

# ACTIVE CURRENT SHAPING FOR BETTER UTILITY INTERFACE

A dissertation submitted to the  
Department of Electrical Engineering, University of Moratuwa  
in partial fulfillment of the requirements for the  
degree of Master of Science

by

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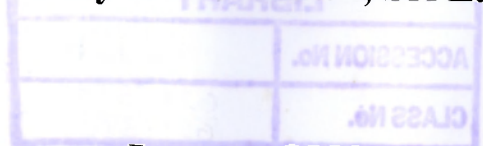


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## DECLARATION

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

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## ABSTRACT

Increased use of nonlinear electrical loads injects harmonic currents to power systems. High levels of power system harmonics create voltage distortion and enlarge power quality problems. Harmonics result in poor power factor, lower efficiency and interference to adjacent communication systems. The harmonic currents flow into the utility supply lines produces extra losses. An active power filter uses a switching inverter to produce harmonic compensating currents.

The major objective of this project was to eliminate effects of harmonics and to improve power factor of a typical nonlinear load. Attempts were made to apply active power filters for current shaping of a specific load, contrary to its common applications of applying at the point of common coupling.

The National Instruments USB-6008 multifunction data acquisition (DAQ) module was used to acquire data from the sample load *viz.* the computer power supply. A potential divider was incorporated to the circuit to acquire voltage signal. Current signal was acquired using a series resistor.

Filter current was implemented by switching an inductor using four insulated gate bipolar transistors (IGBT) arranged in H bridge configuration. The simulation circuit was implemented using MATLAB Simulink software tool. Inductance of the switching inductor, voltage of the step up transformer and the switching frequency of the system were obtained by simulation. Subsequently the above circuit parameters were validated for variable loads using total harmonic distortion as the discerning criterion.

It was possible to reduce THD of the current wave of computer power supply from 107% to 12%. Power factor was improved from 0.66 to unity. By increasing the power factor to unity, the current flow can be reduced by approximately 34%. The observations made herein are applicable for harmonic elimination in nonlinear loads in general with necessary modifications.



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# CHAPTER I

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## INTRODUCTION

The increasing demand of power electronic devices, ranging from CFLs and switch mode power supplies to automated industrial assembly lines, has enlarged power quality problems in the electrical power utility. Those problems include a variety of electrical disturbances, which can originate in several ways and differently affects various kinds of sensitive loads. The proliferation of nonlinear loads increases contamination level in voltage waveform. Specifically it causes harmonic injection that subsequently result excessive neutral currents, and reactive power burden in the power system.



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### 1.1. Power system harmonics & effects of harmonics

Harmonic is defined as “a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency” [1]. Power system harmonics are integer multiples of the fundamental power system frequency. High levels of power system harmonics can create waveform distortion and thereby increase power quality problems.

Major sources of waveform distortion include (1) Electronic switching power converters such as computers, uninterruptible power supplies (UPS), adjustable-speed motor drives, solid-state rectifiers, electronic process control equipment and electronic lighting ballasts; (2) Arcing devices such as discharge lighting

(Fluorescent, Sodium & Mercury vapor), arc furnaces, welding equipment, electrical traction system; (3) Ferromagnetic devices such as transformers operating near saturation level, magnetic ballasts (Saturation Iron Core), induction heating equipment, chokes, motors; (4) Appliances such as television sets, air conditioners, washing machines, microwave ovens, vacuum cleaners, fax machines, photocopiers, printers.

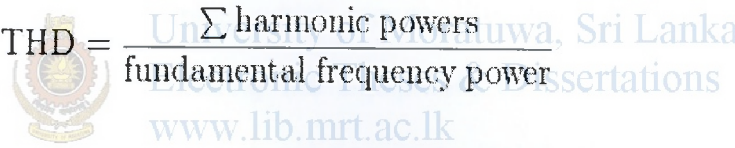
Harmonics result in poor power factor, lower efficiency and interfering with adjacent communication systems. Harmonic currents injected into the utility supply lines produces extra losses and cause voltage distortion. Besides interfering with data communications, telephone circuits, digital controls, they can also overheat transformers and supply apparatus. Harmonics flow into power factor capacitors, power cables and be magnified by resonance which even though not often can lead to disastrous results. Effects of harmonics on the power systems include frequent tripping of circuit breakers and protection relays, frequent fuse blowing, capacitor failures, degrading meters accuracy, overheating of motors and transformers, overloading of transformer neutral, telephone interference, malfunction of motor variable-speed drives, insulation failures, severe lamp flicker, voltage distortion and lagging in power factor. In summery, the major problem of harmonic currents include equipment heating, equipment malfunction, equipment failure, communications interference, fuse and breaker mis-operation, process problems and conductor heating.

## 1.2. Measures of Harmonics

There are three methods of estimating harmonic load content: the Crest-factor (CF), Harmonic Factor or Total Harmonic Distortion (THD) and "K-Factor" [2].

**Crest Factor** is a measure of the peak value of the waveform compared to the true RMS value. The mathematical definition, of the crest factor is the ratio of the peak value of the waveform divided by the rms value of the waveform:

**Total harmonic distortion (THD)** of a signal is the ratio of the sum of the powers of all harmonic frequencies above the fundamental frequency.

$$\text{THD} = \frac{\sum \text{harmonic powers}}{\text{fundamental frequency power}}$$


The **K-factor** is a number derived from a numerical calculation based on the summation of harmonic currents generated by the non-linear load. The higher the K-factor, the more significant the harmonic current content [3].

## 1.3. Importance of harmonic mitigation

Modern technical applications are very vulnerable to power supply quality. International standards (IEC 1000-3-2 and IEEE 519-1992) allow a certain level of harmonic current depending on the source short circuit ratio. Short circuit ratio is the ratio of short circuit current to the load current. At a ratio of 20 or less, the norms allows only 5% total current harmonic distortion [4]. Therefore reducing or even cancelling harmonics in the supply is essential in both economic and technological terms.

The main advantage of elimination or reduction of harmonics in power systems is improvement in productivity and quality [4]. That also minimizes equipment malfunction or failure. Further by minimizing current, it enables to reduce cable sizes especially in neutral conductor. Most importantly reduction of harmonics reduces energy wastage in power systems and reduces power consumption resulting less electrical power bills.

#### **1.4. Methods of harmonic mitigation**

There are two approaches to mitigate power quality problems. The first approach is known as load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the equipment to operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts with the power system disturbances. Both active filters and passive filters can be effectively used for harmonic mitigation under this category.

**Passive filters:** Conventional solution for harmonic distortion has been the use of passive filters to minimize offending harmonics. Voltage harmonic distortion could often be controlled with a simple high pass filter, but reduction of current harmonic levels usually requires installation of multiple tuned traps, each of which reduces only one of the many harmonic frequencies produced by the non-linear load (Figure 1.1).

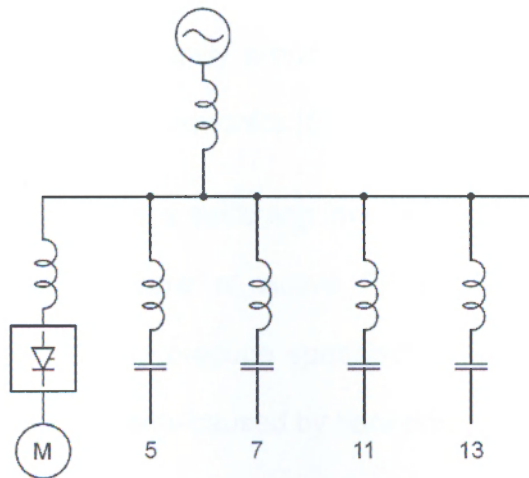


Figure 1.1: Typical arrangement of a passive filter

The other disadvantage is that the current of the filter is not controllable and it can also produce reactive power. Further, passive power filters have the problem of resonance.

**Active filters:** A different solution has been recently introduced as a result of the advances in power semiconductors. Insulation Gate Bi-polar Transistors (IGBTs) made possible to have a power switch with nearly ideal performance and reliability. Consequently two new types of equipments were developed: the Pulse Width Modulated (PWM) -Unity Power Factor rectifiers and the Active Power Filters (APF). By construction, an active filter is similar to a PWM unity power factor rectifier, but different to it by the fact that the inverter for APF applications present a fourth IGBT leg or a centre tap on the main filtering capacitor battery which is connected to the neutral [4].

### 1.5. Active Power Filters

Active power filters were initially proposed by Sasaki and Machida in 1971, as a means of removing current harmonics [5].

An active power filter uses a switching inverter to produce harmonic compensating currents. The basic principle of Active Power Filter (APF) is to utilize power electronics technologies to produce specified current components that cancel the harmonic current components caused by harmonic producing loads.

Active power filters can perform one or more of the functions required to compensate power systems and to improve power quality. Their performance depends on the power rating and the speed of response.

Active power line conditioners are typically equipped with IGBT or GTO (Gate Turn Off) thyristors, voltage source PWM converters and connected to low and medium voltage distribution systems arranged in shunt, series or both at the same time. In comparison to conventional passive LC filters, active power filters offer very fast control response and more flexibility in defining the required control tasks for a particular application. Smaller sizes of the component and been more economical solution are the major advantages of using active filters for harmonic mitigation.

The two major types of active power filters are series active power filters and shunt or parallel active power filters. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. The selection of the type of active power filter to improve power quality depends on the source of the problem.



Parallel active power filter compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this case the shunt active power filter operates as a current source that injects harmonic components generated by the load but with a phase shifted at  $180^\circ$ . This principle is applicable to any type of load that is considered as a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor.

The concept of parallel or shunt active filter can be illustrated by the following figure.

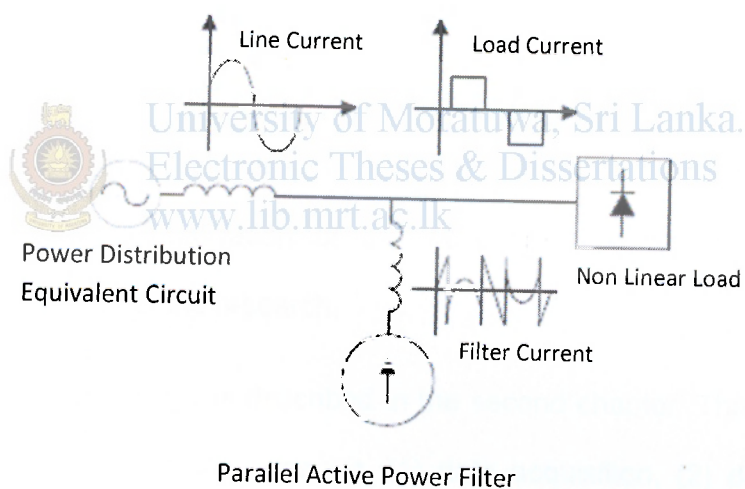


Figure 1.2: Compensation characteristics of a parallel active power filter.

Numerous applications of active power filters are described in literature [6-10].

## 1.6. Objectives

Therefore the major objective of this project was to eliminate effects of harmonics and to improve power factor by using a parallel active power filter. *i.e.* to connect an additional unit (the parallel filter) to the utility in order to inject the appropriate compensation current to eliminate harmonics and to improve power factor. The specific objectives include (1) study and understand the harmonic effects, (2) decide the APF suitable for current shaping and (3) simulating for results.

## 1.7. Thesis Organization

The thesis is composed of four main chapters. The first chapter brief the research background and the motivation of the work been produced. The same also introduces objectives of the research.

The research methodology is described in the second chapter. The subject material is detailed under four main topics *viz.* (1) data acquisition, (2) data analysis, (3) simulating for results and (4) validation of results

Results of the projects are given in the chapter three. The results are presented in four main sections, namely (1) acquired signals, (2) required filter current (3) simulation results and (4) validation of the results.

The project is discussed in the chapter four. This includes a general discussion of the results, specific problems arising from the methodology, protective measures implemented, as well as a discussion of the results and suggestions for future.

# CHAPTER 2

---

## METHODOLOGY

The project basically focus on five main topics viz (1) acquisition of voltage and current signals of a power appliance, (2) analysis of the acquired signals, (3) determination of the appropriate filter (4) simulation to implement active power filter, (5) validation of the acquired circuit parameters.

### **2.1. Acquisition of voltage and current signals of the power appliance**

Accuracy in acquiring voltage and current signals is the major factor that determines the research outcome as well as the value of the results. Type of load, properties of the data acquisition card and auxiliary hardware circuit has to be compatible for proper and efficient functioning of the system.

#### 2.1.1. Sample load

Extremely high frequency components are not usually present in computer power suppliers since they are supported with passive low pass filters (Annex\_1). According to the preliminary studies made on computer power supply the approximate current wave form maintain a high peak to rms ratio (or crest factor). Use of Rectifiers (to convert AC to DC voltage) is a known cause to produce such observations.

Power rating of computer power supply utilized as the sample load was 400 W. However since the power demand of a computer is determined by several factors, including weather different components such as cooling fans, optical drivers, hard disk drives and processor are activated or not, on average the power demand of the sample load was around 150 W (without monitor). Once the data is acquired at a particular instant, it was assumed that the power is constant for the period of operation. However for better performance data acquisition at regular intervals is needed.

### 2.1.2. Data acquisition card

The National Instruments USB-6008 multifunction data acquisition (DAQ) module (Annex\_2) was used to acquire data from the sample load viz. the computer power supply. MATLAB software facilitates data communication with the NI USB-6008. USB-6008 is supported in Data Acquisition Toolbox 2.8 (MATLAB R2006a) or newer. There were eight analog input channels of which the input resolution was 12 bit and the maximum sampling rate was up to 10 kS/s. The input impedance was 144 K $\Omega$ . The input range and the relevant level of accuracy are given in the table 1.

*Table 2.1: The input range and the relevant level of accuracy.*

Input range (V)	$\pm 20$	$\pm 10$	$\pm 5$	$\pm 2$	$\pm 1$
Accuracy (mV)	14.7	7.75	4.28	2.21	1.53

Details of the National Instruments USB 6008 DAQ card can be obtained online via <http://sine.ni.com/nips/cds/view/p/lang/en/nid/14604>.

### 2.1.3. Hardware circuit

The circuit diagram of the hardware circuit that was utilized to obtain the voltage and current signal of the sample load is given below.

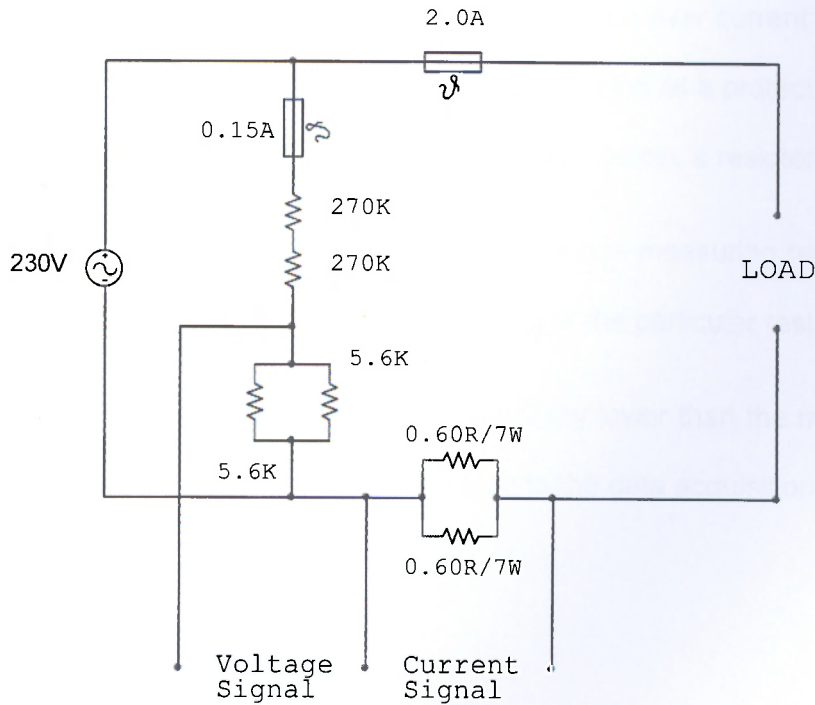


Figure 2.1: Hardware circuit to obtain voltage and current signals

**Procedure to acquire the current signal:** Current signal was acquired using a series resistor. This configuration causes voltage reduction across the sample load. Therefore for higher accuracy the voltage across the resistor was maintained at minimum, approximately 0.2 – 0.3 V rms.

**Procedure to acquire the voltage signal:** In order to obtain the voltage signal a potential divider technique was incorporated to the circuit such that the arrangement satisfy the following conditions (1) to limit power consumption at a

minimum; (2) to limit peak value of the voltage wave around 1-2 V. Application of the above conditions enables the voltage signal to be acquired within the same range where the current signal falls. The same further minimizes power losses.

**Protective measures:** Thermal fuses, 2.0 A fuse in the load path and a 0.15 A fuse in the potential divider path of the circuit, were used as over current protectors.

An additional resistor in parallel configuration was used as a protective measurement against open circuit faults when measuring voltage across a resistor.

Similarly two resistors in series were used as the non measuring resistor of potential divider to prevent failures due to short circuiting of the particular resistor.

Maximum measuring limits were kept substantially lower than the maximum limits of the input range in order to minimize damages to the data acquisition card due to high voltage.

#### 2.1.4. Acquisition of voltage and current signals using MATLAB

The device and two of the channels within were configured to obtain current and voltage signals by specific MATLAB commands.

Sampling rate was set to a value of 5000 samples per second, which is half of the maximum sampling rate available. The sample rate was determined such that the data bulk does not overload the data acquisition card. By selecting the sample rate as 5000 samples per second, the system can identify up to 50<sup>th</sup> harmonic which is adequate for general applications.



The device was triggered by using the voltage signal. Data acquisition was triggered at zero and at the rising crossings of the voltage signal. Data was acquired throughout a single complete power cycle at a time.

### 2.1.5. MATLAB Data acquisition tool box

Data Acquisition Toolbox provides a complete set of tools for analog input, analog output, and digital I/O from a variety of PC-compatible data acquisition hardware. The toolbox permits to configure external hardware devices, read data into MATLAB and Simulink environments for immediate analysis, and send out data [11].

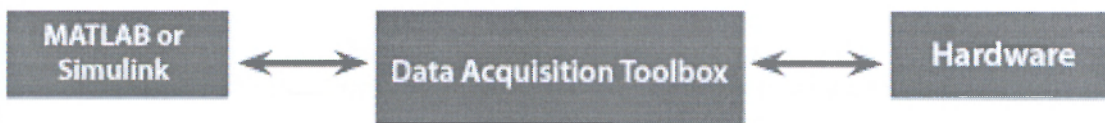


Figure 2.2: Schematic representation of the data acquisition using MATLAB

MATLAB Data acquisition tool box version 2.8 or above is required to communicate with NI USB 6008. DAQ tool box 2.8 or above is available at MATLAB R14SP3+ or later versions.

MATLAB commands used for data acquisition are illustrated on the following figure (Figure 2.3). Commands are described by bold letters.

```

ai = analoginput('nidaq','Dev1'); % Configure an National
                                Instruments DAQ input Object

Voltage = addchannel(ai,1);      % Add channel of input
                                object
Current = addchannel(ai,0);

ai.SampleRate = 5000;           % Set sampling rate
ai.SamplesPerTrigger = 0.02*5000; % Set number of samples
                                per one trigger

set(ai,'TriggerType','software'); % software trigger is
                                used
set(ai, 'TriggerRepeat', 0);     % Execute the trigger
                                once when the trigger condition is
                                met.
set(ai,'TriggerCondition','rising'); % The trigger occurs
                                when the signal has a positive
                                slope when passing through the
                                specified value
set(ai,'TriggerConditionValue',0); % set specified value
                                for TriggerCondition
set(ai, 'TimeOut', 2);          % Specify the waiting
                                time to complete a read or write
                                operation
set(ai,'TriggerChannel',ai.Channel(1)) % Specify channel
                                serving as trigger source

start(ai);                      % To start ai

[d,t] = getdata(ai);           % To acquire data for
                                under conditions

stop(ai);                      % To stop ai

```

Figure 2.3: MATLAB commands used for data acquisition



## 2.1. Analysis of acquired signals using MATLAB

The acquired voltage and current signals was analyzed subsequently in order to obtain parameters of the wave forms including instantaneous values, root mean square (rms) values, active power, effective power factor, total harmonic distortion (THD), harmonic spectrum, percentage harmonics, and distortion factor. Low magnitude higher order harmonics were shed for convenience in data analysis.

### Instantaneous values of voltage and current

Instantaneous voltage was determined by multiplying the acquired voltage signal by a factor of 194. Factor 194 arises from the ratio of resistors of the potential divider. The instantaneous current values were obtained by dividing the voltage across the series resistor, by which the current signal is determined, by the resistance of the same. The resistance value is 0.3.

### RMS values of voltage and current

Root mean square (rms) value of voltage ( $V_{rms}$ ) and current ( $I_{rms}$ ) signals were calculated by the square roots of the average sum of square values of the sample points.

$$rms\ value = \sqrt{(\text{Sum of square of instantaneous values}/\text{No of samples})}$$

### Active power

Active power ( $P$ ) was obtained by integrating the product of instantaneous voltage and current values for a complete power cycle using following relationship.

$$Active\ Power\ (P) = \int_t^{t+T} (V(t) \cdot I(t)) dt$$

Where  $t$  indicated time,  $T$  was the period of the wave, and  $V(t)$  and  $I(t)$  were instantaneous voltage and current values



### Effective power factor

Effective power factor was calculated by dividing the active power calculated as above by both  $V_{rms}$  and  $I_{rms}$ .

$$\text{Effective power factor } (\phi) = \frac{\text{Active power (P)}}{V_{rms} \times I_{rms}}$$

### Total harmonic distortion (THD)

Magnitudes of harmonics were acquired by fast Fourier transform of instantaneous signals. The harmonic magnitudes were then used to calculate THD as follows.

$$\text{Total harmonic distortion (THD)} = \frac{\sqrt{A_2^2 + A_3^2 + A_4^2 + \dots + A_N^2}}{A_1}$$

Where  $A_N$  is the amplitude of  $N^{\text{th}}$  harmonic component.

### Harmonic spectrum and percentage harmonics

Harmonic magnitudes obtained by fast Fourier transformation were used to obtain harmonic spectrum and the percentage harmonic magnitudes.

### Distortion factor

Distortion factor was calculated using the following relationship.

$$\text{Distortion factor} = \frac{1}{\sqrt{1 + THD^2}}$$

All MATLAB commands used for waveform analysis are illustrated in the following figure (Figure 2.6).

```

%Instantaneous voltage and current
V = 194*d(:,1); I = d(:,2)/30;

%Calculating true power.
P = trapz(t,V.*I)/T;

%Calculating RMS values.
Vrms = sqrt(sum(V.^2)/(N-1)); Irms = sqrt(sum(I.^2)/(N-1));

%Calculating effective power factor.
EPF = P/(Vrms*Irms);

%Calculating FFT of current signal.
X = fft(I'); Amplitudes = [X(1)/N, 2*abs(X(2:N))/N];

%Error correction
K= floor(N/2); Amplitudes = Amplitudes(1:K);

%Calculating Total Harmonic Distortion.
THD = sqrt(Amplitudes(3:K)*(Amplitudes(3:K))')/Amplitudes(2);

%Calculating Distortion Factor
DF = (1+THD^2)^(-0.5);

%Calculating Percentage Harmonic Levels.
H_Percent = 100*Amplitudes/Amplitudes(2);

%Shedding Negligable Percentages.
k = K;
while H_Percent(k)<2
    if H_Percent(k)<2
        H_Percent = H_Percent(1:k-1);
    end;
    k=k-1;
end;

```

Figure 2.4: MATLAB commands used for waveform analysis

### 2.3. Determination of the appropriate filter current

Load current was obtained directly using the data acquisition card as described in section 2.1.1. The ideal sinusoidal total current was determined using the following equation.

$$P = VI \cos \phi \quad \text{-----} \rightarrow \text{Equation--1}$$

Where; P = active power, V = rms voltage, I = rms current and  $\cos \Phi$  = power factor.

P and V were obtained as described in section 2.1.4. In order to keep the ideal current in the same phase with the voltage, power factor was considered as unity.

Then,

$$I = \frac{P}{V} \quad \text{-----} \rightarrow \text{Equation--2}$$

The total current obtained from the utility for the whole system, consisting of the sample load (computer power supply) and the filter, is equal to the sum of load current and the filter current as the filter is configured in parallel with the load. Therefore filter current is equal to the subtraction of actual load current from the ideal sinusoidal total current.



## 2.4. Simulation to implement active power filter

Once the appropriate current was determined as described above, a circuit was constructed in simulation, by which the correct current waveform could be generated.

### 2.4.1 Circuit arrangement of the simulation

Filter current was implemented by switching an inductor using four insulated gate bipolar transistors (IGBT) arranged in H bridge configuration. A charged capacitor was employed to provide the appropriate voltage to the inductor and thereby the required current was obtained. To charge the capacitor a step up transformer with a full bridge rectifier converter was used. The simulation circuit is given in Figure 2.5. S1-S4 are IGBT switches.

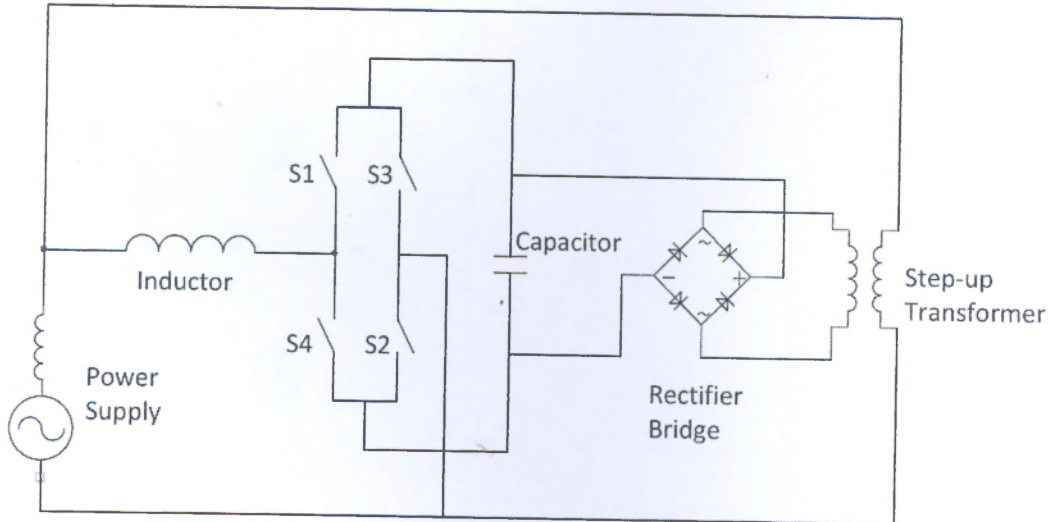


Figure 2.5: Circuit diagram of the parallel active filter

The simulation circuit was implemented using MATLAB Simulink software tool.

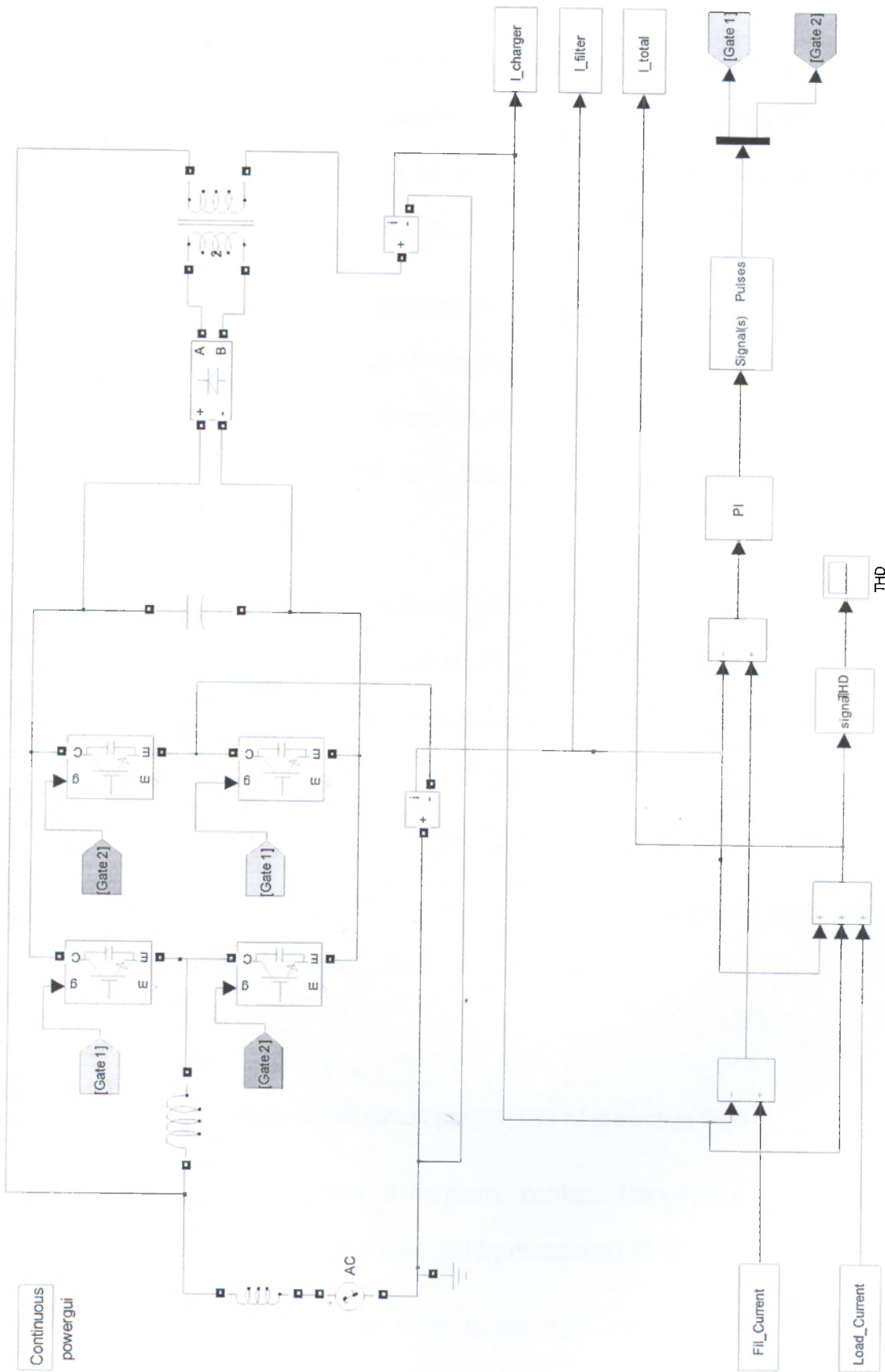


Figure 2.6: Simulation circuit

As the sampling rate available in the NI USB 6008 data acquisition card was not sufficient for precise implementation of the simulation, the number of sample points was increased by generating additional sample points using the MATLAB software. For-loop technique was made use of assuming linearity between two adjacent sample points for the purpose (Annex\_3).

Current signal and voltage signal acquired from Data Acquisition Card was saved as "V" and "I" in MATLAB workspace. As described in section 2.3, filter current was determined and saved in MATLAB workspace as "Fil\_current". Subsequently the acquired load current was saved as "Load\_current" in MATLAB workspace, for convenience in identification.

The current signal need to be obtained by switching circuit ( $i_r$ ) was determined by subtracting capacitor charging current from the filter current. Deference between the current described above ( $i_r$ ) and the actual current through the inductor was fed to the switching signal generator via a PI controller. Subsequently the signals generated by the switching signal generator were fed to IGBTs.

The total current of the system was obtained by adding acquired load current, charging circuit current and current through the inductor.

#### 2.4.2 Simulation to obtain circuit parameters of the active filter

THD was used as the measure of harmonic content. Hence, the optimal circuit parameters of the active filter were obtained by minimizing THD.

The capacitance of the capacitor need to be sufficient in order to deliver the appropriate electrical charge to the system. Yet, installing a large capacitor is not

feasible because of physical size of it and the cost. A capacitor with the capacity of 200  $\mu\text{F}$  was used in the simulation.

Inductance of the switching inductor, voltage of the step up transformer and the switching frequency of the system were worked out by simulation. However, THD of the simulation circuit varies with all three factors mentioned above i.e. (1) inductance of the Inductor, (2) output voltage of the step up transformer, (3) switching frequency of IGBTs. The simulation program was highly complex since all three factors were to be optimized simultaneously. Therefore, the first parameter was optimized while the other two were kept under minimum sensitivity. Once one of the parameters was optimized as above the next was optimized for the optimum value of the first parameter.

**Determination of the inductance of the switching inductor:** Application of the appropriate inductance is essential as in a given voltage; large inductance has less potential to remove higher order harmonics. On the other hand the wave signals tend to deviate more from the reference wave when the inductance was small.

A range of inductance values starting from 10 mH up to 100 mH in intervals of 10 mH were studied under four different combinations of two different switching frequencies viz. (1) 50 kHz, (2) 100 kHz, and transformer voltages viz. (1) 300V and (2) 400 V. The resulting waveforms and Total harmonic distortions (THDs) were observed.

Physical parameters (size) of the inductor were important as when Inductors of high inductance were bulky and hence not suitable for low power applications as the one



being studied. Therefore Inductors of inductance higher than 100 mH was not considered in the simulation.

**Voltage of the step up transformer:** The appropriate inductance was identified as 50mH. Higher voltages increase handling difficulties, insulation requirements and require equipments with high rated voltage. In contrast low voltages were incapable to supply the required filter current. Therefore four different transformer voltages; 250 V, 300 V, 350 V, 400 V were studied at three switching frequencies 20 kHz, 50 kHz, 100 kHz. The resulting waveforms and THD were observed.

**Switching frequency of the system:** As described above the proper inductance and Transformer voltage were identified as 50 mH and 350 V respectively. The waveforms and THDs were studied at a range of switching frequencies starting from 5 kHz up to 200 kHz at 50 mH inductance and 350V step up transformer voltage. Even though high switching frequencies were considered in the simulation such is extremely difficult to achieve in practical applications.

## **2.5. Validation of the acquired circuit parameters**

At the best possible inductance of 50mH, transformer voltage of 350V, and switching frequency of 100 kHz which were chosen by the simulation, the behavior of the active power filter was studied under different (1) load variations (50% to 200%) and (2) system voltage variations (90% to 110%).

Total harmonic distortion and the current wave form were observed.

### 3.1. Electrical parameters of the sample load

#### 3.1.1. Voltage signal of the sample load

With the exception of a slight distortion observed towards the peaks, the voltage wave of the sample load was nearly perfect sinusoidal wave. Higher order harmonics were negligibly low (Figure 3.1).

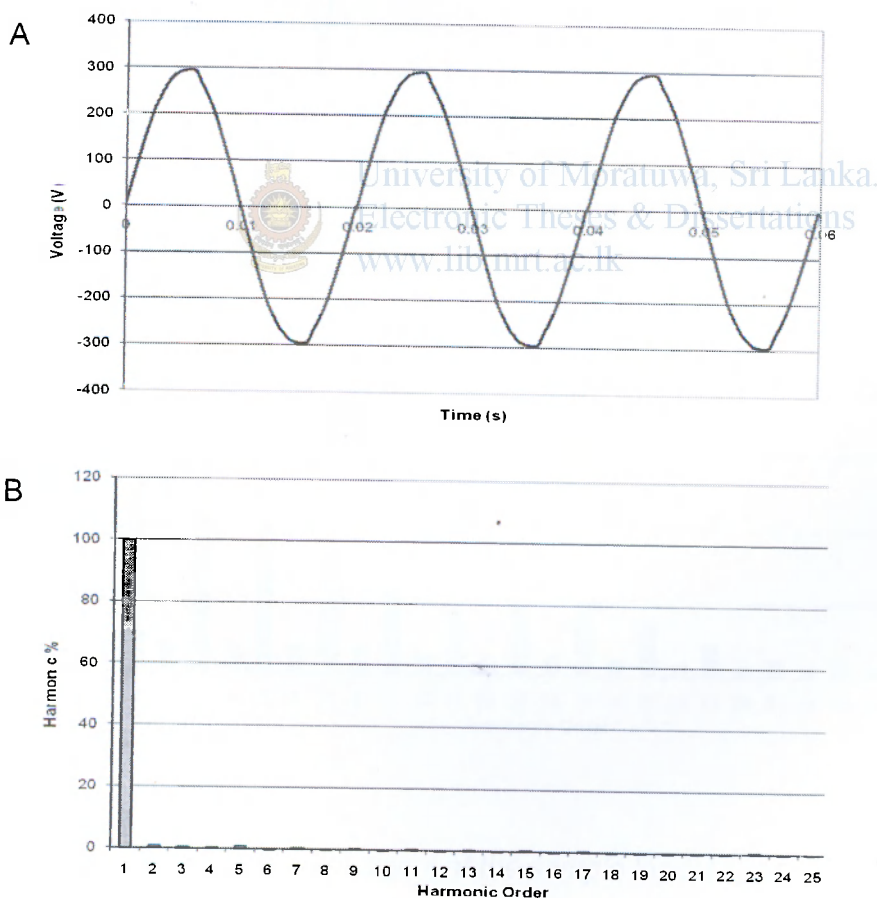


Figure 3.1: Voltage signal of the sample load. (A) voltage waveform, (B) voltage harmonic distribution

### 3.1.2. Current signal of the sample load

Unlike the voltage waveform of the load current was highly distorted, and in addition to the fundamental higher order harmonics were quite prominent. Among them the 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup> and 9<sup>th</sup> order harmonics were foremost.

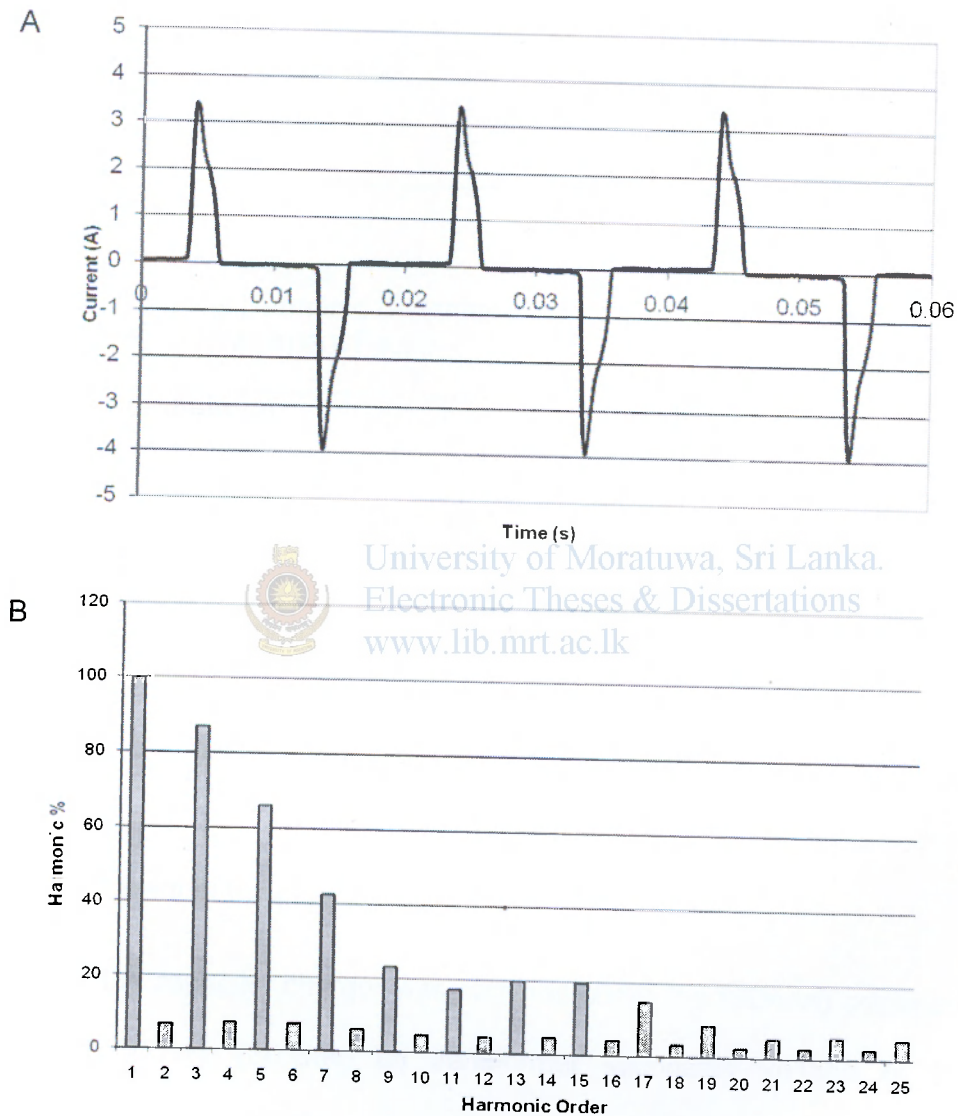


Figure 3.2: Current signal of the sample load. (A) current waveform, (B) current harmonic distribution

### 3.1.3. Electrical parameters of the sample load

Electrical parameters of the acquired voltage and the current signal are given in the table 3.1.

Table 3.1: Electrical parameters of the sample load

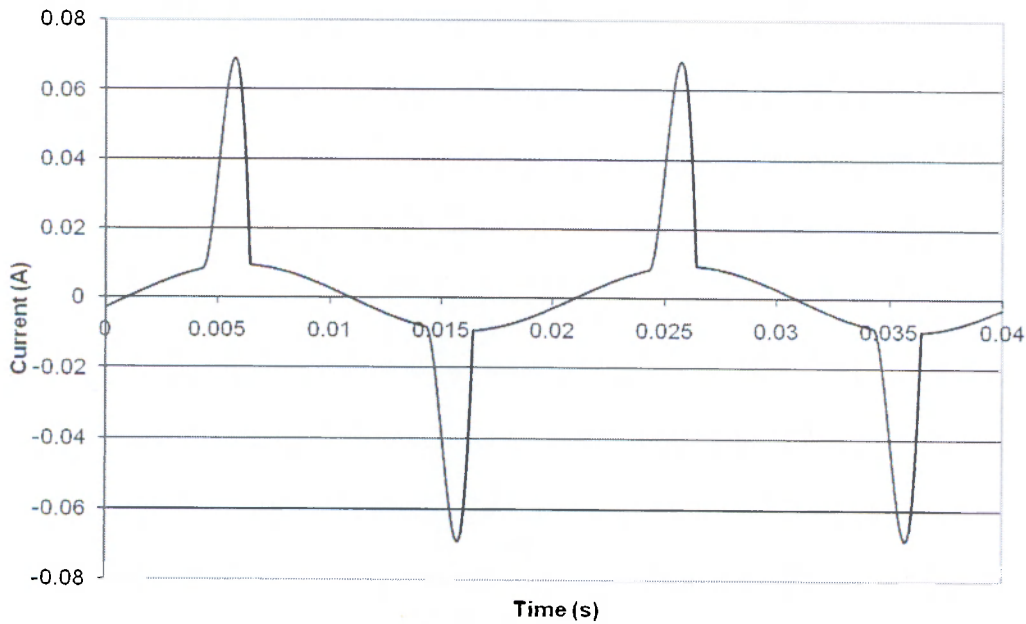
Active power of the load	= 144 W
Power factor	= 0.66
<b>Voltage signal</b>	
1. Rms voltage	= 229.7 V
2. Total Harmonic Distortion	= 2.68%
3. Displacement Factor	= 0.9996
<b>Current signal</b>	
1. Rms current	= 0.945 A
2. Total Harmonic Distortion	= 107%
3. Displacement Factor	= 0.683

### 3.2. Required current from the filter

#### 3.2.1. Current of the capacitor charger .

The current of the capacitor charger was obtained under the following condition viz. (1) Inductance of 50 mH, (2) Step up transformer secondary voltage of 350 V, (3) Switching frequency of 100 kHz.

The current was measured once the capacitor was stabilized. The current of the capacitor charger was significantly low compared to the filter current.



*Figure 3.3: Current wave of the capacitor charger*

### 3.2.2. Filter current with capacitor charger

The required filter current was determined as described in the section 2.2. Incorporation of the capacitor charging circuit into the filter circuit did not significantly affect the filter current.

Following figure (Figure 3.4) describes the required current from the active power filter in order to eliminate harmonic effects. The current variation resulted after incorporating capacitor charging circuit with the active filter was insignificant.

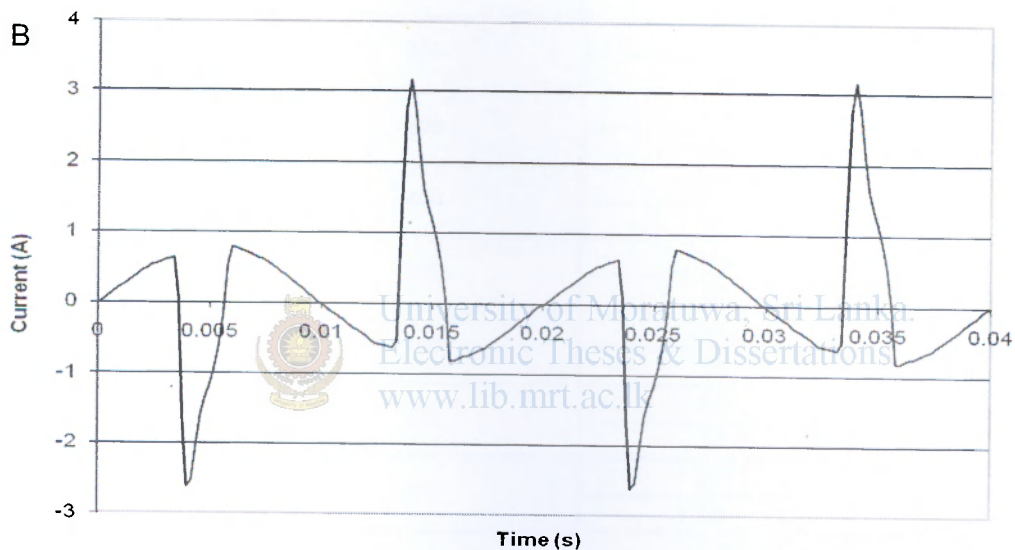
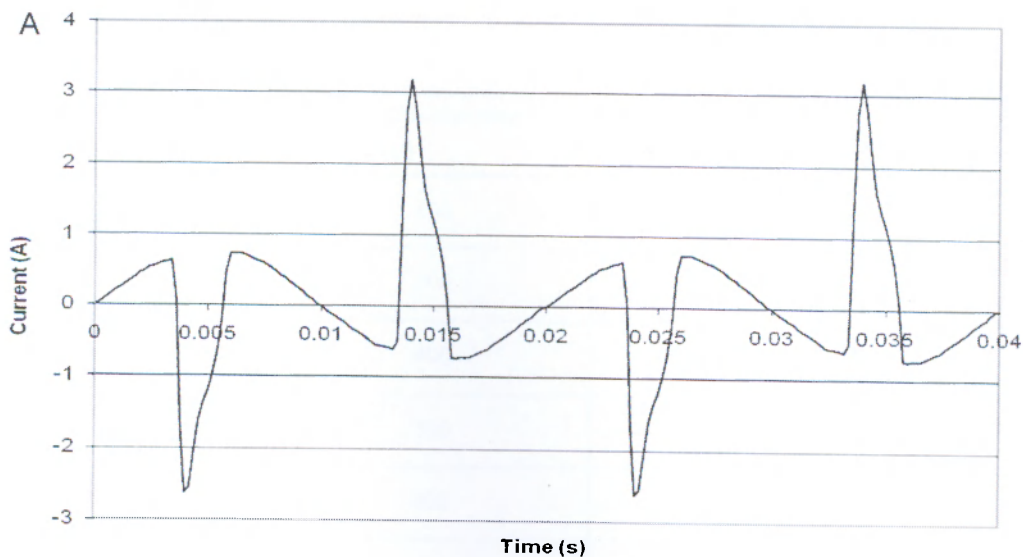


Figure 3.4: Current waveform required from the parallel active filter, (A) The capacitor charger incorporated, (B) In the absence of the capacitor charger

### 3.3. Simulation results

#### 3.3.1. Selection of the inductor

Percentage THD for different inductance values were obtained in the simulation of filter current. The table 3.2 provides THD of the total current.



Table 3.2: Total harmonic distortion variation with the inductance

Inductance (mH)	Step up transformer voltage (V)	Switching frequency (kHz)	Total Harmonic Distortion (%)
10	400	100	76
		50	335
	300	100	59
		50	251
20	400	100	29
		50	81
	300	100	24
		50	60
30	400	100	18
		50	45
	300	100	14
		50	34
40	400	100	14
		50	31
	300	100	16
		50	24
50	400	100	11
		50	24
	300	100	22
		50	32
60	400	100	9
		50	21
	300	100	48
		50	62
70	400	100	8
		50	19
	300	100	87
		50	89
80	400	100	8
		50	15
	300	100	125
		50	143
90	400	100	10
		50	17
	300	100	175
		50	217
100	400	100	16
		50	24
	300	100	232
		50	260

Total current is the summation of the load current and the filter current. Inductance value of 50 mH which resulted acceptable THD percentages was selected for further studies. Along with the THD percentages waveforms and other parameters were taken into consideration when the inductor was selected.

Rapid waveform variations observed under lower inductance values are shown in the following figure (Figure 3.5).

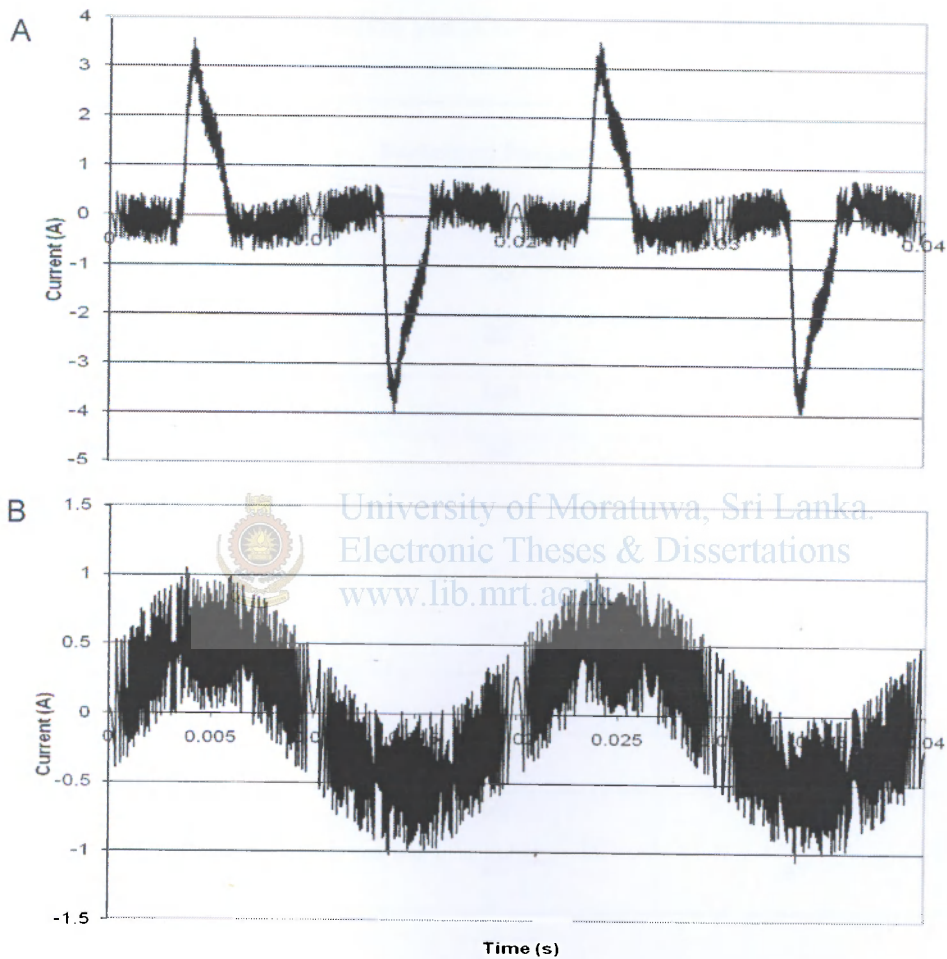


Figure 3.5: Waveform obtained for inductance of 10mH, Step up voltage of 400V and switching frequency of 100kHz, (A) active filter current, (B) resultant total current



### 3.3.2 Selection of the step up transformer

Inductance value was selected to be 50 mH, The simulation results of the step up transformer secondary voltage at three different switching frequencies; 20 kHz, 50 kHz, and 100 kHz were observed, at the selected inductance of 50 mH. Results are given in the table 3.3.

Table 3.3: Total harmonic distortion variation with the step up transformer voltage

Step up transformer voltage (V)	Switching frequency	Total Harmonic Distortion (%)
250	100	335
	50	372
	20	375
300	100	23
	50	32
	20	50
350	100	11
	50	21
	20	60
400	100	11
	50	24
	20	67

The most appropriate step up transformer secondary voltage was selected as 350 V that produced minimum or acceptable THD percentage. Secondary voltage of 350 V was used in further studies to determine the suitable switching frequency.

The filter is unable to produce required current shape for lower step up voltages. Following figure (Figure 3.6) indicates the incapability of the filter in providing required current shape, for lower voltages.

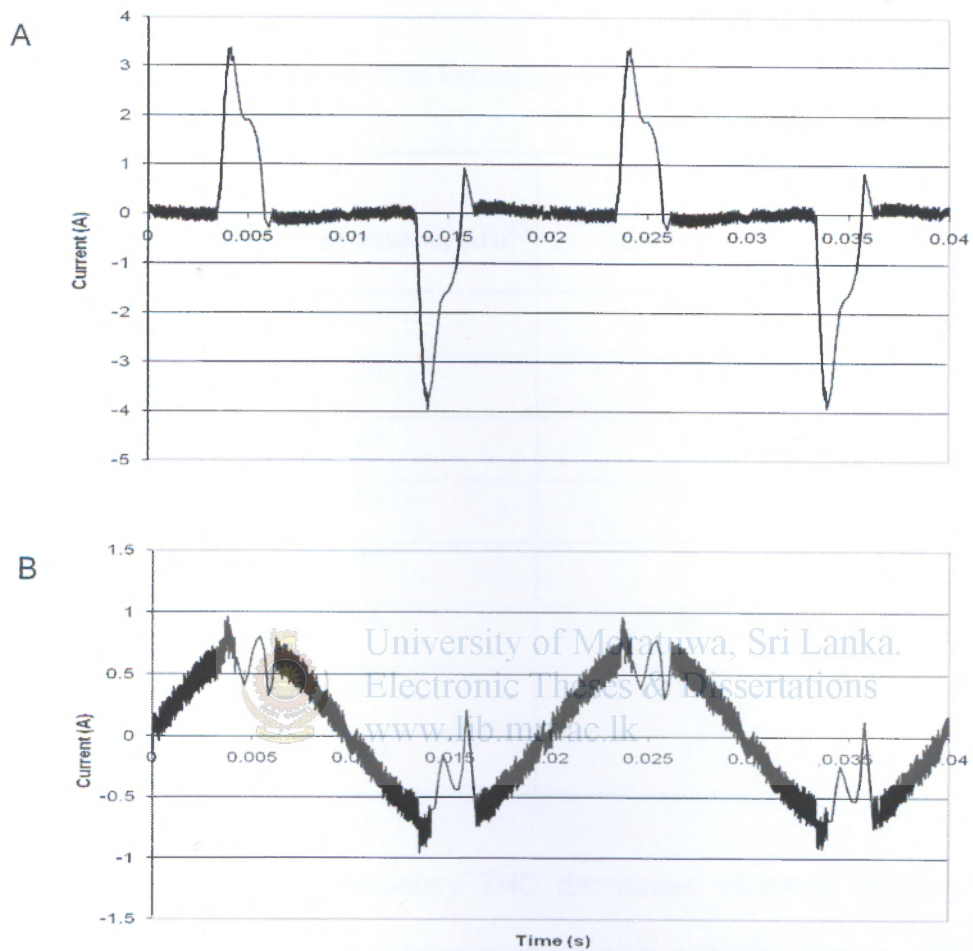


Figure 3.6: Waveform obtained for inductance of 50mH, Step up voltage of 300V and switching frequency of 50kHz, (A) active filter current, (B) resultant total current

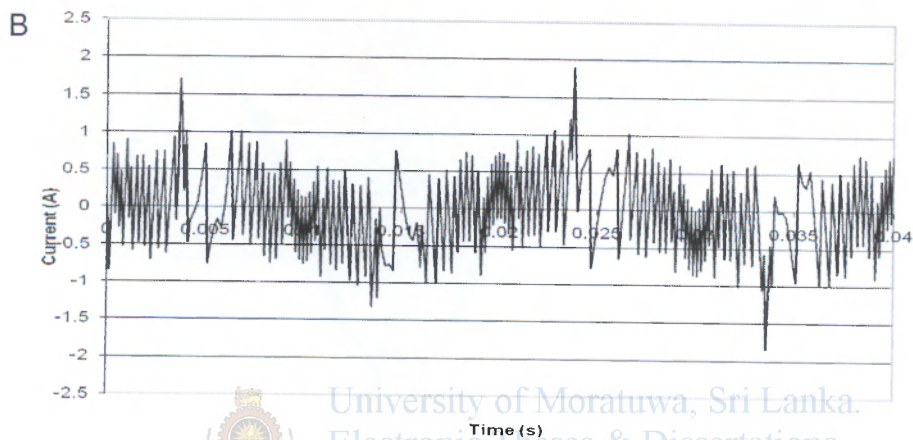
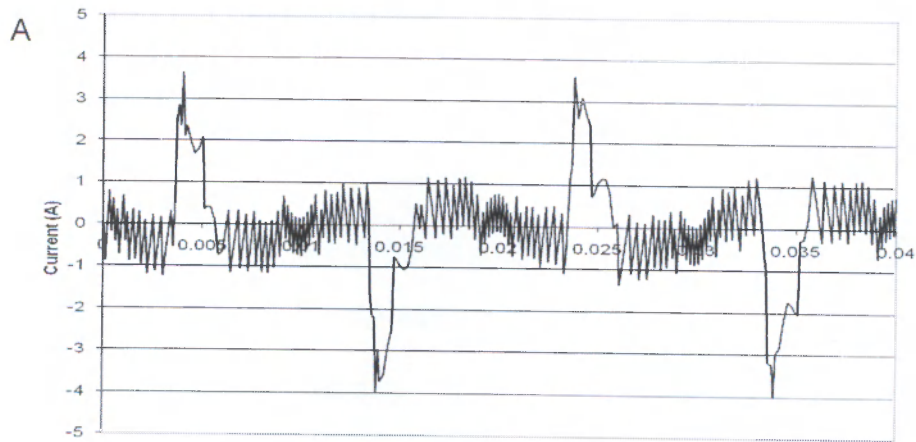
### 3.3.3 Selection of the switching frequency

The simulation results of the switching frequency of the APF at the selected inductance of 50 mH and the transformer secondary voltage of 350 V are given in the table 3.4.

Table 3.4: Total harmonic distortion variation with switching frequency

Switching frequency (kHz)	Total Harmonic Distortion (%)
5	305
10	225
20	57
25	42
40	23
50	21
100	11
200	5

With increasing switching frequency THD decreases. However higher switching frequencies cause practical problems such as high switching losses, difficulties to implement. Therefore 100 kHz switching frequency was selected to proceed with the simulation. Following figure (Figure 3.7) represents current waveform variations observed under lower switching frequency, under transformer secondary voltage of 350 V and inductance of 50 mH.



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Figure 3.7: Waveform obtained for inductance of 50mH, Step up voltage of 350V and switching frequency of 10kHz, (A) active filter current, (B) resultant total current

### Resultant total current for selected parameters

The resultant total current observed applying the selected parameters *viz.* inductance of 50 mH, switching frequency of 100 kHz, and step up transformer secondary voltage of 350 V are depicted in the figure 3.8. The figure depicts higher order harmonics up to 40th order even though miniature higher order harmonics were present even above 40th order.

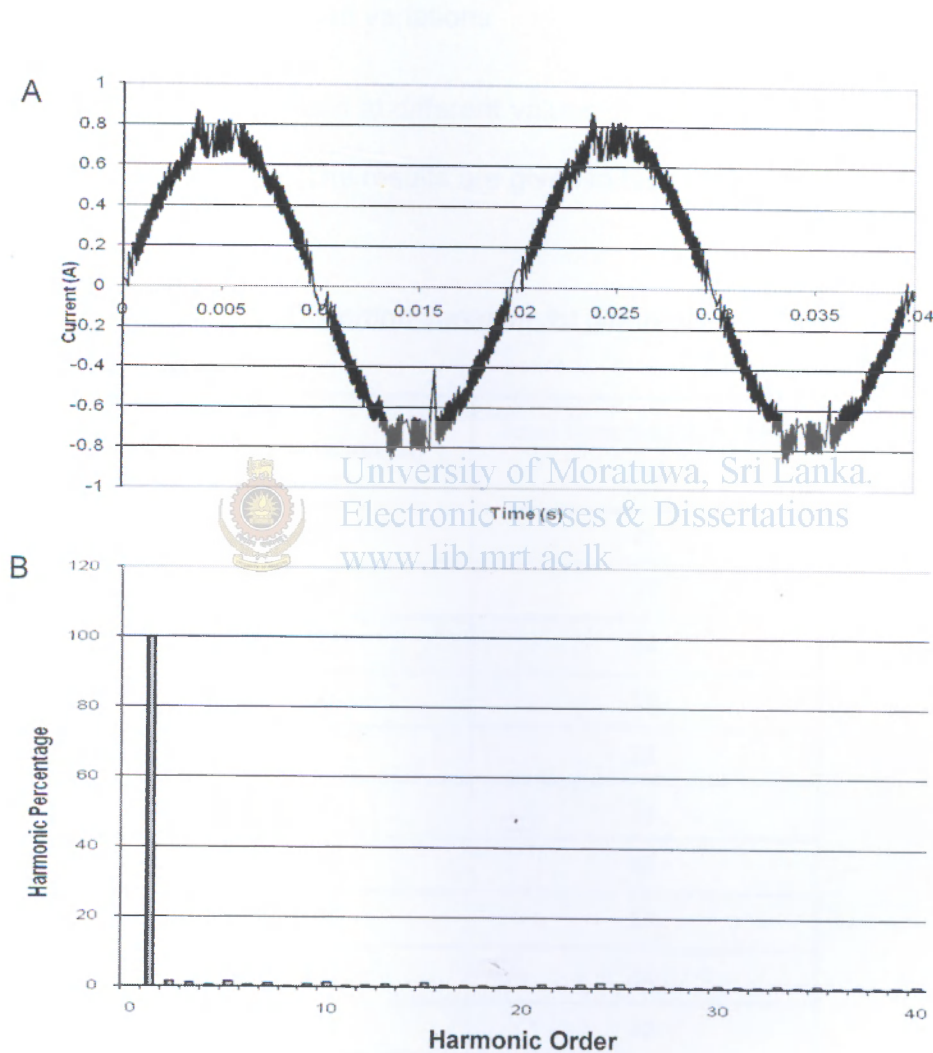


Figure 3.8: Resultant total current observed under inductance of 50 mH, switching frequency of 100 kHz, and step up transformer secondary voltage of 350 V, (A) Waveform, (B) harmonic distribution

### 3.4. Validation

The parameter values determined by the simulation were 50 mH for the inductance of the inductor, 350 V for the transformer voltage and 100 kHz for the switching frequency. Validity of those values was further confirmed using a range of values of sample loads and supply voltages

#### 3.4.1. Validation for load variations

The parameters were validated at different values of load currents assuming to be of the same waveform shape. The results are given in table 3.5.

*Table 3.5: Total Harmonic Distortion variation for different load variation*

Load variation (%)	Total Harmonic Distortion (%)
50	21
60	17
70	14
80	13
90	11
100	11
120	12
140	14
160	21
180	32
200	55

Following figures represent waveform shape and harmonic distribution, for 50% of load and for 160% of load. For the range of 50%of load to 160% of load, the maximum observed THD was only 21%.

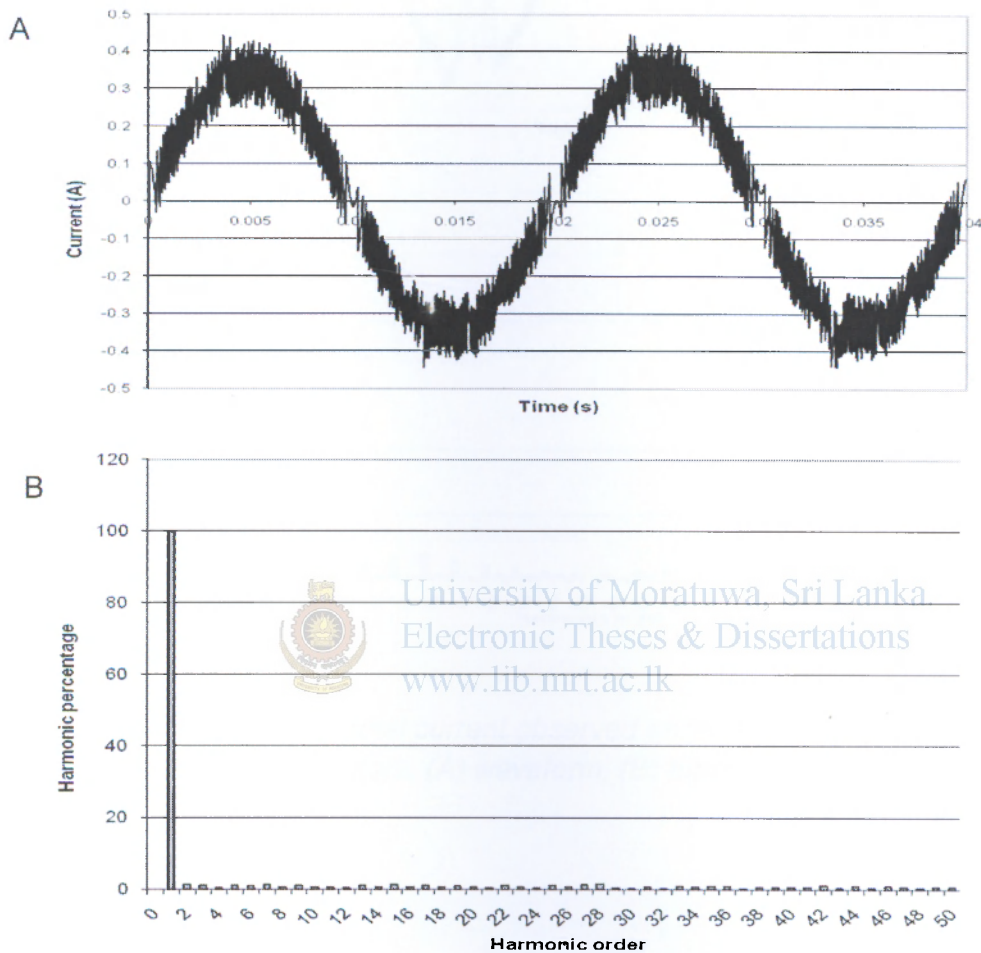


Figure 3.9: Resultant total current observed under 50% load under selected circuit parameters, (A) waveform, (B) harmonic distribution

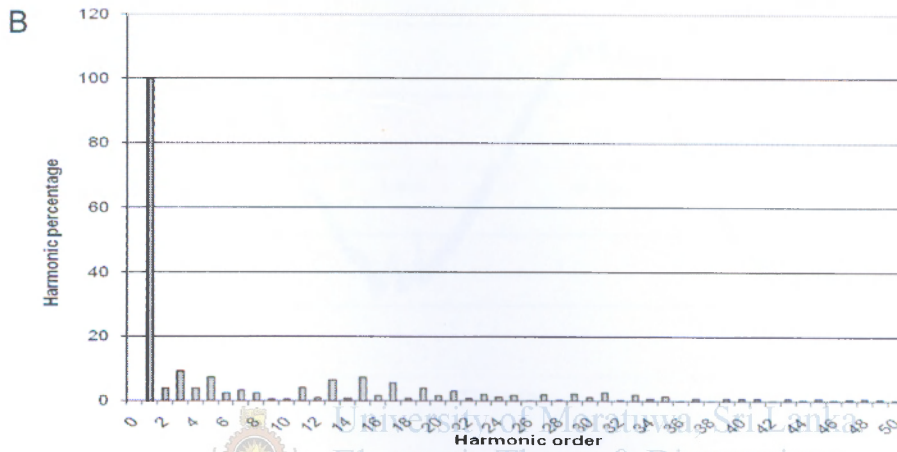
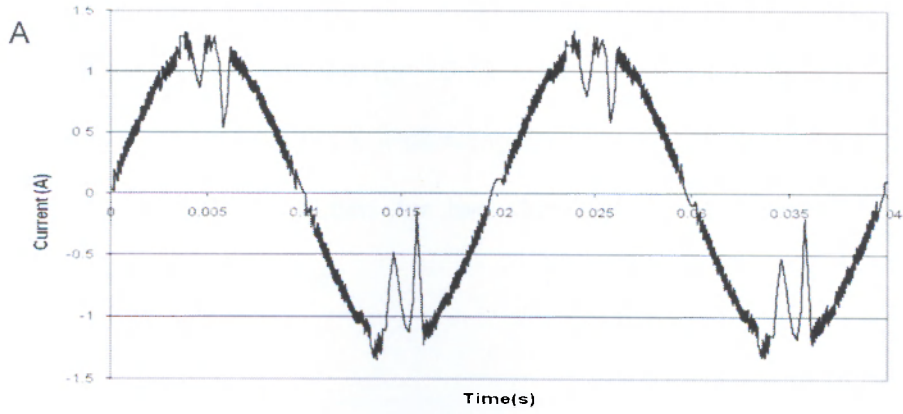


Figure 3.10: Resultant total current observed under 160% load under selected circuit parameters, (A) waveform, (B) harmonic distribution



### 3.4.2. Valication for supply voltage variations

The parameters were validated for 10 % supply voltage variations assuming the same active power consumption. Following figures represent resultant current wave shape and harmonic distribution for two different supply voltages. Higher order harmonics were not significant.

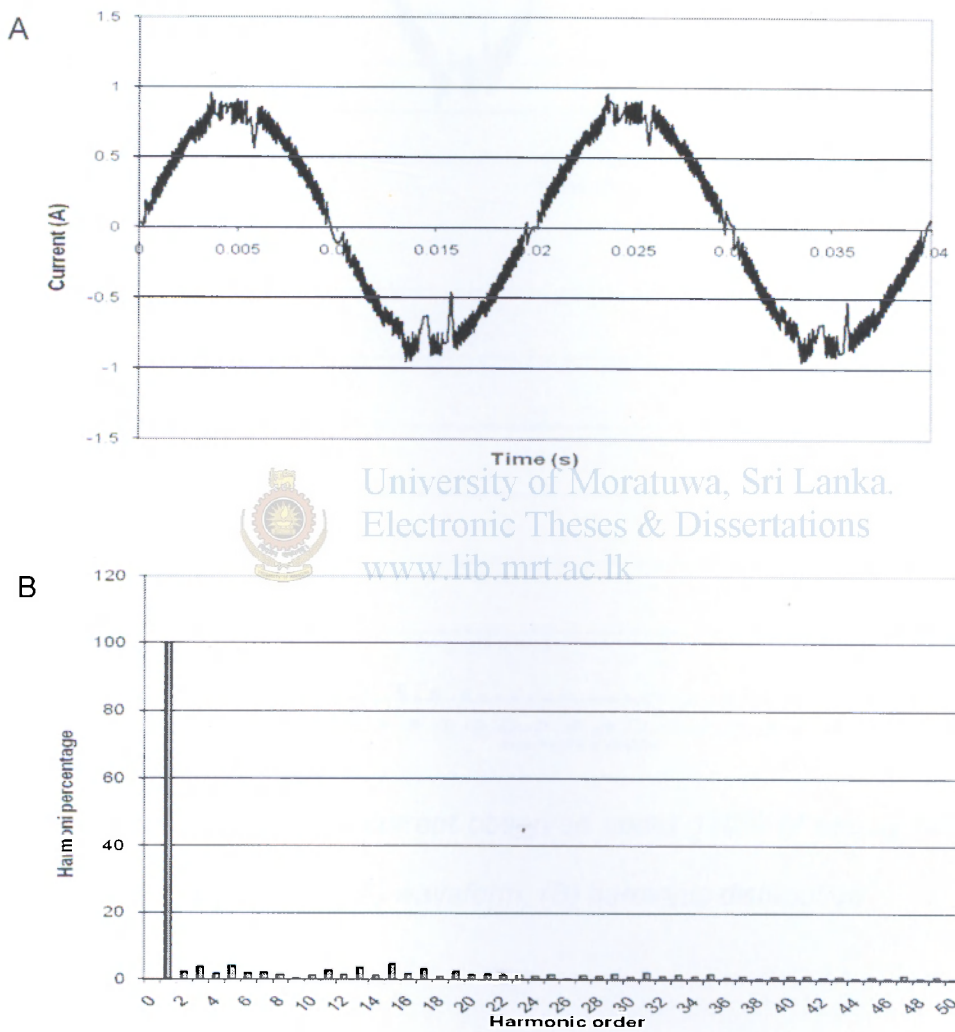


Figure 3.11: Resultant total current observed under 90% of supply voltage under selected circuit parameters, (A) waveform, (B) harmonic distribution

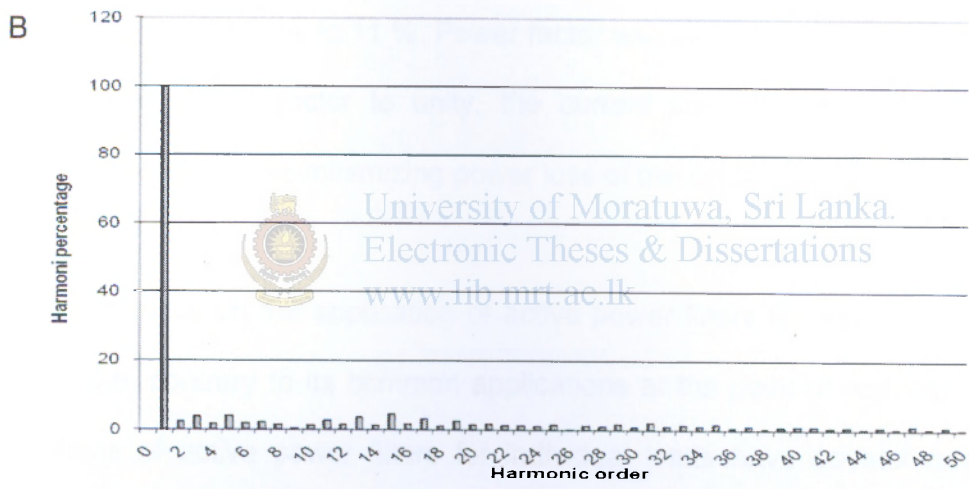
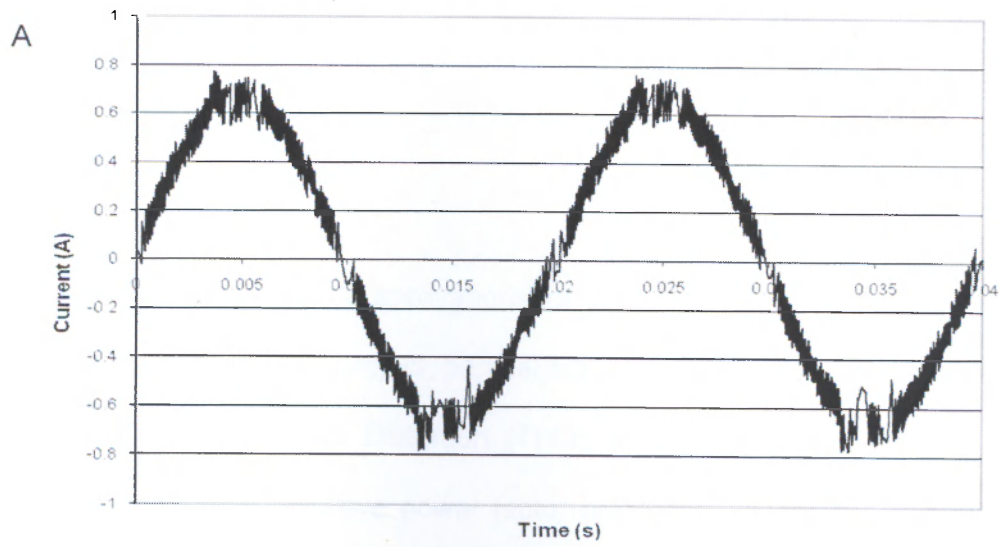


Figure 3.12: Resultant total current observed under 110% of supply voltage under selected circuit parameters, (A) waveform, (B) harmonic distribution

# CHAPTER 4

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## DISCUSSION

Active power filters have wide applications for controlling harmonic currents injected from nonlinear loads. In this project, parallel active power filters were effectively used to minimize Total Harmonic Distortion (THD), which used to measure harmonic contents, as well as to improve power factor using a computer power supply as a sample load. It was possible to reduce THD of the current wave of the computer power supply from 107 % to 11 %. Power factor was improved from 0.66 to unity. By increasing the power factor to unity, the current flow is possible to reduce by approximately 34% while minimizing power loss of the system.



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This project focus on the application of active power filters for current shaping of a specific load, contrary to its common applications at the point of common coupling. Applications of active power filters for individual loads have several advantages. Firstly, application of active filter to specific loads simplify the generation of reference current compared to the arrangement where the active filter is at the point of common coupling. Further when the active filter is at the point of common coupling it does not mitigate internal harmonic effects, whereas with application of active filters for specific loads the same problem does not arise.

Application of active filters for specific loads is undeniably costly. Naturally wave form distortion is more in individual specific loads compared to that at the point of

common coupling. Consequently, the specific loads require more sensitive and highly efficient active filters.

One of the main advantages of the prototype developed is its ability to display and analyze voltage and current waveforms of power appliances. Therefore, optimum filter circuit parameters for specific loads can be determined with much convenience.

The same feature enables to use the prototype as a power quality monitoring unit in addition to its usage for current shaping. Certain modifications, such as changing the series resistor being used for acquiring the current signal, are required for the purpose.

Despite computers consume low power, with the escalating usage; computers emerge as a potential source for utility system waveform distortions. Therefore as a typical nonlinear load computer power supply was studied in detail. Yet, the conclusions derived in the study are applicable to nonlinear loads in general. The conclusions were derived for the sample load, computer power supply which require specific load with narrow limits. Further the results were validated within narrow limits. Therefore it is necessary to study applicability of the results on alternative loads such as variable speed drives, CFL bulbs, switch mode power supplies and uninterrupted power supplies to implement a general purpose APF.

IGBT switching causes additional power loss. The loss of power is proportional to the switching frequency [11]. The fact need to be considered when such switching systems are implemented in low power appliances.

The system was run using a computer. Yet it is possible to design electronic circuits or programmed micro-controller systems to achieve the same. This would increase efficiency as well as the expediency of the system.

THD was used as the discerning criteria in this study. THD can be effectively used to improve power quality and to economize power loss. However rather than the total harmonics studying specific harmonics are more important in some situations such as radio interference and other instances where resonance takes place. THD exclusively does not provide all the details of the waveform distortion. Therefore in order to make better judgment, the nature of the harmonics needs to be studied further.

In order to develop the prototype worked out in this project to the level of implementation further studies are needed in the areas of IGBT switching specifically on the application of IGBT driving circuits.

Excessive presence of harmonics in power systems is harmful not only to the consumer who is responsible for the non-linear load but also to other consumers and utility supplier. Therefore with the increasing harmonics in the power systems regulatory measures such as introducing tariff barriers against THD need to be implemented in future.

Technical problems and concerns are discussed in detail in the following paragraphs.

**Data acquisition and analysis:** A series resistor was used in order to obtain the current signal. Therefore for accurate results, it is essential to maintain the voltage of the resistor at a minimum. When the rms voltage is maintained at around 0.3 V the peak voltage would be approximately 1-2 V. In order to obtain high level of accuracy in measurement of both current and voltage signals it is essential that the peak value of the voltage signal is retain at 1 -2 V.

Zenner diodes a frequent solution for over voltage protection was not applicable here because of the conduction drop of the diode that causes waveform distortions. As an alternative over voltage protection was achieved by selecting the maximum operating limits substantially lower (approximately 20%) than the maximum limits of the input range.

Ability to use operational amplifiers as signal amplifiers and as signal buffers was investigated. However the same was not suitable for the purpose as the driving voltage of the operational amplifier was considerably high. This would possibly be risky on the data acquisition card. Since the resolution of the data acquisition card was high, it was possible to obtain an appropriate current signal by 0.3 V voltage drop which was negligible. Consequently amplifiers were not necessary. Input impedance of 144 k $\Omega$  was also sufficient so that the need of impedance matching did not arise.

**Determination of appropriate filter current:** In determining the filter current the voltage was assumed to be a pure sinusoidal wave and ideal current was obtained by multiplying the instantaneous voltage values from the ratio of rms current to rms voltage. This assumption is valid as the THD was very low in the voltage signal.



**Simulation to implement active power filter:** Waveform of the supply voltage was assumed to be of pure sinusoidal. However, practically certain level of distortion specifically in the maximum and minimum points of the waveform was observed violating those assumptions. Yet, since the distortion effect was not significant it did not cause noteworthy alternations in the results.

Physical size of the inductor was a considerable issue when selecting the inductor. Selecting inductors larger than 50 mH was not practical since the purpose was to eliminate harmonics in a computer which is comparatively small. Also the current injection inductor must be small enough so that the injected current  $di/dt$  will be greater than that of the reference current (the compensating current signal in the active power filter) for the injected current to track the reference.

One step up transformer was used with a rectifier bridge to deliver the required voltage to charge the dc capacitor. Capacitive voltage multipliers are a better option for the purpose since the space requirement could be reduced when compared to use of a step up transformer.

In order to minimize the drive voltage, one capacitor with four IGBTs was configured as a H bridge. The same can be achieved by using two IGBTs with two capacitors instead of one. However this cause the drive voltage of the circuit would be doubled, which is not advisable when safety is considered.

Even though extremely high switching frequencies could be applied in simulations such could not be used practically. Switching frequencies higher than 100 kHz s are practically difficult to achieve.

The resultant total current had least amount of higher order harmonics other than the fundamental. Higher frequencies are extremely dangerous to some components such as capacitor banks, power transformers. These higher order harmonics can be easily eliminated using simple passive low pass filters. But using a low pass filter in the filter circuit reduces its capability to eliminate higher order harmonics. Therefore, as simulation was carried out only for the filter circuit, the effect of low pass filter can not be simulated.

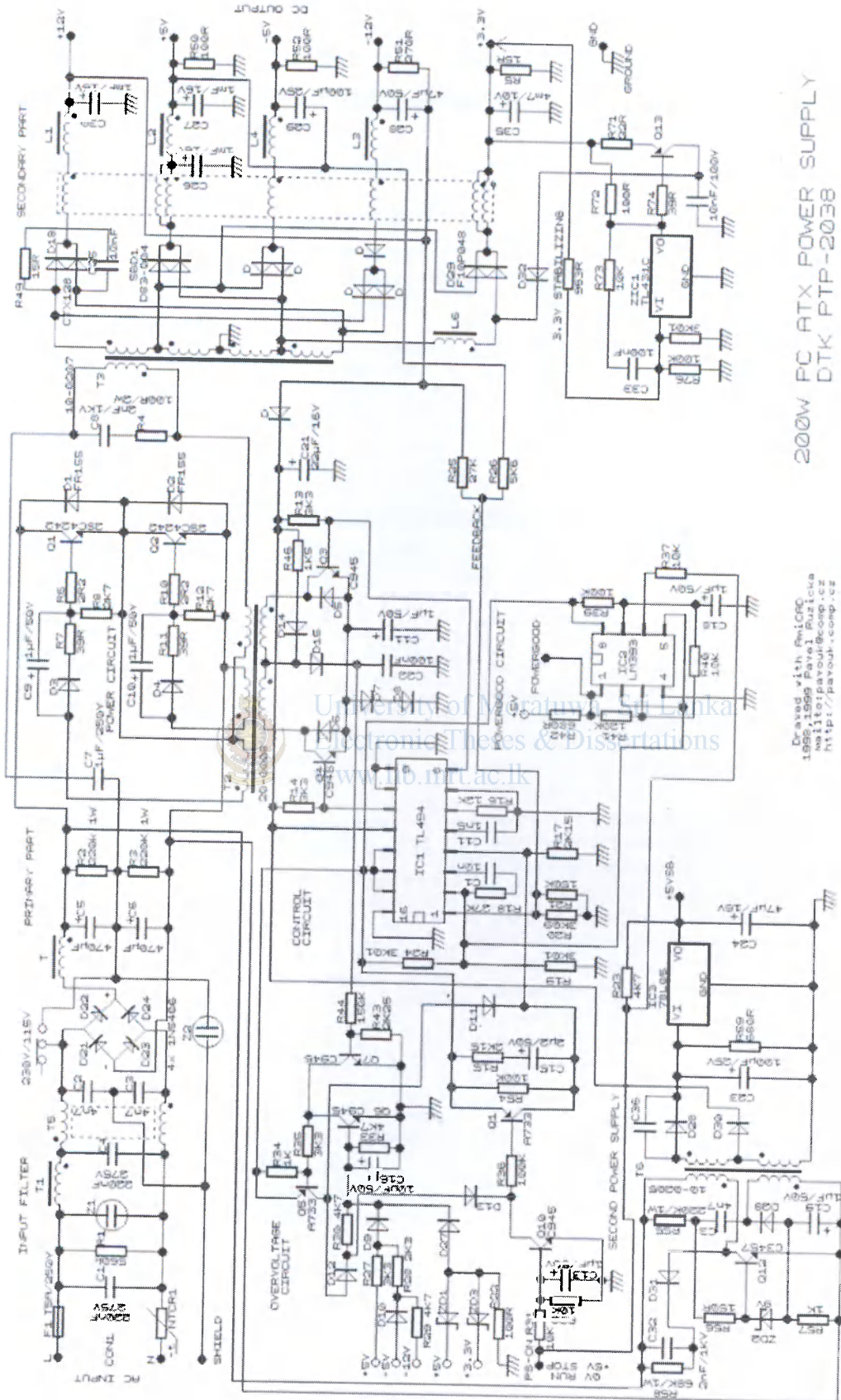


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# Low-Cost, Bus-Powered Multifunction DAQ for USB – 12- or 14-Bit, up to 48 kS/s, 8 Analog Inputs

## NI USB-6008, NI USB-6009

- 8 analog inputs at 12 or 14 bits up to 48 kS/s
- 2 analog outputs at 12 bits software-timed
- 12 TTL/CMOS digital I/O lines
- 32-bit, 5 MHz counter
- Digital triggering
- Bus-powered
- 1-year warranty

### Operating Systems

- Windows Vista (32- and 64-bit)/XP/2000
- Mac OS X<sup>1</sup>
- Linux<sup>1</sup>
- Windows Mobile<sup>1</sup>
- Windows CE<sup>1</sup>

### Recommended Software

- LabVIEW
- LabVIEW SignalExpress
- LabWindows/CVI
- Measurement Studio

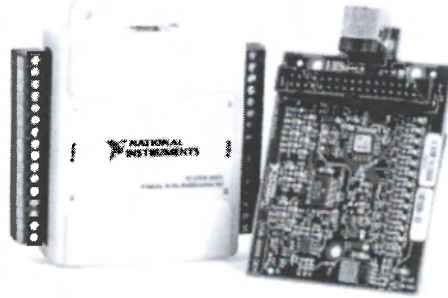
### Other Compatible Software

- C#, Visual Basic .NET
- ANSI C/C++

### Measurement Services Software (included)

- NI-DAQmx driver software
- Measurement & Automation Explorer configuration utility
- LabVIEW SignalExpress LE

<sup>1</sup>You need to download NI-DAQmx Base for these operating systems.



Product	Bus	Analog Inputs <sup>1</sup>	Input Resolution (bits)	Max Sampling Rate (kS/s)	Input Range (V)	Analog Outputs	Output Resolution (bits)	Output Rate (Hz)	Output Range (V)	Digital I/O Lines	32-Bit Counter	Trigger
USB-6009	USB	8 SE/4 DI	14	48	±1 to ±20	2	12	150	0 to 5	12	1	Digital
USB-6008	USB	8 SE/4 DI	12	10	±1 to ±20	2	12	150	0 to 5	12	1	Digital

<sup>1</sup>SE = single-ended, DI = differential. <sup>2</sup>Software-timed

## Overview and Applications

With recent bandwidth improvements and new innovations from National Instruments, USB has evolved into a core bus of choice for measurement applications. The NI USB-6008 and USB-6009 are low-cost entry points to NI flagship data acquisition (DAQ) devices. With plug-and-play USB connectivity, these modules are simple enough for quick measurements but versatile enough for more complex measurement applications.

The USB-6008 and USB-6009 are ideal for a number of applications where low cost, small form factor, and simplicity are essential. Examples include:

- Data logging – quick and easy environmental or voltage data logging
- Academic lab use – student ownership of DAQ hardware for completely interactive lab-based courses (Academic pricing available. Visit [ni.com/academic](http://ni.com/academic) for details.)
- OEM applications as I/O for embedded systems

### Recommended Software

National Instruments measurement services software, built around NI-DAQmx driver software, includes intuitive application programming interfaces, configuration tools, I/O assistants, and other tools designed to reduce system setup, configuration, and development time. National Instruments recommends using the latest version of NI-DAQmx

driver software for application development in NI LabVIEW, LabVIEW SignalExpress, LabWindows/CVI, and Measurement Studio software. To obtain the latest version of NI-DAQmx, visit [ni.com/support/daq/versions](http://ni.com/support/daq/versions).

NI measurement services software speeds up your development with features including:

- A guide to create fast and accurate measurements with no programming using the DAQ Assistant.
- Automatic code generation to create your application in LabVIEW.
- LabWindows/CVI, LabVIEW SignalExpress, and C#, Visual Studio .NET, ANSI C/C++, or Visual Basic using Measurement Studio.
- Multithreaded streaming technology for 1,000 times performance improvements.
- Automatic timing, triggering, and synchronization routing to make advanced applications easy.
- More than 3,000 free software downloads available at [ni.com/zone](http://ni.com/zone) to jump-start your project.
- Software configuration of all digital I/O features without hardware switches/jumpers.
- Single programming interface for analog input, analog output, digital I/O, and counters on hundreds of multifunction DAQ hardware devices. M Series devices are compatible with the following versions (or later) of NI application software – LabVIEW, LabWindows/CVI, or Measurement Studio versions 7.x, and LabVIEW SignalExpress 2.x.



Annex-3

MATLAB commands used for increasing sampling rate

```
I(101,:)=I(1,:);
N=100;
for i = 0:99
    for j = 1:N
        I1(i*N+j,:)=I(i+1,:)+(( I(i+2,:)- I(i+1,:))*j/N);
    end
end
end
for k = 1:10000
    T(k,:)=(k-1)*0.000002;
end
T1=[T;T+0.02;T+0.04;T+0.06;T+0.08];
I2=[I1;I1;I1;I1;I1];
Load_current = [T1 I2];
V(101,:)=V(1,:);
for l = 0:99
    for m = 1:N
        V1 (l*N+m,:)=V(l+1,:)+(( V(l+2,:)- V(l+1,:))*m/N);
    end
end
end
V2=[V1;V1;V1;V1;V1];
Load_voltage =[T1 V2];
```



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