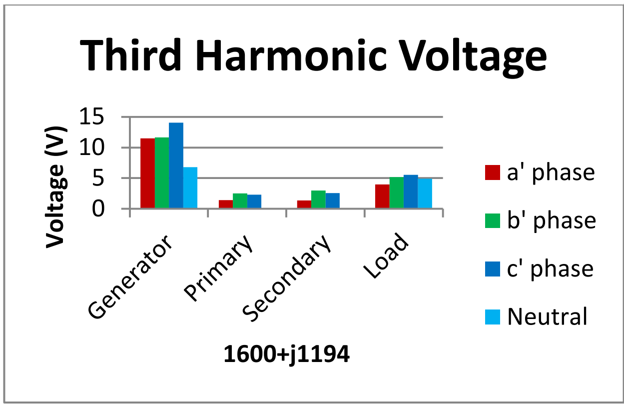
4800+j3581
4800+j3581
4800+j3581
4800+j3581
D
D
D
D
1
-6.26
1
-96.58
1
-104.9
1
-105.4

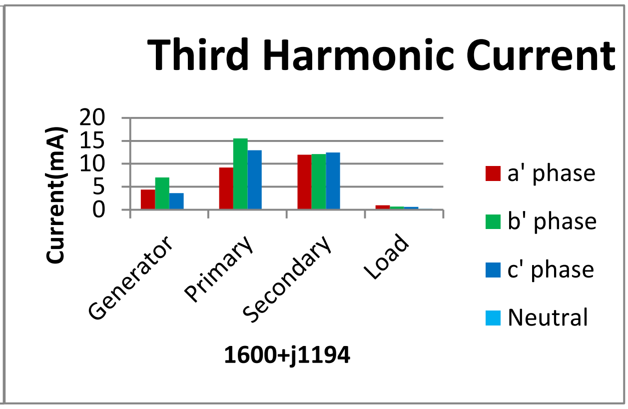


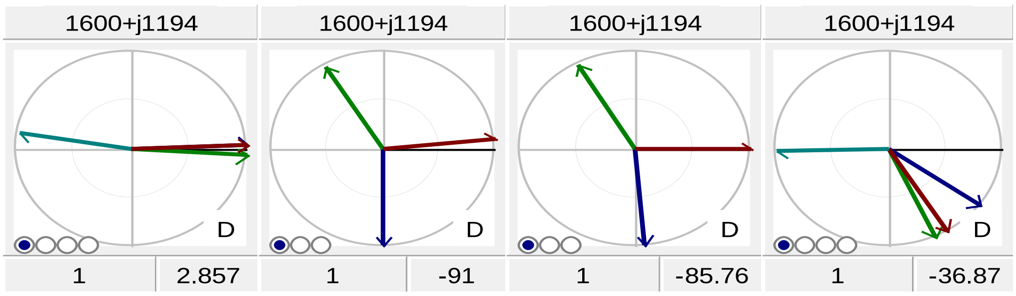
4800+j3581
4800+j3581
4800+j3581
4800+j3581
D
D
D
D
1
161.9
1
-53.41
1
-145.3
1
65.75

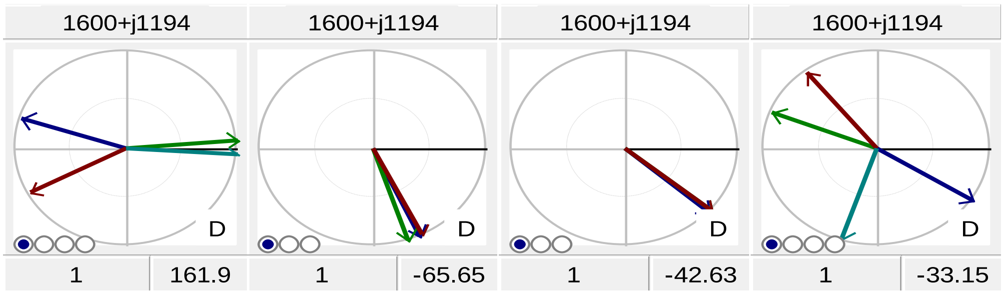
Appendix J

1600+j1194

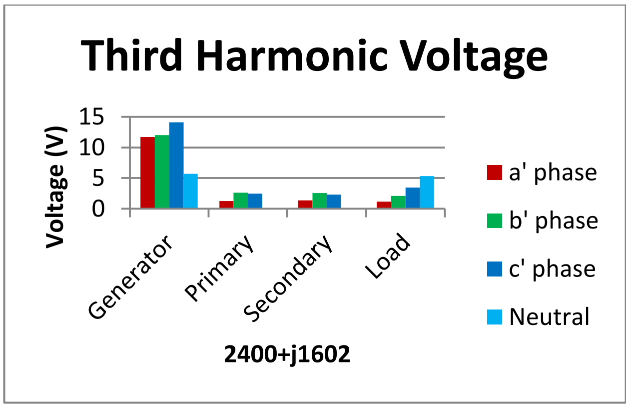


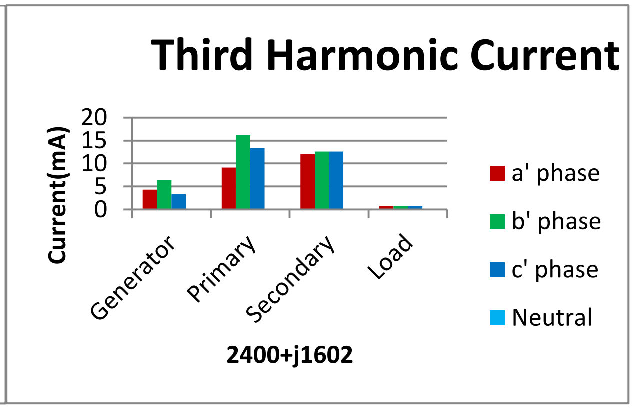


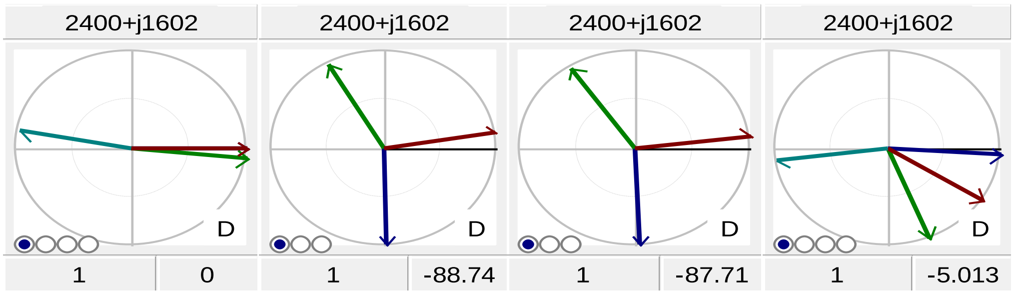


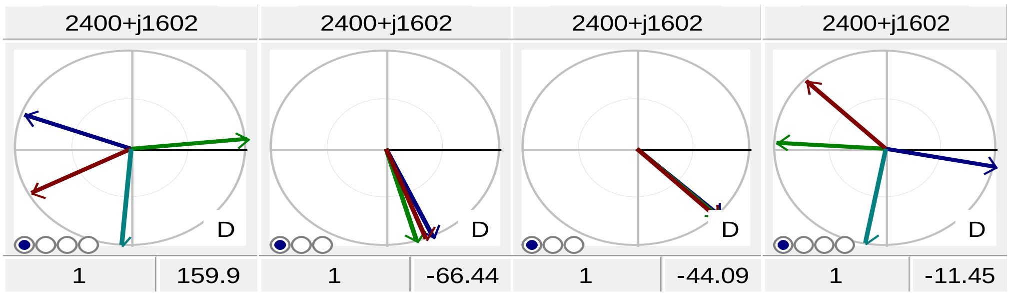


2400+j1602

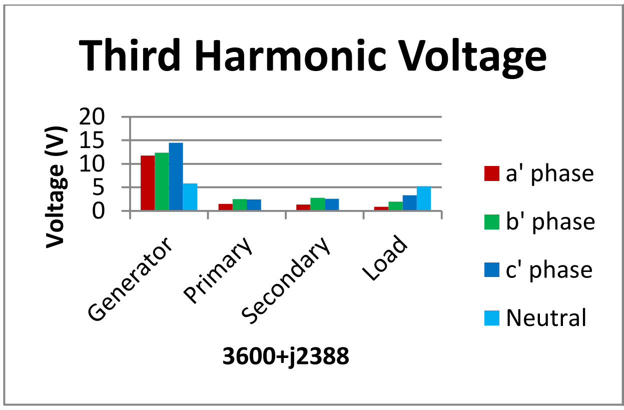

Third Harmonic Voltage
Voltage (V)
15
10
5
0
Generator
Primary
Secondary
Load
2400+j1602
a' phase
b' phase
c' phase
Neutral

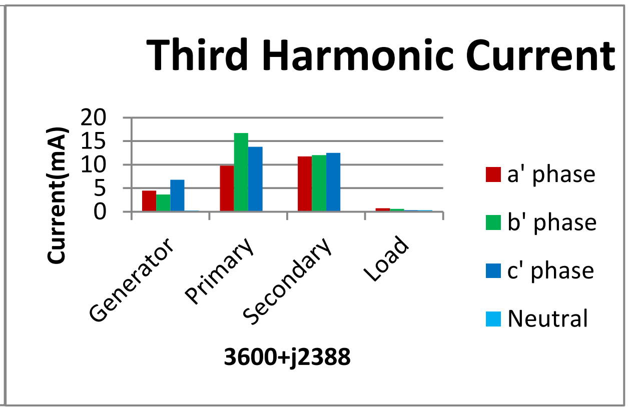

Third Harmonic Current
Current(mA)
20
15
10
5
0
Generator
Primary
Secondary
Load
2400+j1602
a' phase
b' phase
c' phase
Neutral

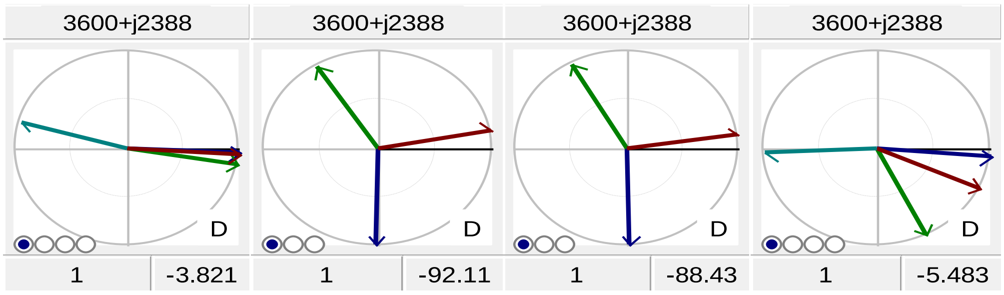

2400+j1602
2400+j1602
2400+j1602
2400+j1602
D
D
D
D
1
0
1
-88.74
1
-87.71
1
-5.013

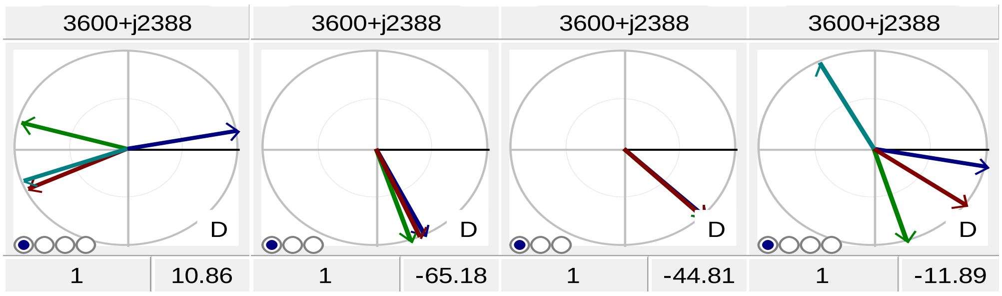

2400+j1602
2400+j1602
2400+j1602
2400+j1602
D
D
D
D
1
159.9
1
-66.44
1
-44.09
1
-11.45

3600+j2388

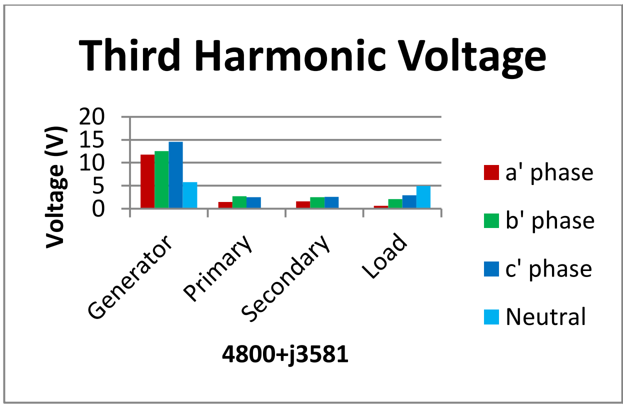

Third Harmonic Voltage
Voltage (V)
20
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
3600+j2388


Third Harmonic Current
Current(mA)
20
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
3600+j2388

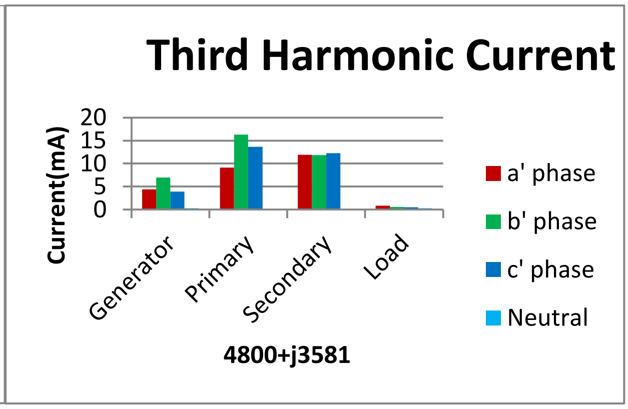

3600+j2388
3600+j2388
3600+j2388
3600+j2388
D
D
D
D
1
-3.821
1
-92.11
1
-88.43
1
-5.483


3600+j2388
3600+j2388
3600+j2388
3600+j2388
D
D
D
D
1
10.86
1
-65.18
1
-44.81
1
-11.89

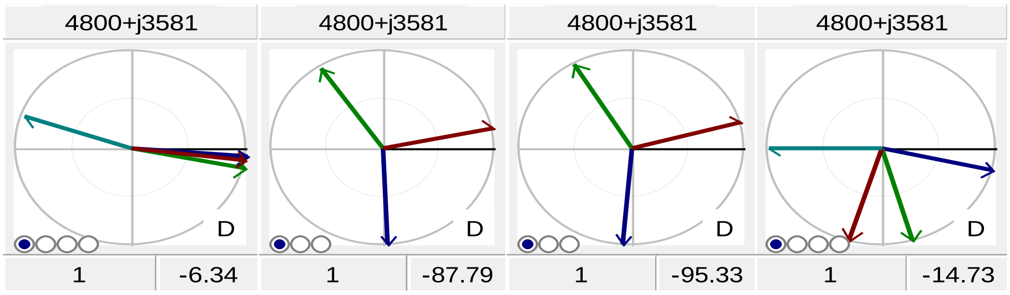
4800+j3581



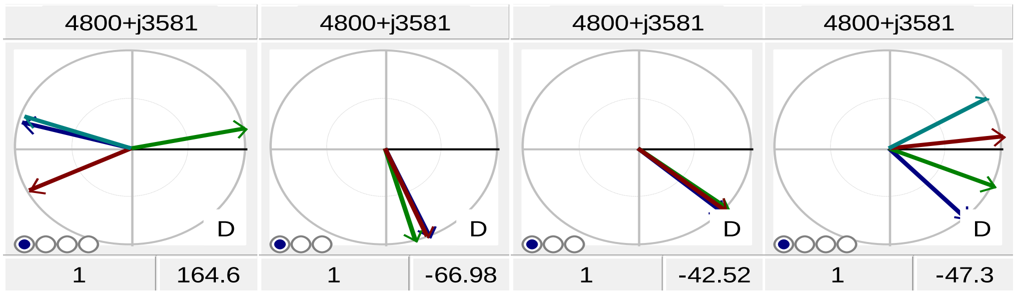
Third Harmonic Voltage
Voltage (V)
20
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
4800+j3581



Third Harmonic Current
Current(mA)
20
15
10
5
0
Generator
Primary
Secondary
Load
a' phase
b' phase
c' phase
Neutral
4800+j3581



4800+j3581
4800+j3581
4800+j3581
4800+j3581
D
D
D
D
1
-6.34
1
-87.79
1
-95.33
1
-14.73



4800+j3581
4800+j3581
4800+j3581
4800+j3581
D
D
D
D
1
164.6
1
-66.98
1
-42.52
1
-47.3