INTERACTION OF TRIPLEN HARMONICS PRODUCED BY SYNCHRONOUS GENERATOR WHEN CONNECTED WITH RECTIFIER

By

MUHAMMAD ANNAITULLAH B MOHD AYOB

FINAL PROJECT REPORT

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

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak DarulRidzuan

CERTIFICATION OF APPROVAL

INTERACTION OF TRIPLEN HARMONIC PRODUCED BY SYNCHRONOUS GENERATOR WHEN CONNECTED WITH RECTIFIER

by

Muhammad Annaitullah B Mohd Ayob

A project dissertation submitted to the
Department of Electrical & Electronic Engineering
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

Approved:

____

Ir. Mohd Faris B Abdullah
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 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.

____

MUHAMMAD ANNAITULLAH B MOHD AYOB

ABSTRACT

The third harmonic has caused much power quality problem in the neutral of distribution system. Salient pole synchronous generator and non-linear load have been known and recognized as the source of triplen harmonics. Main purpose of this project is to study the characteristics of triplen harmonics current produced by synchronous generator when connected with rectifier and various types of loads. This research is done by shunt connecting full bridge rectifier between synchronous generator and load. The measurement of third harmonics is taken at generator, rectifier and load to see the characteristics of the third harmonics. In this research, the phase angle of the third harmonics is also taken into account. When full bridge rectifier is shunt connected between synchronous generator and load, the third harmonic current at rectifier and load are actually coming from the generator that depend on the load impedance and phase angle. The third harmonic current of the generator is the vector sum of both load and rectifier third harmonic current for generator load with rectifier connection. In parallel operation of synchronous generator with rectifier and load, the third harmonic current at generator does not affected by rectifier due to the delta of transformer blocking the third harmonic from flowing to the load and rectifier. However, the third harmonic current recorded at rectifier is due to the rectifier drawing the current in non-sinusoidal form from the star side of transformer. From overall findings of the project, the rectifier affects the third harmonic current level at generator when operated in island mode with and without the existence of transformer. However, it does not affect the third harmonic currents level at generator in parallel operation.

ACKNOWLEDGEMENTS

First and foremost, thanks to Allah for His blessing and giving me the opportunity to successfully complete this Final Year Project.

I would like to express my very great appreciation to my supervisor, Ir. Mohd Faris B Abdullah for his support, encouragement and useful critiques all the way from the beginning to the end of this project. Besides, I would like to thank him for the guidance and tireless supervision throughout this project.

I am particularly grateful for the assistance given by the lab technicians in Power Systems Lab and Power Electronic Lab in order for me to do all the experiments and complete the project. Besides, I would also like to give special appreciation to them for their cooperation and guidance.

Deepest thanks and appreciation to my colleagues, Helmi Syazwan, Aizuddin and Izzuddin for their assistance, cooperation and constructive suggestion throughout the project development. Without their cooperation and assistance, this project might not be finished successfully.

In addition, my deepest gratitude goes to Universiti Teknologi Petronas (UTP) particularly Electrical Electronic Department for giving me such opportunity to gain experience in doing this reseach. Again, I would like to extend my thanks to UTP for the complete facilities that fulfil my project requirement.

Last but not least, I would like to express my sincere gratitude to my beloved parent and family for endless support and encouragement. To those who indirectly contributed in this research, I appreciate all the support given. Thank you very much.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background Study

Ideally, an electrical supply should show a perfectly sinusoidal voltage signal at the point of supply. However, utilities often find it hard to preserve such desirable conditions due to the deviation of the voltage and current waveform from sinusoidal called harmonic distortion. Harmonic distortion causes the increases of current in power systems that lead to losses and even equipment damage. The study which will be carried in this research focuses mainly on triplen harmonics currents which are zero sequence harmonic currents. The consequence of this zero sequence harmonic is that the magnitude of this current on three phases are additive in the neutral which may lead to high circulating current in neutral increasing the temperature of neutral line. Based on published reports, the triplen harmonics currents produced by synchronous generator flow through Neutral Earthing Resistor (NER) causes the increase of temperature of the NER during the islanded operation and when connected to utility grid. Apart from that, the non-linear load is also known as the main source of triplen harmonics. Relating to these findings, the purpose of this study is to investigate the interaction of triplen harmonics produced by a synchronous generator when connected to a rectifier (non-linear load). Based on this study, we will be able to see the effects and characteristics of the interaction of triplen harmonics between synchronous generator and rectifier (non-linear load).

1.2 Problem Statement

The triplen harmonics have caused the increase in temperature of the NER of synchronous generator in Gas District Cooling (GDC) in Universiti Teknologi Petronas (UTP) especially when connected to utility grid. In order to solve this problem, the characteristics of triplen harmonics must be studied under various conditions. Hence, since the synchronous generator and non-linear loads are known as the component in power system which produces harmonics, the study on the characteristics of these two should be done.

1.3 Project Objectives

The main objectives of this project are;

(1) To study the characteristics of triplen harmonics when synchronous is directly connected to various type of load.

(2) To study the characteristics of triplen harmonics currents produced synchronous generator when connected with rectifier.

1.4 Scope of Study

The focus of this study is to investigate the characteristics of zero sequence triplen harmonics currents. Literature review is going to be done by studying published journals, books, articles and thesis. After that, the lab-scale experiments will be carried out in power system lab where parameters that will influence triplen harmonics will be varied. The results then will be analysed and discussed in order to understand the relationship of characteristics of triplen harmonics currents produced by synchronous generator when connected with rectifier.

1.5 Relevancy of Project

The study of triplen harmonic which produced by synchronous generator is very important in power system analysis. As we know, synchronous generators are used widely in power system including in islanded operation such as at platform in oil rig. One example in application of synchronous generator can be seen in Gas District Cooling (GDC) Power Plant in Universiti Teknologi Petronas (UTP). The synchronous generators used in this power plant produce triplen harmonics currents that flow through generator NER when operating in islanded mode and when connected to utility grid. On the other hand, the rectifier will be used in this research to represent non-linear loads which are known as the main cause of triplen harmonic currents in power system. Hence, it is relevant to conduct this project to observe the characteristics of triplen harmonic currents when synchronous generator is connected to rectifier (non-linear load). The findings in this project would be beneficial to power system study in the future in terms of quality and efficiency.

1.6 Feasibility of Project

In order to complete this project, the study of the project will be divided into two phases which is Final Year Project 1(FYP1) and Final Year Project 2(FYP2). In FYP1, the study of the project will be mainly focused on the fundamental theories and concept besides planning on the whole project flow. The study will be involving reliable sources such as published journals, conference proceedings and books to improve and prepare a good planning for the project. After that, the lab scaled experiments will be carried in the same phase of the project. In FYP2, the project will be continued by finishing the rest of lab experiments. Detail analysis and discussion will be done on the result to observe the characteristics of triplen harmonics currents when synchronous generator and rectifier. Based on the planning on the key milestone of this project, the study will be successfully completed within the time allocated.

CHAPTER 2
LITERATURE REVIEW

2.1 Triplen Harmonics

Harmonic distortion is a phenomenon where a voltage and current waveform deviated from perfect sinusoidal signal. Basically, harmonics in voltage and current waveform can be described as sinusoidal components of frequencies multiple of the fundamental frequency of voltage and current;

$$f_h = (h) \times \text{(fundamental frequency)} \quad (1)$$

where h is an integer. The increasing use of non-linear loads in power system increases the harmonic distortion in distribution networks reducing the quality of power system [1]. Generally, harmonics currents flow toward the supply because the source impedance is low [2].

Meanwhile, triplen harmonics is harmonic distortion which are the odd multiple of third harmonics (3rd, 9th,15th,etc.). In three phase system, triplen harmonics currents are additive at neutral as it has the same phase angle in nature [3]. Under balance conditions, triplen harmonics currents flow through neutral with magnitude of three times the phase current value. Triplen harmonic waveform is shown in Figure 1.

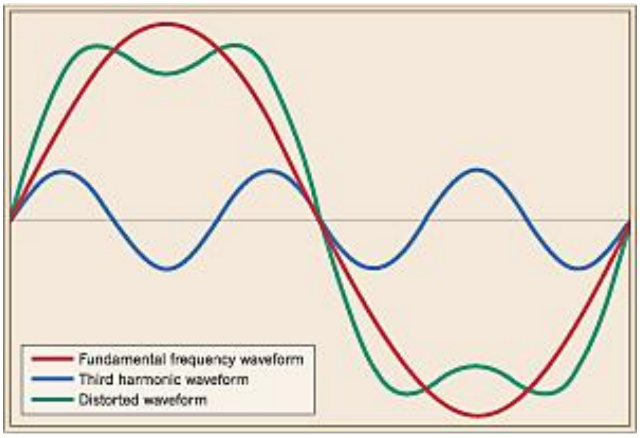


Figure 1.Triplen harmonic waveform

The magnitude of harmonics voltages and currents decreases with respect to the increases of harmonics order. Therefore, the increase in harmonics frequency results in the decrease of triplen harmonic currents due to higher zero sequence inductive reactance. Hence, third harmonic current becomes a major component in triplen harmonics studies due to its magnitude. Besides that, as a high value of triplen harmonics frequency is always opposed by a higher value of impedance, the studies on the third harmonics currents is appropriate [4].

2.2 Effects of Triplen Harmonics

Triplen harmonics currents may cause the neutral line to be overloaded and damaged due to the excessive heat. Investigation by [5] has shown that triplen harmonics has caused the temperature increases in Neutral Earthing Resistor(NER) of synchronous generator due to the flow of large current.

In addition, for the transformer, triplen harmonics circulate in delta connection and for wye connection, it flows to the neutral conductors. Therefore, the delta-wye or delta-delta connections of transformers are used to trap triplen harmonics currents in delta. This technique is used to avoid the increase in temperature of neutral conductor. However, the circulating triplen harmonics currents in delta will produce additional heat in transformer producing losses and even damaging the transformer. The effects of harmonics on electrical equipment such as conductors and circuit breakers have been documented in [6].

Apart from all, journal published by [7] has revealed that in real distribution system, harmonic order such as 2nd, 3rd, 4th, etc. are no corresponding to negative, zero, positive, etc. sequence due to unbalance and wave distortion. Hence, the assumption that triplen harmonic is zero sequence in nature no longer hold and so three phase harmonic measurement should be taken and analysed.

2.3 Triplen Harmonics Produced By Synchronous Generator

Synchronous generator produces triplen harmonics voltage at the terminal even when it is not connected to the load. Meanwhile, the triplen harmonics currents only present when the generator starts supplying a load. Referring to [3], triplen harmonics produced by synchronous generator is based on the winding design parameter such as pitch factor, distribution factor, and slot skew.

Moreover, synchronous generator produces triplen harmonics currents which increase the temperature of Neutral Earthing Resistor (NER) of the generator. The investigation in [5] shows that the NER temperature become higher when generator operating in parallel with the utility grid compared to when it is operating in island mode. Besides, it has been proven that the triplen harmonics currents produced by the synchronous generator flow in the opposite direction of load flow when the generator is operating in parallel mode with utility grid. The triplen harmonics currents flow to the zero sequence impedance of the network where large influence on triplen harmonics currents come from transformer winding configuration and underground cable capacitance.

Besides that, triplen harmonics voltages induction produced by synchronous generator has caused the noise interference in telephone lines as reported in [8]. Triplen harmonics voltage produced by synchronous generator can have different causes under various types of loads. When synchronous generator is operating under no load condition, salient pole and concentrated field winding are the main causes. Furthermore, synchronous generator produces triplen harmonics with different characteristics under balanced and unbalanced load.

2.4 Non-linear Load

Non-linear loads are loads in which the current waveform does not follow the voltage waveform. Hence, non-linear loads can be conceptualized as those loads in which Ohm's law cannot describe in the relation between voltage (V) and current (I) [1]. Meanwhile, linear loads are the loads in which voltage and current signal follow one another closely. Therefore, the circuits with linear loads are simple to calculate voltage and current waveforms. The common non-linear loads that can be found in power system are all types of rectifying devices such as power converters, power sources, uninterruptible power supply (UPS) units, and arc devices like electric furnaces and fluorescent lamp. In term of relationship between voltage and impedance, a non-linear load is a load in which its impedance changes with the applied voltage. Figure 2 and Figure 3 shows the voltage and current waveform for both linear loads and non-linear loads respectively.

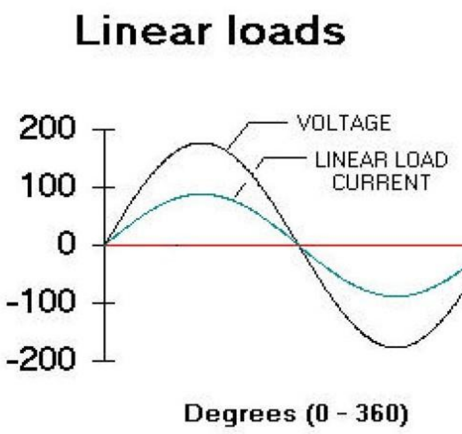


Figure 2.Voltage and Current Waveform of Linear Load

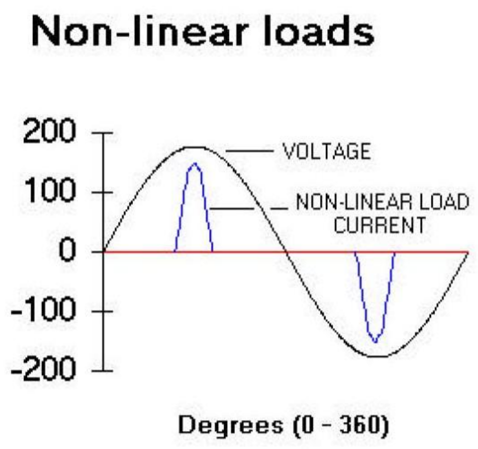


Figure 3.Voltage and Current Waveform of Non-Linear Load

Non-linear loads may cause disturbances such as voltage waveform distortion, telephone interference, transformer overheating. In the operation of generator, a non-linear load produces a voltage waveform distortion at the generator terminal. In previous report in [2], a non-linear load which connected to generator with 60-Hz voltage by utility draws current in non-sinusoidal form and returns a distorted waveform to the system.

Conference paper published by [9] revealed that one the effect of harmonics currents produced by non-linear loads is additional heating in transformers. The transformer which is not specifically constructed and design to supply nonlinear loads must be derated to take into account the additional winding eddy current losses caused by harmonic currents.

CHAPTER 3
METHODOLOGY

3.1 Project Activities

Research activities in this project consist of several stages. Firstly, the research will be started with preliminary research works. After that, the project continues with lab scaled experiments followed with the analysis and discussion of the results. Last but not least, the final stage will be the final documentation of the project where the report will include the process from the beginning of the project up to the final outcome of the project. The overall process of research work can be referred to the Figure 4.

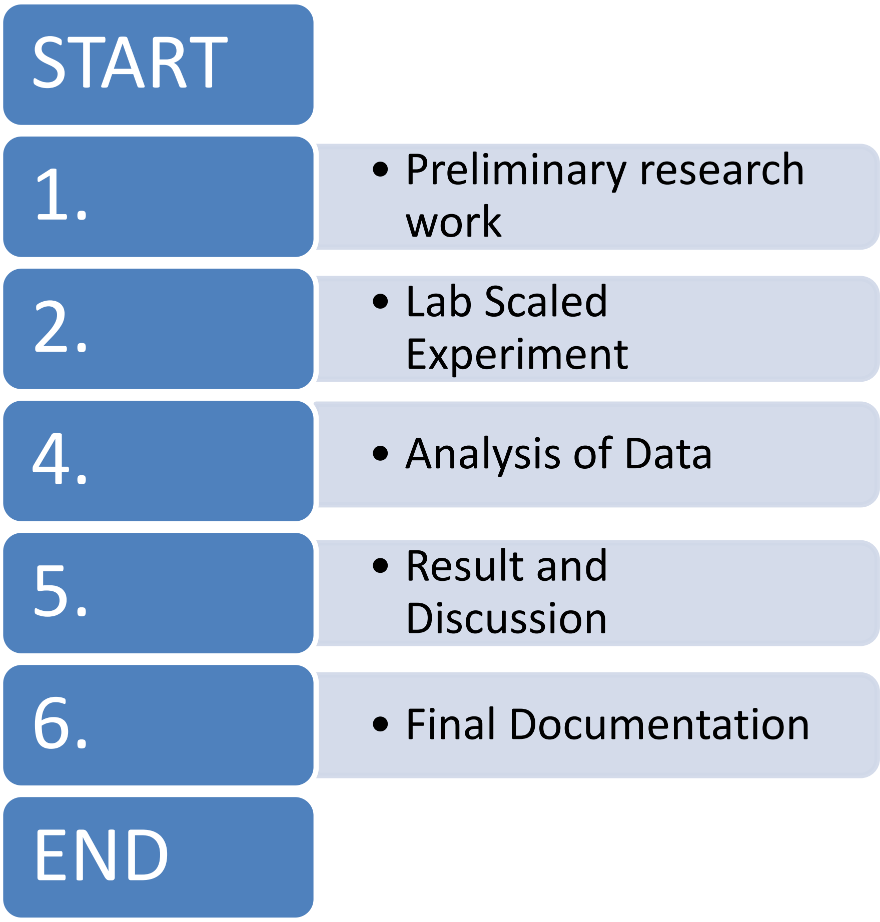


Figure 4. Research methodology chart

3.1.1 Preliminary Research Work

Preliminary research work mainly focus on data collection related to the project. Data collection involves the compilation of data and information gained from previous works such as journals, books, conference proceedings and other technical paper related to the this research project. The importance of this stage is to develop good understandings in power quality, especially on load flow and triplen harmonics propagation in power system networks which will be used in writing the proposal and other stages of the project.

3.1.2 Lab Scaled Experiment

In this stage, the lab scaled experiment on the interaction of triplen harmonics produced by synchronous generator when connected with rectifier will be done. This lab experiment will be conducted in power system lab using a lab scaled synchronous generator, linear loads and rectifier provided in the lab. The measurement of voltage and current along with triplen harmonics will be taken by using a three phase power quality analyzer.

The experiment will consists of single synchronous generator connected to various types of linear loads which consists of resistive load and inductive load. Besides that, the synchronous generator will also be connected to these load and shunt connected to rectifier. The experiments will be conducted under two different scenarios where the synchronous generator will be operated under islanded mode and then connected with the utility grid. The connection of synchronous generator and loads that will be used in the experiments are in 3-phase with 4 wires system. Besides, impedance of loads will be varied with different magnitude and angle to see how characteristics of triplen harmonics response to the changes. The focus of the experiment will be on the characteristics of triplen harmonics when synchronous generator is connected with rectifier. The rectifier that will be used in the experiments will be constructed by using two types of devices which is power diodes and power thyristors. The use of these types of devices is to represent the passive and active non-linear loads in power system. A general wye-wye connection with four wires system that will be used in this project is shown in Figure 5.

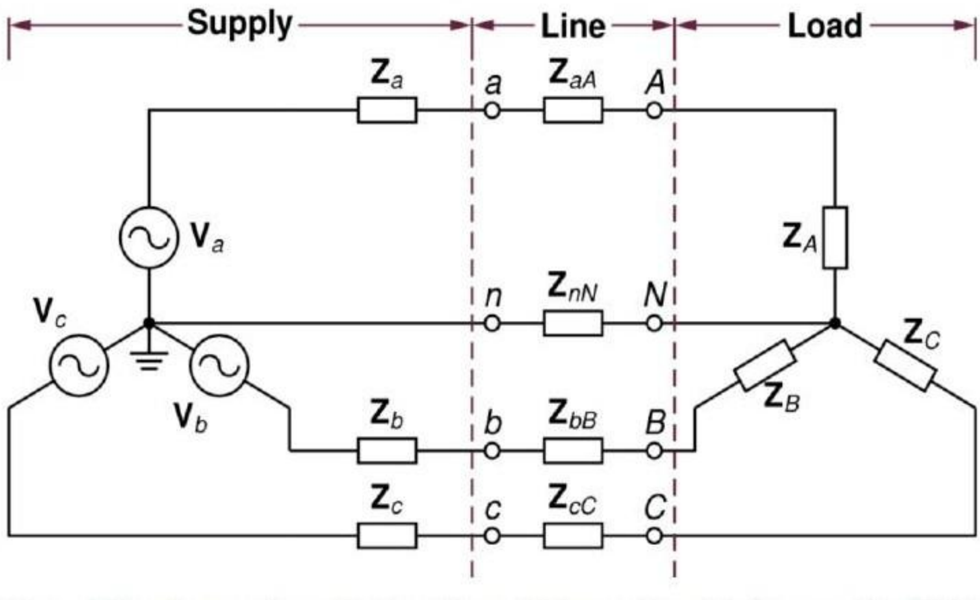


Figure 5. Wye-Wye connection with four wires system

The lab scale experiments that will be conducted under the two scenarios will be;

a) Single synchronous generator in islanded operation
   i. Connected to balanced resistive loads.
   ii. Connected to balanced inductive loads.
   iii. Connected to balanced resistive and inductive loads.
   iv. Connected to balanced resistive load with full bridge rectifier.
   v. Connected to balanced inductive load with full bridge rectifier.
   vi. Connected to balanced resistive and inductive load with full bridge rectifier.
b) Single synchronous generator in parallel operation with power grid
   i. Connected to balanced resistive and inductive load with full bridge rectifier.

The load impedance angle for the combination of resistive and inductive load that will be used for both first and second scenario is varied to see the effect of it to the triplen harmonics characteristics. Besides that, the impedance for combination of resistive and inductive load are also varied for the impedance angle between 32˚- 37˚ which is correspond to 0.8 – 0.85 power factor in real life case.

Apart from that, in parallel operation experiments, only the combination of resistive load and inductive load will be used where the impedance magnitude of the load will be varied. Besides, the contribution of the generator is also varied for one constant impedance angle by changing the output current of the generation. Figure 6 to Figure 14 shows the connection/wiring diagram used in this project. Meanwhile, Figure 15 and Figure 16 show the actual connection for the project.

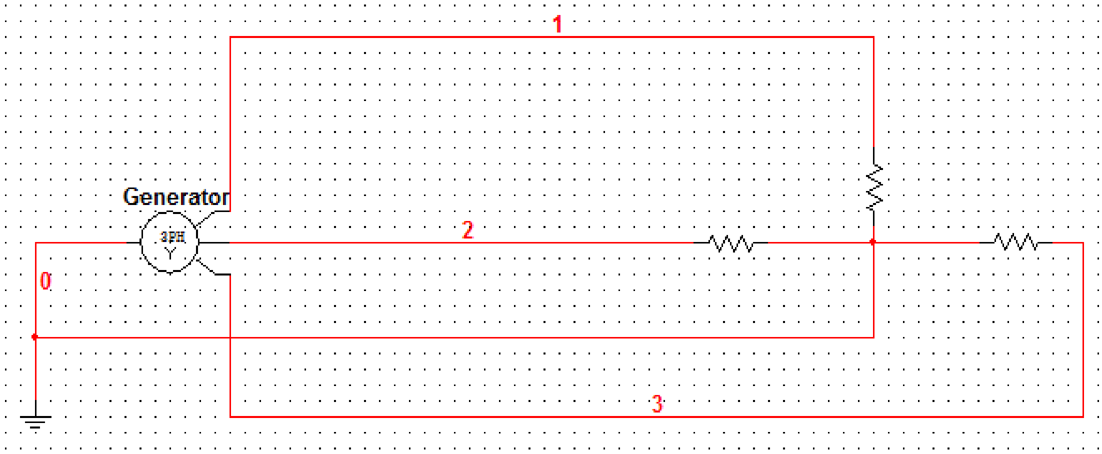


Figure 6. Synchronous generator connected to balanced resistive load

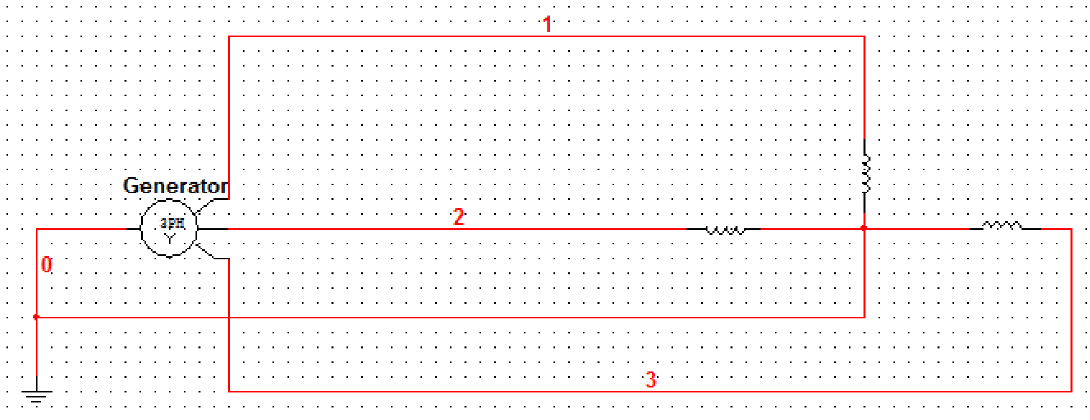


Figure 7. Synchronous generator connected to balanced inductive load

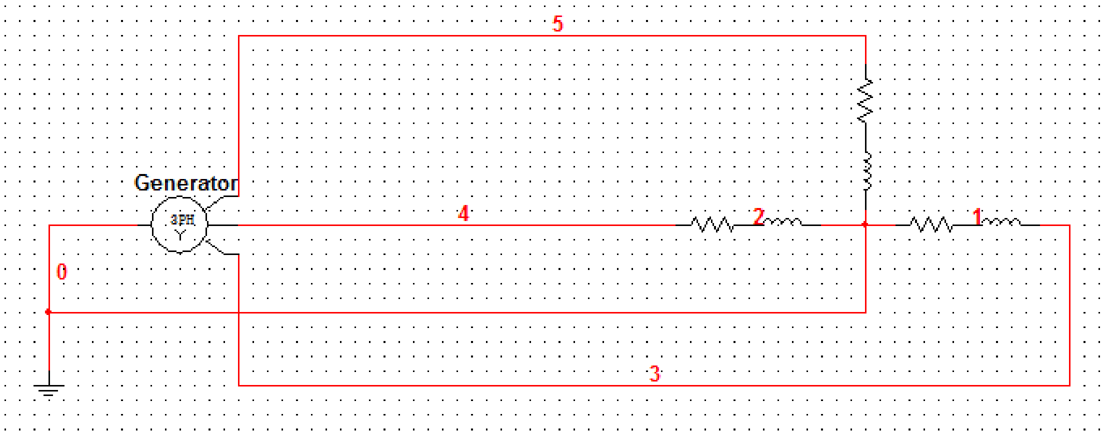


Figure 8. Synchronous generator connected to balanced resistive and inductive load

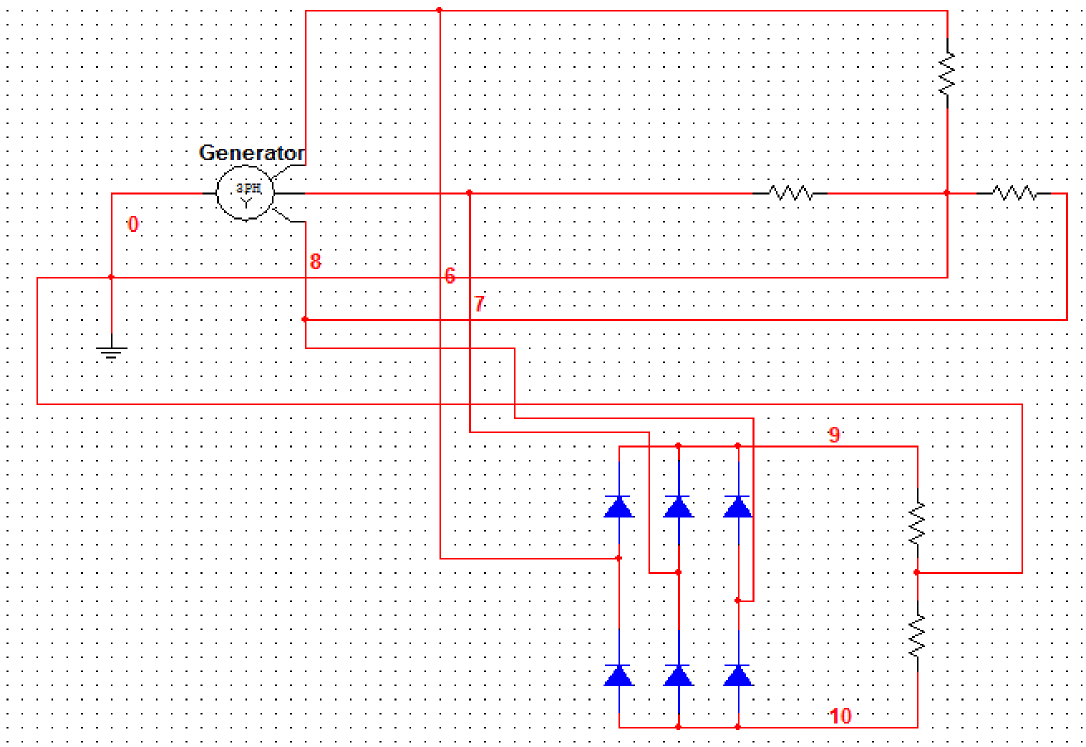


Figure 9. Synchronous generator connected to balanced resistive load and full bridge rectifier

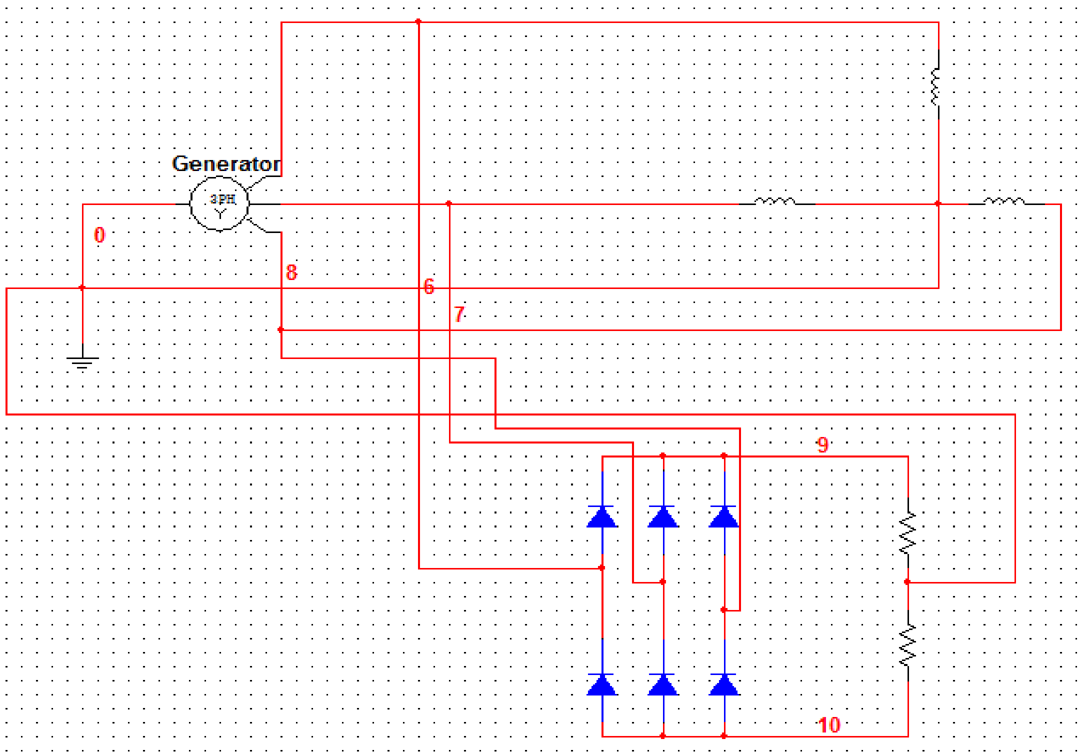


Figure 10. Synchronous generator connected to balanced inductive load with full bridge rectifier

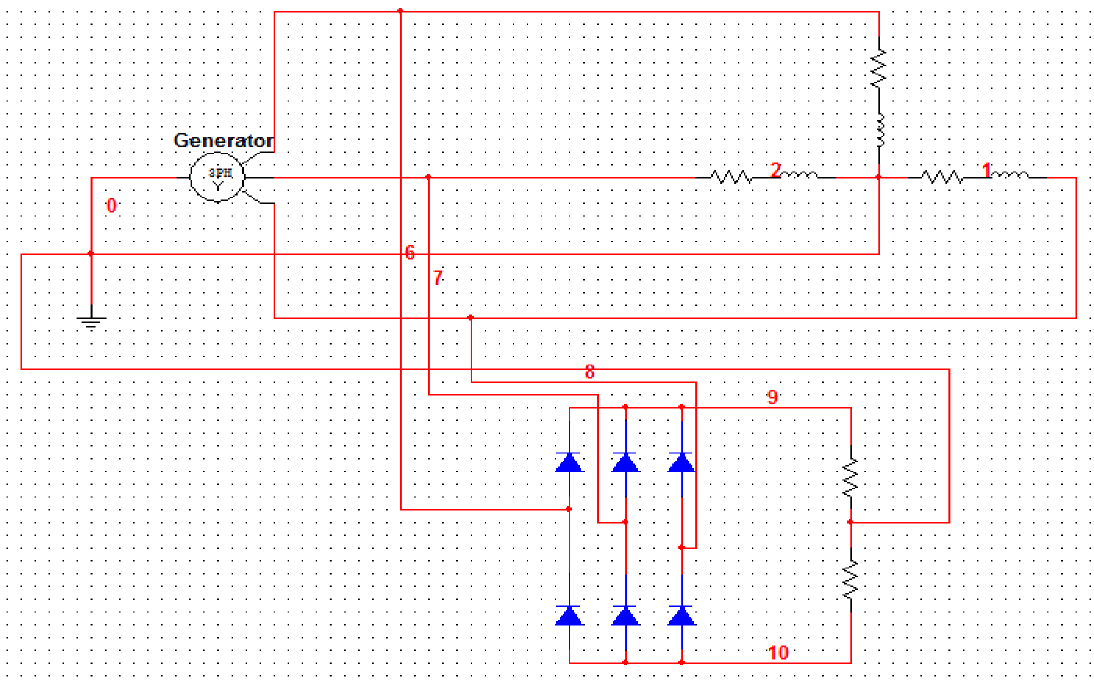


Figure 11. Synchronous generator connected to balanced resistive and inductive load with full bridge rectifier

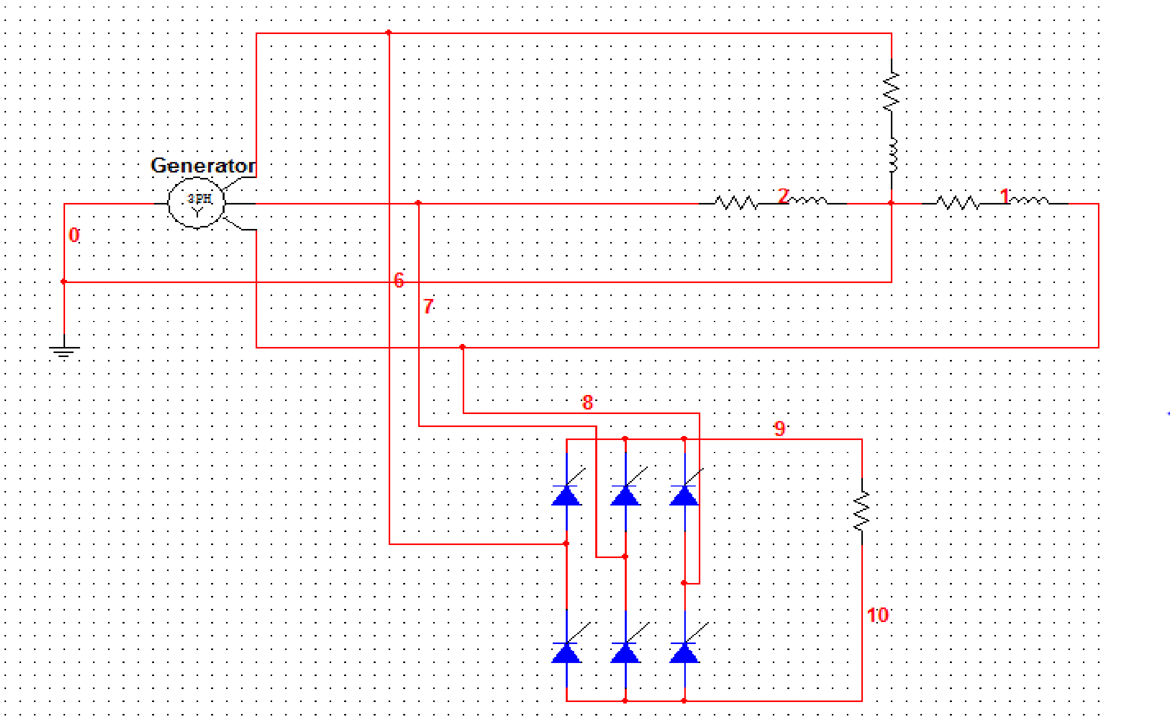


Figure 12. Synchronous generator connected to balanced resistive and inductive load with full bridge rectifier (power thyristors)

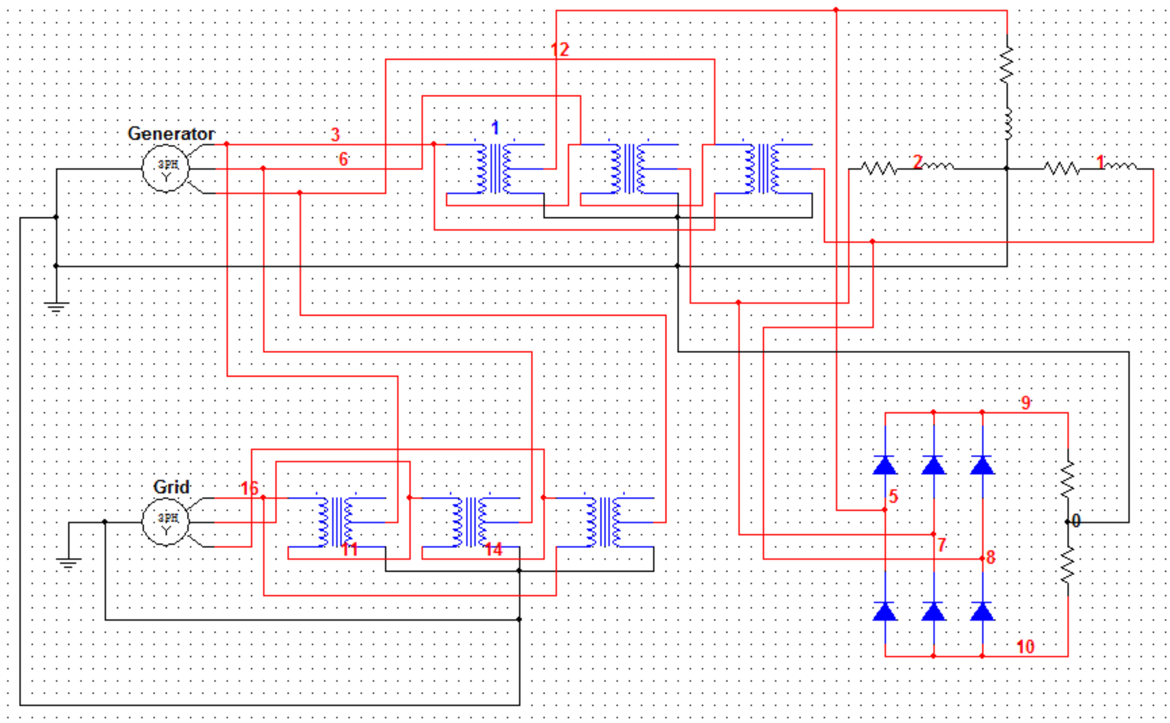


Figure 13. Synchronous generator in parallel operation with power grid connected to balanced resistive and inductive load with full bridge rectifier (power diodes)

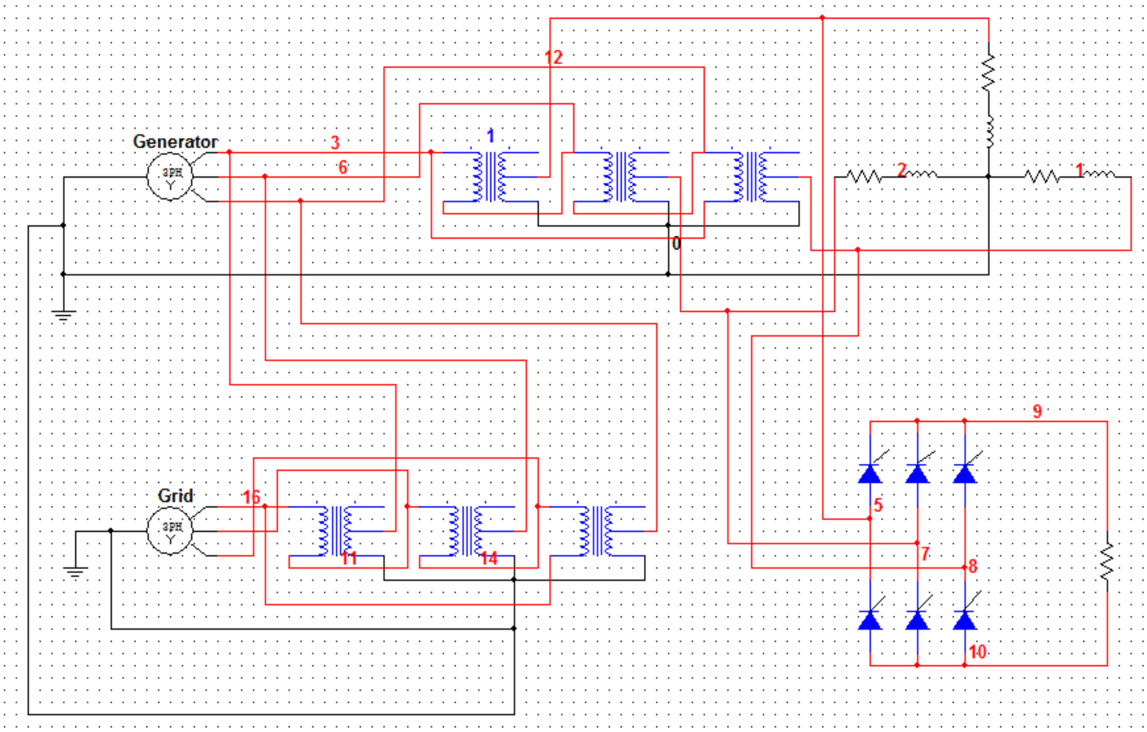


Figure 14. Synchronous generator in parallel operation with power grid connected to balanced resistive and inductive load with full bridge rectifier (power thyristors)

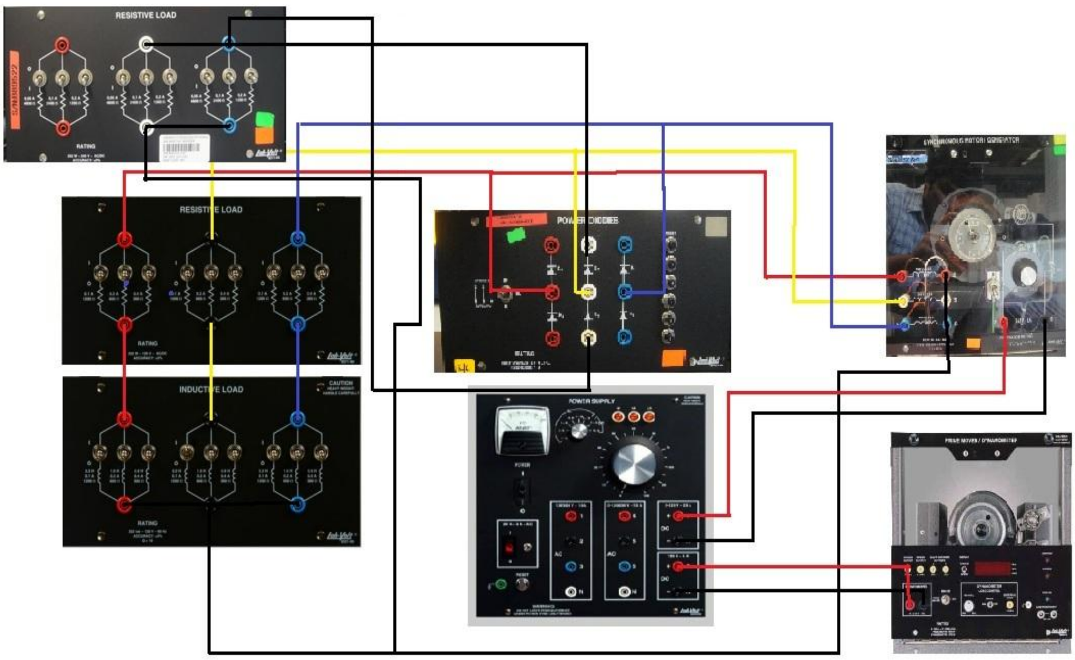


Figure 15. Actual connection for lab scaled experiment (Islanded Operation)

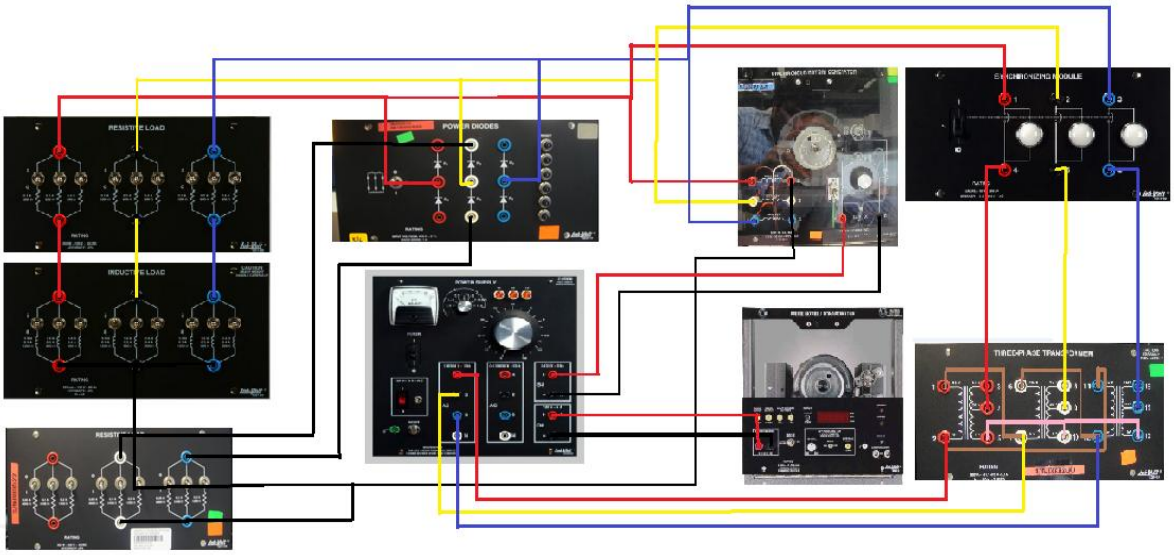


Figure 16. Actual connection for lab scaled experiment (Parallel Operation)

Table 1 shows the value of resistive loads and inductive loads together with the combinations of those two that will be used in the experiments.

Table 1. Resistive and inductive loads with impedance angle variation

Resistor (Ohm-Ω)	Inductor (Henry- H)	Combination	Impedance angel (θ)
686	2.53	686(Ω)	0
800	3.8	4800(Ω) + 2.1836(H)	8
1200	5.1	1200(Ω) +2.1836(H)	30
1600	7.6	686(Ω) + 2.1836(H)	45
2400	15.3	686(Ω) + 3.8(H)	60
3600		686(Ω) + 15.3(H)	82
		3.8(H)	90

Apart from the variation of impedance angle, the combination of resistive and inductive load with impedance magnitude variation is shown in Table 2.

Table 2. Resistive and inductive loads with impedance magnitude variation

Combination	Impedance magnitude (Ohm-Ω)	Impedance angel (θ)
960(Ω) + 2.1836(H)	1165	34.51
1600(Ω) + 3.8(H)	1996.4	36.7
2400(Ω) + 5.07(H)	2885.6	33.72
3600(Ω) + 7.6(H)	4320	33.56
4800(Ω) + 11.4(H)	5988.6	36.7

3.1.3 Result and Discussion

In this stage, the data and results gained from previous stage will be analysed and evaluated. The findings on triplen harmonics will be discussed and studied to satisfy the project requirement. Modification on the project could be made to improve the results from the project if necessary.

3.1.4 Final Documentation

In this final stage, all the processes and works in the project started from research works, methodology to the outcomes and findings will be documented for future use. The documentation will be done continuously from the beginning stage to make sure the documentation on the project will be completed on time.

3.2 Key Milestone

The progress of the research project is monitored by using a key milestone to make sure that the project is on schedule. The key milestone for both first phase and second phase is shown in Table 3.

Table 3. Key milestone for the project

FIRST SEMESTER															
NO	DETAIL/ WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Completion of Preliminary Research Work														
2	Lab Scaled Experiment														
SECOND SEMESTER															
NO	DETAIL/ WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	Completion of Lab Scaled Experiment														
4	Completion of Data Analysis														
5	Completion of Result and Discussion														
6	Completion of Final Documentation														

3.3 Gantt Chart

The Gantt Charts is constructed to show the timeline of the research project. The schedule of the project may subject to changes from time to time depending on work progress. Gantt charts for the first semester and second semester are shown in Table 4 and Table 5 respectively.

Table 4. Gantt chart for First Semester

NO	DETAIL/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection and Confirmation of Project Title								Mid-Semester Break							
2	Preliminary Research Work on Related Topics															
3	Submission of Extended Proposal															
4	Lab Scaled Experiment															
5	Proposal Defense															
6	Lab Scaled Experiment Continues															
7	Submission of Interim Draft Report															
8	Submission of Interim Final Report															

Table 5. Gantt chart for Second Semester.

NO	DETAIL/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Lab Scaled Experiment Continues								Mid-Semester Break							
2	Data Analysis															
3	Submission of Progress Report															
4	Result and Discussion															
5	Pre-EDX															
6	Submission of Draft Report															
7	Submission of Final Report (Soft cover)															
8	Submission of Technical Paper															
9	Oral Presentation															
10	Submission of Final Report (Hard cover)															

3.4 Tools Required

Tools that are going to be used in this research project consist of three parts which are tools for lab scaled experiment and harmonic measurement tools. In lab scaled experiment, Lab-Volt Electromechanical Training System will be used. This tool is a modular program in electrical power technology which contains of modules. These modules are used to form subsystem in electrical system for lab scaled project. The diagrams and symbols of the modules indicated on clearly silk-screened on the faceplates. Besides, the safety 4mm jacks with standard colour coded is going to be used to establish connection between components. The equipment from Lab-Volt Electromechanical Training that will be used in this project is shown in Figure 17, Figure 18, Figure 19, Figure 20, Figure 21, Figure 22, Figure 23, Figure 24, Figure 25 and Figure 26.

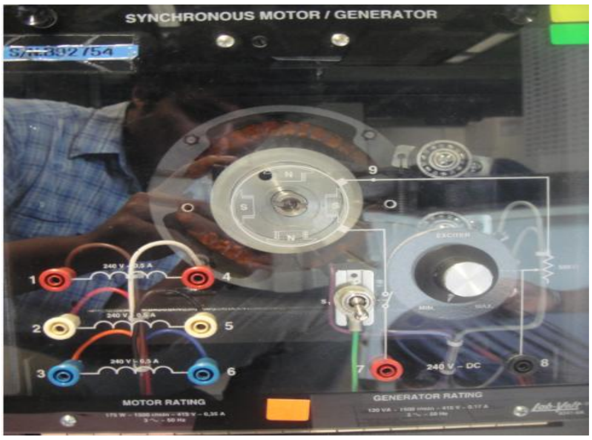


Figure 17. Lab scaled three phase synchronous generator

Figure 18. Lab Scaled Prime Mover/Dynamometer

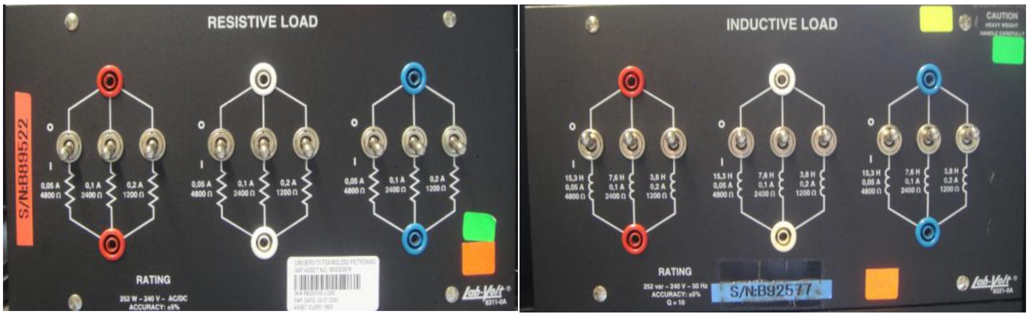


Figure 19. Lab scaled resistive and inductive loads

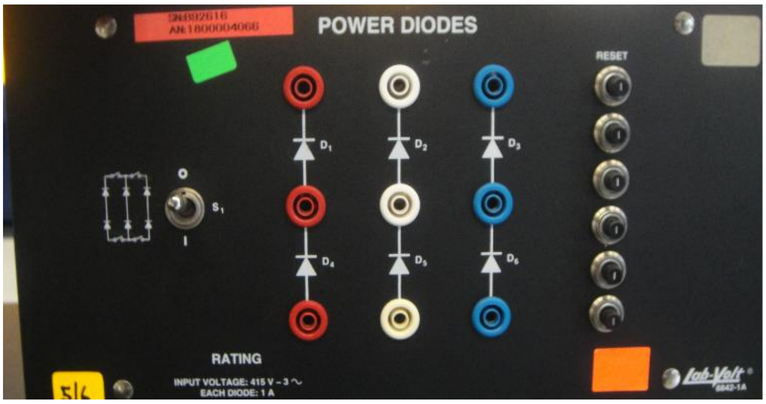


Figure 20. Lab scaled power diodes

Figure 21. Power supply

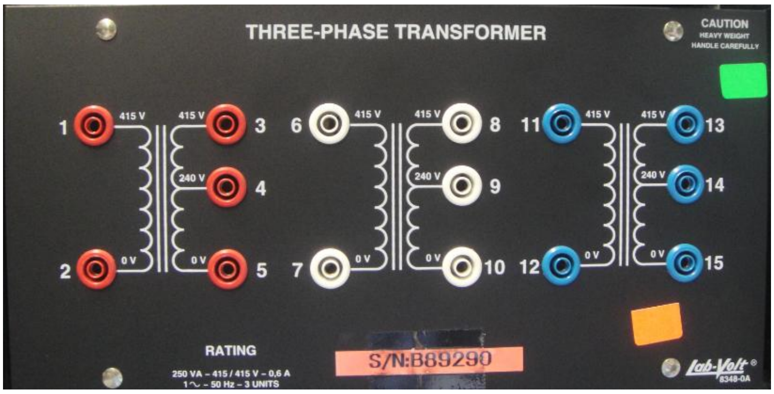


Figure 22. Lab scaled three phase transformer

Figure 23. Connection probes

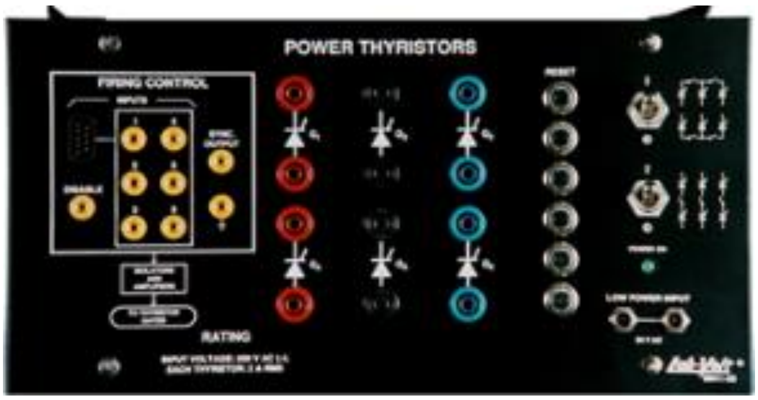


Figure 24. Lab scaled power thyristors

Figure 25. Thyristor firing unit

Figure 26. Power Supply

In order to measure the harmonics distortion in lab scaled experiment, Fluke Three Phase Power Quality Analyzer will be used. Fluke Three Phase Power Analyzer is a tool to conduct studies on electrical energy consumption and electrical load analysis besides performing power quality logging and analysis. It is a three phase troubleshooting tools that can be used to measure every power system parameter such as current, voltage, frequency, power, energy consumption, power factor, unbalance system, harmonics and inter-harmonics. The measurement work using Fluke Three Phase Power Quality Analyzer will be based on interconnection with computer using Flukeview software to transfer the data to the computer. The

Fluke Three Phase Power Quality Analyzer specification is attached in Appendix A. The picture of the Fluke Three Phase Power Quality Analyzer is shown in Figure 27.

Figure 27. Fluke Three Phase Power Quality Analyzer

.

CHAPTER 4
RESULT AND DISCUSSION

Based on the experiments that have been done during the two phases of the project, all required data from experiments have been recorded to see the characteristics of triplen harmonics. Throughout the experiments, two types of voltage and currents were measured, fundamental and triplen harmonics However, in this report only third harmonic component will be presented as we focused on the third harmonic component where the magnitude of harmonic current is the highest among triplen harmonic. Besides, the phasor values of the results are also measured.

4.1 Single Synchronous Generator in Islanded Operation Connected to Balanced Load

4.1.1 Connected to Balanced Resistive Load

Based on Figure 28, the third harmonic voltage magnitude increases when the load resistance increases. However, the third harmonic current magnitude decreases with respect to the increase of load resistance as shown in Figure 29. All third harmonic voltages and third harmonic currents are almost in phase as shown in Figure 30 and Figure 31respectively.

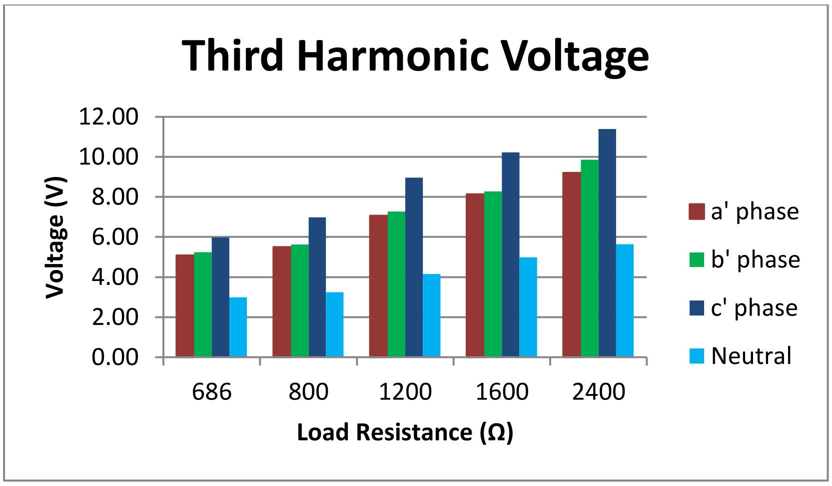


Figure 28. Third harmonic voltage

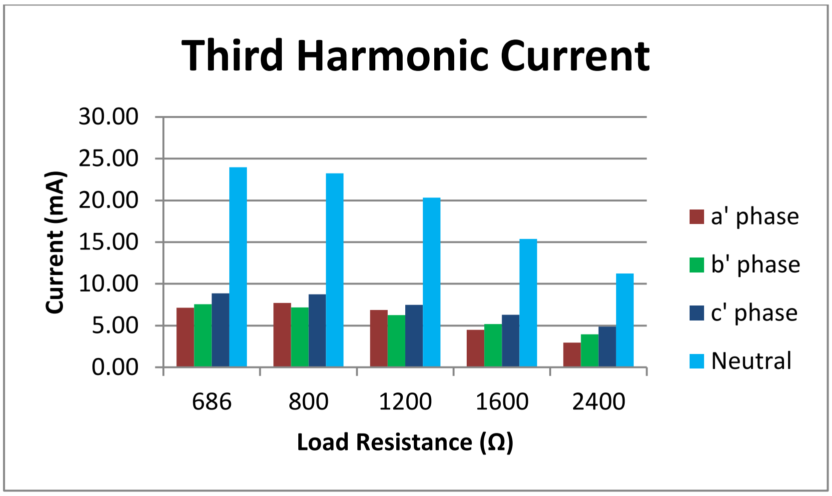


Figure 29. Third harmonic current

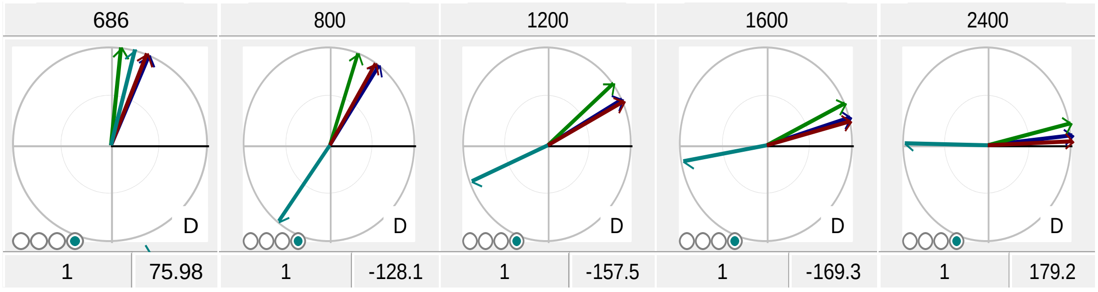


Figure 30. Voltage phase angle for generator connected directly to resistive load

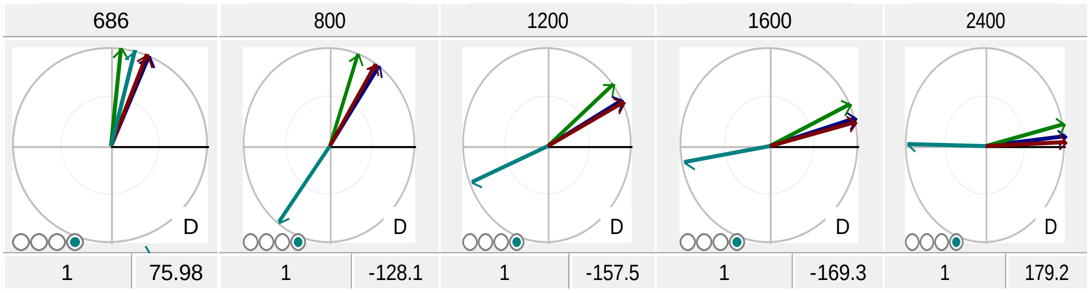


Figure 31. Current phase angle for generator connected directly to resistive load

The third harmonic current being in phase resulted in their addition in the neutral. Besides, the increase of load resistance also results in the decrease of third harmonic current in the neutral line.

4.1.2 Connected to Balanced Inductive Load

The third harmonic voltage tends to decrease when the load inductance increases as shown in Figure 32. However, the third harmonic current magnitude decreases with respect to the increase of load inductance as in Figure 33. Besides, all third harmonic voltages and third harmonic currents are almost in phase as shown in phasor diagrams in Figure 34 and Figure 35 respectively.

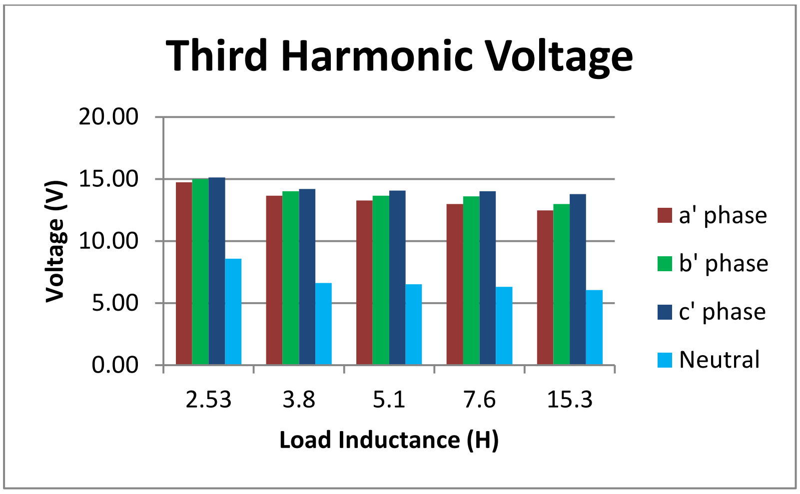


Figure 32. Third harmonic voltage

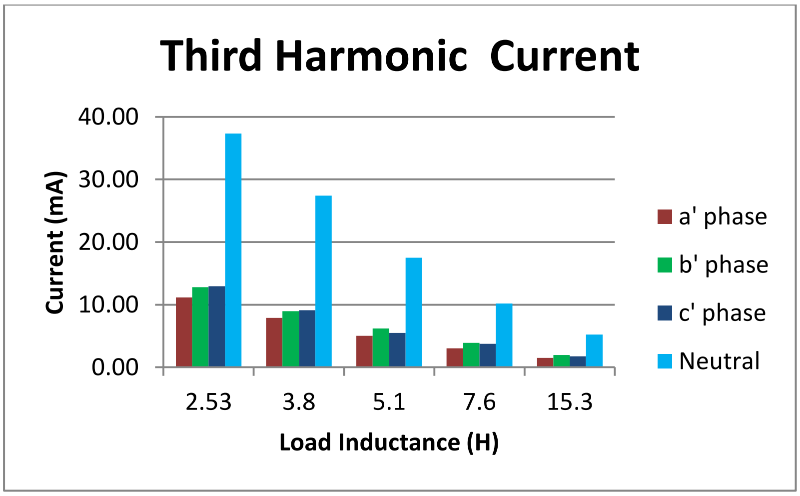


Figure 33. Third harmonic current

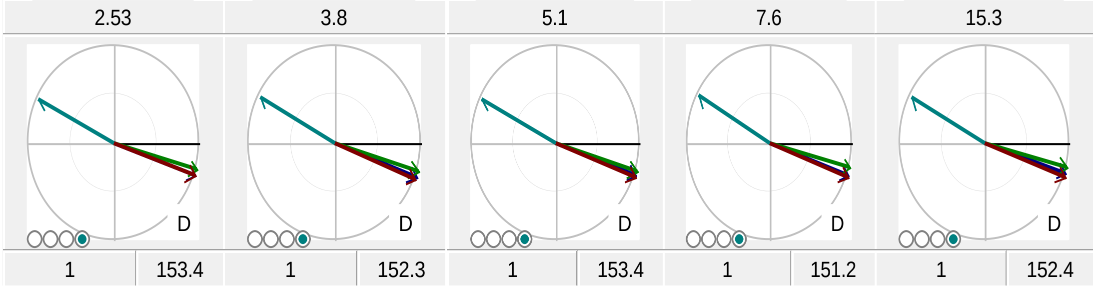


Figure 34. Voltage phase angle for generator connected directly to inductive load

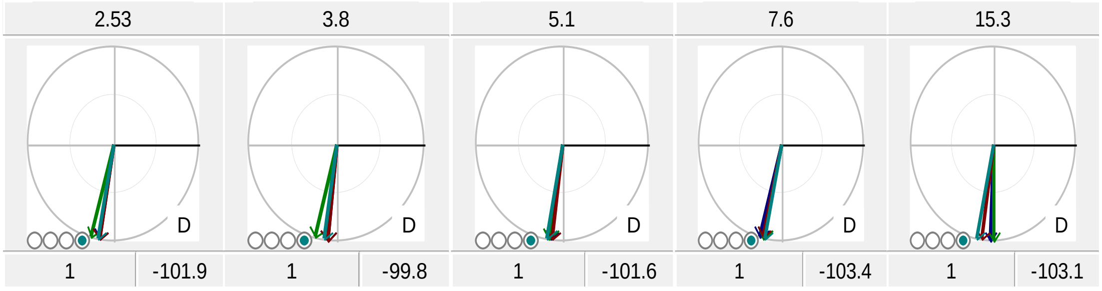


Figure 35.Current phase angle for generator connected directly to inductive load

Being in phase, the third harmonic current added at neutral causing the neutral almost three times the phase current. The third harmonic current magnitude in the neutral decreases with respect to the increase of load inductance. Moreover, the third harmonic current lags the third harmonic voltage in all cases for inductance load. However, it lags less than the fundamental current lags the fundamental voltage.

4.1.3 Connected to Balanced Resistive and Inductive Load

Based on Figure 36, the third harmonic voltage magnitude increases when the resistive or inductive component of impedance increases. The increase of third harmonic voltage magnitude is more obvious when the inductive component increases compare to the increase of resistive component of the impedance. Meanwhile, the magnitude of the third harmonic current decreases when the resistive and inductive component of the impedance increases as shown in Figure 37.The third harmonic voltages and third harmonic currents for all value of impedance are almost in phase as shown in Figure 38 and Figure 39. The result of this characteristic is that the third harmonic current added at neutral causing neutral current to be almost three times the phase current.

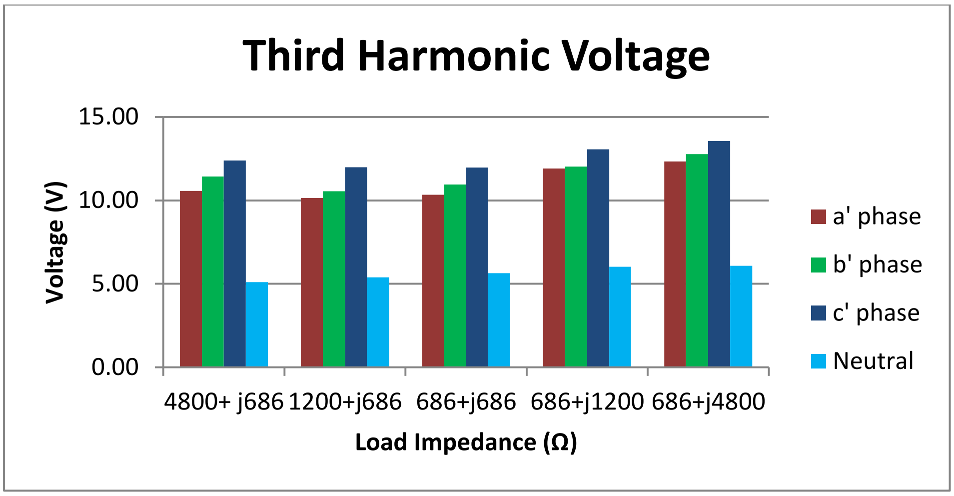


Figure 36. Third harmonic voltage

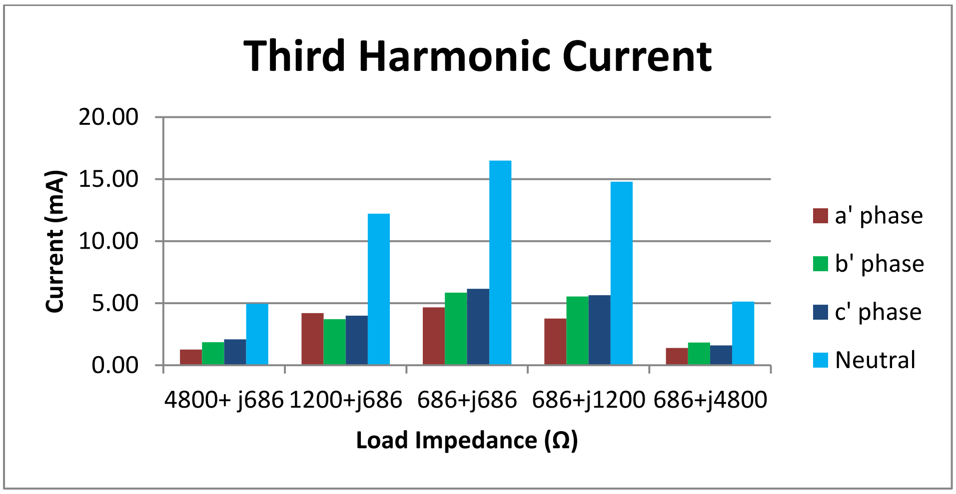


Figure 37. Third harmonic current

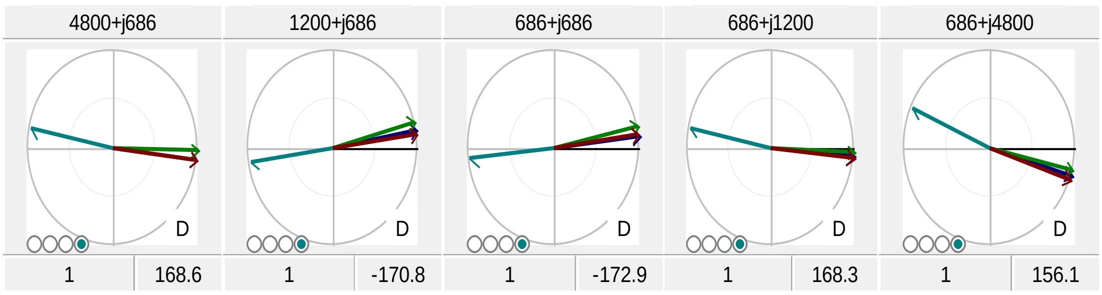


Figure 38. Voltage phase angle for generator connected directly to resistive and inductive load

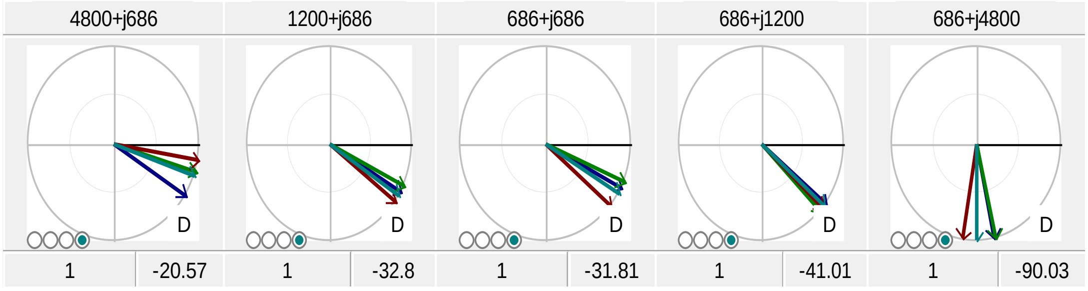


Figure 39. Current phase angle for generator connected directly to resistive and inductive load

4.2 Single Synchronous Generator in Islanded Operation Connected to Balanced Load and Full Bridge Rectifier

4.2.1 Connected to Balanced Resistive and Inductive Load (Impedance Angle Varied) with Full Bridge Rectifier Using Power Diode

In this experiment, the measurements were taken at three different points, at generator, load and rectifier. The third harmonic voltage magnitude measured at generator, rectifier and load are almost equal as shown in Figure 40, Figure 41, and Figure 42 respectively. Apart from that, the magnitude of third harmonic current at generator increases with respect to the increase of resistive or inductive component of the impedance at load as shown in Figure 43. The third harmonic current magnitude at rectifier is almost same for all value of load impedance as shown in Figure 44. This is due to fact that fix resistance were used at the output of rectifier and only the load impedance was changed. However, Figure 45 shows that the magnitude of third harmonic current at load decreases as the resistive or inductive component of the impedance increases. The third harmonic voltages and currents at all points are almost in phase as shown in Figure 46 and Figure 47. The phasor diagrams shown in Figure 46 and Figure 47 are based on 686+686jΩ load result but overall characteristic is deduced taking into account all load impedance used in this experiment. Based on data analysis, it can be concluded that the generator third harmonic current is actually the vector sum of both rectifier and load third harmonic currents.

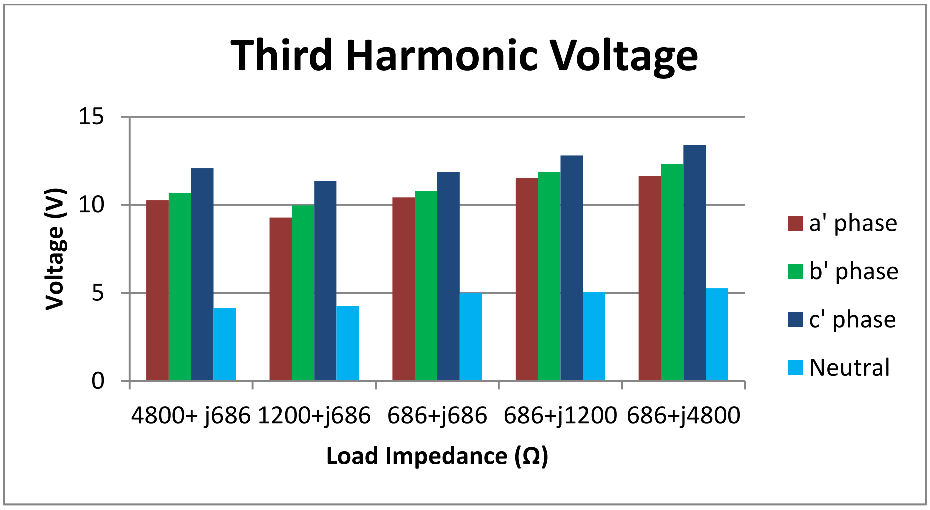


Figure 40. Third harmonic voltage (at generator)

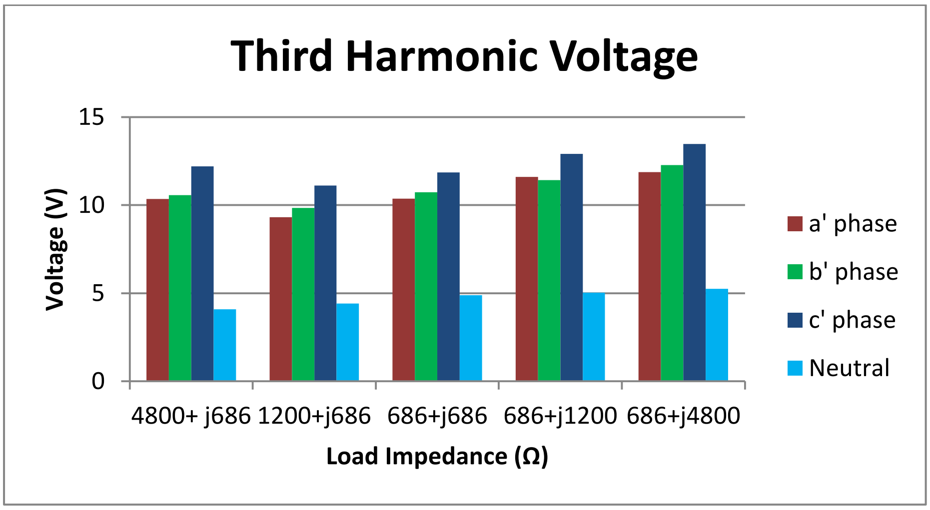


Figure 41. Third harmonic voltage (at rectifier)

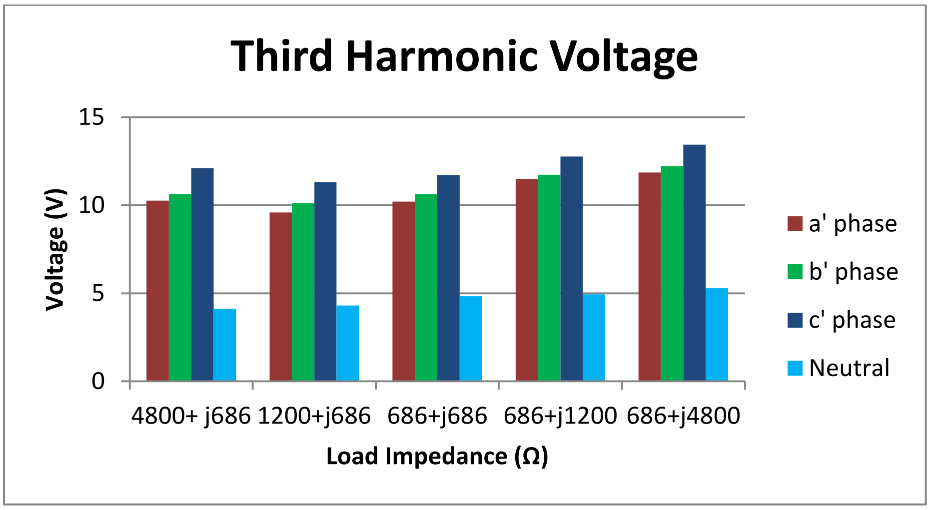


Figure 42. Third harmonic voltage (at load)

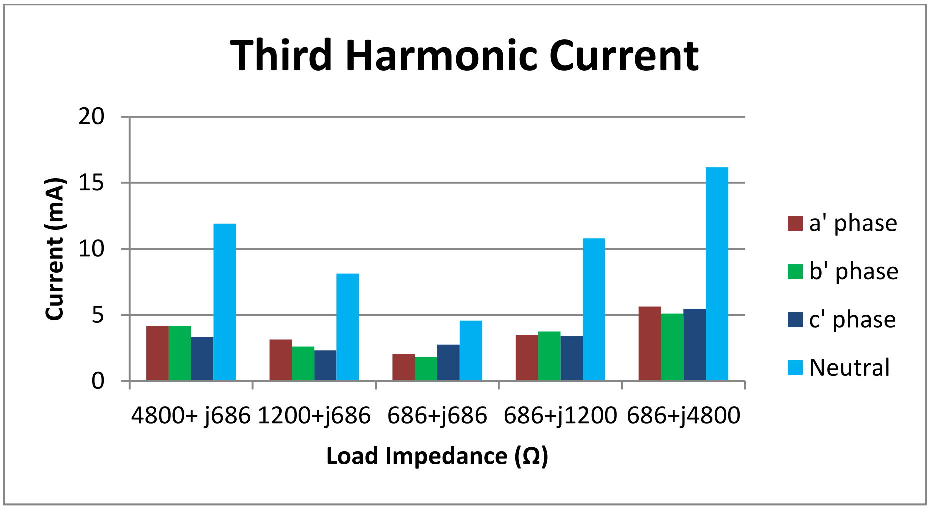


Figure 43. Third harmonic current (at generator)

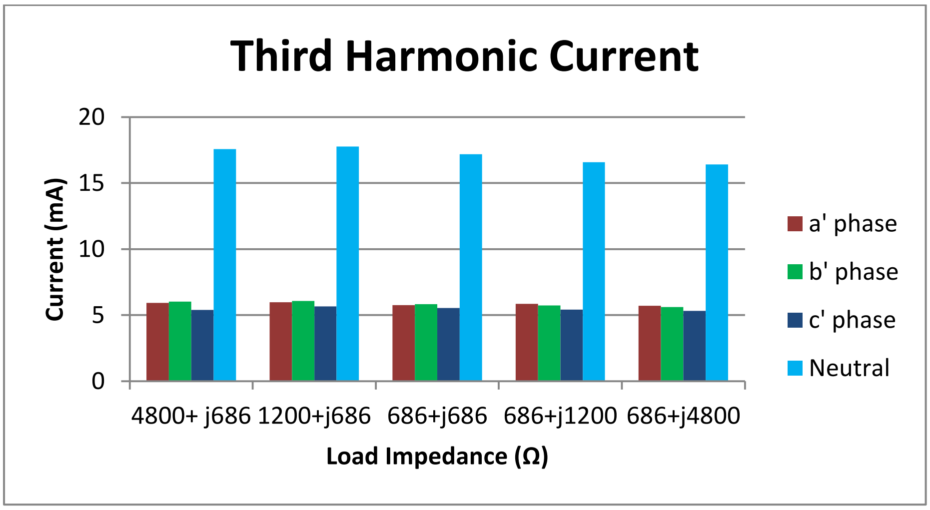


Figure 44. Third harmonic current (at rectifier)

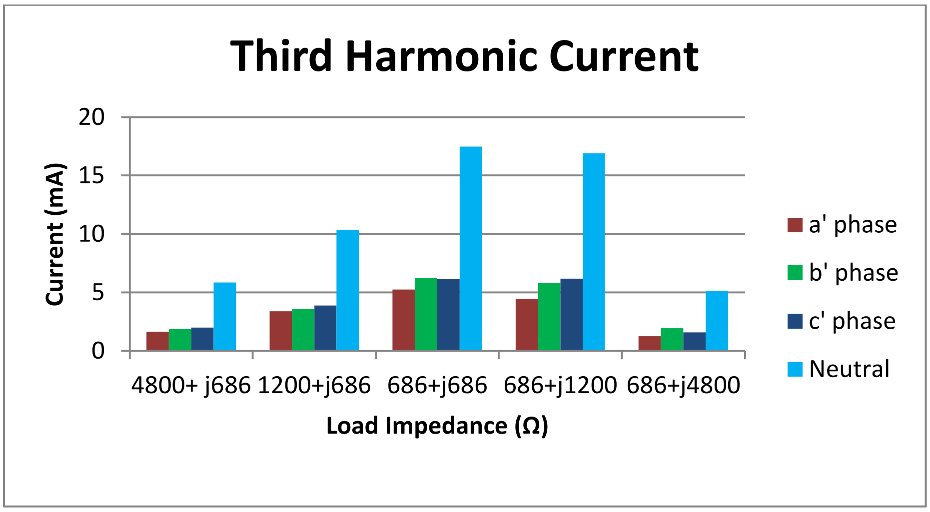
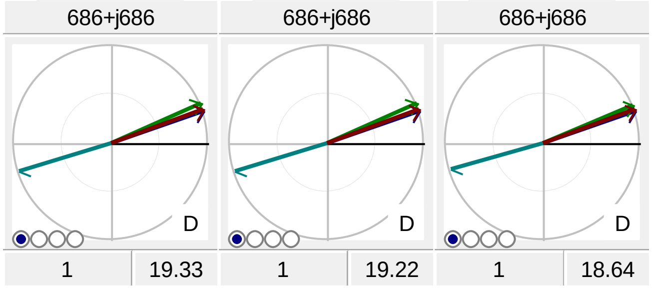
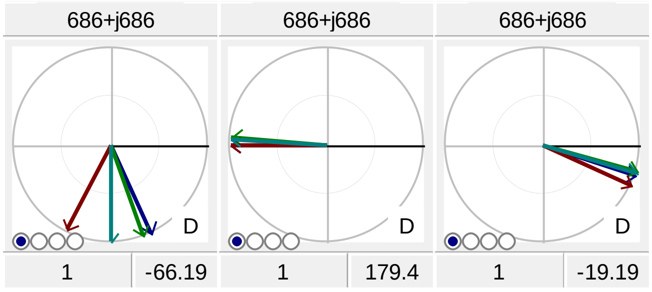


Figure 45. Third harmonic current (at load)



Generator Rectifier Load

Figure 46. Voltage phase angle for generator connected directly to load with rectifier



Generator Rectifier Load

Figure 47. Current phase angle for generator connected directly to load with rectifier

4.2.2 Connected to Balanced Resistive and Inductive Load (Impedance Magnitude Varied) with Full Bridge Rectifier Using Power Diode

The third harmonic voltages magnitude measured at generator, rectifier and load are almost equal despite the changes of impedance magnitude at load as shown in Figure 48, Figure 49 and Figure 50. Apart from that, the magnitude of triplen harmonic current at generator decreases as the load impedance magnitude increases as shown in Figure 51. Meanwhile, at rectifier the magnitude of third harmonic current are almost similar for all value of load impedance magnitude as can be seen in Figure 52. However, the magnitude of third harmonic current at load decreases drastically with respect to the increase of load impedance magnitude as in Figure 53. Besides, the third harmonic voltages at all points of measurement are almost in phase as shown in Figure 54. The third harmonic currents are almost in phase or zero sequence in nature at generator, load and especially at rectifier as shown in Figure 55. The phasor diagrams used for Figure 54 and Figure 55 is based on load impedance of 2400 + j1602Ω.

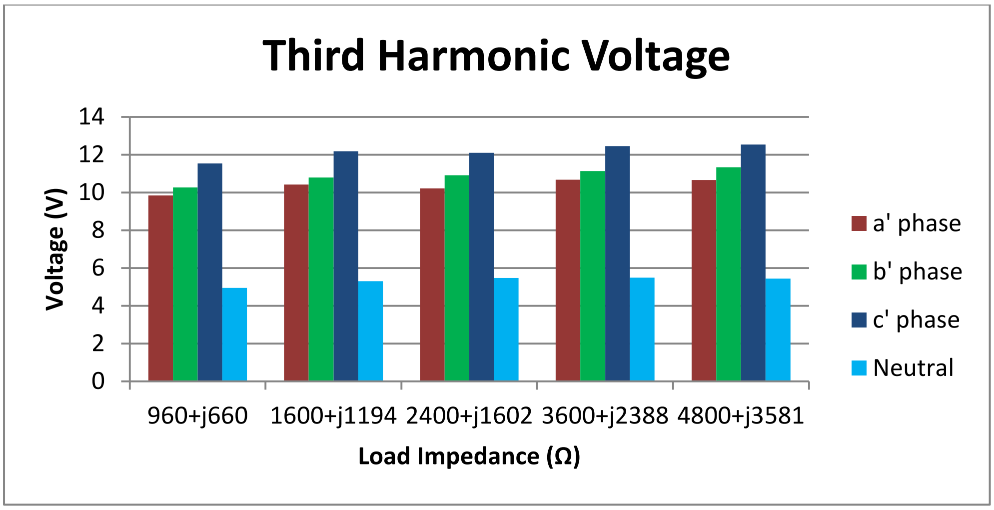


Figure 48. Third harmonic voltage (at generator)

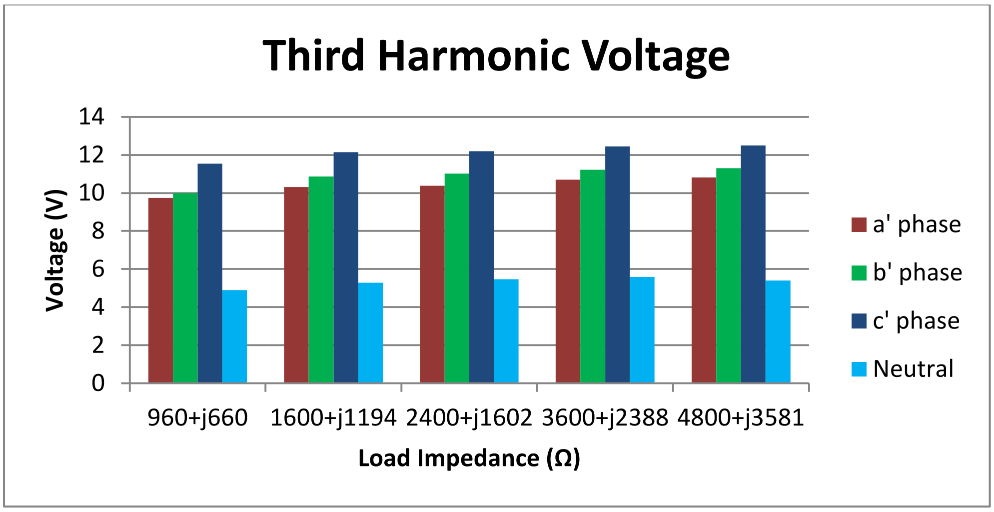


Figure 49. Third harmonic voltage (at rectifier)

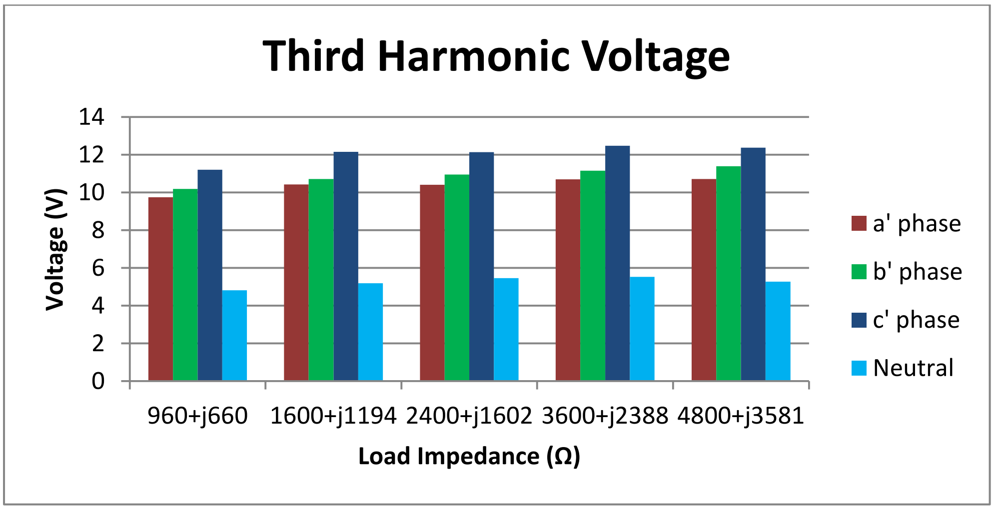


Figure 50. Third harmonic voltage (at load)

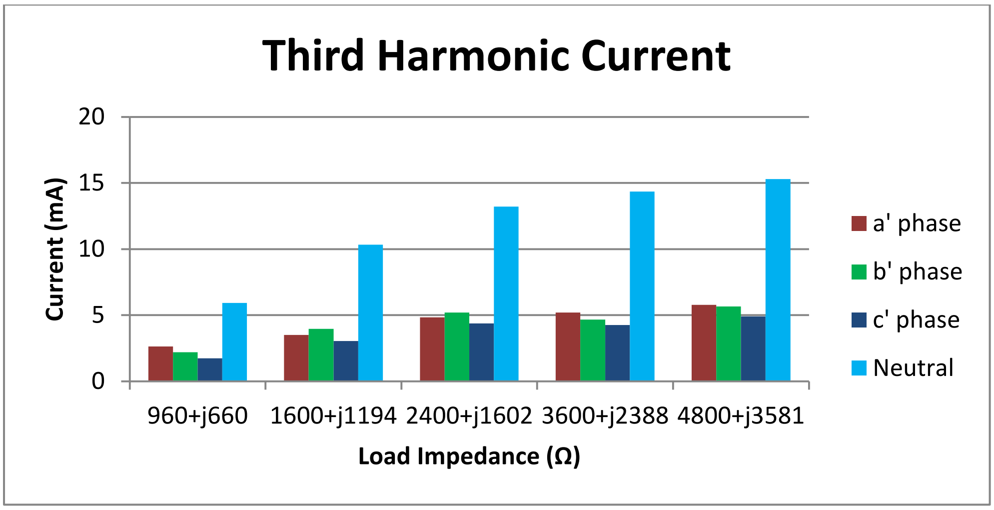


Figure 51. Third harmonic current (at generator)

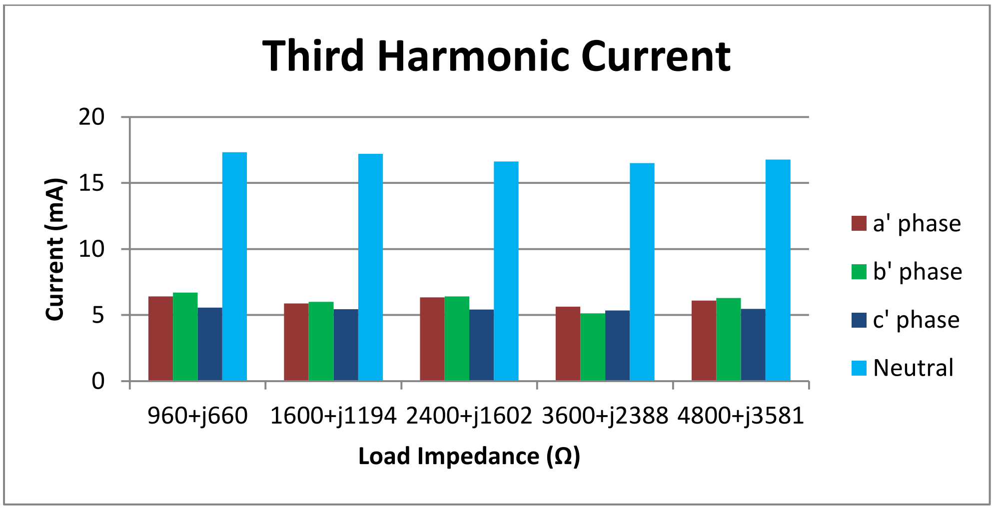


Figure 52. Third harmonic current (at rectifier)

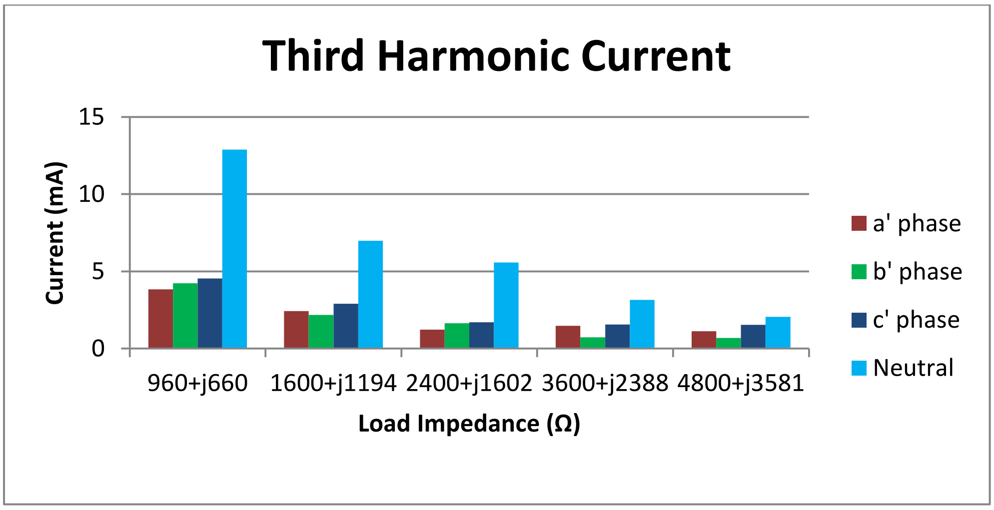


Figure 53. Third harmonic current (at load)

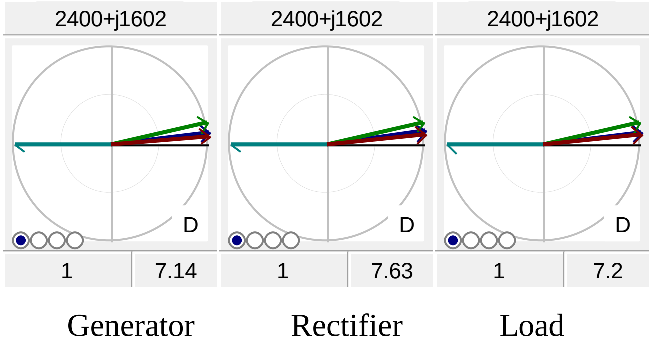


Figure 54.Voltage phase angle for generator connected directly to load with rectifier

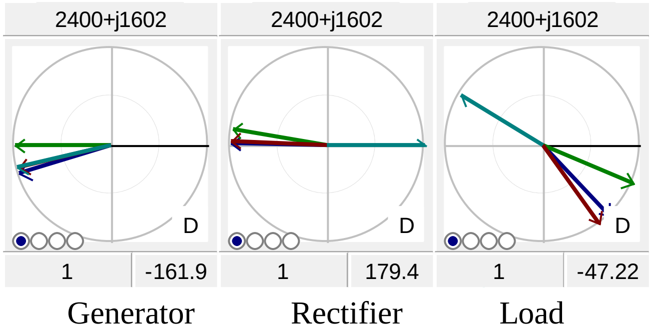


Figure 55.Current phase angle for generator connected directly to load with rectifier

Based on the data gathered from the experiment, the third harmonic current at generator is found to be the vector sum of the third harmonic currents at rectifier and load despite the changes of load impedance magnitude. Thus, it can be stated that the third harmonic current source is coming from generator flowing through rectifier and load.

4.2.3 Connected to Balanced Resistive and Inductive Load (Impedance Angle Varied) with Full Bridge Rectifier Using Power Thyristors

The experiments using power thyristors to construct a full bridge rectifier are done by using the same setup as the one using power diodes except that the power thyristors were connected to thyristor firing unit. Besides, the neutral line was not connected to the Direct Current (DC) output of the rectifier. Based on the results gained from this experiment, the magnitude of third harmonic voltage at generator increases when the inductive component of the load impedance increases as shown in Figure 56. The third harmonic voltage magnitude at rectifier increases when the resistive or inductive component of load impedance increases as can be seen in Figure 57. Meanwhile, the third harmonic voltage magnitude at load seems similar despite the load impedance is varied as shown in Figure 58. The third harmonic current magnitude at generator decreases when the resistive or inductive component of load impedance increases as shown in Figure 59.However, at rectifier, the third harmonic current of each phase are almost zero and unbalanced when the resistive or inductive component of load impedance is varied as shown in Figure 60.The third harmonic current magnitude at load decreases when the resistive or inductive component of load impedance is increases as shown in Figure 61. Phasor diagram used in next two figures to represent the phase angle of third harmonic is based on 686+j686Ω. The third harmonic voltage at generator, rectifier and load are almost in phase. Meanwhile, the third harmonic current at generator and load seems to be almost in phase. However, the third harmonic currents are not in phase at rectifier. The third harmonic currents are actually flow to the load which depends on the load impedance magnitude and angle. Meanwhile the third harmonic currents do not flow at rectifier for all cases due to no neutral being connected at its DC output.

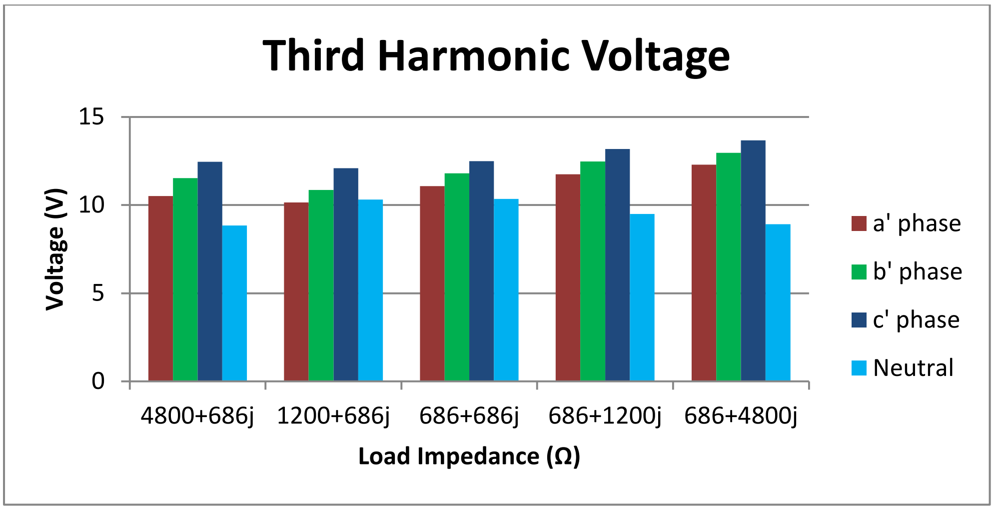


Figure 56. Third harmonic voltage (at generator)

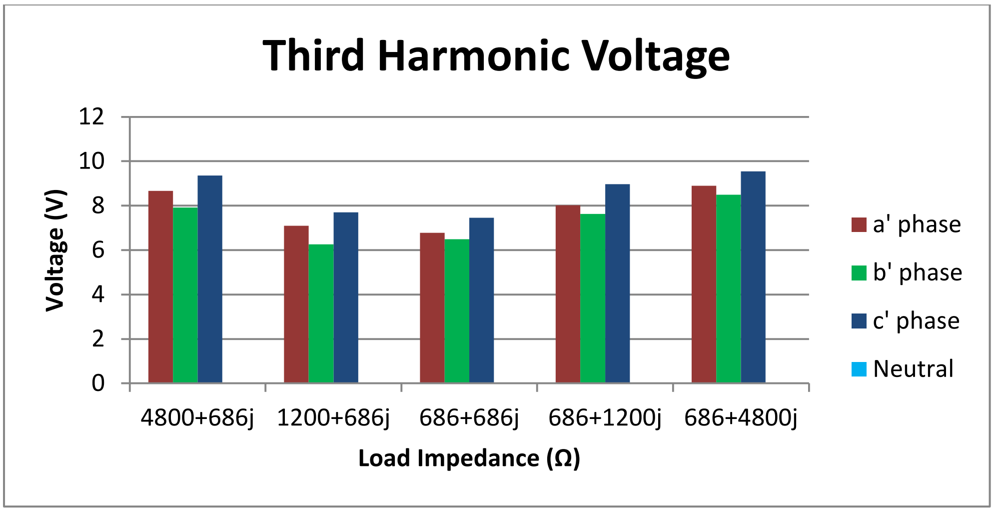


Figure 57. Third harmonic voltage (at rectifier)

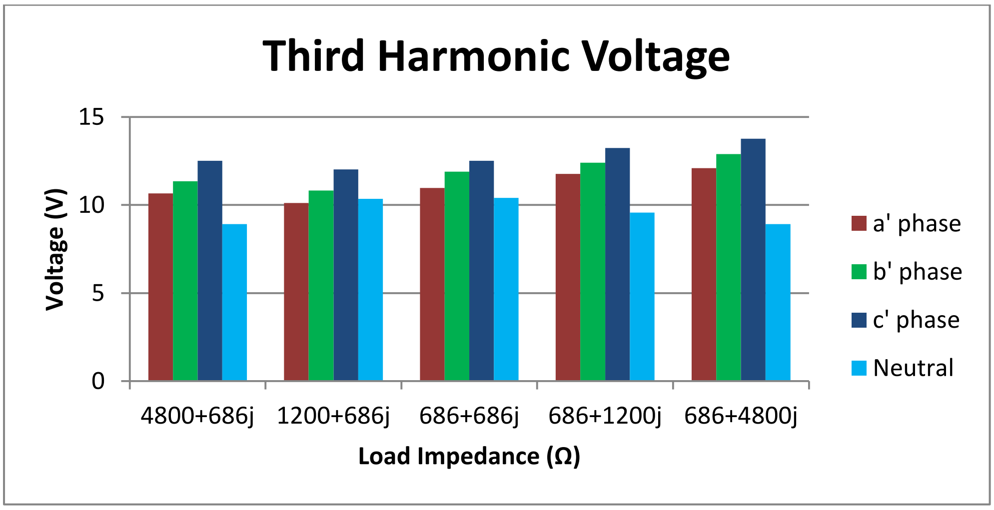


Figure 58. Third harmonic voltage (at load)

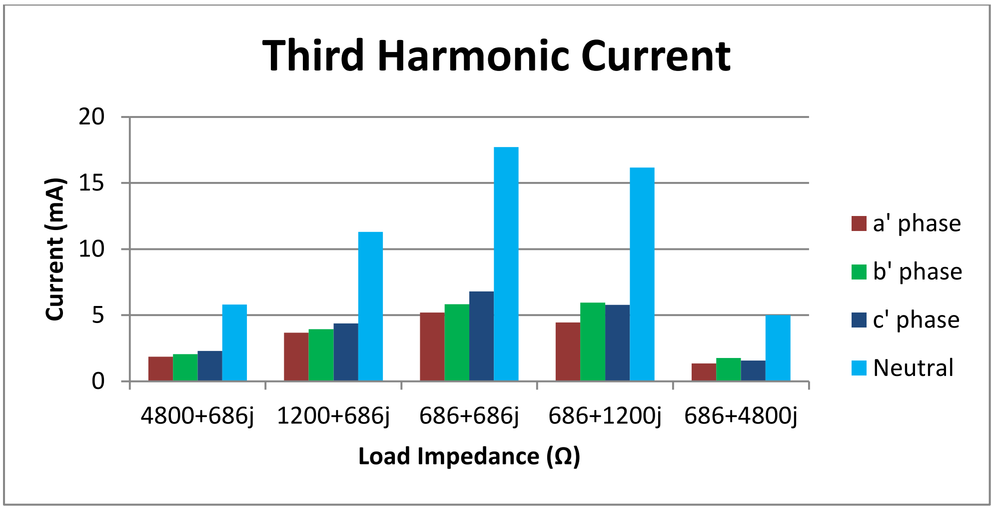


Figure 59. Third harmonic current (at generator)

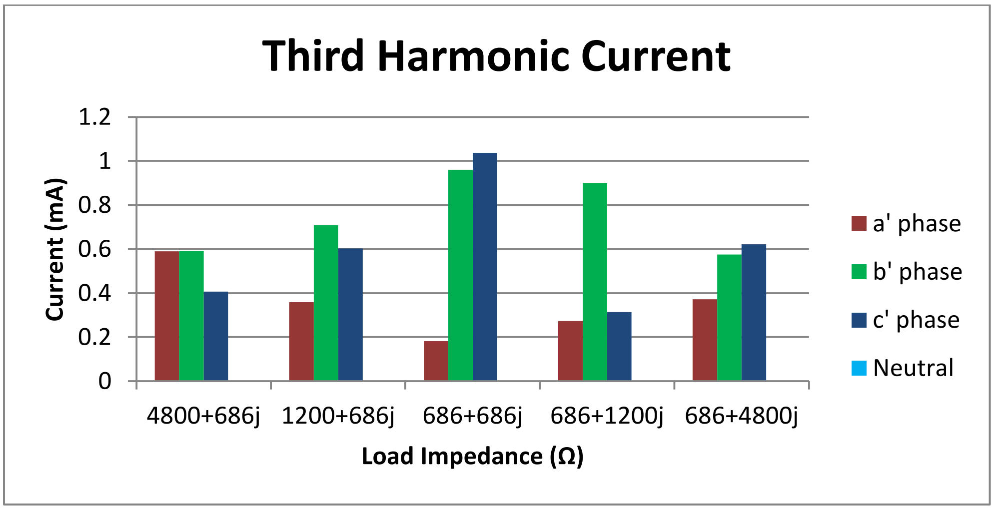


Figure 60. Third harmonic current (at rectifier)

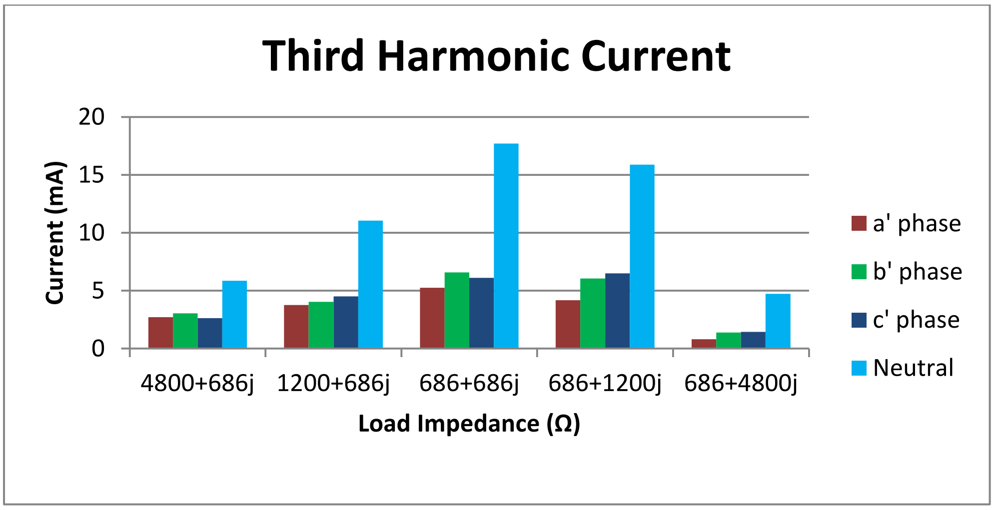


Figure 61. Third harmonic current (at load)

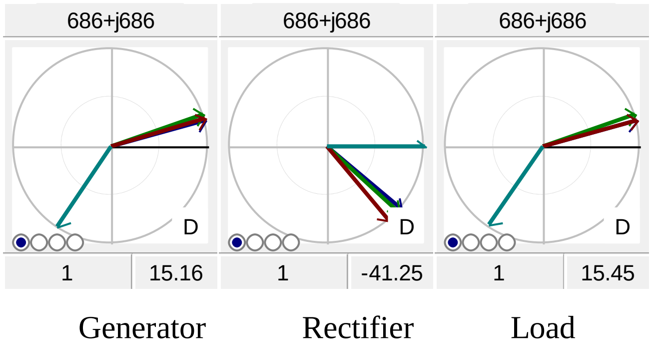


Figure 62. Voltage phase angle for generator connected directly to load with rectifier

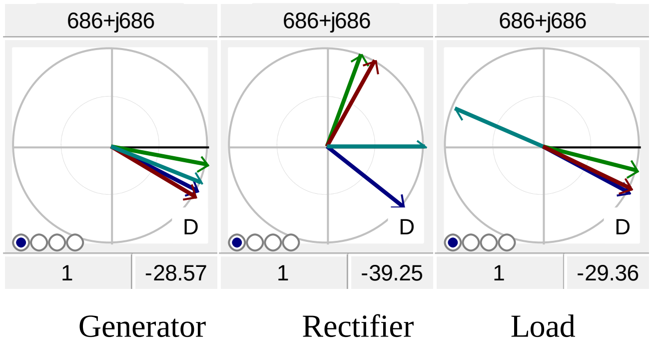


Figure 63. Current phase angle for generator connected directly to load with rectifier

4.2.4 Connected to Balanced Resistive and Inductive Load (Impedance Magnitude Varied) with Full Bridge Rectifier Using Power Thyristors

The third harmonic voltage magnitude at generator and load are almost the same at different magnitude of load impedance as shown in Figure 64 and Figure 65. However the third harmonic voltage magnitude at neutral of generator and load decreases as the load impedance magnitude increases. Meanwhile, the third harmonic voltage magnitude at rectifier increases as the load impedance increases as shown in Figure 66. Apart from that, the third harmonic current magnitude at generator and load decrease when the load impedance magnitude increases as shown in Figure 67 and Figure 69 respectively. However, the third harmonic current magnitude at rectifier is very small and almost zero and seems unbalanced as shown in Figure 68. Moreover, the third harmonic voltages are almost in phase at generator, rectifier and load as shown in Figure 70. Besides, the third harmonic currents are also almost in phase at all measurement points as can be seen in Figure 71. Based on the result, it can be seen that the third harmonic currents flow from generator to the load and not to the rectifier due to no neutral line being connected to the output of rectifier.

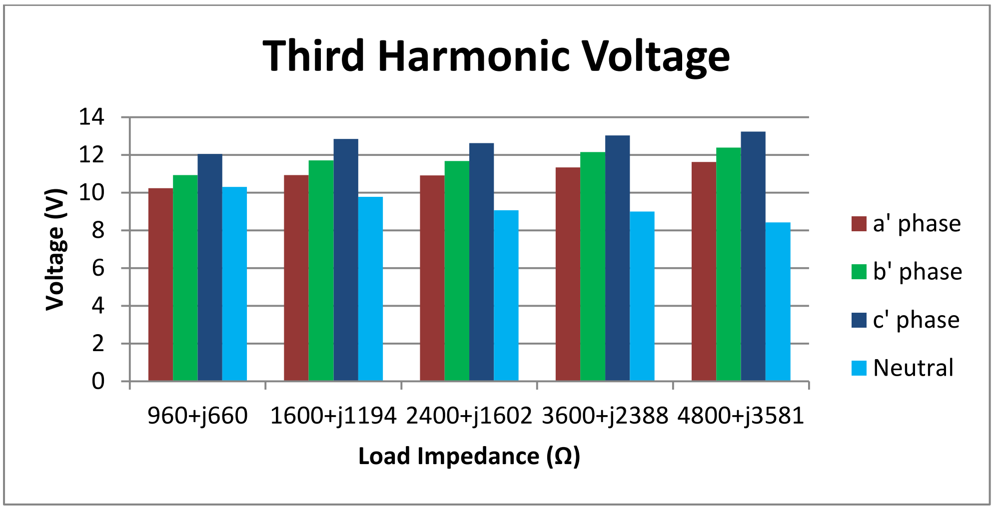


Figure 64. Third harmonic voltage (at generator)

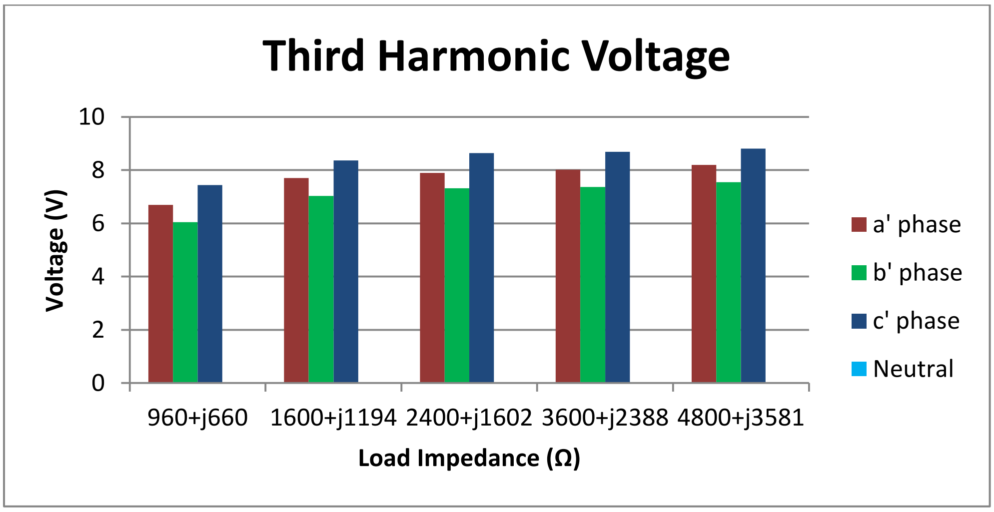


Figure 65. Third harmonic voltage (at rectifier)

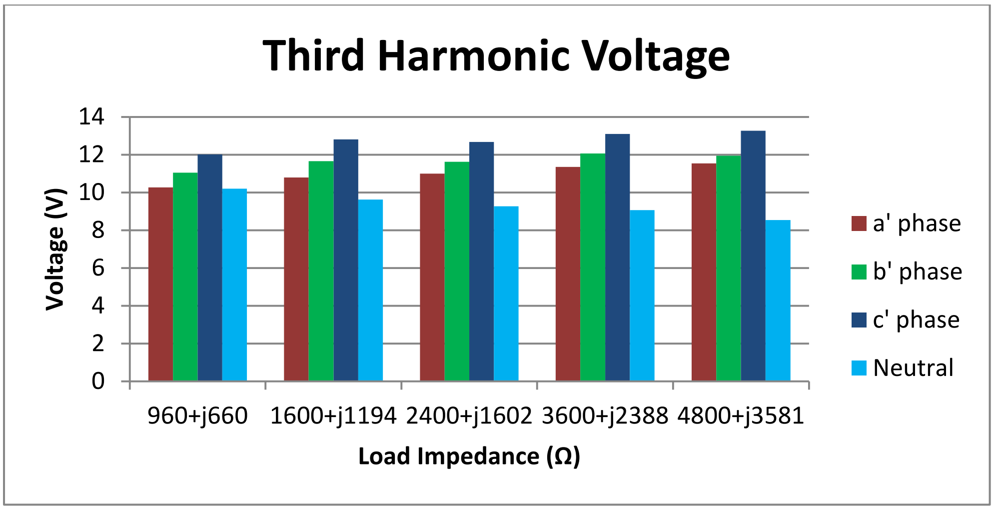


Figure 66. Third harmonic voltage (at load)

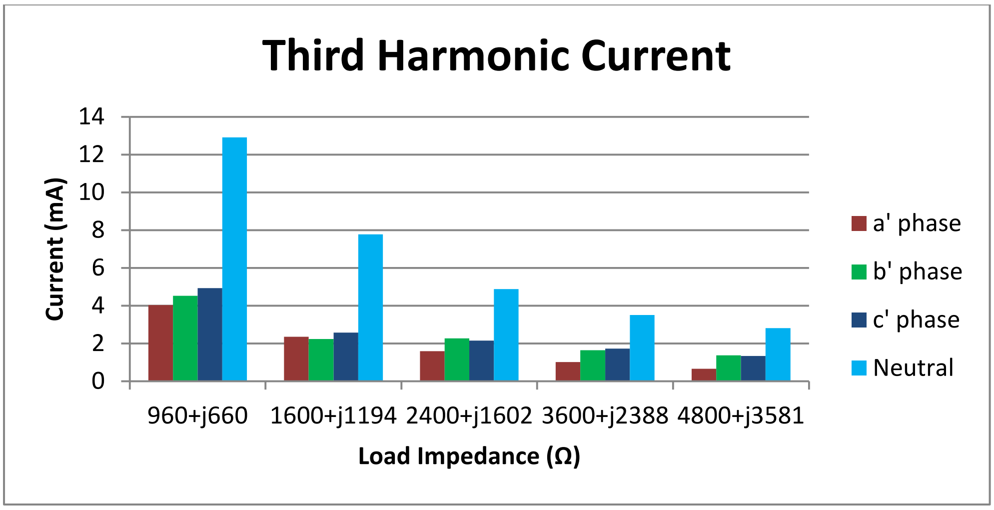


Figure 67. Third harmonic current (at generator)

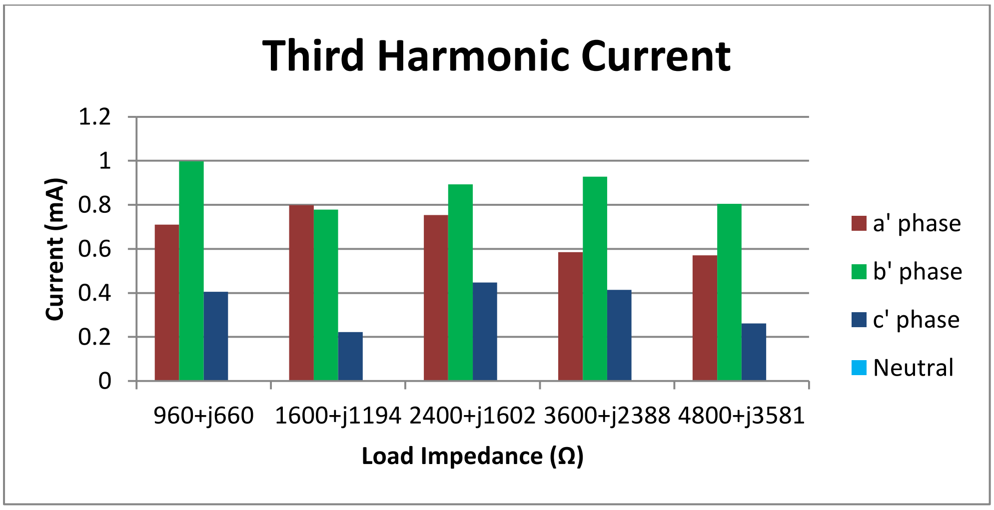


Figure 68. Third harmonic current (at rectifier)

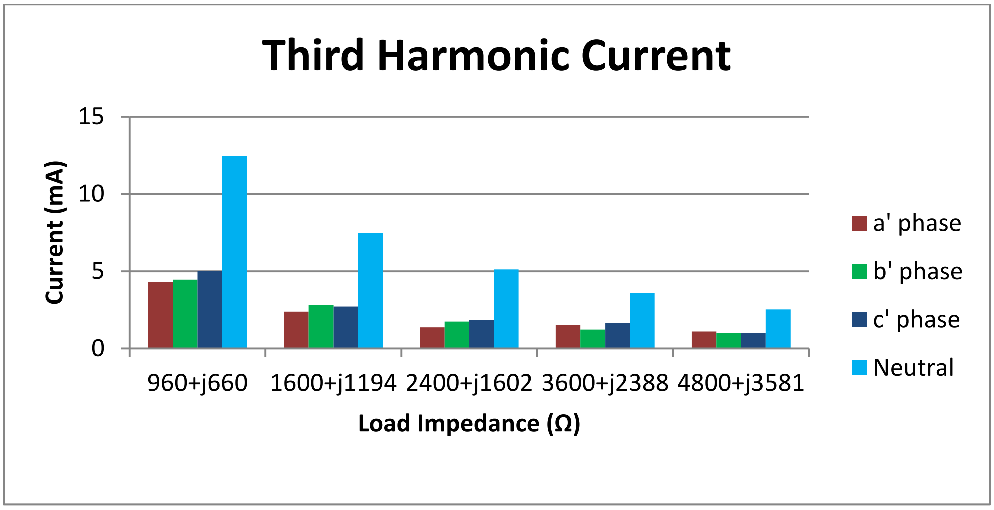


Figure 69. Third harmonic current (at load)

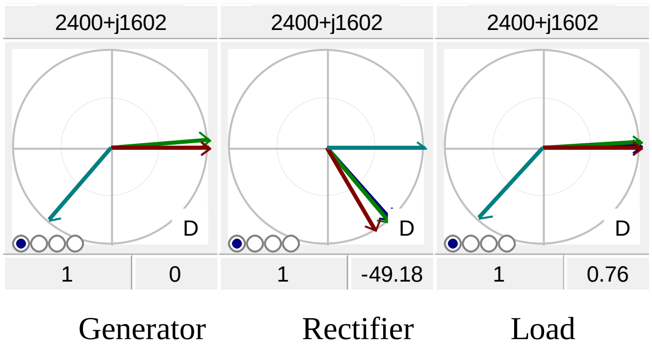


Figure 70. Voltage phase angle for generator connected directly to load with rectifier

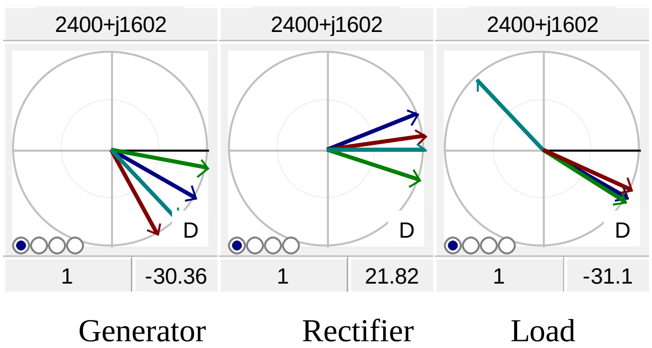


Figure 71. Current phase angle for generator connected directly to load with rectifier

4.3 Single Synchronous Generator in Parallel with Grid Connected to Balanced Load and Full Bridge Rectifier

4.3.1 Connected to Balanced Resistive and Inductive Load (Impedance Magnitude Varied) with Full Bridge Rectifier Using Power Diode

The results from the experiments were gained by measuring the third harmonics at eight different points in the parallel setup as in methodology section shown previously. The result shown in Figure 72 and Figure 73 is based on 2400+j1602 Ω load but it represents the overall data for different loads used in the experiment. The third harmonic voltage magnitude at generator terminal and at star side of transformer after grid is almost same as shown in Figure 72. Besides, the third harmonic voltage magnitude at both side of transformer before load, delta side of transformer after grid, at load and rectifier are almost similar. The highest third harmonic voltage magnitude is at grid terminal. The third harmonic current magnitude at star side of transformer before load and rectifier are almost the same as shown in Figure 73. However, the third harmonic current magnitude at grid terminal and load is very small compared to the other measurement points. The third harmonic current magnitude at generator terminal and star side of transformer after grid are very high and almost the same. The third harmonic current at generator and star transformer after grid is almost the same as the third harmonic current could not flow through delta side transformer before load and it circulates inside the delta. However at star side transformer after grid, the third harmonic currents from the generator could flow through its neutral which is connected to the generator neutral. This is the reason of the same magnitude of third harmonic current at generator and the star side of transformer after grid.

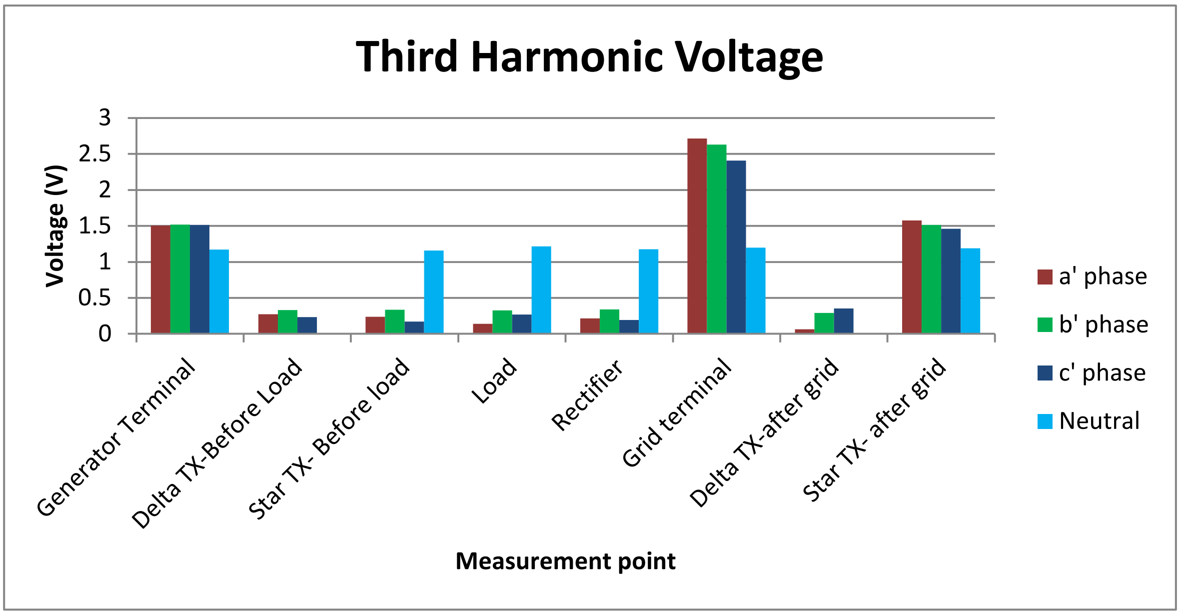


Figure 72. Third harmonic voltage

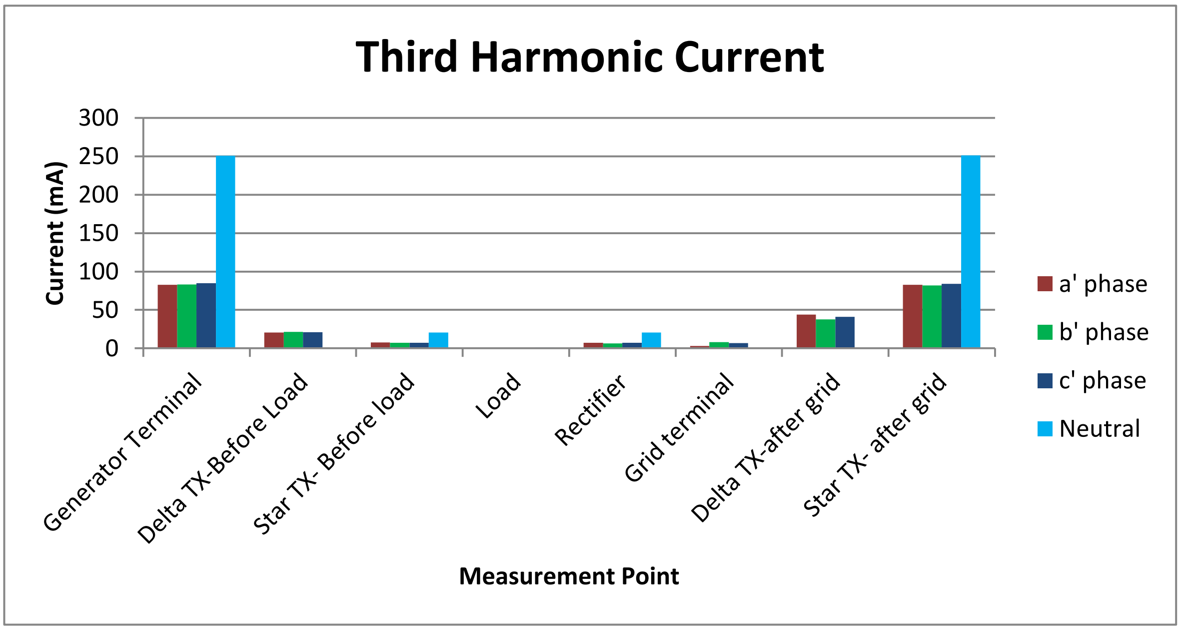


Figure 73. Third harmonic current

The third harmonic current magnitude at generator is almost same for small increment of load impedance magnitude as shown in Figure 74. When load impedance magnitude is increased in large amount, the third harmonic current at generator increases. The third harmonic current magnitude at generator for first two load impedance is almost the same but the difference can be seen in the other two load impedance used. Meanwhile, the third harmonic current magnitude at rectifier is almost the same for all load impedance magnitude as shown in Figure 75. Besides, the third harmonic current magnitude at star side of transformer before load is also almost similar for all load impedance magnitude as shown Figure 76. The third harmonic current magnitude at rectifier and star side of transformer before load is almost similar for each load impedance magnitude. Only small amount of third harmonic current flows through the load compared to the third harmonic current flows to the rectifier and star side of transformer before the load. The third harmonic current magnitude at load is depending on the load impedance magnitude. The third harmonic current magnitude at load decreases when the load impedance magnitude increases as shown in Figure 77.

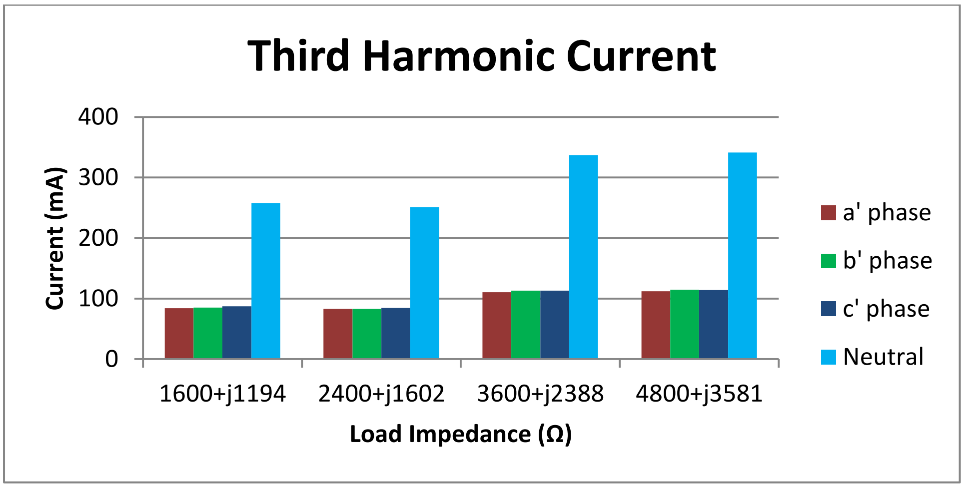


Figure 74. Third harmonic current (at generator)

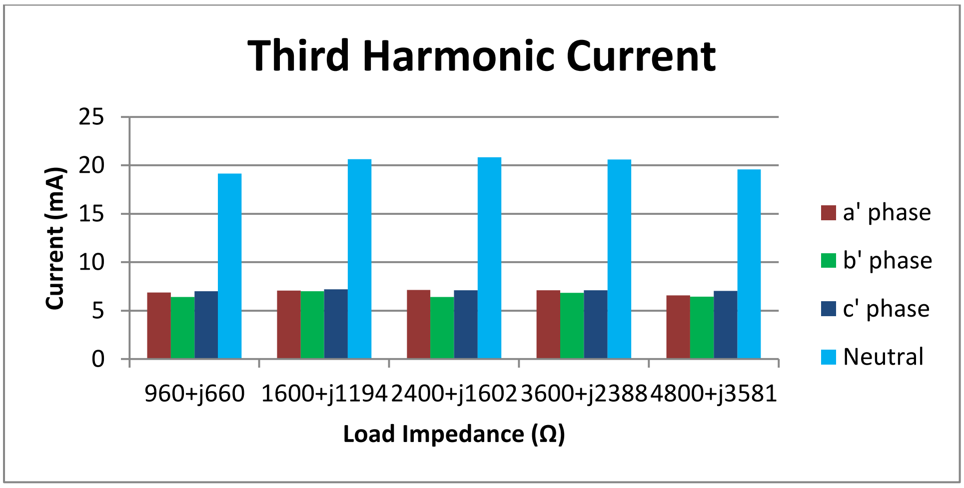


Figure 75.Third harmonic current (at rectifier)

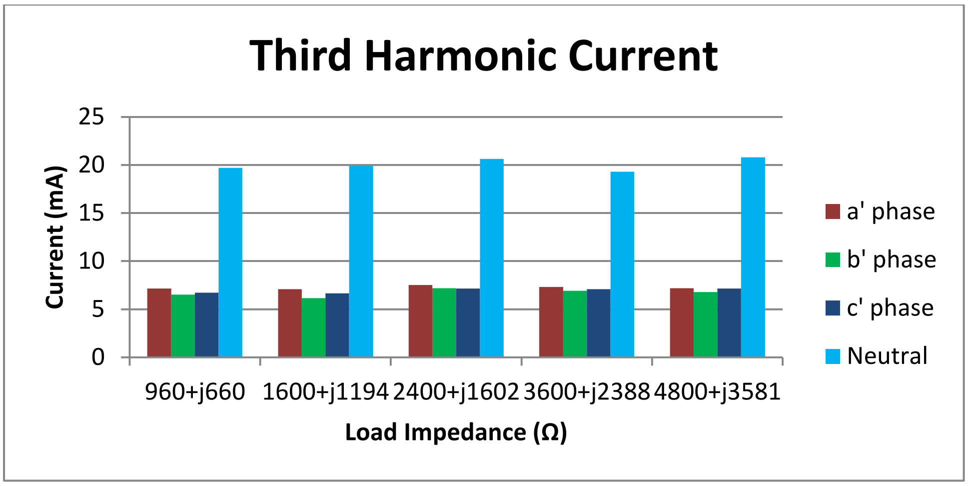


Figure 76.Third harmonic current (at star TX before load)

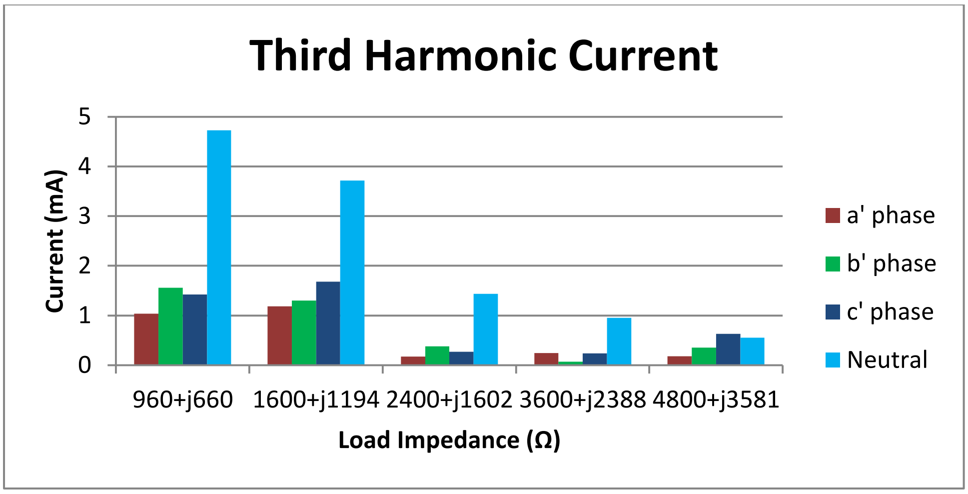


Figure 77.Third harmonic current (at load)

Based on the data from the experiment, the rectifier draws a constant amount of third harmonic current regardless of load impedance magnitude variation. The rectifier does not affect the results of third harmonic current at generator due to the delta side of transformer before load which blocks the harmonics from going into the load. The result of third harmonic measured at rectifier is due to that the rectifier draws the current in non- sinusoidal form from the star side of transformer before the load. Besides, the impedance at star side of transformer after grid is lower therefore allowing the third harmonic currents to flow through the transformer and back to generator through the neutral line.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

Based on the result and findings of the project, it can be concluded that when synchronous generator is connected directly to resistive and inductive load, the third harmonic current and voltage depend on the load impedance magnitude and phase angle. The obvious impact on the third harmonic voltage and current is higher when inductive component of load impedance is changed compared changes to the resistive component despite they have the same load impedance magnitude. Generally, the third harmonic voltage magnitude increases as the inductive or resistive increases but the third harmonic current magnitude decreases. The third harmonic voltage and third harmonic current phase angle are almost in phase for all cases where the generator is directly connected to load. Being in phase, the third harmonic currents at neutral become high as the third harmonic current at each phase added at the neutral.

Besides, when full bridge rectifier constructed by using power diodes is shunt connected between generator and load, there is no additional third harmonic current being produced by the full bridge rectifier. The vector sum of third harmonic current at load and the full bridge rectifier is actually equals to the third harmonic current at generator where it depends on the load impedance magnitude and phase angle. Apart from that, when full bridge rectifier constructed by using power thyristors is connected between generator and load, the third harmonic current recorded at generator, rectifier and load are less compared to the full bridge rectifier constructed by using power diodes. The third harmonic currents are actually flow to the load and not to rectifier. This is why the third harmonics currents recorded at rectifier are almost zero for all cases. The reason of this result is that the full bridge rectifier constructed by using power thyristors were done without connecting the neutral line to the DC output of the rectifier.

Moreover, in parallel operation of generator with grid, the third harmonic current magnitude at generator is high due to the delta side of transformer before load which blocks the third harmonic current to flow from the generator. The rectifier does not affect the results of third harmonic current at generator. The third harmonic current at rectifier is due to the rectifier drawing non- sinusoidal form of current from the star side of transformer before load. The low impedance at star side of transformer after grid allows the third harmonic current from the generator to flow to the transformer and back to the generator through the neutral line with the addition of third harmonic current of each phase results in high amount of third harmonic current at neutral.

Furthermore, in order to get more information of the flow of triplen harmonics currents, it is recommended that the experiments is extended by using another types of nonlinear loads such as power converter used to control the electrical machines.

REFERENCES

[1] Francisco C. De La Rosa, “Harmonics and Power Systems”, Taylor& Francis, 2006.

[2] Gregory W. Massey, “Power distribution system design for operation under non-sinusoidal load conditions,” IEEE Transactions on Industry Applications, Vol. 31, pp. 513-519, No. 3, May/June 1995

[3]M. F. Abdullah, N. H. Hamid, Z. Baharudin, M. F. I. Khamis, M. H. M. Nasir, “ The Study of Triplen Harmonics Currents Produced by Salient Pole Synchronous Generator,” 2011 International Conference on Electrical and Informatics, July.2011

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

[5]M. F. Abdullah, N. H. Hamid, Z. Baharudin, M. F. I. Khamis, N. S. R. Hashim, S. Yusof, “Investigation On High Neutral Earthing Resistor Temperature When Islanded Generator Connected To Utility Grid,” The 9th International Power and Energy Conference, Oct. 2010.

[6] Wagner, V.E.; Balda, J.C.; Griffith, D.C.; McEachern, A.; Barnes, T.M.; Hartmann, D.P.; Phileggi, D.J.; Emannuel, A.E.; Horton, W.F.; Reid, W.E.; Ferraro, R.J.; Jewell, W.T.; , "Effects of harmonics on equipment," Power Delivery, IEEE Transactions on , vol.8, no.2, pp.672-680, Apr 1993

[7] G. Chiccoa, P. Postolache, C. Toader, “Triplen Harmonics: Myths and Reality,” Electric Power Systems Research, 81, pp. 1541–1549, 2011 Elsevier.

[8]R. H. Barnes, “Telephone interference problem caused by generator triplen harmonic earth currents on an island system,” IEE Colloquium on Safeguarding Industrial Plant During Power System Disturbances, December 1989.

[9] McGranaghan, M.; , "Controlling harmonics from nonlinear loads in commercial facilities ," Harmonics and Quality of Power Proceedings, 1998. Proceedings. 8th International Conference On , vol.2, no., pp.872-877 vol.2, 14-18 Oct 1998

APPENDICES

APPENDIX A: Fluke Three Phase Power Quality Analyzer Specifications

Technical Data	
Inputs	**Number:** 4 voltage and current (3 phases + neutral) **Maximum voltage:** 1000 Vrms (6 kV peak) **Maximum sampling speed:** 200 kS/s on each channel simultaneously
Volt/Amps/Hertz	**Vrms (AC + DC)** **Measurement range:** 1 ... 1000 V **Accuracy:** 0.1% of Vnom **Vpeak** **Measurement range:** 1 ... 1400 V **Accuracy:** 5% of Vnom **Crest factor, voltage** **Measurement range:** 1.0 ... > 2.8 **Accuracy:** ±5% **Arms (AC + DC)** **Measurement range:** 0 ... 20 kA **Accuracy:** ±0.5% ± 5 counts **Apeak** **Measurement range:** 0 ... 5.5 kA **Accuracy:** 5% **Crest factor, A** **Measurement range:** 1 ... 10 **Accuracy:** ±5% **Hz 50 Hz nominal** **Measurement range:** 40 ... 70 Hz **Accuracy:** ±0.01 Hz
Dips and swells	**Vrms (AC+DC) [2]** **Measurement range:** 0.0% … 100% of Vnom **Accuracy:** ±0.2% of nominal voltage **Arms (AC+DC) [2]** **Measurement range:** 0 ... 20 kA □ **Accuracy:** ±1% ± 5 counts
Harmonics	**Harmonic (interharmonic) (n)** **Measurement range:** DC, 1..50; (Off, 1..49) measured according to IEC 61000-4-7 **Vrms** **Measurement range:** 0.0 … 1000 V **Accuracy:** ±0.05% of nominal voltage **Arms** **Measurement range:** 0.0 … 4000 mV x clamp scaling **Accuracy:** ±5% ± 5 counts **Watts** **Measurement range:** Depends on clamp scaling and voltage **Accuracy:** ±5% ± n x 2% or reading, ± 10 counts **DC voltage** **Measurement range:** 0.0 … 1000 V **Accuracy:** ±0.2% of nominal voltage **THD** **Measurement range:** 0.0 … 100.0% **Accuracy:** ±2.5% V and A (± 5% Watt) **Hz** **Measurement range:** 0 … 3500 Hz **Accuracy:** ± 1 Hz **Phase angle** **Measurement range:** -360º ... +360º **Accuracy:** ± n × 1.5º
Power and energy	**Watt, VA, VAR** **Measurement range:** 1.0 … 20.00 MVA[1] **Accuracy:** ±1% ± counts **kWh, kVAh, kVARh** **Measurement range:** 00.00 …200.0 GVAh[1]

	Accuracy: ± 1.5% ± 10 counts **Power Factor/ Cos Φ / DPF** **Measurement range:** 0…1 **Accuracy:** ± 0.03
Flicker	**Pst (1 min), Pst, Plt, PF5** **Measurement range:** 0.00 … 20.00 **Accuracy:** ±5%
Unbalance	**Volts** **Measurement range:** 0.0 … 5.0% **Accuracy:** ±0.5% **Current** **Measurement range:** 0.0 … 20% **Accuracy:** ± 1%
Transient Capture	**Volts** **Measurement range:** ±6000 V **Accuracy:** ±2.5% of Vrms **Minimum detect duration** 5 µs (200kS/s sampling)
Inrush mode	**Arms (AC+DC)** **Measurement range:** 0.000 … 20.00 kA[1] **Accuracy:** ±1% of meas ± 5 counts **Inrush duration (selectable)** **Measurement range:** 7.5 s ... 30 min **Accuracy:** ±20 ms (Fnom = 50 Hz)
Autotrend recording	**Sampling:** 5 readings/sec continuous sampling per channel **Memory:** 1800 min, max and avg points for each reading **Recording time:** Up to 450 days **Zoom:** Up to 12x horizontal zoom
Memory	**Screens & data:** 50, shared memory divided between logging, screens and data sets
Notes	[1] Depending on clamp scaling □[2]Value is measured over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle

Environmental Specifications	
Operating Temperature	0 ºC to +50 ºC

Safety Specifications	
Safety	EN61010-1 (2nd edition) pollution degree 2; 1000 V CAT III / 600 V CAT IV ANSI/ISA S82.01

Mechanical & General Specifications	
Size	256 x 169 x 64 mm
Weight	2 kg
Battery Life	**Rechargeable NiMH pack (installed):** >7 hours **Battery charging time:** 4 hours typical
Shock & Vibration	**Shock:** 30 g **Vibration:** 3 g according to MIL-PRF-28800F Class 2
Case	Rugged, shock proof with integrated protective holster, IP51 (drip and dust proof)
Warranty	3 years