The Study of Third Harmonic Current Contribution

During Three phase-to-ground Fault

by

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CERTIFICATION OF APPROVAL

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(ELECTRICAL AND ELETRONICS)

Approved by,

____

(Ir Mohd Faris bin Abdullah)

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January 2015

CERTIFICATION OF ORIGINALITY

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

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NG JING CI

ABSTRACT

Harmonic is defined as the voltage and current distortion in the waveform. It exists from the source such as synchronous generator and non-linear load. Third harmonic is the presence of voltage and current distortion expressed in terms of harmonics frequencies 150 Hz. During three phase-to-ground fault, the fundamental fault current share the same return path as third harmonic. Thus, the synchronous generator is used as the source of third harmonic in the lab experiment to investigate the characteristic of third harmonic and the amount of its contribution to the system during three phase-to-ground fault. In the experiment, the variables that are varied including the fault impedance (Zf), filter mode (by zig-zag transformer) and Neutral Earthing Resistor (NER). The load impedance sets are also changed to study how the load can affect the contribution of third harmonic current. The ratio of third harmonic current to fundamental current is computed and compared where the ratio has increased 0.73 % with NER and 31.56 % without NER under normal mode. The overall fault level is compared under normal mode and filter mode whereby it is found that the contribution of third harmonic to the system has reduced to half using filter: zig-zag transformer. The third harmonic current from synchronous generator contributes to the overall fault level of the system during three phase-to-ground fault.

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ABBREVATIONS AND NOMENCLATURES

NER =Neutral Earth Resistor

Zf =Fault Impedance

EMS =Electromechanical System

CHAPTER 1
INTRODUCTION

1.1 Background of Study

It has been discovered that the existence of the voltage and current waveforms distortion on the mains supply waveforms which are termed as harmonic current and voltage in power system. Third harmonic component can be originated from generators, transformers, non-linear loads and etc.

There are odd and even harmonic where odd harmonic is mostly originated from non-linear loads and salient pole generator in terms of harmonics frequencies which are odd integer multiples of the generated frequency. Sources of harmonic generate odd harmonic and most of them will be triplen harmonic which are 3^{rd}, 9^{th}, 15^{th} and etc. The magnitude of higher order harmonic can be neglected because the value is generally small. Hence, third harmonic is the main current and voltage distortion in the waveform which can cause overloading to the equipment.

Fault happened when there is very high current flowing in the circuit following the improper path. When all the three-phases of the system are short-circuit to ground then it is called three phase-to-ground fault. It does not happen frequently but it is the high severity and dangerous fault.

1.2 Problem Statement

Third harmonic current continuously flow from synchronous generator and return to its neutral during steady state condition via neutral/ground path. During three phase-to-ground fault, the fundamental fault current also shares the same return path as third harmonic. Therefore, during this fault, there are uncertainties on third harmonic behaviour and its contribution towards the overall fault current.

1.3 Objectives

- To study on the characteristics of third harmonic current before and during three phase-to-ground fault
- To analyze on the contribution of third harmonic current during symmetrical fault: three-phase-to-ground fault

1.4 Scope of Study

The source of third harmonic in this research is origin from salient pole synchronous generator. During pre-fault condition, the salient pole synchronous generator is operating at rated speed and within its capacity. The fault type in this study is confined to three phase-to-ground fault only. The contribution of third harmonic current during this fault is measured and calculated in term of the ratio and percentage.

CHAPTER 2

LITERATURE REVIEW

Generally, electricity is generated under constant frequencies of 50 Hz or 60 Hz and the generator's e.m.f is considered practically sinusoidal. The resulting current might not be always perfectly sinusoidal, for example this happens due to the connection of non-linear device or load to a sinusoidal voltage source. This current with the existence of system impedance lead to the non-sinusoidal voltage drop as well as voltage distortion. The presence of voltage and current distortion can be expressed in terms of harmonics frequencies which are integer multiples of the generated frequency [1].

There are two types of harmonics namely odd harmonics (odd number 3,5,7,9,…) and even harmonics (even number 2,4,6,8,…). Number 0 and 1 are neither odd nor even harmonics. Harmonic number 0 is the constant or DC component of the waveform whereas harmonic number 1 is defined as fundamental frequency component of the waveform. The odd harmonics origin from non-linear loads and even harmonics exist only under certain condition [2]. In a balanced three phase system, phase voltages have the same magnitude but 120° apart and so does the phase current. The fundamental frequency current component relationship is described as below:

$$i_{a1=}I_{a1}\sin(\omega t) \quad (2.1)$$

$$i_{b1=}I_{b1}\sin(\omega t-120°) \quad (2.2)$$

$$i_{c1=}I_{c1}\sin(\omega t-240°) \quad (2.3)$$

The third harmonic phase currents are in phase:

$$i_{a3=}I_{a3}\sin(\omega t) \quad (2.4)$$

$$i_{b3=}I_{b3}\sin 3(\omega t-120°)=I_{b3}\sin(3\omega t-360°)=I_{b3}\sin(3\omega t) \quad (2.5)$$

$$i_{c3=}I_{c3}\sin 3(\omega t-240°)=I_{c3}\sin(3\omega t-720°)=I_{c3}\sin(3\omega t) \quad (2.6)$$

However, the fifth harmonics have opposite phase sequence as fundamental current (negative sequence circuit) whereas the phase sequence of seventh harmonics is same as the fundamental (positive sequence circuit). Positive and negative sequence having three-phase-to-neutral components of equal magnitude but 120° apart add vectorially to zero at the generator neutral. Moreover, the magnitude of higher order harmonics voltage in zero sequence (6,9,12,…) is generally small and can be neglected [2] [3] .

Third harmonic can cause effect on power systems as well as communication network based on their sensitivity to harmonics. Resonances in harmonics might be existed which will lead to increase in current and voltage of the device and initiate the increment of network losses. These may cause overheating and damage as well as reduction of insulation material's life time [1].

The observation of [4] states that the magnitude of the third harmonic current is affecting the third harmonic voltage magnitude where they are in proportion. Harmonics generally generated by converters, transformers, rotating machines, arc furnaces, fluorescent lighting and etc. Due to the practical and economical design of electrical machines, they are also the main source of the harmonics. The magnetic flux in a machine rarely distributed perfectly around the air gap, particularly in salient pole machines [1]. Salient pole synchronous generator is used as the source of triplen harmonics currents to observe the influence of load impedance, generator Neutral Earth Resistor (NER) value and transformer winding configurations. It is found that the third harmonic current in neutral is almost triple the phase current magnitude whereby the phase current magnitude are almost equal to each other. Both the magnitude of phase and neutral third harmonic currents are inversely proportional to the load impedance [5].

Third harmonic currents magnitude is also inversely proportional to generator NER resistance because the generator NER is in series connection with zero sequence network [4] [5]. An investigation is conducted by [6] on the temperature rise of NER when the generator is operating. It is found that during one generator and utility grid in parallel connection, high amount of triplen harmonics currents flow through and lead to the high NER temperature. The presence of third harmonic has caused overheating of equipment, destruction to NER and etc. Long-term overheat on the generator NER may cause deterioration of the insulation life which might cause to failure if the situation proceed.

It is observed that the low voltage load connected to the delta-wye transformer are not causing effect to the third harmonic current since the delta winding of primary transformer is blocking the third harmonic current to flow towards the load [4]. Connecting load via delta-wye transformer connection, third harmonic voltage are observed almost in phase at generator side but not at load and both transformer windings. On the other hand, third harmonic current are almost in phase at load and both transformer winding but not at generator [7].

Fault or short circuit study is important where the power system can be designed for correct protection grading and the adequate rating selection of equipments such as switchgear and circuit breaker. Fault happen when there is very high current flowing in the circuit in the improper path. This can happen when the phase connection connected to another phase or to ground under certain circumstances [8]. It also could be due to insulation failure or mechanical damage in the equipment and natural events such as tree fallen on the cable.

There are two types of fault in power system namely symmetrical fault and unsymmetrical fault. Symmetrical fault/balanced fault occur when all the three-phases of the system are in short-circuit. There are few types of unsymmetrical fault which is unbalanced fault occur only to one or two phase of the system. Those include single line-to-ground, double line-to-ground or line-to-line. Compare to unsymmetrical fault, three phase-to-ground fault happens infrequently but it is the highest severity and dangerous fault among all [9]. Figure 1 illustrated three phase-to-ground fault.

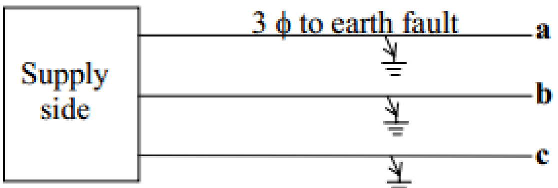

Figure 1: Three phase-to-ground fault

The higher harmonics in a ground fault current might affect and increased the voltage on the faulted phase. The impedance at the fault location with harmonics distortion is almost two times greater than the fault impedance (Zf) calculated at fundamental frequency which indirectly reduces the time to reach stable arcing. Disconnection of faulted feeders by simply perform low-ohmic resistance grounding is a suggested way to protect power equipment during single-phase-to-ground fault [10].

There are several application can be used to reduce third harmonic component of a distribution system which included derating the distribution transformer size by 50% or using three-phase four-wire active power filter [11] [12]. However, due to the high cost, connecting zig-zag transformer to the system is proposed to attenuate the third harmonic of the system. This is because zig-zag transformer is able to provide the path for zero sequence current. The result of the paper [12] proved that zig-zag transformer can effectively attenuate neutral current and zero sequence current under balanced non-linear load. Due to that, the total harmonic distortion (THD) also can be reduced. The circuit connection of zig-zag transformer is shown in Figure 2.

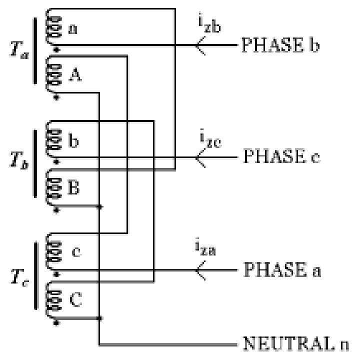

Figure 2: Zig-zag transformer circuit connection

CHAPTER 3
METHODOLOGY

3.1 Research Methodology

Lab-scale experiments are conducted using the equipments provided in the power system lab. The main focus of the experiment is to observe third harmonic current characteristic under two conditions: non-fault and three phase-to-ground fault. The flow chart of the experiment is shown in Figure 3.

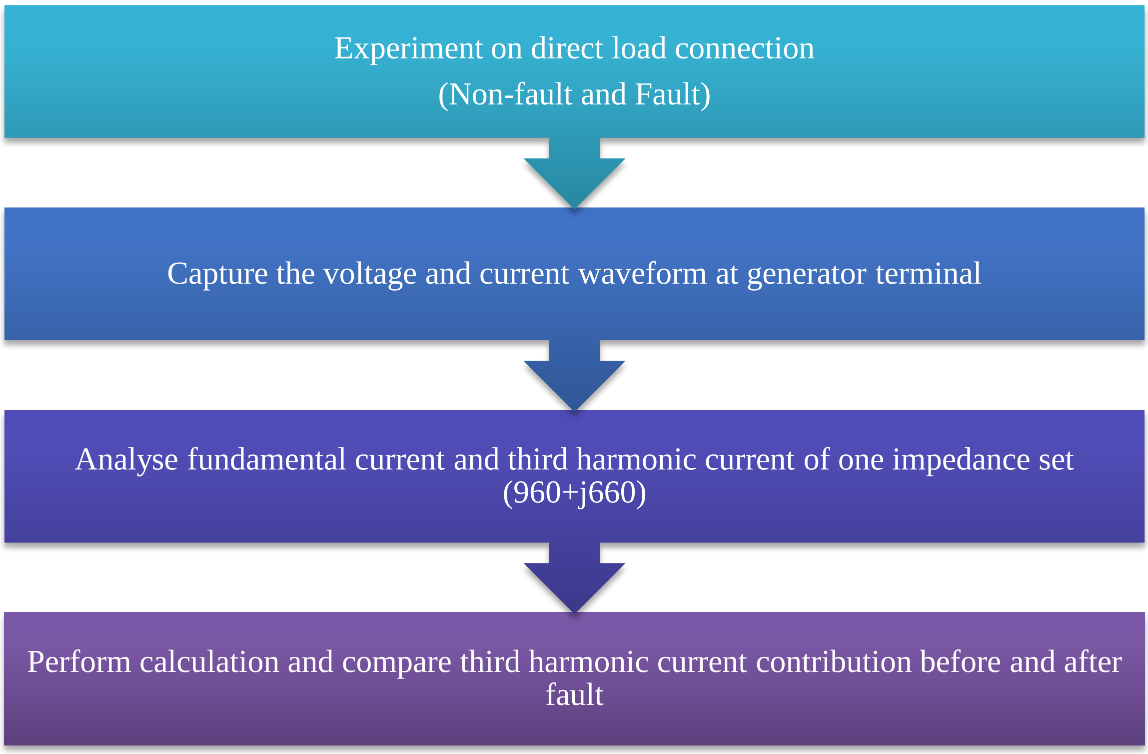

Figure 3: Flow chart of experiment

The synchronous generator as shown in Figure 4 is used as the source of third harmonic in this project. The voltage of the generator is 240 V with full-load-current of 0.17 A.

Figure 4: Synchronous generator

The base data of the experiment is obtained during the non-fault and used as the base value for the whole experiment. Fault which is supplying high current will be applied to create three phase-to-ground fault using universal fault module in fault experiment for analysis. Then, the comparison on the characteristics of the third harmonic current before and after fault occurred can be made.

In the experiment, load impedance sets used are listed in Table 1. There are 5 sets of them will be tested in the experiment. For each set of the load impedances, the value is determined by the resistive load and inductive load. The resistor load and inductance load value in the Electromechanical System (EMS) workstation can be adjusted to fulfill the listed impedance and inductance values by pushing the switch to 0 or 1 as shown in Figure 5.

Table 1: Load impedance sets

Resistance (Ω)	Inductance (Ω)	Impedance(Ω)
960	660	1165∠34.5
1600	1194	1996∠36.7
2400	1602	2886∠33.7
3600	2388	4320∠33.6
4800	3581	5989∠36.7

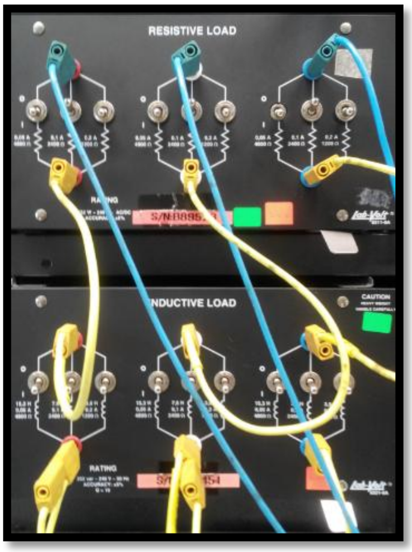

Figure 5: Load settings on EMS workstation

A. Measurement of Experiment

The connection of direct load will be made for non-fault experiment and fault experiment as shown in Figure 6 where the load is connected directly to the generator.

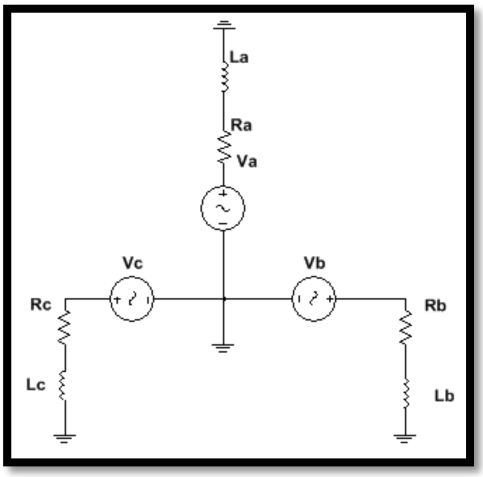

Figure 6: Conceptual circuit for direct load connection

Third harmonic current will be measured at:

i) After the generator (Generator Terminal)

ii) Before the load (Load Terminal)

iii) At the fault location (Fault Terminal)

B. Experiment Cases

The fault is created at the location after the generator and before the load impedance as shown in Figure 7 by universal fault module of EMS workstation.

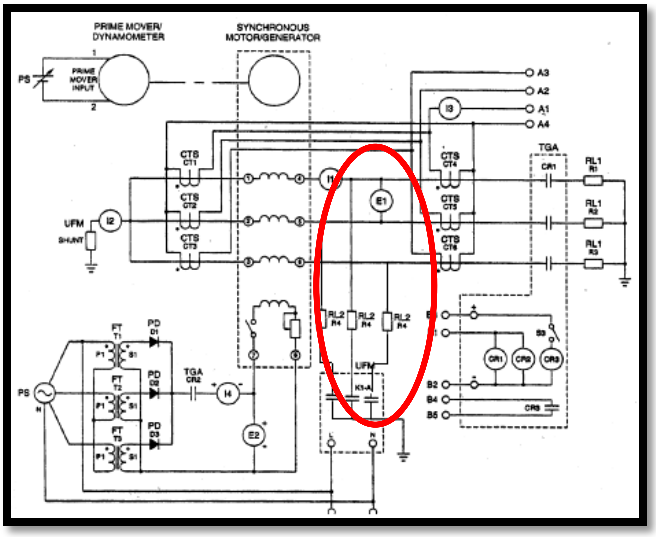

Figure 7: Fault location in the EMS workstation

Under fault experiment, there are three variables to be controlled namely Zf, filter mode and NER. Firstly, study on the characteristic of third harmonic current for bolted fault and fault with Zf (50.53 Ω). Then, the existence of NER (800 Ω) is controlled under normal mode and filter mode. From the variables, the effect of Zf and NER on third harmonic current and fundamental fault current can be observed. The filter mode using zig-zag transformer is to compare with normal mode on the contribution of third harmonic current to the overall system. The cases of the fault experiments are illustrated in Figure 8.

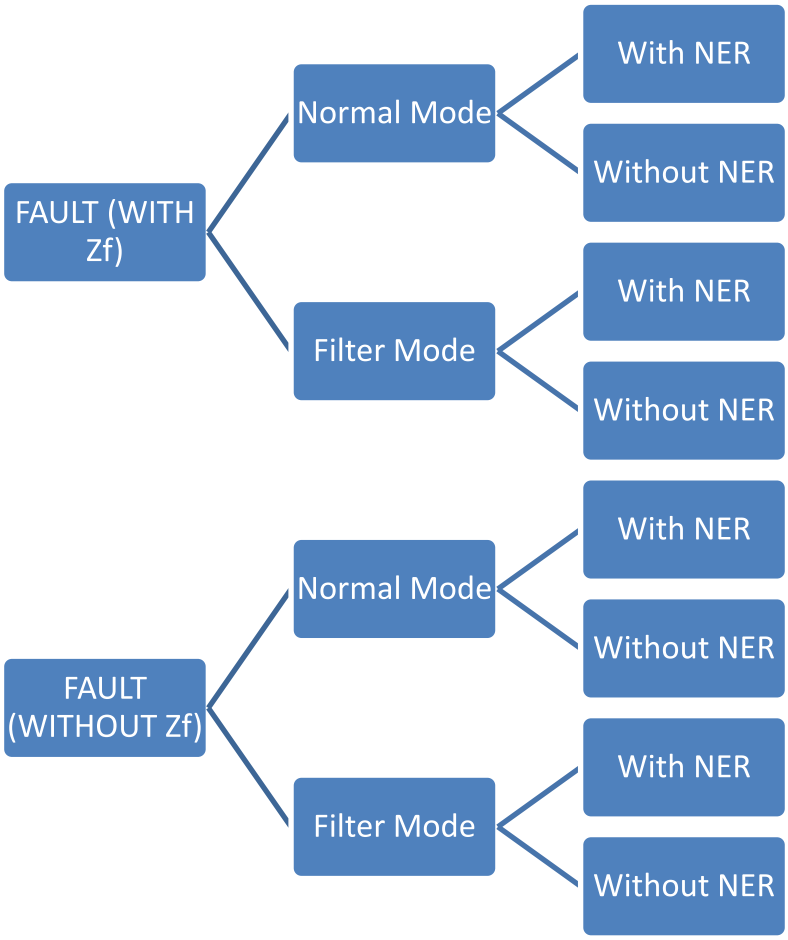

Figure 8: Cases of fault experiment

The equipments of EMS workstation and equipment of protective relaying control station are connected as shown in Figure 9 and 10 respectively. High voltage are present in the experiment, thus it is important to turn off the power supply and set voltage knob to position 0 when making any connection. The settings of various equipments including synchronous generator, prime mover, AC/DC current relative relay, transmission grid 'A' and universal fault module are set based on the lab manual. After the settings are set, the experiments for direct load connection are carried out for non-fault and fault experiment. The button "Initiate Fault" on the universal fault module is pressed to initiate three phase-to-ground fault to the system.

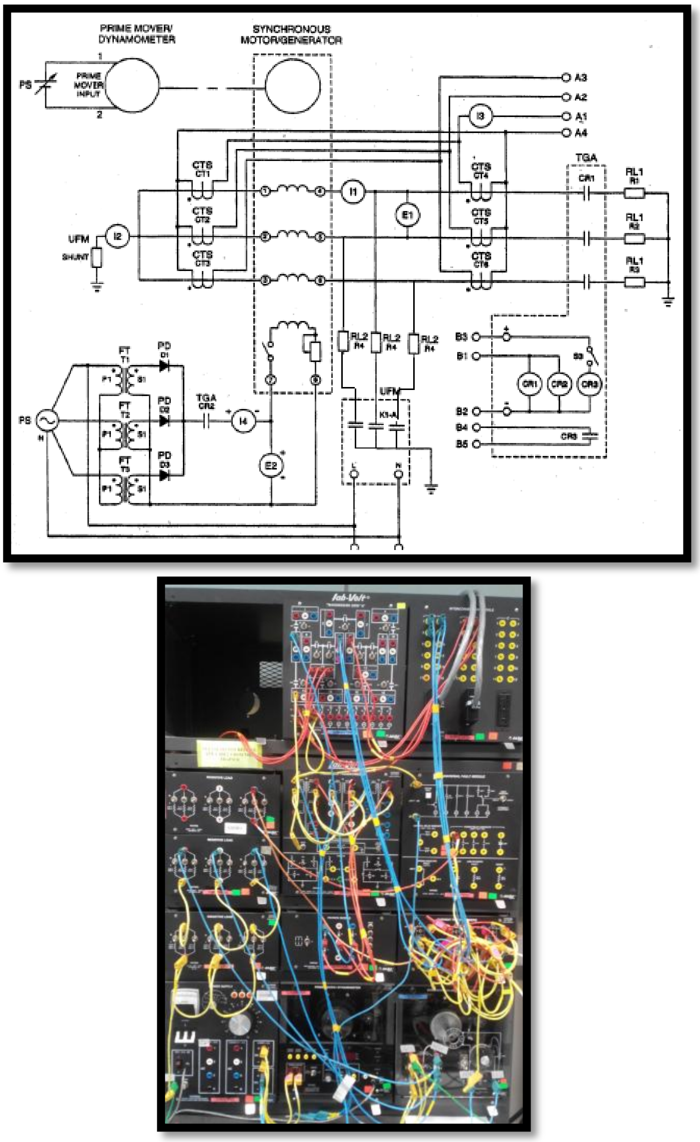

Figure 9: Equipment connection for EMS workstation

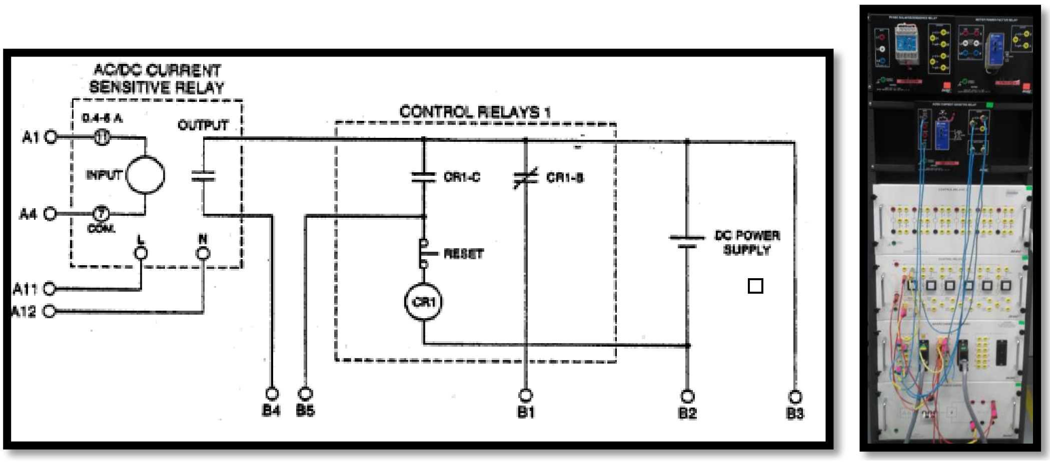

Figure 10: Equipment connection for protective relaying control station

*The EXCITER knob of synchronous generator needs to be readjusted so that the line-to-line voltage remains almost the nominal value of 415 V.

*The voltage control knob of power supply needs to be readjusted so that the generator rotation speed remains almost the nominal value of 1500rpm.

3.2 Key Milestone

The key milestones of the project which need to achieve are listed as below:

- ✓ Carry out the lab experiment on direct load connection for all the impedance set and get the data correctly
- ✓ Analyze the results based on theory studied
- ✓ Obtain the waveform of the generator for analysis purpose
- ✓ Prepare progress report
- ✓ Perform calculation and compare on the contribution of third harmonic to the system before and after fault
- ✓ ELECTREX, technical paper and final dissertation preparation

3.3 Gantt Chart

Week / Activities	FYP 1													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project Title selection	■	■												
Study on papers and literature review		■	■	■	■	■	■	■	■	■	■	■	■	■
Study on methodology			■	■	■									
Familiarize with the lab equipment and software					■	■								
Extended Proposal Submission						●								
Compare different units of Fluke Power Quality Analyzer							■							
Experiment on Direct Load Connection (Non-fault and fault)-960+j660								■	■					
Proposal Defence									●					
Experiment on Direct Load Connection (Non-fault and fault)-all impedance sets										■	■	■	■	
Preparation of Report												■	■	
Interim Draft Report Submission													●	
FYP1 Report Submission														●

- ● Suggested Milestones
- ■ Process

Week / **Activities**	FYP 2													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Study on papers and literature review														
Experiment on Direct Load Connection (Non-fault and fault)-all impedance sets														
Analyse the results based on theory														
Experiment on Direct Load Connection (Non-fault and fault)-waveform for one impedance set														
Progress Report Submission								•						
Perform calculation and compare on third harmonic contribution														
ELECTREX											•			
Preparation of Final Dissertation and Technical Paper														
Draft Final Dissertation Submission													•	
Technical Paper and Final Dissertation Submission														•
Viva														•

- Suggested Milestones

Process

3.4 Tools

Hardware:

- EMS Workstation
- Protective Relaying Control Station
- Fluke 434/435 Three Phase Power Quality Analyzer
- Wire cable
- Multi meter

Software:

- FlukeView Power Quality Analyzer Software
- Microsoft Excel

Fluke 435 Series 2 Three Phase Power Quality Analyzer

It is a measuring tool for the third harmonic voltage and current measurement at each point by clamping the current clamp on the wire cable. FlukeView Power Quality Analyzer software is used to observe the phase angle and magnitude of the measured component in computer (Excel and text file) where the data is transferred from the analyzer to computer.

Figure 11: Fluke 435 three phase power quality analyzer

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Non-fault Experiment

Under non-fault experiment, the fundamental current at generator terminal is equal to the fundamental current load terminal. The equivalent circuit is illustrated in Figure 12.

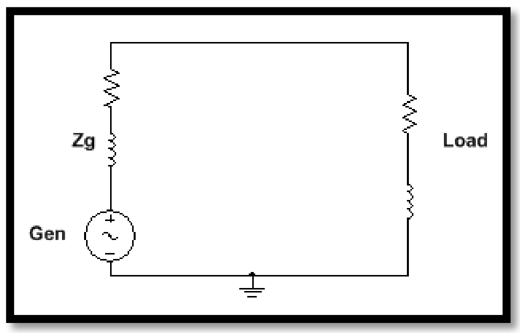

Figure 12: Non-fault experiment circuit diagram

The third harmonic current behaviors observed at the generator and load terminal are shown in the Figure 13 and 14.

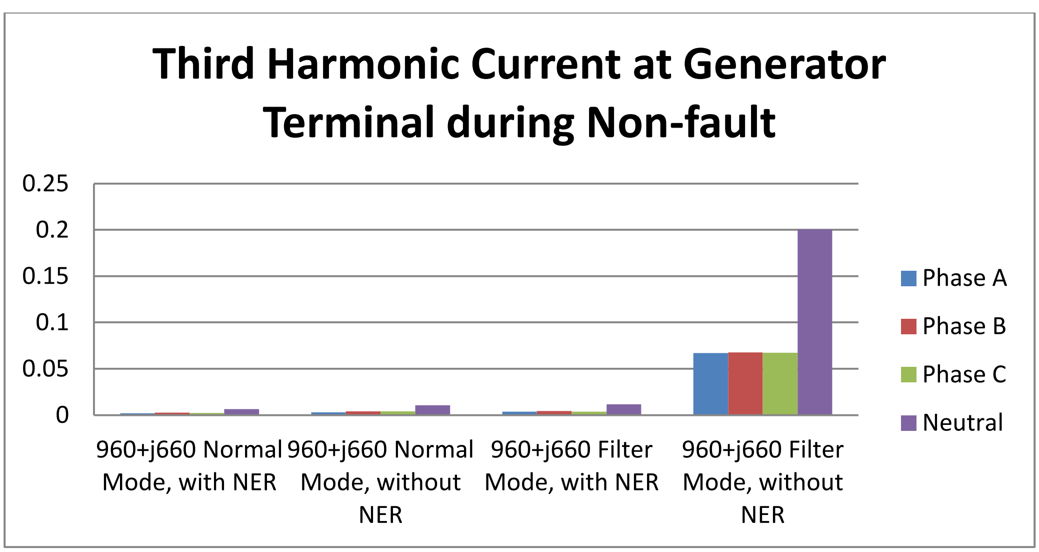

Figure 13: Third harmonic current at generator terminal during non-fault

It is obvious that the third harmonic current is the highest at the neutral phase regardless of the types of cases provided at the generator terminal. The third harmonic current is observed to be almost three times the current at each single phase. This is proven that the statement of third harmonic current in neutral is almost triple the phase current magnitude whereby the phase current magnitudes are almost equal to each other in the literature review. The results show that the third harmonic current is highest at the generator terminal for the cases under filter mode and without NER connected.

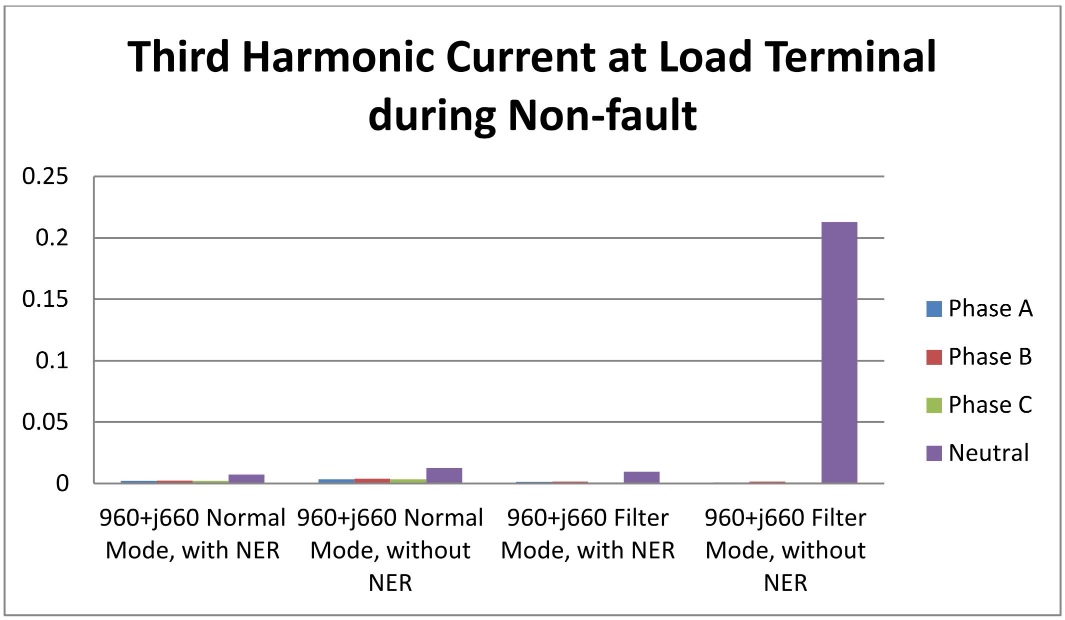

Figure 14: Third harmonic current at load terminal during non-fault

The neutral current at load terminal are also triple the phase current except in both of the cases under filter mode. With the existence of the zig-zag transformer, the load current at neutral phase no longer three times the phase current at load terminal. For the case with NER under filter mode, the current at neutral phase is almost 7 times the phase current. Without NER under filter mode, the neutral current even higher and almost over 100 times the phase current. The third harmonic current at the fault terminal during non-fault is equal to zero under all cases since no current flow through it.

The third harmonic current at generator and load terminal are compared in Table 2.

Table 2: Third harmonic current at generator and load terminal at non-fault

Cases	Third Harmonic Current	
	Generator Terminal	Load Terminal
Normal Mode, with NER	0.0020 A	0.0019 A
Filter Mode, with NER	0.0039 A	0.0014 A
Normal Mode, without NER	0.0035 A	0.0033 A
Filter Mode, without NER	0.0831 A	0.0010 A

Since there is no fault in between generator and load, the current at generator terminal equal to current at load terminal under normal mode as shown in the equivalent circuit Figure 12. When zig-zag transformer is connected to the system (parallel to load) under filter mode, some of the third harmonic current flow to the zig-zag transformer and can be seen that the third harmonic current at load terminal is reduces under both filter mode.

4.2 Fault Experiment

Under fault experiment, the current in the circuit are interpreted in current divider circuit. The equivalent circuit is illustrated in Figure 15.

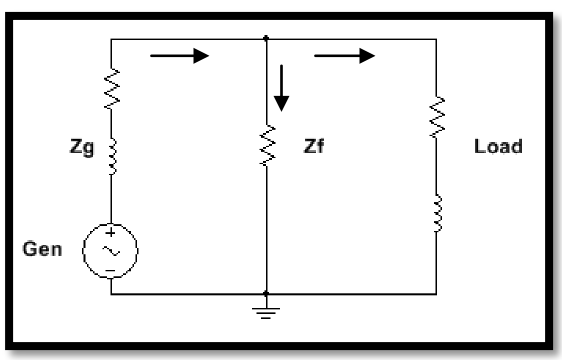

Figure 15: Fault experiment circuit diagram

4.2.1 Fundamental Current Analysis

The experiment is conducted for 8 times with different cases as listed in Figure 8 of methodology part. Only phase A of each terminal is tabulated in Figure 16 and 17 for the ease of presentation. Moreover, the complete data for phase A, B and C are tabulated in the Appendix A where phase A, B and C are observed to have close values.

The fundamental current at fault terminal and load terminal are verified that the sum of them is almost equal to the fundamental current at generator terminal. This fulfilled the current divider interpretation. The fundamental current is observed at fault terminal and load terminal for different conditions as in Figure 16 and 17.

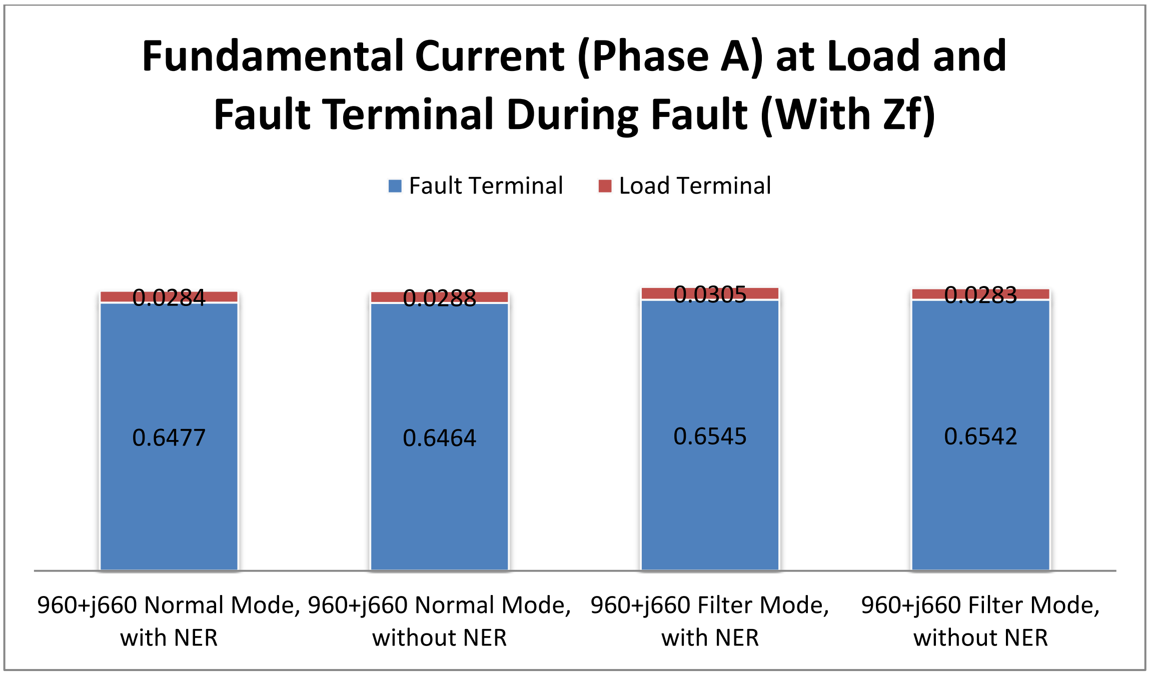

Figure 16: Fundamental current at load and fault terminal during fault (with Zf)

It can be seen in Figure 16 that in the case with Zf, the existence of NER does not affect much on the fundamental fault current since the current are close values when compared to the same mode. However, it is observed that the fundamental current under filter mode at fault terminal is slightly higher than normal mode. This can be explained that under filter mode, the zig-zag transformer is connected which is parallel to Zf and load, the impedance of the circuit becomes lower in this case. Based on Ohm′s Law, the current is higher when the impedance is lower. Since the current flow to load terminal is small, so the increment of current due to lower impedance load is not obvious.

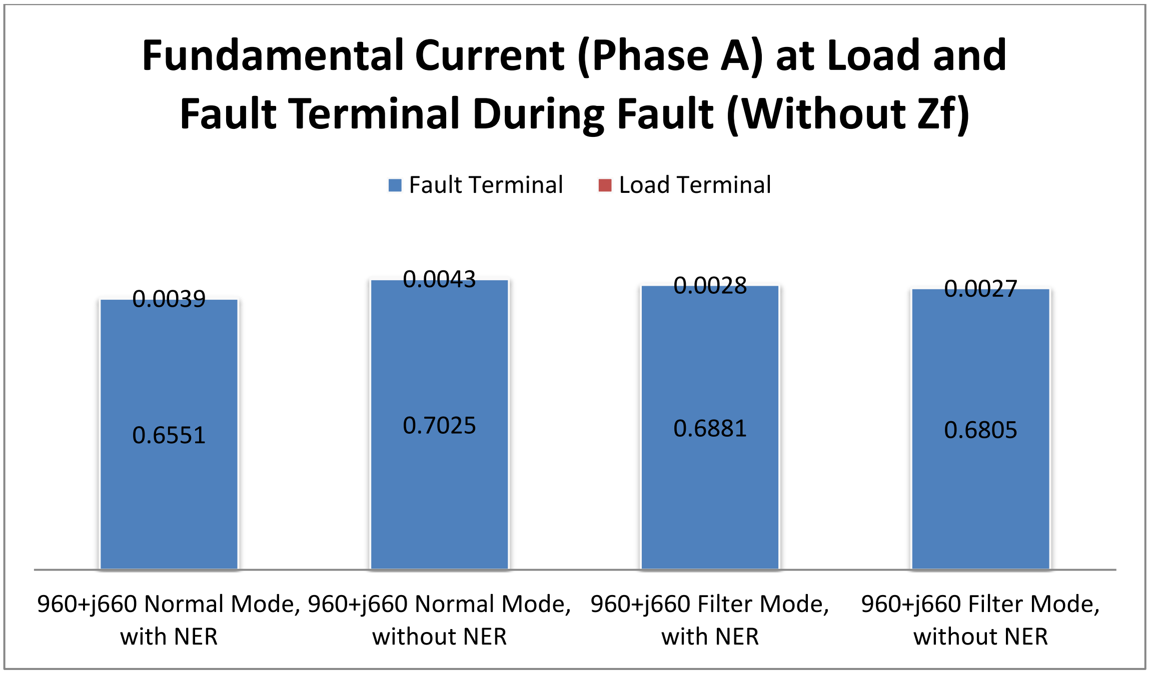

Figure 17: Fundamental current at load and fault terminal during fault (without Zf)

Figure 17 shows the fundamental current at load and fault terminal during bolted fault without Zf. The fundamental phase current at load terminal is lower compare to the case with Zf. Without Zf, the current more likely to flow towards fault location since the line is with lower impedance (compare to load's line), and thus the current at load terminal slightly decreases until almost 0 A (which can be neglected) and the current at fault terminal increased as compared to Figure 16.

The results are used to analyze whether the system is balanced or not by observing the data at fault terminal. It is observed that the bolted three phase-to-ground fault causing the system to have unbalanced voltage at the fault terminal where the angles are not 120° apart (refer to Appendix A). This is due to the removal of Zf and causing short circuit to the three phases during fault. However, the fault currents are observed to be higher during bolted fault. Since this project studies on balanced fault, the cases without Zf are omitted from this point onward.

4.2.2 Third Harmonic Analysis

4.2.2.1 Normal Mode

The third harmonic current for the cases with Zf of 50.53 Ω are interpreted as it is balanced. The third harmonic current at fault terminal are tabulated in term of ratio to fundamental current under normal mode as shown in Figure 18.

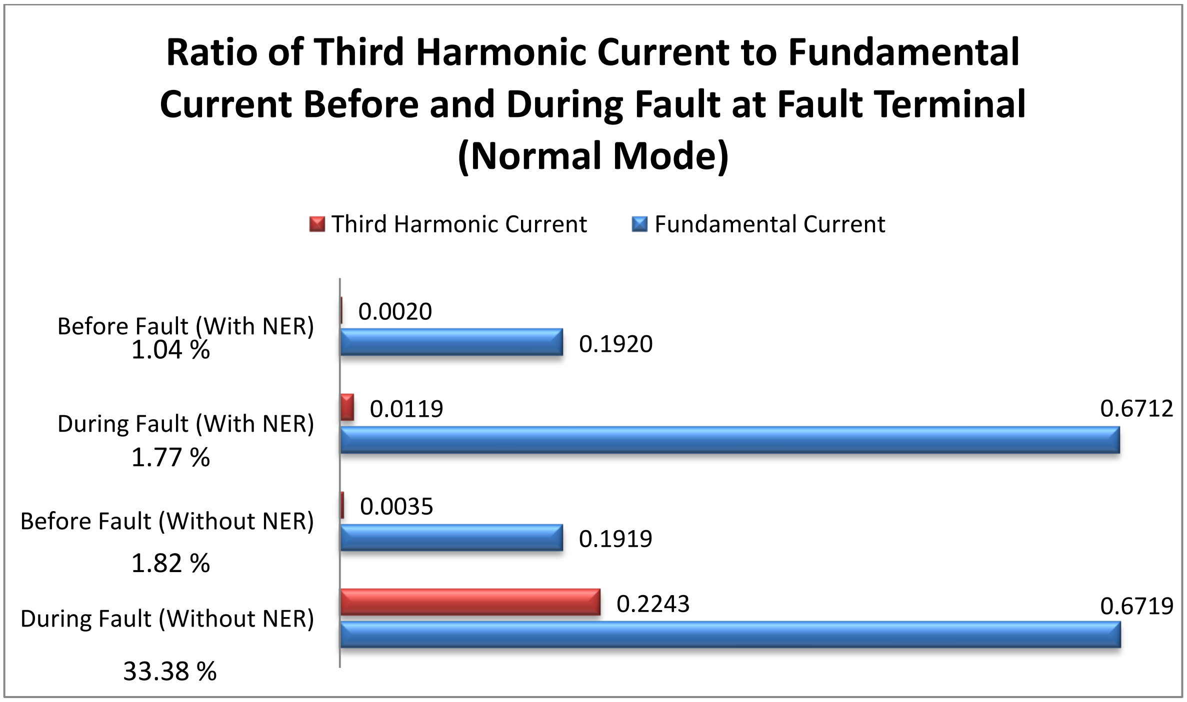

Figure 18: Ratio of third harmonic current to fundamental current before and during fault at fault terminal under normal mode

The third harmonic current is compared before and after fault in normal mode. The ratio of third harmonic current calculated shows that it is 1.04 % of fundamental current before fault with NER. When three phase-to-ground fault happened, third harmonic current is increased to 1.77 % of fundamental current. The third harmonic current is observed to be higher for the case without NER. Theoretically, NER contributes to the zero sequence impedance which is $3Z_n$ in the circuit. With NER in the circuit, the zero sequence impedance is higher and lead to lower third harmonic current. The existence of NER shows its importance as the results proved that without NER, the third harmonic current is higher. It has been increased from the ratio of 1.82 % to 33.38 % to fundamental current during fault without NER. The percentage of ratio increment is illustrated in Table 3 where without NER, the ratio of third harmonic current to fundamental current has increased as high as 31.56 %.

Table 3: Percentage of ratio increment

Cases	Ratio of Third harmonic current to fundamental current	Ratio increment
Before Fault (With NER)	1.04 %	0.73 %
After Fault (With NER)	1.77 %	
Before Fault (Without NER)	1.82 %	31.56 %
After Fault (Without NER)	33.38 %	

4.2.2.2 Compare Normal and Filter Mode

The third harmonic current at generator and fault terminal under normal and filter mode are tabulated in Figure 19.

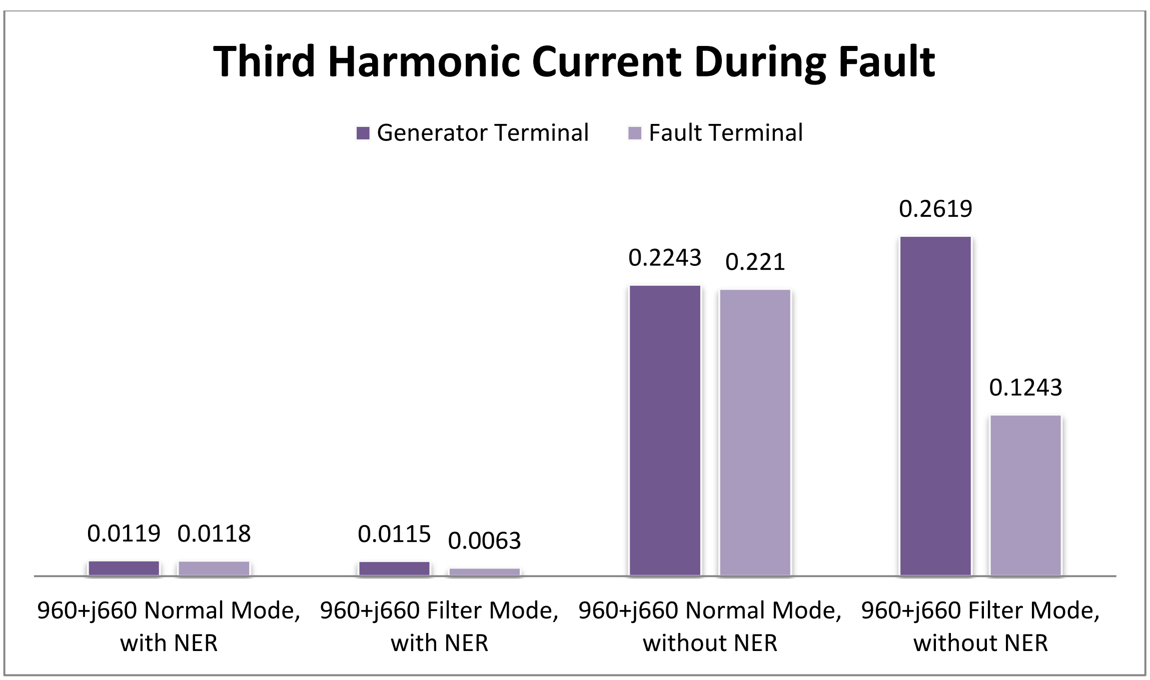

Figure 19: Third harmonic current during fault

At the generator terminal, the third harmonic current under filter mode without NER is higher than the current under normal mode without NER. This is because the fundamental current at generator terminal increased when zig-zag transformer is connected to the system under filter mode as explained in part 4.2.1, and so does the third harmonic current.

However, by comparing the results of third harmonic current at fault terminal as shown in Figure 19, the filter reduces the third harmonic current in both case with and without NER. This can be said that the filter mode did decrease the third harmonic current at fault terminal but not at the generator terminal. Filter does not reduce the burden of generator fault current but it can limit the amount of third harmonic current flow to the overall system during three phase-to-ground fault.

The contribution of third harmonic current at fault terminal to the overall fault level is then calculated and compared under normal and filter mode as shown in Table 4.

Table 4: Third harmonic current contribution at fault terminal

Cases	Fundamental Fault Current	Third Harmonic Current During Fault	Overall Fault level	Overall Third Harmonic Contribution
Normal Mode, with NER	0.6477 A	0.0118 A	0.6481 A	1.82 %
Filter Mode, with NER	0.6545 A	0.0063 A	0.6548 A	0.96 %
Normal Mode, without NER	0.6464 A	0.2210 A	0.6834 A	32.34%
Filter Mode, without NER	0.6542 A	0.1243 A	0.6662 A	18.66%

The third harmonic current at fault terminal is recorded in third column of Table 4. It can be observed that the third harmonic having highest magnitude at the normal mode without NER. As explained in the part 4.2.2.1, the case without NER has lower zero sequence impedance therefore the third harmonic current is higher. By comparing the normal and filter mode under both case of with NER and without NER, the magnitude of third harmonic current actually decreases by almost 50% under filter mode. This shows that the zig-zag transformer actually can provide the path for third harmonic current to flow and reducing the amount of third harmonic current to flow to the fault terminal.

The overall fault level is calculated using the equation (4.1), I_{rms} as shown to compare how the overall fault level can be affected by third harmonic current during fault in the system. Equation (4.1) considers up to third harmonic as this project mainly is to study third harmonic current characteristic. The higher orders of harmonic are relatively small and can be neglected.

$$I_{rms} = \sqrt{{I_{rms1}}^2 + {I_{rms2}}^2 + {I_{rms3}}^2} \qquad (4.1)$$

Where I_{rms1}=Fundamental current

I_{rms2}=Second harmonic current

I_{rms3}=Third harmonic current

By referring to forth column of Table 4, the overall fault level with NER is not observable decreased although under filter mode. This is because the increment in fundamental current due to the lower system impedance (as zig-zag transformer parallel to Zf and load impedance) is more than the decrement in third harmonic current after filtered. Thus, overall fault level is not reduced but rise even though with filter mode.

The overall fault level is observed to be decreased in the case of filter mode without NER as the third harmonic current is reduced in a bigger scale as compared to the case with NER. The decrement of third harmonic current is more than the increment of fundamental current due to lower system impedance. The overall fault level decrement might be minor, but this decrement is important to the system as it can reduce the fault rating and equipment rating.

Then the overall third harmonic contribution to the overall fault level is calculated by using equation (4.2).

$$\text{Overall third harmonic contribution} = \frac{\text{Third Harmonic Current}}{\text{Overall Fault Level}} \times 100\% \qquad (4.2)$$

For the case with NER, the contribution of third harmonic to the overall fault level actually can be observed decreases from 1.82 % to 0.96 % under filter mode although the overall fault level is not decreasing as explained before. Without NER, the contribution of third harmonic to the overall fault level also decreased from 32.34 % to 18.66 % under filter mode as observed in Table 4. It can be said that overall third harmonic current contribution is decreased with filter mode in the case of with and without NER.

The third harmonic current at load terminal as shown in Table 5 is relatively small compare to the current at fault terminal as the fundamental current flow to the load terminal is also lower than the fault terminal, as close as zero. Although the third harmonic current value is relatively small, but the results still able to observe that the cases without NER have the higher third harmonic current compare to those with NER as explained in part 4.2.1 however the third harmonic current also reduces under filter mode.

Table 5: Third harmonic current at fault and load terminal during fault

Cases	**Third Harmonic Current**	
	Fault Terminal	Load Terminal
Normal Mode, with NER	0.0118 A	0.0004 A
Filter Mode, with NER	0.0063 A	0.0001 A
Normal Mode, without NER	0.2210 A	0.0050 A
Filter Mode, without NER	0.1243 A	0.0029 A

4.2.3 Waveform Analysis

The waveform of current at generator terminal is observed for the four cases with Zf. Comparing the cases with and without NER in term of third harmonic as discussed before, the cases without NER have third harmonic current more than 15 times of the cases with NER. Thus, the waveform of the cases without NER can be observed highly distorted due to third harmonic in Figure 21 compare to the cases with NER in Figure 20. With NER, the third harmonic current is not obviously distorted but still third harmonic current exist based on the recorded data.

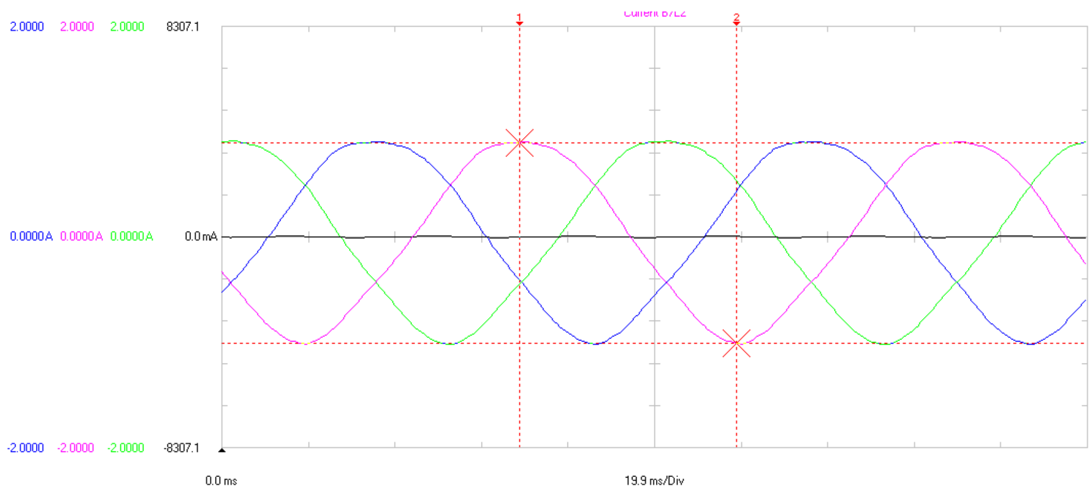

Figure 20: Current waveform at generator terminal during fault (with NER)

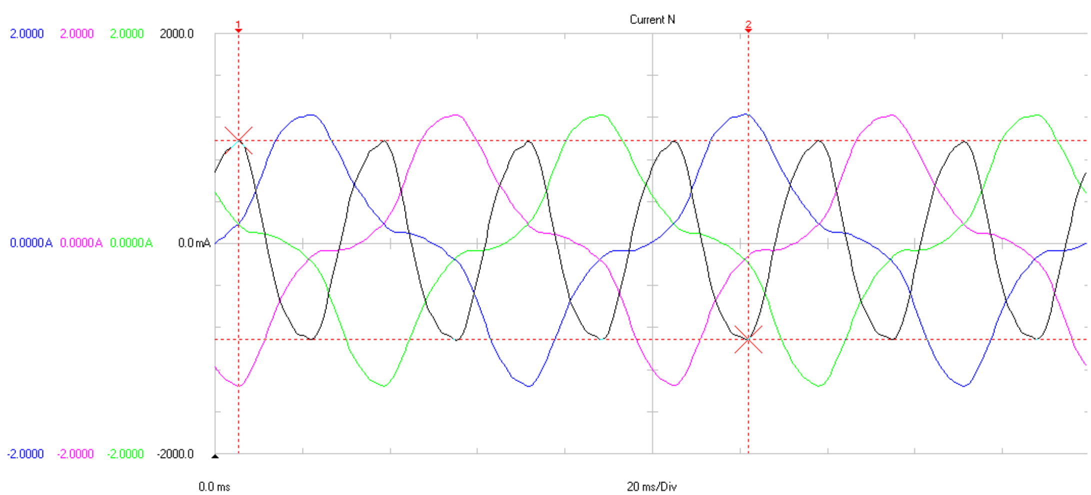

Figure 21: Current waveform at generator terminal during fault (without NER)

4.2.4 Different Load Impedance Sets

The experiment is done on different sets of load impedance to observe how the load impedance will affect the results. The results are shown in term of fundamental current and third harmonic current. Figure 22 shows the fundamental current at the fault terminal with varies load impedance. It is observed that fundamental fault current is affected which is gradually decreases when load impedance increases. However, the third harmonic current is not affected by the load impedance in fault terminal as the values close to each other even the load impedance are varied shown in Figure 23.

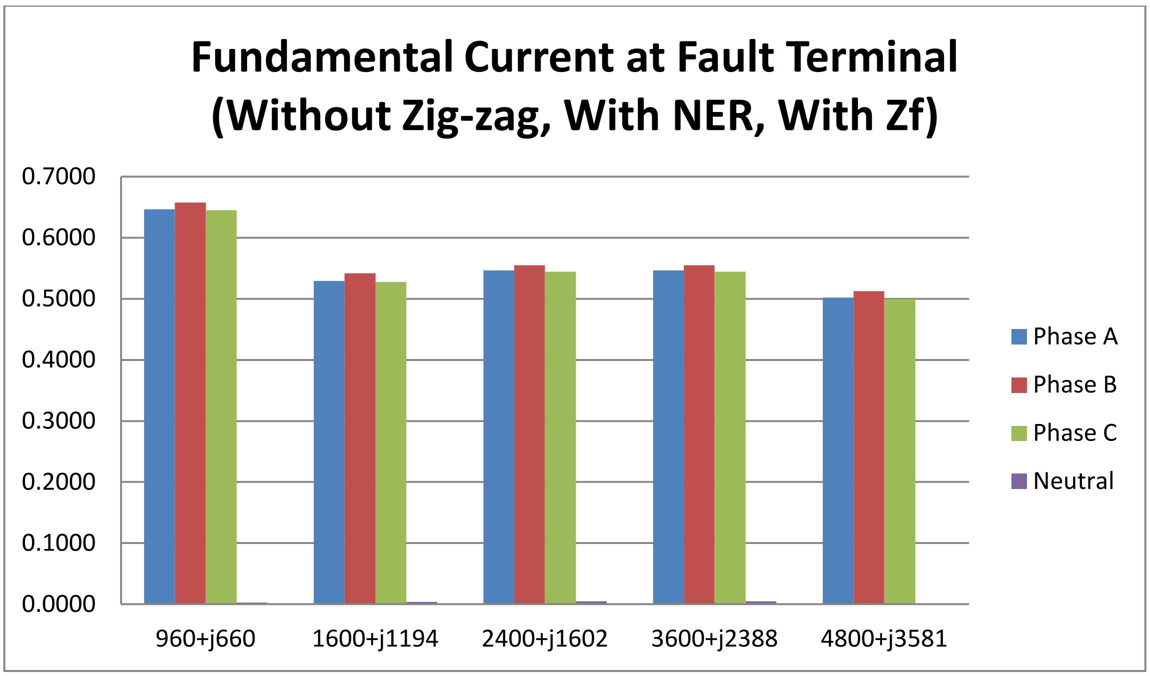

Figure 22: Fundamental current at fault terminal during fault at varies load

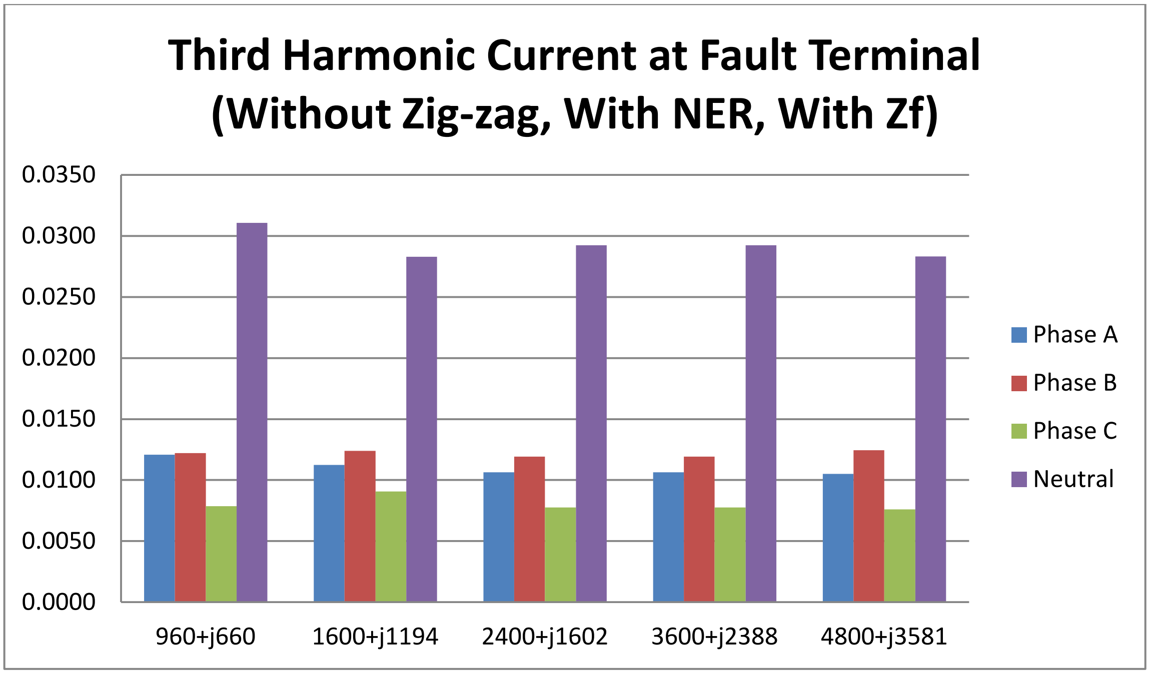

Figure 23: Third harmonic current at fault terminal during fault at varies load

CHAPTER 5
CONCLUSION & RECOMMENDATIONS

During non-fault experiment, the third harmonic current of generator terminal at neutral phase is triple the phase current. In the fault experiment, the variables that varied are Zf, filter mode and NER. Without Zf, the fundamental fault current and third harmonic current at the fault terminal is higher because the current flow towards the line with lower impedance fault terminal in nature. However, the system become unbalanced since the voltage is unbalanced and not 120° apart.

The ratio of third harmonic current to the fundamental current at fault terminal is calculated and compared its contribution during three phase-to-ground fault under normal mode. The ratio increases at the range of 0.73 % to 31.56 % depends on the existence of NER. The existence of NER contributes to the zero sequence impedance to the system, higher impedance results in lower third harmonic current. Therefore, higher third harmonic current is observed for any case without NER.

However, zig-zag transformer is used in filter mode to reduce third harmonic current as proven in the result. The overall contribution of third harmonic current to overall fault level is computed and reduced to almost half of the value under normal mode. Thus, it is recommended to place the NER in the system to increase the zero sequence impedance and reduce the third harmonic current by connecting filter in the system.

The load impedances are varied to study its effect on the fundamental current and third harmonic current at fault terminal. The fundamental fault current is observed gradually decreases when load impedance increases but the third harmonic current is not affected by the load impedances.

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APPENDIX A

1. Load Impedance=960+j660, normal mode, with NER=800 Ω, with Zf=50.53 Ω

Non-Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.91	0.00	0.1920	-33.09
237.94	-119.83	0.1916	-152.63
239.77	120.09	0.1908	87.09
0.01	129.10	0.0010	35.06

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
4.59	21.79	0.0020	3.24
5.44	28.54	0.0026	3.44
5.64	20.57	0.0021	-12.29
0.00	20.93	0.0068	177.04

Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.86	0.00	0.1918	-33.04
238.06	-119.81	0.1904	-153.08
239.82	120.07	0.1892	87.45
0.01	128.64	0.0015	-173.31

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
4.58	22.14	0.0019	9.87
5.47	29.18	0.0025	8.19
5.63	19.66	0.0022	-17.23
0.00	19.45	0.0066	-8.12

Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.84	0.00	0.0009	101.00
237.92	-119.81	0.0004	-80.90
239.83	120.07	0.0007	-171.14
0.01	128.08	0.0003	52.92

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
4.52	21.76	0.0002	177.65
5.46	29.47	0.0006	-158.44
5.70	19.66	0.0001	126.25
0.00	65.79	0.0002	0.00

Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
34.44	0.00	0.6712	-0.65
34.38	-119.69	0.6707	-119.94
34.55	120.34	0.6738	119.29
0.00	126.18	0.0007	-8.79

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.65	-127.77	0.0119	-129.44
0.63	-135.12	0.0113	-135.80
0.64	-136.52	0.0113	-138.14
0.00	-9.44	0.0342	45.31

Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
35.01	0.00	0.0284	-32.04
34.97	-119.66	0.0287	-151.26
35.11	120.26	0.0285	89.33
0.00	123.14	0.0007	179.89

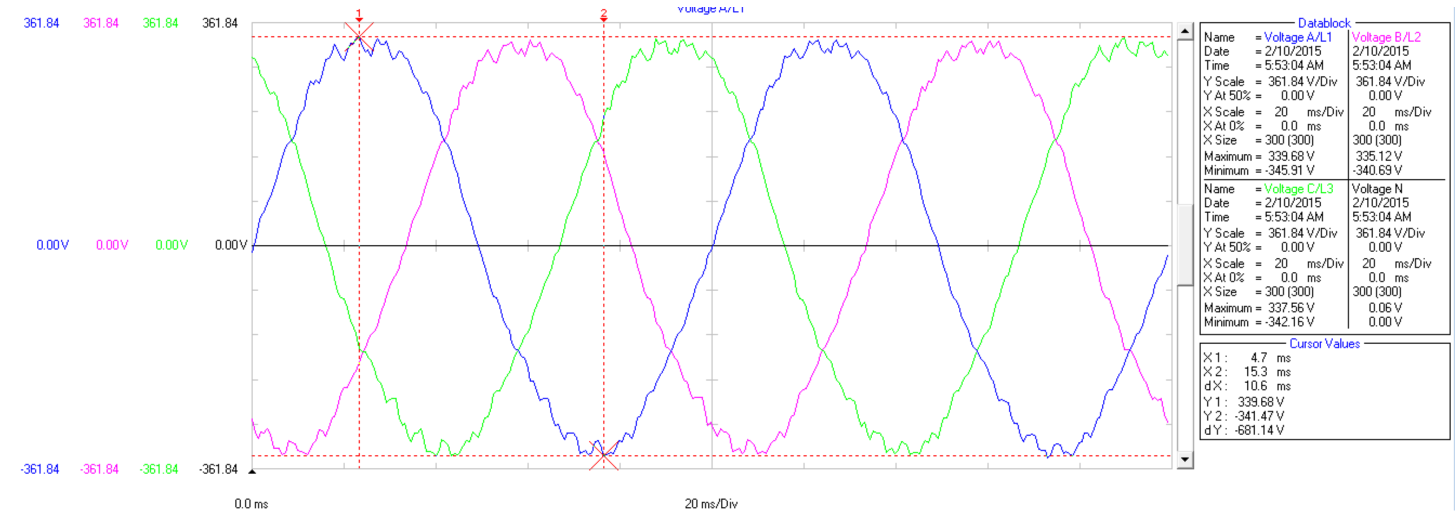
Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.66	-131.25	0.0004	137.44
0.64	-137.13	0.0003	135.50
0.66	-130.69	0.0003	127.44
0.00	120.37	0.0013	-136.14

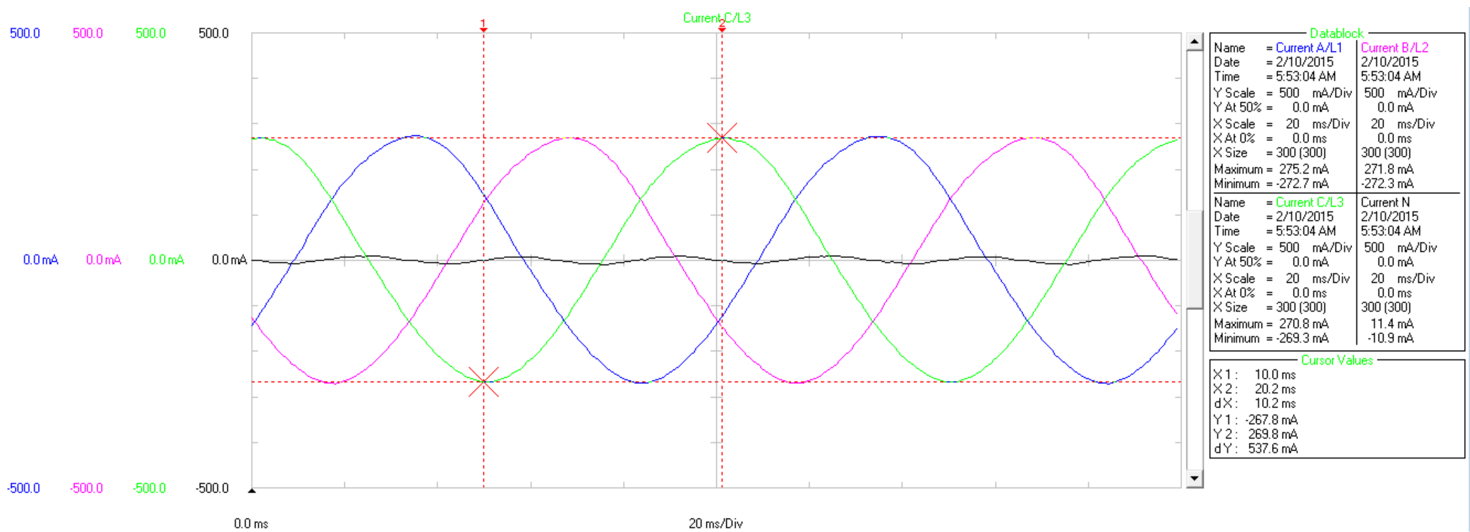
Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
34.58	0.00	0.6477	0.39
34.35	-120.10	0.6483	-119.15
34.63	119.69	0.6480	120.36
0.00	130.48	0.0016	139.01

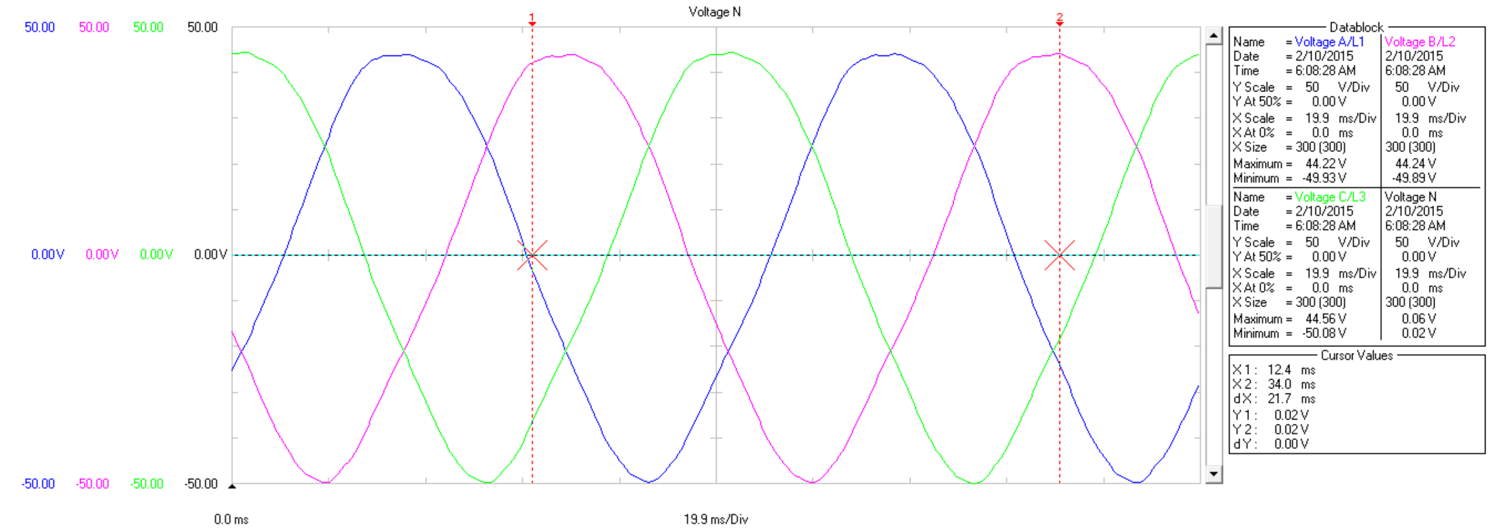
Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.34	-22.26	0.0118	-133.27
0.31	-6.04	0.0106	-137.67
0.27	-33.45	0.0117	-132.83
0.00	-101.33	0.0339	-134.86

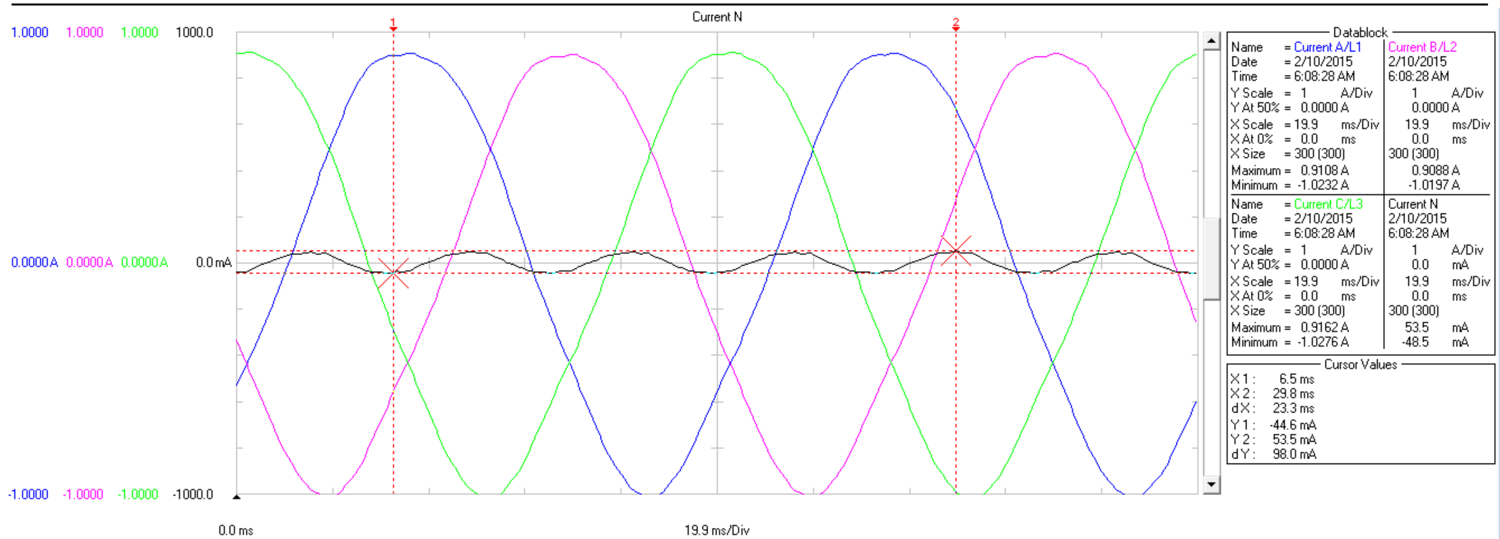
1. Load Impedance=960+j660, normal mode, with NER=800 Ω, with Zf=50.53 Ω (NON-FAULT)





1. Load Impedance=960+j660, normal mode, with NER=800 Ω, with Zf=50.53 Ω (AFTER FAULT)





2. Load Impedance=960+j660, normal mode, with NER=800 Ω, without Zf=50.53 Ω

Non-Fault Experiment:

Gen (Vf / If):

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.91	0.00	0.1920	-33.09
237.94	-119.83	0.1916	-152.63
239.77	120.09	0.1908	87.09
0.01	129.10	0.0010	35.06

Gen (Vt / It):

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
4.59	21.79	0.0020	3.24
5.44	28.54	0.0026	3.44
5.64	20.57	0.0021	-12.29
0.00	20.93	0.0068	177.04

Load (Vf / If):

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.86	0.00	0.1918	-33.04
238.06	-119.81	0.1904	-153.08
239.82	120.07	0.1892	87.45
0.01	128.64	0.0015	-173.31

Load (Vt / It):

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
4.58	22.14	0.0019	9.87
5.47	29.18	0.0025	8.19
5.63	19.66	0.0022	-17.23
0.00	19.45	0.0066	-8.12

Fault (Vf / If):

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.84	0.00	0.0009	101.00
237.92	-119.81	0.0004	-80.90
239.83	120.07	0.0007	-171.14
0.01	128.08	0.0003	52.92

Fault (Vt / It):

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
4.52	21.76	0.0002	177.65
5.46	29.47	0.0006	-158.44
5.70	19.66	0.0001	126.25
0.00	65.79	0.0002	0.00

Fault Experiment:

Gen (Vf / If):

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
2.82	0.00	0.6570	7.86
2.81	-106.27	0.6561	-111.68
2.82	128.66	0.6590	127.67
0.00	138.71	0.0007	-113.03

Gen (Vt / It):

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.06	-115.92	0.0149	-85.97
0.07	-101.86	0.0132	-94.90
0.07	-82.81	0.0139	-98.14
0.00	-94.60	0.0375	86.41

Load (Vf / If):

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
4.17	0.00	0.0039	-14.74
4.15	-104.74	0.0035	-55.24
4.18	131.36	0.0035	45.41
0.00	-131.18	0.0007	-71.34

Load (Vt / It):

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.09	-144.04	0.0001	156.92
0.10	-123.80	0.0001	125.26
0.11	-132.96	0.0001	-47.75
0.00	78.46	0.0010	-102.46

Fault (Vf / If):

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
2.84	0.00	0.6551	79.86
2.85	-30.71	0.6553	-39.68
2.85	-65.62	0.6560	-160.03
0.00	134.00	0.0019	-11.81

Fault (Vt / It):

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.21	-121.73	0.0151	124.87
0.21	-121.55	0.0133	119.31
0.21	-121.52	0.0134	126.02
0.00	-20.43	0.0373	122.35

3. Load Impedance=960+j660, normal mode, without NER=800 Ω, with Zf=50.53 Ω

Non-Fault Experiment:

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.74	0.00	0.1919	-33.12
239.07	-119.85	0.1926	-152.59
240.18	120.33	0.1911	87.31
0.01	127.80	0.0022	5.14

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.60	0.00	0.1919	-32.90
239.12	-119.75	0.1909	-153.12
240.29	120.41	0.1911	87.73
0.01	129.39	0.0023	-170.91

Gen — Load

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
9.61	11.49	0.0035	-24.98
10.01	14.78	0.0039	-24.56
10.48	9.11	0.0039	-35.88
0.00	18.36	0.0113	149.98

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
9.38	9.87	0.0033	-29.33
10.12	15.90	0.0040	-21.41
10.60	10.05	0.0040	-37.40
0.00	16.81	0.0109	-34.81

Fault (upper)

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
240.20	0.00	0.0009	72.82
238.86	-119.71	0.0005	-115.17
240.01	120.26	0.0005	-155.30
0.01	129.98	0.0002	-86.09

Fault (lower)

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.76	100.77	0.0001	-156.86
1.49	85.96	0.0005	34.39
1.03	45.56	0.0002	-91.28
0.00	66.76	0.0003	-51.91

Fault Experiment:

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
36.03	0.00	0.6719	-0.65
35.92	-119.84	0.6699	-120.06
36.06	120.12	0.6722	119.09
0.00	125.42	0.0062	-127.57

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
35.36	0.00	0.0286	-31.16
35.31	-119.83	0.0286	-152.06
35.50	120.19	0.0285	89.13
0.00	114.37	0.0009	57.95

Gen — Load

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
11.45	-168.35	0.2243	-169.39
11.42	-168.48	0.2237	-169.32
11.47	-169.22	0.2237	-170.44
0.00	107.83	0.6704	10.42

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
11.49	-168.43	0.0050	134.53
11.43	-168.70	0.0050	132.31
11.44	-167.90	0.0051	132.55
0.00	-159.35	0.0154	129.28

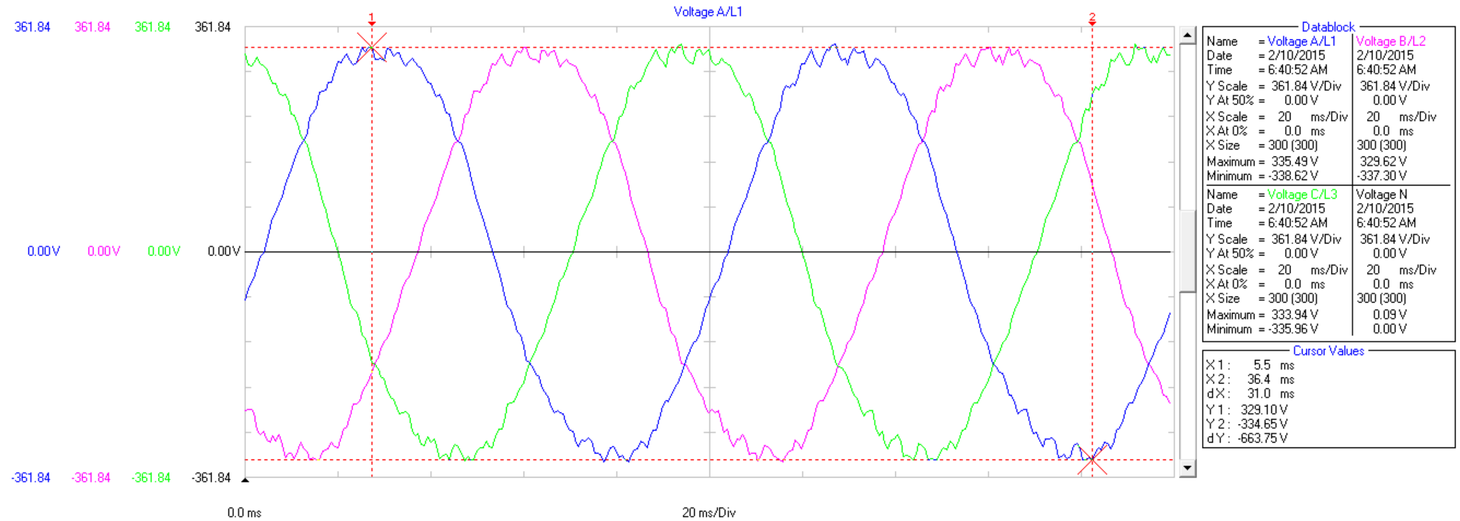
Fault (upper)

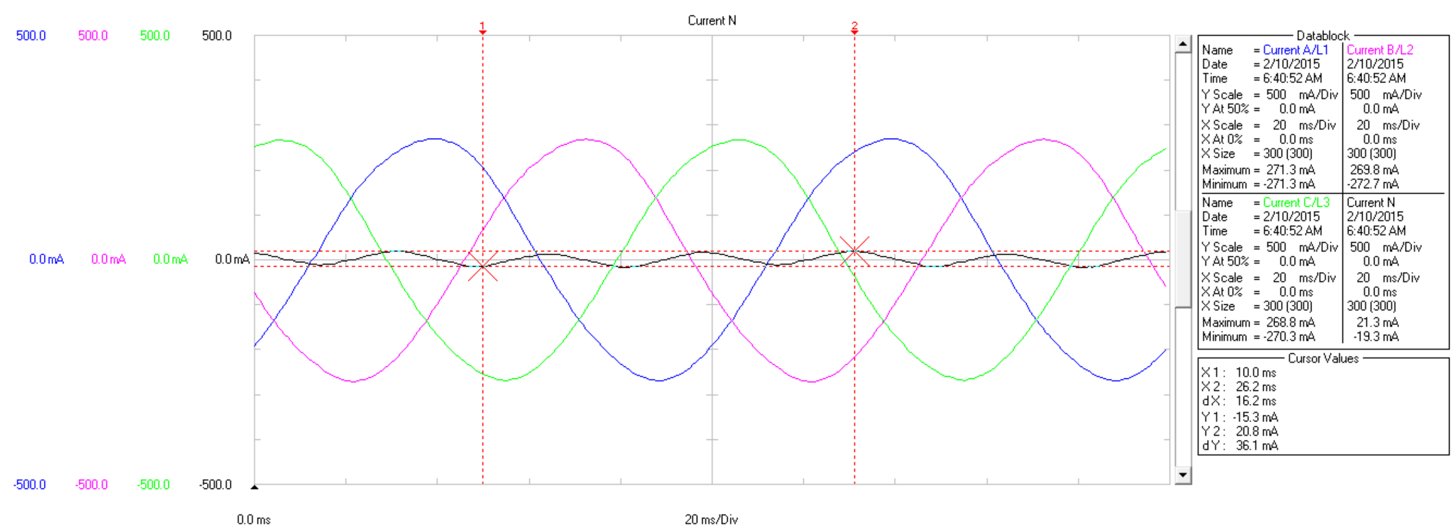
Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
35.77	0.00	0.6464	0.60
35.69	-119.81	0.6461	-119.10
35.93	119.82	0.6481	120.51
0.00	117.19	0.0058	111.37

Fault (lower)

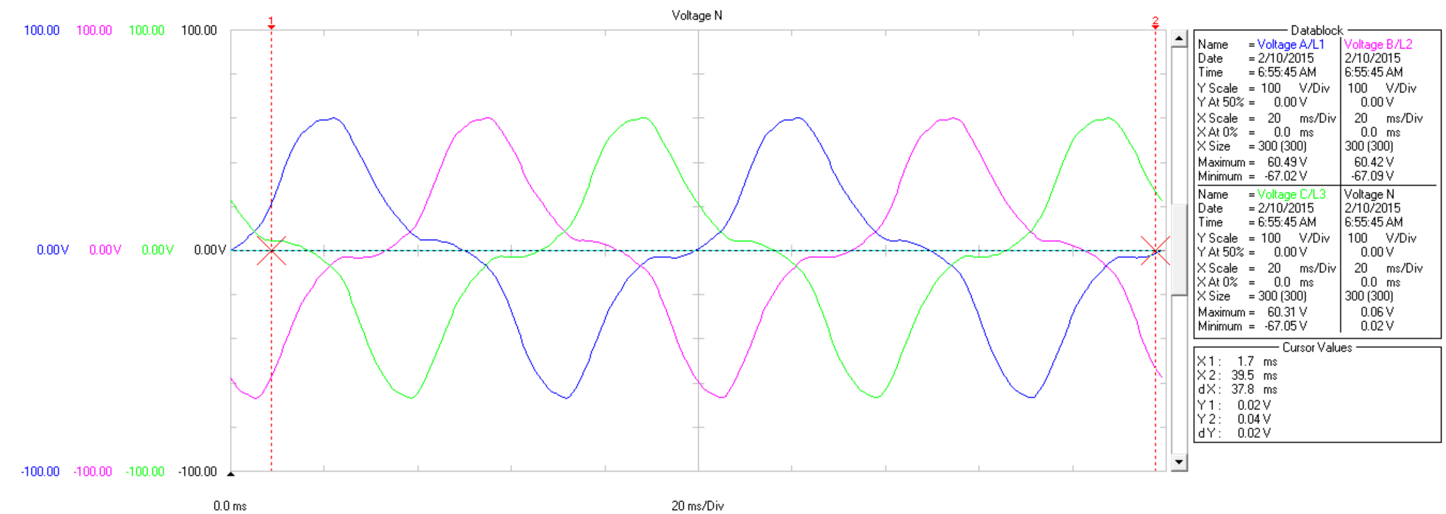
Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
1.37	-106.20	0.2210	-168.81
1.26	-102.31	0.2216	-169.05
1.27	-99.50	0.2205	-168.96
0.00	-111.23	0.6605	-169.27

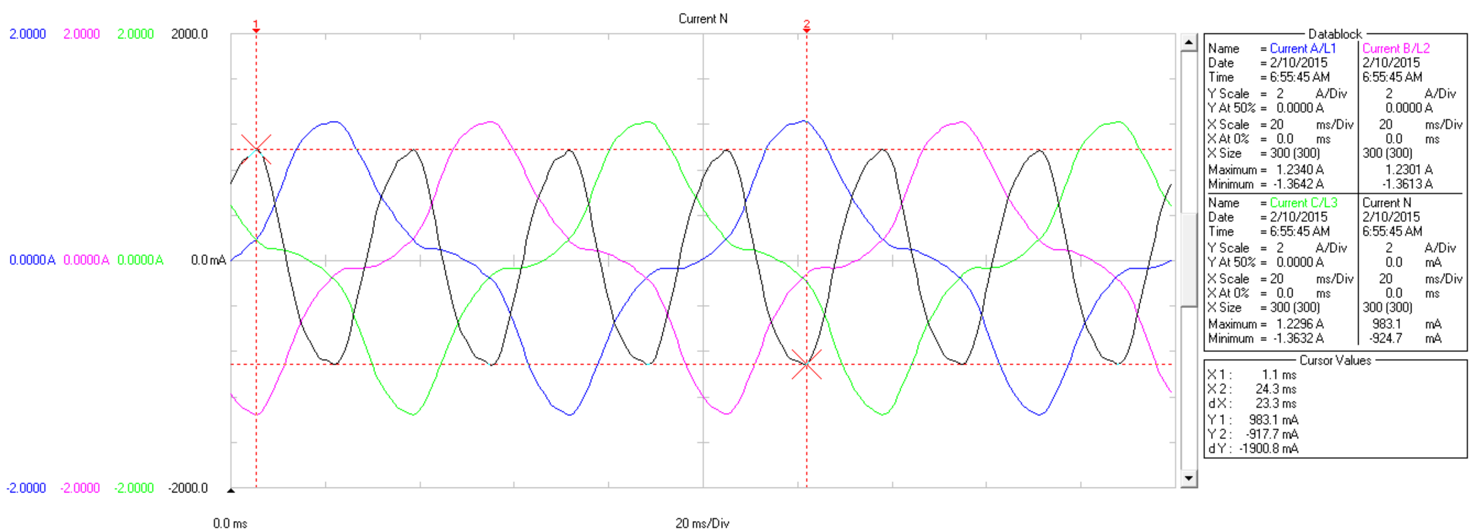
3. Load Impedance=960+j660, normal mode, without NER=800 Ω, with Zf=50.53 Ω (NON-FAULT)





3.Load Impedance=960+j660, normal mode, without NER=800 Ω, with Zf=50.53 Ω (AFTER FAULT)





4. Load Impedance=960+j660, normal mode, without NER=800 Ω, without Zf=50.53 Ω

Non-Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.74	0.00	0.1919	-33.12
239.07	-119.85	0.1926	-152.59
240.18	120.33	0.1911	87.31
0.01	127.80	0.0022	5.14

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
9.61	11.49	0.0035	-24.98
10.01	14.78	0.0039	-24.56
10.48	9.11	0.0039	-35.88
0.00	18.36	0.0113	149.98

Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.60	0.00	0.1919	-32.90
239.12	-119.75	0.1909	-153.12
240.29	120.41	0.1911	87.73
0.01	129.39	0.0023	-170.91

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
9.38	9.87	0.0033	-29.33
10.12	15.90	0.0040	-21.41
10.60	10.05	0.0040	-37.40
0.00	16.81	0.0109	-34.81

Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
240.20	0.00	0.0009	72.82
238.86	-119.71	0.0005	-115.17
240.01	120.26	0.0005	-155.30
0.01	129.98	0.0002	-86.09

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.76	100.77	0.0001	-156.86
1.49	85.96	0.0005	34.39
1.03	45.56	0.0002	-91.28
0.00	66.76	0.0003	-51.91

Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
5.48	0.00	0.7091	7.45
5.47	-106.84	0.7052	-112.12
5.51	129.05	0.7104	127.21
0.00	-18.78	0.0106	-52.44

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.24	-145.27	0.3642	-147.66
0.27	-144.59	0.3636	-147.86
0.26	-144.13	0.3632	-148.07
0.00	46.42	1.0878	32.27

Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
4.67	0.00	0.0043	-43.57
4.65	-103.76	0.0040	-82.20
4.70	128.66	0.0039	18.42
0.00	112.89	0.0007	-88.22

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.20	-140.25	0.0002	84.44
0.24	-140.17	0.0002	19.89
0.22	-139.33	0.0002	-126.78
0.00	35.50	0.0013	155.07

Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
5.83	0.00	0.7025	-126.88
5.80	12.98	0.7036	113.41
5.85	3.94	0.7039	-6.75
0.00	140.14	0.0110	92.12

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.18	168.45	0.3621	168.73
0.20	168.62	0.3627	169.02
0.19	168.10	0.3628	169.17
0.00	164.18	1.0820	168.61

5. Load Impedance=960+j660, filter mode, with NER=800 Ω, with Zf=50.53 Ω

Non-Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.90	0.00	0.1961	-32.97
238.87	-119.76	0.1947	-152.84
240.19	120.31	0.1943	86.97
0.01	128.97	0.0005	-14.64

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.50	-122.87	0.0039	12.11
0.62	99.04	0.0046	10.41
0.79	-6.57	0.0039	2.91
0.00	38.98	0.0124	-170.82

Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
241.35	0.00	0.0008	99.55
239.19	-119.06	0.0006	-34.07
238.50	120.84	0.0007	167.31
0.01	130.85	0.0002	148.53

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.64	-134.05	0.0001	127.39
0.77	96.52	0.0004	102.27
0.64	0.73	0.0018	120.84
0.00	98.36	0.0001	71.92

Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.87	0.00	0.1916	-33.03
238.87	-119.75	0.1904	-153.04
240.12	120.30	0.1904	87.40
0.01	127.97	0.0006	-101.50

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.51	-118.51	0.0014	87.26
0.64	94.99	0.0016	65.13
0.75	-6.16	0.0008	57.73
0.00	58.58	0.0125	6.78

Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
37.60	0.00	0.6799	-0.71
37.51	-119.81	0.6763	-120.25
37.68	120.26	0.6800	119.15
0.00	126.33	0.0023	-8.89

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.32	-121.24	0.0115	-137.06
0.32	-108.26	0.0113	-130.36
0.35	-123.11	0.0119	-137.69
0.00	87.87	0.0348	45.80

Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
36.52	0.00	0.6545	-1.26
36.42	-124.70	0.6533	-120.99
38.76	119.19	0.6550	118.55
0.00	122.61	0.0011	177.02

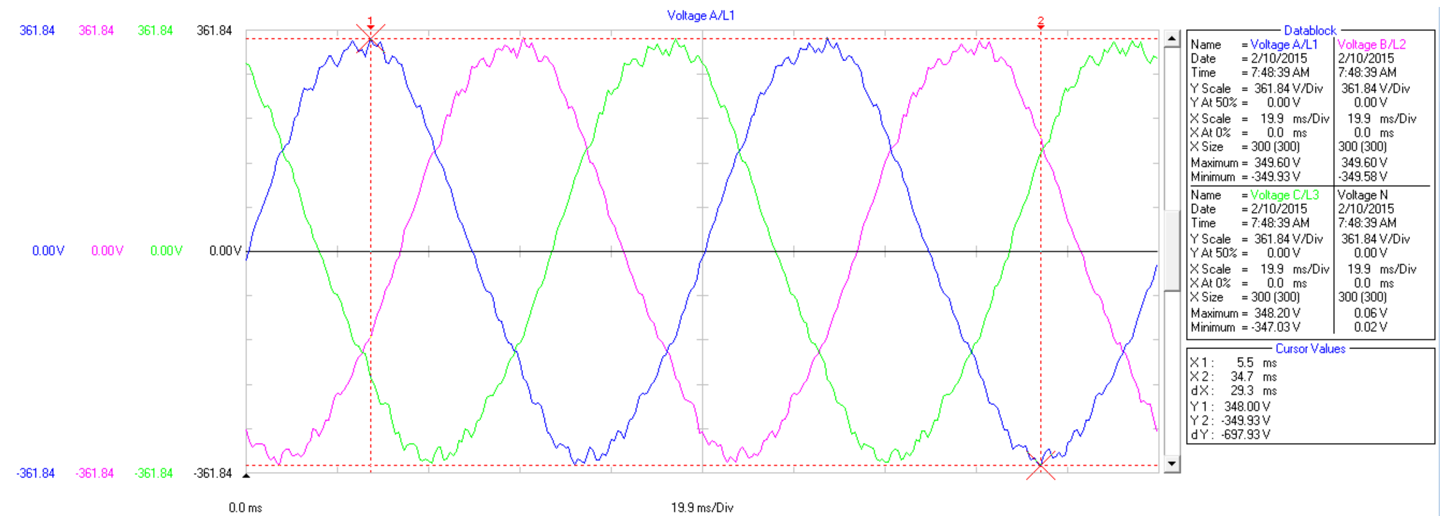
Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.25	86.83	0.0063	-132.68
0.27	30.72	0.0052	-116.74
0.23	47.50	0.0059	-148.96
0.00	151.13	0.0164	-125.13

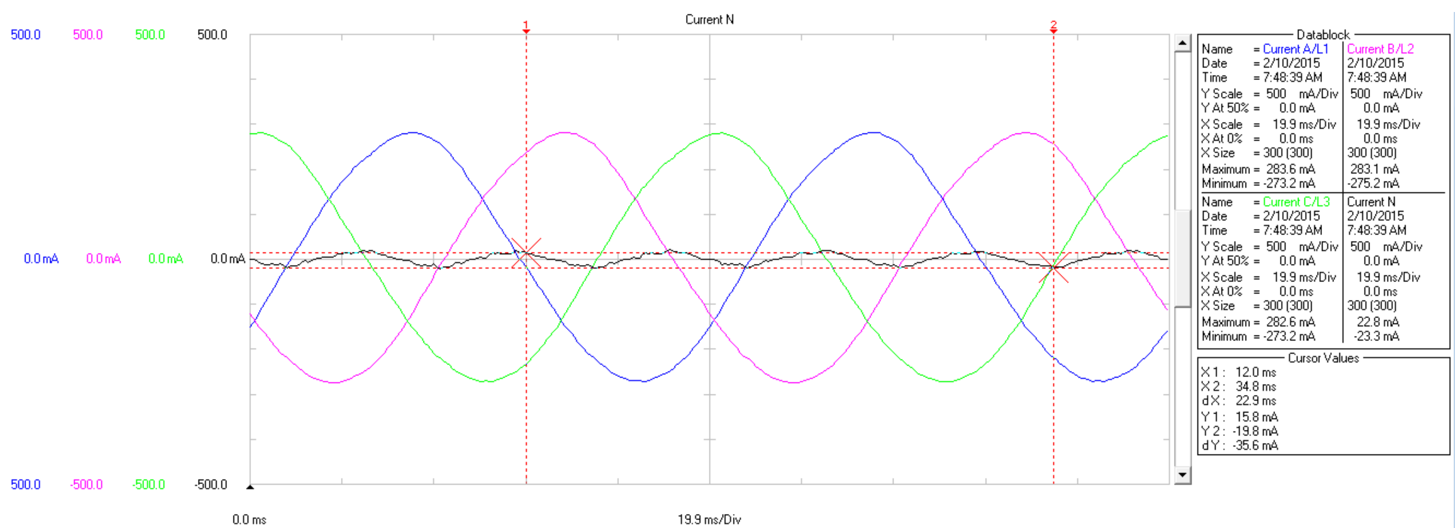
Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
36.92	0.00	0.0305	-32.56
36.83	-119.79	0.0303	-151.02
36.99	120.22	0.0300	89.12
0.00	121.07	0.0016	-179.29

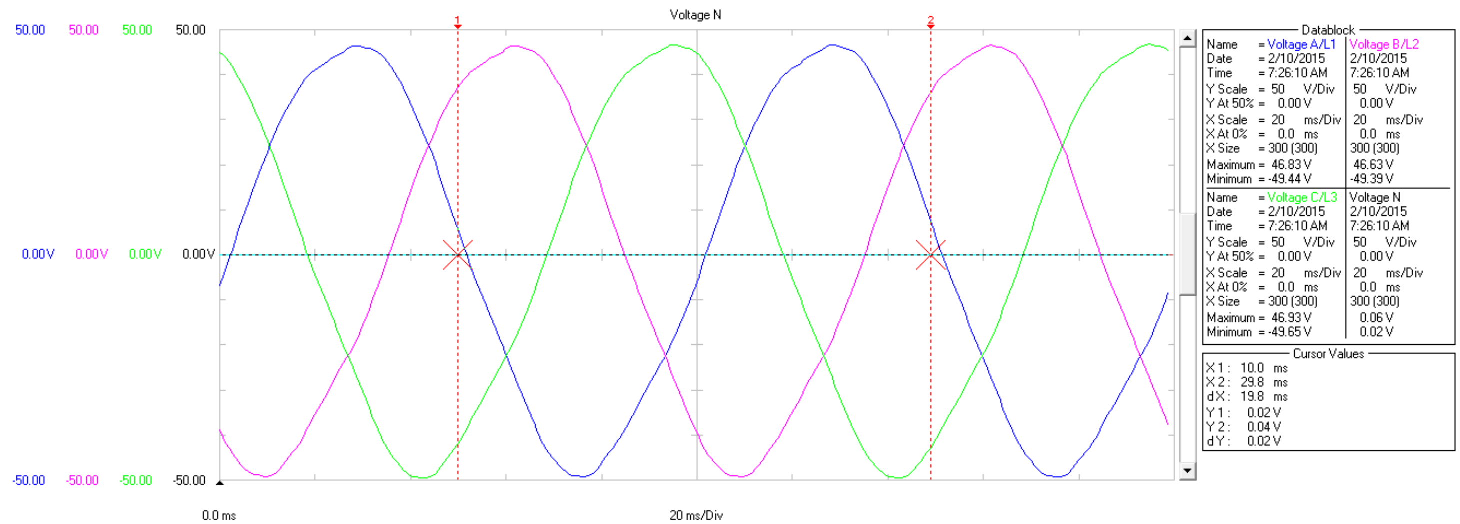
Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.33	-125.87	0.0001	75.94
0.31	-107.82	0.0002	151.23
0.33	-118.79	0.0002	87.96
0.00	-164.90	0.0202	-148.37

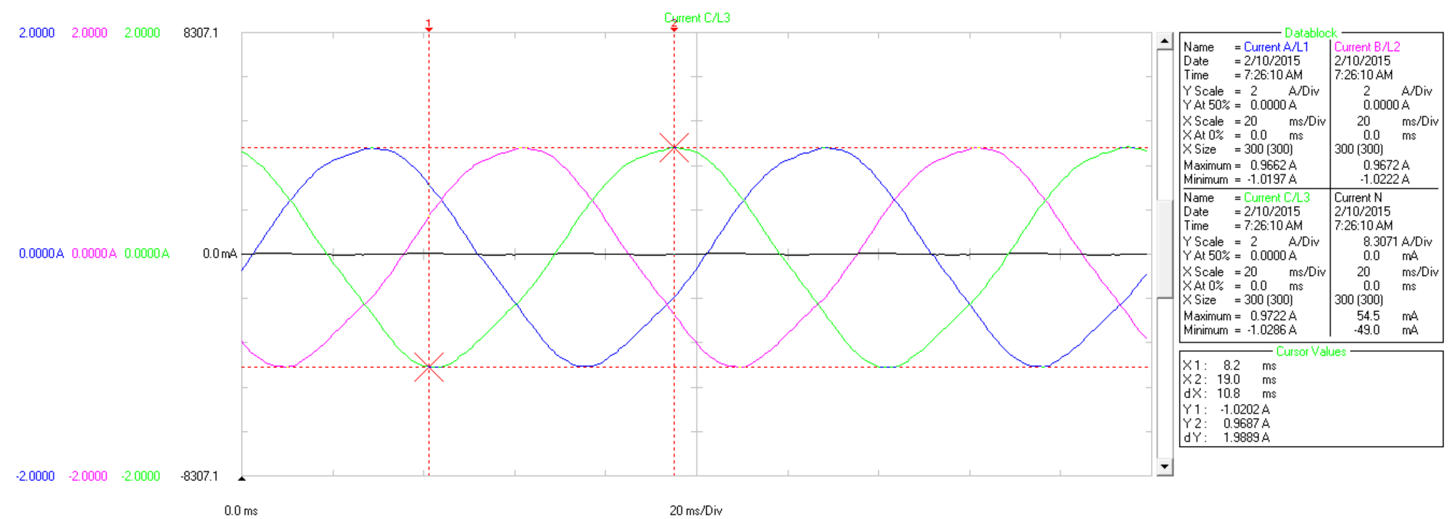
5.Load Impedance=960+j660, filter mode, with NER=800 Ω, with Zf=50.53 Ω (NON-FAULT)





5.Load Impedance=960+j660, filter mode, with NER=800 Ω, with Zf=50.53 Ω (AFTER FAULT)





6. Load Impedance=960+j660, filter mode, with NER=800 Ω, without Zf=50.53 Ω

Non-Fault Experiment:

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.90	0.00	0.1961	-32.97
238.87	-119.76	0.1947	-152.84
240.19	120.31	0.1943	86.97
0.01	128.97	0.0005	-14.64

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
239.87	0.00	0.1916	-33.03
238.87	-119.75	0.1904	-153.04
240.12	120.30	0.1904	87.40
0.01	127.97	0.0006	-101.50

Gen

Load

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.50	-122.87	0.0039	12.11
0.62	99.04	0.0046	10.41
0.79	-6.57	0.0039	2.91
0.00	38.98	0.0124	-170.82

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.51	-118.51	0.0014	87.26
0.64	94.99	0.0016	65.13
0.75	-6.16	0.0008	57.73
0.00	58.58	0.0125	6.78

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
241.35	0.00	0.0008	99.55
239.19	-119.06	0.0006	-34.07
238.50	120.84	0.0007	167.31
0.01	130.85	0.0002	148.53

Fault

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.64	-134.05	0.0001	127.39
0.77	96.52	0.0004	102.27
0.64	0.73	0.0018	120.84
0.00	98.36	0.0001	71.92

Fault Experiment:

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
2.91	0.00	0.6913	9.66
2.91	-104.16	0.6876	-109.99
2.92	131.08	0.6911	129.49
0.00	123.52	0.0024	2.80

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
2.45	0.00	0.0028	-4.19
2.45	-101.60	0.0022	-68.02
2.47	132.01	0.0021	35.87
0.00	123.88	0.0010	-108.02

Gen

Load

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.01	-107.91	0.0150	-80.17
0.02	-108.00	0.0122	-94.48
0.02	-106.07	0.0137	-90.51
0.00	111.34	0.0386	91.61

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.01	-95.27	0.0002	-175.82
0.01	-9.80	0.0001	83.32
0.02	-18.57	0.0001	-82.68
0.00	144.64	0.0013	-138.88

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
4.89	0.00	0.6881	150.61
4.88	0.00	0.6880	30.94
4.85	-1.27	0.6900	-89.36
0.00	-106.12	0.0018	32.65

Fault

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.26	38.94	0.0149	-22.25
0.26	39.15	0.0121	-28.44
0.26	39.11	0.0137	-14.62
0.00	-40.88	0.0389	-25.81

7. Load Impedance=960+j660, filter mode, without NER=800 Ω, with Zf=50.53 Ω

Non-Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
240.27	0.00	0.1940	-33.65
239.39	-119.65	0.1984	-152.93
240.66	120.42	0.1941	88.03
0.01	130.24	0.0107	11.03

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
3.28	-12.84	0.0831	-30.77
3.64	16.98	0.0837	-30.20
4.37	-5.26	0.0834	-31.27
0.00	10.47	0.2492	149.32

Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
240.18	0.00	0.1917	-33.17
239.65	-119.82	0.1911	-153.15
240.79	120.20	0.1914	87.45
0.01	128.27	0.0103	-178.25

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
3.03	-1.35	0.0010	22.12
3.81	10.28	0.0018	1.48
4.40	-10.77	0.0012	-44.22
0.00	48.04	0.2651	-31.90

Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
243.11	0.00	0.0011	52.25
238.62	-118.99	0.0006	-61.27
238.73	119.89	0.0010	-161.20
0.01	128.97	0.0001	-40.86

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.85	89.82	0.0001	132.76
1.47	98.58	0.0004	97.50
1.25	15.04	0.0019	105.69
0.00	49.26	0.0001	113.21

Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
35.95	0.00	0.6781	-0.65
35.85	-119.89	0.6747	-120.30
35.98	120.22	0.6777	119.14
0.00	119.74	0.0059	-69.75

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
6.44	-163.37	0.2619	179.76
6.35	-163.78	0.2608	179.62
6.42	-163.98	0.2608	179.25
0.00	-124.13	0.7826	0.00

Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
35.46	0.00	0.0283	-30.49
35.39	-119.96	0.0285	-151.73
35.48	120.17	0.0287	89.09
0.00	139.07	0.0062	76.69

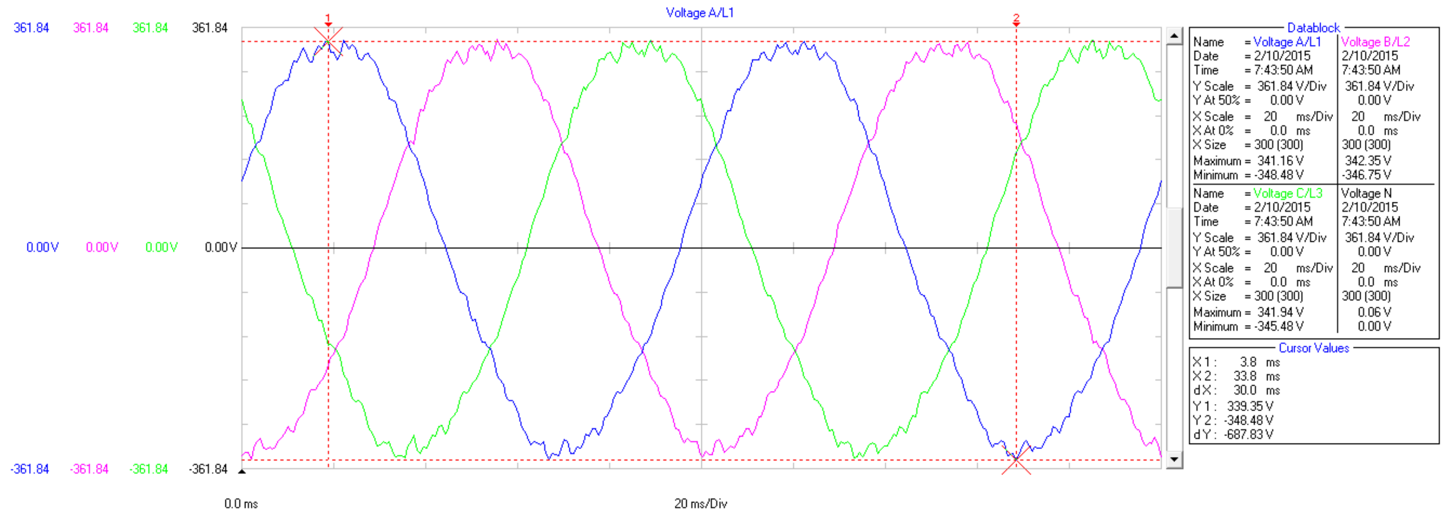
Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
6.41	-163.45	0.0029	138.46
6.31	-163.26	0.0029	134.53
6.41	-163.94	0.0025	133.24
0.00	22.36	0.7892	164.58

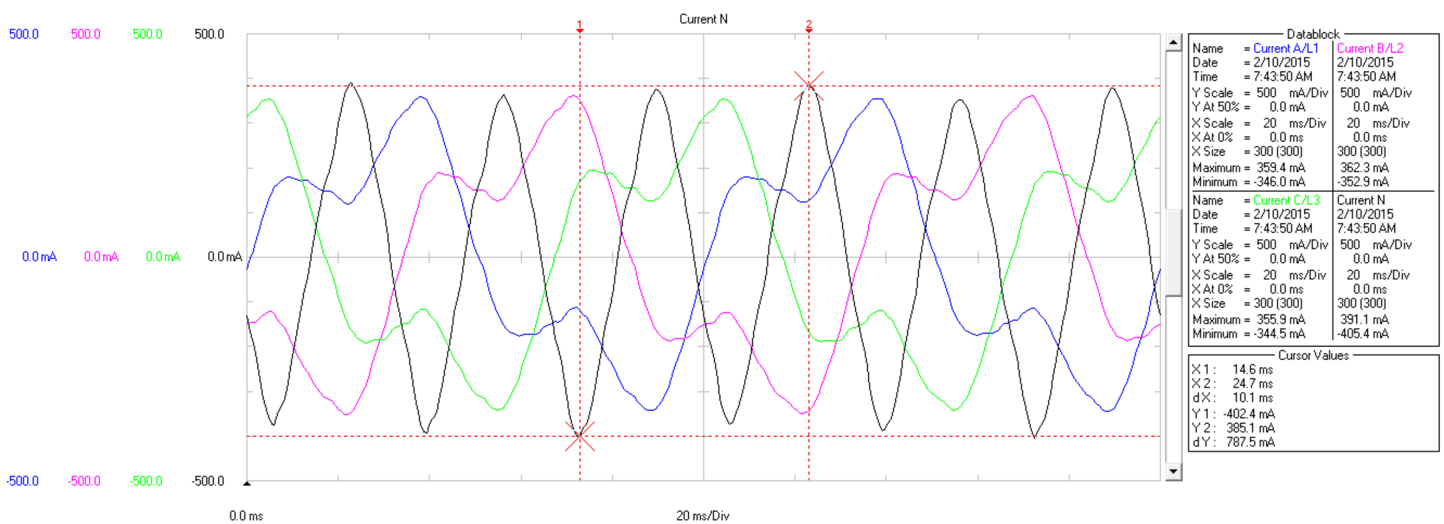
Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
37.65	0.00	0.6542	1.28
34.91	-116.02	0.6520	-118.51
35.29	118.25	0.6528	121.40
0.00	125.36	0.0045	73.73

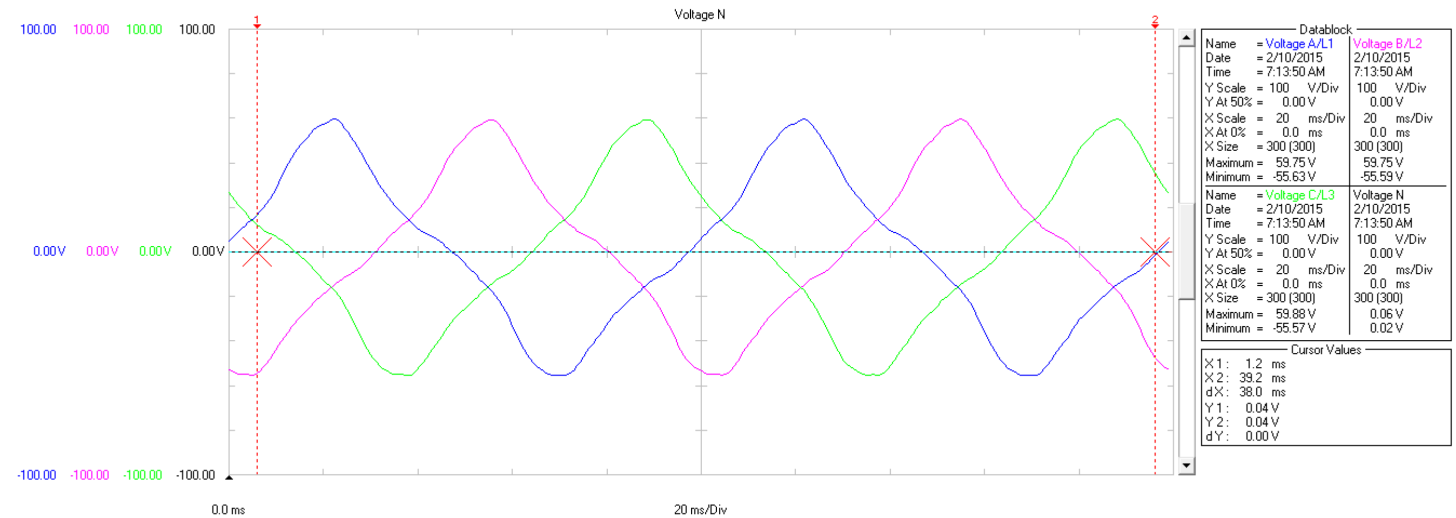
Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
1.15	-81.21	0.1243	-161.10
1.07	-78.18	0.1230	-162.66
1.11	-79.72	0.1237	-162.86
0.00	168.41	0.3694	-162.12

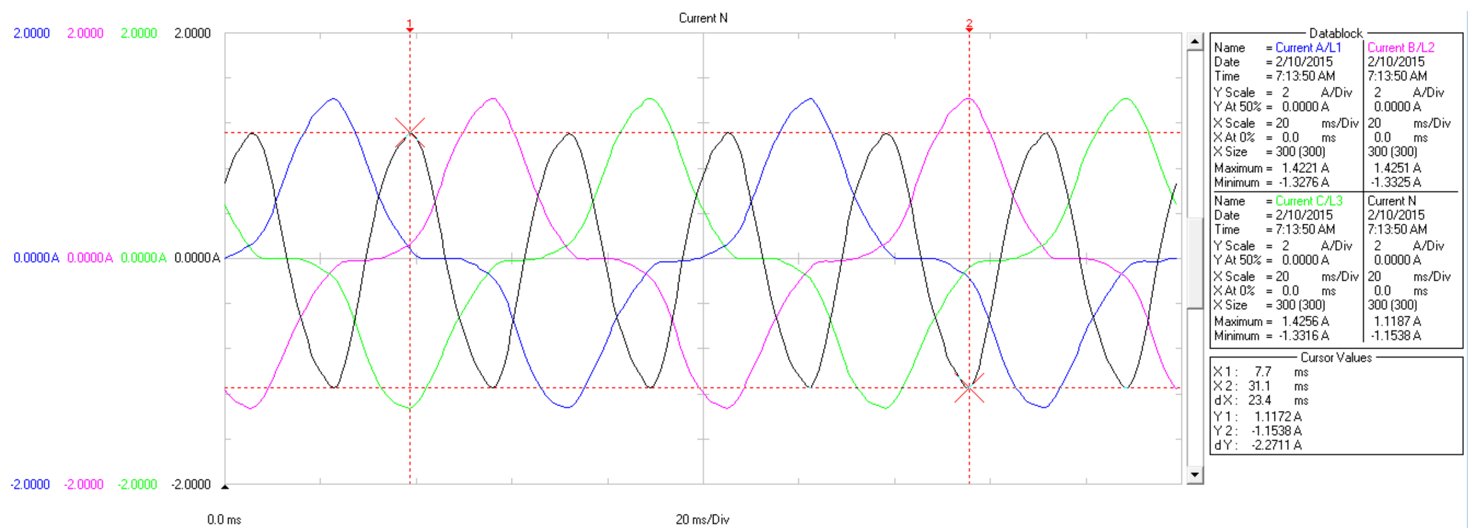
7. Load Impedance=960+j660, filter mode, without NER=800 Ω, with Zf=50.53 Ω (NON-FAULT)





7.Load Impedance=960+j660, filter mode, without NER=800 Ω, with Zf=50.53 Ω (AFTER FAULT)





8. Load Impedance=960+j660, filter mode, without NER=800 Ω, without Zf=50.53 Ω

Non-Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
240.27	0.00	0.1940	-33.65
239.39	-119.65	0.1984	-152.93
240.66	120.42	0.1941	88.03
0.01	130.24	0.0107	11.03

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
3.28	-12.84	0.0831	-30.77
3.64	16.98	0.0837	-30.20
4.37	-5.26	0.0834	-31.27
0.00	10.47	0.2492	149.32

Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
240.18	0.00	0.1917	-33.17
239.65	-119.82	0.1911	-153.15
240.79	120.20	0.1914	87.45
0.01	128.27	0.0103	-178.25

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
3.03	-1.35	0.0010	22.12
3.81	10.28	0.0018	1.48
4.40	-10.77	0.0012	-44.22
0.00	48.04	0.2651	-31.90

Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
243.11	0.00	0.0011	52.25
238.62	-118.99	0.0006	-61.27
238.73	119.89	0.0010	-161.20
0.01	128.97	0.0001	-40.86

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.85	89.82	0.0001	132.76
1.47	98.58	0.0004	97.50
1.25	15.04	0.0019	105.69
0.00	49.26	0.0001	113.21

Fault Experiment:

Gen

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
2.56	0.00	0.6831	4.63
2.56	-109.24	0.6767	-114.55
2.57	126.02	0.6819	124.57
0.00	-14.52	0.0204	131.94

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.07	-152.75	0.3568	-156.13
0.09	-152.27	0.3552	-154.71
0.08	-152.67	0.3557	-155.80
0.00	18.54	1.0662	24.56

Load

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
2.44	0.00	0.0027	115.27
2.44	-106.76	0.0022	55.99
2.45	125.38	0.0020	153.41
0.00	-136.73	0.0008	6.71

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.06	-148.26	0.0002	-166.88
0.07	-147.53	0.0001	87.06
0.07	-147.61	0.0001	-70.61
0.00	142.36	0.0047	-166.33

Fault

Vf(Volt)	Vf°(deg)	If(A)	If°(deg)
4.30	0.00	0.6805	26.47
4.25	-1.08	0.6792	-93.35
4.25	0.00	0.6826	146.29
0.00	76.10	0.0202	104.40

Vt(Volt)	Vt°(deg)	It(A)	It°(deg)
0.14	29.62	0.3558	-90.42
0.15	29.65	0.3533	-91.12
0.15	30.05	0.3539	-91.34
0.00	-4.01	1.0572	-91.28