Third Harmonic Filter Design in Mitigating High Current At the Generator Neutral

by

NUR AFIFAH BINTI GHAZALI

16387

Dissertation submitted in partial fulfilment of

the requirements for the

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(Electrical and Electronic Engineering)

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

____

(Ir. Dr. Mohd Faris Abdullah)

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR,

TRONOH, PERAK

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.

NUR AFIFAH BINTI GHAZALI

ABSTRACT

Harmonic is commonly known power quality problem which caused by non-linear load. Nevertheless, harmonic was also found at the synchronous generator instead of at the load. The effect of the triplen harmonic to the generator neutral is high current which lead to high temperature of the component at the generator neutral. Recent researches had identified the major component of the triplen harmonic is third harmonic which initiated by the synchronous generator itself. There are numerous techniques to reduce the effect of harmonic in power system network. By installing harmonic filter is one of the techniques to mitigate the harmonic current. A study about installing harmonic filter at the generator neutral had been introduced to counter this arising issue. The objectives of this study are to study the various harmonic filters used in mitigating the third harmonic current and to design harmonic filter that can reduced the third harmonic current at generator neutral and validate the modelling with experimental values. This method had been tested using the Matlab Simulink simulation to show how the filter mitigates the high third harmonic current at the generator neutral. Before running the simulation, the fundamental and third harmonic current modelling is constructed and validates the modelling using the experimental values. Series passive filter and active filter can reduce the high current at the generator neutral.

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Not to forget, appreciation to the family members and friends that always there to give moral support throughout this project.

Lastly, lots of thanks to the parties that involved directly or indirectly in helping the author to complete this project.

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CHAPTER 1

INTRODUCTION

1.1. Background Of Study

Power quality problem is an unwanted phenomenon in electrical power system such as harmonic, surge, transient etc. Harmonic in the electrical system is commonly caused by the non-linear load.

In recent research at Universiti Teknologi Petronas (UTP), it was found that triplen harmonic current circulating at generator neutral that originated from the synchronous generator itself. Third harmonic is the major component of this triplen harmonic current. Salient pole synchronous generator is one of harmonic sources and its third harmonic depends on winding design in terms of pitch factor, distribution factor and slot skew.

There are many methods to minimize third harmonic currents from synchronous generator such as using 2/3 pitch winding generator, zigzag connection alternator, resonance shunts on the generator, third harmonic current trap, Petersen Coil and harmonic filter. Filter in electric power system is designed to mitigate the harmonic problem. Harmonic filters in general can be categorized as passive or active filters.

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 has caused the neutral grounding resistor to experience high temperature at UTP Gas District Cooling (GDC) plant. Therefore, it is very important to mitigate this high third harmonic current using suitable harmonic filter.

1.3. Objective And Scope Of Study

The objectives of this project:

- To study the various harmonic filters used in mitigating the third harmonic current.
- To design the harmonic filter that effectively reduced the third harmonic current at generator neutral and validate with experimental value.

The scope of study is to design the harmonic filter to mitigate the high third harmonic current originated from salient pole synchronous generator that return to its neutral. The configuration is such that salient pole synchronous generator is directly connected to the load whether at medium or low voltage system.

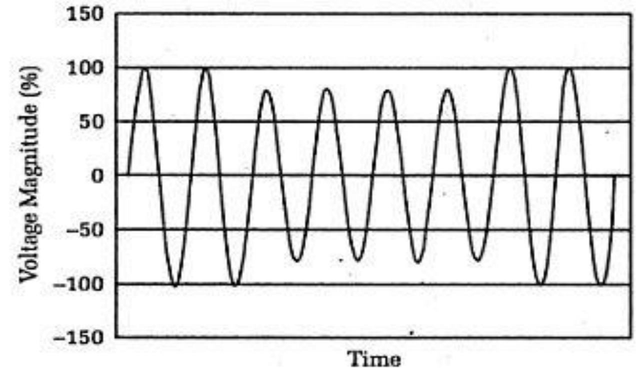
CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Power Quality

In electrical power system, there is a parameter to measure the quality of the power in order to enhance or to maintain the respective electrical devices. This parameter is called power quality. There are a few definitions for power quality according to different sources. For example, according to [1], power quality is the characteristics of the voltages during the standard operation. In the other hand, power quality is defined as the suitability of the grounding and powering with the other connected devices in standard operation [2]. Figure 1 shows a few examples of power quality problems.

Power quality is divided into three groups which are voltage stability, power supply continuity and voltage waveform. First level is normal quality, second level is high quality and third level is premium quality. The purpose of these levels is to classify the level of the power quality. In the event of harmonic voltage, the power quality level is premium level where it can be compensated occasionally. While harmonic current level of power quality is also premium quality except the event is fully compensated [3]. These three levels of power quality depend on the demand characteristics of the customers [4].

Power quality problem would arise when there is harmonic in voltage and current on the electrical power system. Harmonic in electrical power system is a norm and mostly is caused by the non-linear load such as rectifiers and variable frequency drives.

<table>
<tr><td>
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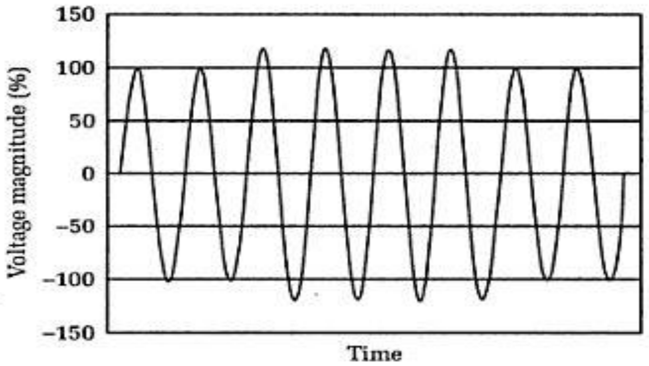
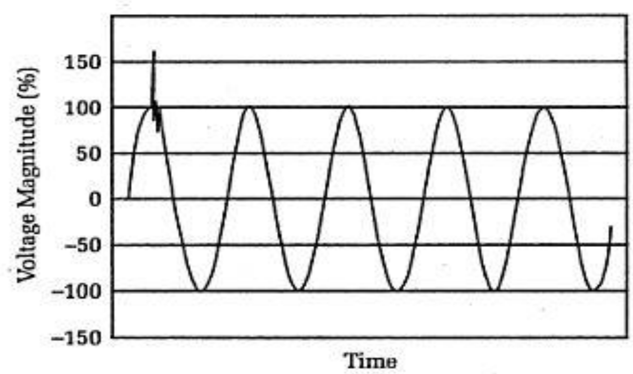
<tr><td>
</td><td>Voltage swell</td></tr>
<tr><td>
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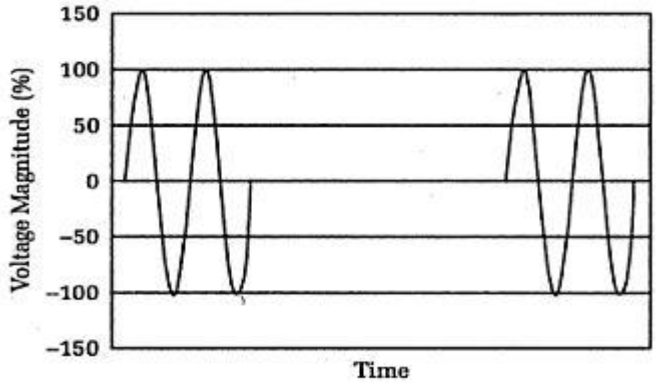
<tr><td>
</td><td>Voltage interruption</td></tr>
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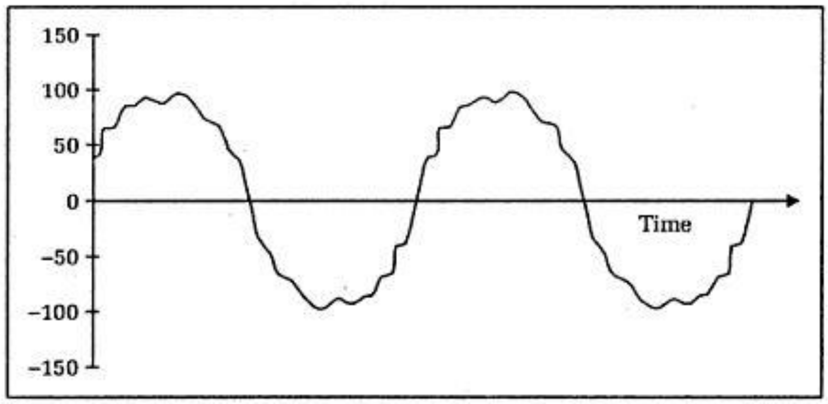	Harmonic voltage

FIGURE 1 Example of power quality problems [5]

2.2. Harmonic

Harmonic is distorted current or voltage waveforms causes by short pulses when flow back to the other part of power system. There are three groups of harmonic which include positive, negative and zero sequence harmonic. Positive sequence harmonic consist of 1^{st}, 4^{th}, 7^{th}, 10^{th} etc order of harmonic. These harmonic develop current that rotate in same direction with the fundamental frequency. For negative sequence harmonic, it is the vice versa of the positive sequence where it includes 2^{nd}, 5^{th}, 8^{th}, 11^{th} etc order of harmonic. There is one more group of harmonic which is zero sequence harmonic. The current does not rotate in any direction and it flows in the neutral wire which leads to additional losses in the power system. Triplen harmonic (3^{rd}, 6^{th}, 9^{th} etc) are a part of zero sequence harmonic [6]. However, it is rarely to find even numbered triplen harmonic in AC system. This is because even harmonic will cancel each other. According to [7], the third harmonic model is achieved by connecting the synchronous generator third harmonic sequence network to the zero-sequence network of the power system. Figure 2 shows the third harmonic propagation model. The third harmonic model parameters for synchronous generator are determined from the open circuit and short circuit tests.

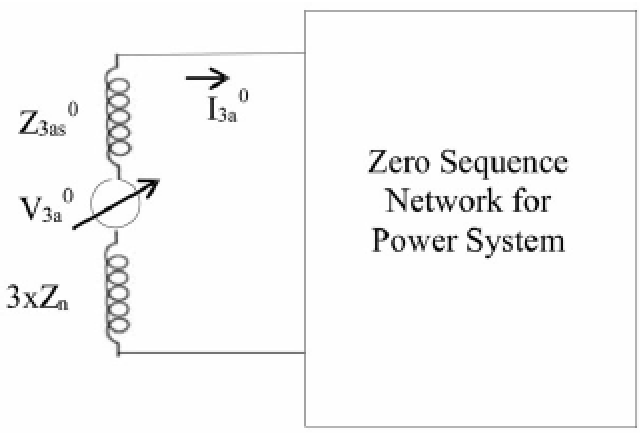

FIGURE 2 Third harmonic propagation model [7]

2.3. Neutral Earthing Impedance

Generator equipped with Neutral Earthing Resistor (NER) for the purpose to reduce earth fault current. NER in generator is designed to reduce the physical damage during earth fault current event by dispersing the over voltage that pass through the neutral point up to the safe value.

The study carried by [8] had proved that besides non-linear load as the source of harmonic, there is one other source which causes the harmonic. The source is the synchronous generator. The effects of the harmonic is the generator NER become hot especially during its parallel operation with the utility grid.

2.4. Filters

The function of filter in power system is to provide low impedance path to trap the harmonic at the respective place where the filter is tuned. Logically, the filter absorbs the harmonic by having a zero impedance at the tuning frequency [9].

2.4.1. Active filter

Active filter is made up of complex power electronics converter. Its working principle is by injecting the harmonic current into the power system. The filter is placed before the non-linear load. There are two types of existing active filter which are voltage sourced active power filter and current sourced active power filter.

2.4.1.1. Voltage Sourced Active Power Filter

For voltage sourced active power filter, it injects AC voltage at the output where the filter is an inductor as shown in Figure 3. The voltage sourced is lighter and cost effective [10]. Shunt active filter is more suitable to be used as static var generator to improve and stabilize the voltage profile. One of the methods in active filter is by constructing a controllable filter made up of LC circuit and an electronics switch. The filter will produce same amplitude of harmonic current with the existing harmonic current at the load.

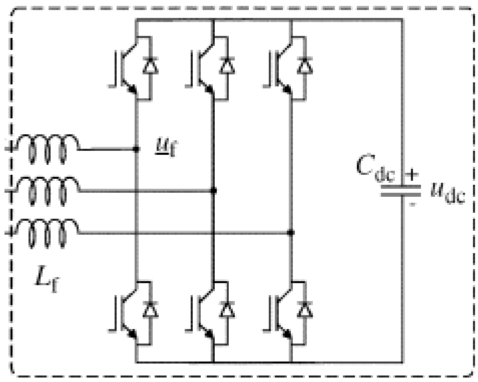

FIGURE 3 Voltage Sourced Active power filter [11]

2.4.1.2. Current Sourced Active Power Filter

In the other hand, current sourced active power filter as shown in Figure 4 injects AC current at its output and the filter is a shunt capacitor. It is connected in series before the load through a coupling transformer to remove the harmonic voltage and balance the supply voltage. The function of coupling transformer is to isolate the PWM inverters from the source and to match the supply voltage rating with the PWM inverters. The drawback of this filter is the parallel capacitor filters should be higher [10].

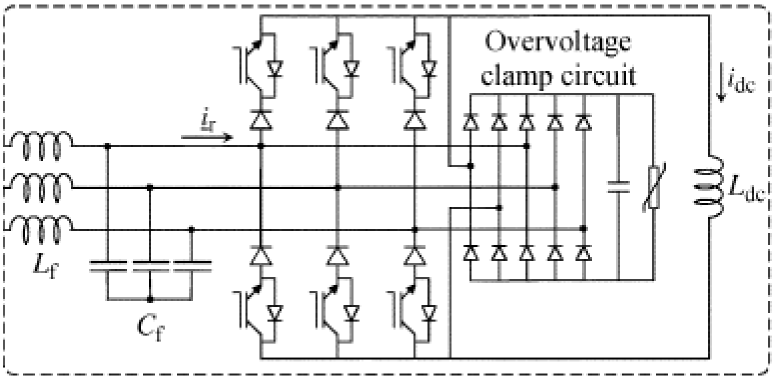

FIGURE 4 Current Sourced Active power filter [11]

2.4.2. Passive filter

Capacitor, resistor and inductor are examples of passive components which are used for passive filter. The passive filter functions by adjusting the frequency of resonance to eliminate the desired harmonic. Figure 5 shows the connection of passive filter from the source to the load. The classification of the filters is based on the type of harmonic generation components source present in the system. Passive filters are classified as passive series filter and shunt filter.

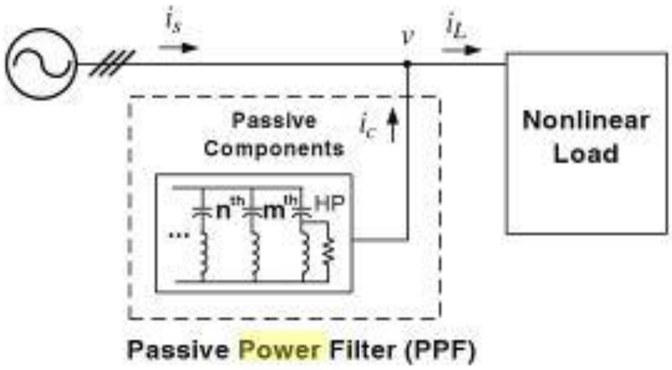

FIGURE 5 Passive power filter [12]

2.4.2.1. Passive series filter

The components of the passive series filter are connected in series with the load as shows in Figure 6 where the components arrangement as shows in Figure 7. Normally, the series filter is to block a single harmonic current such as third harmonic current since it only works in single frequency. This is because it is limited in blocking multiple harmonic currents [13]. The disadvantage of the passive series filter is the components need to be designed according to the rated load current [14].

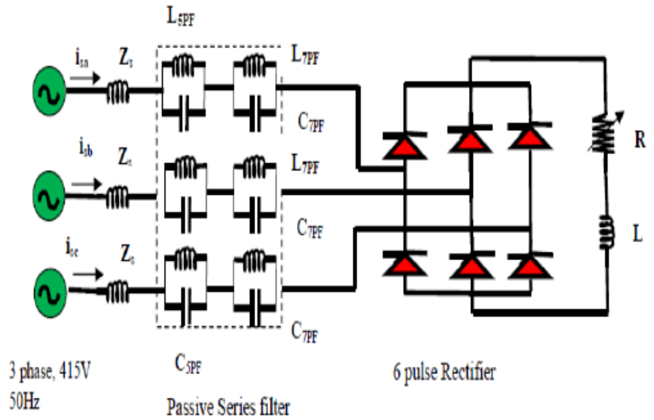

FIGURE 6 Example of Application of Passive Series Filter [15]

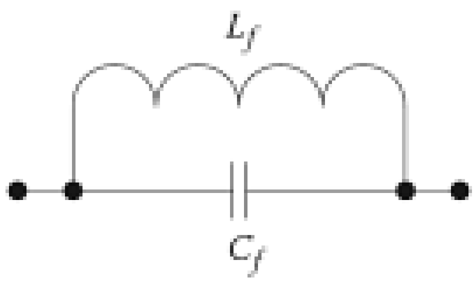

FIGURE 7 Passive series filter configuration [14]

2.4.2.2. Passive shunt filter

Passive shunt filter is connected in parallel as shown in the Figure 8. The components are connected in series as shown in Figure 9. The designed passive shunt filter will provide very low impedance path for harmonic current equivalent to its tuned frequency. There are two types of passive shunt filter, which are:

A. Single tuned filter
B. High pass filter

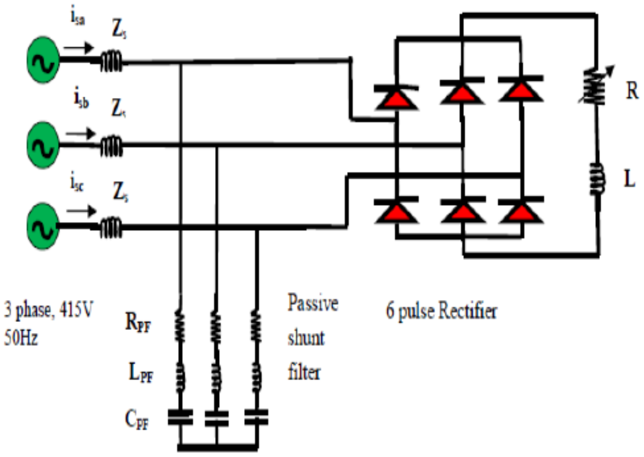

FIGURE 8 Example of Application of Passive Shunt Filter [15]

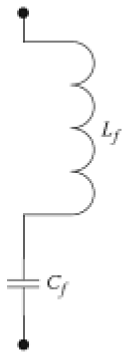

FIGURE 9 Passive shunt filter configuration [14]

A. Single tuned passive filter

Figure 10 is one of the non-complex shunt passive filter which consist of designable inductor and capacitor to provide the lowest impedance path by increasing the frequency order. The components of passive filter are simple hence it also cost effective compared to complex active filter. According to [16], calculation can be done to get the designed parameters. All the steps to calculate the parameters are given by (1) to (5).

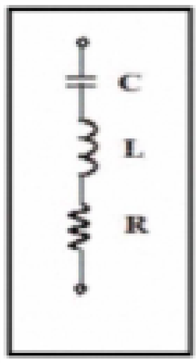

FIGURE 10 Single tuned passive filter [17]

Reactive power, kVAR

$$\text{kVAR} = \text{kVA x } \sin(\cos^{-1}(PF)) \tag{1}$$

Filter reactance, X_{fil}

$$X_{fil} = \frac{\text{kV}^2(1000)}{\text{kVAR}}\ \Omega \tag{2}$$

Capacitive Reactance, X_{cap}

$$X_{cap} = \frac{X_{fil} \times h^2}{h^2 - 1}\ \Omega \tag{3}$$

Inductive Reactance, X_L

$$X_L = \frac{X_{cap}}{h^2}\ \Omega \tag{4}$$

Harmonic frequency, f_h

$$f_h = \frac{1}{2\pi\sqrt{LC}}\ \text{Hz} \tag{5}$$

Where,
h = Harmonic order
L = Inductance (H)
C = Capacitance (F)

B. High pass filter

High pass filter provides a filter with a corner frequency to which it is tuned and also to frequencies above this corner frequency. This filter passes the higher frequencies well but reduces the amplitude of lower frequencies lower than the filter cutoff frequency [18]. The configuration of high pass shunt filter is shown in Figure 11.

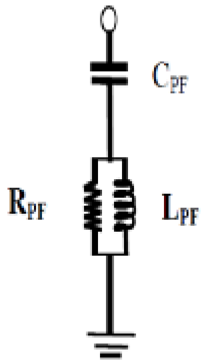

FIGURE 11 High Pass shunt filter configuration[18]

2.4.3. Hybrid power filter

The combination of shunt passive filter and shunt active filter is called hybrid power filter. It includes both components that exist at passive filter and active filter. The examples of the components are electronics switching device, capacitors, inductors etc. The function of shunt active power filter is to filter low order harmonics while shunt passive filter function is to filter the higher order harmonics [19]. Figure 12 shows the configuration of hybrid power filter [17].

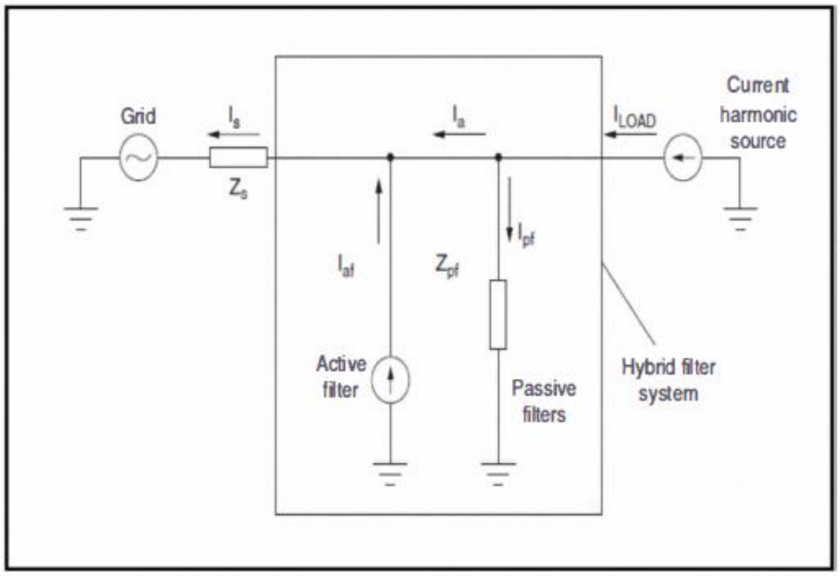

FIGURE 12 Hybrid Power filter [17]

CHAPTER 3
METHODOLOGY

3.1. Research Methodology

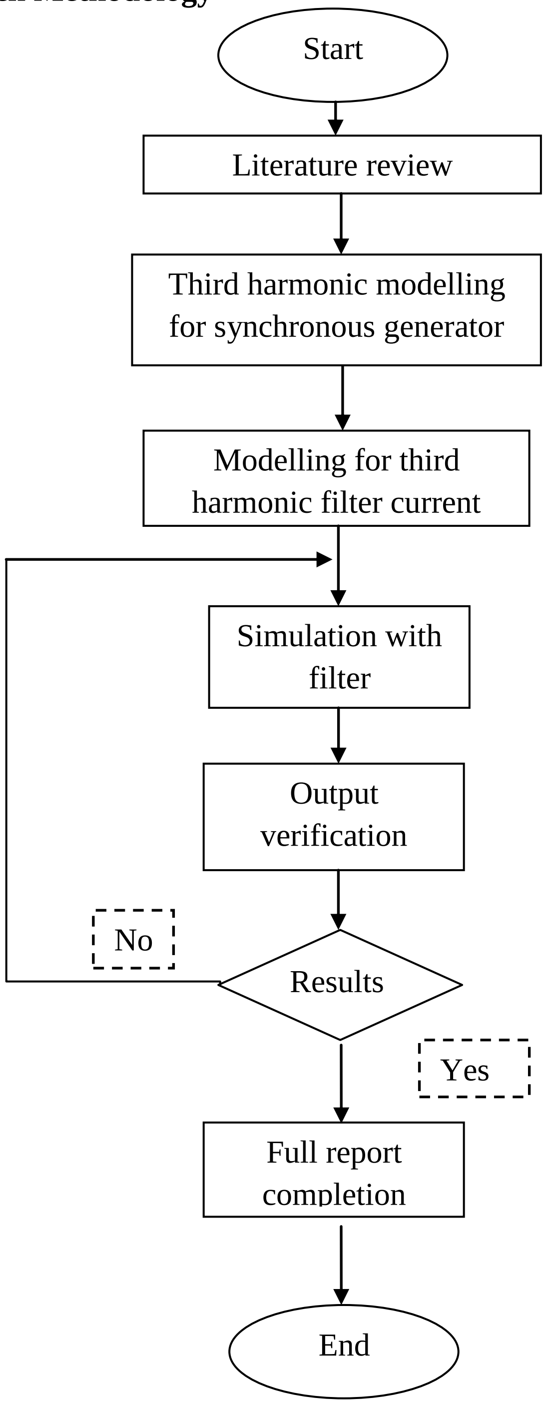

FIGURE 13 Flowchart

Based on the flow chart in Figure 13, the project starts with the literature review. The author reads through the research paper, journals, books and other resources related to the project title to get the overall understanding. The information about types of filter is gathered in order to design the filter.

After the completion of literature review, the author starts with the modelling the third harmonic of synchronous generator and harmonic filter using the Matlab Simulink. Once the modelling is complete, the simulation for the filter is carried out. The output of the simulation is verified. If the result shows the third harmonic is successfully removed then the objectives of the project are achieved. If not, the simulation will continue with different design of filter until the desired result is achieved.

3.2. Project Gantt Chart

The purpose of a Gantt chart is to show the time scale of the tasks for the final year project. The Gantt chart in Table 1 is to ensure the author to keep on track to ensure the project timeline of the key milestone is followed accordingly.

TABLE 1 Project Gantt chart

	Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
No.	Tasks															
1	Literature Review															
2	Familirizing with the simulation tools															
3	Modelling third harmonic for generator															
4	Model various type of filter															
5	Simulation with the experimental data															
6	Verifying the output of the simulation															

3.3. Key Milestone

A key milestone is developed to keep on track on the project timeline in order to complete the project within the time frame. The key milestone is as shown in Table 2.

TABLE 2 Key milestones

	Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
No.	Tasks															
1	Literature review completion															
2	Third harmonic filter model achieved															
3	Simulation with filter is carried out															
4	Output verification															
5	Result achieved															
6	Full report completion															

3.4 System Modelling

Before running the simulation, the author first needs to design the fundamental model and third harmonic model for synchronous generator by using Matlab Simulink. The author implements the respective parameters in the modelling. The result of simulation from the modelling is compared with the experimental value.

3.4.1 Fundamental Model

Each of the blocks shown in Figure 14 has its own parameters as stated in Table 3. The circuit was modelled based on diagram in Figure 2 with fundamental frequency which is 50 Hz. The circuit is analysed at the output of three phase VI measurement where it measure the current and voltage from the source. The simulation is carried out by varying the voltage and the load impedance simultaneously. The RMS value of the current is displayed at the display block.

3.4.1.1 Resistive Load

The modelling for the fundamental model with resistive load is as in Figure 14. Table 3 shows the parameters for the simulation of fundamental model.

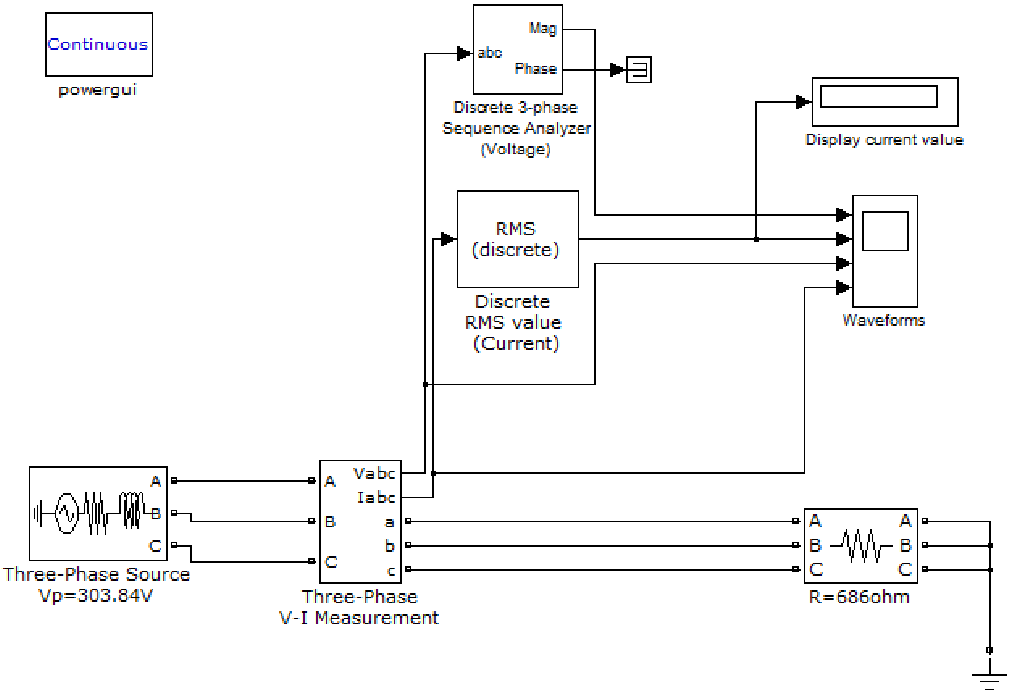

FIGURE 14 Fundamental Model with Resistive Load

TABLE 3 Parameters for Fundamental Model with Resistive Load

Parameters	Values				
Source resistance (Ω)	48				
Source Inductance (H)	1.53				
Frequency (Hz)	50				
No Load Voltage (V)	303.84	292.16	266.67	256.89	249.06
Load Impedance (Ω)	686.00	800.00	1200.00	1600.00	2400.00

3.4.1.2 Inductive Load

Figure 15 is the modelling for fundamental with inductive load. The parameters for the model are in Table 4.

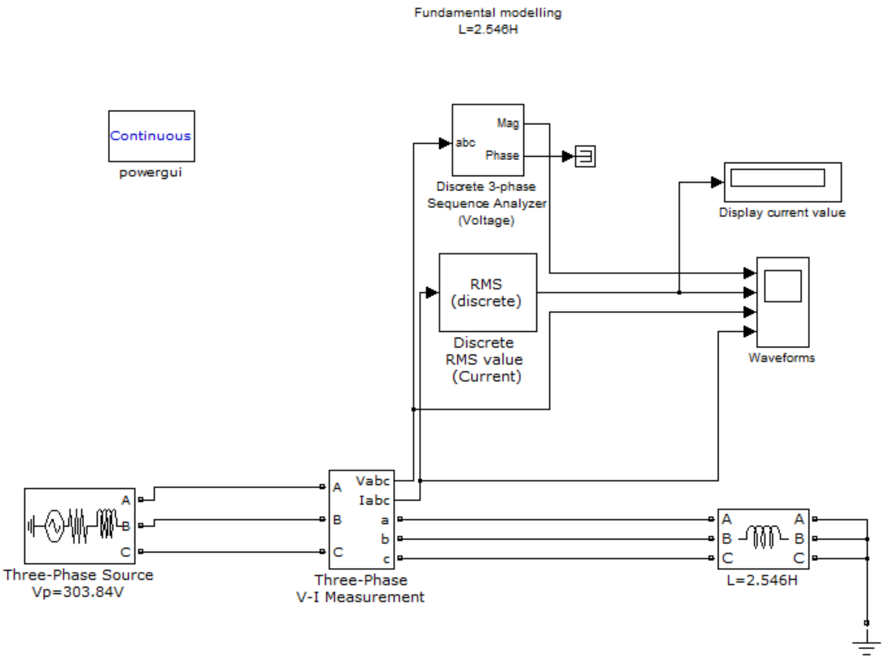

FIGURE 15 Fundamental Model with Inductive Load

TABLE 4 Parameters for Fundamental Model with Inductive Load

Parameters	Values				
Source resistance (Ω)	48				
Source Inductance (H)	1.53				
Frequency (Hz)	50				
Input Voltage (V)	374.60	338.06	315.44	289.62	265.93
Load Impedance (H)	2.546479	3.819719	5.092958	7.639437	15.278875

3.4.1.3 RL Load

The model in Figure 16 is the fundamental model with RL load. The parameters for the fundamental model with RL load is stated in Table 5.

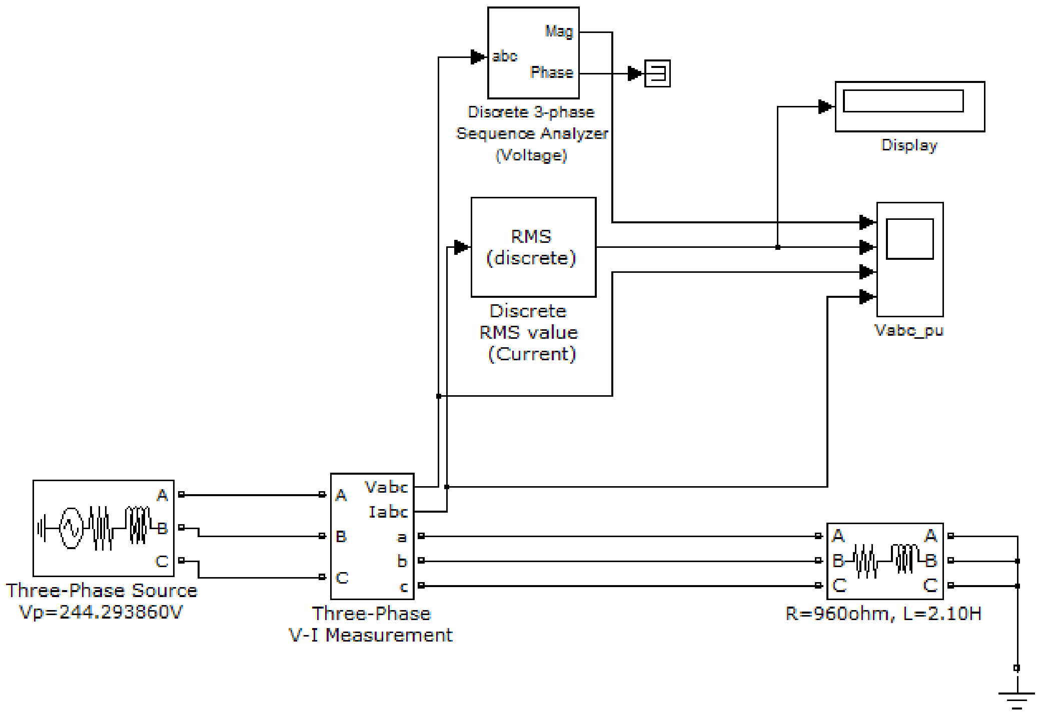

FIGURE 16 Fundamental Model with RL load

TABLE 5 Parameters for Fundamental Model with RL load

Parameters	Values				
Source resistance (Ω)	48				
Source Inductance (H)	1.53				
Frequency (Hz)	50				
Input Voltage (V)	244.29386	236.480826	236.877646	238.307222	238.246143
Resistive load (Ω)	960.00	1600.00	2400.00	3600.00	4800.00
Inductive load (H)	2.101	3.80062004	5.09932438	7.60124008	11.398677

3.4.2 Third Harmonic Model

The circuit for third harmonic was modelled based on diagram in Figure 2 with frequency 150 Hz. The third harmonic model uses three separate sources to achieve the zero sequence where the voltages are in the same phase. Since the voltage sources do not have the source impedance, external RL branch is added to be the source impedance. The circuit is analysed at the output of three phase VI measurement where it measure the current and voltage from the source. Besides, the neutral current is also measured in order to compare its values before and after the filter is added. The simulation is carried out by varying the voltage and the load impedance simultaneously. The RMS value of the current is displayed at the display block.

3.4.2.1 Resistive Load

The model in Figure 17 is the third harmonic model with resistive load. Table 6 showed the parameters for third harmonic model with resistive load.

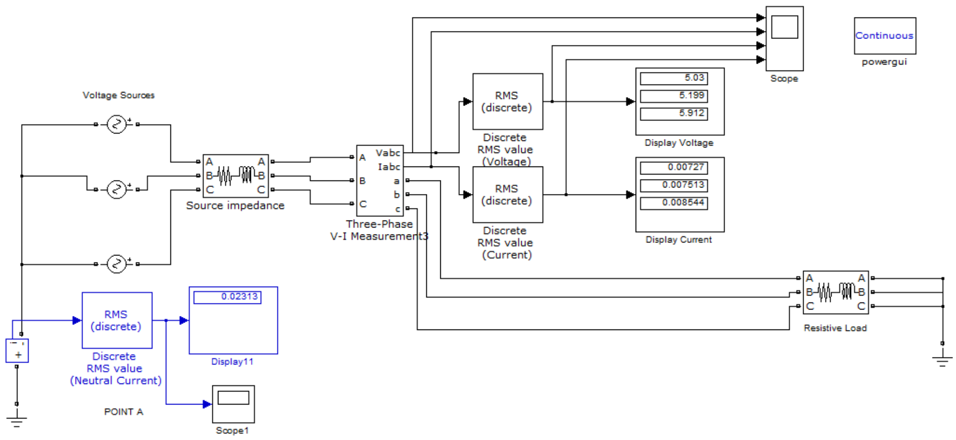

FIGURE 17 Third Harmonic Model with Resistive Load

TABLE 6 Third Harmonic Model with Resistive Load Parameters

Parameters		Values				
Source resistance (Ω)		3.92				
Source Inductance (H)		0.041656				
Frequency (Hz)		150				
Input Voltage (V)	A	5.08	5.50	7.07	8.13	9.20
	B	5.25	5.62	7.27	8.28	9.86
	C	5.97	6.97	8.96	10.21	11.38
Phase Angle (◦)	A	74.06	57.35	27.19	14.31	2.85
	B	85.82	71.10	39.53	25.92	12.77
	C	67.79	55.25	28.53	16.66	5.29
Load impedance (Ω)		691.21 Ω 0.03385 H	764.72 Ω- 0.00245 H	1127.74 Ω -0.02387 H	1663.75 Ω - 0.07770H	2582.34 Ω - 0.07808H

3.4.2.2 Inductive Load

Figure 18 is the modelling for third harmonic with inductive load. The parameters for the model are in Table 7.

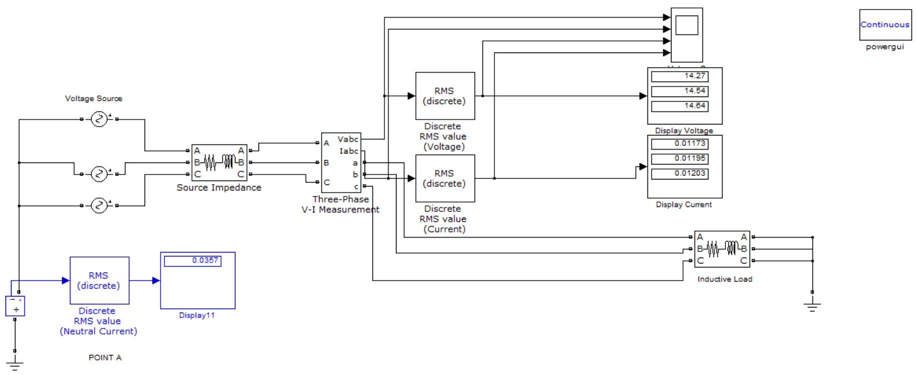

FIGURE 18 Third Harmonic Model with Inductive Load

TABLE 7 Parameters for Third Harmonic Model with Inductive Load

Parameters		Values				
Source resistance (Ω)		3.92				
Source Inductance (H)		0.041656				
Frequency (Hz)		150				
Input Voltage (V)	A	14.73	13.66	13.27	12.97	12.48
	B	15.01	14.02	13.65	13.60	12.97
	C	15.11	14.20	14.07	14.02	13.78
Phase Angle (◦)	A	-20.71	-22.51	-21.74	-21.18	-21.63
	B	-17.21	-18.09	-17.77	-15.75	-15.41
	C	-20.40	-21.65	-20.25	-20.15	-18.95
Load impedance (Ω)		145.79Ω 1.28142H	299.90Ω 1.68539H	445.56Ω 2.56431H	270.75 Ω 4.03679H	1907.36Ω 7.69842H

3.4.2.3 RL Load

The configuration in Figure 19 is the third harmonic model with RL load. The parameters for the fundamental model with RL load is stated in Table 8.

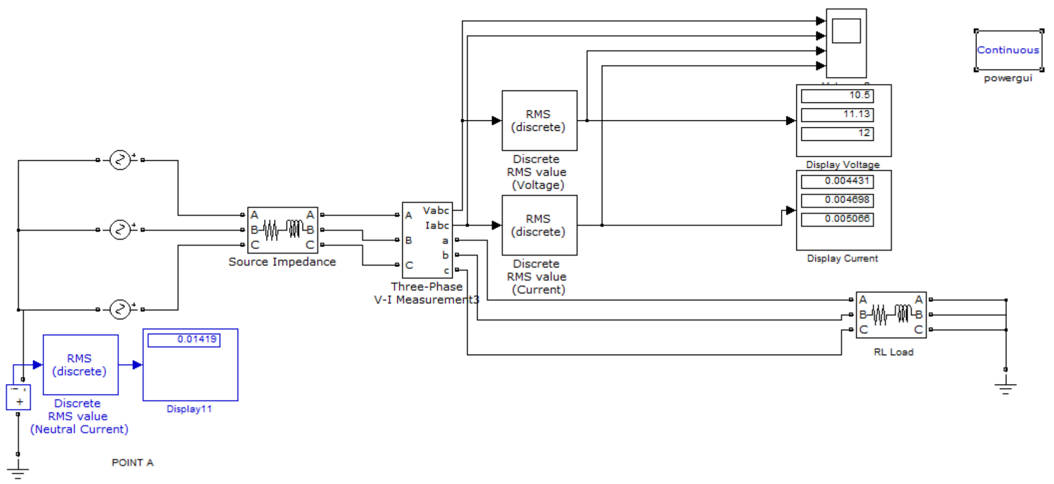

FIGURE 19 Third Harmonic Model with RL Load

TABLE 8 Parameters for Third Harmonic Model with RL Load

Parameters		Values				
Source resistance (Ω)		3.92				
Source Inductance (H)		0.041656				
Frequency (Hz)		150				
Input Voltage (V)	A	10.62	11.02	11.20	11.49	11.52
	B	11.26	11.68	11.78	12.04	12.10
	C	12.14	12.82	12.72	12.92	12.94
Phase Angle (◦)	A	10.69	-1.83	-6.06	-10.58	-14.12
	B	14.54	3.93	0.19	-4.81	-7.72
	C	10.12	-0.81	-4.13	-8.40	-12.05
Load impedance (Ω)		1864.40Ω 1.55098H	3776.65Ω 3.04459H	5146.09Ω 5.29564H	5686.03Ω 8.32488H	10742.96Ω 9.76574H

3.4.3 Comparison Analysis using Fundamental Model and Third Harmonic Model with Experimental Values

The complete results for the simulation of fundamental model and third harmonic model with resistive load, inductive load and RL load can be referred at Appendices section and summary of the percentage error is in Table 9. The percentage error is the percentage difference between the the value of current experimental and simulation.

According to the result in Appendices, the percentage error for between the experimental values and simulation values for fundamental model is in range 0% to 2%. On the other hand, third harmonic model had the zero percentage error. During the experiment, it is found that the values of the measured load impedance are different with the theoretical values. In order to model the circuit respective to the experiment, the author used the measured values of the load impedance instead of the rated values. Thus, the percentage error of circuit modelled is zero.

The author managed to achieve the circuit modelling according to the experiment based on the experimental values in her modelling. All components like power source, impedance, VI measurement and loads can be obtained from Simulink Library Browser. The type of the filters used for the simulation circuits are also modelled using Matlab which will be discussed in the next part.

TABLE 9 Summary of Percentage Error

Type of modelling	Type of load	Range of percentage error (%)
Fundamental	Resistive Load	0 – 2
	Inductive Load	0 – 2
	RL Load	1 – 6
Third Harmonic	Resistive Load	0
	Inductive Load	0
	RL Load	0

3.4.4 Third Harmonic Model with Filters

The third harmonic models are added with the filter to observe the behaviour of the third harmonic in the system. There are a few important things that must be considered when doing the analysis which are the neutral current, voltage and current at different nodes. Hence, there are three points of measurements to identify if there are any changes with the system once the filter is connected. Point A is where the neutral current is measured, point B is current between the source and the filter is measured and last but not least point C is current measured at the load. The phase current considered is only in phase A because the other two phases have the same pattern and values are not much different with phase A.

3.4.4.1 Shunt Passive Filter

Figure 20 shows the example of third harmonic circuit modelled with shunt passive filter.

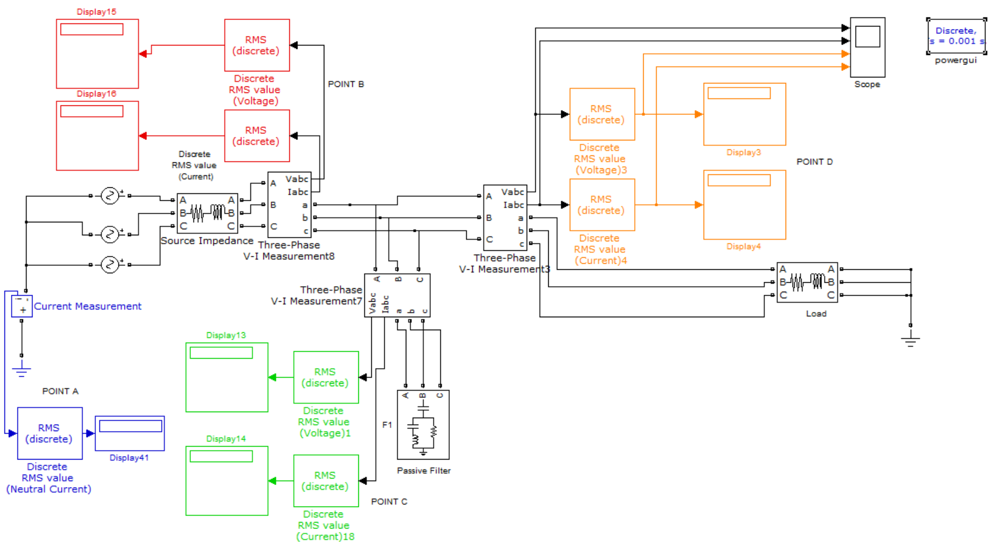

FIGURE 20 Third Harmonic Model with Shunt Passive Filter

There are three types of passive filters available in Matlab Simulink which includes single tuned filter, high pass filter and c type high pass filter. The values of the parameters were referring to the experimental values.

3.4.4.2 Series Passive Filters

Another method in mitigating the high current in neutral current is by connecting the passive filter in series. Figure 21 shows the example of third harmonic circuit modelled with shunt passive filter.

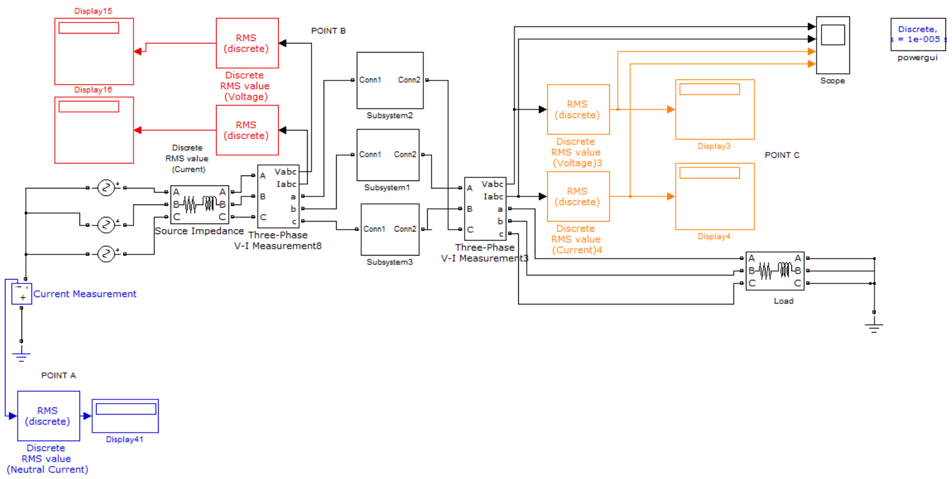

FIGURE 21 Third Harmonic Model with Series Passive Filter

There are also three types of passive filters connected which are single tuned filter refer Figure 22, high pass filter refer Figure 23 and C type high pass filter refer Figure 24. Since the connection is in series, so each of the phase is connected with passive filter. The subsystem components are representing the passive filter. The parameters for each of the components for the filter can be found in the Appendix VII.

FIGURE 22 Single Tuned Passive Filter

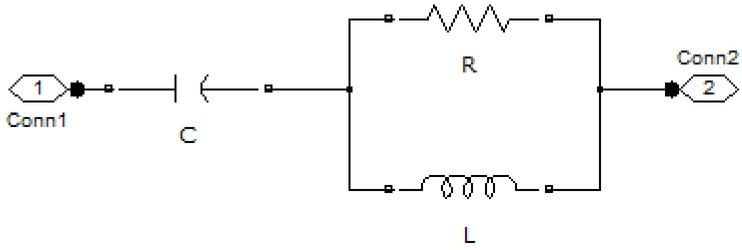

FIGURE 23 High Pass Passive Filter

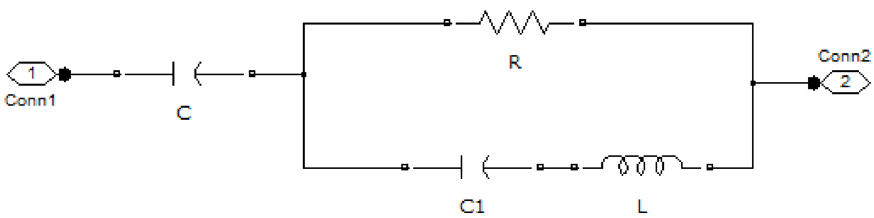

FIGURE 24 C type High Pass Passive Filter

3.4.4.3 Active Filters

Active filter is one of the methods to reduce harmonic current. Figure 25 shows the design of third harmonic model with shunt active filter.

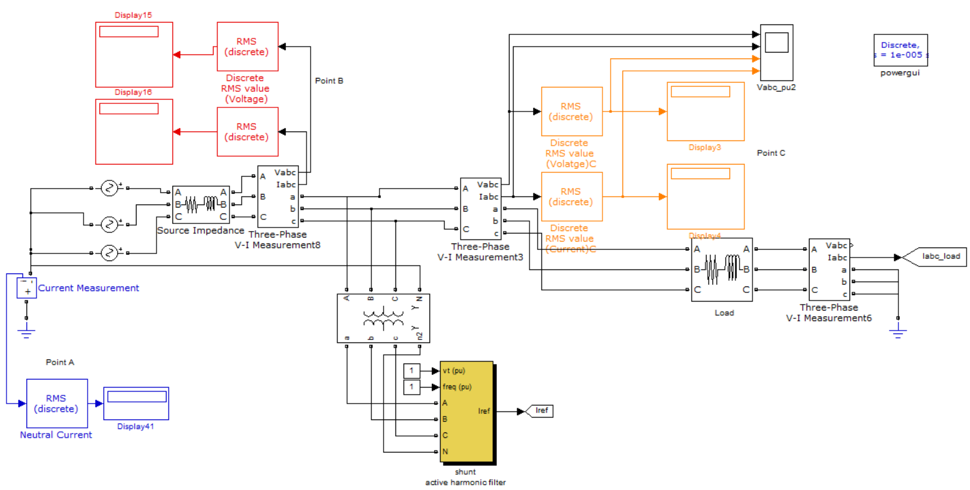

FIGURE 25 Third Harmonic Model with Active Filter

The active filter configuration is shown in Figure 26. In order to make the circuit uncomplicated, the subsystem is used to represent the active filter.

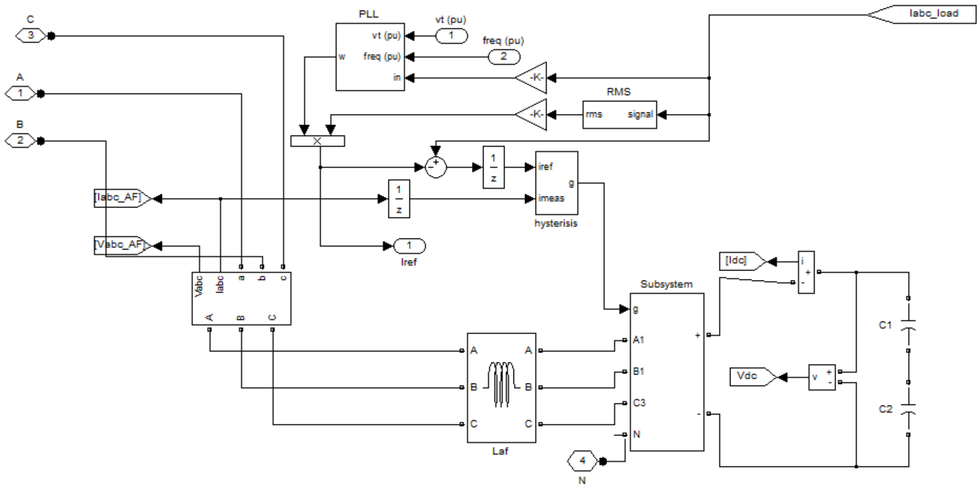

FIGURE 26 Active Filter Configurations

3.4.4.4 Hybrid Filters

Hybrid filter is the combination of shunt active filter and shunt passive filter. Figure 27 shows the design of hybrid filter.

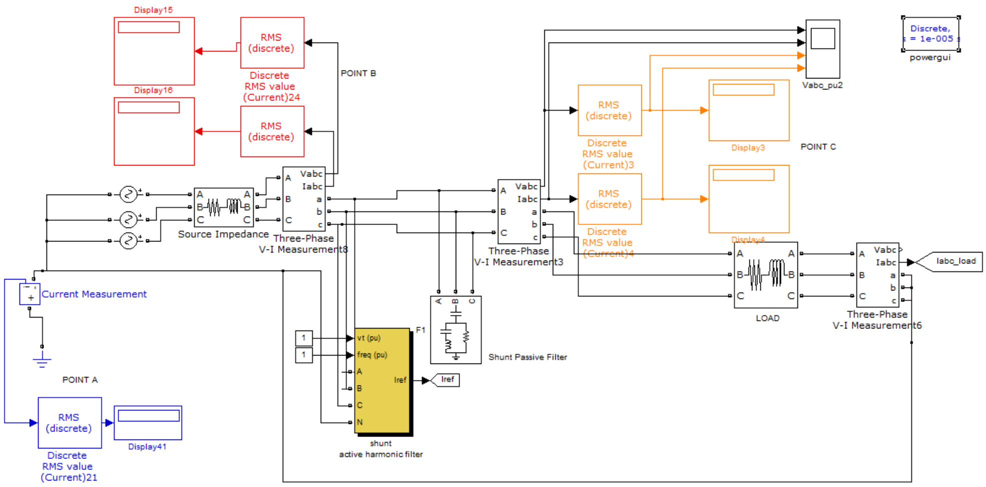

FIGURE 26

FIGURE 27 Third Harmonic Model with Hybrid Filter

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Shunt Passive Filters at the R load, L load and RL load

Figure 28 and Figure 29 shows that the current is higher after the single tuned filter is connected to the R load system. While Figure 30 shows the phase current at the load is less after the shunt single tuned filter is connected. This proves that by connecting the shunt single tuned filter, the third harmonic current at the load is reduced. Nevertheless, the current at other points of measurement especially at the neutral is very high after the filter is connected. Therefore, the single tuned filter in the circuit modelled is not the solution to mitigate the high current at the neutral as proven with the simulation result.

Results for the high pass filter and results for C type high pass filter in Appendix IX show that the same pattern of current with single tuned filter which is current is higher after the filter is connected to the system. The current at the load is less after the filter is connected. This proves that the by connecting only the shunt passive filter, the third harmonic current at the load is reduced. Nonetheless, the current at other points of measurement especially at the neutral is very high after the passive filter is connected in parallel. Even with L load and RL load connected, the pattern of the results are the same. Therefore, the shunt passive filter in the circuit modelled for R load, L load and RL load are not the solution to mitigate the high current at the neutral as proven with the simulation result.

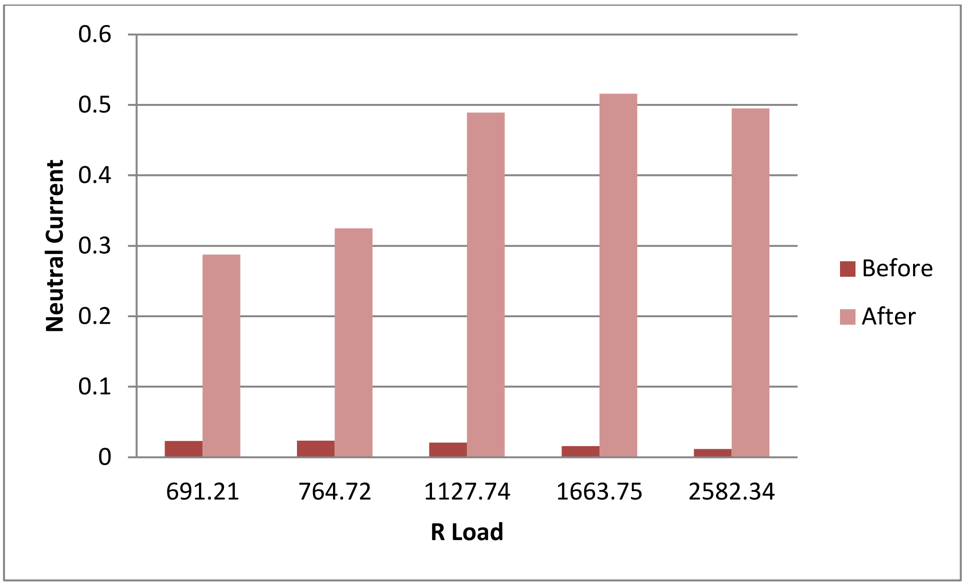

FIGURE 28 Comparison of Neutral Current (Point A) with and without Third harmonic Shunt Single Tuned Filter for R load

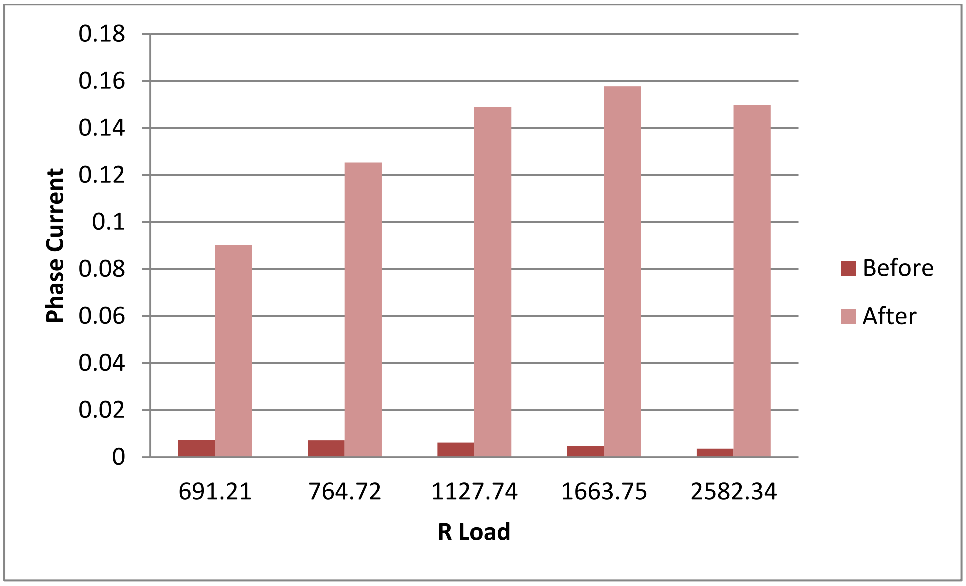

FIGURE 29 Comparison of Current at Point B with and without Third harmonic Shunt Single Tuned Filter for R load

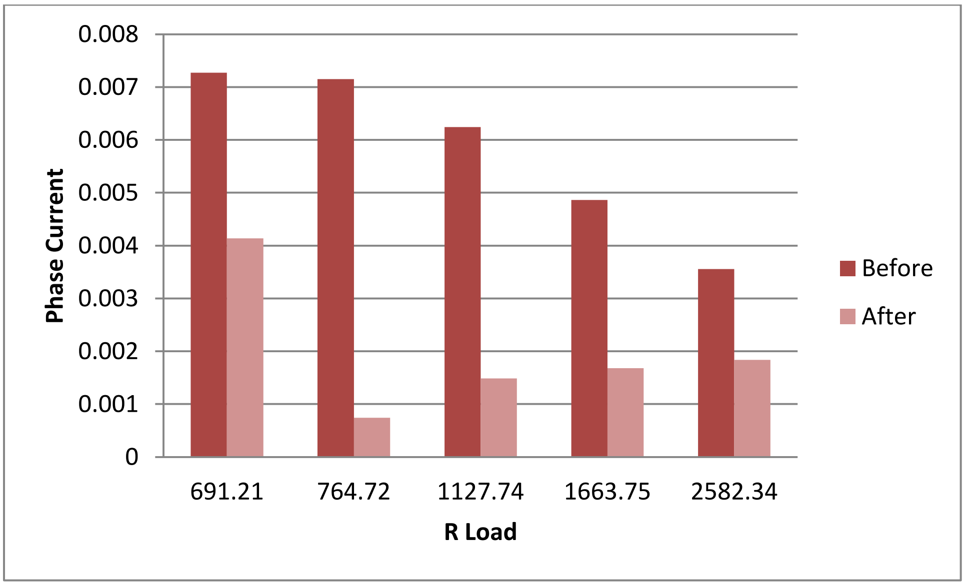

FIGURE 30 Comparison of Current at Point C with and without Third harmonic Shunt Single Tuned Filter for R load

The neutral current and phase current at the source and filter are higher than with shunt passive filter connected. In the other hand, the current at load have significantly reduced after the shunt filter connected based on the simulation result. Table 10 shows the summary for the neutral current and phase current from the shunt passive filters. From the table, it shows that percentage difference of current at the load is highest when C type High Pass filter is connected. This is because C type high pass filter filter the most third harmonic current at the load compared to other filters. As a result, C type High Pass filter is the most suitable filter to filter the third harmonic current at the load which has average percentage difference -76% at the R load, -98% at the L load and -100% at the RL load but not feasible to filter the third harmonic current at the generator neutral. The graph of average percentage difference for R load can be referred at Figure 31, Figure 32 for L load and Figure 33 for RL load.

TABLE 10 Summary of Percentage Difference of Neutral Current and Phase Current Before and After Shunt Passive Filter

	Average Percentage Difference at Neutral Current (%)			Average Percentage Difference at Phase Current at Load (%)		
	Single Tuned Filter	High Pass Filter	C Type High Pass Filter	Single Tuned Filter	High Pass Filter	C Type High Pass Filter
R Load	2398	2957	2916	-65	-71	-76
L Load	7551	7690	7661	-98	-98	-98
RL Load	19287	19341	19330	-99	-99	-100

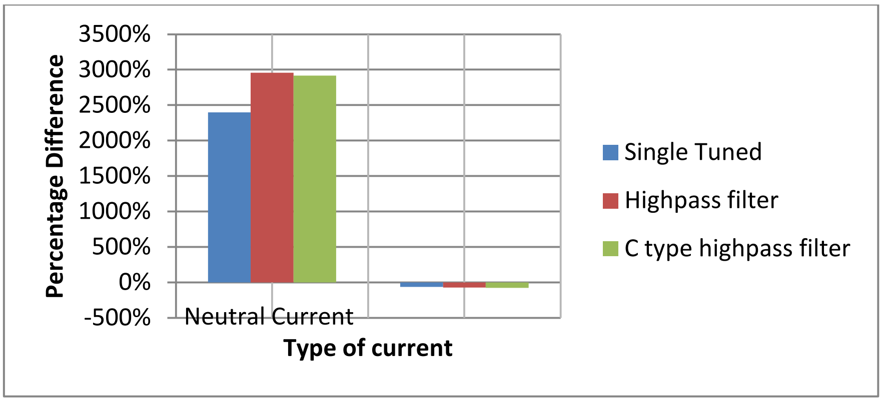

FIGURE 31 Percentage Difference between Filters at Different Point of Current for R Load

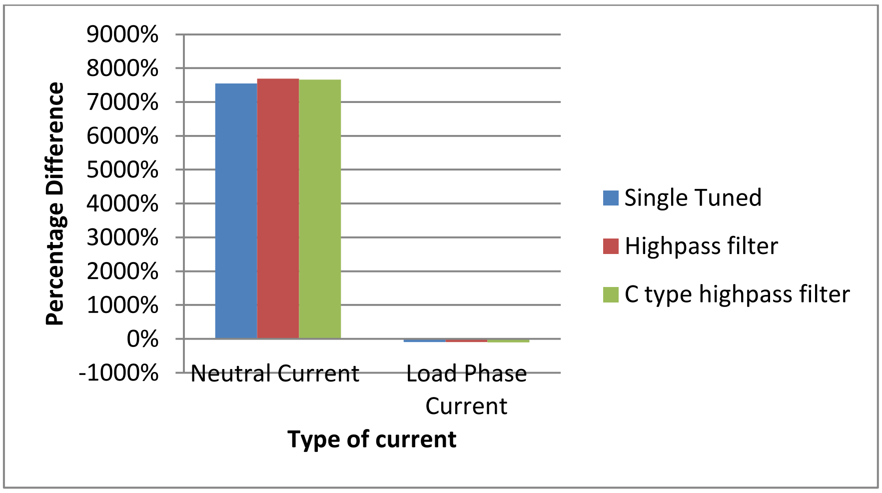

FIGURE 32 Percentage Difference between Filters at Different Point of Current for L Load

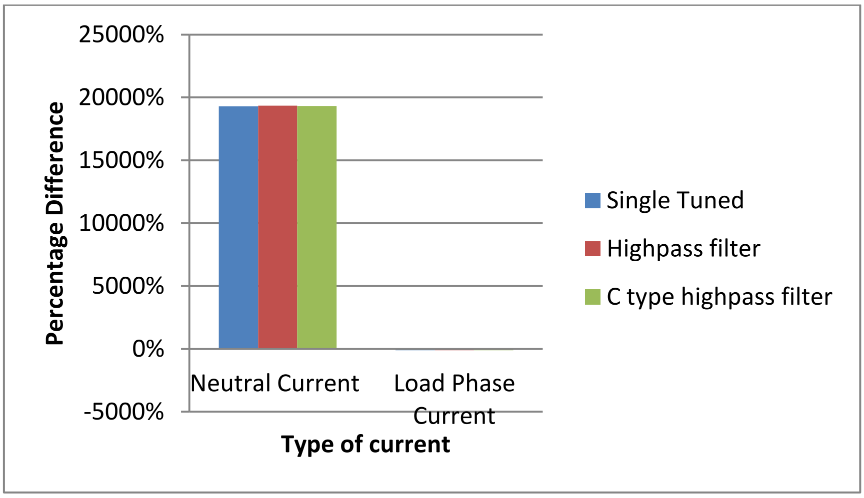

FIGURE 33 Percentage Difference between Filters at Different Point of Current for RL Load

4.2 Series Passive Filters at the R load, L load and RL load

When single tuned filter connected in series for each of the phase from the source, the result of the neutral current at Figure 34 shows that the current reduced. At the point B and point C, the current also decreased as shown in Figure 35 and 36 respectively. According to result of series passive filter for all types of load in Appendix IX, the current at each point is reduced which means the third harmonic current circulating at load and the neutral is reduced significantly. Therefore, the series passive filter in the circuit modelled for R load, L load and RL load are the the solution to mitigate the high current at the neutral as proven with the simulation result.

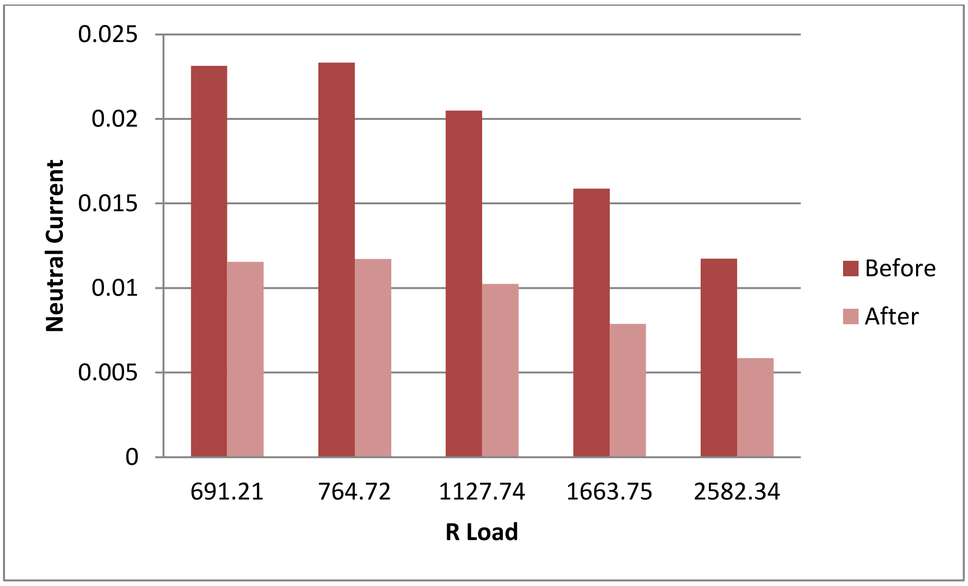

FIGURE 34 Comparison of Neutral Current (Point A) with and without Third harmonic Series Single Tuned Series Passive Filter at R Load

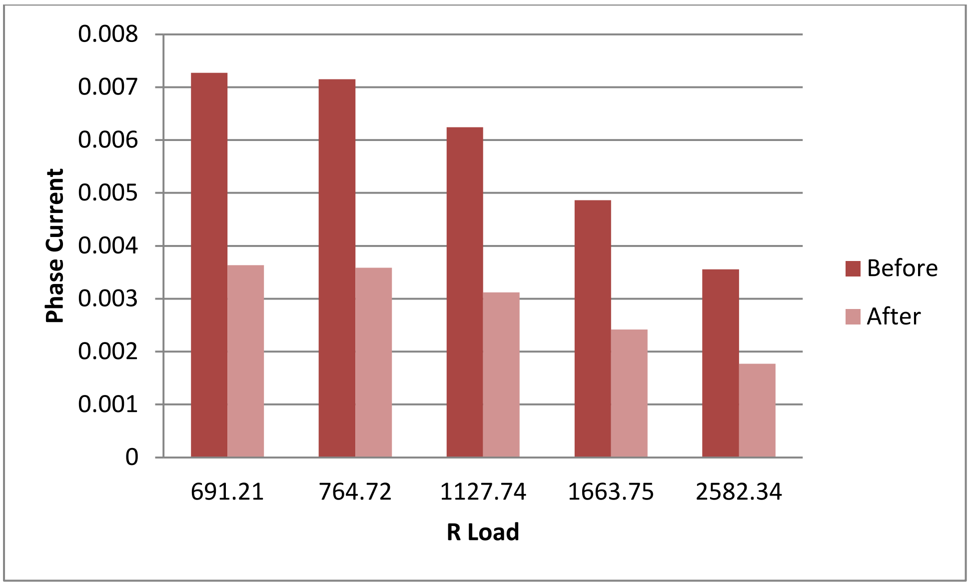

FIGURE 35 Comparison of Phase Current at Point B with and without Third harmonic Series Single Tuned Series Passive Filter for R load

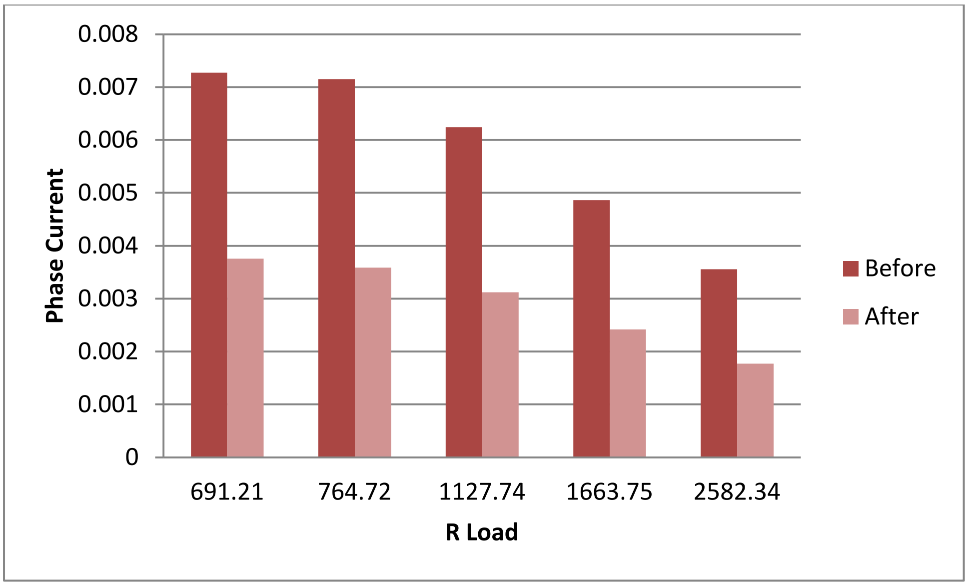

FIGURE 36 Comparison of Phase Current at Point C with and without Third harmonic Series Single Tuned Series Passive Filter for R load

The neutral current and phase current at every point are decreased with series passive filter connected. In order to identify which filter can filter the most current, the percentage difference between the values of current before and after filter is calculated. Table 11 shows the summary for the neutral current and phase current from the different type of series passive filters. The higher the percentage difference means more harmonic current had been filtered. From the table, it shows that percentage difference of current at the R load is highest which is -50% when series single tuned filter is connected. While for L load and RL load, the highest percentage difference is -87% and -82% respectively when series C type High Pass filter. As a result, series C type High Pass filter is the most suitable filter for the L load and RL load while series single tuned filter is suitable for R load to filter the third harmonic current. Figure 37, Figure 38 and Figure 39 show the graph of percentage difference with different type of filters and loads respectively.

TABLE 11 Summary of Percentage Difference of Neutral Current and Phase Current Before and After Series Passive Filter

	Average Percentage Difference at Neutral Current (%)			Average Percentage Difference at Phase Current at Load (%)		
	Single Tuned Filter	High Pass Filter	C Type High Pass Filter	Single Tuned Filter	High Pass Filter	C Type High Pass Filter
R Load	-50	-6	-14	-50	-1	-12
L Load	-85	-87	-87	-85	-87	-87
RL Load	-80	-80	-82	-79	-62	-82

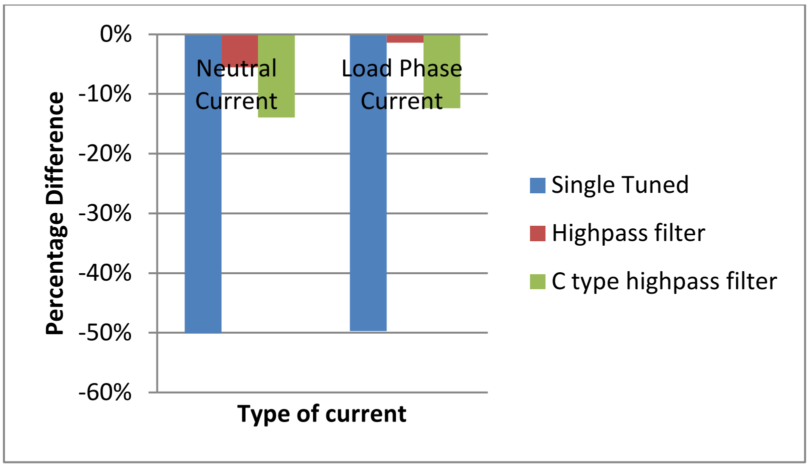

FIGURE 37 Percentage Difference between Filters at Different Point of Current for R Load

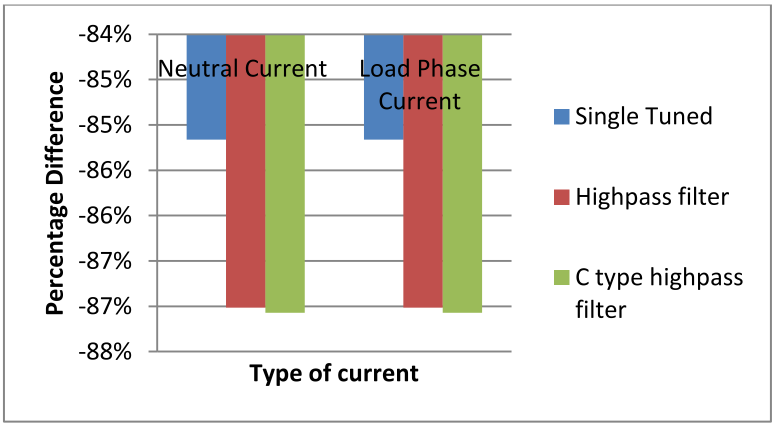

FIGURE 38 Percentage Difference between Filters at Different Point of Current for L Load

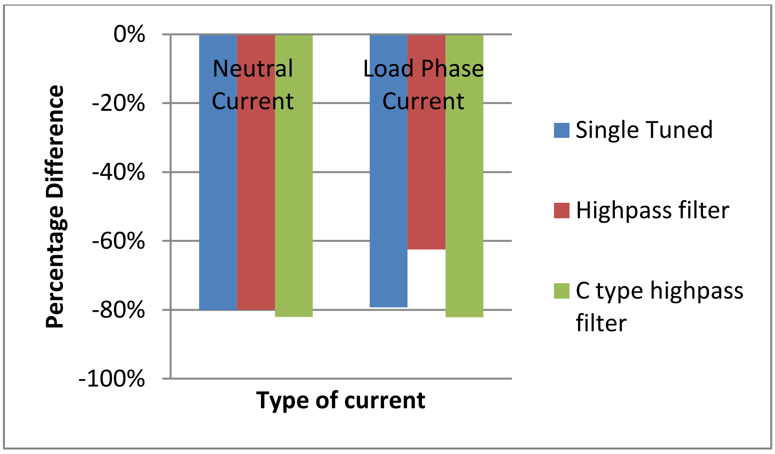

FIGURE 39 Percentage Difference between Filters at Different Point of Current for RL Load

4.3 Shunt Active Filters at the R load, L load and RL load

When shunt active filter is connected, the result of the neutral current at Figure 40 shows that the current is slightly reduced. On the other hand at the point B, the current is increased as shown in Figure 41 while at point C referred to Figure 42 the current is slightly decreased. According to result of shunt active filter for all types of load in Appendix IX, the current at each point A and point C is reduced which means the third harmonic current circulating at load and the neutral is reduced except at point B.

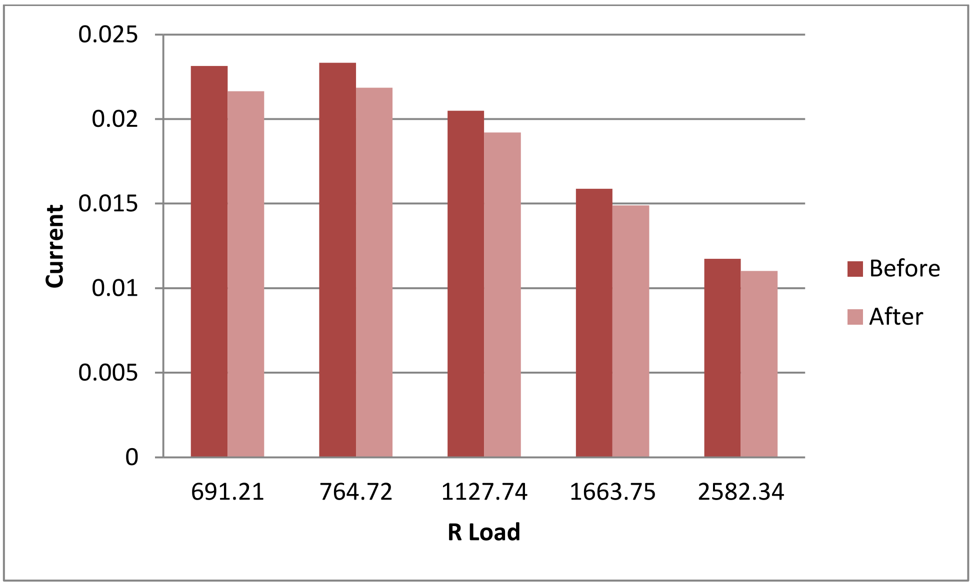

FIGURE 40 Comparison of Neutral Current (Point A) with and without Third harmonic Shunt Active Filter

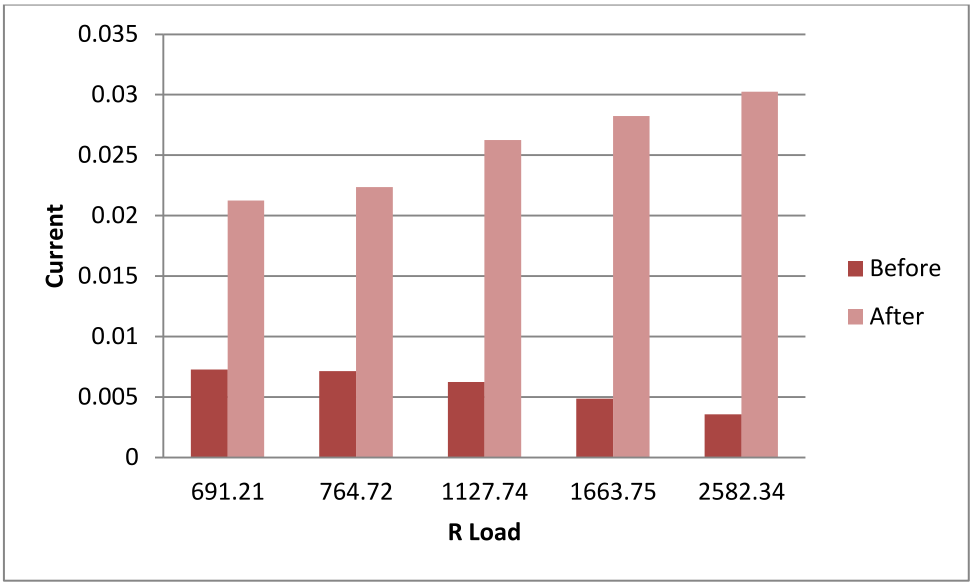

FIGURE 41 Comparison of Phase Current at Point B with and without Third harmonic Shunt Active Filter

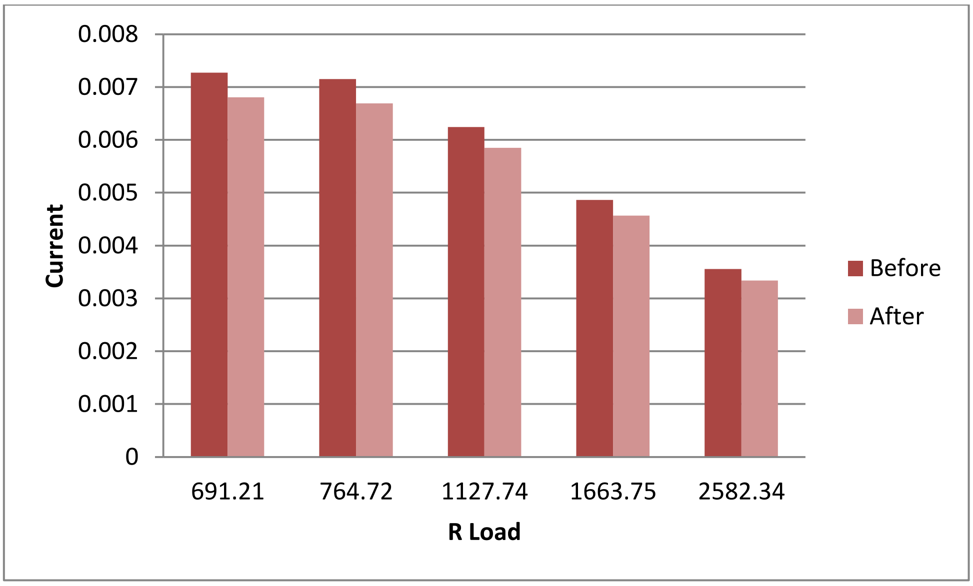

FIGURE 42 Comparison of Phase Current at Point C with and without Third harmonic Shunt Active Filter

The neutral current and phase current at the load are decreased with shunt active filter connected. In order to identify which filter can filter the most current, the percentage difference between the values of current before and after filter is calculated. Table 12 shows the summary for the neutral current and phase current from the shunt active filters. The higher the percentage difference means more harmonic current had been filtered. As a result, shunt active filter is suitable filter for the R load, L load and RL load to filter the third harmonic current with -6% percentage differences.

TABLE 12 Summary of Percentage Difference of Neutral Current and Phase Current Before and After Shunt Active Filter

	Average Percentage Difference at Neutral Current (%)	Average Percentage Difference at Phase Current at Load (%)
R Load	-6	-6
L Load	-6	-6
RL Load	-6	-6

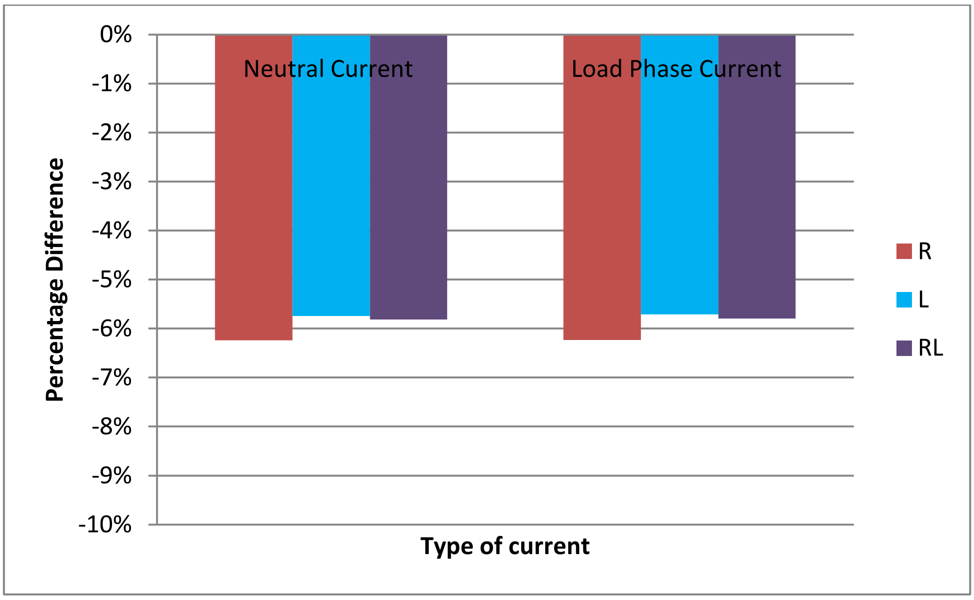

FIGURE 43 Percentage Difference between Filters at Different Point of Current for all Load

4.4 Hybrid Filters at the R load, L load and RL load

The combination of shunt active filter with shunt passive filter is called hybrid filter. When the filters is connected, the result of the neutral current at Figure 44 shows that the current is considerably reduced. On the other hand at the point B, the current is increased as shown in Figure 45 while at point C referred to Figure 46 the current is decreased. According to result of shunt active filter for all types of load in Appendix IX, the current at each point A and point C is reduced which means the third harmonic current circulating at load and the neutral is reduced except at point B.

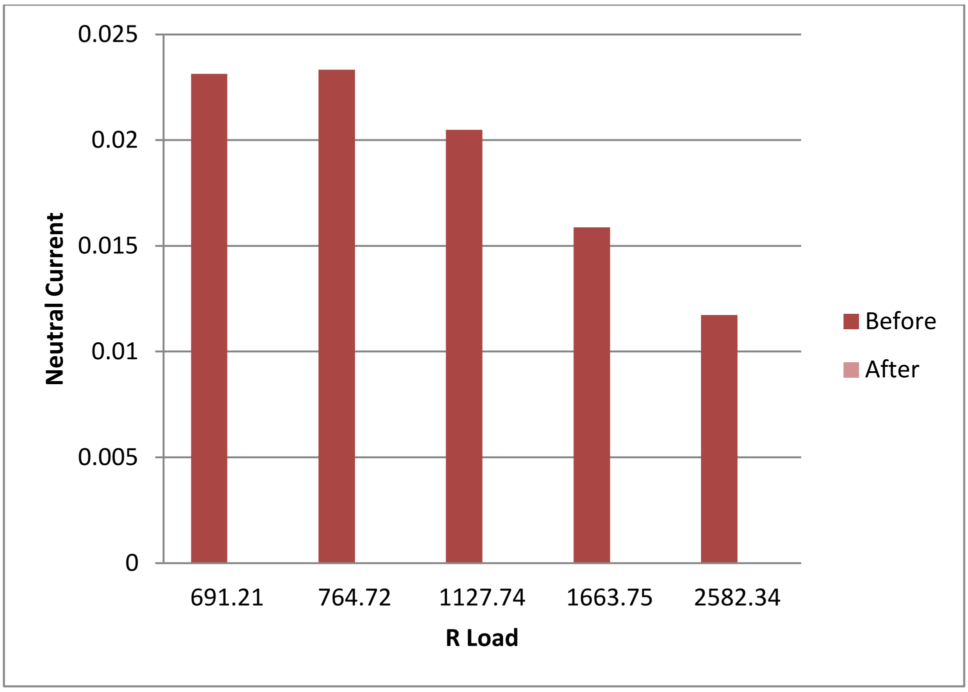

FIGURE 44 Comparison of Neutral Current (Point A) with and without Third harmonic Hybrid Filter

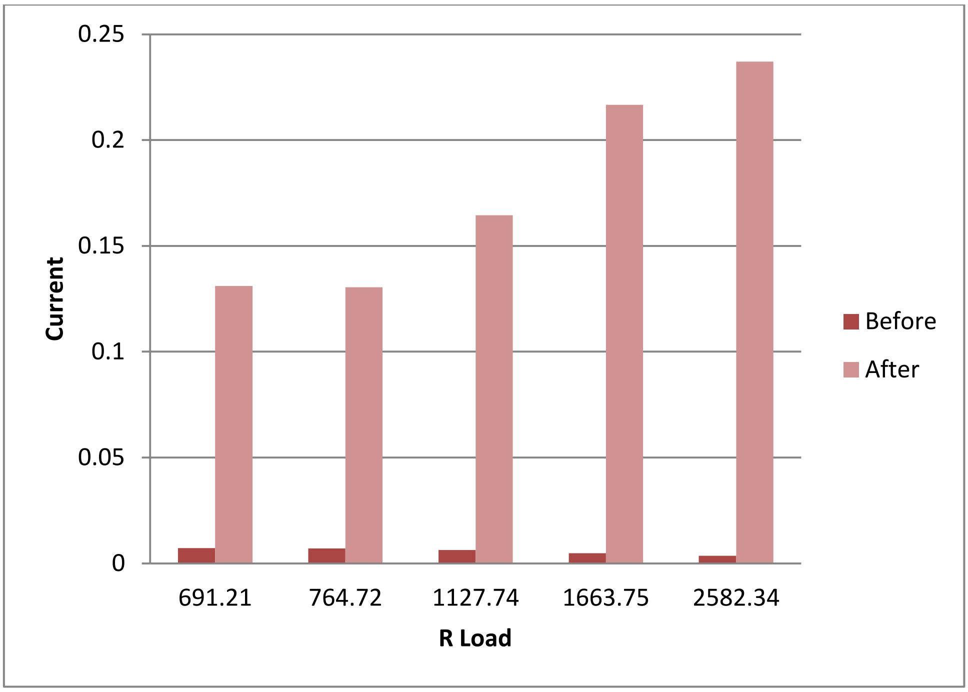

FIGURE 45 Comparison of Phase Current at Point B with and without Third harmonic Hybrid Filter

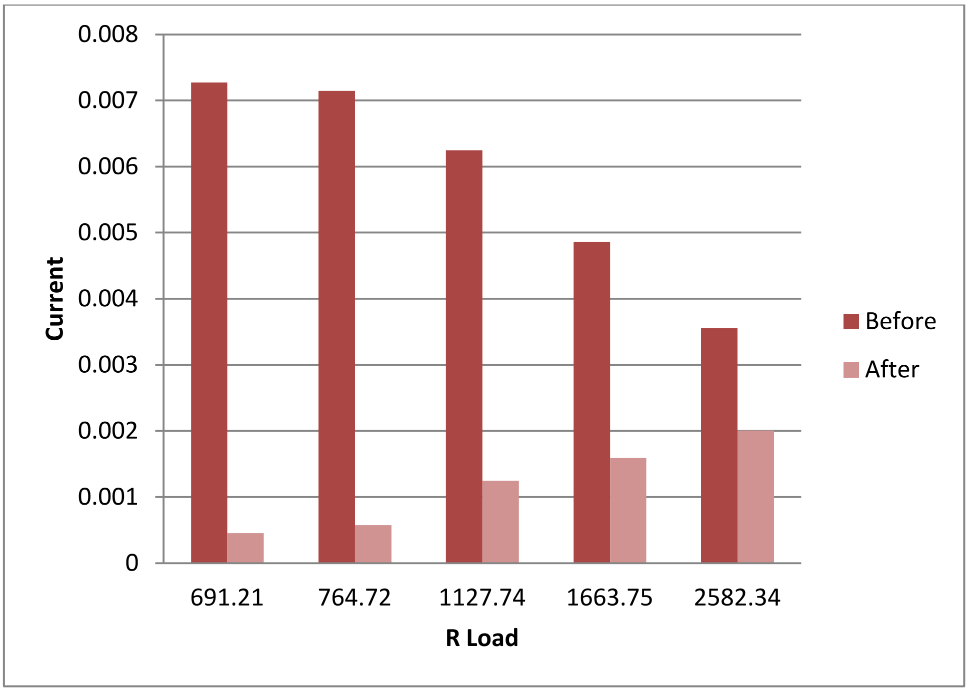

FIGURE 46 Comparison of Phase Current at Point C with and without Third harmonic Hybrid Filter

The neutral current and phase current at the load are decreased with shunt active filter connected. In order to identify which filter can filter the most current, the percentage difference between the values of current before and after filter is calculated. Table 13 shows the summary for the neutral current and phase current from the shunt active filters. The higher the percentage difference means more harmonic current had been filtered. As a result, shunt active filter is suitable filter for the R load, L load and RL load to filter the third harmonic current with percentage difference range in 75% to 100%. The graph for percentage difference for different load is shown in Figure 47.

TABLE 13 Summary of Percentage Difference of Neutral Current and Phase Current Before and After Shunt Active Filter

	Average Percentage Difference at Neutral Current (%)	Average Percentage Difference at Phase Current at Load (%)
R Load	-100%	-75%
L Load	-100%	-98%
RL Load	-100%	-100%

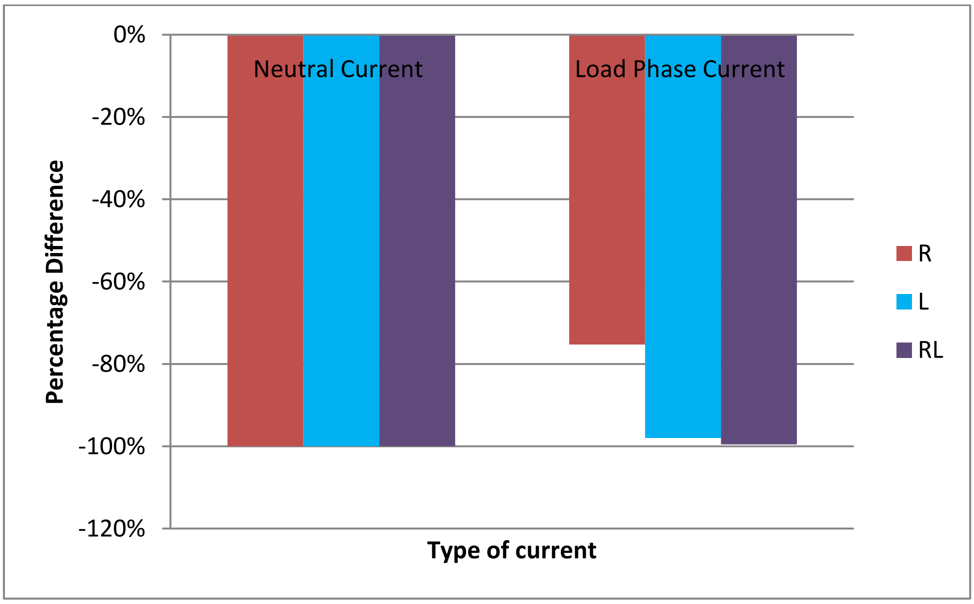

FIGURE 47 Percentage Difference between Filters at Different Point of Current for All Load

4.5 Practical Implementation and Economic Consideration

According to the simulation result above, the suitable filters to filter the third harmonic are series passive filter, shunt active filter and hybrid filter. In term of practical implementation, there are a few criteria need to be considered. One of it is the economic consideration. Customer usually will choose product which is cheap, very reliable, low maintenance and economy wise.

Series passive filter can filter out most of the third harmonic current at the generator neutral compared to other type of filter as referred to the result. However, implementation of series passive filter to the real system can cause high cost. This is because the design of series passive filter will need to be attached at the existing system in series which it may need to interrupt the configuration of the existing system. With this kind of interruption to the real system, it may cause any unnecessary side effect to the existing system.

The other two types of filters are shunt active filter and hybrid filter (shunt passive filter and shunt active filter). These two types of filters are connected in parallel with the existing system which it will not disrupt the existing system. Besides, the cost of implementation will be less because of the parallel connection.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In conclusion, modelling the fundamental and third harmonic current in Matlab Simulink and compare with the experimental values can show the reliability of the simulation using the modelling. With the tolerate percentage error between the simulation values and experimental values proved that the Matlab Simulink simulation can be used as a model to design the third harmonic current filter. Therefore, it is easier to simulate the mitigation of high current when the third harmonic filter had been designed. Hence, it reduced the time consumption to do the experiment and also can be used as a guideline for real installation.

Shunt passive filter is where passive filter is connected parallel to the system. The outcomes when shunt passive filter is connected to the system are the third harmonic current at the three different type of load is reduced while the neutral current increased.

When passive filter is connected in series for each phase, the third harmonic current at the system including the neutral current is reduced. Series single tuned filter is the filter that can reduce the most neutral current at R load while series C type passive filter is most suitable with L load and RL load.

Shunt active filter and hybrid filter are both filters had the neutral current reduced. The different between these two filters are the percentage difference of the neutral current. Hybrid filter had higher percentage difference compared to shunt active filter.

As recommendation, when the simulation with third harmonic filter design achieved the objectives, the implementation to the real system should be carry out to test the functionality with taking into consideration of economy and maintenance aspect of the filter design towards the existing system such as the generator neutral.

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APPENDICES

I. Fundamental model and experimental current comparison with varies load impedance R and no load voltage.

Vnoload, V (V)	Load impedance, R (Ω)	Experimental current, Iae (A)	Model current, Iam (A)	Percentage error
303.84423	686.00	0.34704	0.3463	0%
292.16429	800.00	0.30448	0.2997	2%
266.66744	1200.00	0.20294	0.1994	2%
256.88680	1600.00	0.15214	0.1496	2%
249.06461	2400.00	0.10176	0.09984	2%

II. Fundamental model and experimental current comparison with varies load impedance L and no load voltage.

Vnoload, V (V)	Inductance, X_L	Load impedance, L (H)	Experimental current, Iae (A)	Model current, Iam (A)	Percentage error
374.59558	j800.000	2.546479	0.28859	0.2923	1%
338.06370	j1200.000	3.819719	0.20154	0.2011	0%
315.44411	j1600.000	5.092958	0.15418	0.1516	2%
289.62288	j2400.000	7.639437	0.10230	0.1005	2%
265.92982	j4800.000	15.278875	0.05035	0.05036	0%

III. Fundamental model and experimental current comparison with varies load impedance RL and no load voltage.

Vnoload, V (V)	Load impedance, R (Ω)	Load impedance, L (H)	Experimental current, Iae (A)	Model current, Iam (A)	Percentage error
319.173	960	2.101	0.211	0.209	1%
278.294	1600	3.800	0.111	0.118	6%
263.834	2400	5.099	0.078	0.0829	5%
255.996	3600	7.601	0.052	0.0551	6%

251.606	4800	11.39	0.037	0.03978	6%

IV. Third harmonic model and experimental current comparison with varies load impedance R and no load voltage.

Experimental current, Iae (A)	Model current, Iam (A)	Percentage error (%)
0.007780	0.007780	0
0.007827	0.007827	0
0.006853	0.006853	0
0.005310	0.005310	0
0.003917	0.003917	0

V. Third harmonic model and experimental current comparison with varies load impedance L and no load voltage.

Experimental current, Iae (A)	Model current, Iam (A)	Percentage error (%)
0.012284	0.012284	0
0.008630	0.008630	0
0.005558	0.005558	0
0.003545	0.003545	0
0.001741	0.001741	0

VI. Third harmonic model and experimental current comparison with varies load impedance RL and no load voltage.

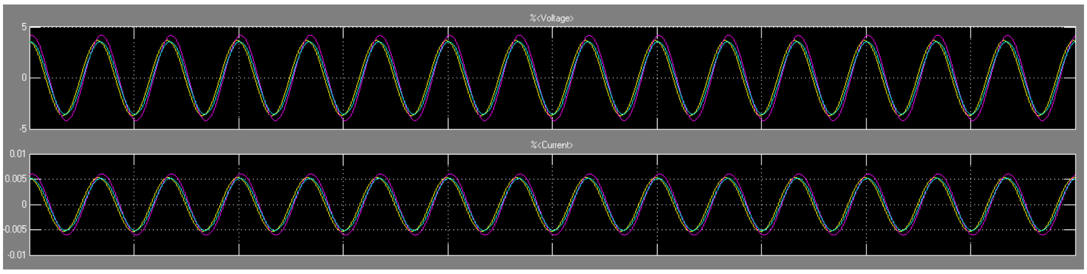
Experimental current, Iae (A)	Model current, Iam (A)	Percentage error (%)
0.004783836	0.004783836	0
0.002493796	0.002493796	0
0.00165784	0.00165784	0
0.001252955	0.001252955	0
0.000860435	0.000860435	0

VII. Parameters for Series Passive Filter Design

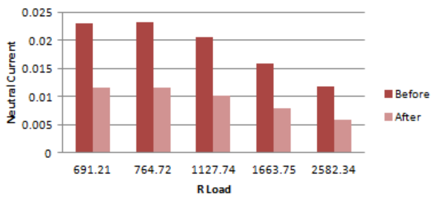
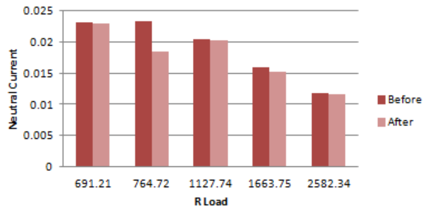
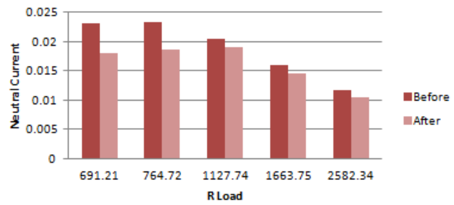
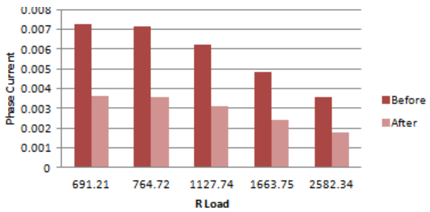
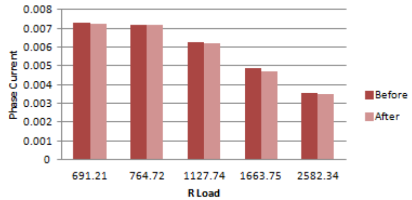
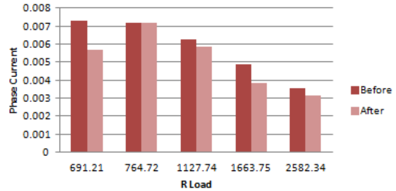
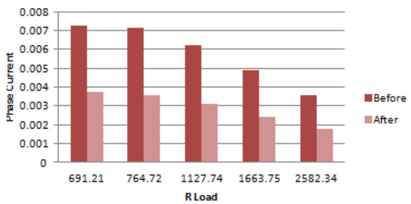
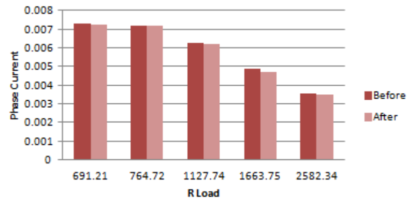
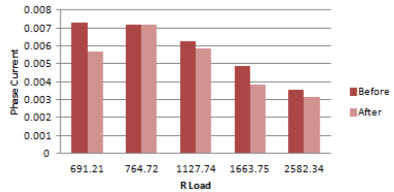
R load	Resistance, R, (Ω)	Inductance, XL	Impedance, L (H)	Capacitance, XC	Impedance C (f)
	691.208543	31.9025032	0.033849607	287.1225289	3.6954E-06
	764.71689	2.30618772	0.002446941	20.75568949	5.112E-05

	1127.73591	22.4942036	0.023867091	202.4478324	5.241E-06
	1663.74659	73.2337694	0.077703443	659.103925	1.6098E-06
	2582.3356	73.5861084	0.078077286	662.274976	1.6021E-06
L load					
	145.793787	1207.71165	1.281421856	10869.40482	9.7616E-08
	299.897469	1588.44444	1.685391895	14295.99995	7.4219E-08
	445.563982	2416.80138	2.564305906	21751.21241	4.878E-08
	270.752933	3804.58918	4.0367945	34241.30265	3.0987E-08
	1907.36223	7255.59426	7.698424606	65300.3483	1.6249E-08
RL load					
	1864.40014	1461.76789	1.550983899	13155.91098	8.0651E-08
	3776.64941	2869.45947	3.04459106	25825.13525	4.1085E-08
	5146.09353	4991.02763	5.295644788	44919.24866	2.3621E-08
	5686.02664	7846.01307	8.324878424	70614.11763	1.5026E-08
	10742.9609	9203.99406	9.765741009	82835.94657	1.2809E-08

VIII. The voltage and current waveform at the load



IX. Results for current value of different load for different types of filters at different points

		Series Passive Filter		
		Single Tuned	High Pass	C type high pass
R	Neutral Current			
	Phase current at the filter			
	Phase current at the load			

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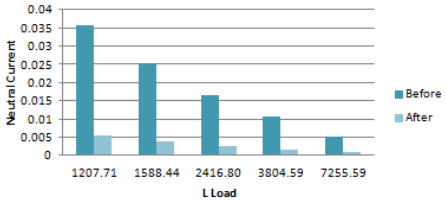
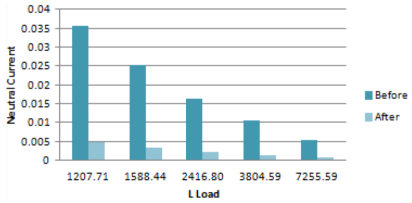
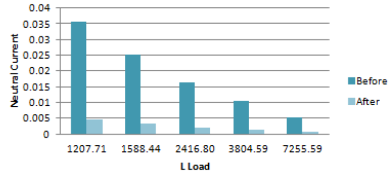
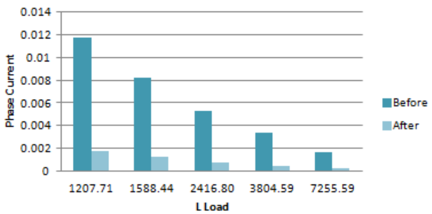
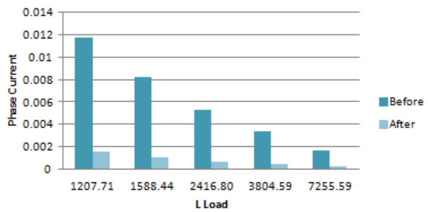
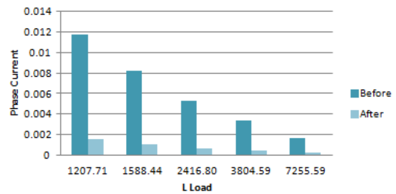
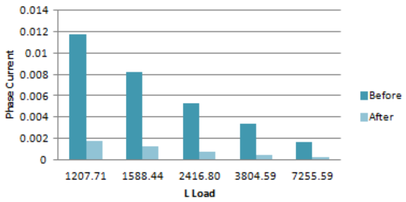
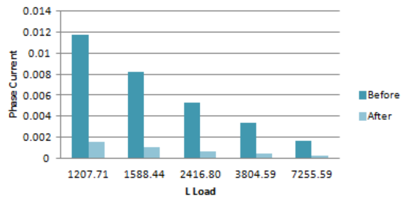
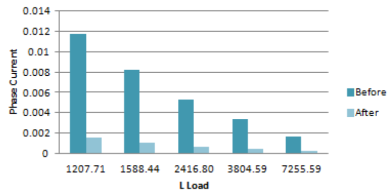
<tr><td>L</td><td>Neutral Current</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Phase current at the filter</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Phase current at the load</td><td></td><td></td><td></td></tr>
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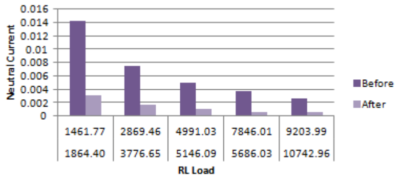
<td>
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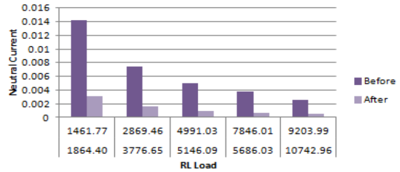
<td>
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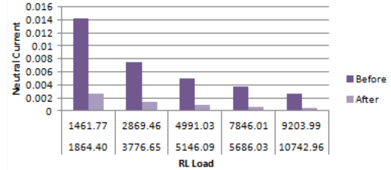
<td>
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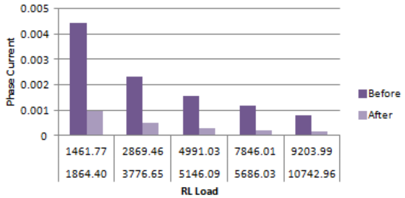
<td>
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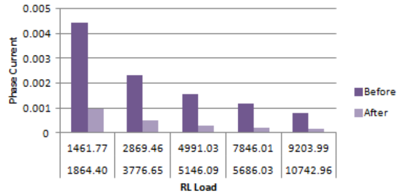
<td>
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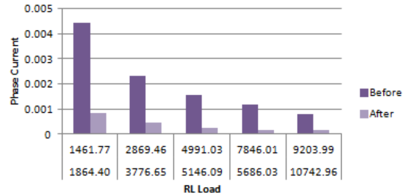
<td>
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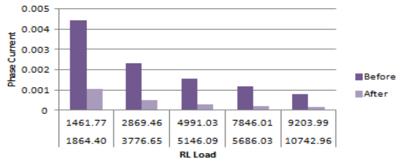
<td>
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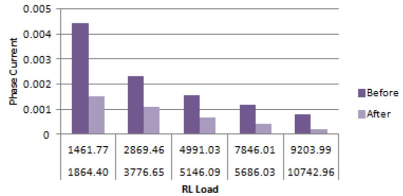
<td>
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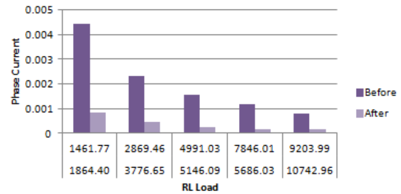
<td>
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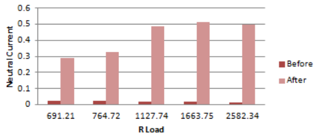
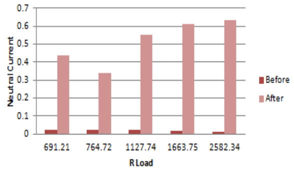
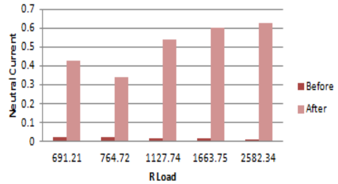
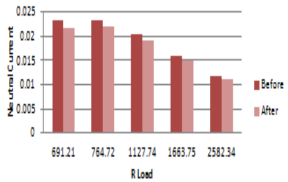
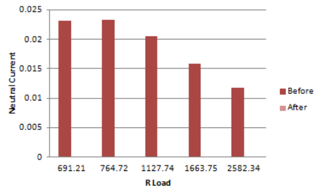
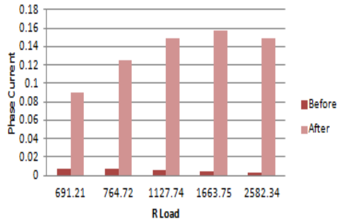
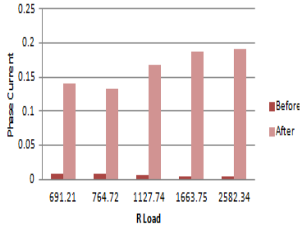
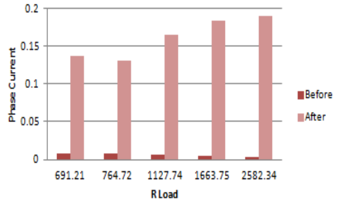
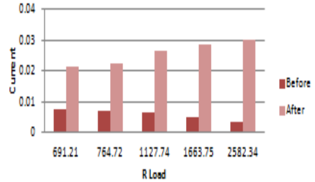
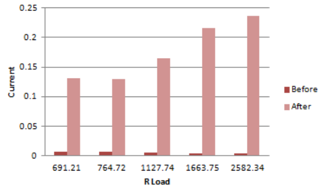
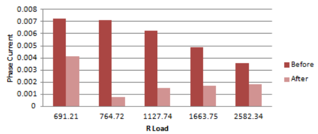
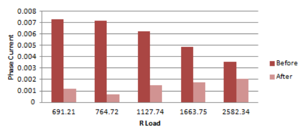
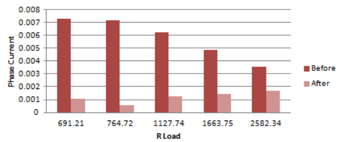
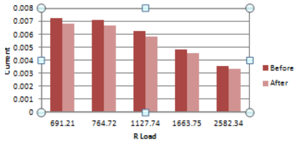
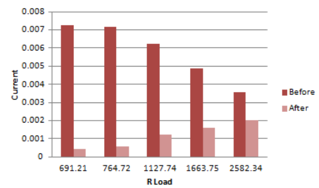
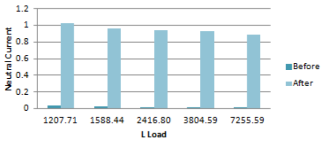
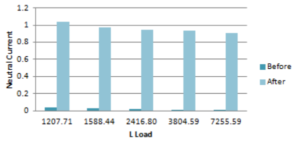
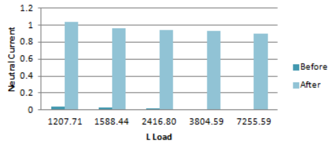
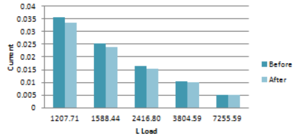
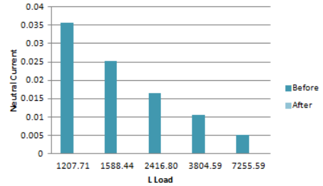
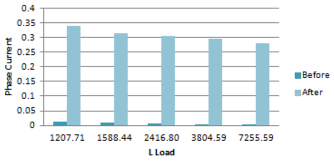
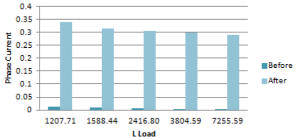
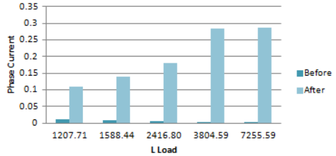
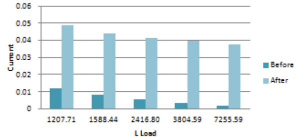
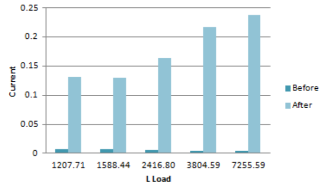
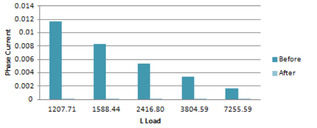
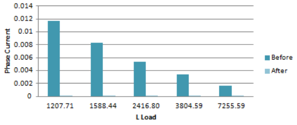
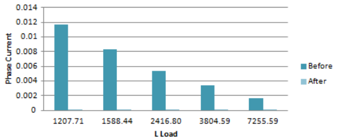
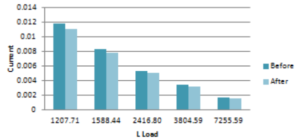
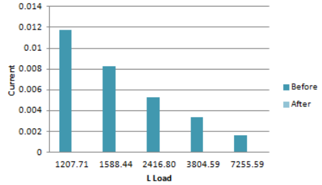
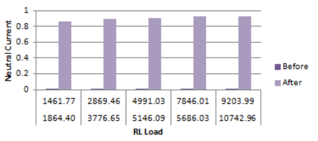
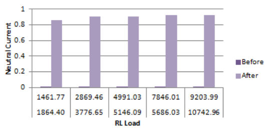
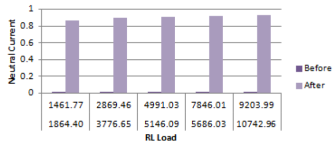
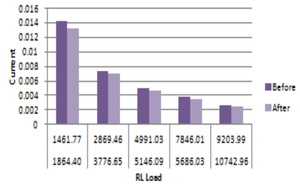
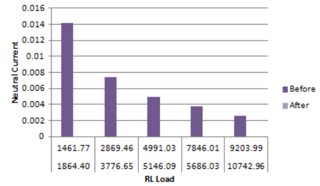
		Shunt Passive Filter			Active filter	Hybrid filter
		Single Tuned	High Pass	C type high pass		
R	Neutral Current					
	Phase current at the filter					
	Phase current at the load					

L	Neutral Current					
	Phase current at the filter					
	Phase current at the load					
RL	Neutral Current					

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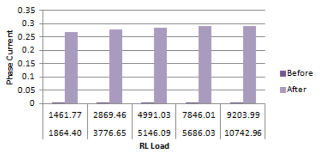
<td>
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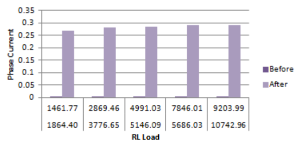
<td>
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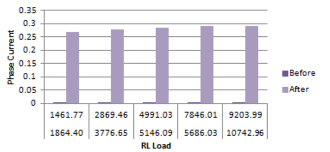
<td>
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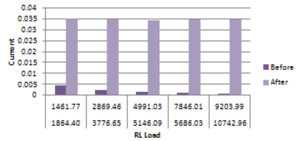
<td>
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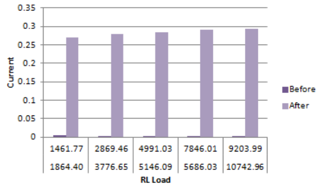
<td>
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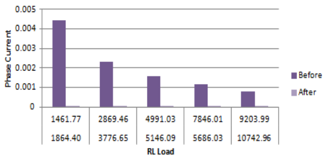
<td>
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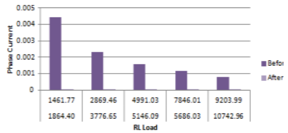
<td>
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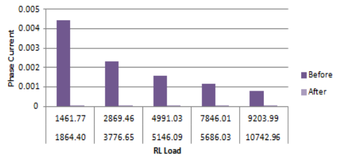
<td>
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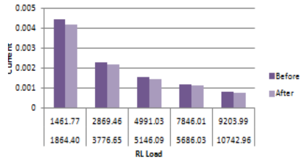
<td>
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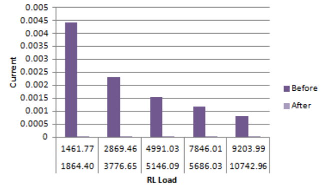
<td>
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