STUDY ON CHARACTERISTICS OF TRIPLEN HARMONICS PRODUCED BY SYNCHRONOUS GENERATOR FLOWING THROUGH TRANSFORMER UNDER VARIOUS LOAD CONDITIONS

AMNINA BINTI KAMALUDIN

A dissertation submitted to the
Electrical & Electronic Engineering Programme
Universiti Teknologi PETRONAS
In partial fulfillment of the requirement
For the BACHELOR OF ENGINEERING (Hons)
(ELECTRICAL & ELECTRONIC ENGINEERING)

SEPTEMBER 2011

Supervisor : Ir. Mohd Faris Abdullah

Universiti Teknologi PETRONAS

Bandar Seri Iskandar, 31750 Tronoh, Perak

CERTIFICATION OF APPROVAL

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Approved by,

(Ir. Mohd Faris Abdullah)

Universiti Teknologi PETRONAS

Tronoh, Perak

SEPTEMBER 2011

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.

AMNINA BINTI KAMALUDIN

ABSTRACT

The existence of triplen harmonics in equipments has been recognized dated back in the 19^{th} century. Even though many discovery has been made regarding the behaviour of triplen harmonics in electrical equipments, 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 variety 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 varies in different resistance and inductance connections in a circuit. The study also covers the PSCAD modeling software. The results obtained from PSCAD modeling can be analyzed and also compare with the laboratory experiments that have been conducted. The results and findings from the lab experiments and PSCAD modeling are to be discussed and thus, able to come up with an appropriate conclusion in the characteristics of triplen harmonics produced by synchronous generator flowing through various transformer winding configurations under various load conditions. In conclusion, this study provides a very important knowledge of triplen harmonics current propagation through transformer.

ACKNOWLEDGEMENT

First and foremost, I would like to express my praises and gratitude to God the Almighty for His blessing upon my well-being and health for the last 22 years.

I would like to gratefully and sincerely thank my supervisor, Ir. Mohd Faris Abdullah for his guidance, understanding, patience, and most importantly, his mentorship during my final year project at Universiti Teknologi PETRONAS. His mentorship was paramount in providing a well rounded experience consistent my long-term career goals. He encouraged me to not only grow as an experimentalist and an engineer but also as an independent thinker. I am not sure many graduate students are given the opportunity to develop their own individuality and self-sufficiency by being allowed to work with such independence. For everything you've done for me, Ir. Mohd Faris Abdullah, I thank you.

I would also like to thank all of the lecturers and staffs of the Electrical & Electronic Engineering Department, for the guidance and consideration throughout my studies here. 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.

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Finally, and most importantly, I would like to thank my parents, Dr. Kamaludin and Mrs Rosemahwati. Their support, encouragement, quiet patience and unwavering love were undeniably the bedrock upon which the past 22 years of my life have been built. Mum, Dad, for your consistent faith in me and allowing me to be as ambitious as I wanted made me as who I am today. It was under their watchful eye that I gained so much drive and an ability to tackle challenges head on.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Universiti Teknologi PETRONAS (UTP) with the area of 4 square kilometers (990 acres) supplies its own electricity throughout campus. The electricity is supplied by two generating units at the gas district cooling (GDC) plant located inside campus. UTP power system usually operates in island mode during normal operation. However, in times of emergency (when load increases) the power system of UTP will be connected in parallel to the utility grid of TNB (Tenaga Nasional Berhad) as shown in Figure 1 [1]. One of the recent study revealed that on both condition of island mode and parallel operation, triplen harmonics propagates through neutral earthing resistor (NER) on each generation units resulting in the increase of temperature especially in parallel condition [2].

Therefore, the problem that is faced by many power system units is the occurrence of triplen harmonics in the distribution system. With the increase of temperature as one of the effects of triplen harmonics current propagation, it clearly shows that more disadvantage are noticeable and with that, studies need to be conducted as to learn the behaviour of triplen harmonics produced by synchronous generator flowing through transformer under various load conditions.

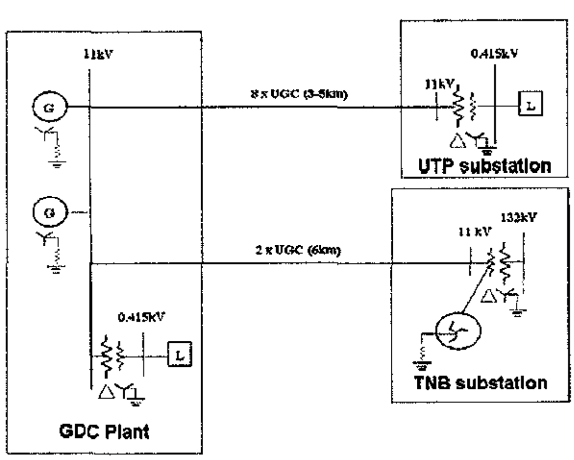


Figure 1: Simplified UTP medium voltage network

1.2 Problem Statement

Synchronous generator produces triplen harmonics that increases the temperature. In addition, propagation of triplen harmonics flowing through transformer will be affected by different transformer winding configuration.

1.3 Objective of Study

The objective of this paper is to study the characteristics of triplen harmonics produced by synchronous generator (single synchronous generator, synchronous generator parallel with the grid system) flowing through various transformer winding configurations (delta-star, delta-delta, star-delta, star-star) under various balanced and unbalanced load conditions (resistive and inductive).

1.4 Scope of Study

The scope of this study mainly focuses on the laboratory experiments using a lab-scaled synchronous generator to study and understand the behaviour of triplen harmonics produced by the generator flowing through various transformer winding configurations under various load conditions. PSCAD simulation will also be conducted to further analyse and understand the behavior of triplen harmonics currents in corresponds to the achieved lab results. Based on this modeling using PSCAD, the author can analyse and predict the voltage and current waveforms for each different transformer winding configurations and also able to further study on the phasor diagram and the harmonics reading that exists during different cases and conditions.

1.5 Relevance of the Project

Triplen harmonics study for harmonics produced by synchronous generator is very important because their presence have caused communication line interference, damage to neutral earthing resistor and heats up the conductors. This heating effect causes neutral and phase conductors to heat up to critical flash over temperatures, and premature failure of motors and transformers. This is costly in terms of down-time, loss of production, repair, and possible reconstruction. Thus to avoid all the occurrence problems, the characteristics of triplen harmonics needs to be researched and studied upon.

1.6 Project Feasibility

The project is planned and scheduled to be done within 2 semesters. The approach that the author planned to use is by running lab experiments and PSCAD simulation to compare, examine and analyse the characteristics of triplen harmonics produced by synchronous generator flowing through transformers under various load conditions. The investigation will revolve on the effects of triplen harmonics towards different transformer winding configurations. Comparison between the different transformer winding configurations will also be made.

CHAPTER 2

LITERATURE REVIEW

2.1 Definition of Triplen Harmonics

Harmonics is defined as the steady state distortion of the fundamental frequency and in Malaysia is 50 Hertz (Hz). It is stated that, when sinusoidal voltage flows through a non-linear load, harmonic currents is being distorted. Meanwhile, voltage is distorted when harmonic currents flow through a distribution system. In a distribution system, the harmonic currents that are widely found are odd-order harmonics (3^{rd}, 5^{th},7^{th}, etc.) and even-order harmonics are not considered since the positive and negative sequence are cancelled out.

Triplen harmonics is the odd multiples of third harmonics (3^{rd}, 9^{th}, 15^{th}, and etc.) and it is a zero sequence harmonics. The magnitude of triplen harmonics currents on a three phase system adds up at the neutral resulting in a very large current circulating that causes an increase in temperature [2].

Transformers in a power system are usually configured as a delta-wye connection because it reduces the triplen harmonics at the secondary side by trapping triplen harmonics at the delta primary side.

2.2 Harmonic Analysis by Mathematics

Harmonics are derived from a mathematical model technique that analyzes currents and voltages in a power system. Distorted waveforms are discussed in terms of harmonic components in a frequency spectrum that can be shown in a mathematical equation. The equation describing a harmonic frequency with the fundamental frequency of 50 Hz in Malaysia can be stated as,

$$f_h = h \times 50\ Hz$$

Where; h is the harmonic order.

Fourier analysis can also be used as the mathematical equation to discuss the harmonic analysis in electrical power system, such that to expand the voltage or current waveform from the frequency component and sum it up with the harmonic components. The Fourier Series is given by,

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

Where; a_o is the dc component

V_h is the peak voltage level

f is the fundamental frequency of 50 Hz

t is the running time

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 [3].

The total harmonic distortion (THD) of a signal is the ratio of the sum of the powers of all harmonic frequencies above the fundamental frequency to the power of the fundamental frequency. The THD is usually expressed in dB 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 terms 2..N are the power levels of the harmonics and term 1 is the power level of the fundamental (the pure tone).

2.3 Triplen Harmonics Current Problem in Three Phase System

Basically, in a three phase system, the equation for neutral current in a power system is the vector sum of the three phase currents.

In a balanced three phase system, the linear current that consists of sinusoidal waves is spaced 120 electrical degrees apart. The summation of the currents at an instant time is zero thus no neutral current exists. However, in some cases when three phase system supplies single-phase loads, it results in an imbalance of the phase current and neutral current. 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 [4].

2.4 Harmonics Produced by Salient Pole Synchronous Generator

By definition, synchronous machine is an ac rotating machine of speed under steady state condition that is proportional to the frequency of current. Synchronous machines are usually used as generators for large power systems. Past studies state that synchronous generator produce triplen harmonics based on the winding such as pitch and distribution factor, and slot skew [5]. At no load condition, salient pole synchronous generator also caused third harmonic voltage [6].

2.5 Interconnection Transformer Winding Configurations

There are four possible different transformer winding configurations in an electrical power system. First configuration that will be discussed is star to star connection. The advantages of such configuration are, more economical than other configurations, better economic fusing than delta connected primary winding, and no phase voltages [7]. On the other hand, the disadvantages are; the distributed generation witness the same imbalance phase as the utility, secondly, in terms of harmonics, 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.

Second transformer winding configuration is the delta to star connection. One of the advantage, is the triplen harmonics from the delta primary side does not reach the secondary side due to delta connection that traps the harmonics. Meanwhile, the disadvantage is the third harmonic current at the delta primary side may cause excessive current flow resulting in high temperature.

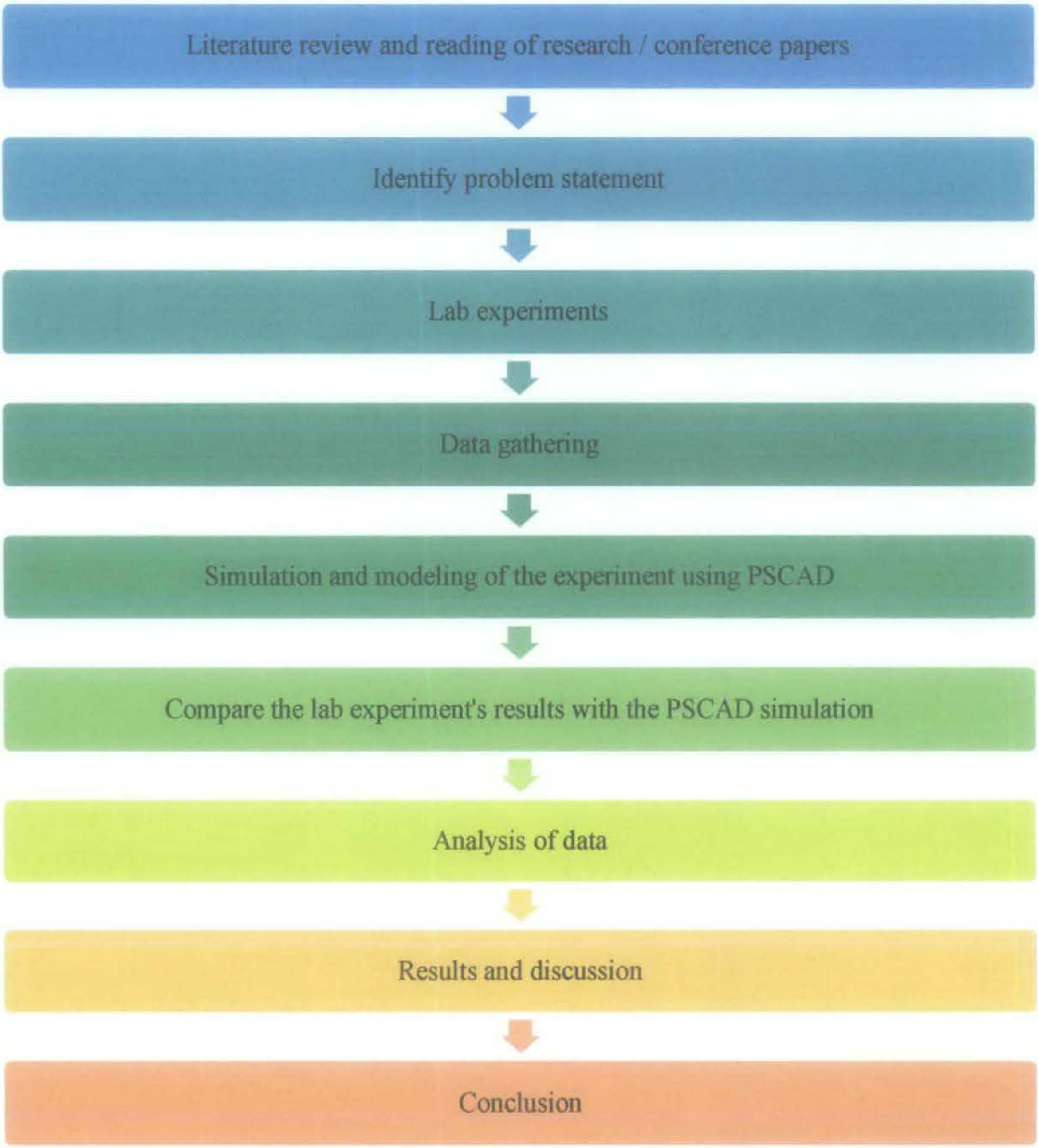
Thirdly, is the star to delta transformer winding configuration. The advantage of this connection is, the delta on the secondary side blocks triplen harmonics that produced by the synchronous generator and result in no flow at the utility side. However, the disadvantage of this connection is triplen harmonic currents that exist in the primary side tend to contribute to transformer heating that could lead to equipment failure.

Lastly is the delta to delta transformer winding configuration. The advantage of using this connection is that it can be adjusted to large unbalanced load, and it is used to suppress harmonics by damping the third harmonic currents within the closed delta. The disadvantage of delta to delta connection could lead to overvoltage and overcurrent resulting in equipment failure.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology



3.2 Project Activities

Literature Review

- Research on triplen harmonics on the web, research and conference papers.
- To fully understand the project title.
- Seek supervisors help and guidance to understand the theory and basics of triplen harmonics and those that are related to it.

Lab Experiments

- Conduct lab experiments on synchronous generator flowing through transformer under various load conditions.
- Observe and note down the results.
- Using a Fluke (PQ meter) to perform three-phase measurements.

PSCAD Simulation

- Simulate the synchronous generator flowing through transformer under the specific details using the lab experiment data.
- Analyze the voltage and currents waveforms, the phasor diagrams and also the harmonics.

3.3 Key Milestone

- FYP1

Week 6

- Submission of Extended Proposal Defense

Week 13

- Submission of Interim Draft Report

Week 14

- Submission of Interim Report

- FYP2

- Week 8: Submission of Progress Report
- Week 11: Pre-EDX
- Week 12: Submission of Draft Report
- Week 13: Submission of Dissertation (soft bound)
- Week 13: Submission of Technical Paper
- Week 14: Oral Presentation
- Week 15: Submission of Project Dissertation (hard bound)

3.4 Gantt Chart

Timeline for FYP1

Table 1: Timeline for FYP1

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	■	■						Mid-semester break							
2	Preliminary Research Work		■	■	■	■										
3	Submission of Extended Proposal Defence						●									
4	Proposal Defence									■	■					
5	Project work continues											■	■	■		
6	Submission of Interim Draft Report														●	
10	Submission of Interim Report															●

● Suggested milestone

■ Process

Timeline for FYP2

Table 2: Timeline for FYP2

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

● Suggested milestone

■ Process

3.5 Tools and Equipments Required

The tools, software and hardware required to undergo this project are:

Software

- PSCAD software
- FlukeView
- Microsoft Excel
- Microsoft Word
- Microsoft PowerPoint

Hardware

- Synchronous generator
- DC Motor
- Transformers
- Power supply
- Resistive loads
- Inductive loads

Tools

- Fluke power meter
- Digital multimeter

More detailed list of equipments is attached at the APPENDIX A.

Table 3: Laboratory equipment ratings

Equipment	Ratings
Generator	415 V; 2 A; 2 kW
Transformer	415 V / 240 V; 250 VA
Resistive load	240 V; 252 W
Inductive load	240 V; 252 Var

Table 4: Measurement resistance test for three-phase synchronous generator

Resistance test at Generator	Resistance
Red	2.35 Ω
Yellow	2.38 Ω
Blue	2.37 Ω

The project can be divided into two experimental parts;

PART 1: Single Generator Operation

PART 2: Generator Parallel with Grid Operation

There are four transformer winding configurations that the author has studied and analysed. The configurations are;

- Delta-Star (DS)
- Star-Delta (SD)
- Delta-Delta (DD)
- Star-Star (SS)

PART 1: Single Generator Operation (Generator flowing through transformers into load)

At the same time, the author researched on the effects of different transformer winding configurations flowing through resistive loads. The author carried out the experiments using six different resistive load values and there are;

- No load condition (R = ∞ Ω)
- 120 Ohm (R = 120 Ω)
- 160 Ohm (R = 160 Ω)
- 240 Ohm (R = 240 Ω)
- 320 Ohm (R = 320 Ω)
- 480 Ohm (R = 480 Ω)

Since, there are many data values that are available; the author will only discuss the no-load condition and 120 Ohm (R = 120 Ω) load. The rest of the resistive load values (160 Ω, 240 Ω, 320 Ω, and 480 Ω) will be at the **APPENDIX B**.

Apart from that, the author also analysed on the effects of generator flowing through Delta-Star transformer into inductive loads. The inductive loads experiments that have been conducted are;

- No load condition
- 0.38 H

- 0.51 H
- 0.76 H

The author will only discuss no load condition and 0.38 H, while the other two inductive loads (0.51 H and 0.76 H) will be attached at the **APPENDIX C**.

PART 2: Generator Parallel with Grid (Generator parallel with grid flowing through transformers into load)

In addition to that, the author has conducted the experiment on generator parallel with the grid network flowing through Delta-Star transformers into load (resistive and inductive).

The resistive loads that were conducted are;

- No load condition
- 120 Ohm at 0.3 A
- 120 Ohm at 1.5 A

Meanwhile, the inductive loads are;

- No load condition
- 0.38 H
- 0.51 H
- 0.76 H
- 1.02 H
- 1.53 H

The author will only discuss the no load condition and 0.38 H, while the rest of the results of the inductive loads (0.51 H, 0.76 H, 1.02 H, and 1.53 H) will be available in **APPENDIX D.**

PSCAD Simulations

PSCAD Simulations will only be discussed on PART 1: Generator Alone experimental results because PSCAD are not able to simulate the condition when generators behave in a parallel operation. Yet computer simulation has become an effective method because of its small quantity of invest, short development cycle and convenient operation, especially in harmonic investigation field.

Before executing the simulation of the experiment, the author needed to find the best voltage source model that resembles a lot like the real laboratory experiments. After a lot of testing and verification of data, the author decided that the best voltage source model is **Inductive Source.**

The author only verified the PART 1: Single Generator Operation; covers the resistive and inductive load with the PSCAD Simulation. This is because PART 2: Generator Parallel with Grid Operation cannot be simulated due to constraints and PSCAD Software is not suitable for the condition.

The PSCAD Software Student Version only allows having limited nodes of measuring points. Thus, that is the reason why PSCAD Simulation only shows certain voltage and current points to be compared with the laboratory experiments.

CHAPTER 4

EXPERIMENTAL RESULTS & DISCUSSIONS

4.1 PART 1: Single Generator Operation

4.1.1 Resistive Load

4.1.1.1 Delta-Star Transformer Winding Configuration

4.1.1.1.1 No Load Condition ($R = \infty\ \Omega$)

For every experiment executed, the author conducts a comparison between two different values. For these experimental studies, the author compares the fundamental frequency (50 Hz) with the third harmonics frequency (150 Hz) to observe any changes. This comparison between 50 Hz and 150 Hz applies to all cases.

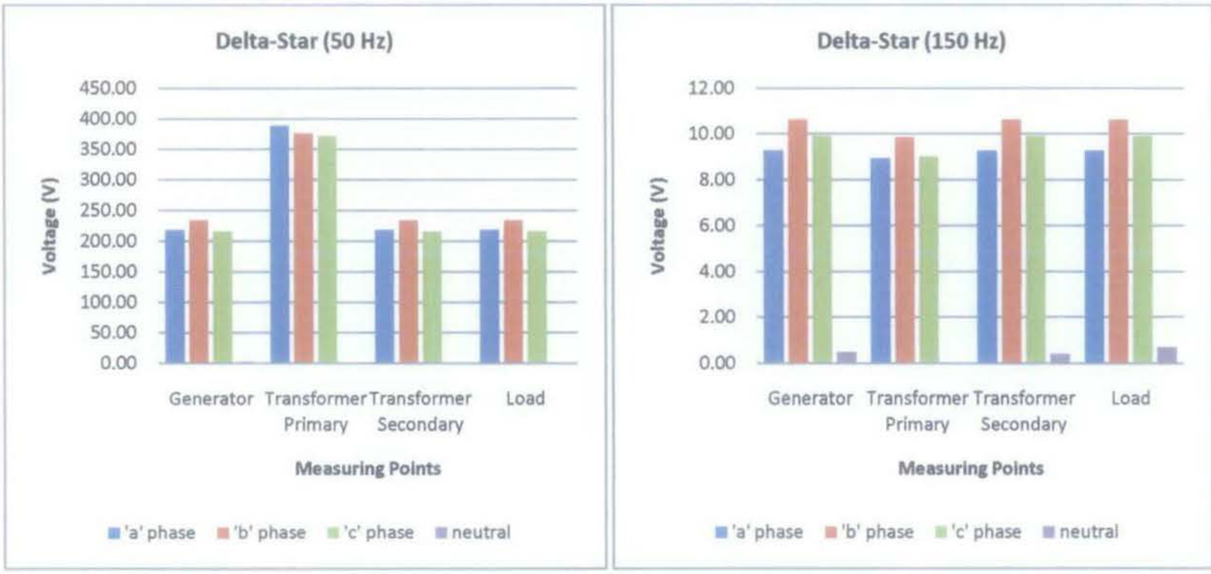


Figure 2: Graphs of voltage on delta to star transformer without load

At no-load condition, it can be observed that the voltage at the delta side for 50 Hz is higher than the other measuring points because the author uses delta-star 415V/240V rated transformer. However, at 150 Hz, the voltage is almost the same at all four measuring points with very small voltage around 9 to 11V with the decrement of 22 times compared to 50 Hz. No neutral voltage during no-load condition.

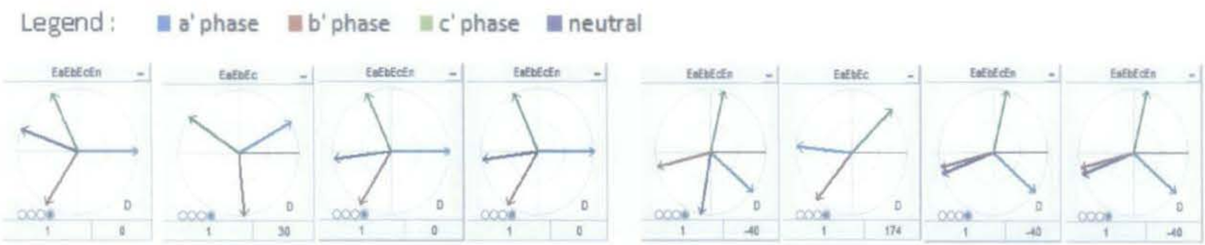


Figure 3: Phasor diagrams of voltage on delta to star transformer without load on four measuring points at 50 Hz and 150 Hz

The phasor diagrams above represent each measuring point (generator, delta-side, star-side, and load) for the voltage at 50 Hz and 150 Hz. Based on the phasor diagram above, the comparison between the voltage at 50 Hz and 150 Hz; it can be observed that the phasor angle acts in the positive sequence.

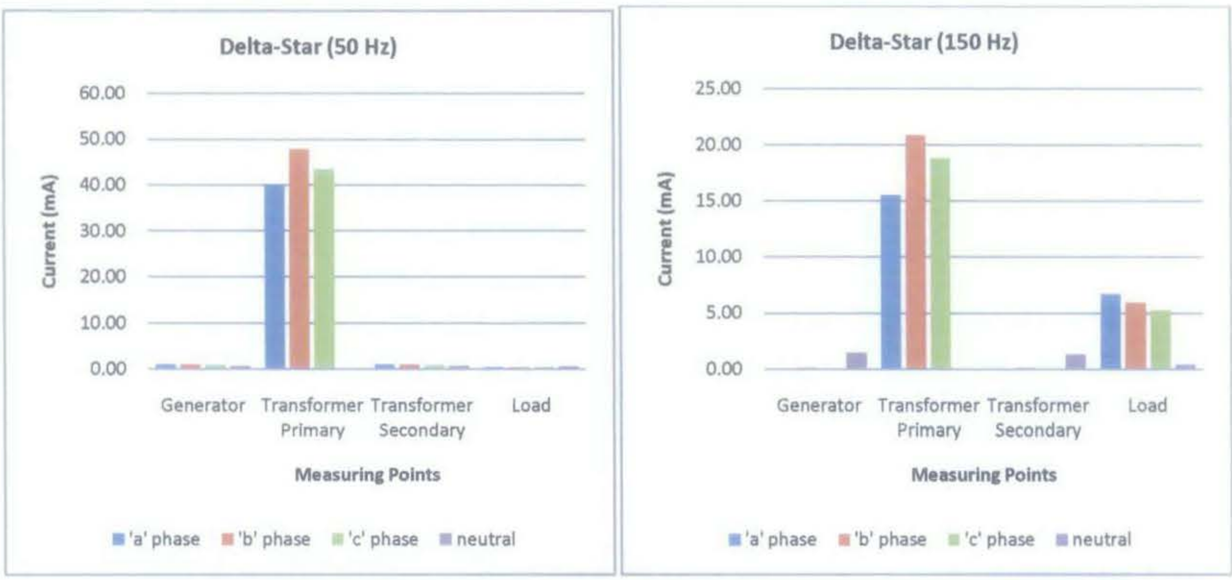


Figure 4: Graphs of current on delta to star transformer without load

For no-load condition, it can be measured that very small phase current (40 mA) exists at the delta-side at 50 Hz. While at 150 Hz, the current decreases with half the ratio compared to 50 Hz. And the current at the load side of 150 Hz can be neglected since it carries very small amount of current (5 mA). This is because triplen harmonics currents only exist when generator begins supply to load. Thus in can be said no current exists at no load condition.

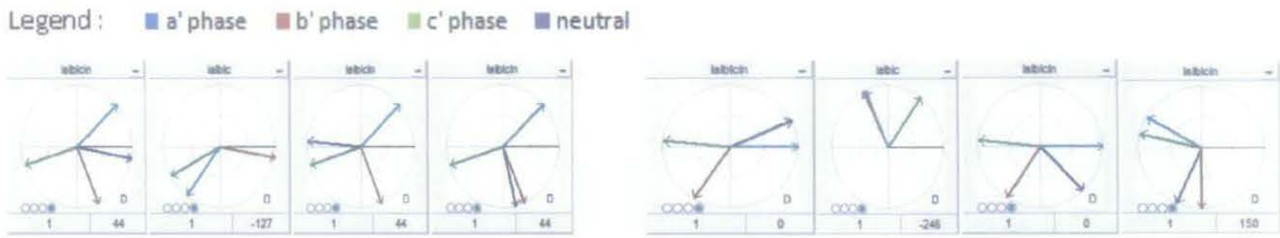


Figure 5: Phasor diagrams of current on delta to star transformer without load on four measuring points at 50 Hz and 150 Hz

For the current phasor diagrams, it can be said that they also act in the positive sequence.

4.1.1.1.2 120 Ohm (R = 120 Ω)

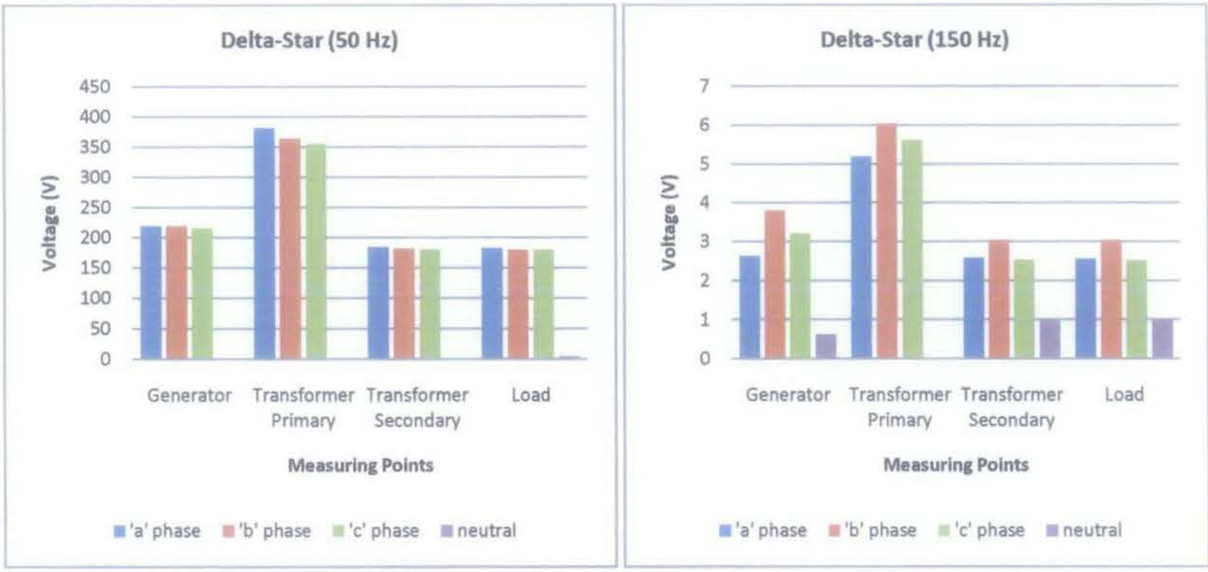


Figure 6: Graphs of voltage on delta to star transformer with load

For 120 Ohm load condition, it can be observed that the voltage at 50 Hz is as similar to the no-load condition. However, for third harmonics frequency (150 Hz) it can be seen that the phases of the voltage waveform are slightly distorted. Also, the existence of neutral voltages also can be seen at the generator, star-winding, and load side.

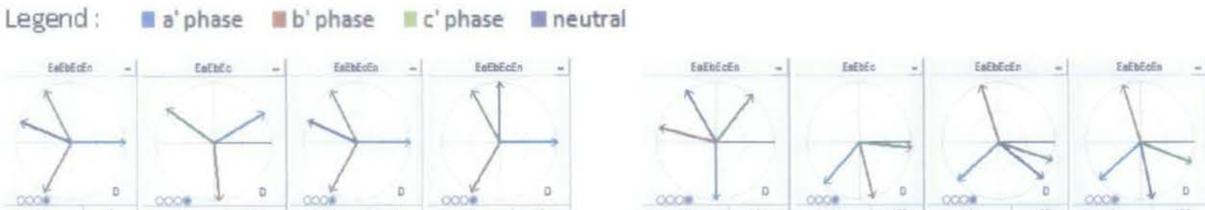


Figure 7: Phasor diagrams of voltage on delta to star transformer with load on four measuring points at 50 Hz and 150 Hz

The voltage phasor diagrams above shows that the phases are in a positive sequence, both for 50 Hz and 150 Hz on all four measuring points (generator, delta-winding, star-winding, and load side).

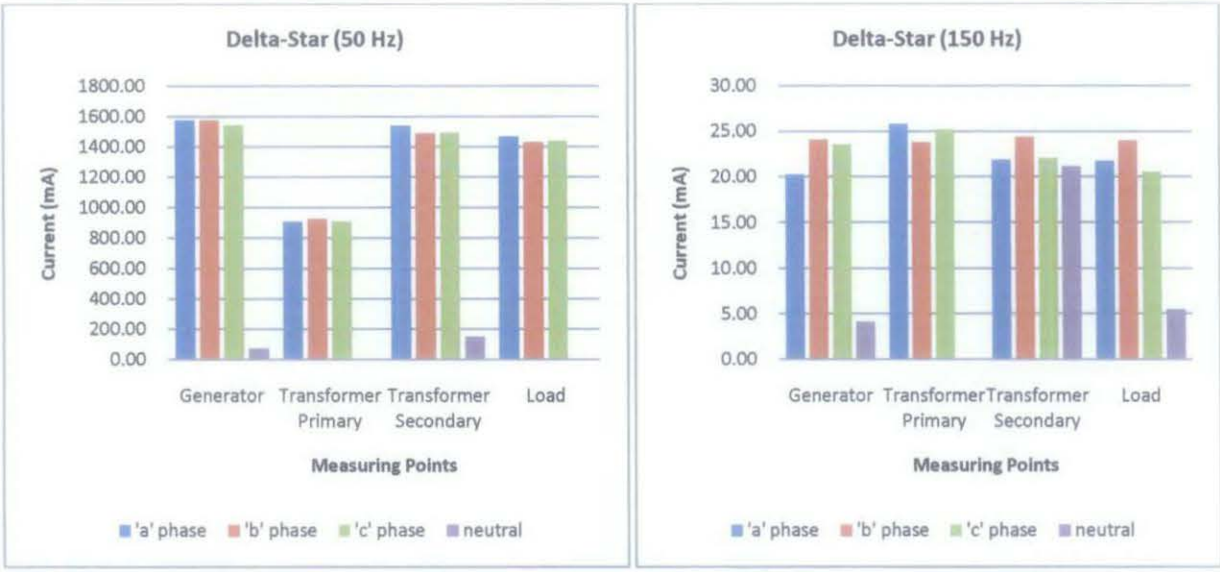


Figure 8: Graphs of current on delta to star transformer with load

For 120 Ohm load condition, the current at fundamental frequency (50 Hz) shows at delta-winding transformer the current is slightly smaller compared to other measuring points.

However, at 150 Hz, phase current on the delta side doesn't resemble as the fundamental frequency (50 Hz), whereby it increases and gives out the same current value as the other measuring points. A very small third harmonic neutral current flows in load due to slight transformer unbalance impedance as noticed in the magnitude and angle (Figure below).

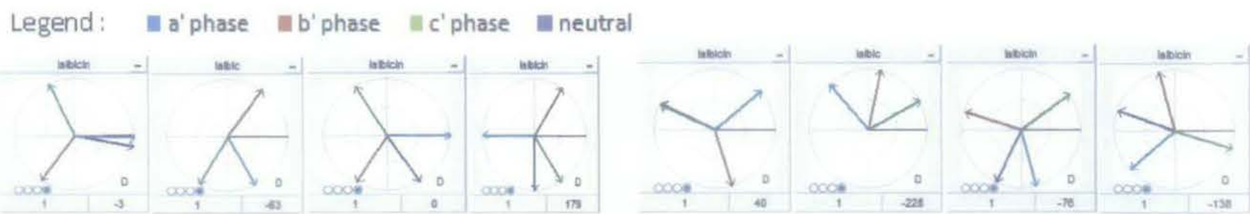


Figure 9: Phasor diagrams of current on delta to star transformer with load on four measuring points at 50 Hz and 150 Hz

The current phasor diagrams of 50 Hz and 150 Hz above shows that it acts in positive sequence for all measuring points.

4.1.1.1.3 PSCAD Simulation (Delta-Star)

A simulation is conducted to verify the lab experiments. By using the no-load voltage at 150 Hz value for the source model, the real experiment value at 150 Hz for synchronous generator flowing through delta-star transformer under 120 Ohm resistive load can be compared with the PSCAD Simulation.

The no-load voltage at generator for delta-star transformer winding configuration is:

Table 5: No-load voltage at generator

Generator	Voltage (V)	Phase Angle (°)
Red phase	9.28	-40.44
Yellow phase	10.64	-166.21
Blue phase	9.90	76.60

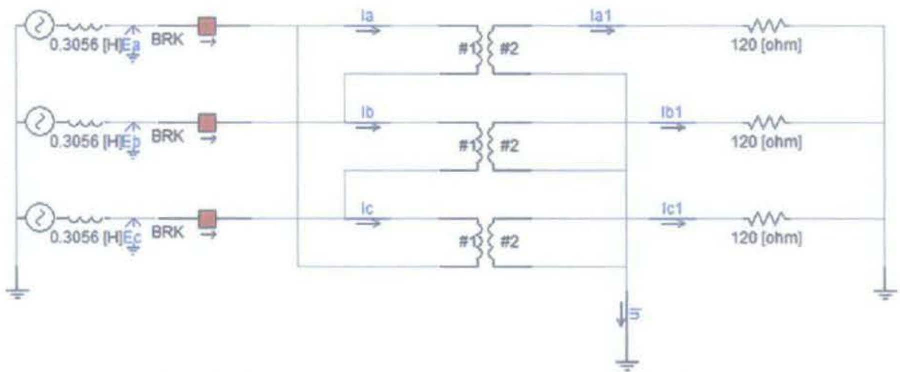


Figure 10: Model diagram of synchronous generator flowing to delta to star transformer with load

The measuring points during 150 Hz are at;

- Voltage at synchronous generator (Ea, Eb, Ec)
- Current at star-winding (Ia1, Ib1, Ic1)

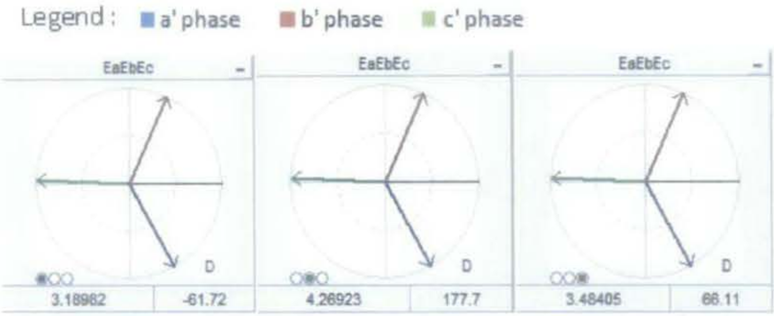


Figure 11: Phasor diagrams of voltage at red, yellow and blue phase at generator

Table 6: Comparison of voltage between lab results and PSCAD Simulation results for delta to star transformer

	Laboratory Results		**PSCAD Simulation Results**	
Generator	**Voltage (V)**	**Phase Angle (°)**	**Voltage (V)**	**Phase Angle (°)**
Red phase	2.64	-91.48	3.19	-61.72
Yellow phase	3.81	165.33	4.27	177.7
Blue phase	3.21	51.0	3.48	66.11

It can be observed the laboratory results with the PSCAD simulation results are almost the same with small increase by 21%. Thus in can be said the experimental results are verified by the simulation.

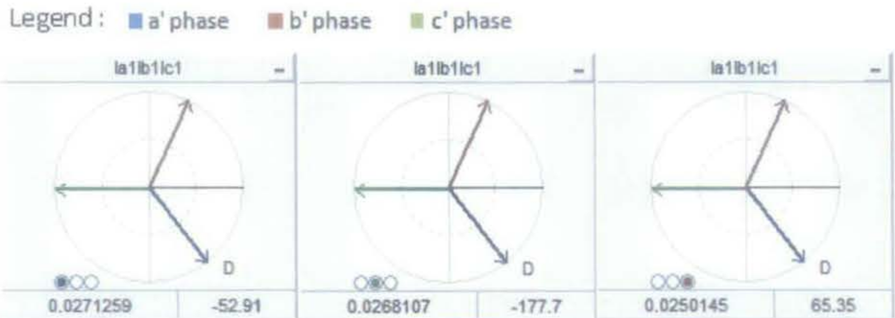


Figure 12: Phasor diagrams of current at red, yellow and blue phase at star-winding side

Table 7: Comparison of current between lab results and PSCAD Simulation results for delta to star transformer

	Laboratory Results		PSCAD Simulation Results	
Star-Winding	**Current (mA)**	**Phase Angle (°)**	**Current (mA)**	**Phase Angle (°)**
Red phase	21.89	-138.2	27.13	-52.91
Yellow phase	24.42	106.38	26.81	-177.7
Blue phase	22.08	-19.99	25.01	65.35

Same goes to the current at the star-winding side whereby the laboratory results are almost the same with the PSCAD simulations with only an increase of 24%.

4.1.1.2 Star-Delta Transformer Winding Configuration

4.1.1.2.1 No Load Condition ($R = \infty\ \Omega$)

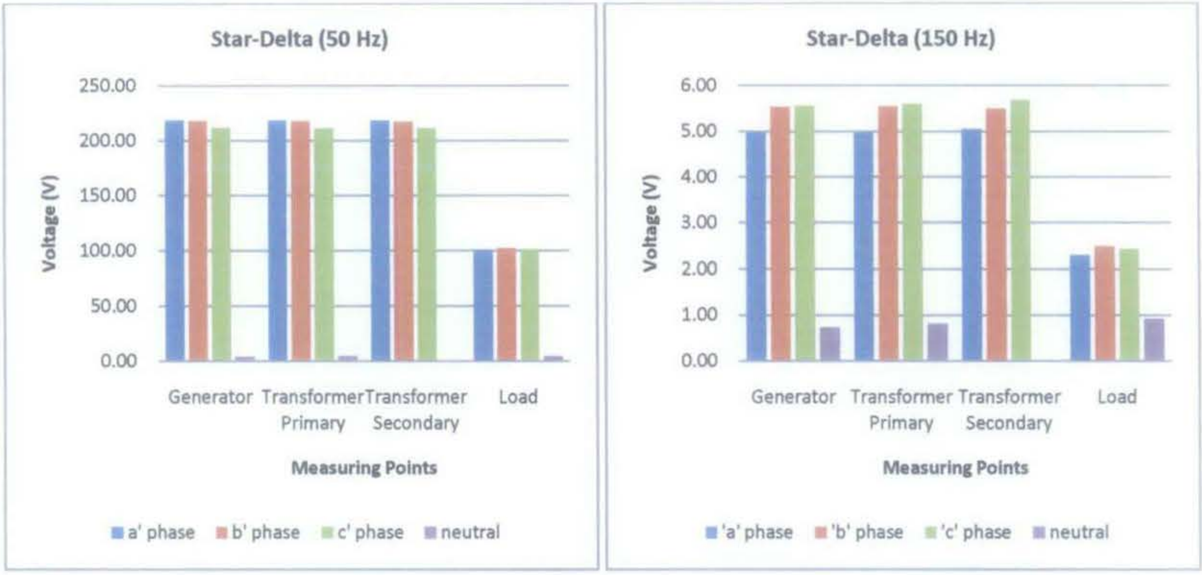


Figure 13: Graphs of voltage on star to delta transformer without load

Under no-load condition for star-delta winding 415V/240V rated transformer configuration, a steady-state voltage at generator, star and delta side during 50 Hz can be observed. Once reaches the load side, the load voltage decreases.

During 150 Hz, the voltage spectrum resembles much of the fundamental frequency with the neutral voltage becomes more visible.

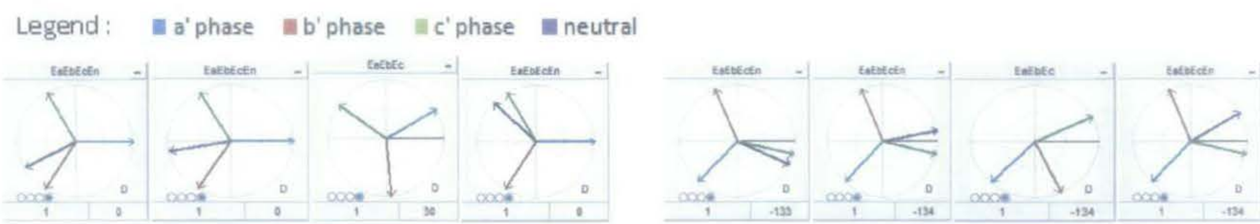


Figure 14: Phasor diagrams of voltage on star to delta transformer without load on four measuring points at 50 Hz and 150 Hz

The voltage phasor diagrams for 50 Hz and 150 Hz shows a positive sequence.

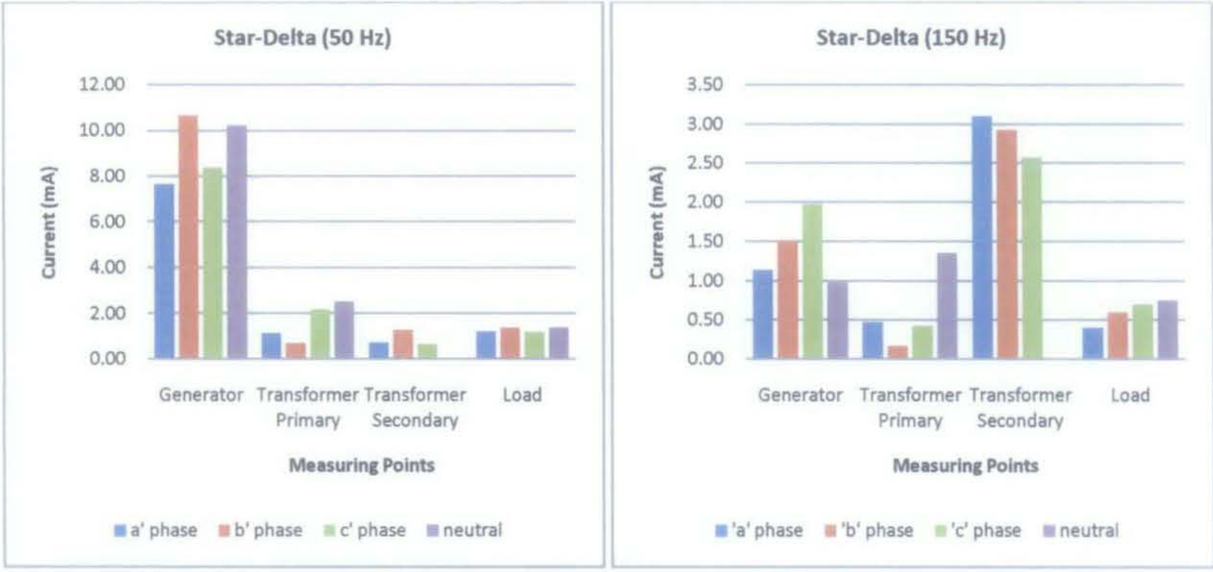


Figure 15: Graphs of current on star to delta transformer without load

No-load condition for current shows some imbalance current phases on every measuring points. At 50 Hz, the neutral current at the generator is equivalent to the phase current. Supposedly, at fundamental frequency, the neutral current should be low in value. But since the equipment error on the current clamp varies from 5 to 7 mA, so in other words the current at the generator side is equivalent to zero Ampere. Same case is applicable to the third harmonics frequency (150 Hz), whereby the current on all measuring points are equivalent to zero. The reason is triplen harmonics current only exists when generator begin to supply load.

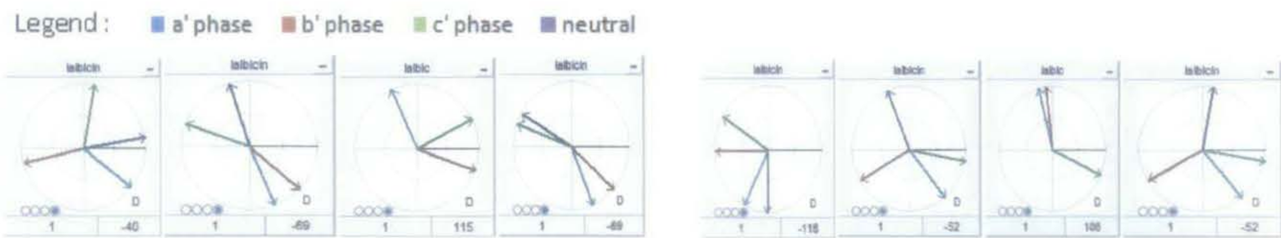


Figure 16: Phasor diagrams of current on star t delta transformer without load on four measuring points at 50 Hz and 150 Hz

The current phasor diagrams for both 50 Hz and 150 Hz also shows a positive sequence.

4.1.1.2.2 120 Ohm (R = 120 Ω)

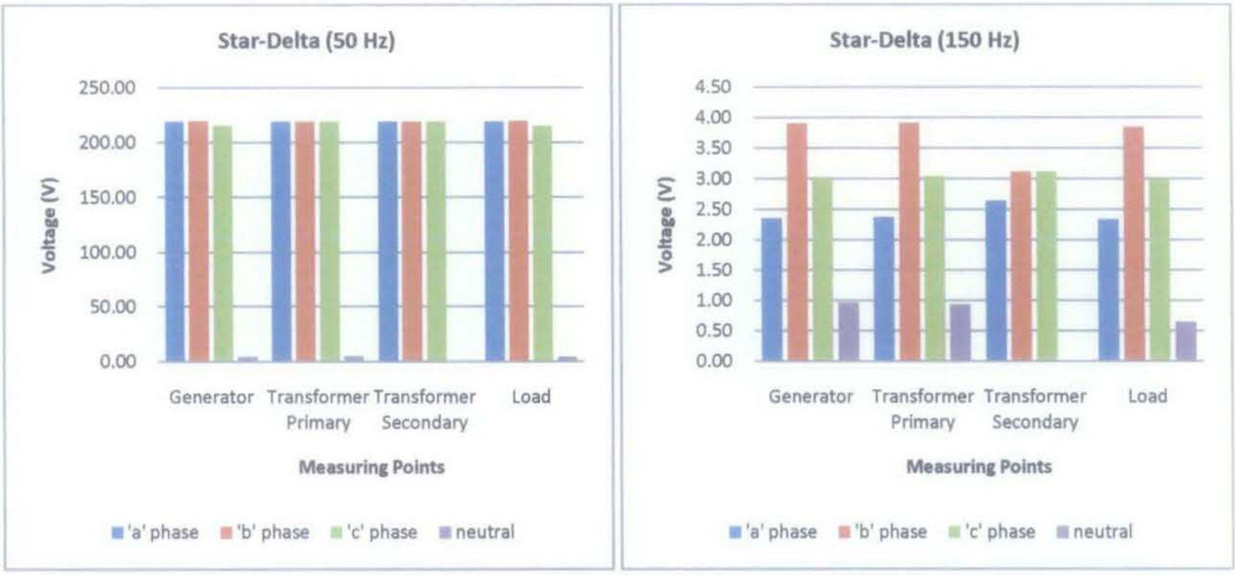


Figure 17: Graphs of voltage on star to delta transformer with load

The voltage at 50 Hz for all measuring points shows the expected value. However, at 150 Hz the voltage distorted at all four measuring points. This shows an imbalance voltage occurs at third harmonics frequency.

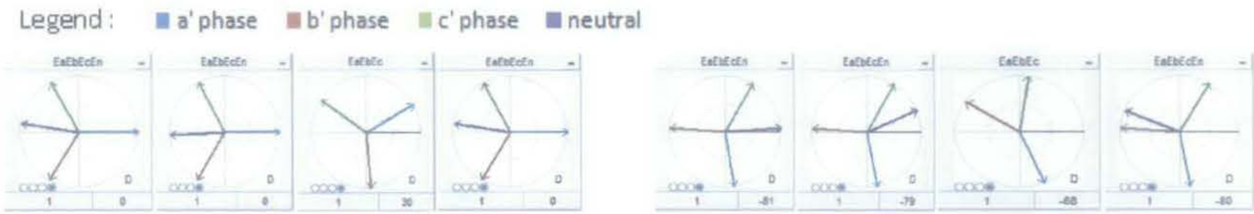


Figure 18: Phasor diagrams of voltage on star to delta transformer with load on four measuring points at 50 Hz and 150 Hz

The voltage phasor diagram for 50 Hz and 150 Hz at Star-Delta transformer winding configurations also shows a positive sequence.

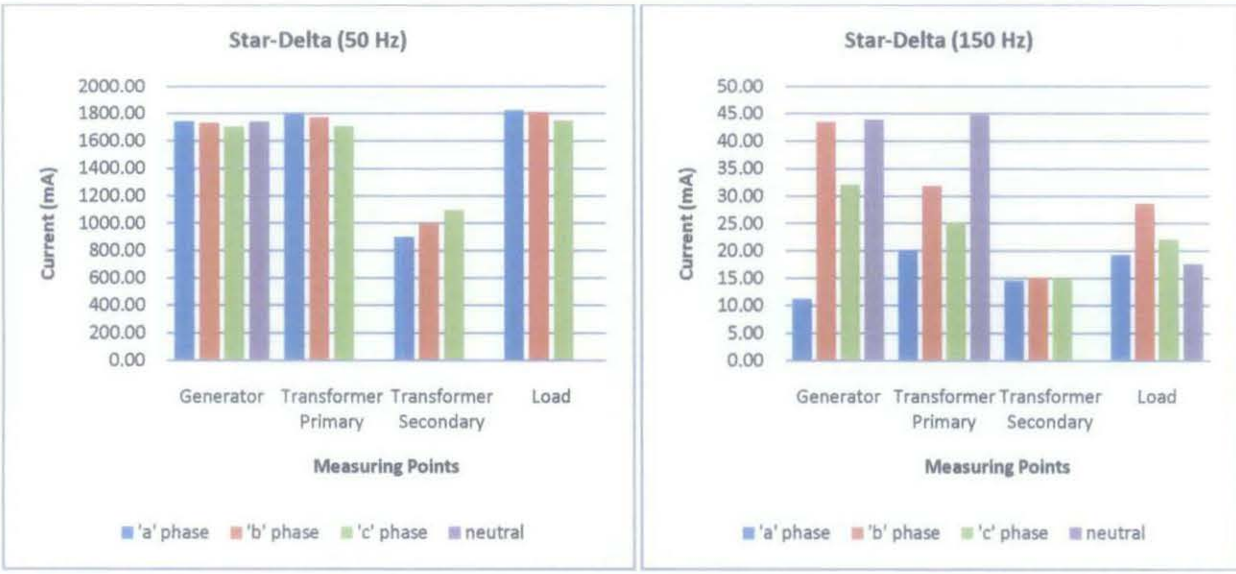


Figure 19: Graphs of current on star to delta transformer with load

The current at 50 Hz shows very high current around 1.7 Ampere, however small current flows at delta-side of the transformer. A very high neutral current can also be observed at the generator side.

However, at 150 Hz, the neutral current has the same magnitude as the phase current at the generator and star side because current carries the same value on a same line. Highest phase and neutral third harmonic currents can be observed.

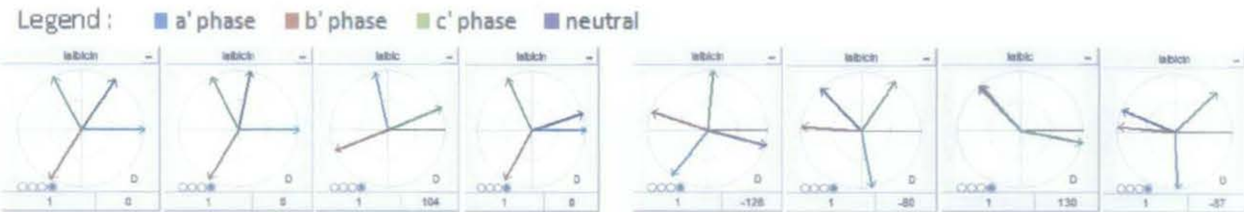


Figure 20: Phasor diagrams of current on star to delta transformer with load on four measuring points at 50 Hz and 150 Hz

A study states that star-primary winding gives lowest zero sequence impedance or a shunt path to neutral [11], but in this case it is obvious that all measuring points gives out positive sequence.

4.1.1.2.3 PSCAD Simulation (Star-Delta)

A simulation is conducted to verify the lab experiments. By using the no-load voltage at 150 Hz value for the source model, the real experiment value at 150 Hz for synchronous generator flowing through star-delta transformer under 120 Ohm resistive load can be compared with the PSCAD Simulation.

The no-load voltage at generator for star-delta transformer winding configuration is:

Table 8: No load voltage at generator

Generator	Voltage (V)	Phase Angle (°)
Red phase	4.99	-133.58
Yellow phase	5.54	112.17
Blue phase	5.56	-14.0

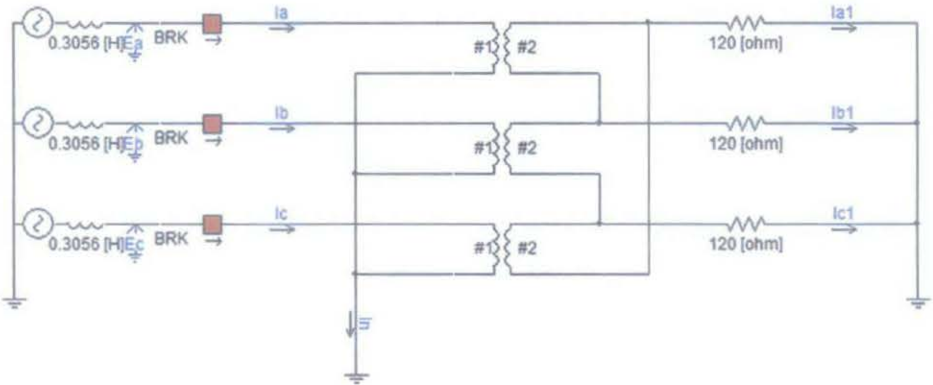


Figure 21: Model diagram of synchronous generator flowing to star to delta transformer with load

The measuring points during 150 Hz are at;

- Voltage at synchronous generator (Ea, Eb, Ec)
- Current at load side (Ia1, Ib1, Ic1)

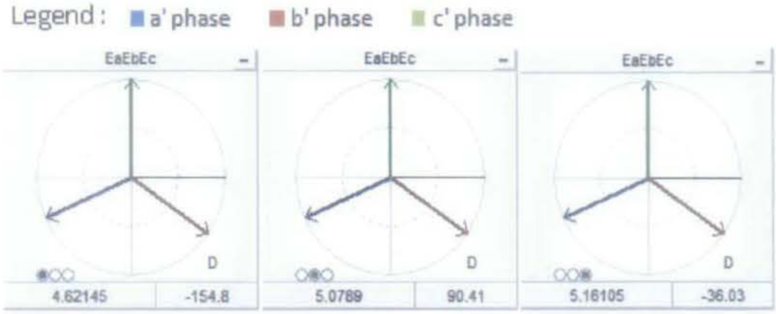


Figure 22: Phasor diagrams of voltage at red, yellow and blue phase at generator

Table 9: Comparison of voltage between lab results and PSCAD Simulation results for star to delta transformer

	Laboratory Results		**PSCAD Simulation Results**	
Generator	**Voltage (V)**	**Phase Angle (°)**	**Voltage (V)**	**Phase Angle (°)**
Red phase	2.35	-81.04	4.62	-154.8
Yellow phase	3.91	176.46	5.08	90.41
Blue phase	3.02	60.14	5.16	-36.03

In comparison, a laboratory result with the PSCAD simulation for the generator voltage side increases by 97%.

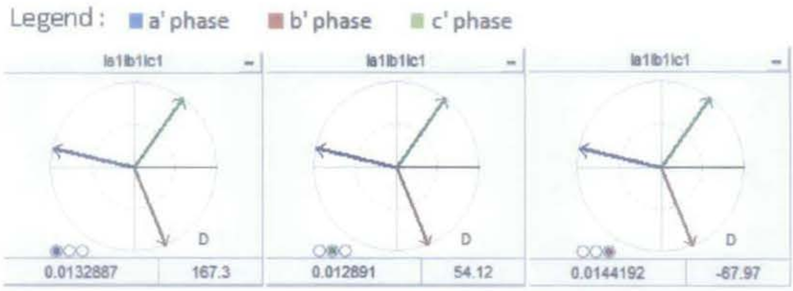


Figure 23: Phasor diagrams of current at red, yellow, and blue phase at load side

Table 10: Comparison of current between lab results and PSCAD Simulation results

	Laboratory Results		**PSCAD Simulation Results**	
Load Side	**Current (mA)**	**Phase Angle (°)**	**Current (mA)**	**Phase Angle (°)**
Red phase	19.30	-87.61	13.29	167.3
Yellow phase	28.73	175.44	12.89	54.12
Blue phase	22.11	43.72	14.42	-67.97

The current at the load side for lab results compare with the PSCAD simulation results decreases by 31%.

4.1.1.3 Delta-Delta Transformer Winding Configuration

4.1.1.3.1 No Load Condition (R = ∞ Ω)

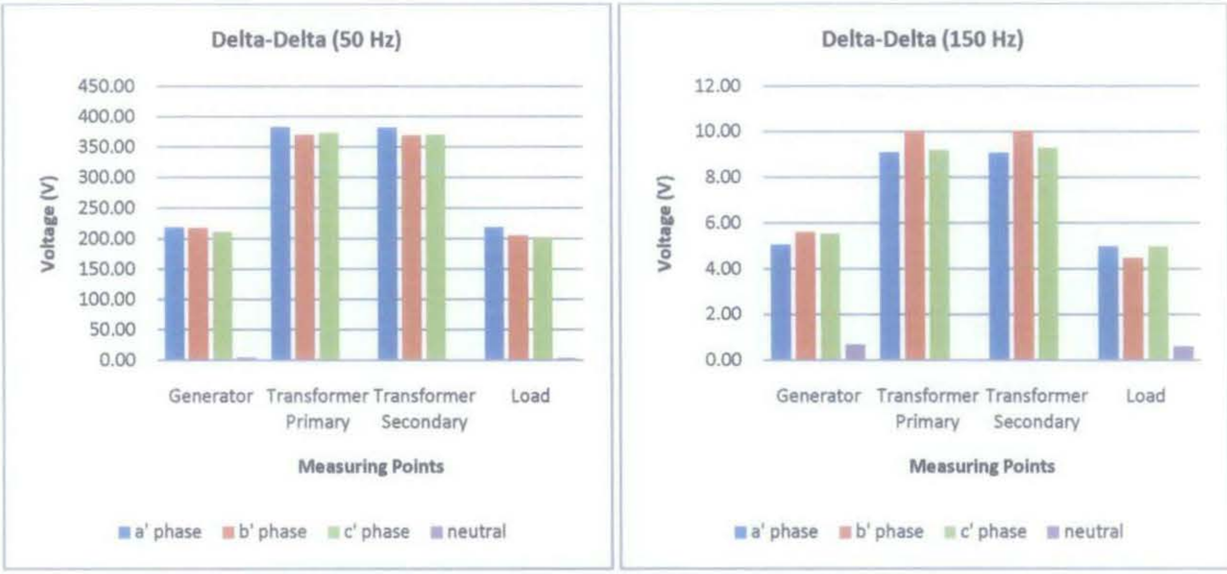


Figure 24: Graphs of voltage on delta to delta transformer without load

No-load condition, for both 50 Hz and 150 Hz, the voltage at delta primary and delta secondary is higher than the generator because the transformer used is 415V/415V rated voltage.

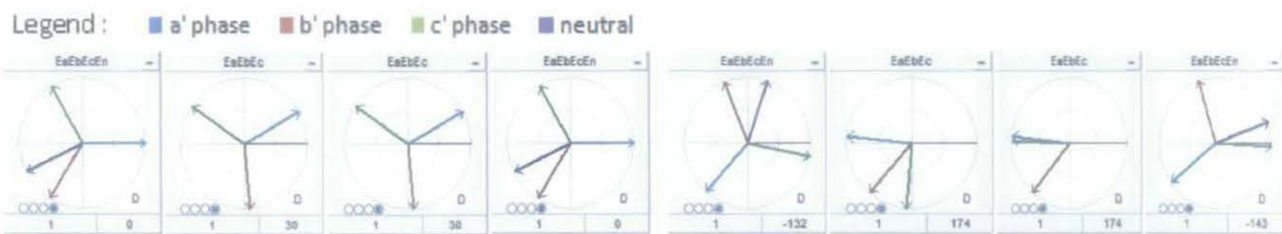


Figure 25: Phasor diagrams of voltage on delta to delta transformer without load on four measuring points at 50 Hz and 150 Hz

The voltage phasor diagrams also position in a positive sequence.

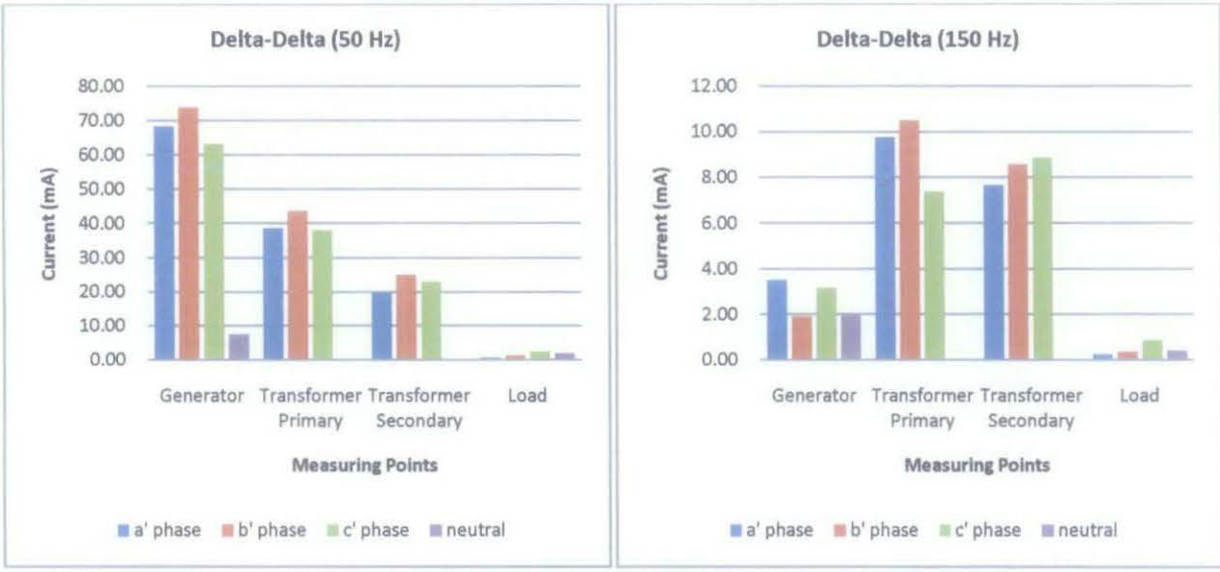


Figure 26: Graphs of current on delta to delta transformer without load

The current at the no-load condition for 50 Hz, shows that high current exists at generator and the current decreases once it enters into delta primary winding and delta secondary side into the load.

However, different case happened to the current spectrum at 150 Hz. The current increases once enter the delta primary side and remain constant at the delta secondary side and decreases to zero at the load side.

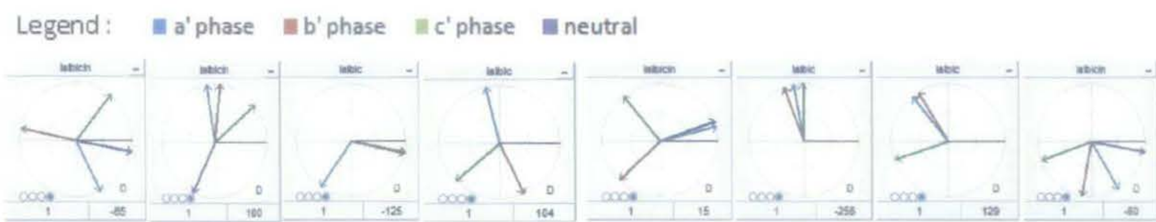


Figure 27: Phasor diagrams of current on delta to delta transformer without load on four measuring points at 50 Hz and 150 Hz

The phasor angle for delta primary side at 50 Hz and 150 Hz acts as a zero sequence. While the other measuring points shows a positive sequence set of currents.

4.1.1.3.2 120 Ohm (R = 120 Ω)

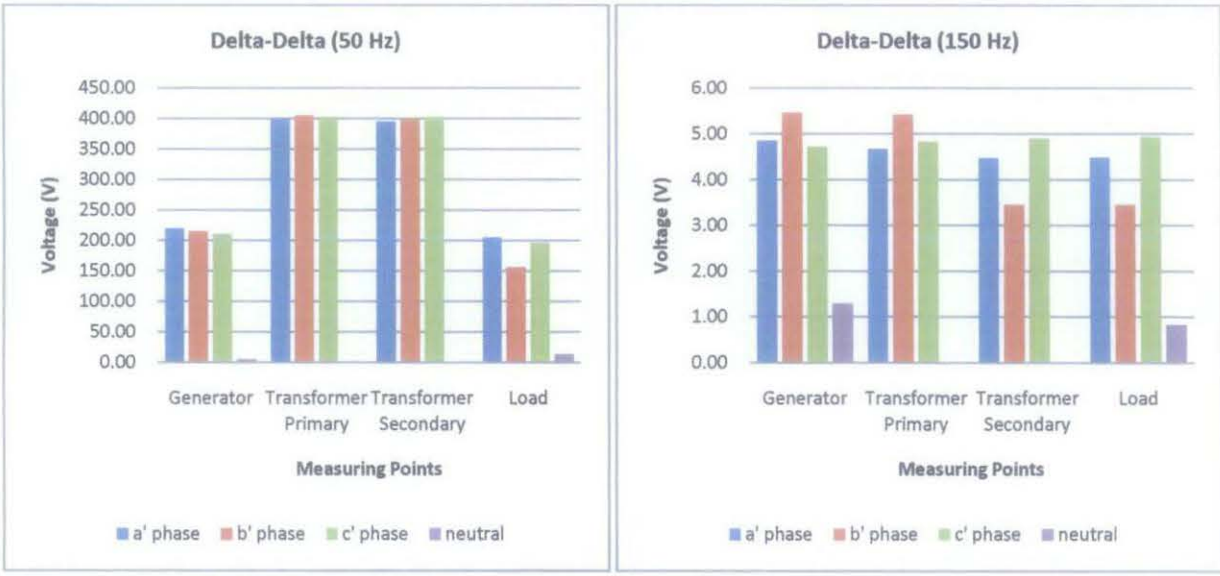


Figure 28: Graphs of voltage on delta to delta transformer with load

The voltage at 50 Hz shows the theoretical results while at 150 Hz shows not much change in magnitude, only a slight voltage decrement at the delta secondary side and load.

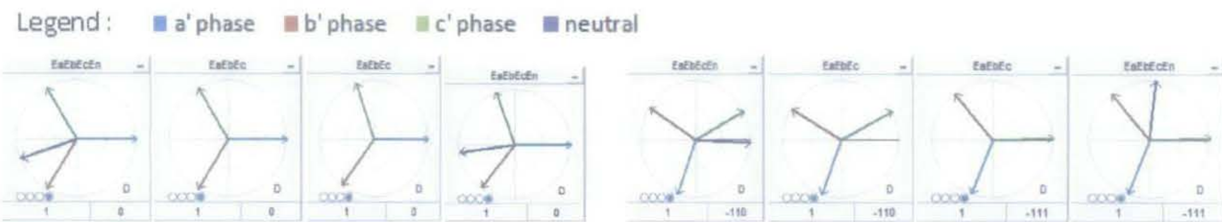


Figure 29: Phasor diagrams of voltage on delta to delta transformer with load on four measuring points at 50 Hz and 150 Hz

These phasor diagrams clearly show a positive sequence set of voltage.

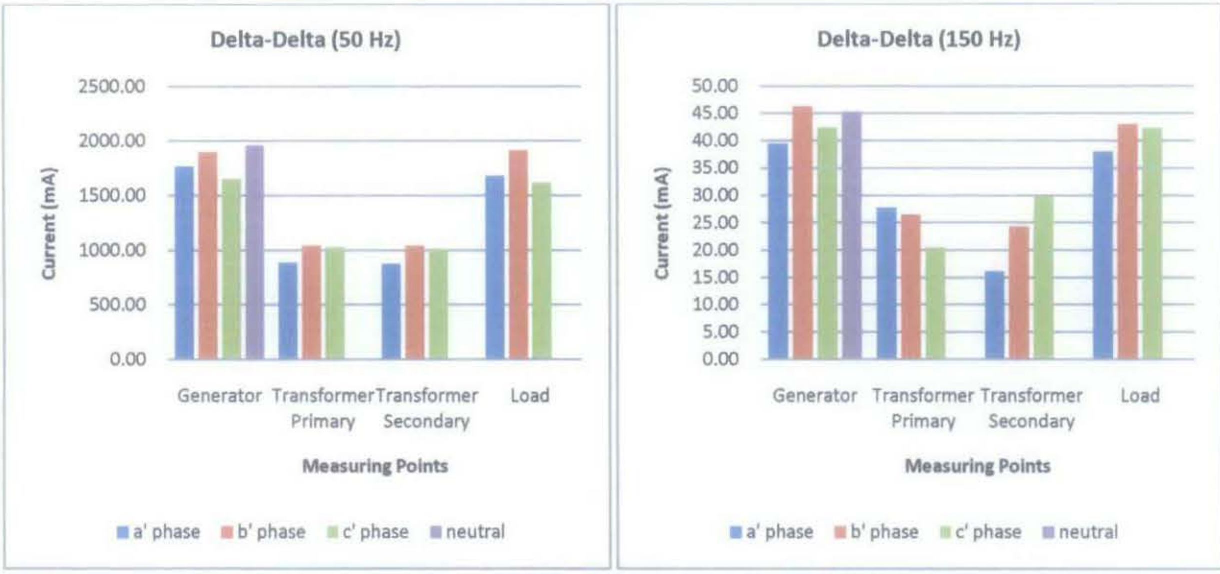


Figure 30: Graphs of current on delta to delta transformer with load

The spectrums for current at delta-delta transformer winding configurations are shown above. Both frequency of 50 Hz and 150 Hz have the same pattern. The current at the generator will decrease once it enters the delta primary and delta secondary and increases to load. The neutral current at the generator side is the same in magnitude as the phase current.

A study states that third harmonic current of delta primary winding is higher than line third harmonic current and third harmonic current trapped in delta primary and secondary windings, thus resulting in no third harmonic current flows into the load [11]. However, in this experimental result it shows that delta does not block third harmonic current.

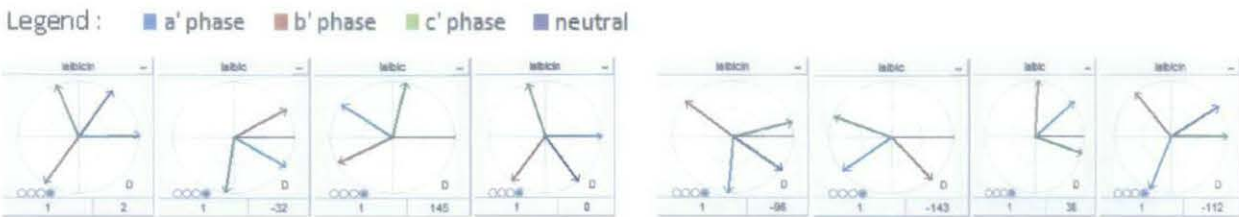


Figure 31: Phasor diagrams of current on delta to delta transformer with load on four measuring points at 50 Hz and 150 Hz

These phasor diagrams also shows a positive sequence set of currents for both fundamental frequency and third harmonic frequency.

4.1.1.3.3 PSCAD Simulation (Delta-Delta)

A simulation is conducted to verify the lab experiments. By using the no-load voltage at 150 Hz value for the source model, the real experiment value at 150 Hz for synchronous generator flowing through delta-delta transformer under 120 Ohm resistive load can be compared with the PSCAD Simulation.

The no-load voltage at generator for delta-delta transformer winding configuration is:

Table 11: No load voltage generator

Generator	Voltage (V)	Phase Angle (°)
Red phase	5.06	-132.54
Yellow phase	5.64	111.41
Blue phase	5.55	-13.17

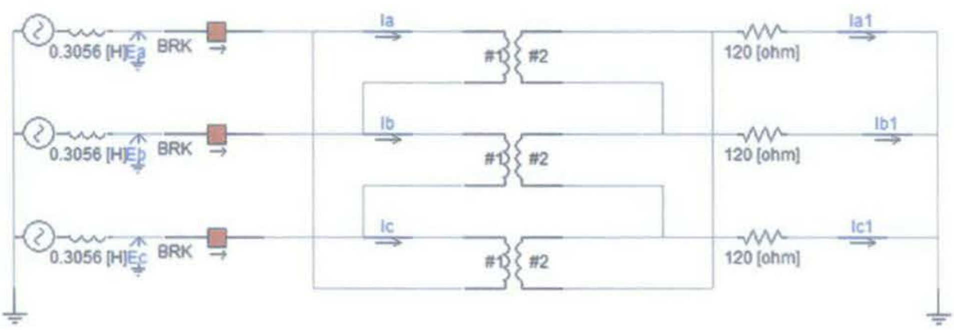


Figure 32: Model diagram of synchronous generator flowing to delta to delta transformer with load

The measuring points during 150 Hz are at;

- Voltage at synchronous generator (Ea, Eb, Ec)
- Current at load side (Ia1, Ib1, Ic1)

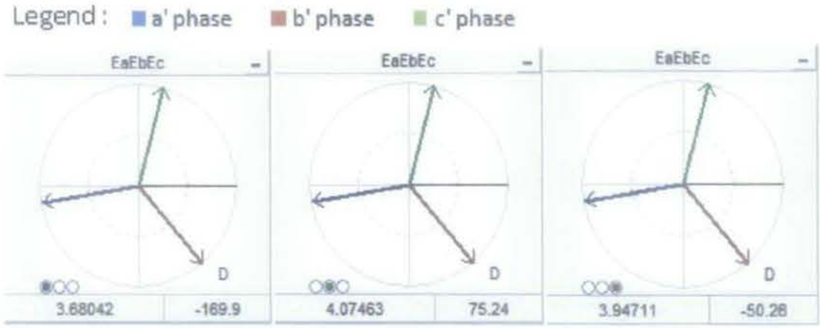


Figure 33: Phasor diagrams of voltage at red, yellow, and blue phase at generator

Table 12: Comparison of voltage between lab results and PSCAD Simulation results for delta to delta transformer

	Laboratory Results		**PSCAD Simulation Results**	
Generator	**Voltage (V)**	**Phase Angle (°)**	**Voltage (V)**	**Phase Angle (°)**
Red phase	4.85	-110.57	3.68	-169.9
Yellow phase	5.46	147.90	4.07	75.24
Blue phase	4.72	28.35	3.95	-50.26

The voltage at generator between lab results and PSCAD simulation results decreases by 24%.

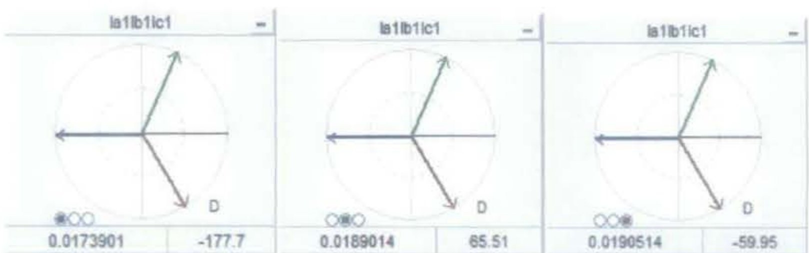


Figure 34: Phasor diagrams of current at red, yellow and blue phase at load side

Table 13: Comparison of current between lab results and PSCAD Simulation results for delta to delta transformer

	Laboratory Results		**PSCAD Simulation Results**	
Load Side	**Current (mA)**	**Phase Angle (°)**	**Current (mA)**	**Phase Angle (°)**
Red phase	38.07	-112.08	17.39	-177.7
Yellow phase	42.99	128.9	18.90	65.51
Blue phase	42.41	0	19.05	-59.95

The current for load side of the laboratory results and PSCAD simulation results decreases by 54%.

4.1.1.4 Star-Star Transformer Winding Configuration

4.1.1.4.1 No Load Condition ($R = \infty\ \Omega$)

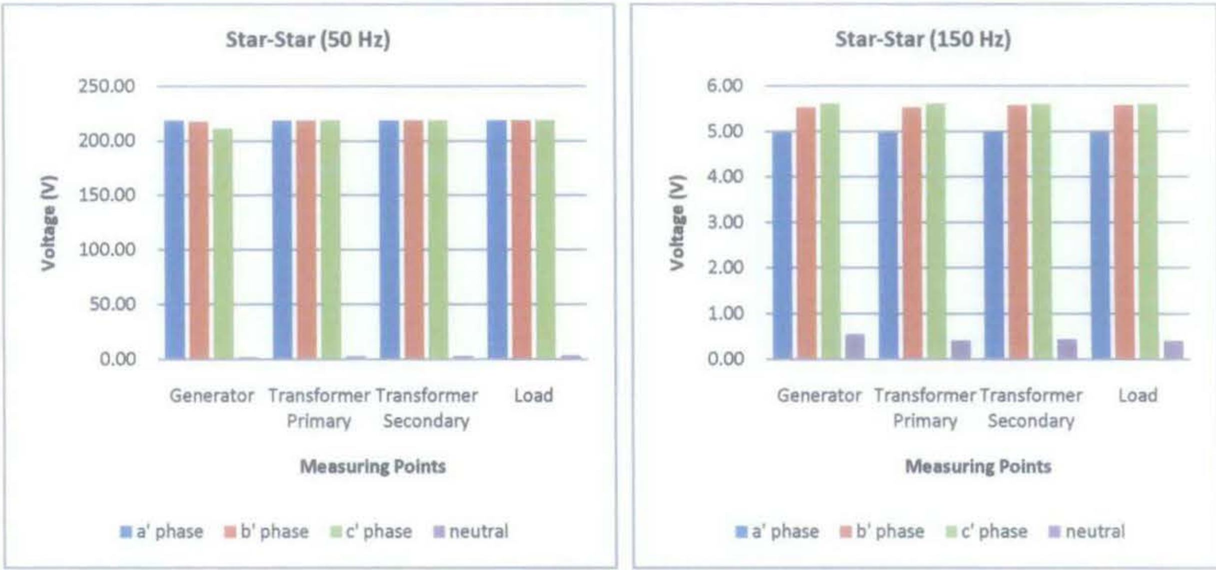


Figure 35: Graphs of voltage on star to star transformer without load

The 50 Hz spectrum for star-star 415V/415V rated transformer winding shows the theoretical voltage trending while at 150 Hz, it shows a constant voltage at all measuring points.

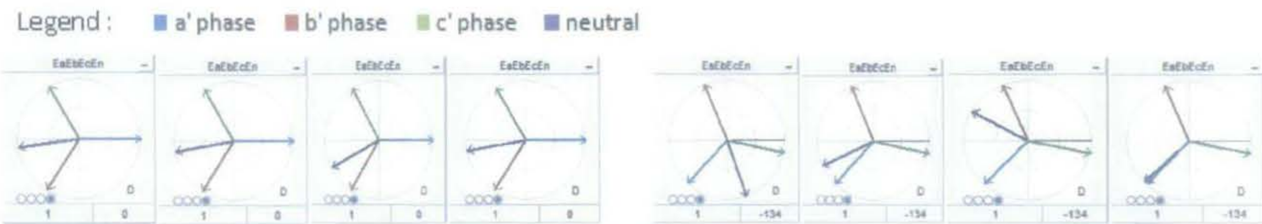


Figure 36: Phasor diagrams of voltage on star to star transformer without load on four measuring points at 50 Hz and 150 Hz

These phasor diagram also shows a positive sequence for both cases of fundamental frequency and third harmonics frequency.

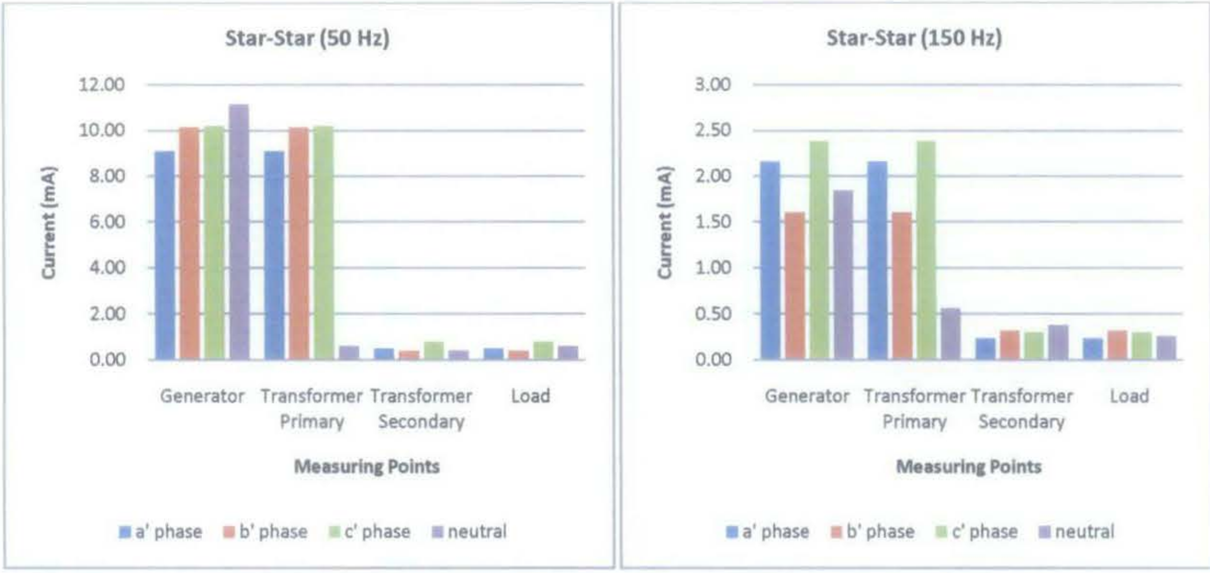


Figure 37: Graphs of current on star to star transformer without load

Under the no-load condition, it can be observed that the spectrum of the third harmonic frequency follows as the fundamental frequency. The neutral current is high at the generator side for both frequencies. Meanwhile, the current decreases at the star secondary winding and load side.

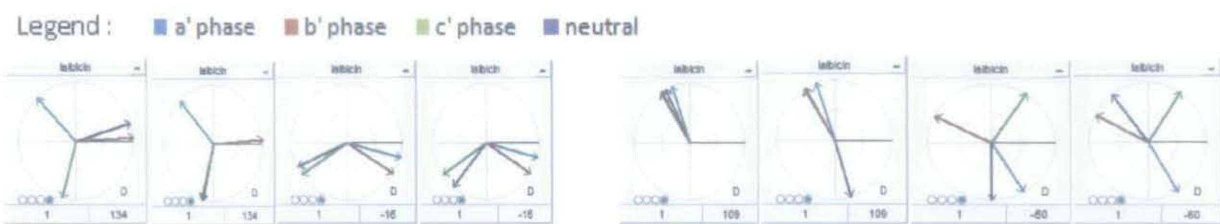


Figure 38: Phasor diagrams of current on star to star transformer without load on four measuring points at 50 Hz and 150 Hz

The phasor diagram above shows that at 150 Hz of the generator side the phase is in a zero sequence. While the imbalance phase angle at 50 Hz of the star secondary and load side. Apart from those three discussed, the rest are in a positive sequence set of currents.

4.1.1.4.2 120 Ohm (R = 120 Ω)

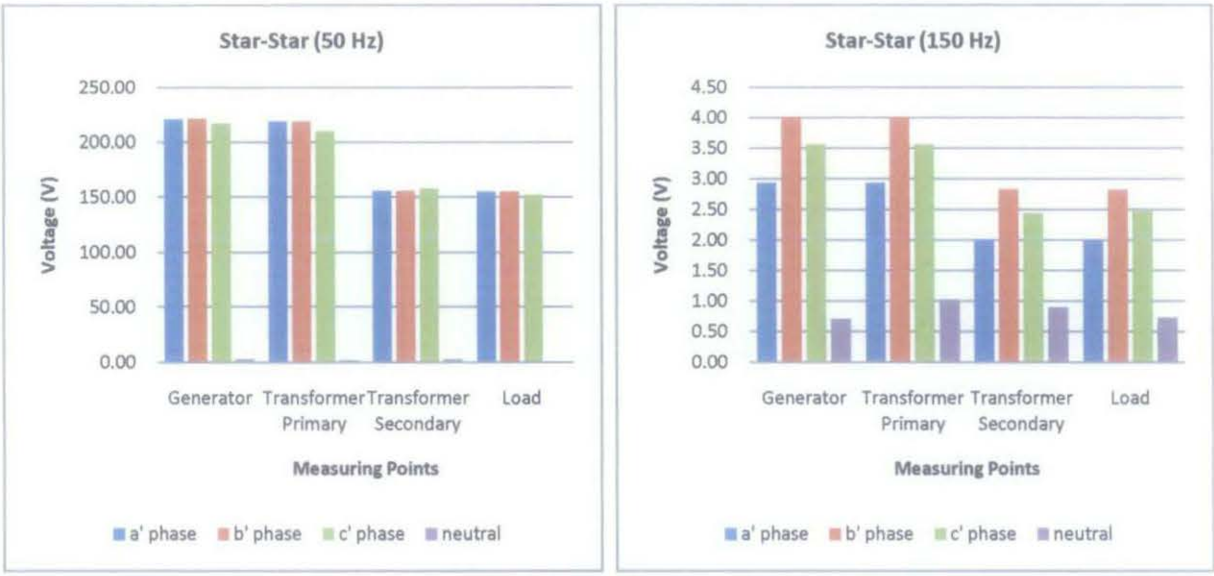


Figure 39: Graphs of voltage on star to star transformer with load

The trending spectrum voltage for fundamental frequency shows the voltage of around 400 V at transformer primary and secondary since its 415V/415V rated transformer used and decreases at the load side. Third harmonics frequency shows variations of phase voltage.

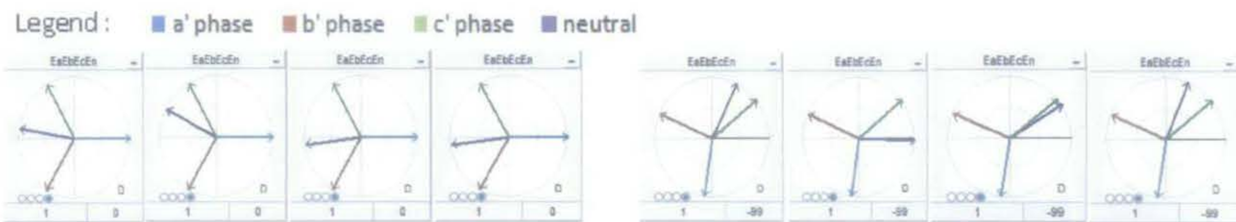


Figure 40: Phasor diagrams of voltage on star to star transformer with load on four measuring points at 50 Hz and 150 Hz

The phasor diagram at both frequencies shows positive sequence set of voltage.

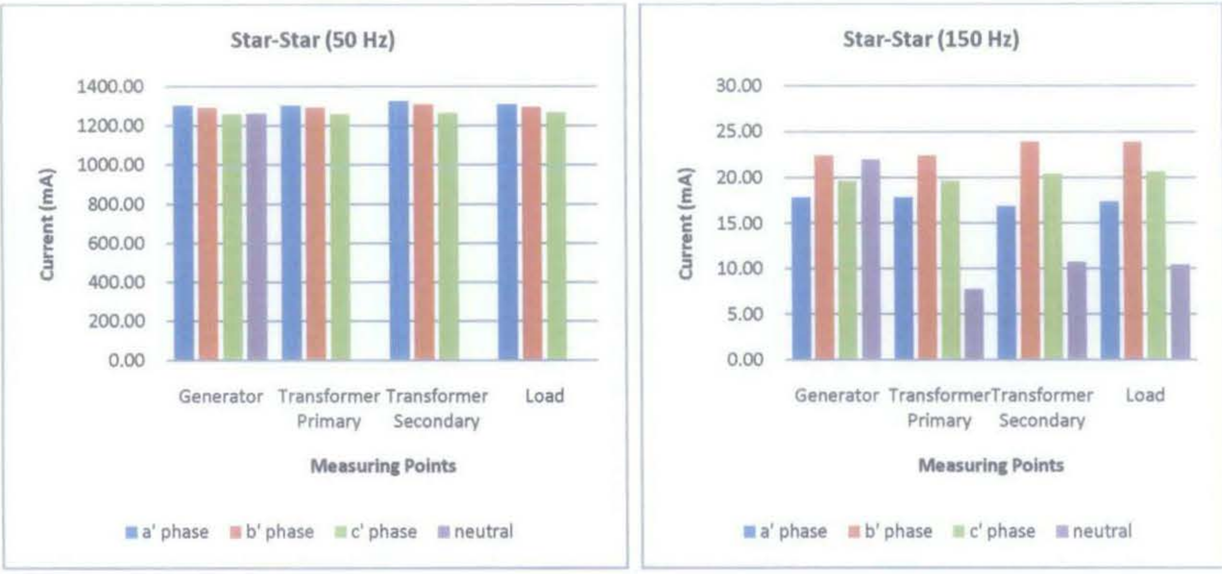


Figure 41: Graphs of current on star to star transformer with load

The current at the measuring points of 50 Hz does not vary much from the generator current. However, a high neutral current exists at the generator side.

In the third harmonics frequency, the current phases vary at each measuring points. The neutral current at the generator side decreases once it reach the star primary side and increases a little once it flows to the star secondary side until reaches the load side. A third harmonic current flows through transformer similar to fundamental harmonic currents, except transformer exhibit higher reactive impedance to third harmonic [11].

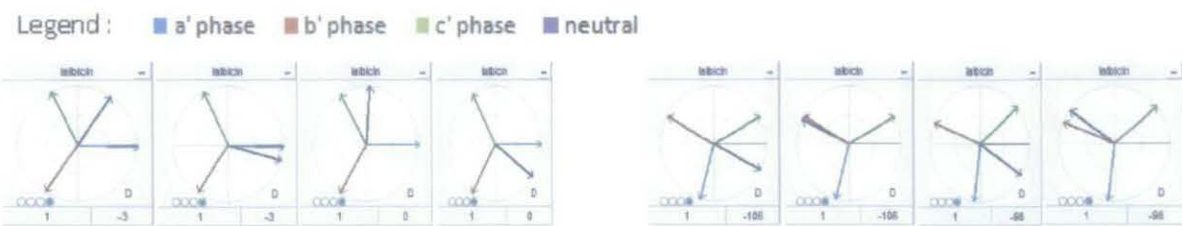


Figure 42: Phasor diagrams of current on star to star transformer with load on four measuring points at 50 Hz and 150 Hz

Similar as in other cases before, the phasor diagram shows a positive sequence set of currents and same goes for star-star transformer winding configuration.

4.1.1.4.3 PSCAD Simulation (Star-Star)

A simulation is conducted to verify the lab experiments. By using the no-load voltage at 150 Hz value for the source model, the real experiment value at 150 Hz for synchronous generator flowing through star-star transformer under 120 Ohm resistive load can be compared with the PSCAD Simulation.

The no-load voltage at generator for star-star transformer winding configuration is:

Table 14: No load voltage at generator

Generator	Voltage (V)	Phase Angle (°)
Red phase	4.97	-134.37
Yellow phase	5.53	112.4
Blue phase	5.62	-13.89

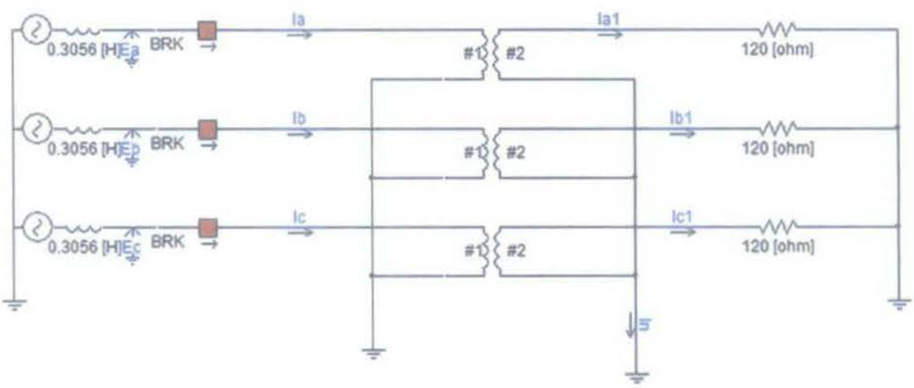


Figure 43: Model diagram of synchronous generator flowing to star to star transformer with load

The measuring points during 150 Hz are at;

- Voltage at synchronous generator (Ea, Eb, Ec)
- Current at star secondary winding side (Ia1, Ib1, Ic1)

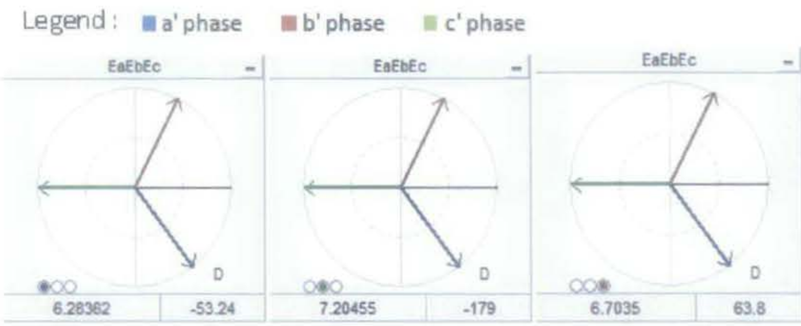


Figure 44: Phasor diagrams of voltage at red, yellow and blue phase at generator for star to star transformer

Table 15: Comparison of voltage between lab results and PSCAD Simulation results for star to star transformer

	Laboratory Results		**PSCAD Simulation Results**	
Generator	**Voltage (V)**	**Phase Angle (°)**	**Voltage (V)**	**Phase Angle (°)**
Red phase	2.94	-99.20	6.28	-53.24
Yellow phase	4.01	156.49	7.20	-179
Blue phase	3.56	38.50	6.70	63.8

The generator voltage for lab results and PSCAD simulation results increases by 114%.

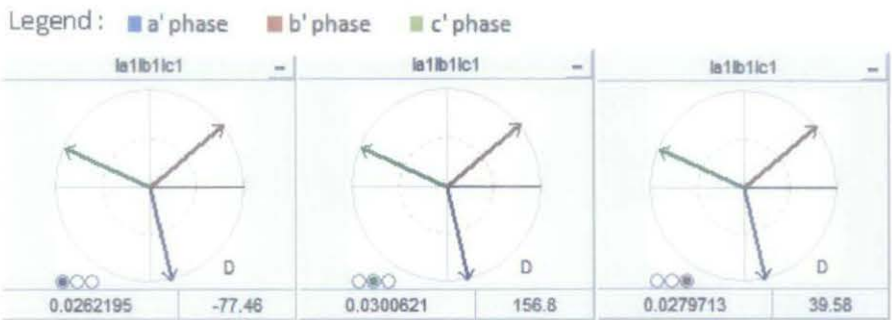


Figure 45: Phasor diagrams of current at red, yellow, and blue phase at star secondary side for star to star transformer

Table 16: Comparison of current between lab results and PSCAD Simulation results for star to star transformer

	Laboratory Results		**PSCAD Simulation Results**	
Star Secondary Side	**Current (mA)**	**Phase Angle (°)**	**Current (mA)**	**Phase Angle (°)**
Red phase	16.92	-98.05	26.22	-77.46
Yellow phase	23.94	157.42	30.06	156.8
Blue phase	20.42	40.35	27.97	39.58

The transformer star secondary side current between lab and PSCAD simulation results shows an increase by 55%.

4.1.2 Inductive Load

4.1.2.1 Delta-Star Transformer Winding Configuration

4.1.2.1.1 No Load Condition

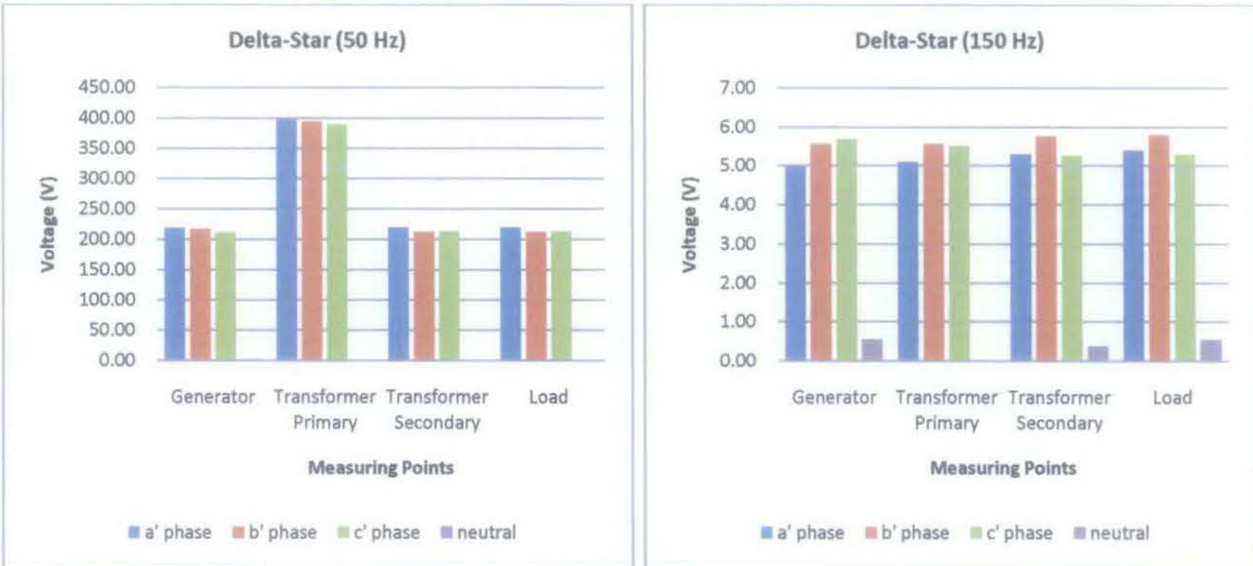


Figure 46: Graphs of voltage on delta to star transformer without load

For no-load condition under inductive load, it can be viewed the voltage at 50 Hz shows the theoretical results. While at third harmonics frequency the voltage has a value around 5.5 V on all measuring points.

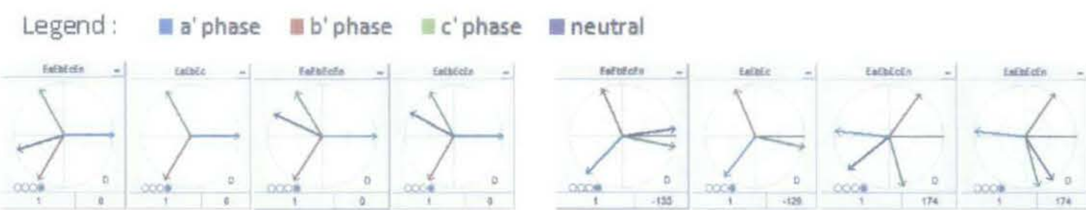


Figure 47: Phasor diagrams of voltage on delta to star transformer without load on four measuring points at 50 Hz and 150 Hz

The phasor diagram for the no-load condition of inductive load shows a positive sequence set of voltage.

Figure 48: Graphs of current on delta to star transformer without load

The current at no-load condition for 50 Hz shows that the current decreases once it reaches delta primary winding and reaches zero (very small current) at the star secondary winding and load side. A high neutral current can be observed produced at the generator.

However, different scenario occurs at the third harmonic frequency (150 Hz) whereby the current at the delta primary side is higher than the generator current. This phenomenon occurs since delta configuration blocks current and thus increases the current inside. But no current exists at star secondary winding and load side due to the no-load condition.

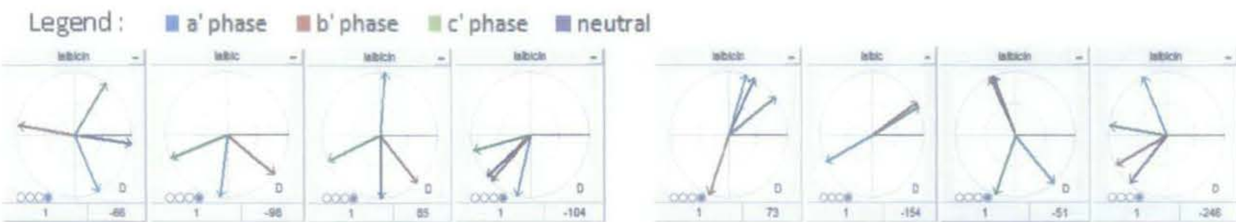


Figure 49: Phasor diagrams of current on delta to star transformer without load on four measuring points at 50 Hz and 150 Hz

The phasor diagram for no-load condition at 50 Hz shows a positive sequence set of currents except at load side where the phases shows a zero sequence.

However, the phasor diagram for 150 Hz shows at the generator and load side is a zero sequence set of currents. While at the delta primary and star secondary shows that the angle are random and thus considered as a positive sequence.

4.1.2.1.2 0.38 H (Henry)

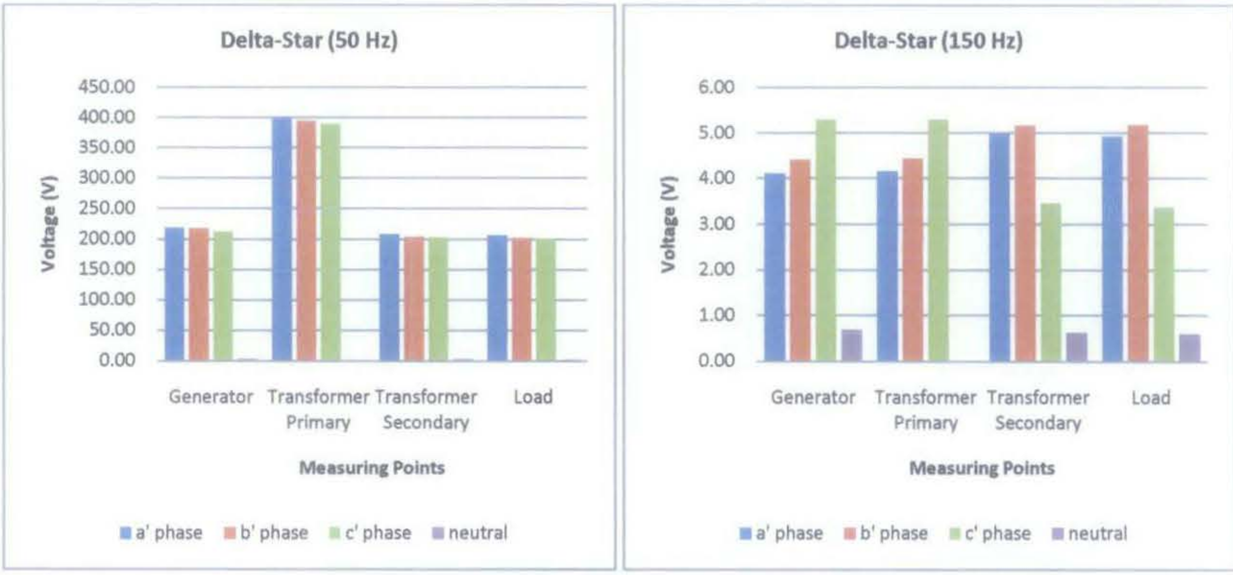


Figure 50: Graphs of voltage on delta to star transformer with load

Under 0.38 Henry inductive load condition, the voltage at the fundamental frequency gives out the theoretical results. The third harmonics frequency (150 Hz) shows a variation of phase voltage.

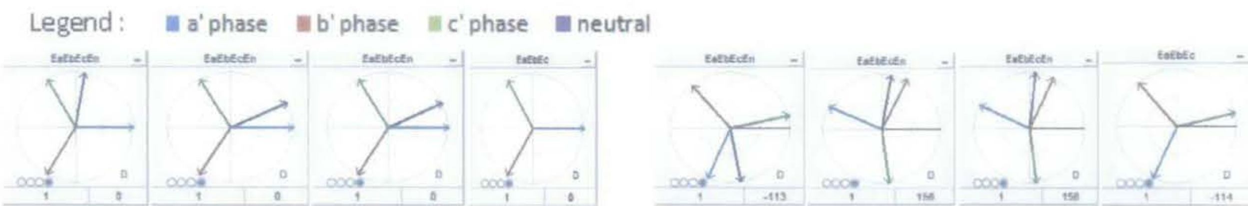


Figure 51: Phasor diagrams of voltage on delta to star transformer with load on four measuring points at 50 Hz and 150 Hz

The phasor diagram for inductive load condition shows a positive sequence set of currents at all four measuring points of both 50 Hz and 150 Hz.

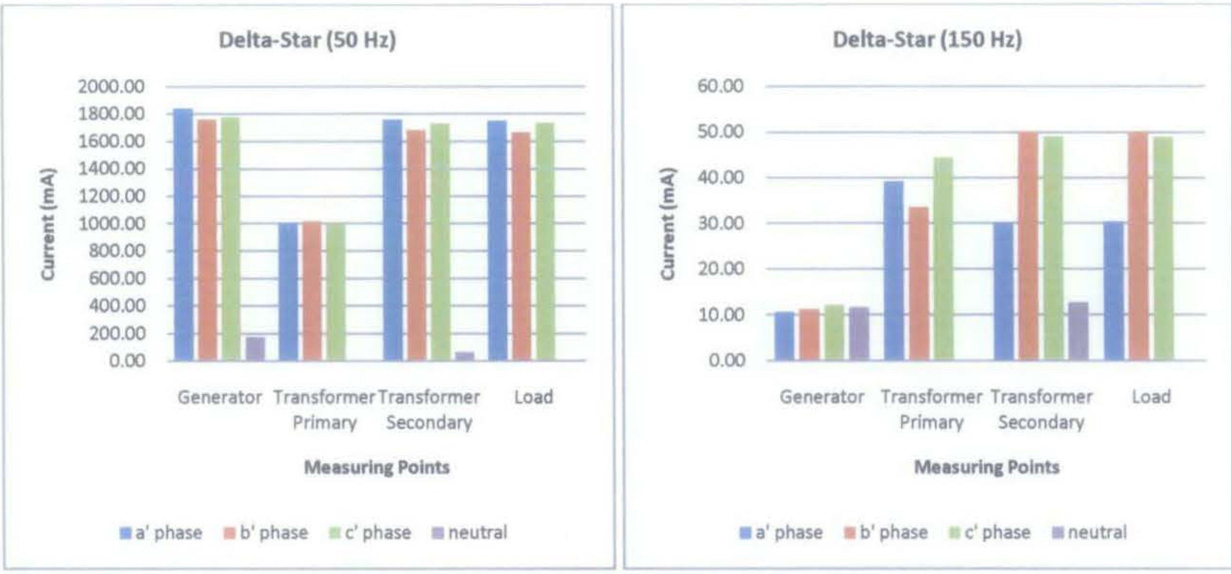


Figure 52: Graphs of current on delta to star transformer with load

The spectrum for inductive load condition shows at 50 Hz the current decreases as the current flows into delta primary side and increases again once reach the star secondary side load side.

However, the behaviour of current trending is different at the third harmonics frequency (150 Hz) with a small current at the generator side and increases as it flows into delta primary side and increases a little more at the star secondary side and load side. This phenomena is the opposite of what happen to the characteristics of current at the fundamental frequency.

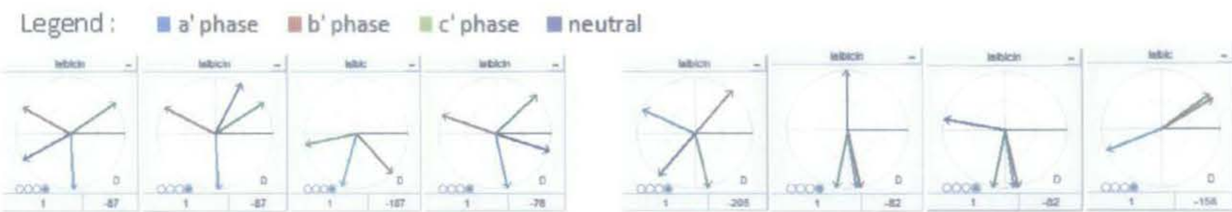


Figure 53: Phasor diagrams of current on delta to star transformer with load on four measuring points at 50 Hz and 150 Hz

The phasor diagram for inductive load operating at 50 Hz shows a positive sequence set of currents. However, during 150 Hz operation, the delta primary side, star secondary side and load side shows a zero sequence set of currents while a positive sequence at the generator side. In compliance with the study that states triplen harmonics are zero sequence under balanced load condition [11].

4.1.2.1.3 PSCAD Simulation (Delta-Star)

A simulation is conducted to verify the lab experiments. By using the no-load voltage at 150 Hz value for the source model, the real experiment value at 150 Hz for synchronous generator flowing through delta-star transformer under 0.38 Henry inductive load can be compared with the PSCAD Simulation.

The no-load voltage at generator for delta-star transformer winding configuration is:

Table 17: No load voltage at generator

Generator	Voltage (V)	Phase Angle (°)
Red phase	1.17	73.03
Yellow phase	2.43	-110.07
Blue phase	1.75	36.14

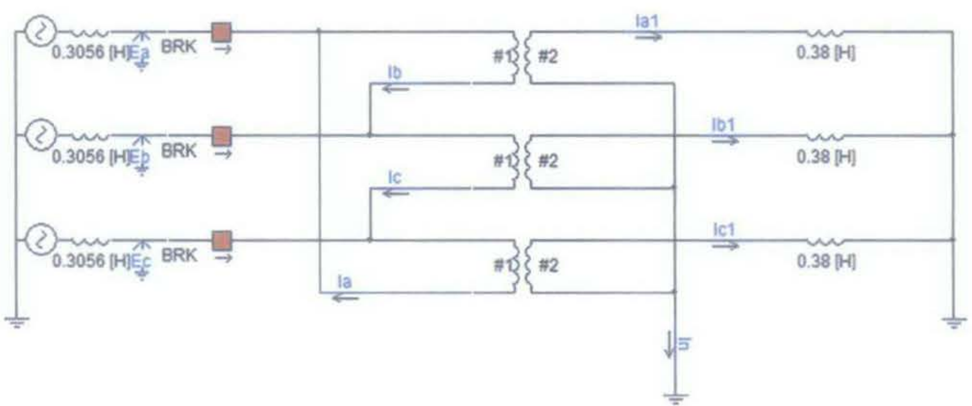


Figure 54: Model diagram of synchronous generator flowing to delta to star transformer with load

The measuring points during 150 Hz are at;

- Voltage at synchronous generator (Ea, Eb, Ec)
- Current at star winding side (Ia1, Ib1, Ic1)

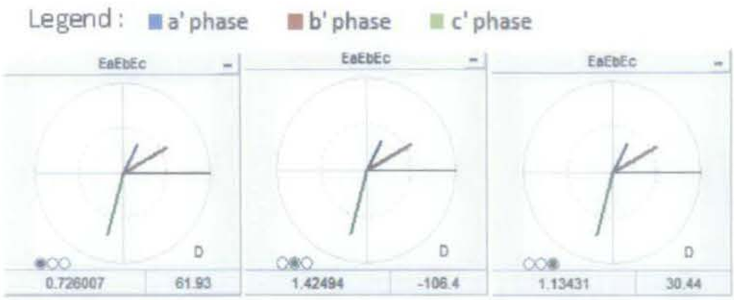


Figure 55: Phasor diagrams of voltage at red, yellow and blue phase at generator

Table 18: Comparison of voltage between lab results and PSCAD Simulation results for delta to star transformer at inductive load

	Laboratory Results		**PSCAD Simulation Results**	
Generator	**Voltage (V)**	**Phase Angle (°)**	**Voltage (V)**	**Phase Angle (°)**
Red phase	4.12	-113.73	0.726	61.93
Yellow phase	4.42	130.82	1.425	-106.40
Blue phase	5.30	12.73	1.134	30.44

The voltage at the generator side for both lab results and PSCAD simulation results shows a big difference by a decrease of 82%. The error is higher during inductive load experiment compared to the resistive load.

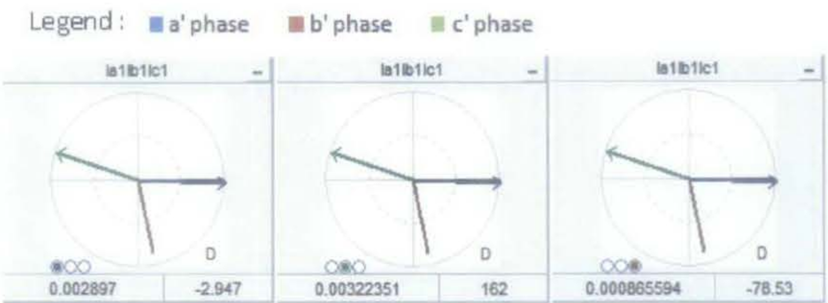


Figure 56: Phasor diagrams of current at red, yellow, and blue phase at star side

Table 19: Comparison of current between lab results and PSCAD Simulation results for delta to star transformer at inductive load

	Laboratory Results		**PSCAD Simulation Results**	
Star Side	**Current (mA)**	**Phase Angle (°)**	**Current (mA)**	**Phase Angle (°)**
Red phase	30.23	-82.22	2.90	-2.95
Yellow phase	50.26	-78.13	3.22	162.0
Blue phase	49.11	-102.28	0.87	-78.53

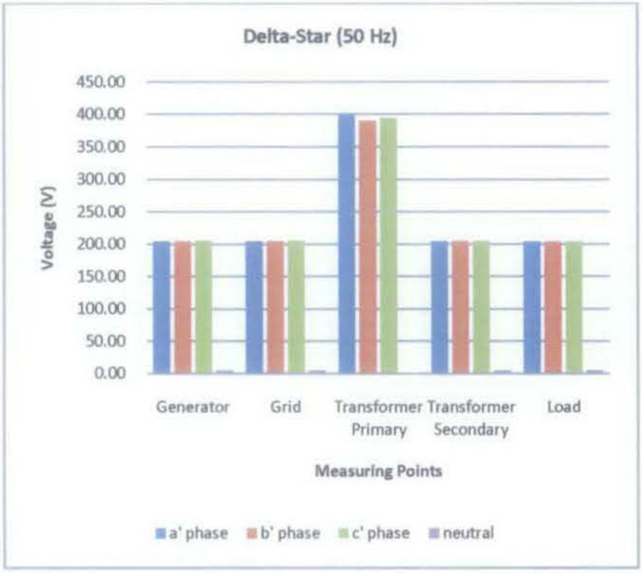
The same case applies to Table 19, it can be observed that the current at the star side has a big difference between lab results and PSCAD simulation results by 90%.

4.2 PART 2: Generator Parallel with Grid Operation

4.2.1 Resistive Load

4.2.1.1 Delta-Star Transformer Winding Configuration

4.2.1.1.1 No Load Condition



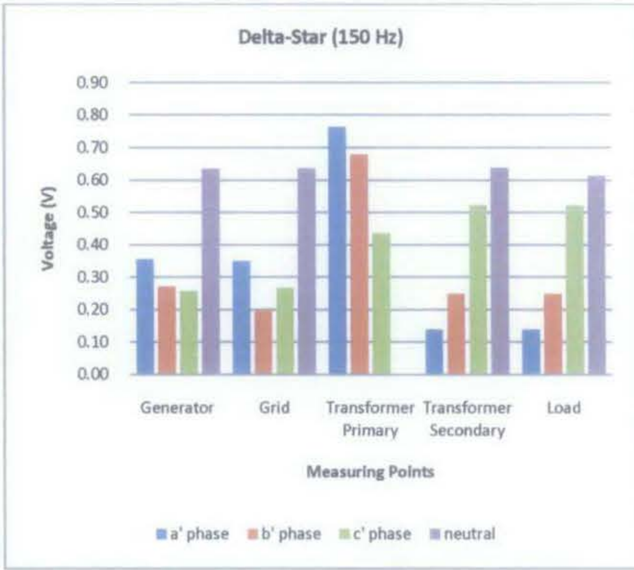


Figure 57: Graphs of voltage on delta to star transformer without load

The voltage spectrum for no load condition of 50 Hz under the operation of generator paralleling with grid flowing through delta-star transformer shows the theoretical results.

However, at the third harmonic frequency (150 Hz) the voltage decreases by 700 times compared to the fundamental frequency. The neutral current at the generator side double the phase current and similar as the grid side. There is an increase of voltage at the delta primary side and it decreases slightly at the star secondary side.

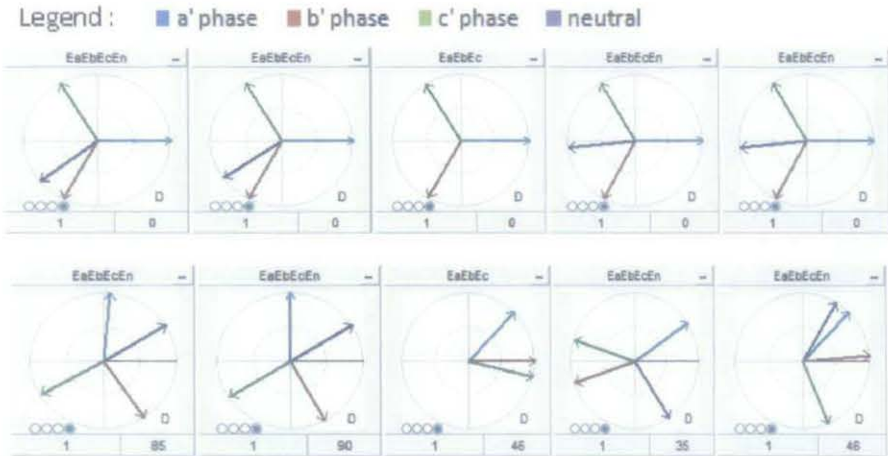


Figure 58: Phasor diagrams of voltage on delta to star transformer without load on five measuring points at 50 Hz and 150 Hz

The phasor diagram above shows the operation of generator paralleling with the grid at delta-star transformer without load at fundamental frequency (50 Hz) and third harmonic frequency (150 Hz). It shows a positive sequence set of voltage at 50 Hz and 150 Hz.

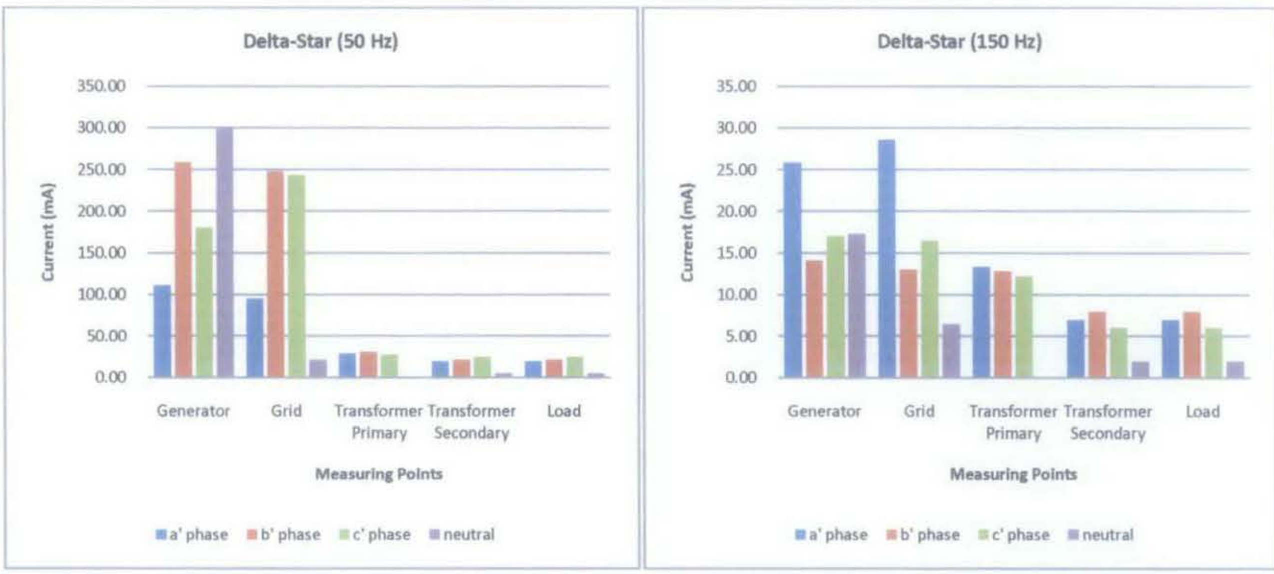


Figure 59: Graphs of current on delta to star transformer without load

The current at 150 Hz decreases by a factor of 10 from 50 Hz. The neutral current at the generator side of 150 Hz is a decrement 20 times of the generator side at the fundamental frequency.

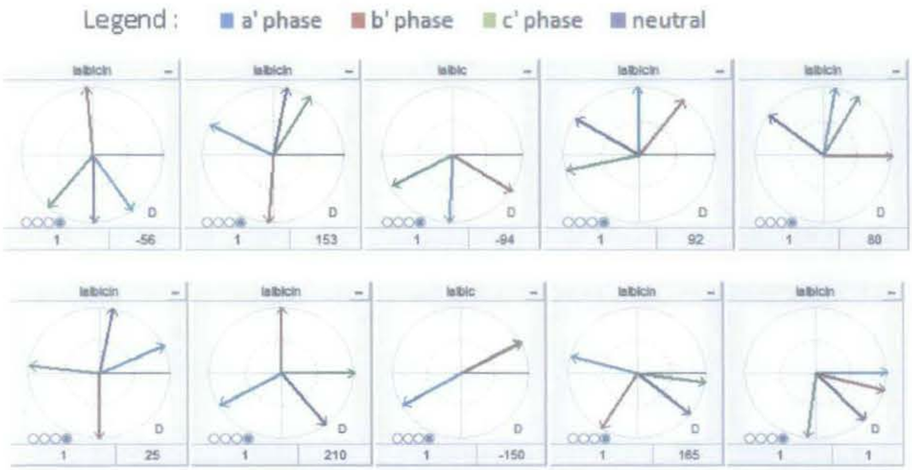


Figure 60: Phasor diagrams of current on delta to star transformer without load on five measuring points at 50 Hz and 150 Hz

These phasor diagrams also show a positive sequence set of currents on all five measuring points.

4.2.1.1.2 120 Ohm at 0.3 A (Ampere)

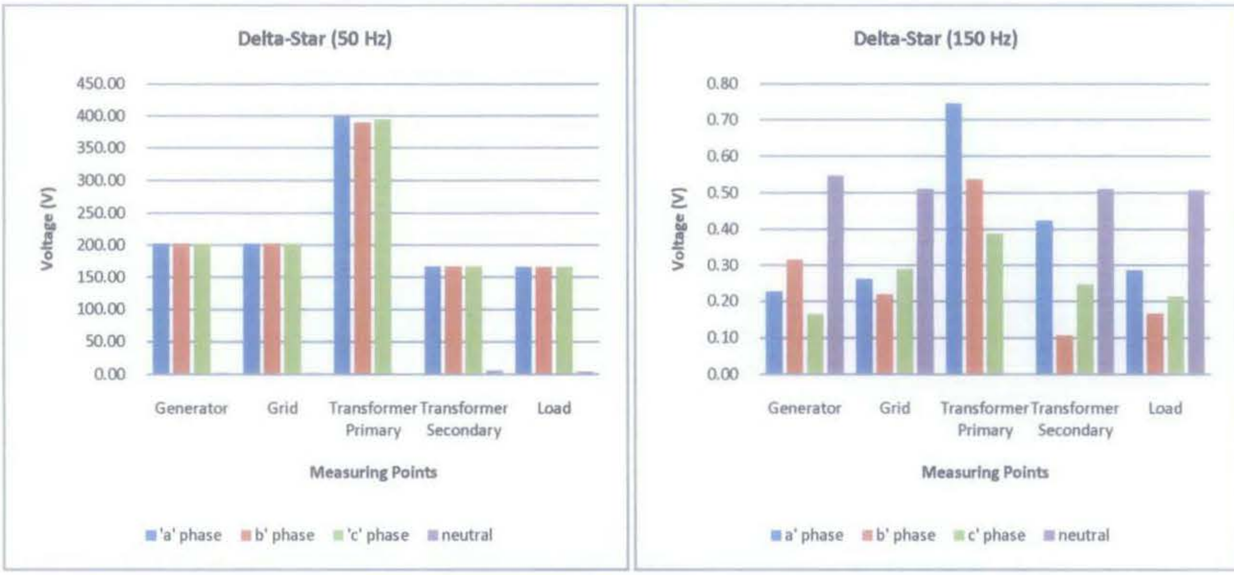


Figure 61: Graphs of voltage on delta to star transformer with load

During paralleling the synchronous generator with the grid network, the value of current and voltage of the system were synchronized. Thus, both synchronous generator and the grid can be said to operate at the same voltage and frequency.

For the voltage spectrum above, it can be observed that the voltage at the fundamental frequency maintains a steady-state voltage at the generator and grid while an increase of voltage occurs at the delta primary side and a decrease at the star secondary winding and the load side due to 415V/240V rated transformer.

However, at the third harmonic frequency (150 Hz), the phase voltage at each measuring point varies a lot in terms of magnitude. It carries a very small third harmonics voltage with a ratio of 1000 times in comparison with the fundamental frequency. The neutral current exist at all measuring points except at the delta primary side.

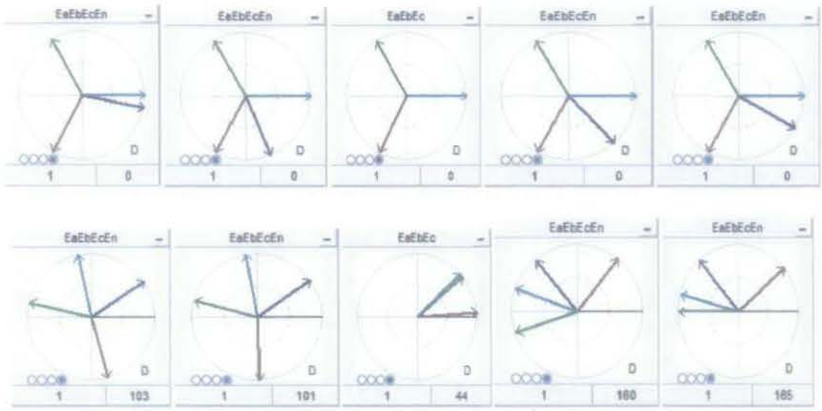


Figure 62: Phasor diagrams of voltage on delta to star transformer with load on five measuring points at 50 Hz and 150 Hz

These phasor diagrams show a positive sequence set of voltage at fundamental frequency (50 Hz) on all five measuring points. Whereas, at the third harmonic frequency (150 Hz), it can be observed that delta primary side behaves in a zero sequence voltage. The rest shows a positive sequence set of voltages.

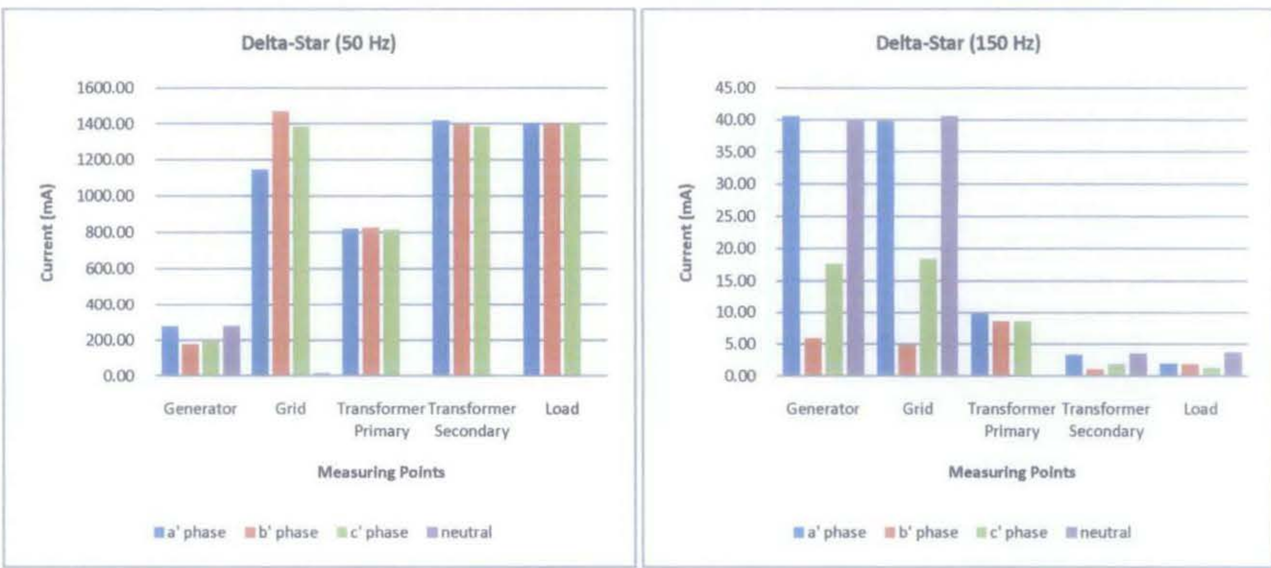


Figure 63: Graphs of current on delta to star transformer with load

The current spectrum for fundamental frequency (50 Hz) of delta to star transformer winding configuration shows a very small current at the generator side (can be neglected) and high current at the grid side that later reduces once reaches the delta primary winding side and increases at the star and load side.

However, during 150 Hz operation, imbalance behaviour of the harmonic currents can be witnessed. Neutral wire current up to three times higher than nominal phase current at the generator and grid side. The current subsides once it reaches the load side may due to the characteristics of delta primary side that traps third harmonic current thus resulting in almost no third harmonic current flows in the load.

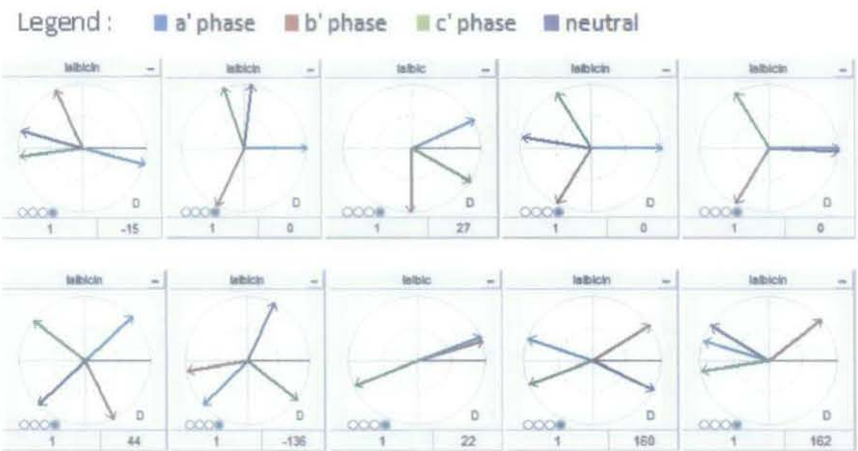


Figure 64: Phasor diagrams of current on delta to star transformer with load on five measuring points at 50 Hz and 150 Hz

The phasor diagrams above acts in the same way as other conditions before this. Most of it shows a positive sequence set of currents.

4.2.1.1.3 120 Ohm at 1.5 A (Ampere)

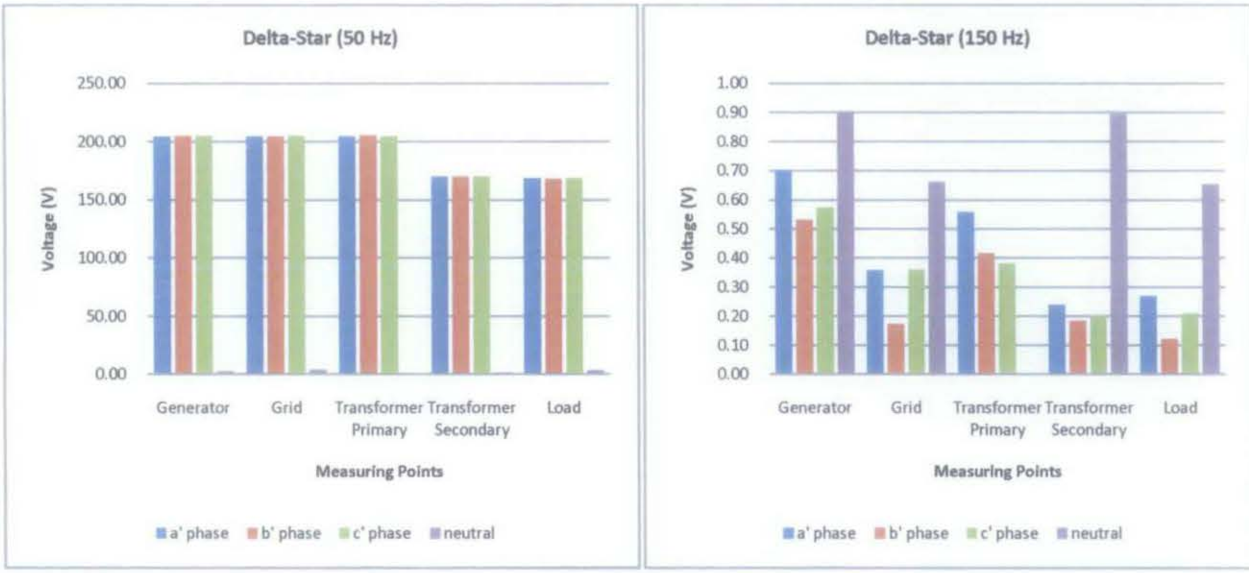


Figure 65: Graphs of voltage on delta to star transformer with load

The voltage spectrum above behaves similar to the condition of **120 Ohm at 0.3 Ampere**. Thus no detailed description will be done for the case above.

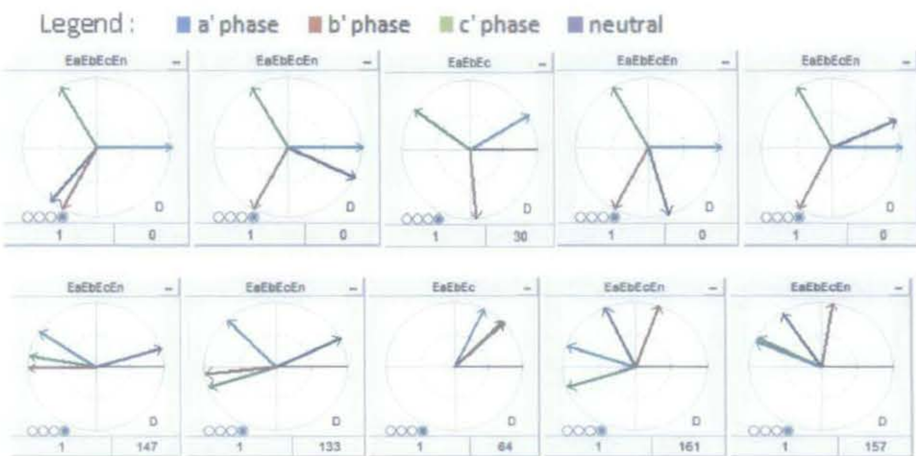
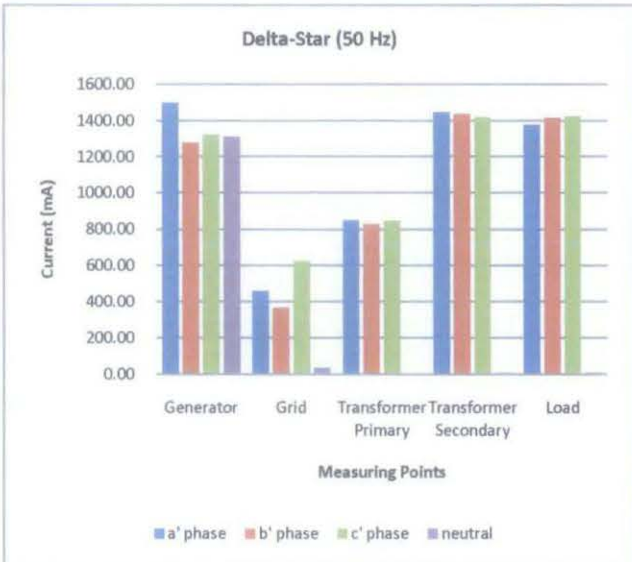


Figure 66: Phasor diagrams of voltage on delta to star transformer with load on five measuring points at 50 Hz and 150 Hz

The phasor diagrams for 50 Hz shows a positive sequence except at the delta primary side, where it shows a zero sequence with the angles are almost in phase only a few degrees apart.

However, at third harmonic frequency voltage, the generator, grid and delta primary side behaves as a zero sequence leaving out the star secondary and load side as a positive sequence set of voltages.



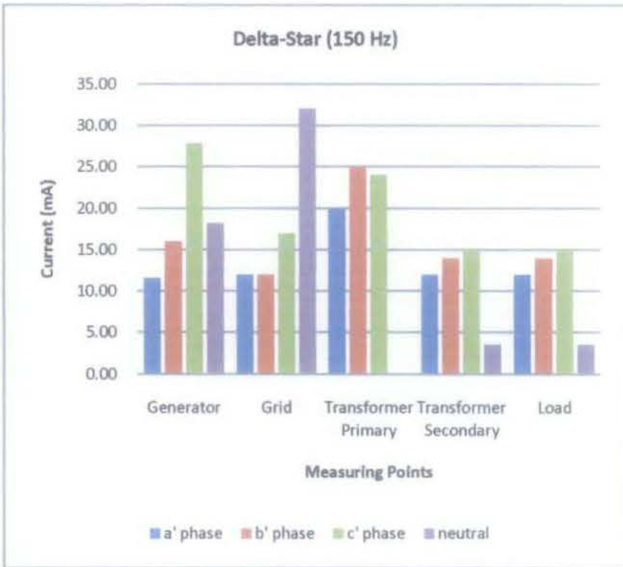


Figure 67: Graphs of current on delta to star transformer with load

The current spectrum for 120 Ohm at 1.5 Ampere condition differs from **120 Ohm at 0.3 Ampere**. At 50 Hz, the phase current at the generator side is high but small phase current can be observed at the grid side. Then gradually increases at the delta primary side and increases more at the star secondary winding and load side. However, at 150 Hz, the generator and grid phase current shows almost similar value then increases at the delta primary side and decreases at the star-secondary winding and load side.

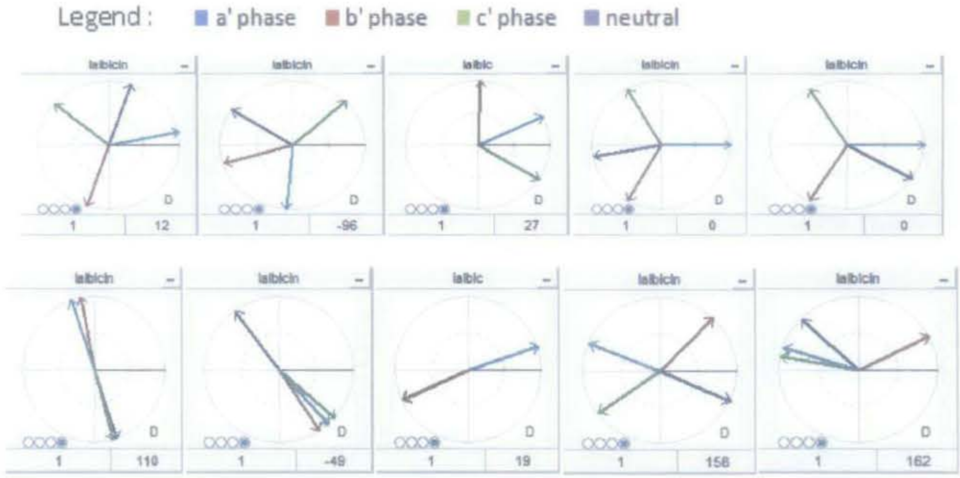


Figure 68: Phasor diagrams of current on delta to star transformer with load on five measuring points at 50 Hz and 150 Hz

The phasor diagrams above shows that at 50 Hz all measuring points act in a positive sequence. However, at 150 Hz, the generator, grid and load side behaves in a zero sequence as others in a positive sequence set of currents.

4.2.2 Inductive Load

4.2.2.1 Delta-Star Transformer Winding Configuration

4.2.2.1.1 No Load Condition

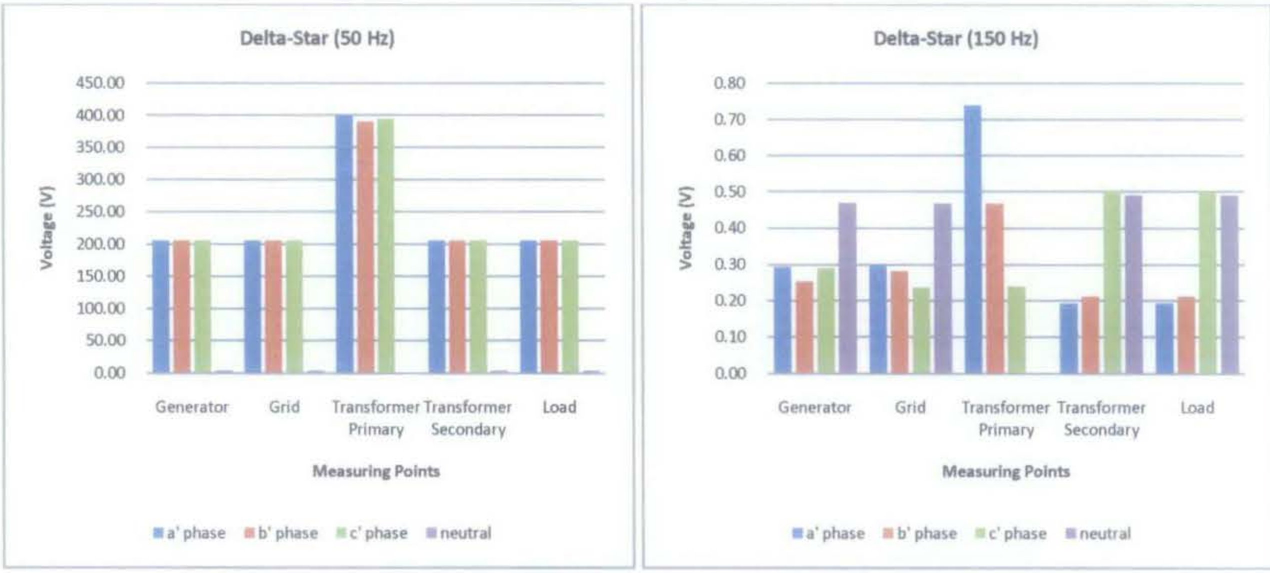


Figure 69: Graphs of voltage on delta to star transformer without load

During no load condition of 50 Hz, the voltage behaves according to theory.

However, during the third harmonic frequency the neutral phase voltage is almost the same value at four measuring points (generator, grid, star and load side).

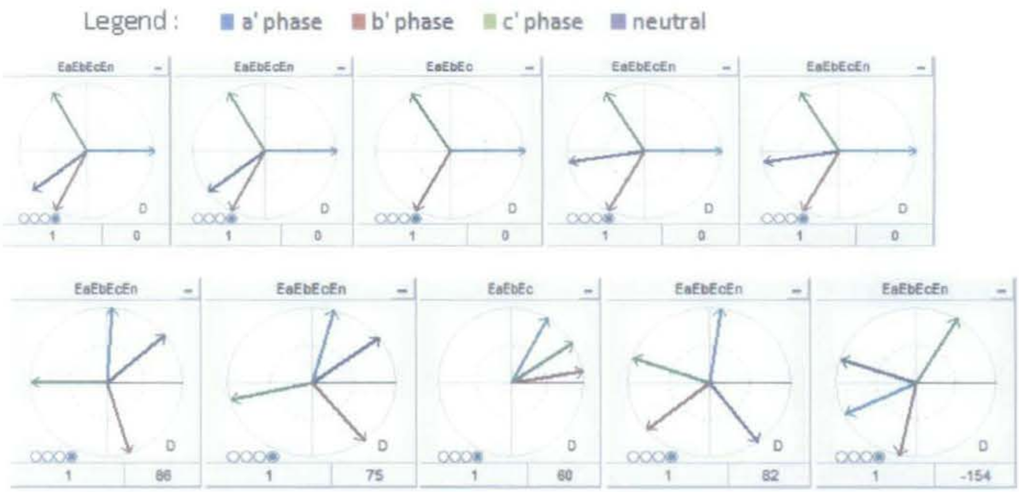


Figure 70: Phasor diagrams of voltage on delta to star transformer without load on five measuring points at 50 Hz and 150 Hz

The phasor diagram shows a positive sequence at all five measuring points during 50 Hz operation. A positive sequence set of currents also occurs during 150 Hz operation.

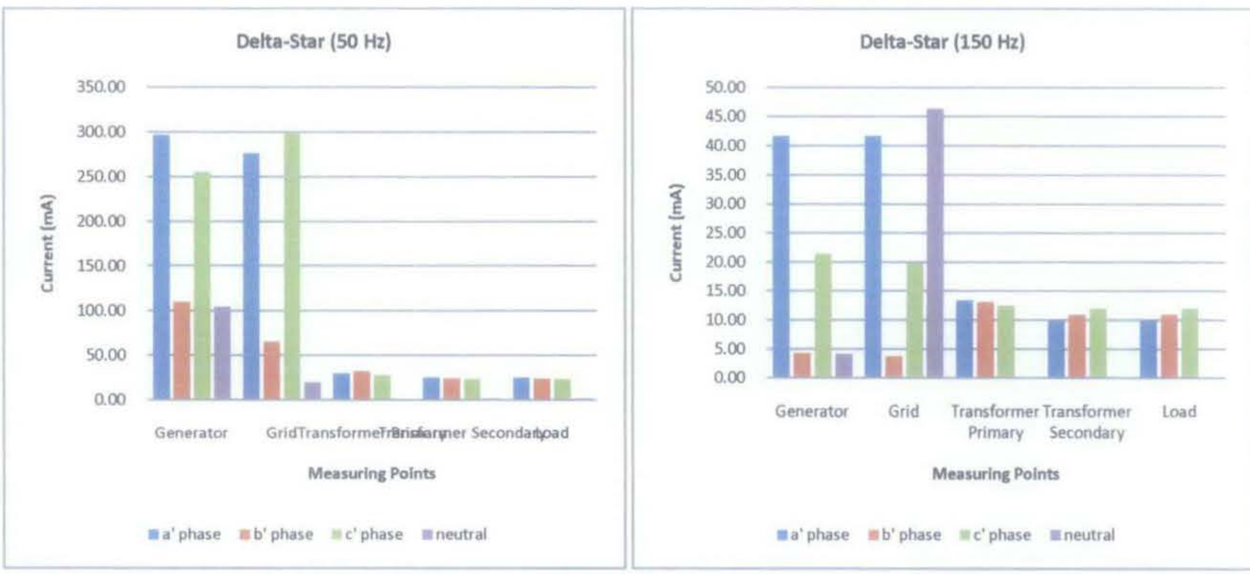


Figure 71: Graphs of current on delta to star transformer without load

No load condition of above case is similar to the **Resistive Load : No Load Condition.** A detailed explanation can be referring back to the case.

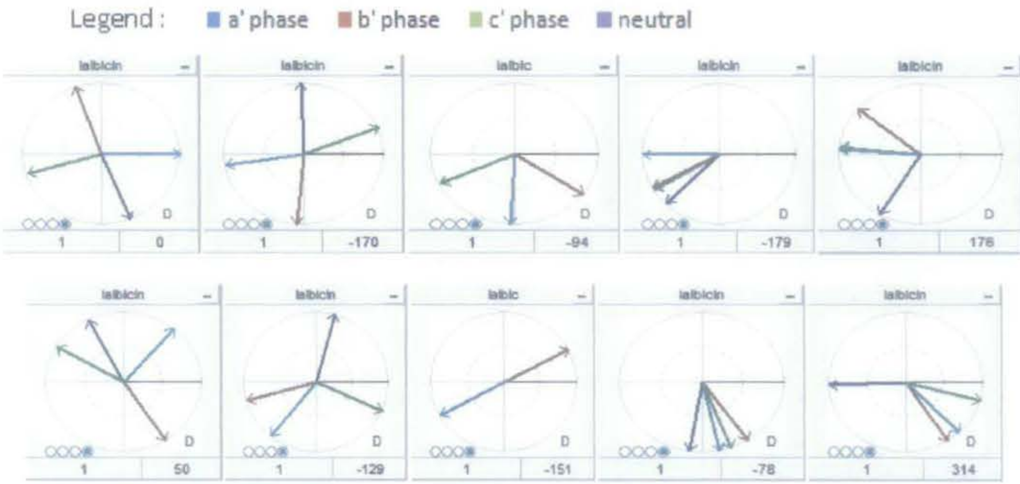


Figure 72: Phasor diagrams of current on delta to star transformer without load on five measuring points at 50 Hz and 150 Hz

A positive sequence set of currents for all measuring points at 50 Hz, except at the star secondary side that behaves as a zero sequence. This also applies to 150 Hz, where generator, grid and delta primary side behaves in a positive sequence while star secondary and load side acts as a zero sequence.

4.2.2.1.2 0.38 H

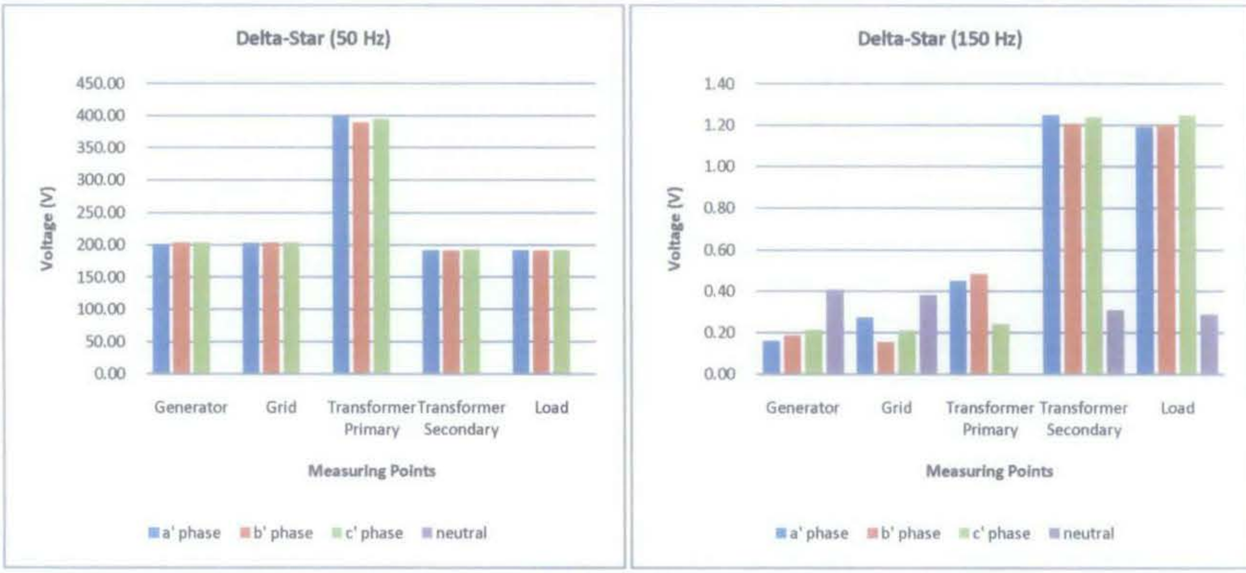


Figure 73: Graphs of voltage on delta to star transformer with load

The voltage at fundamental frequency (50 Hz) behaves according to theory. During the third harmonic frequency (150 Hz), the voltage at the generator and grid side is low. The neutral voltage at the generator side double times the phase voltage. The voltage then increase slightly at the delta primary side and also increases at the star secondary side by a factor of 3.

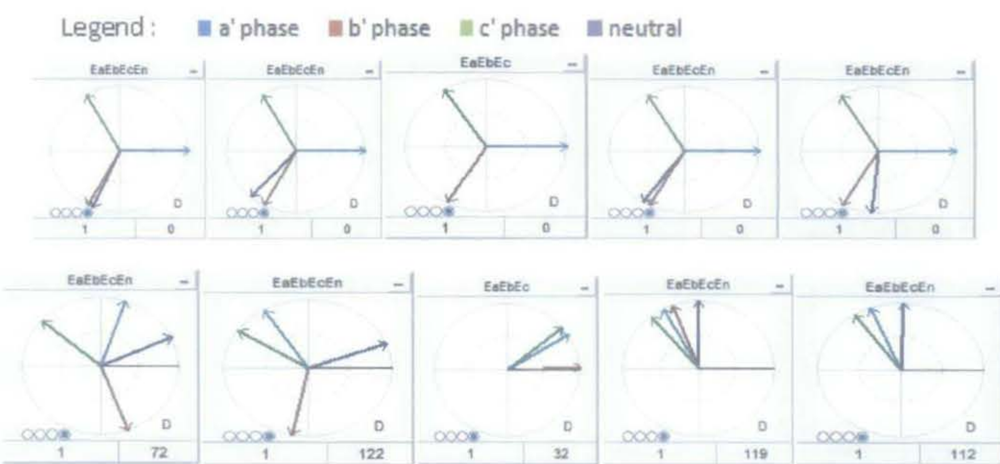


Figure 74: Phasor diagrams of voltage on delta to star transformer with load on five measuring points at 50 Hz and 150 Hz

Referring to Figure 74, at 50 Hz, the phasor diagrams acts as positive sequence. Meanwhile, the delta primary, star secondary winding and load side behaves as a zero sequence at 150 Hz.

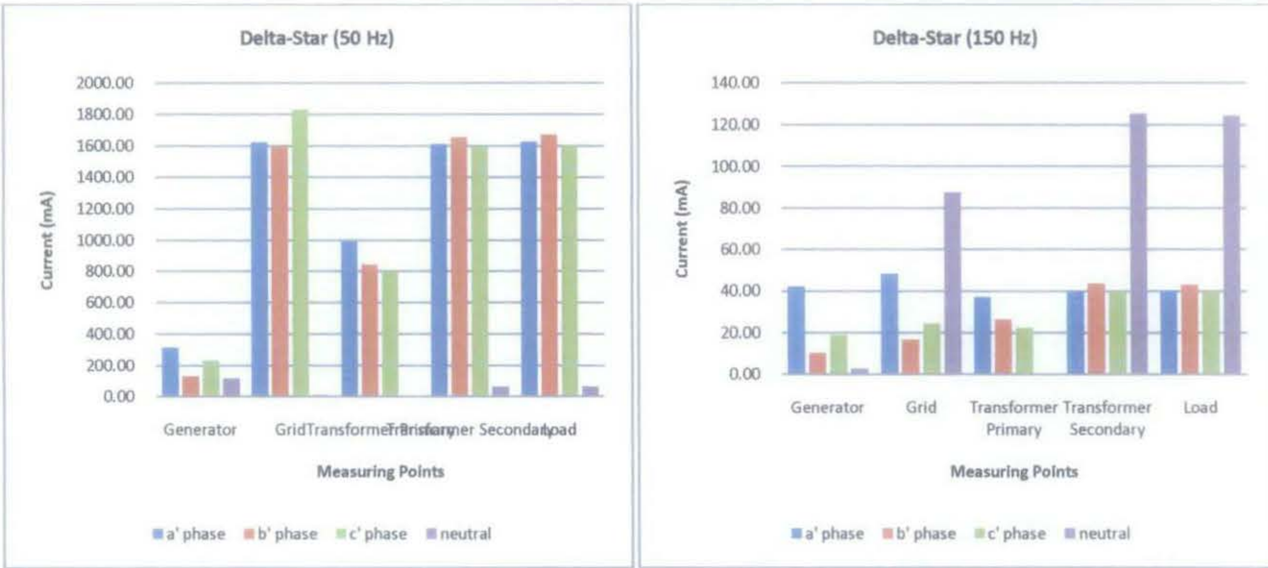


Figure 75: Graphs of current on delta to star transformer with load

The current spectrum during 50 Hz and 150 Hz differs in many ways. During 50 Hz, the generator carries very small current (0.2 A) while the grid current is very high with a ratio of ten times higher than generator current. The current at the delta side is half of the grid current. It increases once reaches the star secondary and load side.

During 150 Hz, the phase current on all five measuring points are very small (can be neglected); ranges from 0.02 A to 0.04 A, whereas the neutral current at the load side is 0.12 A, three times the phase current. Thus, supports the study that states triplen harmonic currents add at neutral with three times the phase value [11].

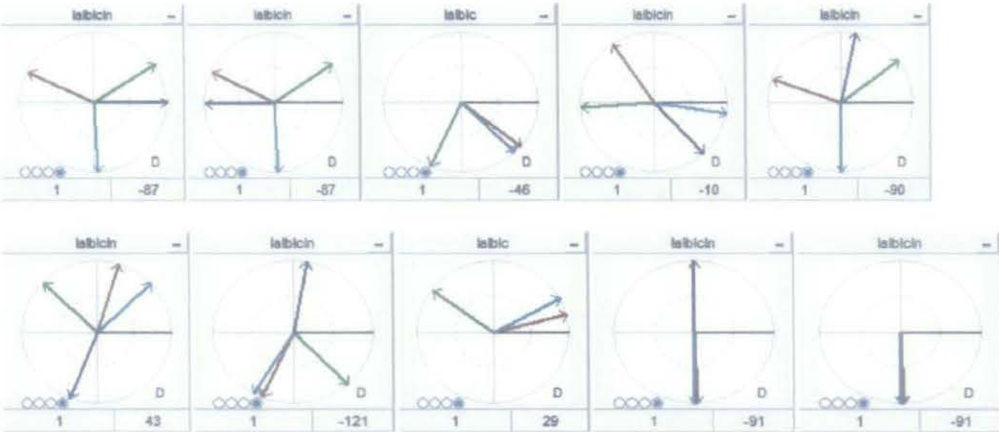


Figure 76: Phasor diagrams of current on delta to star transformer with load on five measuring points at 50 Hz and 150 Hz

The phasor diagrams for 50 Hz currents behave in a positive sequence. Meanwhile, at 150 Hz (first component of triplen harmonics) shows that star secondary and load side behaves in a zero sequence while the rest as positive sequence set of currents.

Part two of the experiment was conducted to study the behaviour of the synchronous generator when paralleling with grid. A study states that synchronous generator works in parallel with network. Synchronous generator often overloads and neutral wire current is up to three times higher than nominal phase current [15]. The theory is supported by the experiments of synchronous generator paralleling with the grid flowing through delta to star transformer configuration under balanced resistive load. Figure 63 strongly supports the statement.

The recommendation is to search for other alternative software to model the program of synchronous generator paralleling with the grid. Since PSCAD are not able to simulate such cases, it is appropriate to use a software that is compatible with Part Two of the experiment.

In conclusion, the objectives of this Final Year Project were met. The author has studied the characteristics of synchronous generator flowing through various transformer winding configurations under balanced resistive and inductive loads then later verified using PSCAD software. In addition, the behaviour of synchronous generator paralleling with grid were also analysed critically.

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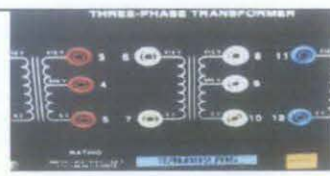
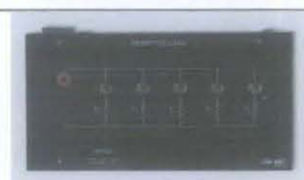
[14] Gianfranco Chicco, Petru Postolache, Cornel Toader, "Triplen Harmonics: Myths and Reality" Department of Electrical Engineering, Polytechnic Torino, Italy, January 2010.

[15] Kus Vaclav, Skala Buchmil, "Generator Overloading Owing to Neutral Wire Current", University of West Bohemia in Pilsen, Czech Republic, 2011 IEEE.

APPENDICES

APPENDIX A

The list of equipments used in the laboratory to conduct the experiments.

No	List of Equipments	Figures
1	DC Motor / Generator	
2	Wiring Module for DC Motor / Generator	
3	Three-Phase Synchronous Motor / Generator	
4	Wiring Module for Synchronous Motor / Generator	
5	Three Phase Transformer	
6	Resistive Load	

7	Inductive Load	
8	Synchronizing Module	
9	Field Rheostat	
10	Power Supply	
11	Speed Sensor / Tachometer	
12	Connection Leads	
13	Grid Network System	
14	Fluke 430 Series Three-Phase Power Quality Analyzer	
15	Current Clamp	

Table 5: List of equipments

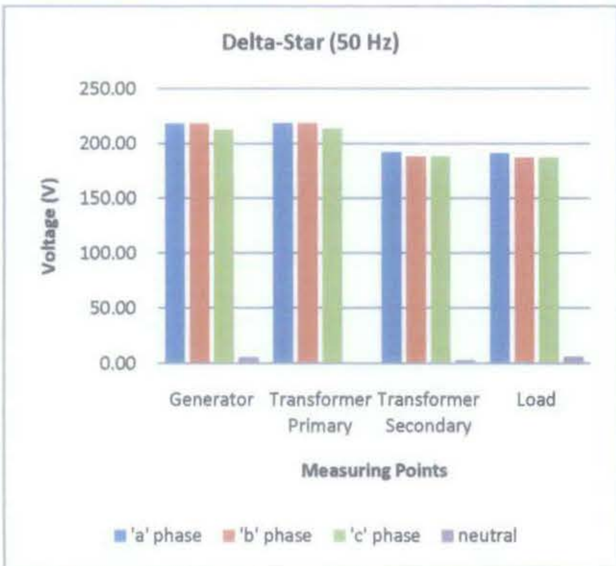
APPENDIX B

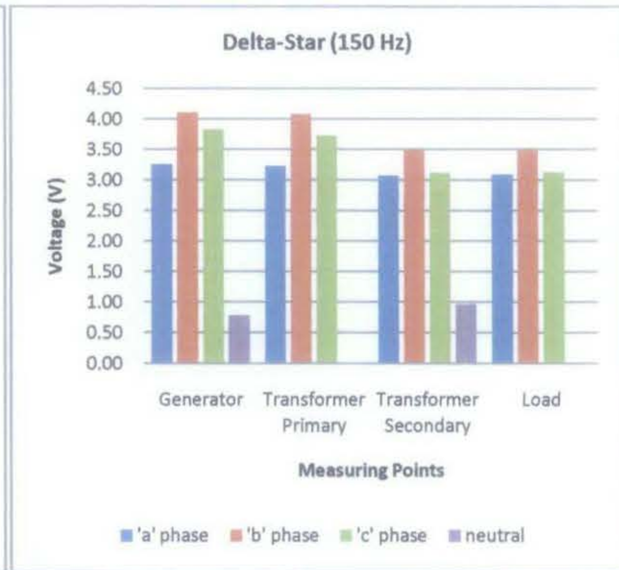
PART 1 : Generator Alone

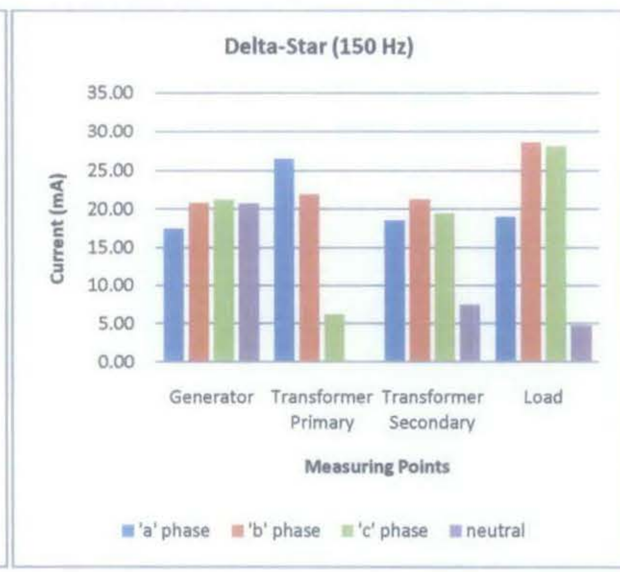
1.1 Resistive Load

1.1.1 Delta-Star Transformer Winding Configuration

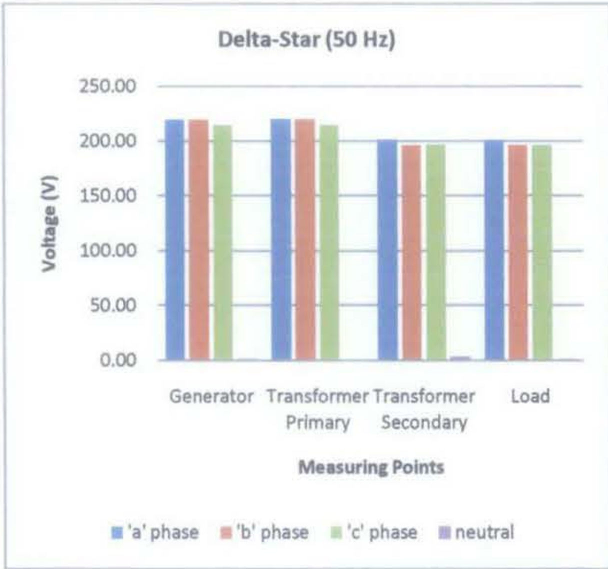
1.1.1.1 160 Ohm

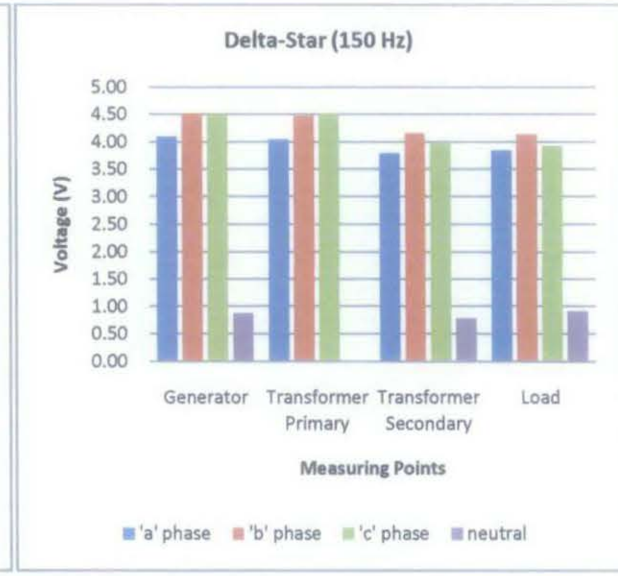


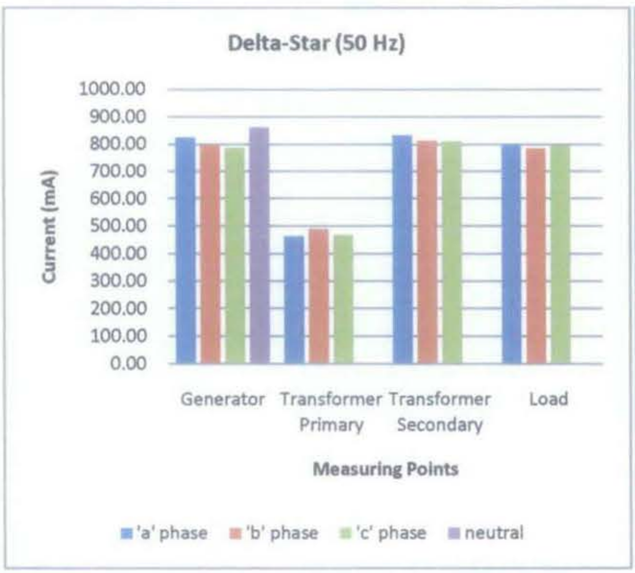


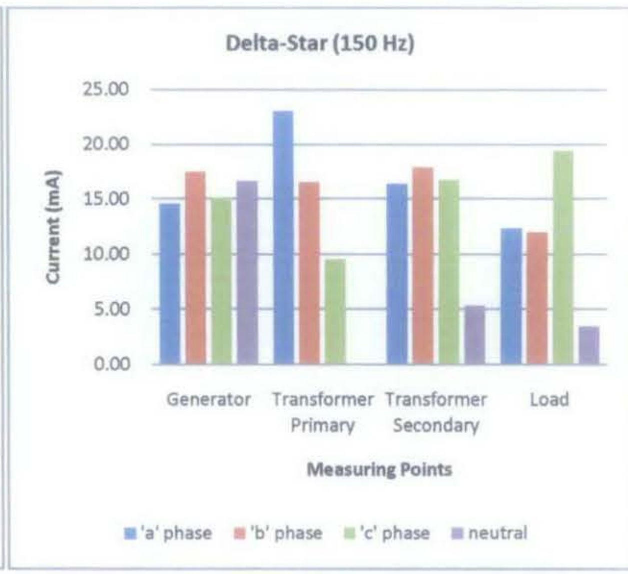


1.1.1.2 240 Ohm

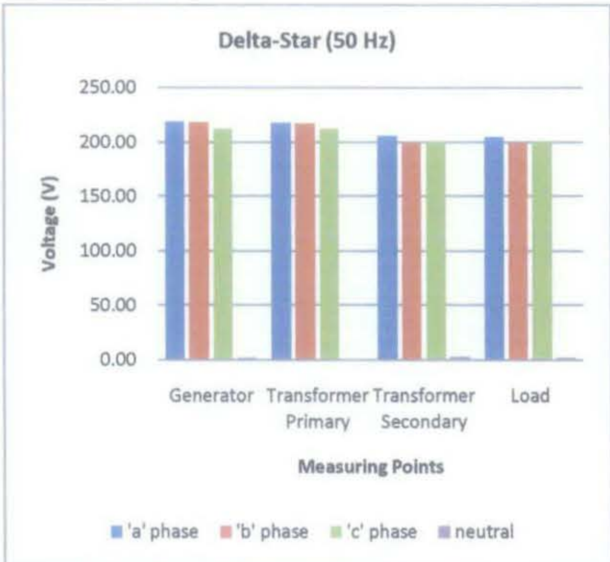

Delta-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

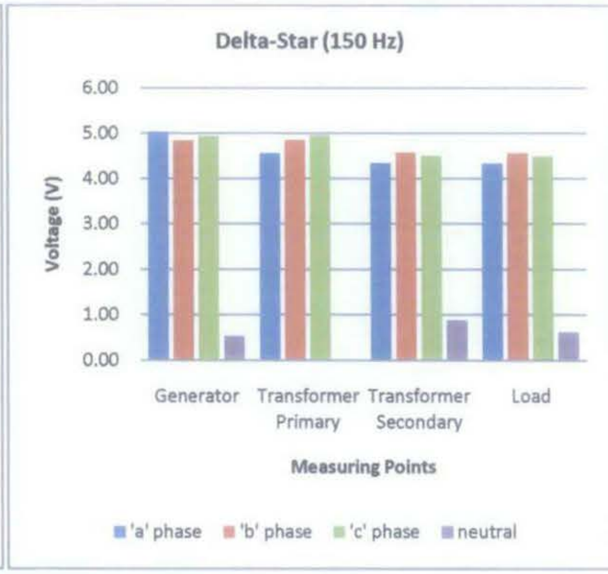

Delta-Star (150 Hz)
Voltage (V)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

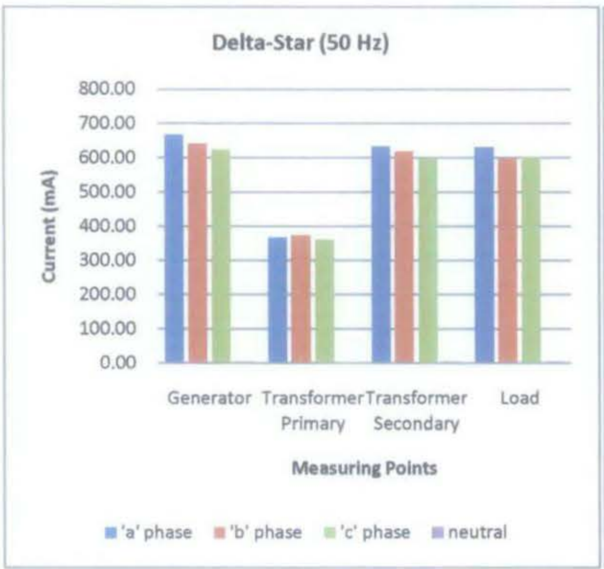

Delta-Star (50 Hz)
Current (mA)
1000.00
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

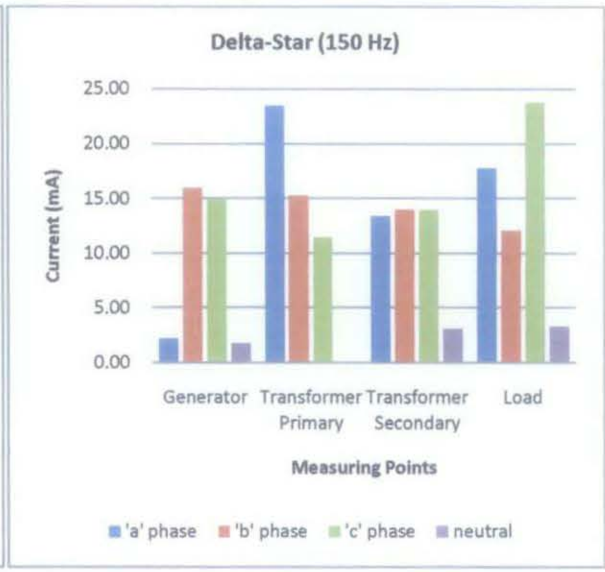

Delta-Star (150 Hz)
Current (mA)
25.00
20.00
15.00
10.00
5.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

1.1.1.3 320 Ohm

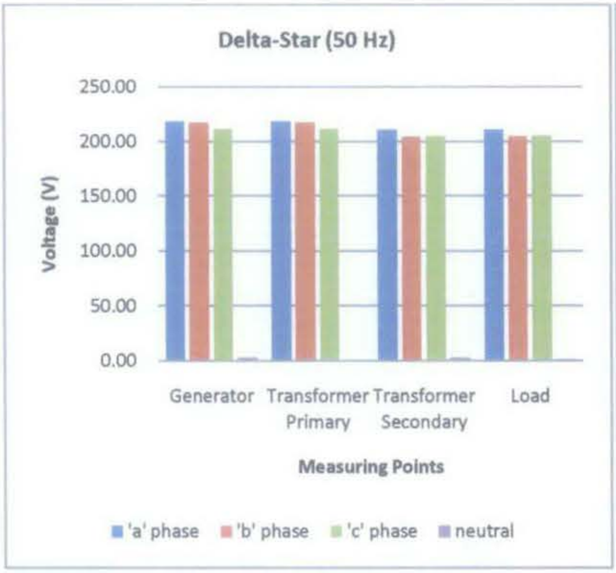

Delta-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

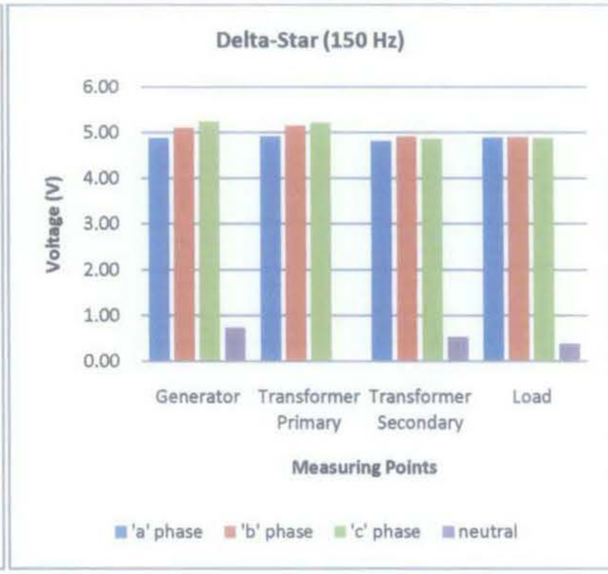

Delta-Star (150 Hz)
Voltage (V)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral


Delta-Star (50 Hz)
Current (mA)
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

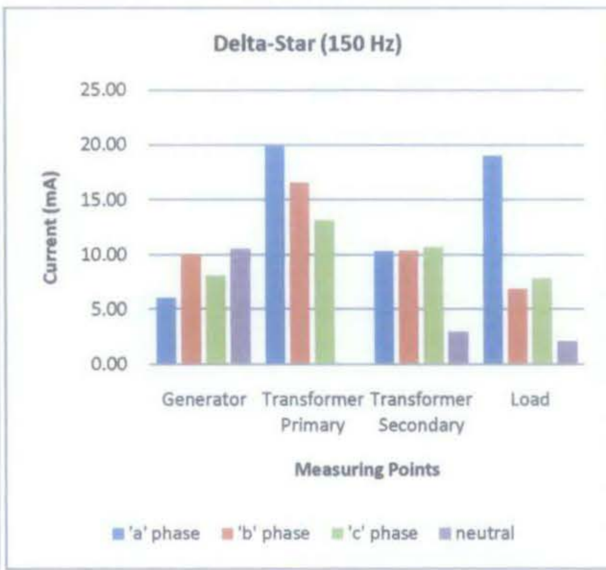

Delta-Star (150 Hz)
Current (mA)
25.00
20.00
15.00
10.00
5.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

1.1.1.4 480 Ohm


Delta-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

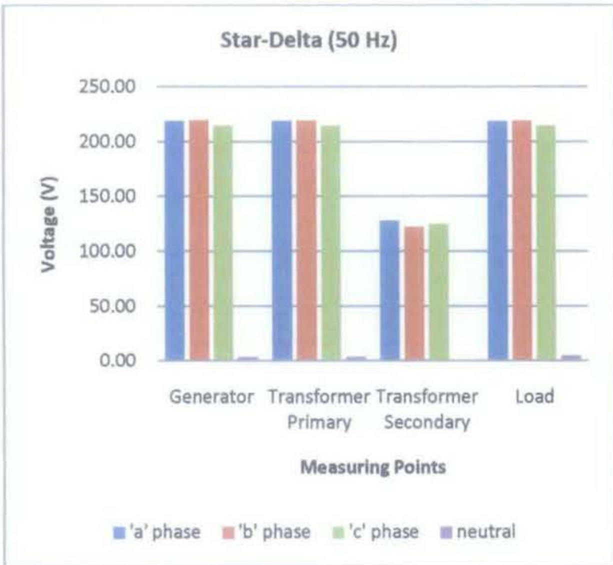

Delta-Star (150 Hz)
Voltage (V)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

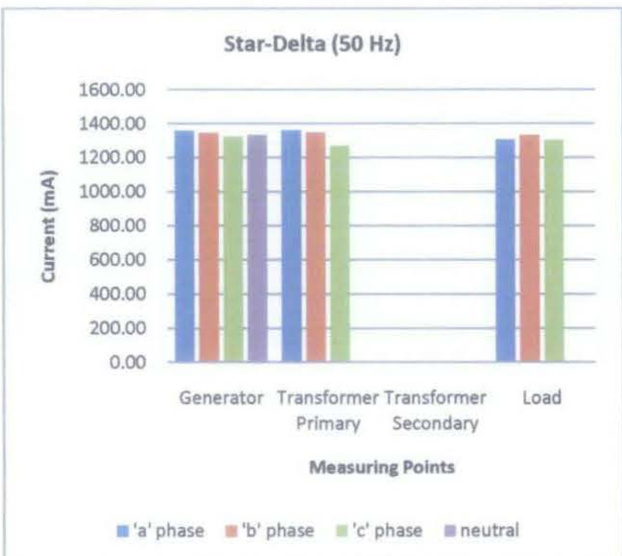

Delta-Star (50 Hz)
Current (mA)
500.00
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

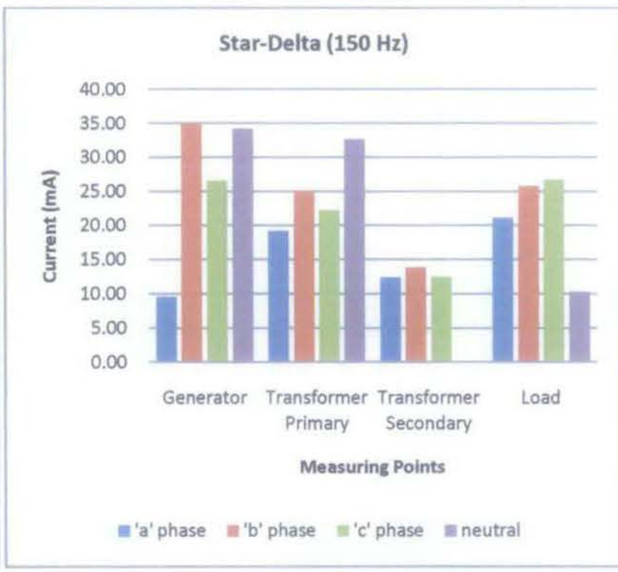

Delta-Star (150 Hz)
Current (mA)
25.00
20.00
15.00
10.00
5.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

1.1.2 Star-Delta Transformer Winding Configuration

1.1.2.1 160 Ohm

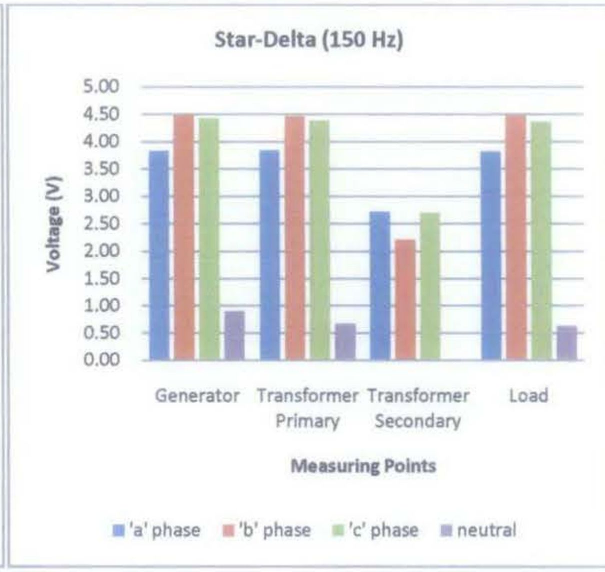




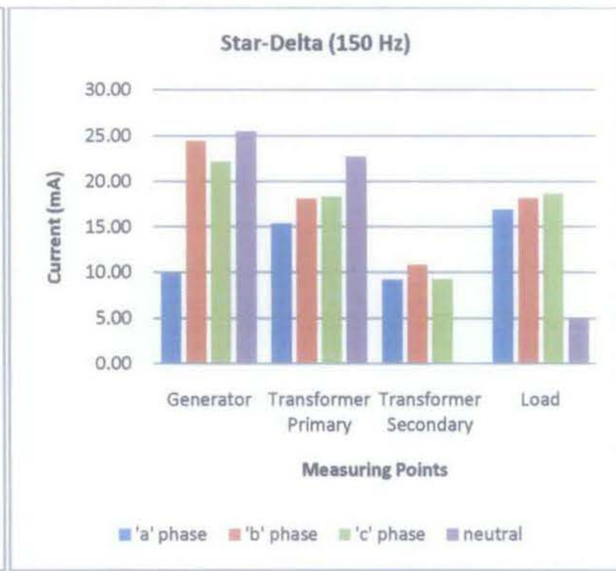


1.1.2.2 240 Ohm

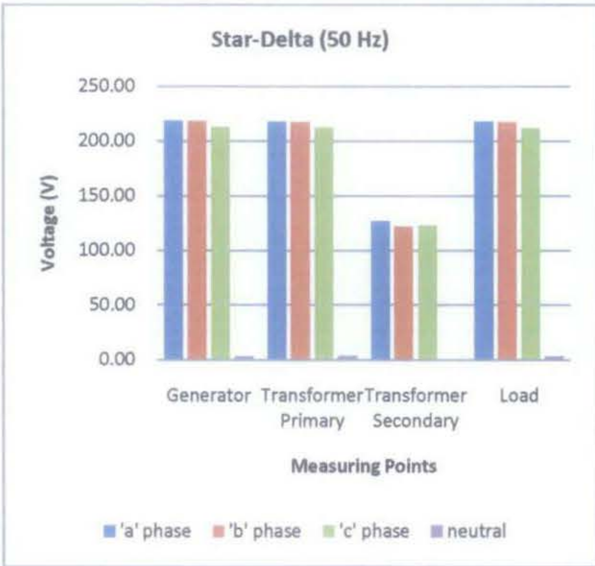

Star-Delta (50 Hz)
250.00
200.00
150.00
100.00
50.00
0.00
Voltage (V)
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral


Star-Delta (150 Hz)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Voltage (V)
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

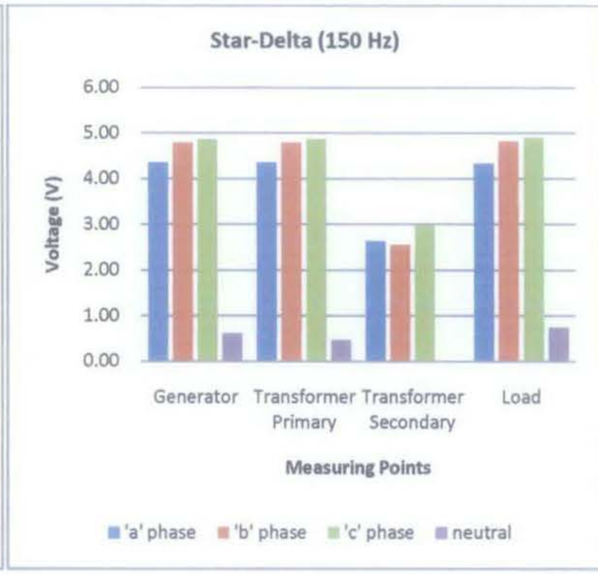

Star-Delta (50 Hz)
1000.00
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Current (mA)
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral


Star-Delta (150 Hz)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Current (mA)
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

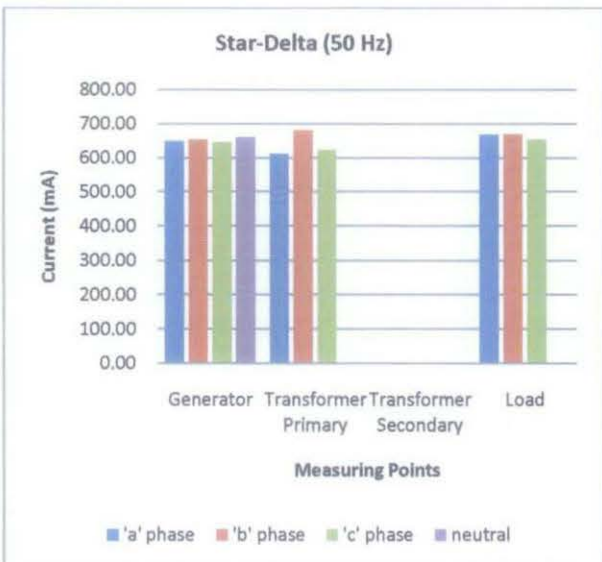
1.1.2.3 320 Ohm



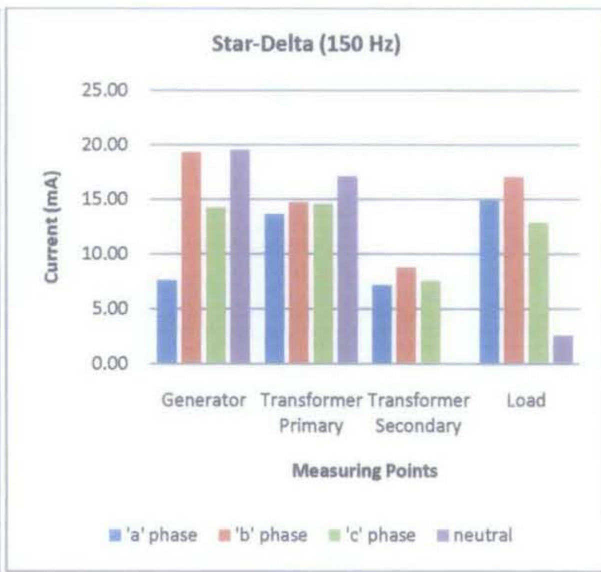
Star-Delta (50 Hz)
250.00
200.00
150.00
100.00
50.00
0.00
Voltage (V)
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral



Star-Delta (150 Hz)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Voltage (V)
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral



Star-Delta (50 Hz)
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Current (mA)
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral



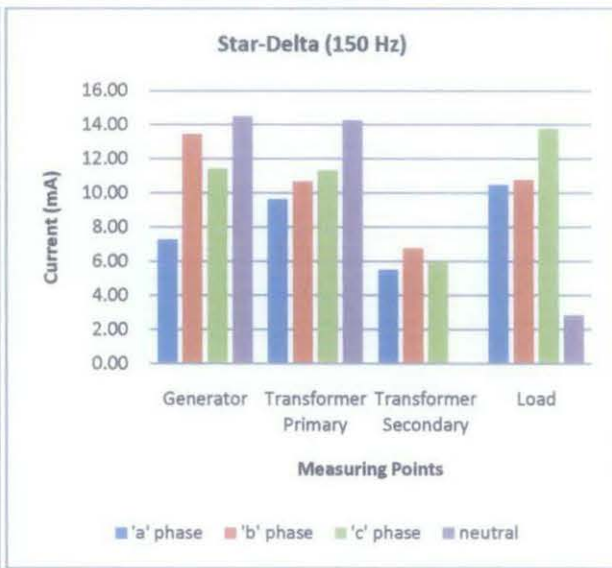
Star-Delta (150 Hz)
25.00
20.00
15.00
10.00
5.00
0.00
Current (mA)
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

1.1.2.4 480 Ohm


Star-Delta (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

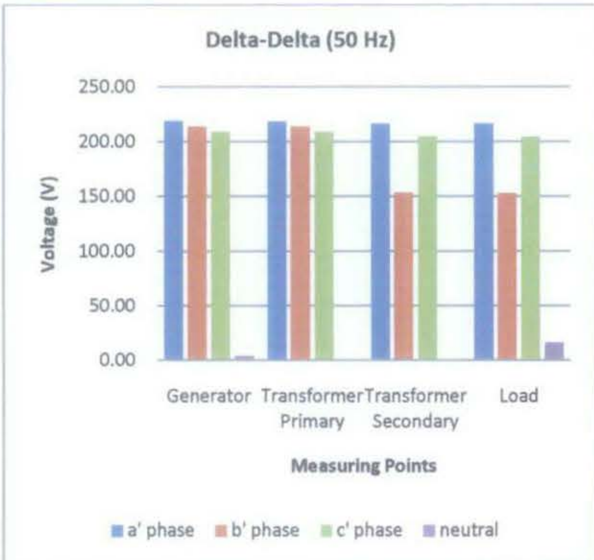

Star-Delta (150 Hz)
Voltage (V)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

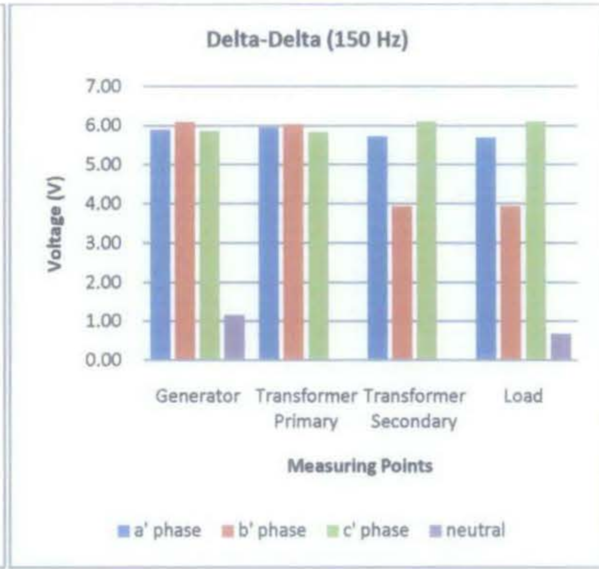

Star-Delta (50 Hz)
Current (mA)
500.00
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

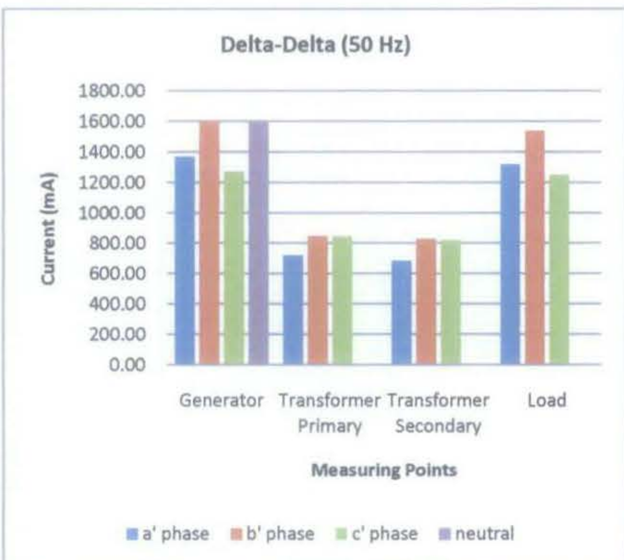

Star-Delta (150 Hz)
Current (mA)
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
'a' phase
'b' phase
'c' phase
neutral

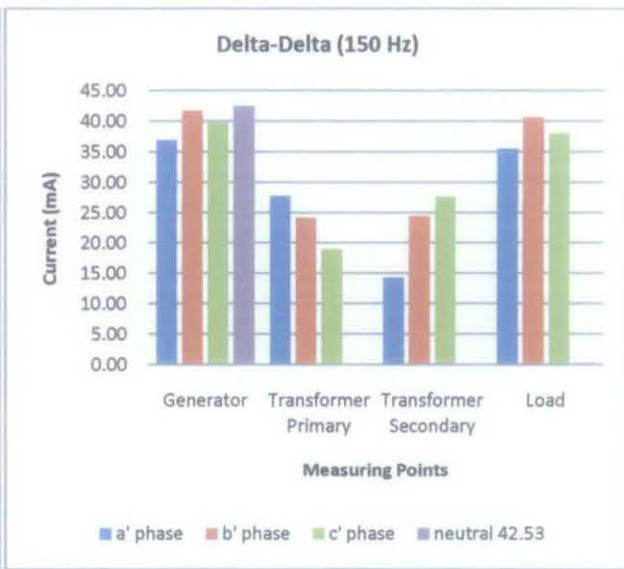
1.1.3 Delta-Delta Transformer Winding Configuration

1.1.3.1 160 Ohm

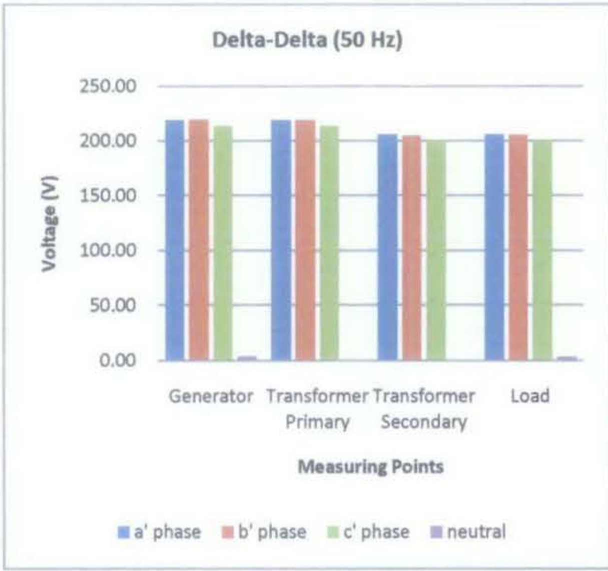


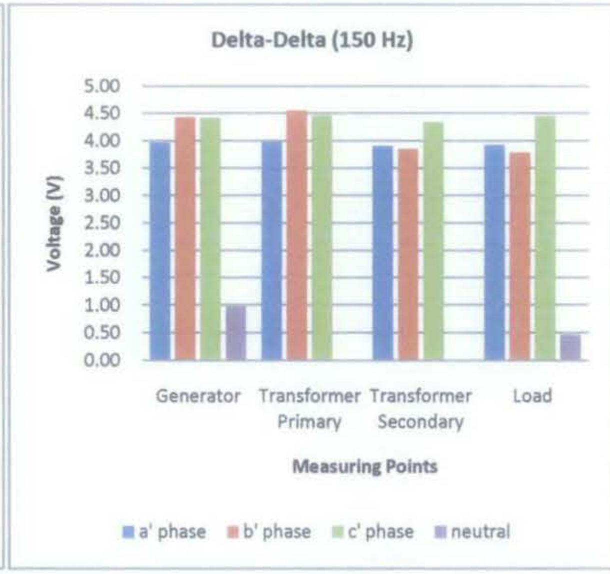


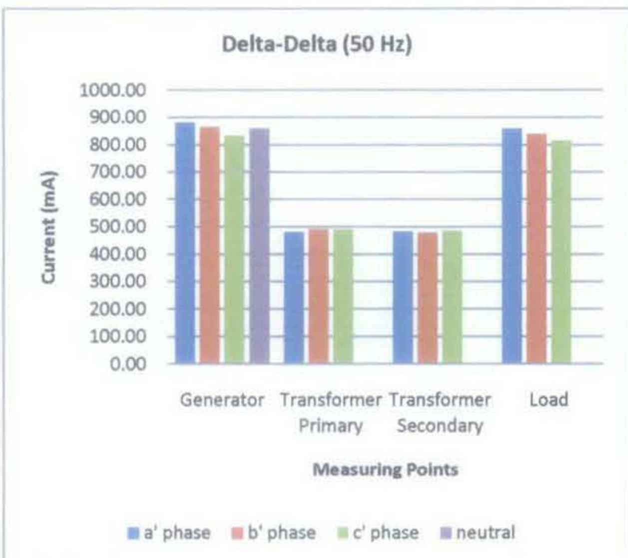


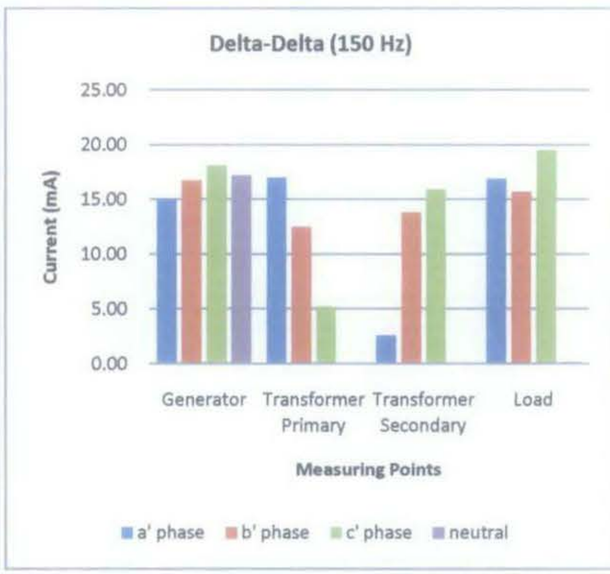


1.1.3.2 240 Ohm

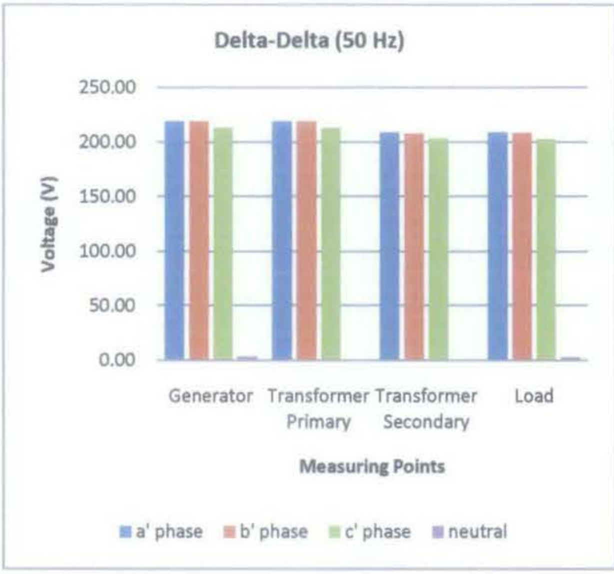

Delta-Delta (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

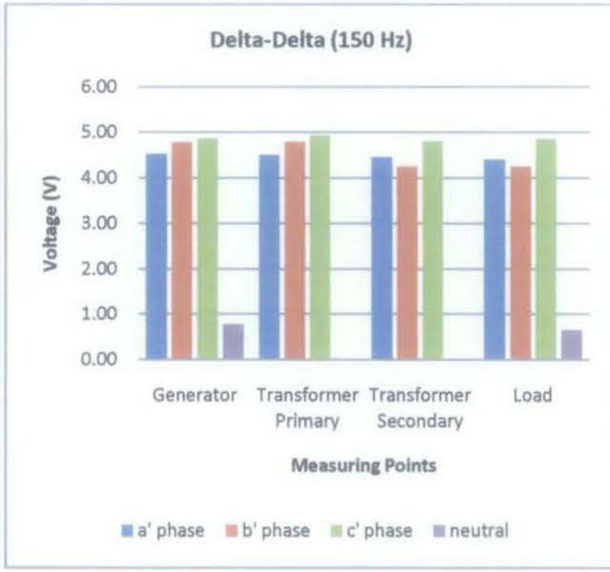

Delta-Delta (150 Hz)
Voltage (V)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

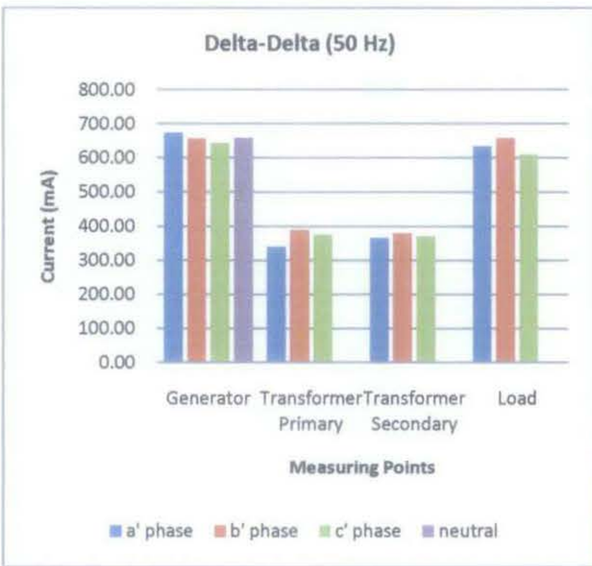

Delta-Delta (50 Hz)
Current (mA)
1000.00
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

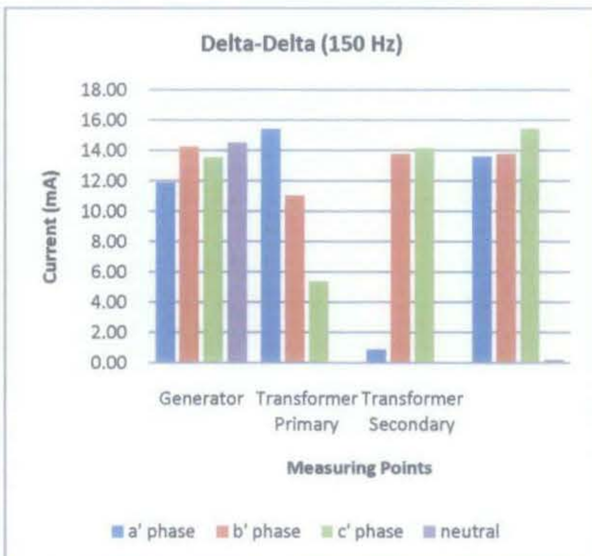

Delta-Delta (150 Hz)
Current (mA)
25.00
20.00
15.00
10.00
5.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

1.1.3.3 320 Ohm

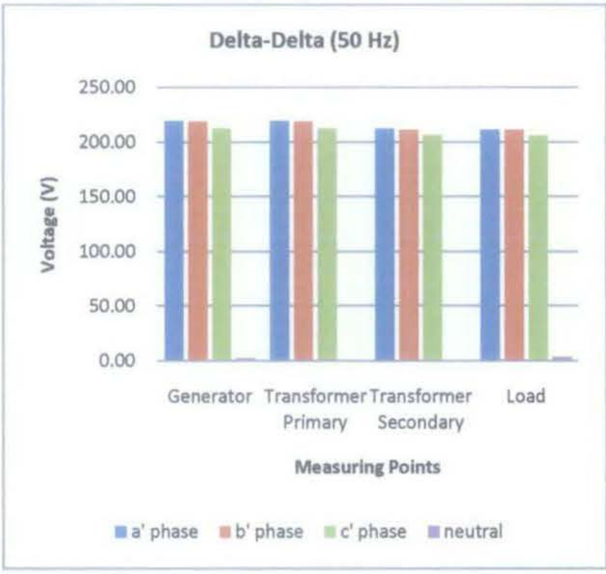

Delta-Delta (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

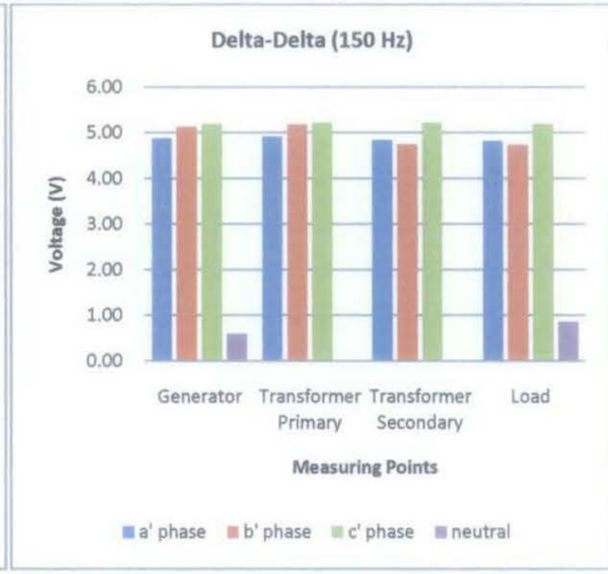

Delta-Delta (150 Hz)
Voltage (V)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

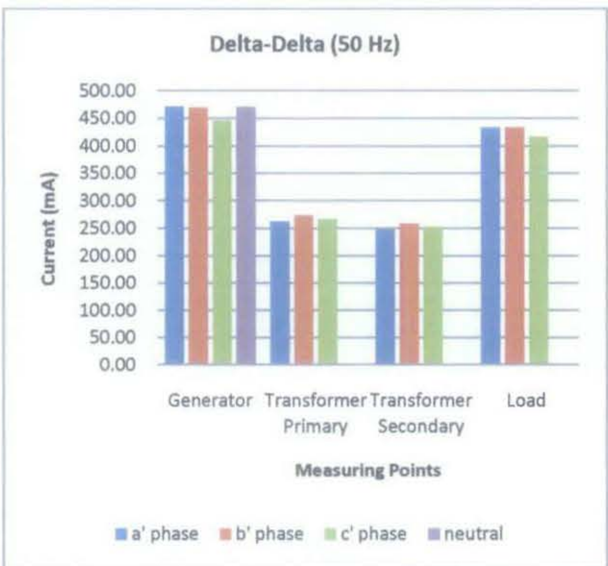

Delta-Delta (50 Hz)
Current (mA)
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

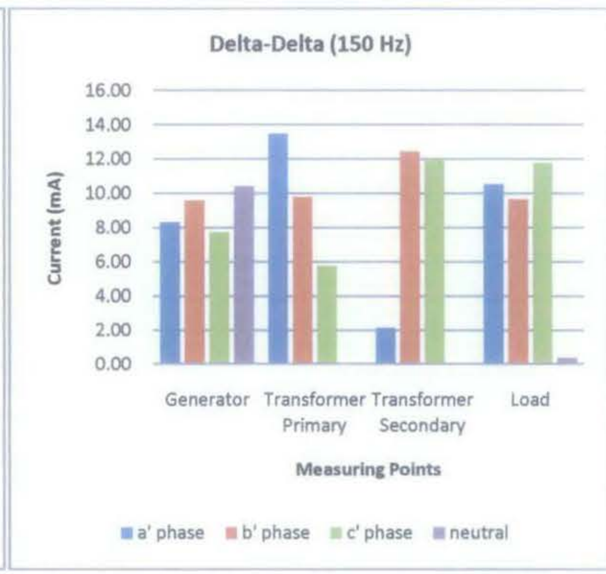

Delta-Delta (150 Hz)
Current (mA)
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Generator
Transformer Primary
Transformer Secondary
Measuring Points
a' phase
b' phase
c' phase
neutral

1.1.3.4 480 Ohm


Delta-Delta (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

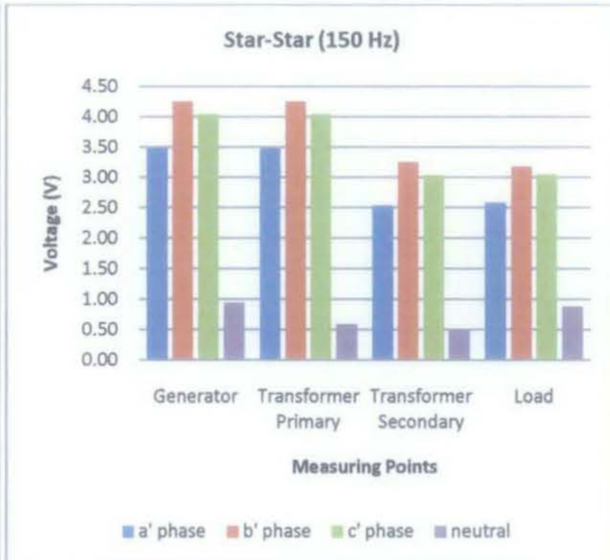

Delta-Delta (150 Hz)
Voltage (V)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

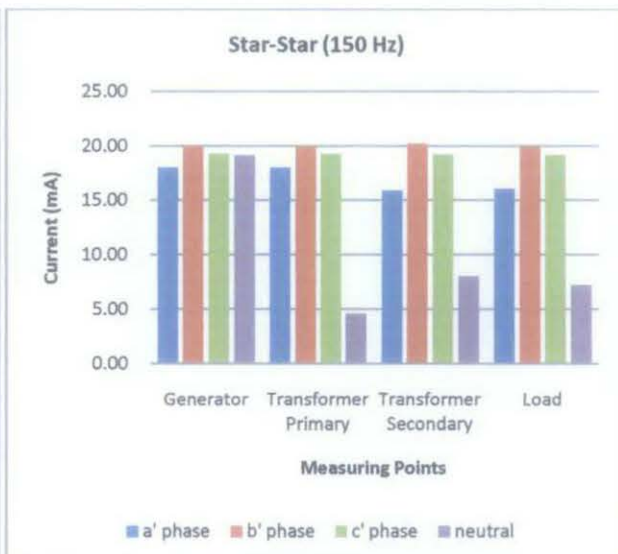

Delta-Delta (50 Hz)
Current (mA)
500.00
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral


Delta-Delta (150 Hz)
Current (mA)
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

1.1.4 Star-Star Transformer Winding Configuration

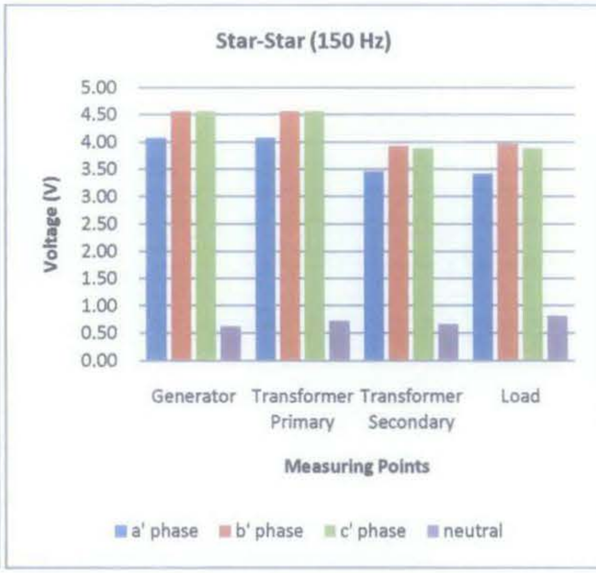
1.1.4.1 160 Ohm





1.1.4.2 240 Ohm

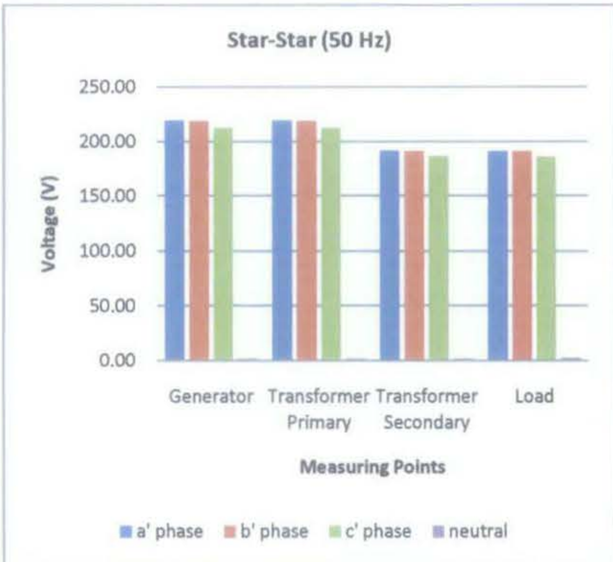

Star-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral


Star-Star (150 Hz)
Voltage (V)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral


Star-Star (50 Hz)
Current (mA)
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral


Star-Star (150 Hz)
Current (mA)
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

1.1.4.3 320 Ohm



Star-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

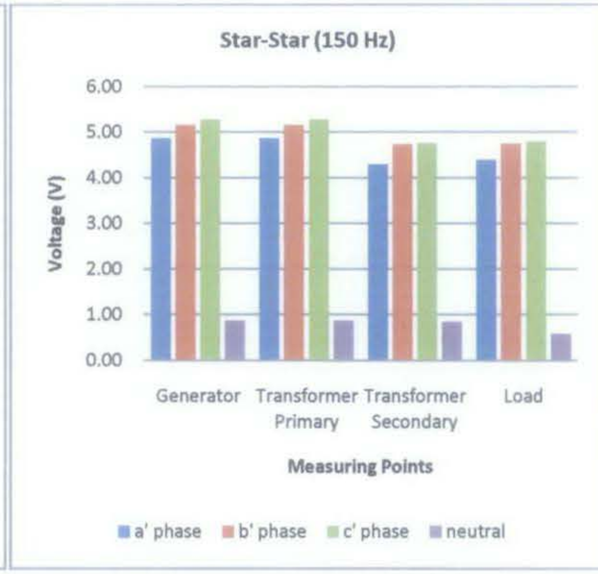
Star-Star (150 Hz)
Voltage (V)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

Star-Star (50 Hz)
Current (mA)
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

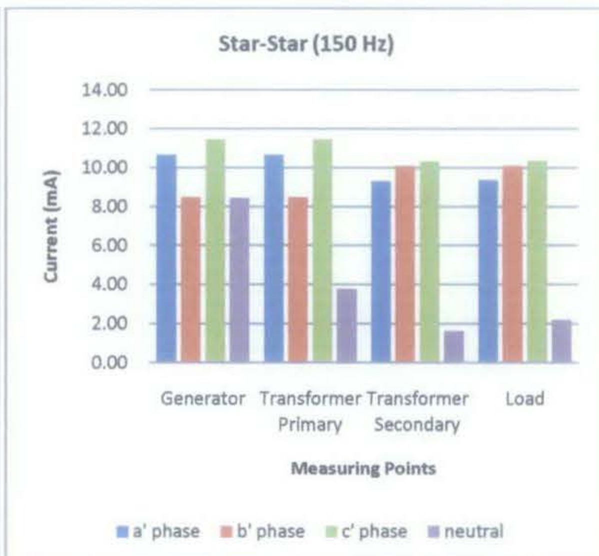
Star-Star (150 Hz)
Current (mA)
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

1.1.4.4 480 Ohm


Star-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral


Star-Star (150 Hz)
Voltage (V)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral


Star-Star (50 Hz)
Current (mA)
500.00
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

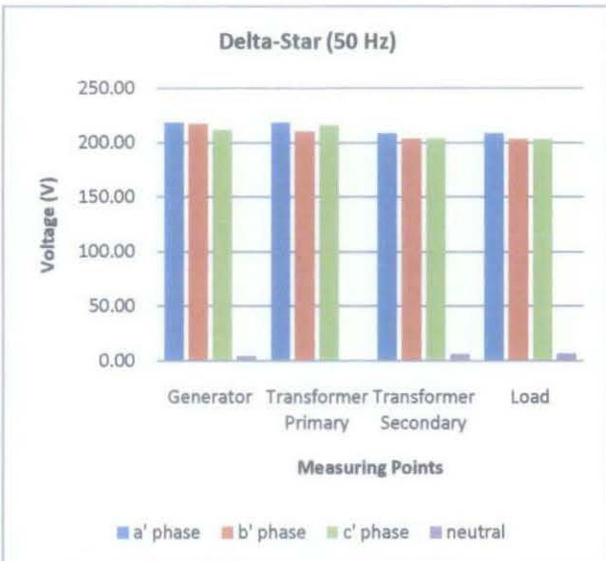

Star-Star (150 Hz)
Current (mA)
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

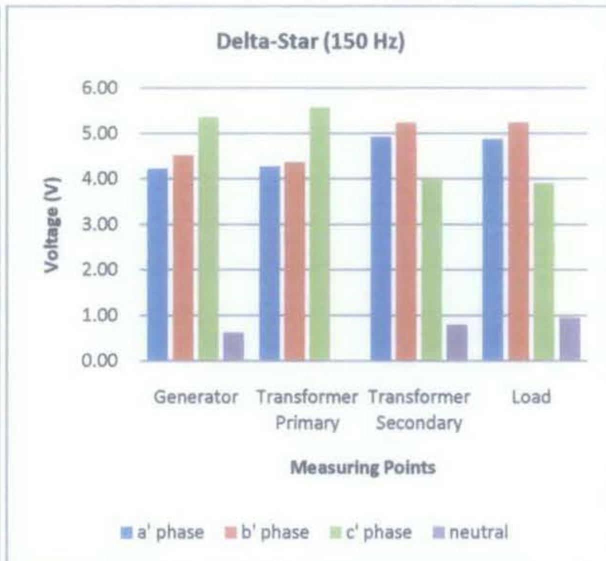
APPENDIX C

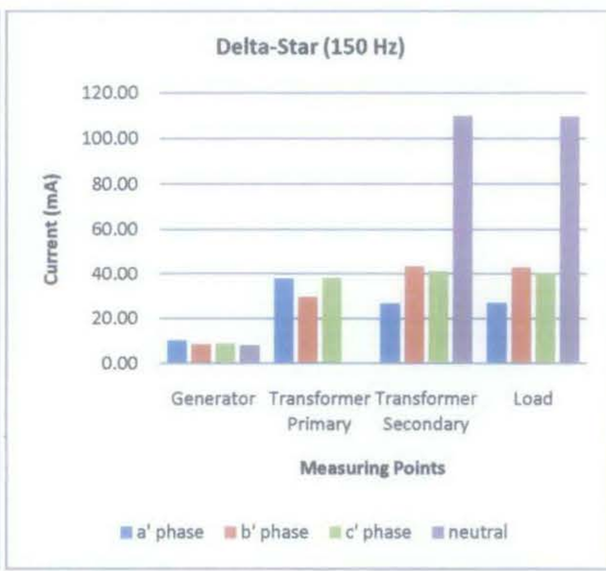
1.2 Inductive Load

1.2.1 Delta-Star Transformer Winding Configuration

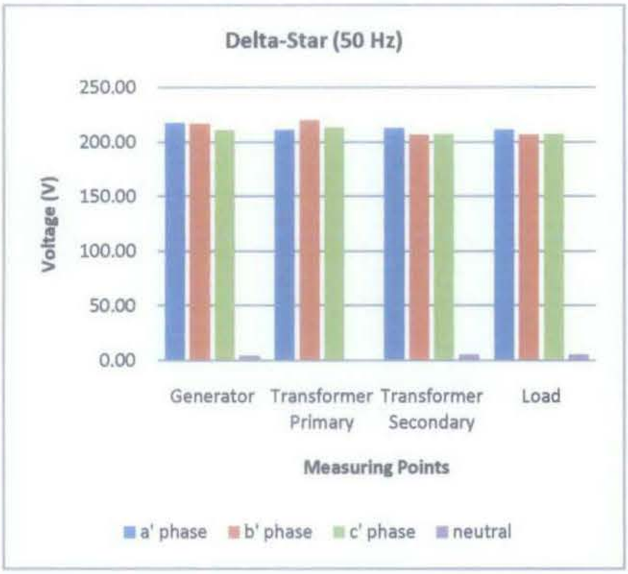
1.2.1.1 0.51 H



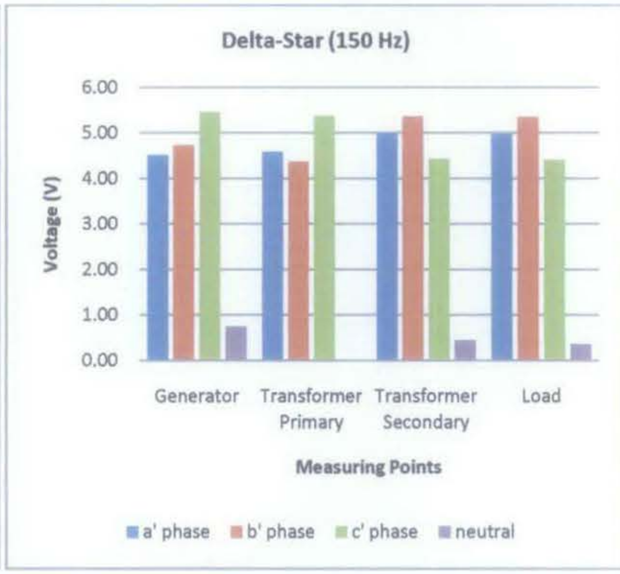




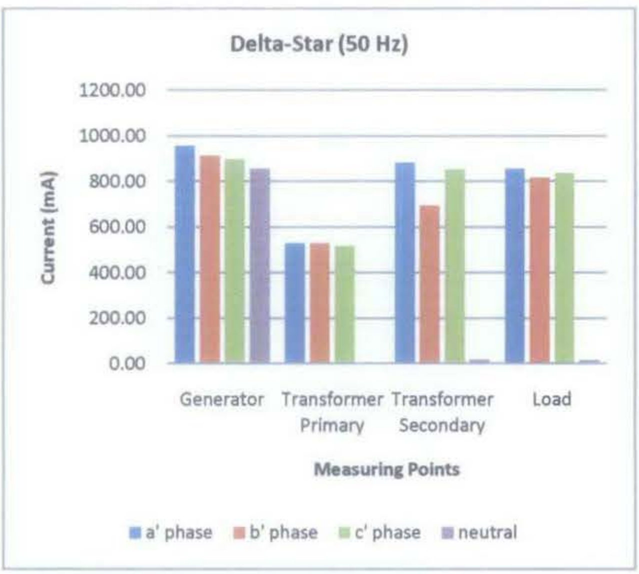
1.2.1.2 0.76 H



Delta-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral



Delta-Star (150 Hz)
Voltage (V)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral



Delta-Star (50 Hz)
Current (mA)
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

Delta-Star (150 Hz)
Current (mA)
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Generator
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

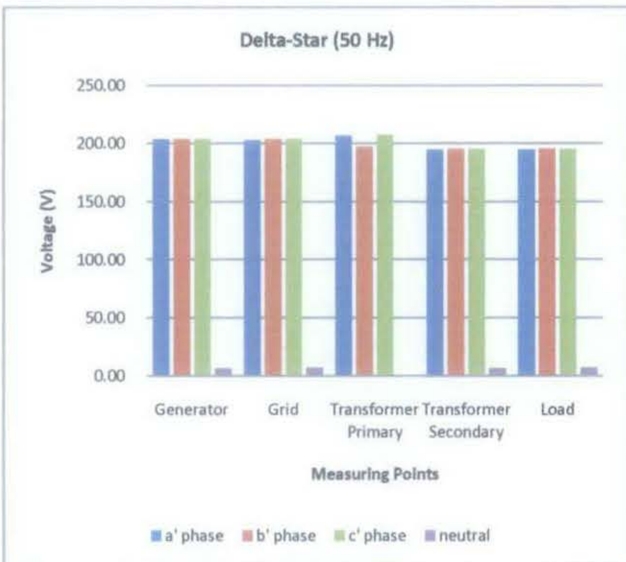
APPENDIX D

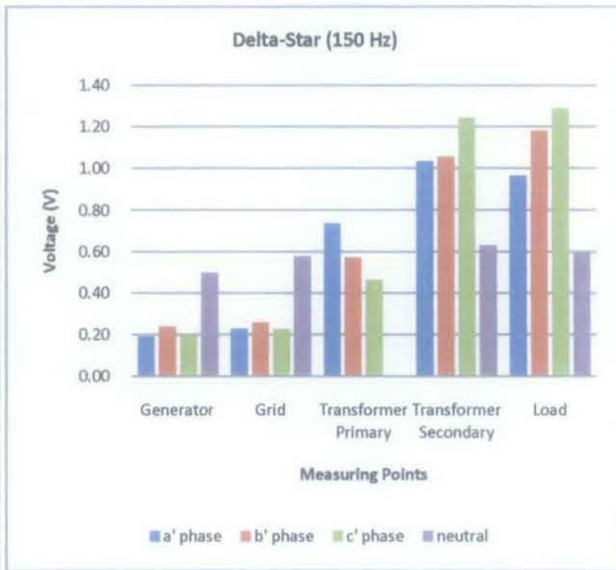
PART 2 : Generator Parallel with Grid

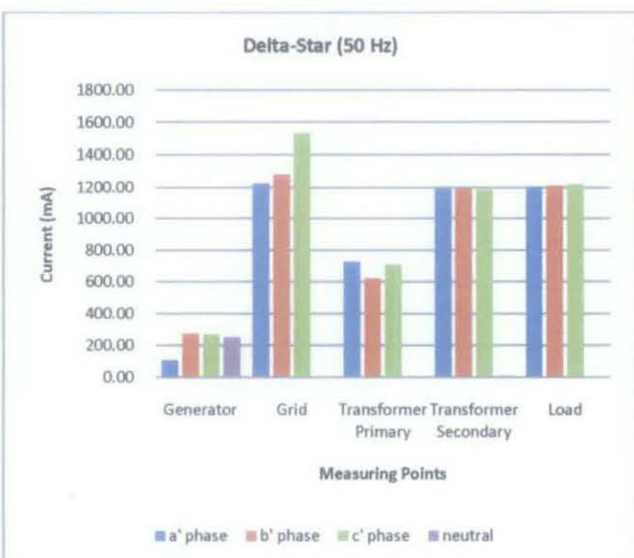
2.1 Inductive Load

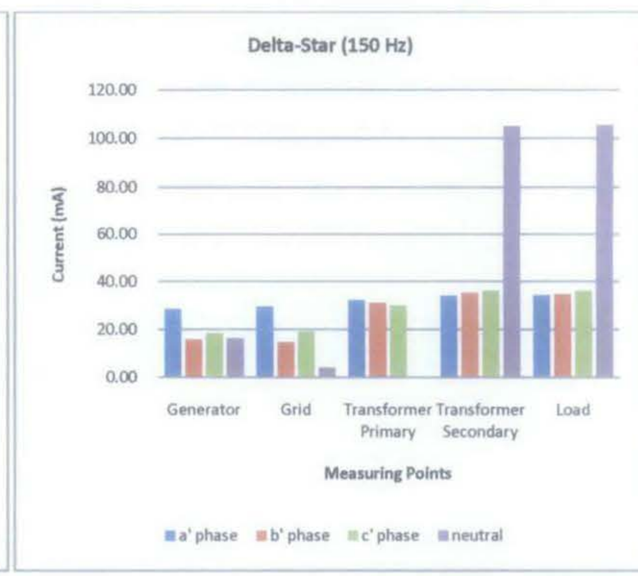
2.1.1 Delta-Star Transformer Winding Configuration

2.1.1.1 0.51 H

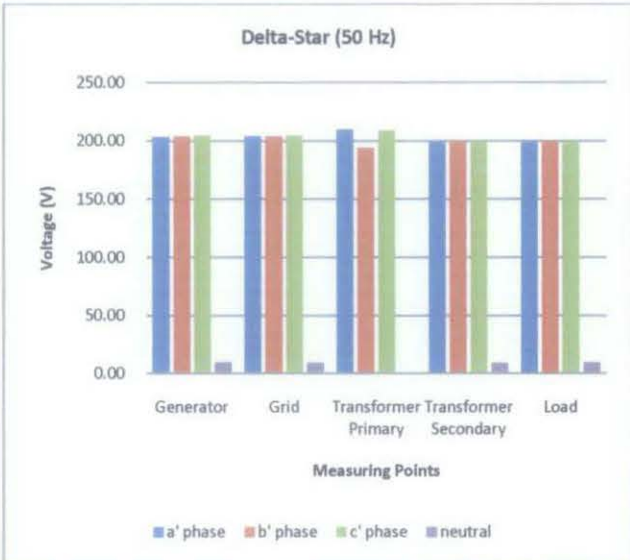




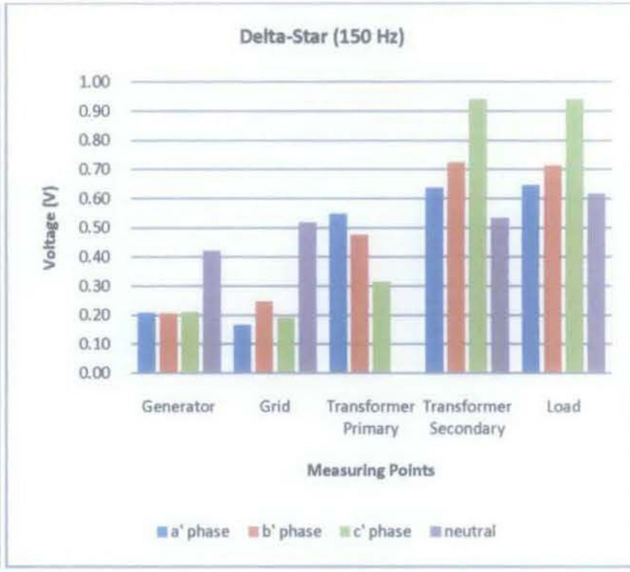




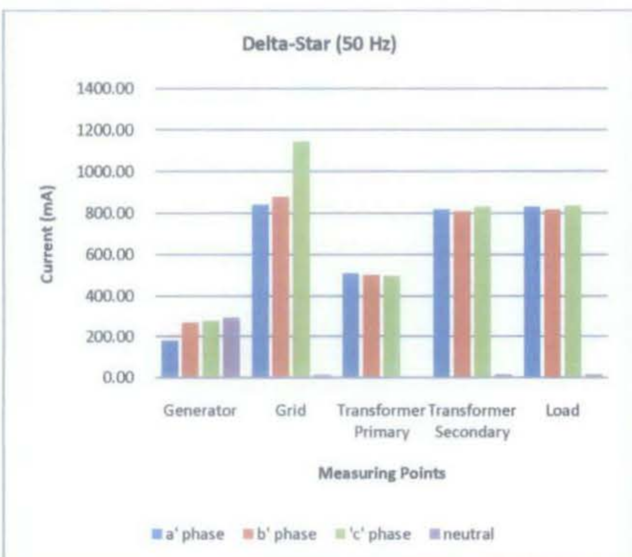
2.1.1.2 0.76 H



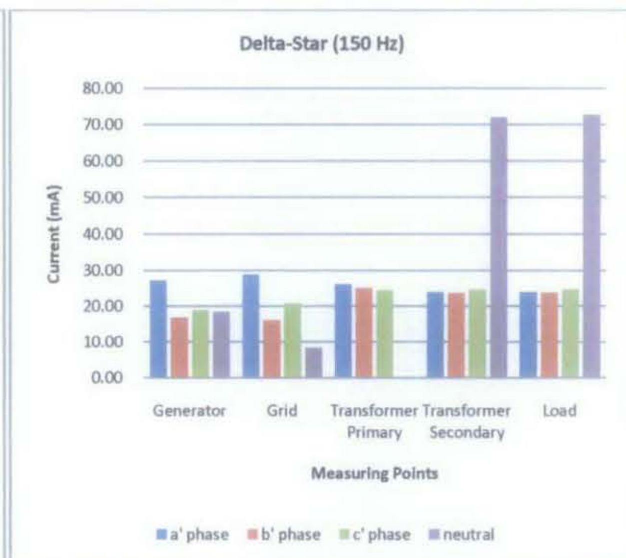
Delta-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral



Delta-Star (150 Hz)
Voltage (V)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

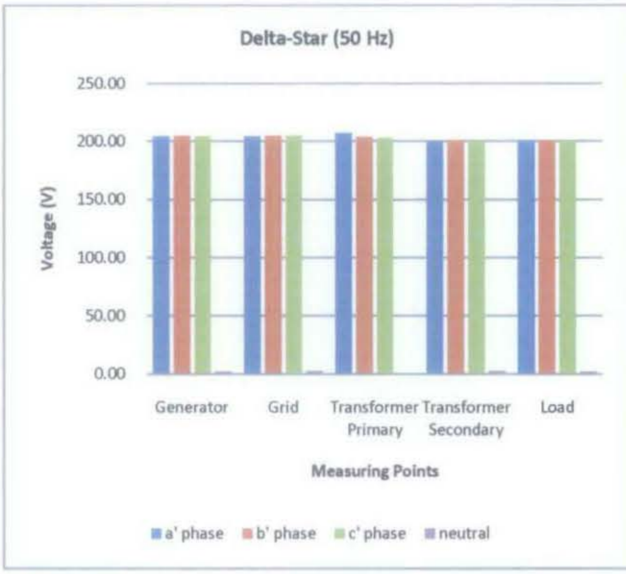


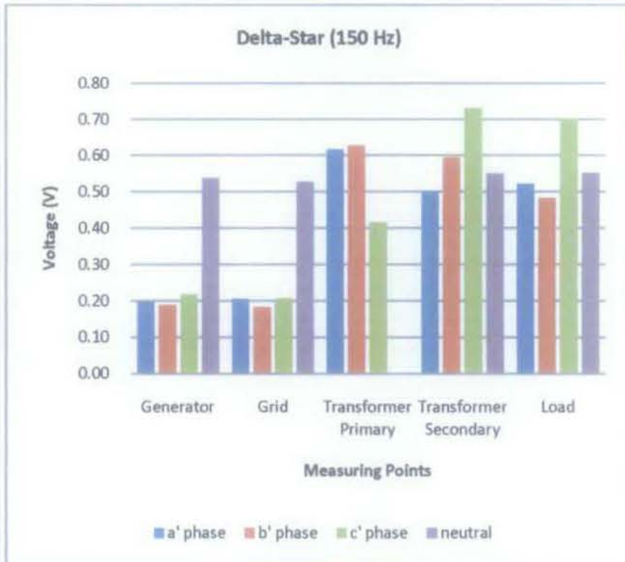
Delta-Star (50 Hz)
Current (mA)
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
'c' phase
neutral

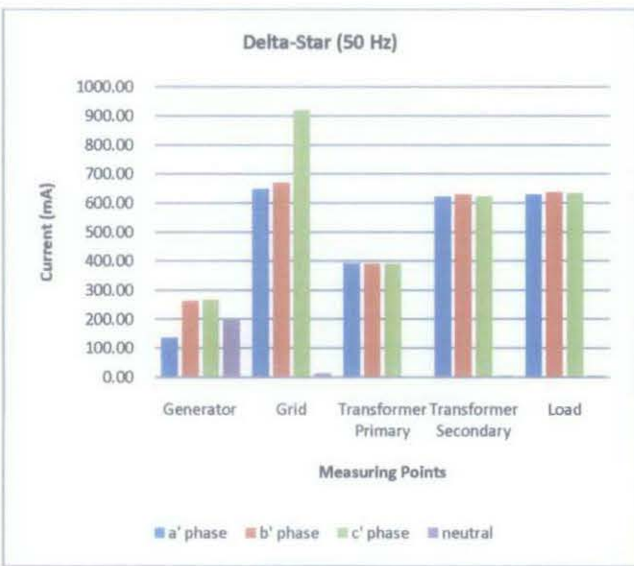


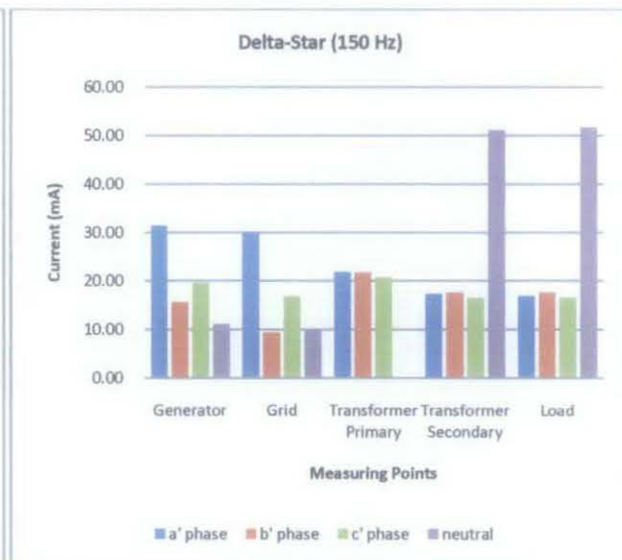
Delta-Star (150 Hz)
Current (mA)
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

2.1.1.3 1.02 H

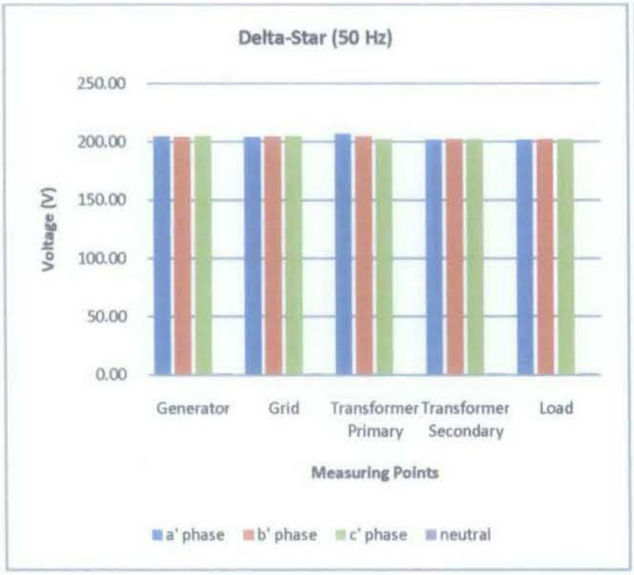

Delta-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

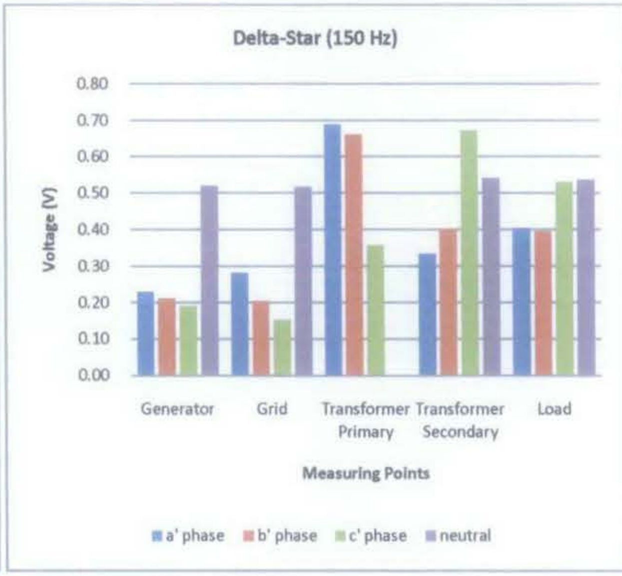

Delta-Star (150 Hz)
Voltage (V)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

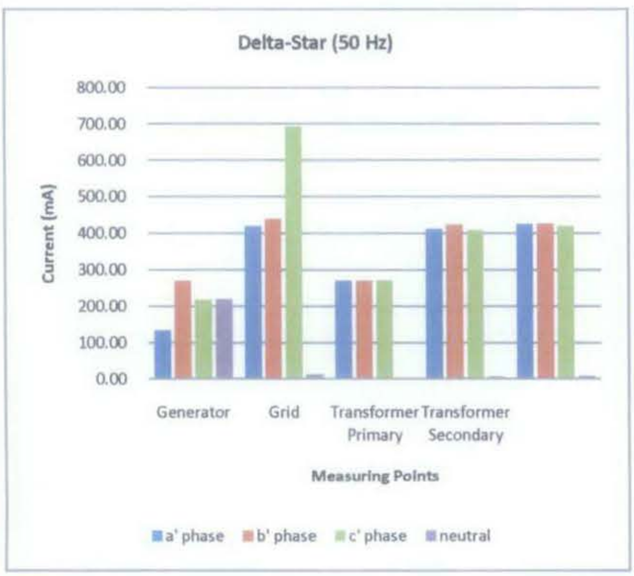

Delta-Star (50 Hz)
Current (mA)
1000.00
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

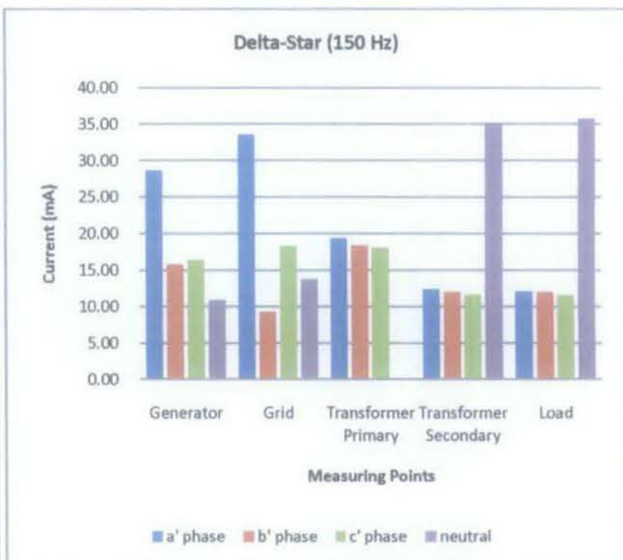

Delta-Star (150 Hz)
Current (mA)
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral

2.1.1.4 1.53 H


Delta-Star (50 Hz)
Voltage (V)
250.00
200.00
150.00
100.00
50.00
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral


Delta-Star (150 Hz)
Voltage (V)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral


Delta-Star (50 Hz)
Current (mA)
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Measuring Points
a' phase
b' phase
c' phase
neutral


Delta-Star (150 Hz)
Current (mA)
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Generator
Grid
Transformer Primary
Transformer Secondary
Load
Measuring Points
a' phase
b' phase
c' phase
neutral