A COMPARATIVE STUDY OF HYBRID COMPENSATION SYSTEMS USING A MULTIPLE FEEDBACK CONTROL SCHEME

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A Comparative Study of Hybrid Compensation Systems Using a Multiple Feedback Control Scheme

By

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Abstract

This thesis is an investigation of hybrid compensation topologies for mitigating load current harmonics, supply and load voltage distortion using a comparison approach. Four hybrid topologies are considered with a hybrid load consisting of current source type and voltage source type nonlinear loads. The compensation systems use the synchronous frame method for harmonic current extraction and propose an extraction scheme for the distortion voltage, which is based on a comparison of the distorted voltage with a fixed reference. The suitability of the multiple feedback loop control scheme was also investigated. It was determined that the scheme is effective in the generation of sinusoidal and distortion components of compensating currents and voltages and hence suitable for active filtering application.

Using the extraction and control schemes, the performance of the compensation systems was examined under different conditions of supply voltage and load currents. The results obtained showed the functionality of the control schemes in the compensation of disturbances caused by non-linear load operations and source end distortions.

A methodical determination of the ratings of the active filters in the hybrid compensators is also presented. The results show that rating curve is a function of the active filter type and the impedance of the passive filter.

Acknowledgements

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Contents

List of Figures

List of Tables

Chapter 1

Introduction and Literature Review

Issues associated with power quality have become important consideration for electricity companies, utilities and the end users of electrical power. Stringent demands are now being placed on the quality of the power being provided by the power companies and utilities. This imposes an obligation on the power providers who in turn place requirements on the consumers as regards power quality. Power quality is a term which refers to the degree to which the power received at a consumer terminals is distorted, that is, it refers to the level of harmonics and distortion present in the voltage at the point of common coupling, (PCC). It is an umbrella concept for different types of power system disturbance. The growing concern is due to the fact that load equipment are becoming more sensitive to power quality variations. Many new load devices now contain microprocessor-based control and power electronic devices that are sensitive to many types of disturbances. High power quality is generally desirable as it ensures normal operation of loads.

On the other hand, low power quality may results in low performance or even failure of some critical equipment such as automated systems and computers causing system down-time and associated increase in costs. Also, the need to improve efficiency of loads has resulted in the increasing use of power electronic based adjustable speed drives. Increased efficiency in the load equipment helps defer large investments in new lines, transformers, generators and substations i.e. it results in a better use of existing facilities.

Harmonics generally refer to sinusoidal voltages and currents in the system which are integer multiples (usually odd integers) of the frequency at which the supply system is designed to operate i.e. the fundamental frequency. Distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics. In single-phase systems the dominant harmonics are the 3^{rd}, 5th and 7^{th}. In general three-phase systems, the dominant harmonics are the 5^{th}, 7^{th} and 11^{th} due to cancellation of the 3^{rd} and other triplens as a result of the 120° shift between the phases. Harmonics are typically caused by the use of non-linear loads such as switch mode power converters, power electronics operated adjustable speed drives, fluorescent lamps, arc furnaces, welding equipment and other non-linear loads used in both domestic and industrial applications. Although the harmonic currents drawn by a single load may be small, large numbers of small loads often concentrated in a small area e.g. an office building may have numerous fluorescent lamps, computer equipment, copiers and other pieces of equipment necessary in a modern office. A factory may have several small rated adjustable speed drive or a few large ones, welding equipment or even an electric furnace. The harmonic currents produced individually in these situations may combine, resulting in very high levels of current and voltage distortion at the point of common coupling. The presence of harmonics in the system results in several effects including increased heating losses in transformers, motors and lines, low power factor, torque pulsation in motors and poor utilization of distribution wiring and plant.

The causes of power quality deterioration include voltage sag and swell. These are short duration decrease or increase in the voltage magnitude of typically between 3 and 30 cycles. Sags or swells of longer duration are considered under voltages and over voltages respectively. Figure 1.1 illustrates a voltage sag and swell. Voltage sags (dips) are mainly caused by phenomena resulting in high currents which in turn cause a voltage drop across the network impedance with a magnitude which decreases in proportion to the electrical distance of the observation point from the source of the disturbance in accordance to circuit laws. Such phenomena may include the sudden switching on and off of large loads in the system as well as faults on the lines.

Voltage notching is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another. Since voltage notching is periodic and occurs continuously, it can be characterized through the harmonic spectrum of the affected voltage. Figure 1.2 illustrates a typical voltage notch caused by current commutation in diode and thyristor converters. During the period when notches occur, there is a momentary short circuit between two phases resulting in close to zero voltage as permitted by the system impedances.

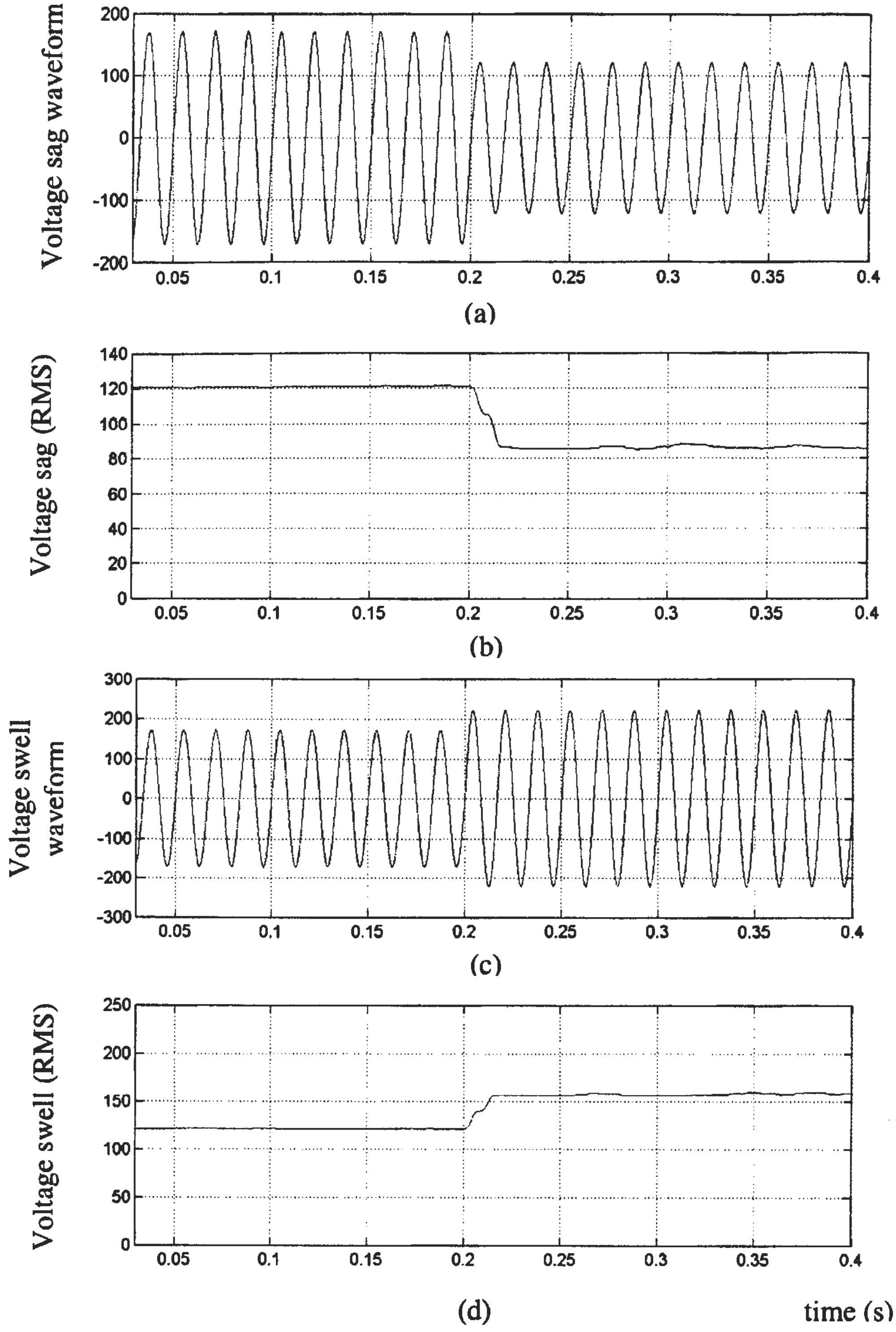

Fig 1.1: Voltage sag and voltage swell

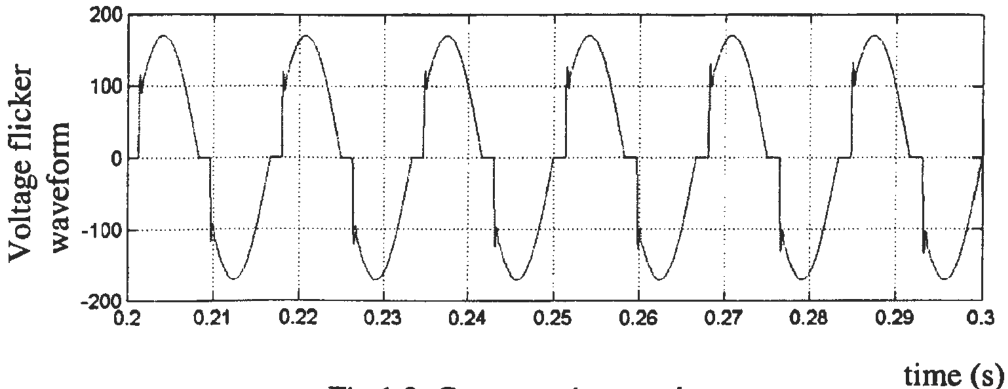

Fig 1.2: Commutation notches

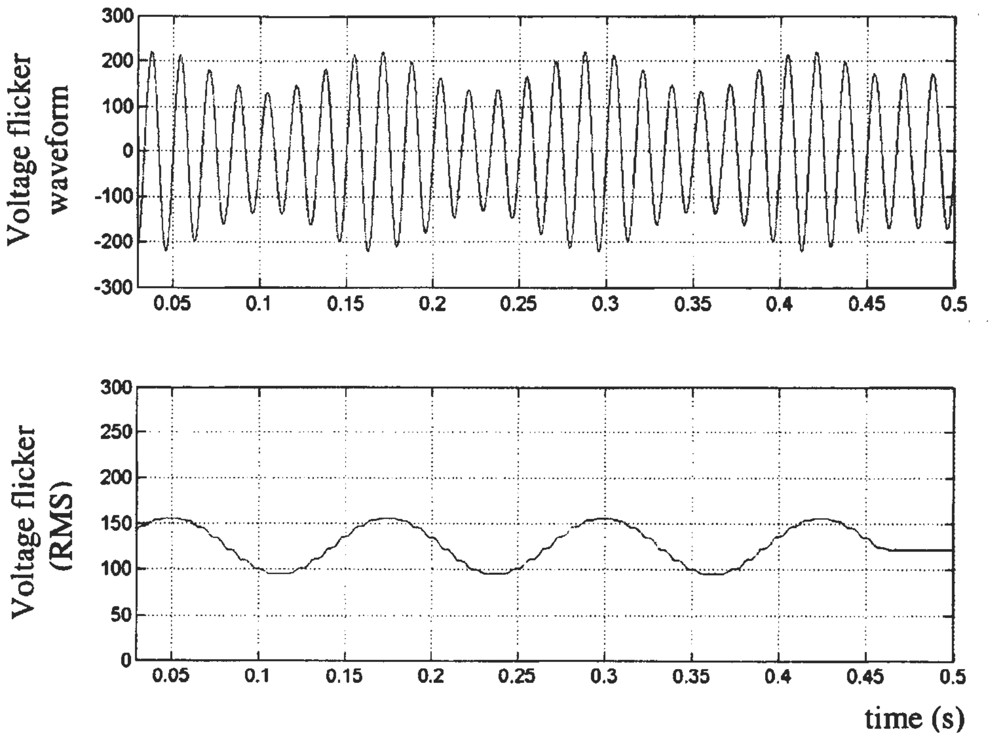

Fig 1.3: Voltage flicker

Voltage flicker, another power quality problem results from the low frequency amplitude modulation of the system voltage. The modulation is usually less than 25Hz. Flicker is caused by large rapidly fluctuating loads such as arc furnaces and electric welding equipment especially during the phase when the arc is being struck. Figure 1.3 illustrates a voltage flicker.

The effect of such disturbances on the terminals of the load is influenced by the distance to the origin of the disturbance, the level of interconnection and the impedance of the transmission links. Terminal load voltages are also affected by switching operations such as connection and disconnection of large loads, power factor correction devices and the operation of static var compensators. In order to counter the adverse effects of these disturbances on the terminals of the load, engineers and researchers have come up with various ingenious ways to mitigate the power quality problem. In the next section, various solutions that have been proposed in the literature will be reviewed. All the methods aim to achieve constant sinusoidal voltage and currents devoid of harmonics, constant frequency, symmetrical three-phase AC power and reliability in the supply, independent of load variations

1.1 Literature Review

In order to mitigate the power quality problem, various power-conditioning devices have been employed to reduce the effects of load current harmonics, voltage sags and distortion. Most harmonic sources have been represented as current sources [1], hence parallel or shunt passive filters have been traditionally used to mitigate nonlinear load harmonics.

In recent times, active filters have attracted a great deal of attention and have been researched intensively for the past 25-30 years [2,3]. They are used to compensate for harmonics and reactive power as well as for balancing unbalanced loads [4,5] and as dynamic voltage restorers [3]. Active filters are used alone or in combination with other devices depending on requirements and control methods. This thesis deals with the application of active filters in hybrid topologies.

Devices used for power quality compensation can be classified as passive, active and hybrid compensators. An overview of each of the compensator type is given below.

1.2 Passive Compensators

Passive compensators or filters are combinations of inductors and capacitors connected in series or parallel to present high or low impedance to the current or voltage harmonics. They are used as shunt passive filters or series passive filters.

1.2.1 Shunt passive filters

Shunt passive filters are series resonant circuits connected in parallel to harmonic current producing nonlinear loads. Due to their low cost and simplicity, they have traditionally been used to absorb the harmonics generated by large loads [6]. At the tuned frequencies, a shunt passive filter has lower impedance than the impedance of the supply. In principle, the filtering characteristics of the shunt passive filter are determined by the impedance ratio of the source and passive filter [6].

Figure 1.4 shows a single-phase model of a harmonic producing load and passive filter. The shunt passive filter has the following shortcomings:

- The source impedance influences the performance of the shunt passive filter and since the source impedance may not be easily determined, the performance of the shunt passive filter becomes difficult to predict.
- The filter may create a series or parallel resonance with the source impedance resulting in the amplification of the harmonics with negative consequences.
- In practice, due to possible resonance, the shunt passive filters are usually off-tuned with respect to the dominant frequencies which defeats their very purpose of installation [7]

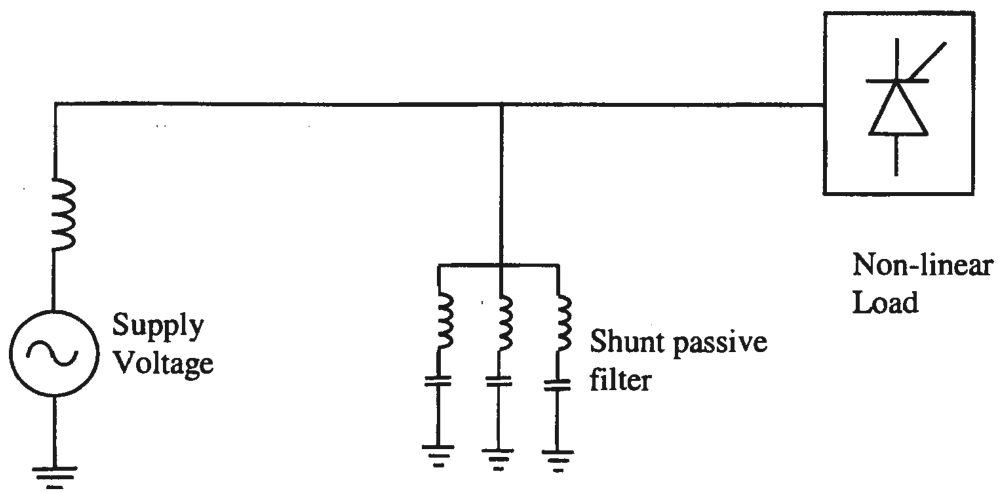

Fig 1.4: Harmonic compensation using the Shunt Passive Filter

1.2.2 Series passive filters

Series passive filters are parallel resonant circuits connected in series with the harmonic causing nonlinear loads. They are low-cost, simple to implement and have been used to limit harmonics caused by large loads [9]. The main drawback in the use of the series passive filters is the voltage drop that occurs at fundamental frequency due to the difficulty in designing sharply tuned filters.

Series passive filters are not as widely used for harmonic compensation as the shunt passive filters. However, it has been proposed that when the load is modeled as a harmonic voltage source instead of a harmonic current source, the series passive filters gives better performance [1,8,9]. Figure 1.5 shows a model of a series passive filter for compensating harmonic voltage-source type nonlinear load.

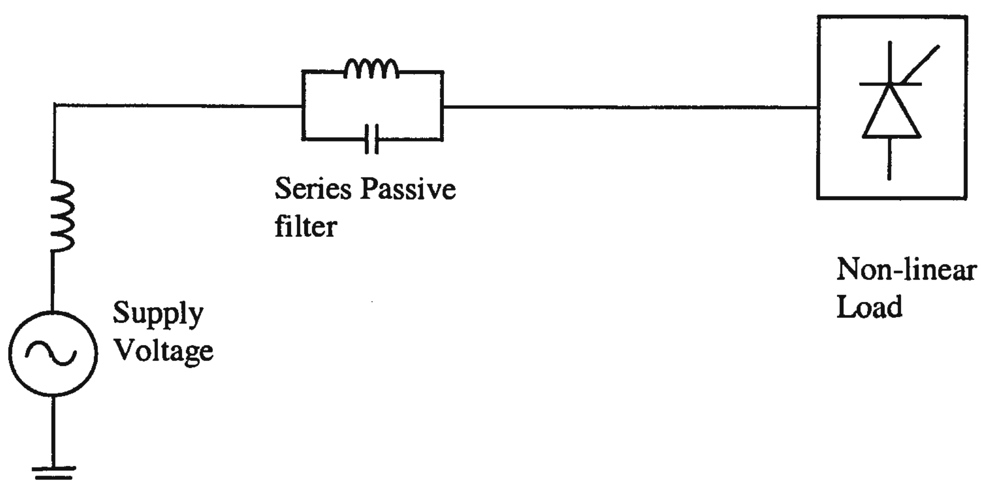

Fig 1.5: Harmonic compensation using the Series Passive Filter

1.3 Active Compensation Devices

To overcome the limitation of passive filters, active filters were developed to provide better harmonic and voltage distortion control. Active filters may also be used for power factor control in static var compensators. Active compensators also known as active filters or active power line conditioners are single-phase or three-phase voltage source inverters used to generate the compensating voltage or current that is injected into the line. They may be connected in series with the line (series active filters) or in parallel with the load (shunt active filters).

1.3.1 Series active filters

The series compensator is used to eliminate voltage harmonics, compensate for voltage dips and swells in dynamic voltage restoration and to generally regulate line voltages [10]. It is also used to damp out harmonic propagation caused by resonance with line impedance and shunt passive filters [11]. Figure 1.6 is a block diagram of the series active compensator and controller. The series active filter does not directly compensate for current harmonics but is can be controlled to act as high impedance to the current harmonics [6]. A drawback to the series active compensator is its inability to directly compensate for current harmonics, suppress neutral currents and balance the load current.

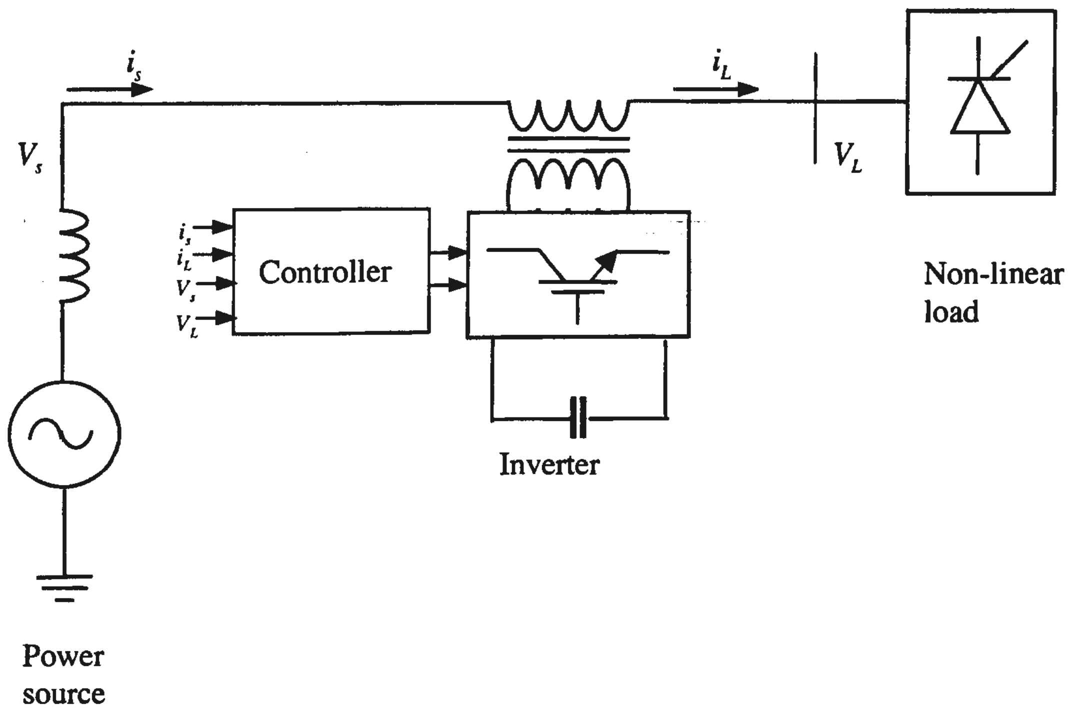

Fig 1.6: General system configuration of the series active filter

1.3.2 Shunt active filter

The shunt active filter is primarily used to compensate for current harmonics, it operates by actively generating the harmonic currents equal to those in the load by means of a switch mode power electronic inverter. The load current harmonics are measured and extracted by the control circuits and then used to regulate the inverter of the active filter. The performance of the active filter is hence independent of the utility system impedance. Figure 1.7 shows the schematic of a shunt active filter. The shunt filter can also be used as a static var generator in power system network for stabilizing and improving the voltage profile and for correcting for power factor [12, 13].

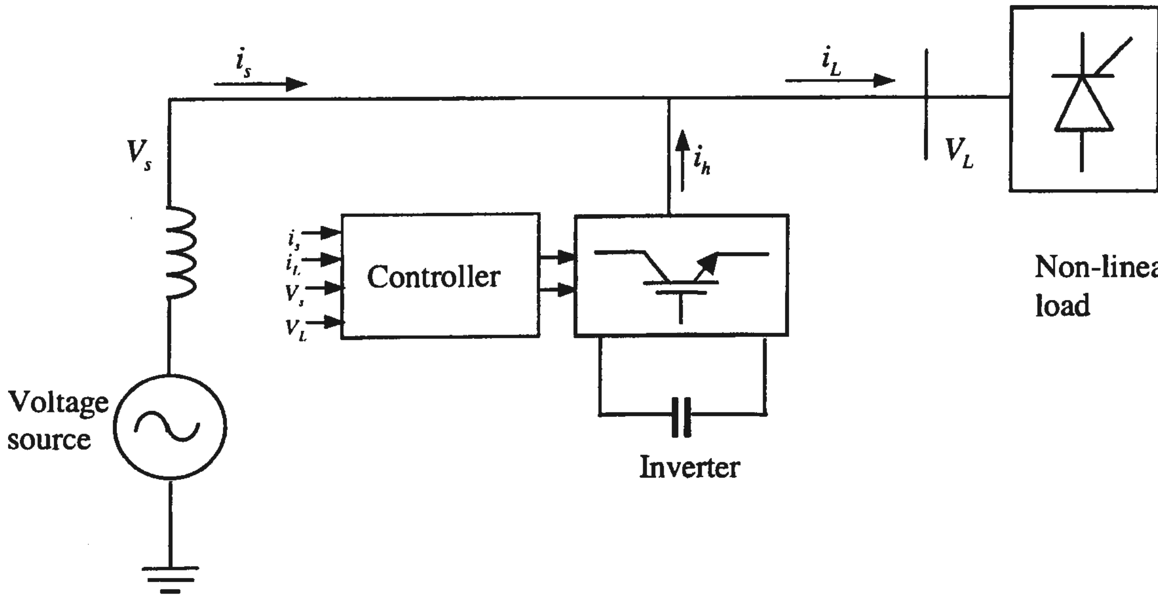

Fig 1.7: General system configuration of the shunt active filter

The shunt active filter has the following drawbacks.

- The VA rating of the power electronic inverter can be quite high since the device is connected in parallel to the load. This is due to the fact that the converter must withstand the line frequency utility voltage and supply harmonic current.
- The inverter output low-pass filter provides attenuation of the inverter switching harmonics. They are also highly susceptible to utility line interaction and may require additional active or passive damping.
- It does not compensate for the harmonic in the load voltage.

1.3.3 Combined series and shunt active filters

This combination also known as the unified power quality conditioner (UPQC) [14, 15] or universal active power line conditioner [16] consists of the series and shunt active filter. Figure 1.8 is the schematic of the UPQC. The UPQC can provide fast and simultaneous control of the system terminal voltage and active and reactive power flow. The system is considered as an ideal active filtering system, which eliminates voltage and current harmonics and is capable of providing compensation to sensitive loads such as computers and medical equipment.

The series filter is controlled as a voltage source; hence it is used for voltage compensation while the shunt filter compensates for harmonic currents. Hence it has the advantages of both the series and shunt filter. The series filter may be used to

- Provide harmonic isolation i.e. suppress harmonic current through the line.
- Control active and reactive power flow by controlling the phase and magnitude of the injected voltage with respect to the line current.
- Eliminate voltage harmonics including negative and zero sequence components at the fundamental frequency.
- Compensate for the reactive power demand of the load.
- Cancel out line current harmonics.

The major limitation of the UPQC is its high cost and control complexity.

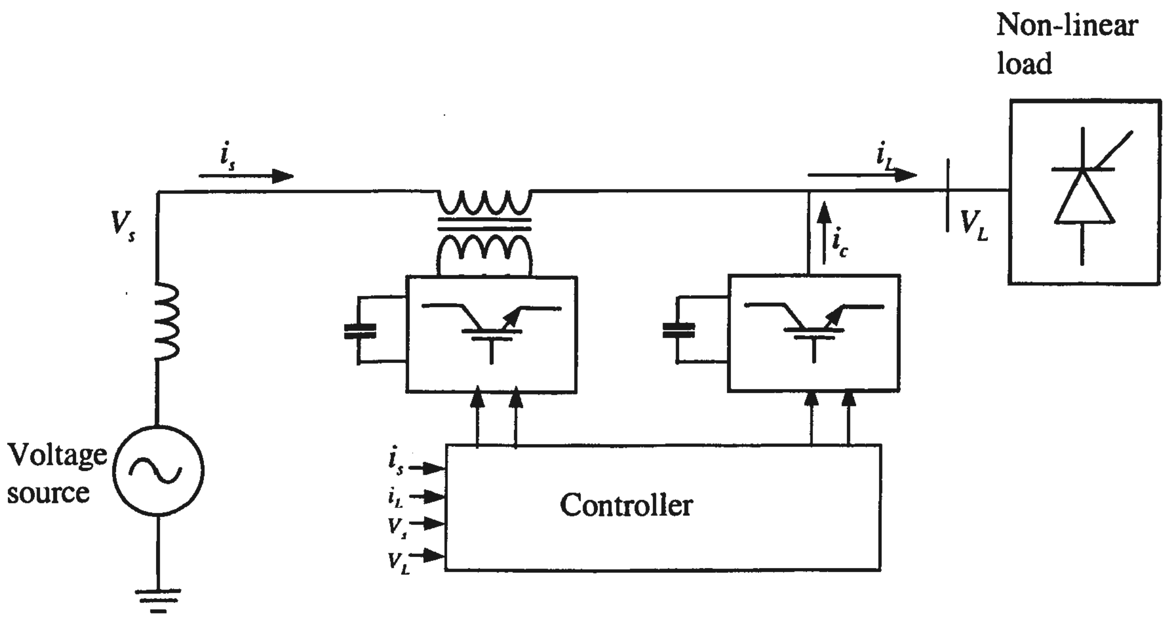

Fig 1.8: The unified Power Quality Conditioner (UPQC) [14]

1.4 Hybrid Filters

Hybrid filters combine the advantages of passive and active filters. They are cost effective solutions to controlling voltage variations and distortions as well as suppressing harmonics. Several combinations of passive and active filters exist in the literature. Peng [1] has presented 14 hybrid filter topologies for use in solving the power quality problem. A few of the more commonly used hybrid compensation topologies are discussed below.

1.4.1 Hybrid shunt filters

This consists of a series combination of an active and passive filter in parallel with the load. This is an attempt to reduce the high VA rating of the shunt active filter without compromising its functions [1, 17], enabling practical implementation of active harmonic current filters.

Figure 1.9 shows the schematic of a shunt hybrid filter. The VA rating is reduced by the fact that the system is designed such that the fundamental voltage is dropped across the passive filter. In practice, a small fundamental voltage appears across the active filter as a result of the finite leakage impedance of the matching transformer. Due to its high rating at fundamental frequency, the var compensating ability of the hybrid filter is diminished. However if var compensation is not an issue as in harmonic compensation, it is an effective device for the dominant harmonic currents. Its major drawback is that the passive filter may attenuate other frequencies generated by the active filters hence reducing the range of harmonics that can be covered.

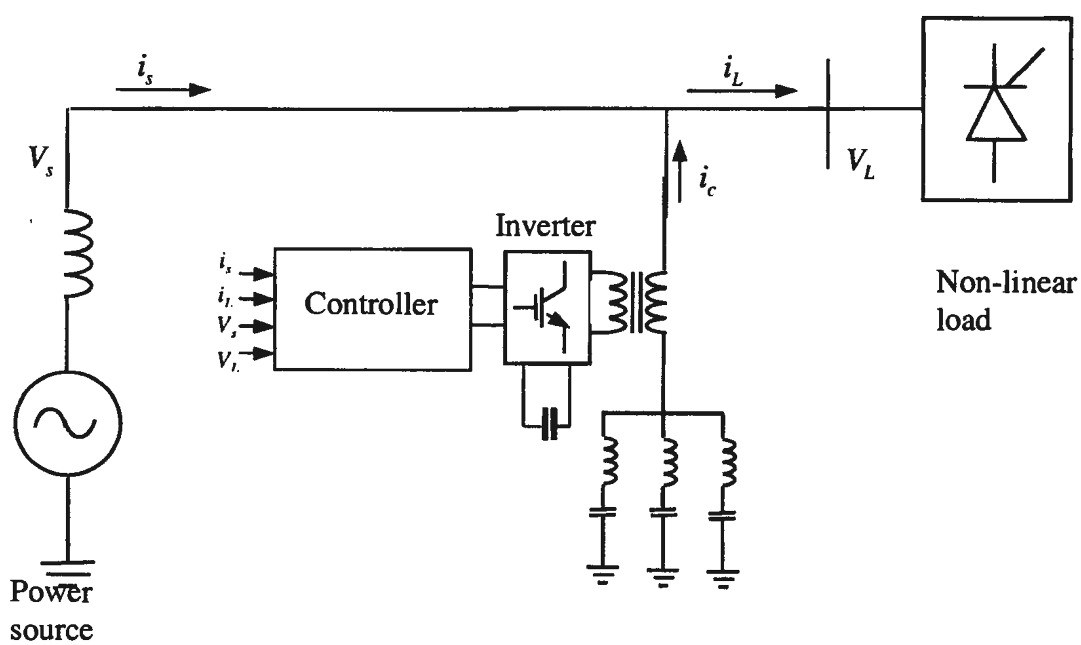

Fig 1.9: The hybrid shunt filter

1.4.2 Hybrid series filters

The series hybrid compensator is a series combination of a series passive filter and a series active filter [1,18]. Figure 1.10 shows the schematic of the series hybrid filter. The series filter operates by injecting a compensating voltage in the line in opposite phase to cancel out any voltage distortion. Depending on the control method adopted, the series filter can be used for

- Harmonic isolation: in this mode, the source currents are extracted and used as a reference for the PWM inverter used in the active compensator. The output voltage from the compensator is injected into the line in phase with the line current harmonics resulting in simulated line impedance in series with the source [14,15]. This active impedance does not significantly affect the fundamental, but serves to constrain the load harmonics into the passive filter. This results in improved performance of the passive filter since the need for precise tuning is reduced. The active filter also provides damping to any resonant current oscillations, which may occur between the passive filter and the supply voltage internal impedance.
- Voltage compensation: if line voltage conditioning is required the series active filter can be used to eliminate voltage sags, swells, flicker, commutation notches, voltage harmonics and other voltage disturbances.

The actual use of the series compensator depends on the objective, the harmonic or distortion extraction method and the inverter control scheme adopted.

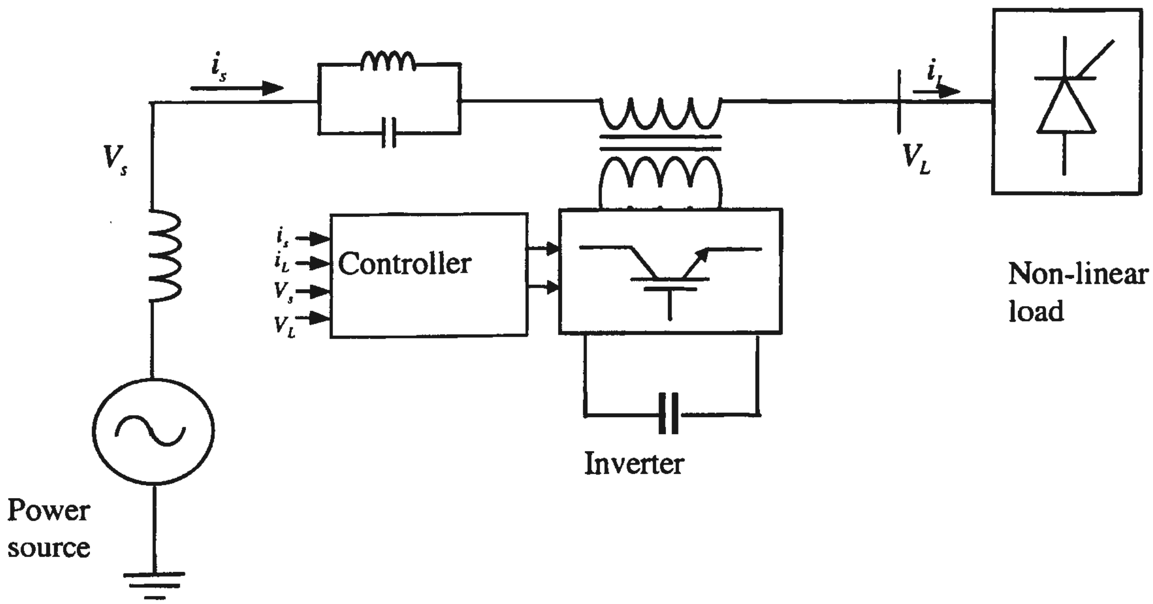

Fig 1.10: The hybrid series filter

1.5 Harmonic Extraction Methods

Several methods exist in the literature for the extraction of the harmonics and distortion in the source and load currents and voltages. A review of some of the methods is provided below.

1.5.1 Fourier transform based extraction methods

This extraction method is based on the Fourier transform based analysis of the load or source currents and voltage. Using the method, the distorted voltage or current signals is separated into its fundamental and harmonic components. The harmonic components are then used as the reference for the active filter inverter to generate the compensating voltages or currents [21, 22]. However the drawback of this method is that the online application of the Fourier transform is cumbersome and results in an unacceptable delay, necessitating the inclusion of predictive algorithms in the control scheme for loads with deterministic harmonics. It is difficult to use for loads that are unpredictable. Figure 1.11 shows a block diagram of the method.

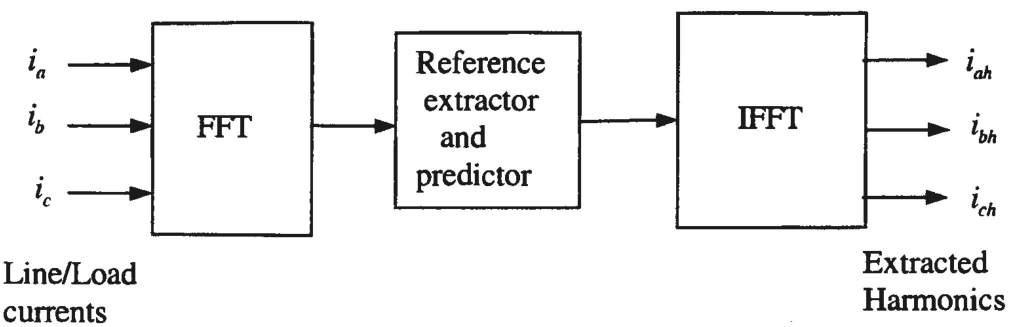

Fig 1.11: Fourier transform based extraction

1.5.2 Instantaneous reactive power theory

Proposed in 1984 by Akagi, et al [19], the IRP theory also known as the **p-q** theory is based on instantaneous voltages and currents in three-phase systems, with or without a neutral wire. The harmonic components can be estimated by determining the contributions of the harmonics to **p** and **q**, where **p** and **q** are the active and reactive power flowing in the line. The estimation is done by computing the instantaneous active and reactive powers and then extracting the harmonic active and reactive powers by the use of a high-pass filter. The major drawback for this scheme is that it considers only balanced conditions without zero sequence components. In the presence of unbalance and zero sequence components, the effectiveness of the scheme is reduced. Figure 1.12 is a block diagram of the method.

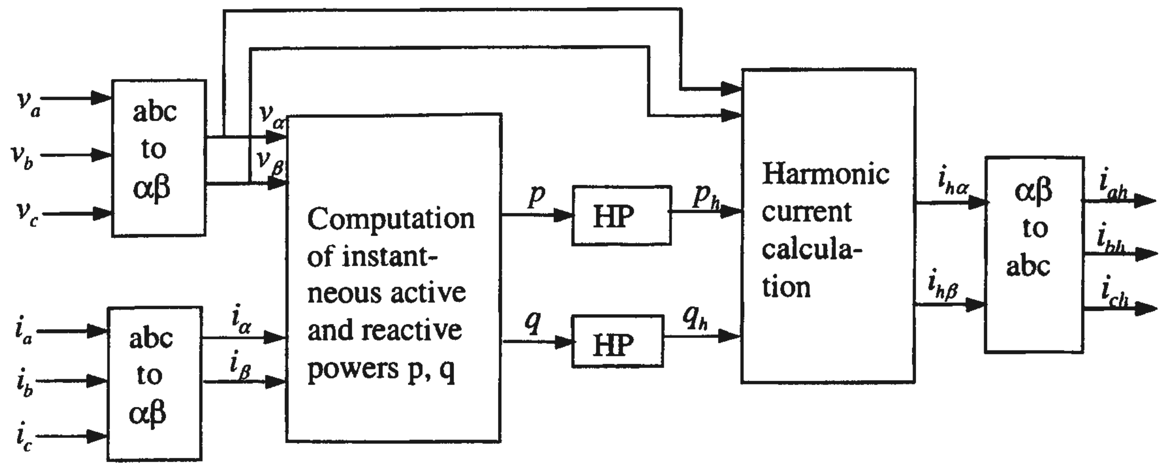

Fig 1.12: Harmonic current extraction based on the IRP theory.

1.5.3 Synchronous reference frame based extraction scheme

In this scheme, the voltage and current signals are transformed by the use of Park's transformation into the rotating reference frame, where the fundamental quantities become dc and all other frequencies are translated downwards in the frequency axis [7]. The dc value in the rotating reference frame is then removed by passing the signal through a high-pass filter. The filtered signal is then transformed to the stationary abc reference frame by applying the inverse Park's transformation. Its drawbacks include the computation involved, its inherent requirement of a three-phase signal, which makes it unsuitable for use in single-phase systems and its non-compensation for reactive power. Besides, the effectiveness of the extraction scheme is severely reduced in the presence of voltage unbalance, making it difficult to achieve independent voltage compensation and voltage balancing. Figure 1.13 is a block diagram of the extraction procedure. A method of overcoming the voltage unbalance limitation was developed by Karthik [27]. The proposed method involves balancing the phases independently by the use of phase shifters before applying the transformation.

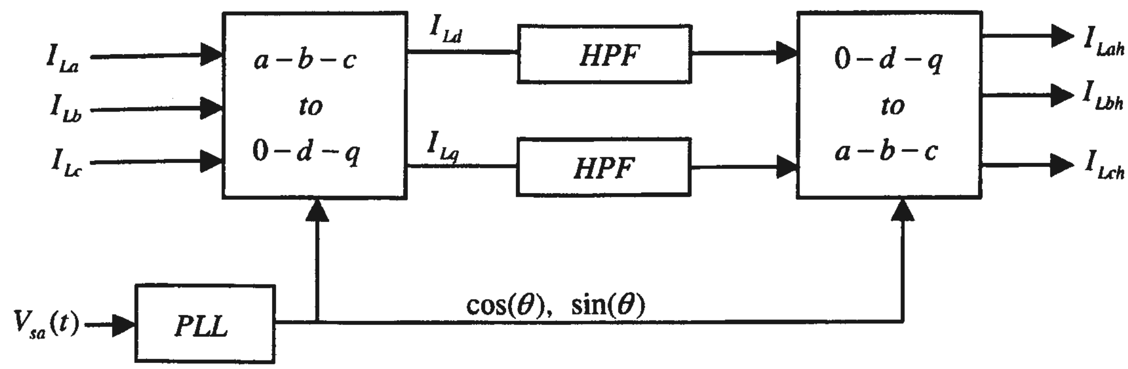

Fig 1.13: Synchronous reference frame extraction method.

1.6 Objectives of the Thesis

Hybrid filters in general are a compromise between the simplicity and robustness of passive filters and the performance and cost of active filters. Different hybrid filtering topologies exist and have been studied. To the best of the author's knowledge, no thorough investigations of the different topologies have been carried out with the aim of determining which topologies are best suited for certain load and source conditions. Also, in previous works, the load has always been modeled as harmonic current sources. However, not all loads can be modeled as such. Furthermore, the same extraction scheme is used in the existing compensators to extract both harmonic current and voltage. This approach leads to a large and complex extraction and control circuitry. The aim of this thesis is to present an extraction and control scheme that decouples the current and voltage compensation process. The proposed control scheme is applied to four different hybrid-filtering topologies with the objective of

- Investigating the performance of the four hybrid compensation topologies under various conditions of the source and load to determine the most appropriate compensation method.
- Investigations of the performance of the compensation topologies when the load is hybrid consisting of loads that are modeled as harmonic current sources and loads that are modeled as harmonic voltage sources.
- Determining rating of each of the compensation system.

1.7 Organization of the Thesis

Chapter one introduces the power quality problem. Current power quality issues are discussed and the problems stated. The voltage sag, swell, flicker and harmonics are defined and their causes and effects explained. Various methods in use in mitigating the power quality problems are identified and presented in a review of existing literature; various control schemes and topologies are identified and described highlighting their advantages and disadvantages. The objectives of the thesis are presented in this chapter.

Chapter 2 introduces the active filter control scheme used in this thesis. The control scheme is described and its advantages for active filter application are discussed. The performance of the scheme in the generation of a replica of the sinusoidal and non-sinusoidal distortion reference voltage is demonstrated. Its limitation is also discussed. The harmonic current extraction scheme is also discussed and its use in the extraction of current harmonics is presented.

In chapter 3, two of the hybrid compensation systems investigated in this thesis are presented. A detailed description, analysis and modeling is carried out to determine the compensation characteristics of the systems. Simulation results are presented to validate their functionality.

Chapter 4 presents the other two hybrid compensation systems. Their description, modeling and analysis are carried out. Also, their performance in the compensation of harmonic currents and voltage distortion and their limitations is demonstrated by simulation. The results are presented in this chapter.

In chapter 5, the ratings of the hybrid filters that make up the four hybrid compensation systems are determined analytically. A quantitative comparison of the four hybrid compensation systems is carried out based on several identified factors.

Finally, chapter 6 summarizes the thesis highlighting the contribution of the research and provides suggestions for further work.

Chapter 2

Active Filter Control

Voltage source inverters play a very important role in the implementation of active filtering schemes. They are used in active filtering schemes to provide compensating voltage in the line to condition the line to desirable voltage and current quality levels. The quality and performance of the active power filter depends on three considerations [13].

- The design of the power inverter
- The modulation and control method used to implement the compensation scheme
- The method used to determine the level of compensation.

Active filters are used in the series and shunt configuration i.e. the series active filter and the shunt active filter. In this chapter, the performance of the series active filter and the shunt active filters based on their ability to generate identical replica of the distortion voltage reference and extracted harmonic currents are investigated.

The generation of the harmonic currents and the distortion voltage is dependent on various conditions

- The effectiveness of the method of extracting the harmonic current and the distortion voltage to be used as a reference for the voltage source inverter
- The performance of the inverter in generating the reference waveform considering that the reference waveform may be highly non-sinusoidal as a result of the presence of various signals of different magnitudes, phases and frequencies.

2.1 Series Compensation

In series active compensation schemes, the inverter in the series active filter (also referred to as the series active compensator or conditioner) is coupled to a line in series with the load through a matching transformer. The inverter is then used to generate and inject the necessary voltage needed for compensation of voltage harmonics, voltage sags and swell, voltage flicker and other voltage disturbances that distort the desired sinusoidal waveform at the point of common coupling.

In order to ensure that the compensation is effective, it is important that the generated voltage be a replica of the measured distortion voltage as much as possible. The response of the inverter should also be fast so that it is able to respond to rapidly changing distortion levels. The inverter control method used in the series active filter scheme determines the inverter performance in terms of stable operation, good dynamic response and minimal deviation of the generated output voltage from the reference distortion voltage.

Several inverter control schemes exist in the literature such as hysterisis control [23], dead-beat control [24], sliding mode control [25] and multiple loop control [26]. In this work, the suitability of the multiple loop control method proposed by Abdel-Rahim and Quaicoe will be examined for series active filter application. The latter scheme has been shown to have good dynamic response, good stability and good performance with generating sinusoidal references for UPS application.

2.2 Operation of the Single-Phase Inverter

Figure 2.1 shows the scheme proposed by Abdel-Rahim and Quaicoe [26]. It consists of a voltage source single-phase half-bridge inverter, a second order filter R_f, L_f and C_f, an inner current feedback loop and an outer voltage feedback loop. Proportional controllers are used in the feed-forward path of the inner current loop to increase the loop bandwidth. The reference voltage V_{dis} is the voltage distortion i.e. the deviation of the actual voltage from the desired one. The series active filter operates to generate the distortion voltage and then to inject the generated voltage in opposite phase so as to cancel the distortion in the actual voltage. The generated voltage is fed back and compared with its reference and the resulting error signal is passed through a proportional controller k_v, the output of the controller is then summed with the error signal obtained from comparing the capacitor current with its reference. The resulting signal is passed through a proportional current controller k_c in the current control loop and the output of the current controller is compared with a fixed switching frequency triangular waveform in a standard sinusoidal pulse width modulation (PWM). The pulse width modulated signals are then used to control the inverter switches after they have been appropriately processed by the gate-drive circuits.

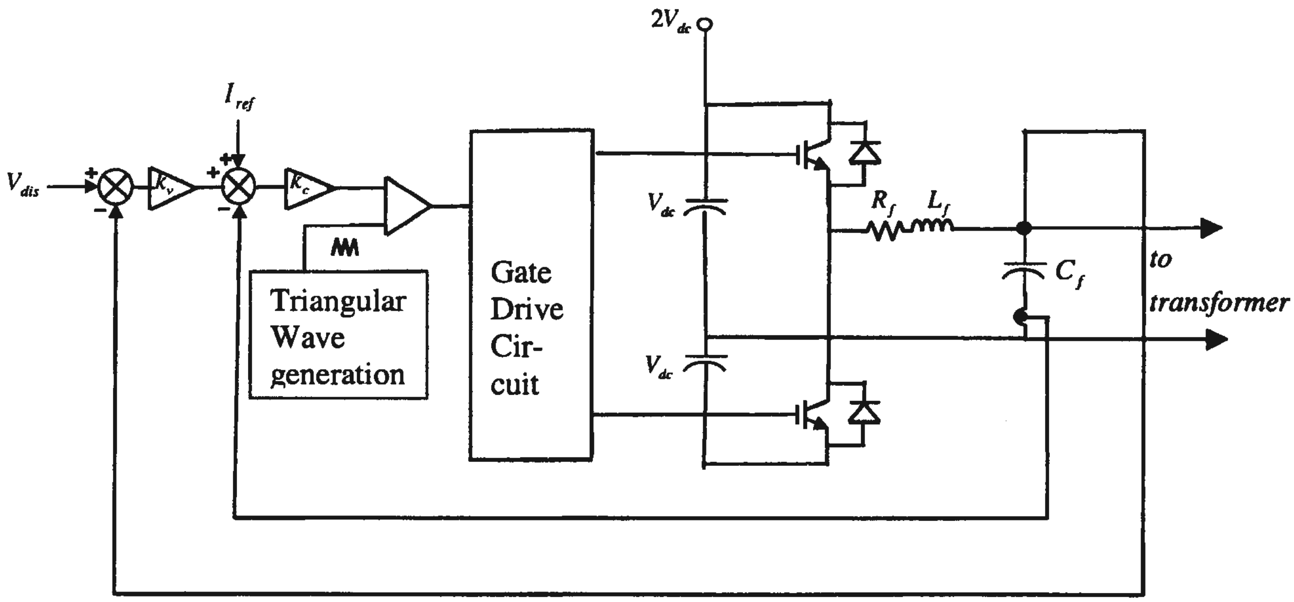

Fig 2.1: Control strategy of the active filter in harmonic and distortion compensation. [26]

The inverter control system adopted for this work offers many advantages for active filter operation. The current control loop provides an inherent peak current limit in the capacitor of the output filter which serves to limit the high current surges at the capacitor output especially during system start up. Also, since the capacitor current represents the rate of change of inverter output voltage, the control scheme is capable of predicting and correcting near future variation in the output voltage, thus providing fast dynamic response of the overall system. The voltage control loop regulates the output voltage and ensures that the inverter output closely follows its reference.

2.3 Characteristics of the LC filter

Figure 2.2 shows the circuit model of the single-phase inverter with a second order filter connected to the power system through a coupling transformer.

In the figure

V_{in} represents the pulse width modulated output voltage obtained from the inverter switches.

R_f is the resistance of the filter inductor

L_f is the filter inductance

C_f is the filter capacitance

R_t is the equivalent resistance of the coupling transformer and lines

L_t is the equivalent inductance of the coupling transformer and lines

$V_s \sin(wt + \phi)$ is the equivalent instantaneous voltage of the power system at the point of coupling.

The transfer characteristics can be expressed as

$$\frac{V_c}{V_{in}} = \frac{(R_t + jX_{Lt})//(-jX_{Cf})}{(R_t + jX_{Lt})//(-jX_{Cf}) + R_f + jX_{Lf}} \tag{2.1}$$

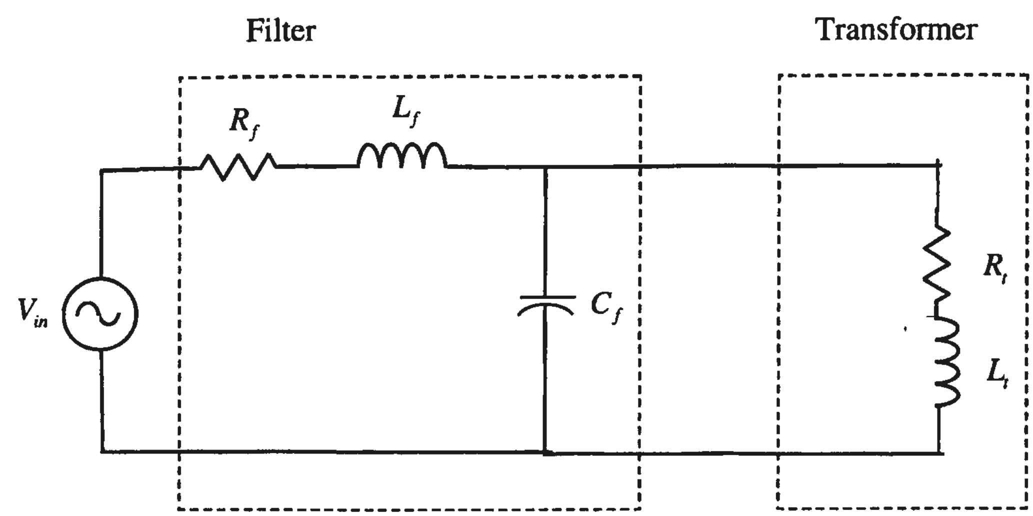

Fig 2.2: Inverter lowpass filter and transformer.

$$\frac{V_c}{V_{in}} = \frac{R_t + jX_{Lt}}{R_t\left(1-\frac{X_{Lf}}{X_{Cf}}\right) + R_f\left(1-\frac{X_{Lf}}{X_{Cf}}\right) + j\left[X_{Lf} + \frac{R_f R_t}{X_{cf}} + X_{Lt}\left(1-\frac{X_{Lf}}{X_{Cf}}\right)\right]} \tag{2.2}$$

The reactance of the inductor and capacitor are functions of the harmonic order n.

Equation 2.2 can then be written as

$$\frac{V_c}{V_{in}} = \frac{R_t + jnX_{Lt}}{R_t\left(1-\frac{n^2X_{Lf}}{X_{Cf}}\right) + R_f\left(1-\frac{n^2X_{Lf}}{X_{Cf}}\right) + jn\left[X_{Lf} + \frac{R_f R_t}{X_{cf}} + X_{Lt}\left(1-\frac{n^2X_{Lf}}{X_{Cf}}\right)\right]} \tag{2.3}$$

Assuming that the resistance of the filter inductor and that of the coupling transformer and lines are negligibly small, (2.3) then reduces to

$$\frac{V_c}{V_{in}} = \frac{X_{Lt}}{\left[X_{Lf} + X_{Lt}\left(1 - \frac{n^2 X_{Lf}}{X_{Cf}}\right)\right]} \tag{2.4}$$

$$\frac{V_c}{V_{in}} = \frac{X_{Lt}}{\left[X_{Lf} + X_{Lt}\left(1 - \frac{n^2 w^2}{w_0^2}\right)\right]} \tag{2.5}$$

where $$\frac{X_{Lf}}{X_{Cf}} = \left(\frac{w}{w_0}\right)^2 \tag{2.6}$$

and $$w_0 = \frac{1}{\sqrt{L_f C_f}} \tag{2.7}$$

The inverter is to be used to generate the distortion voltage which may have sinusoids of various magnitudes, frequencies and phases, including the fundamental in the events of voltage sags, swell and flicker compensation. Hence the selection of the inverter lowpass filter is based on the following criteria:

- The degree of correlation between the reference voltage distortion and the generated output distortion.
- The rating of the filter inductor and capacitor

The size of the lowpass filter is important in the design considerations; an LC filter with small size and low ratings is a measure of the efficiency of the active filter system as well as its cost.

2.4 Performance of the Inverter Under Various Conditions

The circuit of Fig 2.1 was implemented in the Simulink toolbox of Matlab under various conditions. The objective was to ensure that the inverter will generate a replica of the reference voltage i.e. the distortion voltage. Proper selection of the inverter output filter is essential in order to achieve this objective. The investigation was carried out under sinusoidal reference voltage as well as distorted reference voltages. The carrier frequency was chosen to be 5 kHz to minimize switching losses in the implementation. Inverter switching harmonics will occur at integer multiples of the switching frequency. The proper selection of the inverter LC lowpass filter will ensures that such high frequency harmonics do not affect the generated voltage.

2.4.1 Performance with sinusoidal reference and selection of lowpass filter

In the case when the reference voltage V_{dis} is sinusoidal as in during a voltage sag or swell, the inverter implemented as an active filter will be required to generate a sinusoidal voltage to correct for the deviation from the set reference. Figures 2.3 and 2.4 show the generated output waveform with a sinusoidal reference.

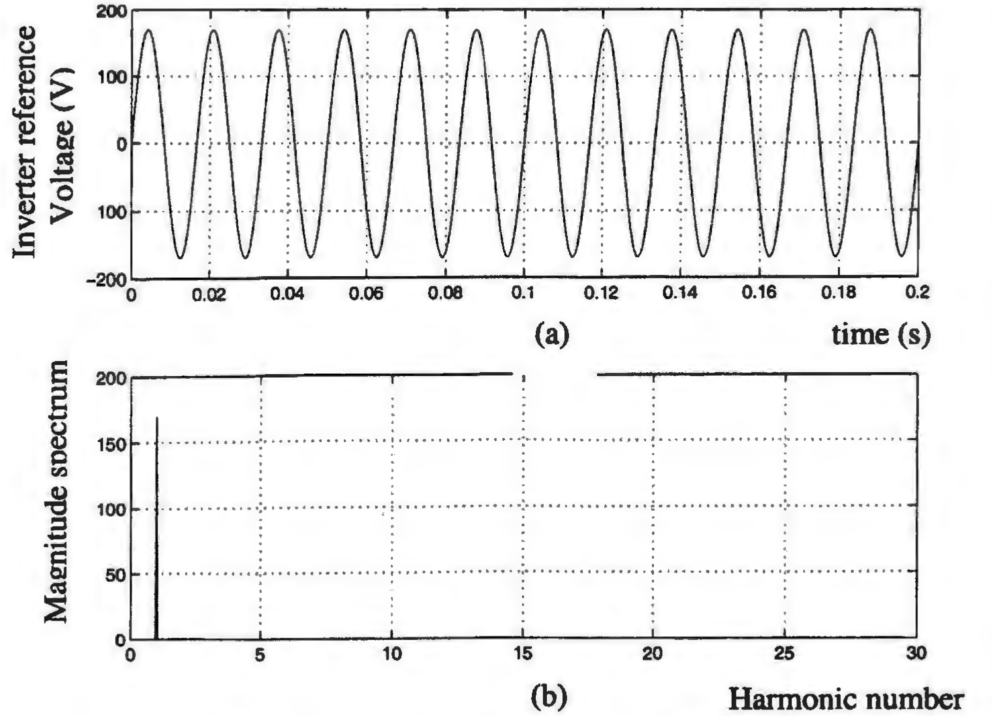

Fig 2.3: (a) The inverter reference voltage, (b) the frequency spectrum

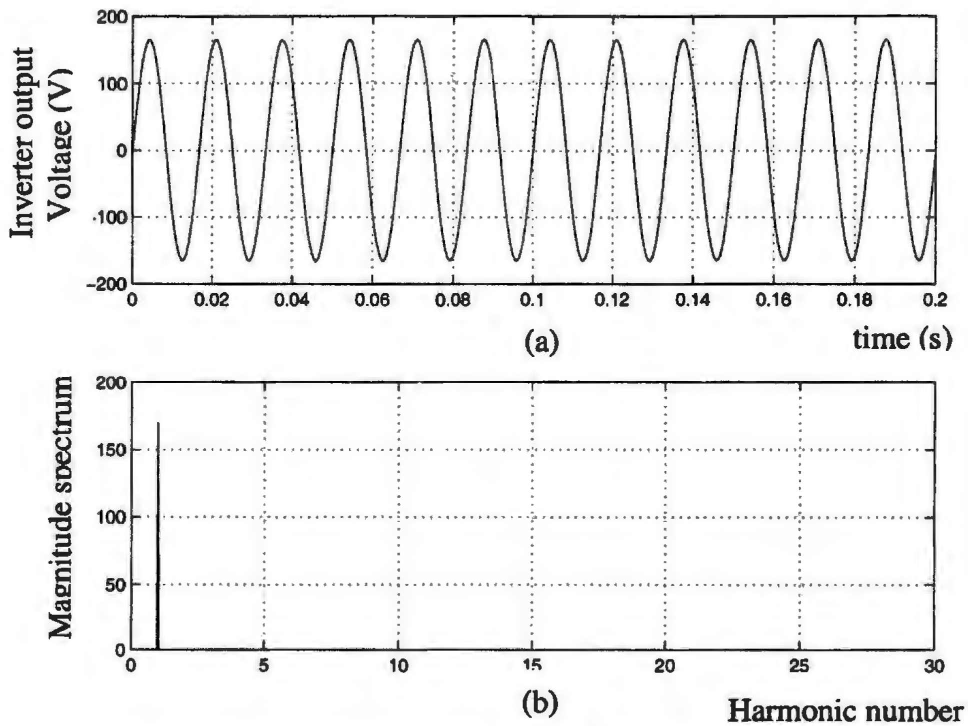

Fig 2.4: (a) The inverter output voltage, (b) the frequency spectrum

Total harmonic distortion consideration is used in selecting the lowpass filter components for sinusoidal reference input. The selected filter parameters are then used to examine the effects on non-sinusoidal voltage generation.

Figure 2.5 shows the plot of the variation of total harmonic distortion with increasing filter capacitance and a fixed inductance. The figure shows that the total harmonic distortion in the generated output voltage is a function of the lowpass filter values chosen.

For a fixed value of filter capacitor, the total harmonic distortion in the inverter output voltage drops with increasing inductance. Since in practical applications, the cost of the inductor is more critical than that of the capacitor, it is therefore necessary to keep the inductance to a minimum for a desired total harmonic distortion and minimum cost. Figure 2.6 shows the total harmonic distortion as a function of the normalized frequency $\frac{f_r}{f_s}$ for various values of filter inductance, where f_r is the resonance frequency of the LC filter, and f_s is the fixed switching frequency.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{2.8}$$

It is observed from Fig 2.5 that the total harmonic distortion exhibits linear characteristics with increasing normalized frequency until $\frac{f_r}{f_s} = 0.12$, from which point the characteristics become nonlinear.

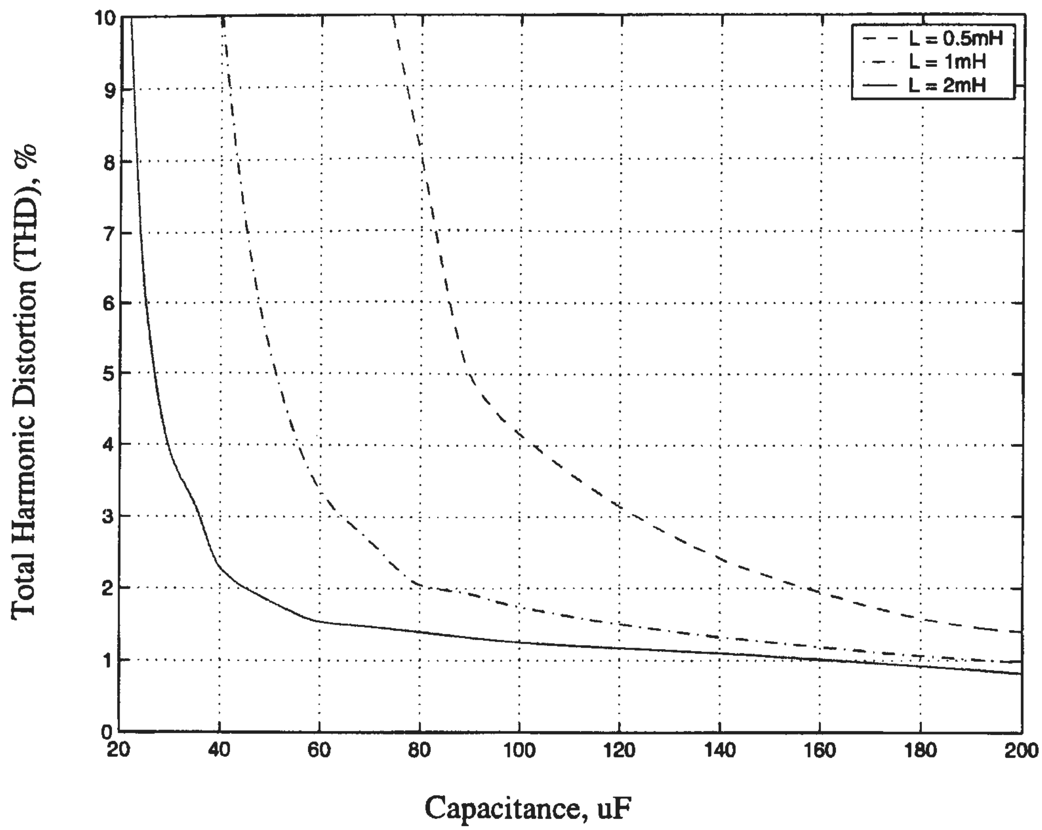

Fig 2.5: Variation of THD with Capacitance

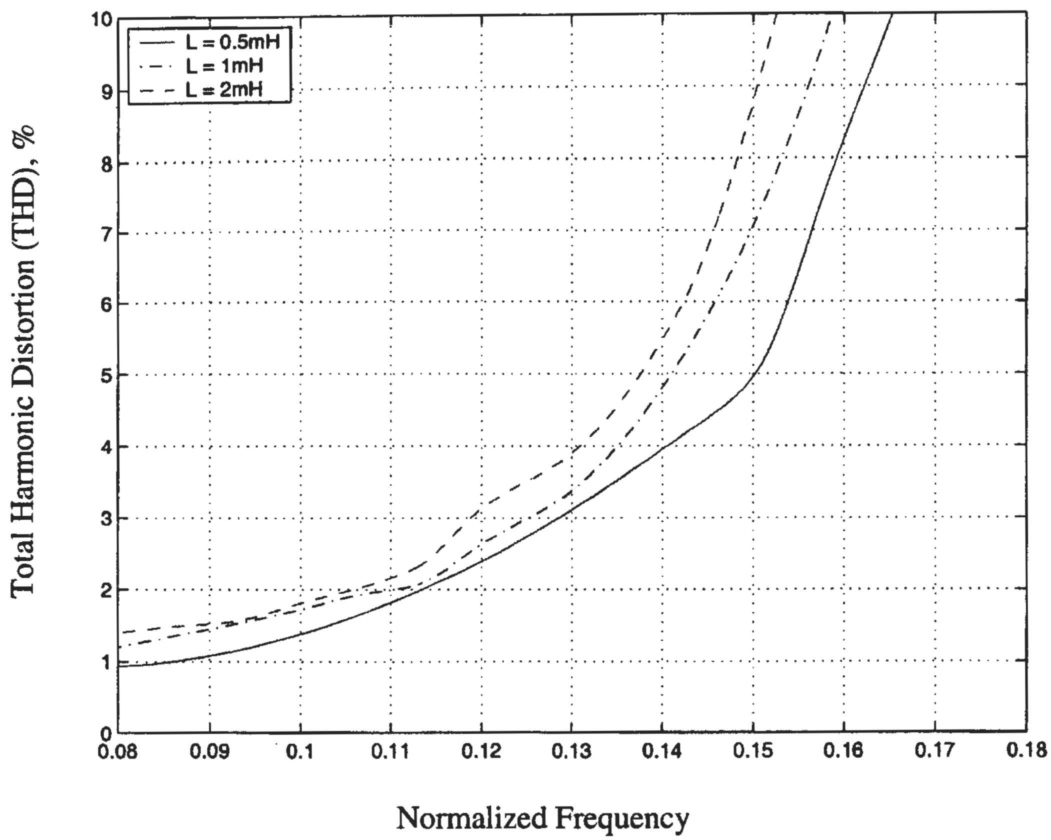

Fig 2.6: Variation of the THD with Normalized Frequency

Therefore for linear and predictable behavior of the inverter, it is necessary to select the filter parameters values such that $\frac{f_r}{f_s} \leq 0.12$. For the remainder of this thesis, the choice of $\frac{f_r}{f_s} = 0.1$ is used. This value is chosen to limit the switching frequency and hence the switching loss in the inverter switches since lower values of the frequency ratio implies higher switching frequency. The choice of $\frac{f_r}{f_s} = 0.1$ ensures that the total harmonic distortion is below 5%. From Fig 2.5 and 2.6, L=1mH and C=80 μF are selected for optimum performance.

2.4.2 Performance with non-sinusoidal (distortion) reference

It has been demonstrated in the previous section that the series active filter of Fig 2.1 can reliably generate sinusoidal references with an acceptable THD. The use of the series active filter in voltage compensation places an additional requirement on its performance since voltage distortions of a non-sinusoidal nature can occur due to nonlinear loads. Figure 2.7 shows the distortion reference voltage and its harmonic spectrum. The harmonic spectrum shows that the distortion voltage consists of a combination of the 5^{th}, 7^{th}, 11^{th}, 13th, 17^{th} 19^{th} and the 23^{rd} harmonics in varying proportions. Fig 2.8 shows the generated output voltage. It is observed from a comparison of figures 2.7 and 2.8 that all the frequency components in the reference are present in the generated output voltage waveform.

For the case when the distortion voltage is a combination of higher frequency harmonics and a fundamental voltage, which can occur in the event of voltage sag or swell and other distortions resulting from the operations of non linear loads, the active filter must then compensate for the deviation of the voltage from the desired value by injecting out of phase, the generated distortion voltage to cancel out the distortion. Figure 2.9 shows a distorted reference voltage, which is a combination of a fundamental component and higher frequency harmonics. The generated output voltage is shown in Fig 2.10. It is observed from Fig 2.10 that the frequency contents present in the reference signal is also contained in the inverter output voltage. This is an essential requirement for active compensation. The error in the generation of the voltages is shown in Fig 2.11, 2.12 and 2.13 where it is shown that the error in the generation of a signal increases with the frequency and is less than 4% up to the 45^{th} harmonic.

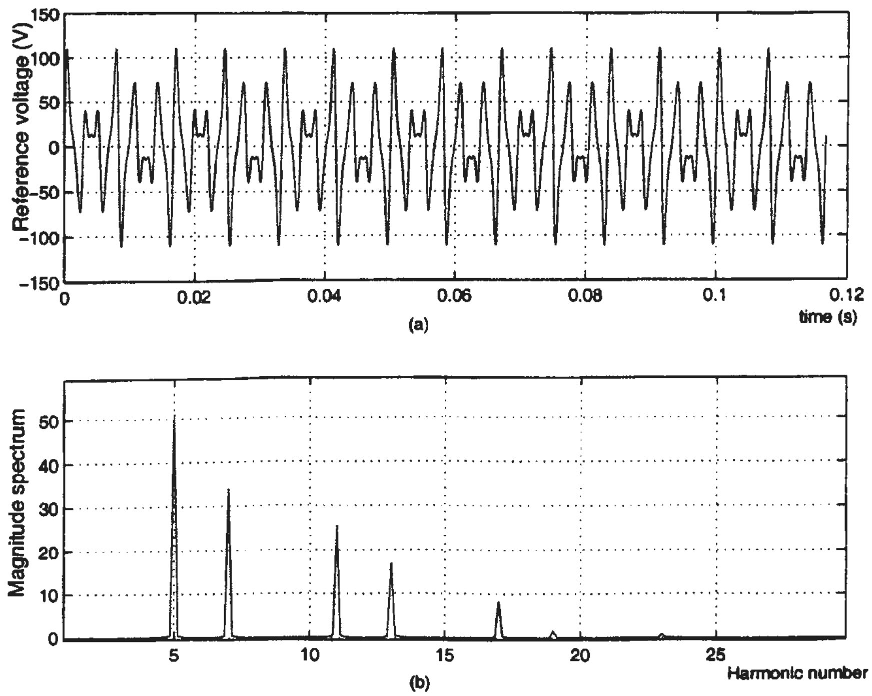

Fig 2.7: Distortion reference and its harmonic spectrum

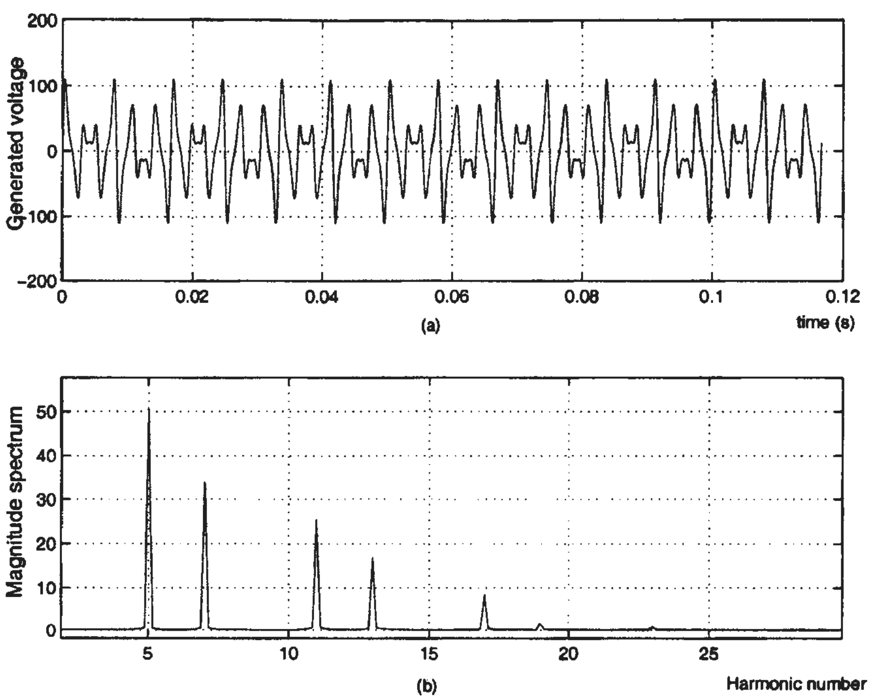

Fig 2.8: The generated distortion voltage at the active filter terminals.

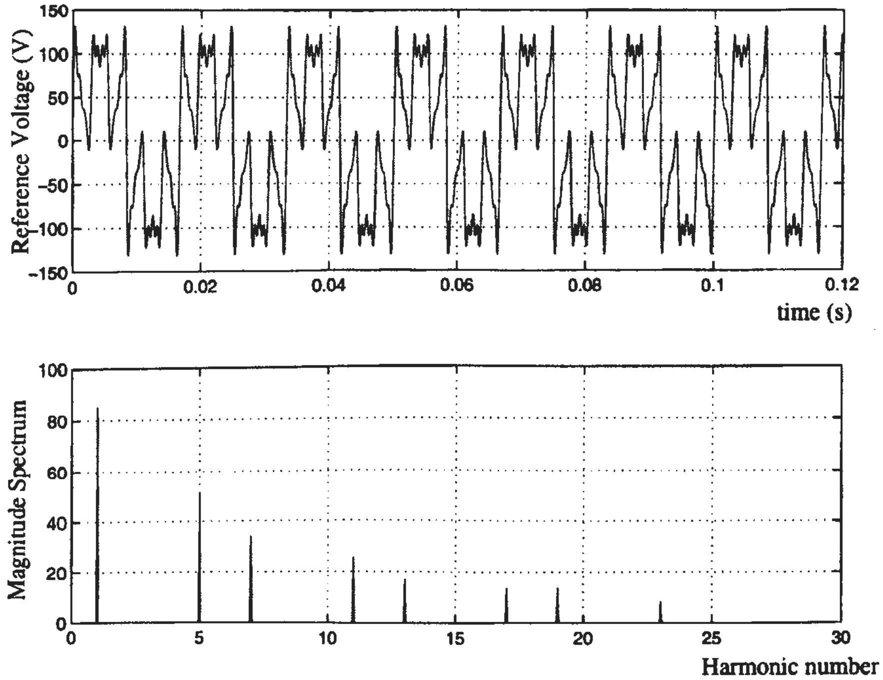

Fig 2.9: Distortion reference voltage with some fundamental components.

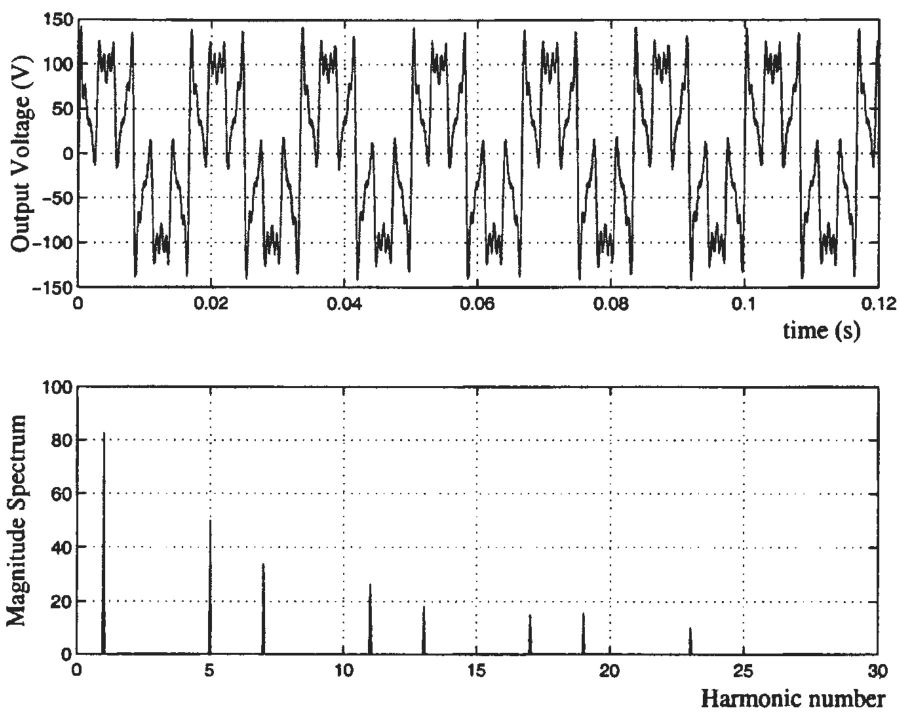

Fig 2.10: Distortion output voltage with some fundamental components.

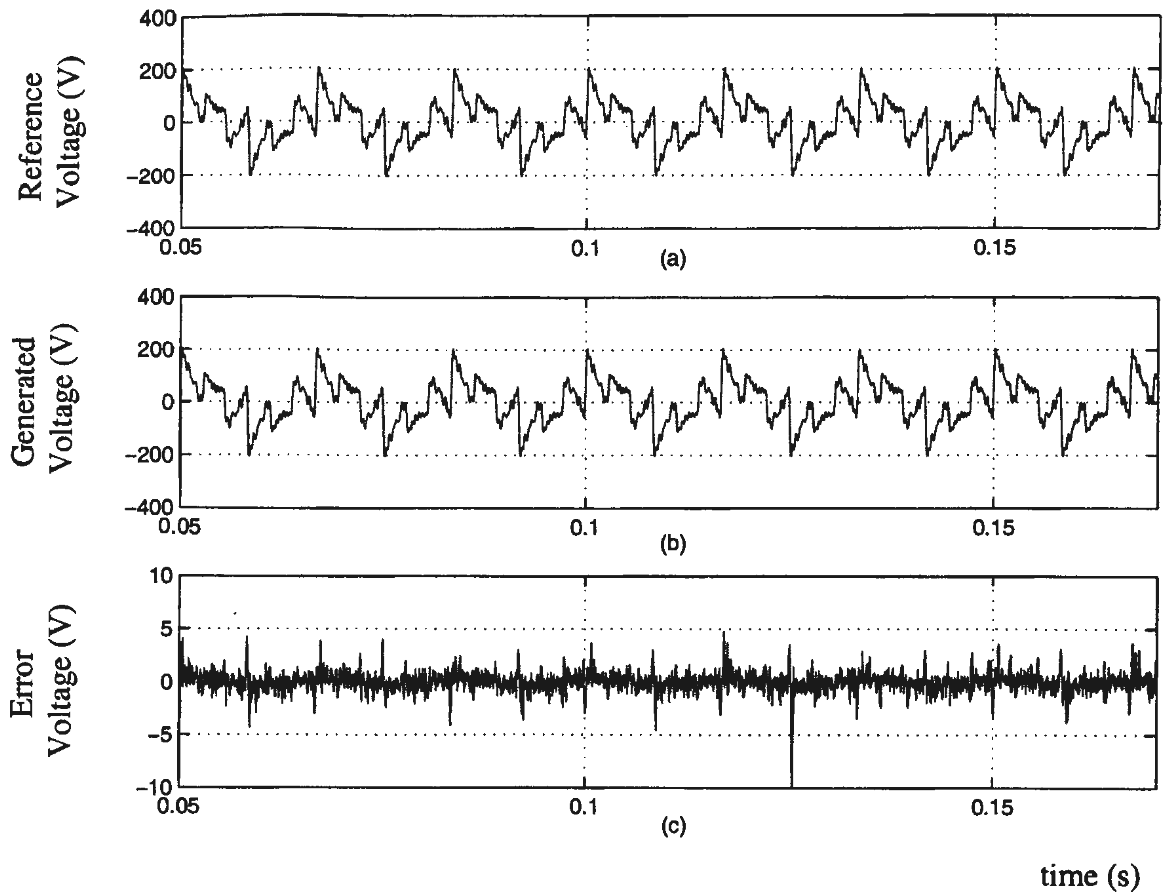

Fig 2.11: (a) Distortion reference, (b) output and (c) error voltage

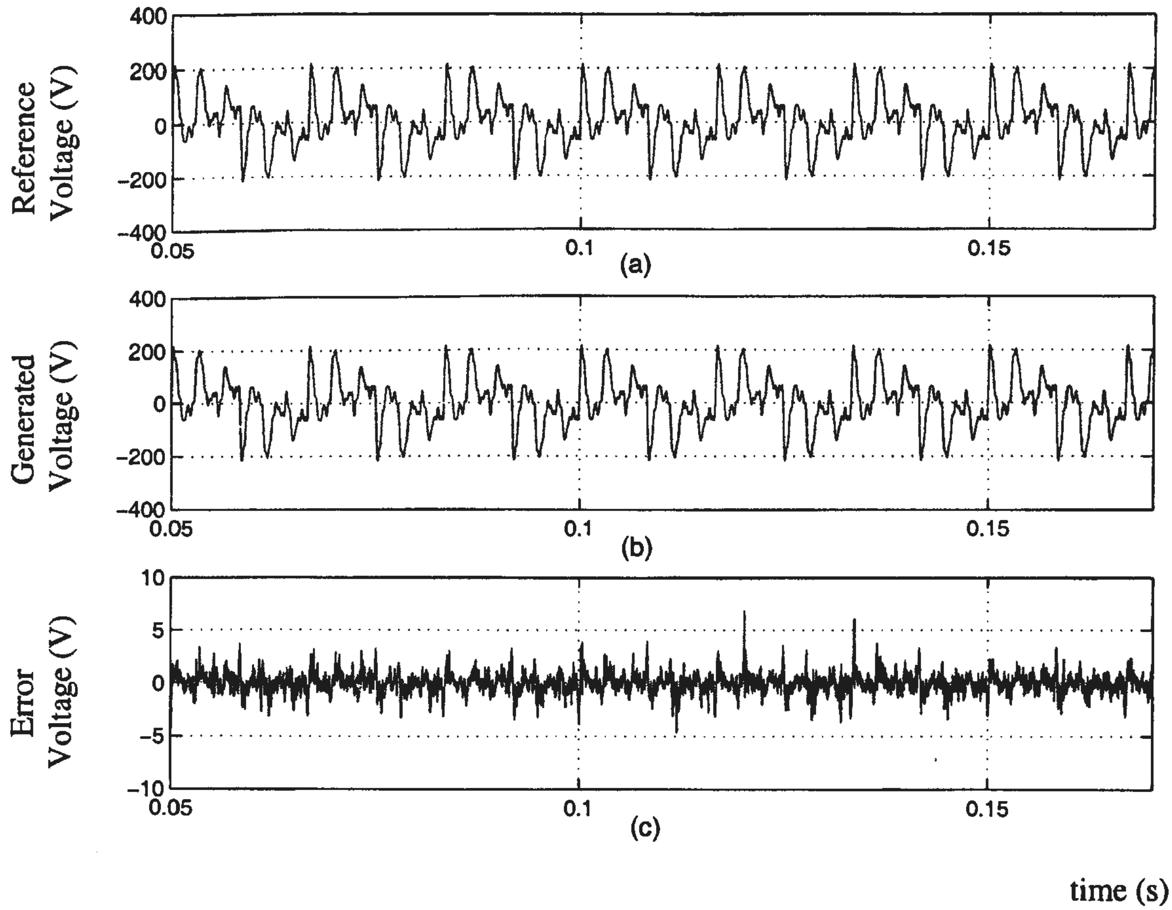

Fig 2.12: (a) Different distortion reference (with different harmonic contents) (b) output and (c) error voltage

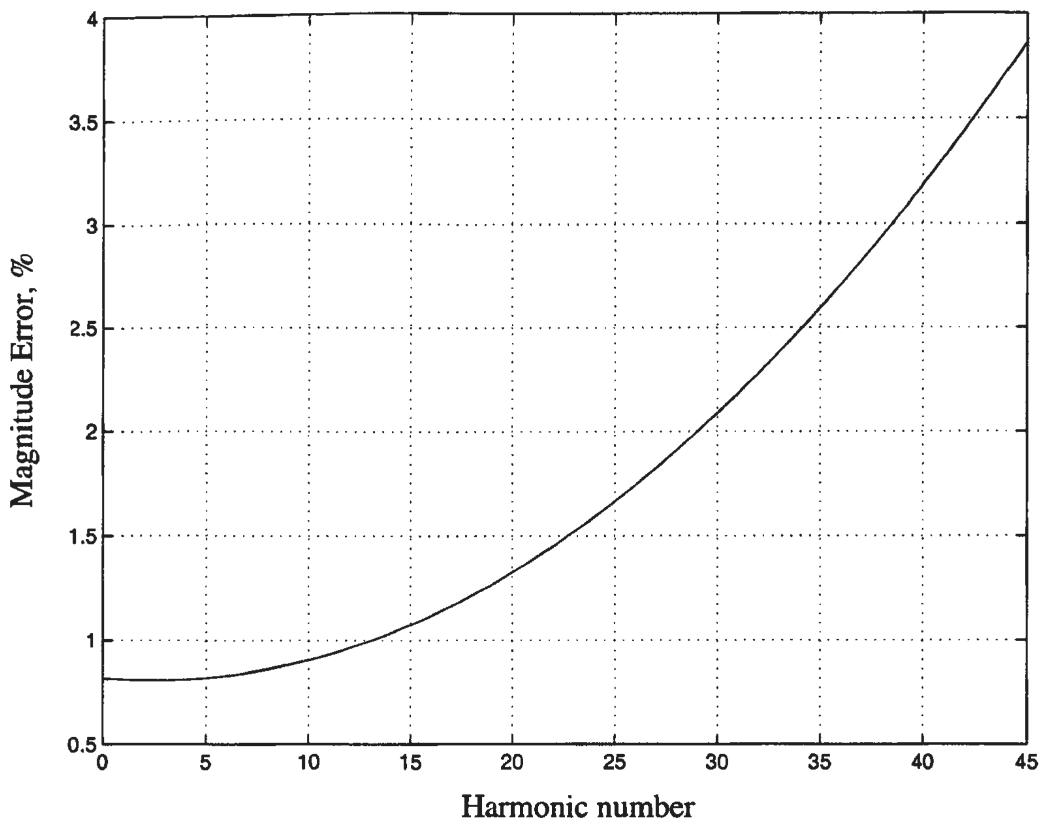

Fig 2.13: Variation of magnitude error as a function of the harmonic order.

2.5 The Shunt Active Filter

In the previous section, the capability of the single-phase inverter with multiple loop control to generate sinusoidal and non-sinusoidal waveforms has been demonstrated. Its suitability for use in the series active filter has also been shown. In this section the use of the single-phase inverter to generate the replica of the harmonic currents will be demonstrated.

The shunt active filter is connected in parallel with the load as shown in Fig 2.14. When the load is non-linear as in adjustable speed drives and arc furnaces, the harmonic currents tend to be drawn from the source resulting in negative consequences for other consumers at the point of common coupling.

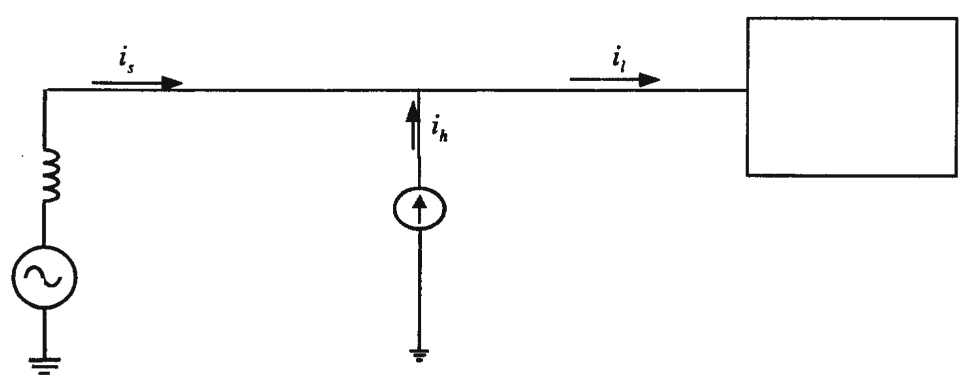

Fig 2.14: The shunt active filter in parallel hybrid topology.

The shunt hybrid filter must be controlled such that it provides a path for all the harmonic currents generated by the load to flow, thereby ensuring that the source current is very near sinusoidal. By Fourier series representation, the non-linear load current is made up of an infinite sum of sinusoids i.e.

$$I_{La} = I_1 \sin(wt + \phi_1) + I_3 \sin(3wt + \phi_3) + I_5 \sin(5wt + \phi_5) + I_7 \sin(7wt + \phi_7) + \ldots\ldots \quad (2.9)$$

The fundamental component flows from the source and the harmonic current are required to flow through the shunt filter.

For the shunt active filter to be able to generate the harmonic current demanded by the load, a feedforward harmonic extraction scheme used. It is based on the synchronously rotating reference frame controller [3]. The load currents are sensed and their harmonic currents are separated from the fundamental, which becomes dc in the synchronously rotating reference frame. A highpass filter is then used to extract the harmonic content. The inverse transformation is then applied to the filtered signal to transform the signal back to the stationary reference frame. The control scheme extracts the harmonics in the load currents and uses the shunt active filter to generate a replica of the extracted harmonics.

The advantages of feedforward schemes are fast response and fewer sensor requirements as compared to feedback control schemes. The downside is that they are highly sensitive to gain inaccuracies due to non-linearity in the filter impulse response and quantisation errors. Feedback schemes on the other hand are self-regulatory (zero steady state error) but suffer from a relatively slow dynamic response. Quick response is crucial in a power system environment in the proximity of fluctuating loads such as arc furnaces and adjustable speed drives.

2.5.1 Harmonic current extraction unit

The harmonic current extraction unit is used to generate the reference current for the single-phase inverter in the shunt active filter. The load currents I_{La}, I_{Lb}, and I_{Lc} in the three phases are sensed and transformed to stationary co-ordinates $I_{Lo}, I_{L\alpha}$, and $I_{L\beta}$ and then to the synchronous frame values I_{Lo}, I_{Ld}, and I_{Lq} respectively. The implementation is simplified by a two-level transformation instead of a one-level direct transformation. The transformation is accomplished by means of Park's transformations as follows.

$$\begin{bmatrix} I_{Lo} \\ I_{L\alpha} \\ I_{L\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1/2 & 1/2 & 1/2 \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \tag{2.10}$$

$$\begin{bmatrix} I_{Lo} \\ I_{Ld} \\ I_{Lq} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) \\ 0 & \sin(\theta) & -\cos(\theta) \end{bmatrix} \begin{bmatrix} I_{Lo} \\ I_{L\alpha} \\ I_{L\beta} \end{bmatrix} \tag{2.11}$$

The phase of the unit vectors ($\theta = \omega t$) is locked in with phase –a voltage using a phase locked loop (PLL).

Since the aim of the harmonic current extraction unit is to block out the fundamental components in the load current from the reference currents provided to the shunt active filter a high pass filter with a cut off frequency of 1Hz is used to extract the harmonics. The output of the highpass filter is then transformed to the a-b-c frame by applying the inverse Park's transformation given by

$$\begin{bmatrix} I_{Lo} \\ I_{L\alpha} \\ I_{L\beta} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) \\ 0 & \sin(\theta) & -\cos(\theta) \end{bmatrix}^{-1} \begin{bmatrix} I_{Lo} \\ I_{Ld} \\ I_{Lq} \end{bmatrix} \tag{2.12}$$

$$\begin{bmatrix} I_{Lah} \\ I_{Lbh} \\ I_{Lch} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} 2/3 & 2/3 & 0 \\ 2/3 & -1/3 & -1/\sqrt{3} \\ 2/3 & -1/3 & 1/\sqrt{3} \end{bmatrix} \begin{bmatrix} I_{Lo} \\ I_{L\alpha} \\ I_{L\beta} \end{bmatrix} \tag{2.13}$$

Where I_{Lah}, I_{Lbh}, I_{Lch} are the extracted harmonics in the load currents for the three phases. The harmonic current extraction unit is shown in Fig 2.15

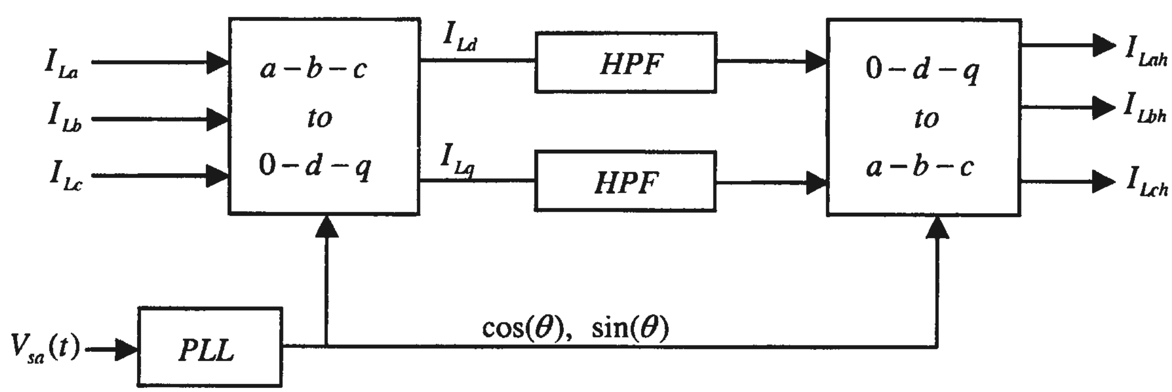

Fig 2.15: Harmonic current extraction unit

The transformation rotates the reference frames in the direction of the positive sequence component. As a result there is a shift in all frequencies equivalent to the angle of rotation. This is illustrated in Fig 2.16. In figure 2.15, $f_{L,abc}$ represents all the frequency in Hz of the components present in the load currents and $f_{L,dq}$ represents the frequencies present after the d-q transformation.

$f_{L,abc}$	0	60	120	180	240	300
$f_{L,dq}$	0	60	120	180	240	300

Fig 2.16: Shift in frequency in d-q transformation

The figure illustrates the shift in frequencies as a result of the transformation where the fundamental components at 60Hz becomes dc and higher frequencies take on the identities of lower frequencies in a shift of 60Hz down the spectrum. Representing the nth harmonic of the load current in the stationary reference domain by $I_{Labc}(f_n t)$ and the current in the d-q domain as $I_{Ldq}(f_{n-1}t)$, the shift in frequencies is represented by

$$I_{Labc}(f_n t) \Rightarrow I_{Ldq}(f_{n-1}t), \qquad n \geq 1 \tag{2.14}$$

Under balanced conditions the linearity of the transformation is retained i.e. one frequency component in the a-b-c frame gives rise to only one component in the d-q frame. This results in a one sided spectral shift.

2.5.2 Performance of the harmonic current extraction unit

Computer simulation of the harmonic current extraction unit was carried out to verify its performance. The load current was assumed to have a total harmonic distortion of 28%. The waveforms of Fig 2.17 are the input current for a rectifier supplying an inductive load, extracted harmonic current and the fundamental. Figure 2.18 shows the frequency spectrum of the filtered currents. The figures show that the scheme is capable of extracting the harmonics and distortion in the line voltage or current for use as a reference in the inverter based active filter. The waveforms of Fig 2.19 show the input current of a rectifier supplying a capacitive load and their extracted harmonic contents. Figure 2.20 is the waveform of a hybrid load, having inductive and capacitive components.

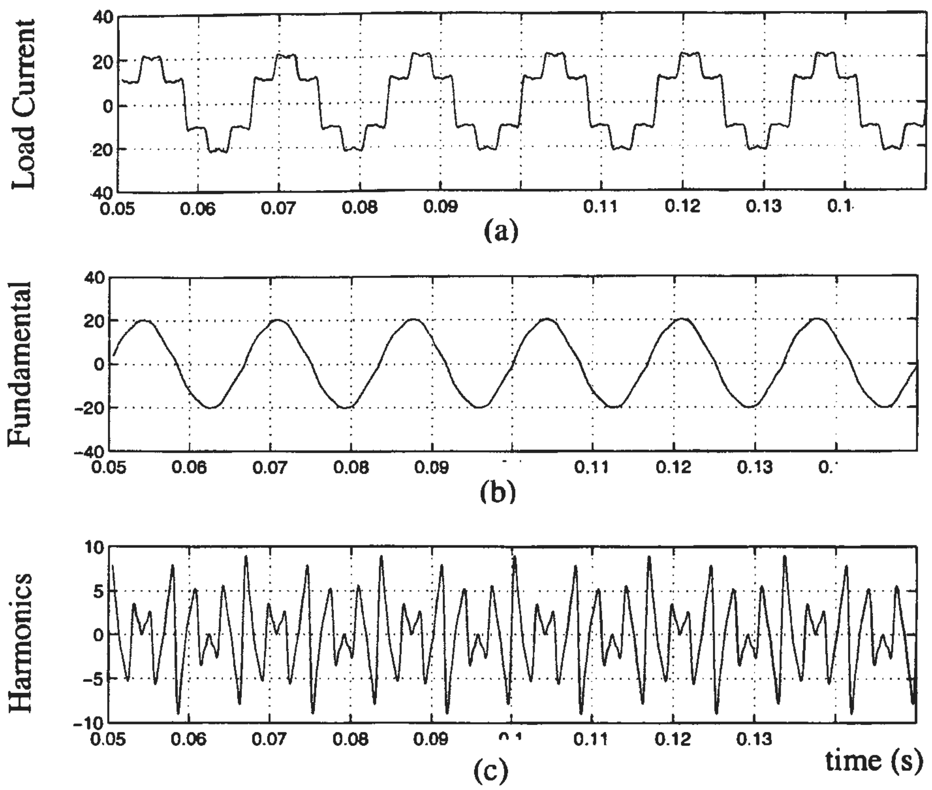

Figure 2.17: (a) Load current; (b) fundamental current; (c) extracted harmonics

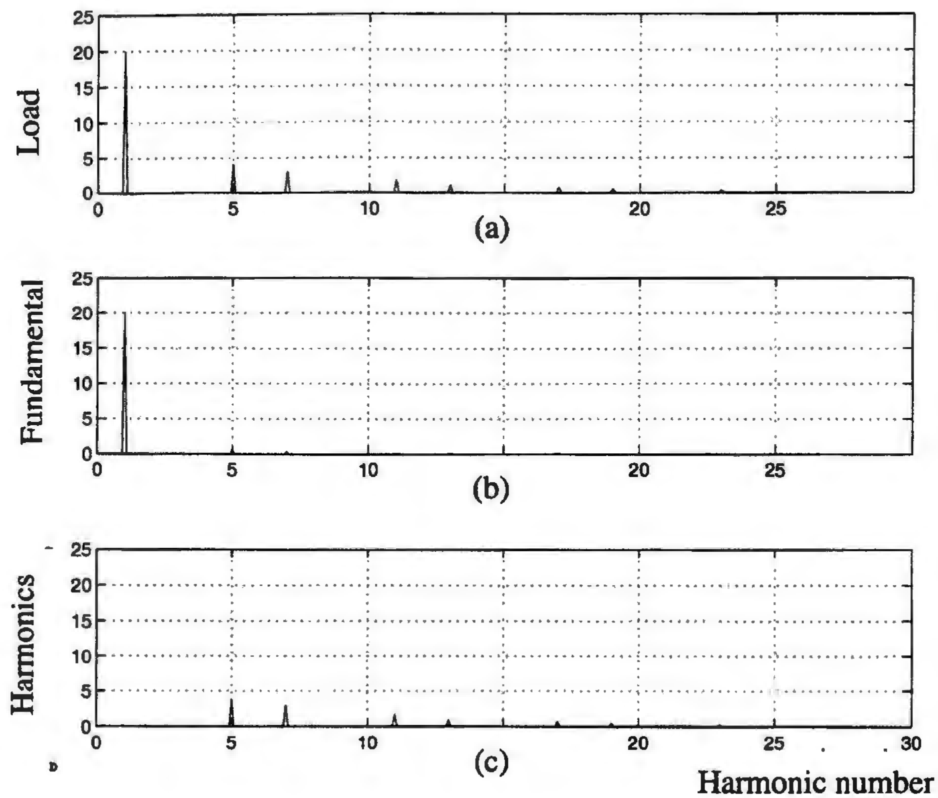

Figure 2.18: Frequency spectra of (a) Load; (b) fundamental and (c) harmonics

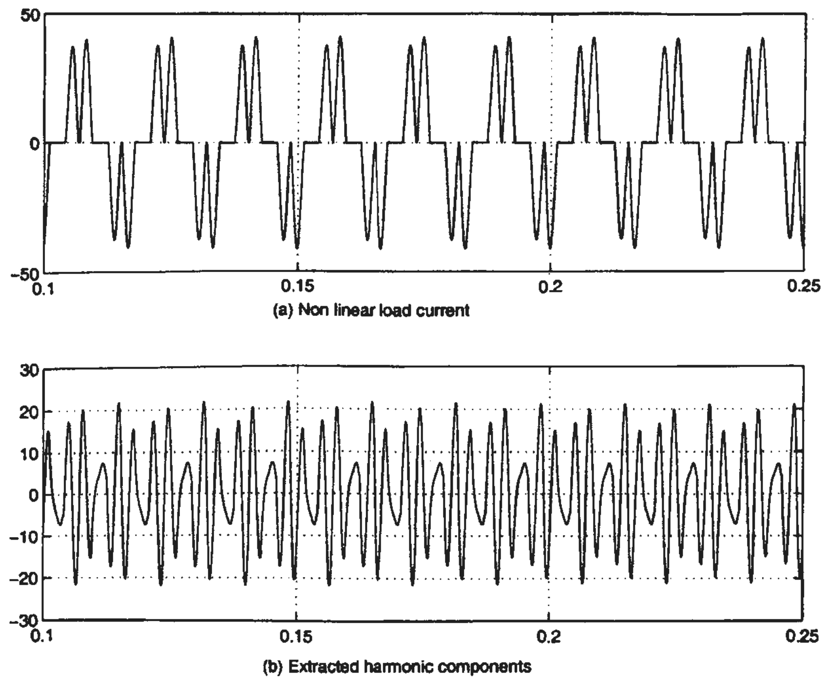

Fig 2.19: Nonlinear load current and extracted harmonic components.

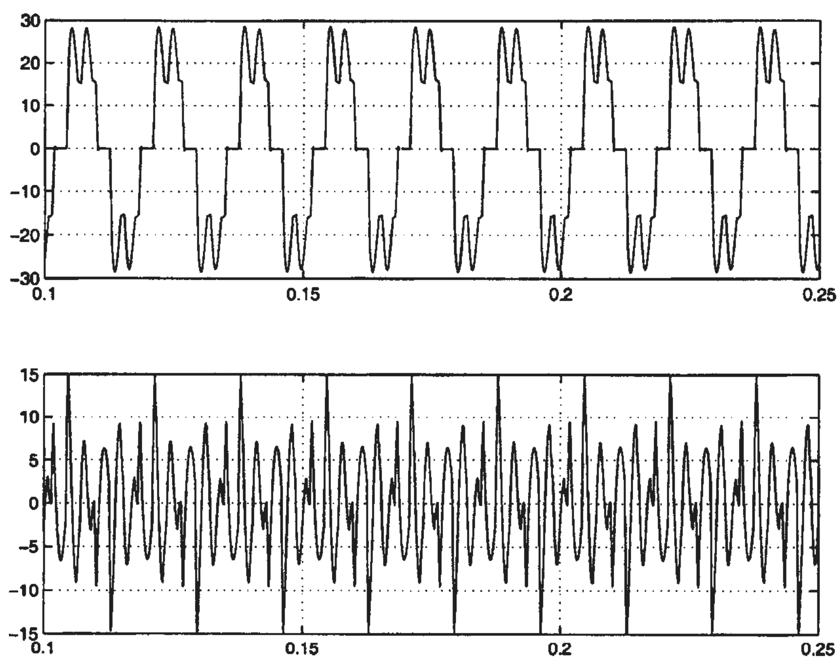

Fig 2.20: Nonlinear load current and extracted harmonic components.

2.6 Summary

This chapter has focused on the development of the series and shunt active filter control schemes. The series active filter based on the multiple feedback loop controlled active filter was investigated and it was demonstrated that the scheme is capable of generating a replica of the sinusoidal or non-sinusoidal (distortion) reference voltage. The characteristics of the lowpass filter were also investigated and the effects of the filter capacitance and inductance on the total harmonic distortion was derived and confirmed by simulation. The use of the direct and quadrature axis transformation in the extraction of harmonics for the shunt active filter was also considered. The effectiveness of the method in the extraction of harmonics was verified by simulation.

Chapter 3

Source-end Voltage and Current Compensation Systems

In the previous chapter the control methods for the series compensation device and the shunt compensation device were presented. It was shown that the control scheme with the series active filter allowed the series active filter to generate sinusoidal and distorted voltage reference. Also the harmonic current extraction scheme was shown to be able to extract the harmonics in the load current, using the control scheme, the shunt active filter is able to generate a replica of the harmonic currents. In this chapter the application of these control methods to the series connected and parallel connected hybrid compensators is investigated.

3.1 Types of Harmonic Sources

Nonlinear loads can generally be classified into two types, namely Voltage source type nonlinear load (VSNL) and Current source type nonlinear load (CSNL). A voltage source type nonlinear load may consist of loads like a diode or thyristor rectifier with a large smoothing capacitor at the load end. It has been shown that traditional passive filters placed in parallel with the non-linear load are not effective in compensating harmonics generated by this kind of load. In addition, the passive filters tend to enlarge the dc voltage ripples and ac peak current of the rectifier [9]. Peng *et al* [8, 9] proposed and demonstrated that a series LC filter is effective in compensating harmonics sources that behave as harmonic voltage sources.

A current source type nonlinear load may consist of a diode or thyristor converter with sufficient dc inductance such that it produces a constant direct current [9]. Figures 3.1 and 3.2 show a typical voltage source and current source nonlinear load. In practice, such clear-cut distinctions in load types may be difficult to make as some harmonic sources may exhibit the characteristics of both.

Peng [1] has presented 22 basic filter configurations suitable for compensating current source and voltage source nonlinear loads. Among them was the use of a combination of the series passive filter and the series active filter for compensating voltage source nonlinear loads and a shunt passive and the shunt active filter for compensating harmonic current source loads. It is usually not feasible to compensate for harmonics and voltage distortion on a load-to-load basis and some sources of harmonics and distortion in the system may not be readily classified as harmonic voltage sources or harmonic current sources. There is therefore the need to investigate compensation systems that mitigate the harmonics and the voltage distortion caused by combinations of both kinds of nonlinear loads or hybrid loads.

The compensation system is expected to establish the following conditions:

- The source current should be free of harmonics
- The voltage at the point of common coupling should have a low total harmonic distortion
- The load terminal voltage should have a low total harmonic distortion
- Harmonic levels in the system should meet harmonic standards (for example, IEEE 519)

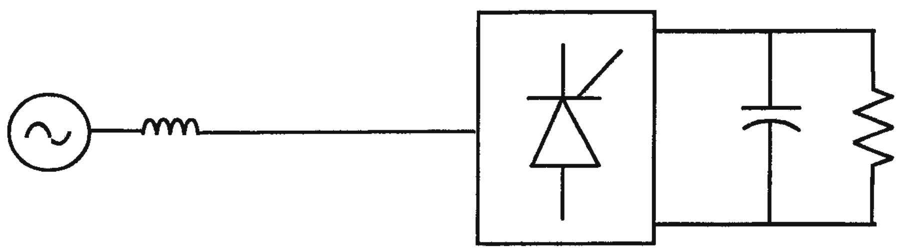

Fig 3.1: Voltage source nonlinear load (VSNL)

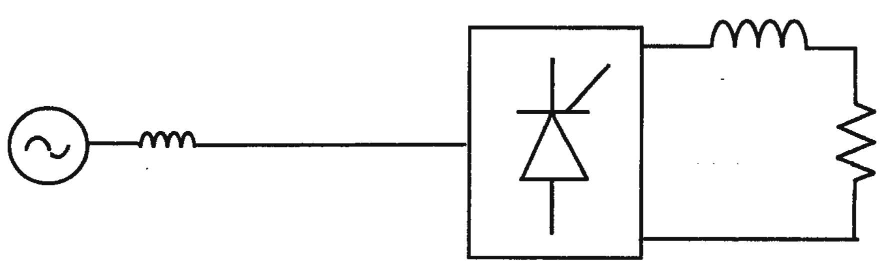

Fig 3.2: Current source nonlinear load (CSNL)

3.2 The Passive Filters

The performance characteristics of the passive filters are very important in the hybrid compensation process. The passive filters used are tuned to the order of the dominant harmonics in the system and the voltages across the filter are primarily due to the current harmonics flowing through them. The magnitude of the voltage drop depends on the impedance characteristics of the filters. The passive filters used in this study are the series and the shunt passive filters. The series passive filter is a parallel resonant circuit having high impedance at the tuned frequencies, while the shunt passive filter is a series tuned resonant circuit having low impedance at the tuned frequencies. The impedance characteristics of the passive filters are shown in Figs 3.3 and 3.4.

Figure 3.3 shows that the series passive filters present a high impedance to the system at the tuned frequencies which in this case are the fifth, the seventh and the eleventh harmonic frequencies, hence serving to significantly attenuate the source currents at those frequencies. Its impedance at the fundamental frequency is minimal. This is important since high impedance at the fundamental frequency may result in appreciable voltage drop.

Figure 3.4 shows that the impedance of the shunt passive filters is very low at the fifth, seventh and eleventh harmonic frequencies and high at the fundamental frequency. The filter provides low impedance path for the harmonic currents thus preventing the harmonics from flowing through the source and preventing the fundamental frequency current from flowing into the passive filter.

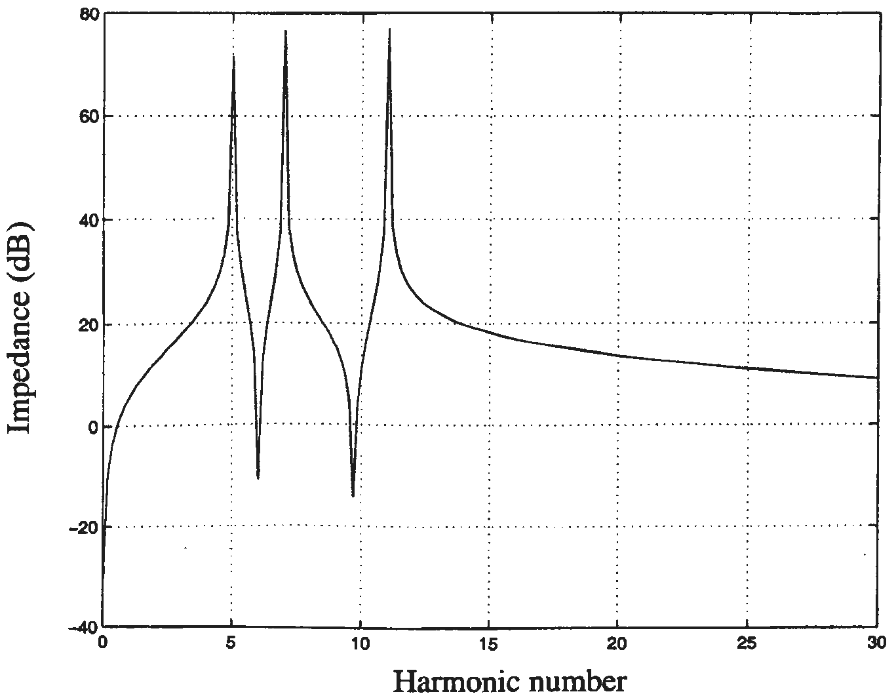

Fig 3.3: Impedance characteristics of the series passive filter

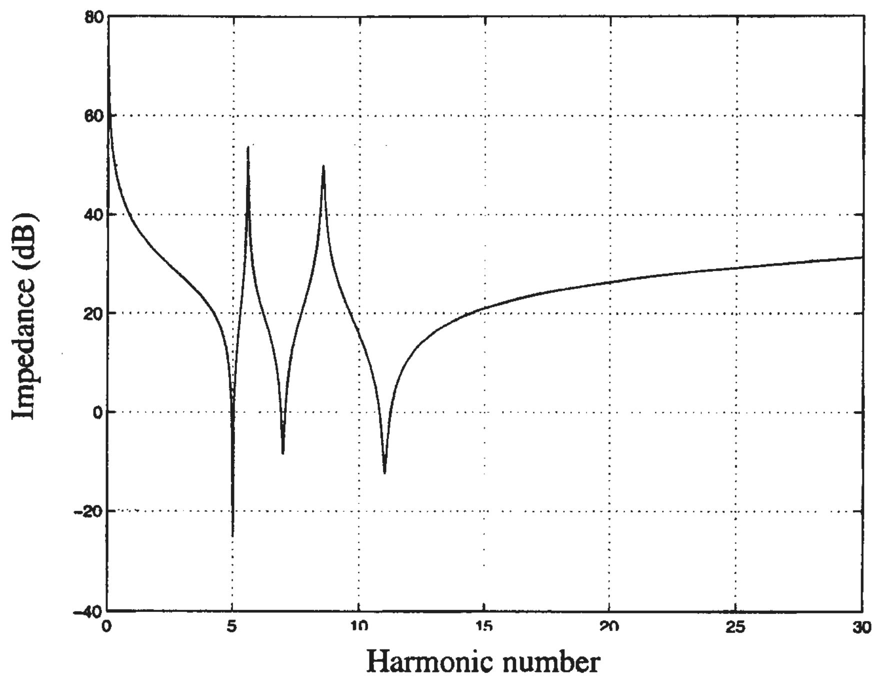

Fig 3.4: Impedance characteristics of the shunt passive filter

3.3 Type A Compensation System

The single-phase diagram of Type A Compensation System is shown in Fig 3.5. It consists of an active filter in series with a parallel resonant passive filter as the hybrid series compensator and a shunt active filter in parallel with a series resonant passive filter to form the hybrid shunt compensator. The shunt passive filters are tuned to the dominant harmonics, i.e. the 5^{th}, 7^{th}, and 11^{th}. The series passive filters are also tuned to the 5^{th}, 7^{th}, and 11^{th} harmonics. The system is suitable for a combination of voltage source nonlinear loads and current source nonlinear loads.

3.3.1 Model of Type A compensation system

Figure 3.6 shows the single-phase equivalent circuit representation of the system. The utility voltage is modeled as an ideal voltage source V_s in series with a Thevenin impedance Z_s. The distortion in the source voltage at the point of common coupling (PCC) is V_{sd}. The current source nonlinear load (CSNL) is modeled by a harmonic current source I_{Lhi} while the voltage source non-linear load (VSNL) is modeled by its Thevenin equivalent circuit, V_{Lhv} in series with Z_{vh}. The active filters and the coupling transformer are modeled as controlled sources. The series active filter is represented by a voltage controlled voltage source V_{AF1}, while the shunt active filter is modeled as a current controlled current source I_{AF2}. The impedance of the series passive filter Z_{sh} is in series with the active compensator while the shunt passive filter Z_{ph} is in parallel with the shunt active filter. Single-phase steady-state analysis is a reasonable choice since the compensation of the three-phase system is achieved via independent compensation of each phase. This way, the compensation scheme corrects for imbalance, sags, swells, and harmonic distortion on each phase.

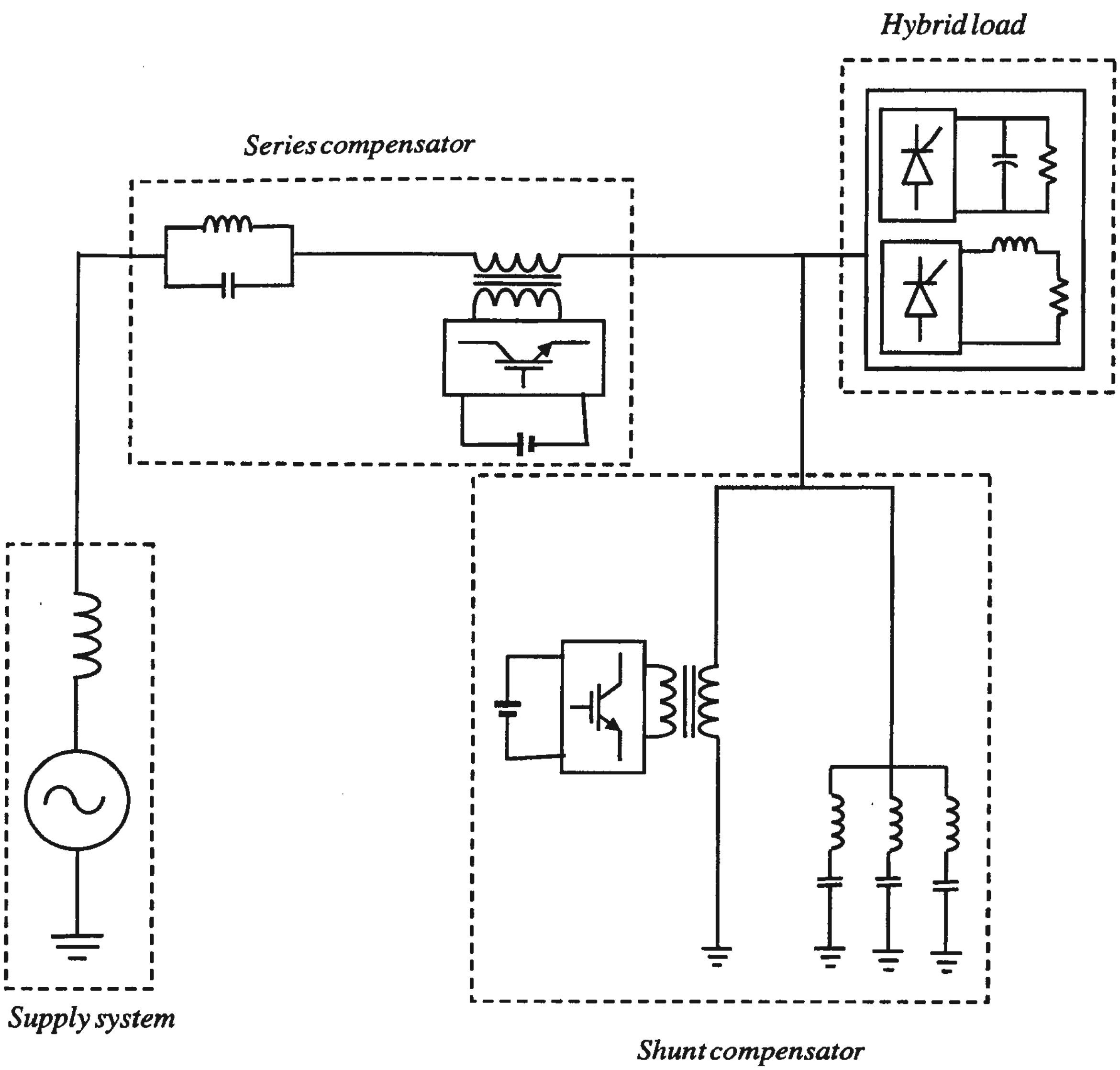

Fig 3.5: A single-phase representation of Type A Compensation System.

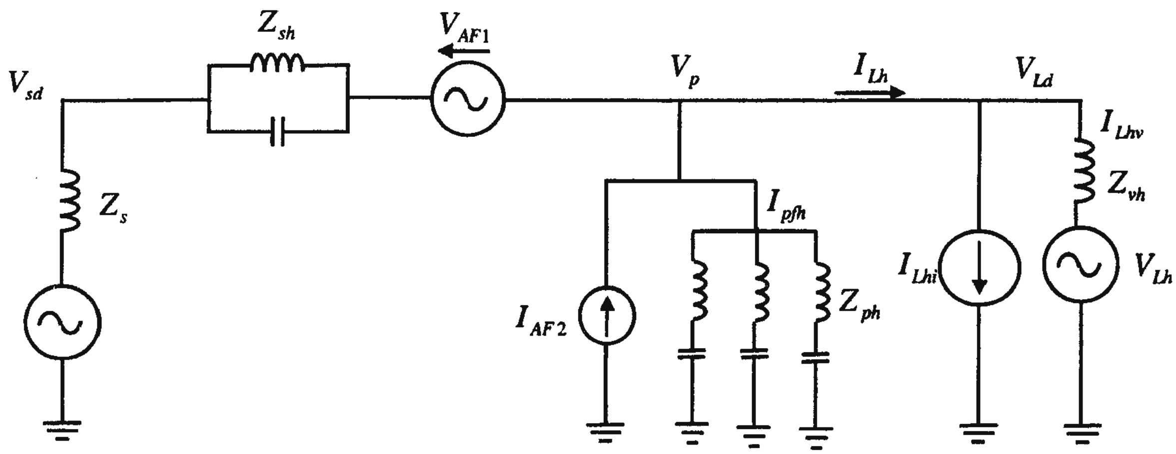

Fig 3.6: Single-phase circuit model of Type A compensation system

3.3.2 Analysis of Type A Compensation System

The analysis is carried out with the aim of determining the control laws that ensure harmonic and distortion mitigation. The gain of the series active filter inverter is k_1 and is defined as the ratio of the inverter output voltage to the distortion reference signal i.e.

$$k_1 = \frac{V_{AF1}}{V_{sd}} \tag{3.1}$$

The gain of the shunt active filter is similarly defined as the ratio of the inverter generated compensating current to the reference current signal.

$$k_2 = \frac{I_{AF2}}{I_{refh}} \tag{3.2}$$

The system components are combined and controlled to realize voltage compensation and current compensation. The active filters are controlled independently. The series active filter is mainly used for voltage compensation hence it is controlled as a voltage controlled voltage source while the shunt active filter is used for current compensation hence its representation as a current controlled current source. The respective inverter gains k_1 and k_2 are unity when the generated compensating voltage or current equals the reference.

For voltage compensation, the series active compensator generates a voltage $k_1 V_{sd}$ and injects it into the line in opposite phase, hence canceling out the distortion at the PCC.

$$V_{AF1} = -k_1 V_{sd} \tag{3.3}$$

Applying superposition theorem and KCL at the passive filter terminals, the resulting voltage at the load is given as

$$V_{Ld} = \frac{V_{sd}(1-k_1)Z_{ph}}{Z_{ph}+Z_{sh}} + \frac{I_{Lh}(Z_{sh}+Z_s)}{Z_{sh}+Z_s+Z_{ph}} Z_{ph} \tag{3.4}$$

where I_{Lh} is the harmonic component of the total load currents, and V_{Ld} is the distortion component of the load voltage. The distortion voltage across the load is a combination of two components i.e. the component due to the source end distortion voltage V_{sd}, and the component due to the drop across the passive filter $I_{Lh}Z_{ph}$. The source end distortion may consists of voltage sag, swell, flicker and harmonics occurring at the point of common coupling as a result of the operation of linear or non-linear loads or line faults somewhere along the line. Equation 3.4 also shows that if the active filter control gain is tightly controlled such that $k_1 = 1$, then the distortion component in the load voltage due to the source end distortion can be cancelled. The second term in (3.4) shows that the harmonic currents flowing in the passive filter produce distortion in the load voltage. A conclusion can therefore be reached that Type A Compensation System cannot guarantee a load end voltage that is free of distortion.

From Fig 3.6 the harmonic current tending to flow through the source is obtained as follows. Applying KCL at the passive filter terminals

$$I_{sh} = I_{Lh} - I_{pfh} - k_2(I_{Lh} - I_{pfh}) + \frac{V_{sd}(1-k_1)}{Z_s + Z_{sh}} \tag{3.5}$$

where

$$I_{Lh} = I_{Lhi} + I_{Lhv} \tag{3.6}$$

and

$$I_{Lhv} = \frac{V_{Ld} - V_{Lhv}}{Z_{vh}} \tag{3.7}$$

The compensating current generated by the shunt active filter is

$$I_{AF2} = k_2(I_{Lh} - I_{pfh}) \tag{3.8}$$

where the extracted reference harmonic current is

$$I_{refh} = (I_{Lh} - I_{pfh}) \tag{3.9}$$

Equation 3.5 shows that the harmonic current in the source is due to the combined load harmonics and the distortion in the source voltage. However, with $k_1 = 1$ and $k_2 = 1$, the distortion in the source current can be minimized or eliminated. If the active filters are controlled so that the gain conditions are met and the series passive filters are tuned to trap any residual harmonics, the source current harmonics can be eliminated.

3.4 Performance of Type A Compensation System Under Various Conditions

A computer simulation model of the compensation system was constructed in MATLAB (see Appendix A) to verify its performance under various operating conditions such as sags, swell, flicker and harmonics and in the absence of distortion. The CSNL load is represented by a dc motor drive with the six-pulse thyristor rectifier rated at 3 KVA. The VSNL is represented as a six-pulse thyristor rectifier with a large output capacitor driving a dc motor, also rated at 3 KVA. The control of the active filters has been discussed in Chapter 2.

The supply is a distribution system of 120V (rms) per phase with a source inductance of 1mH. The series and shunt passive filter parameters are given in Table 3.1.

Table 3.1: Passive filter parameters

	5^{th}	7^{th}	11^{th}
L	28.1mH	14.4mH	5.8mH
C	10uF	10uF	10uF
Q	20	20	20

The series active filter parameters are: DC Voltage, $V_{DC} = 250V$; Lowpass filter, $L_f = 1mH, C_f = 80\mu F$; Controller gains, $k_v = 2.0$ and $k_c = 2.0$, Carrier waveform frequency of 5KHz was used.

The shunt active filter parameters: DC voltage, $V_{DC} = 100V$; Lowpass filter, $L_f = 1mH, C_f = 80\mu F$.

3.4.1 Normal operations

Under normal operations i.e. when there is no system disturbance of any form and with the system loaded by the VSNL and CSNL, Fig. 3.7 and 3.8 show the waveform and harmonic spectrum of the system currents and voltages.

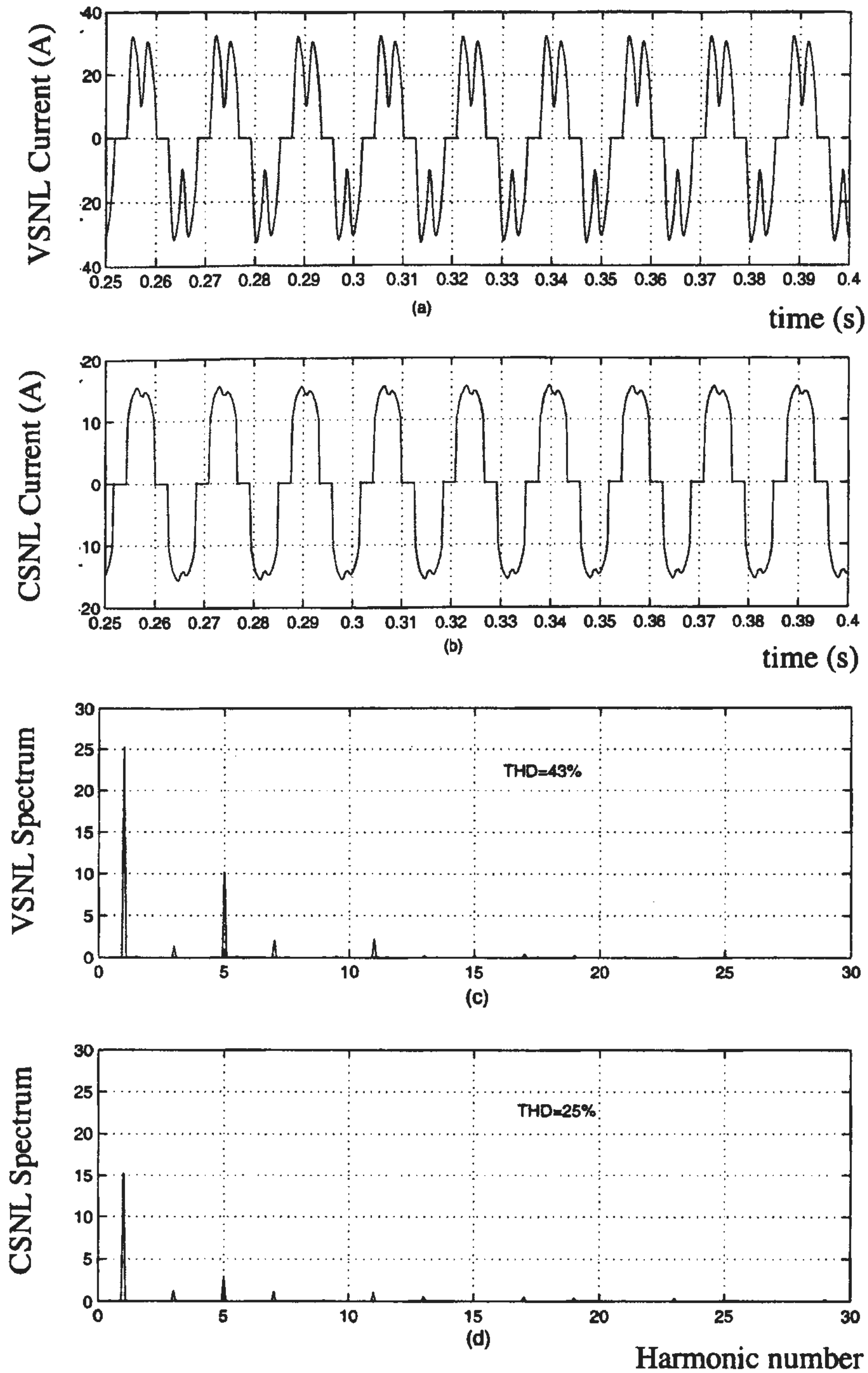

Fig 3.7: (a) VSNL input current; (b) CSNL input current; (c) Harmonic spectrum of VSNL current; (d) Harmonic spectrum of CSNL current

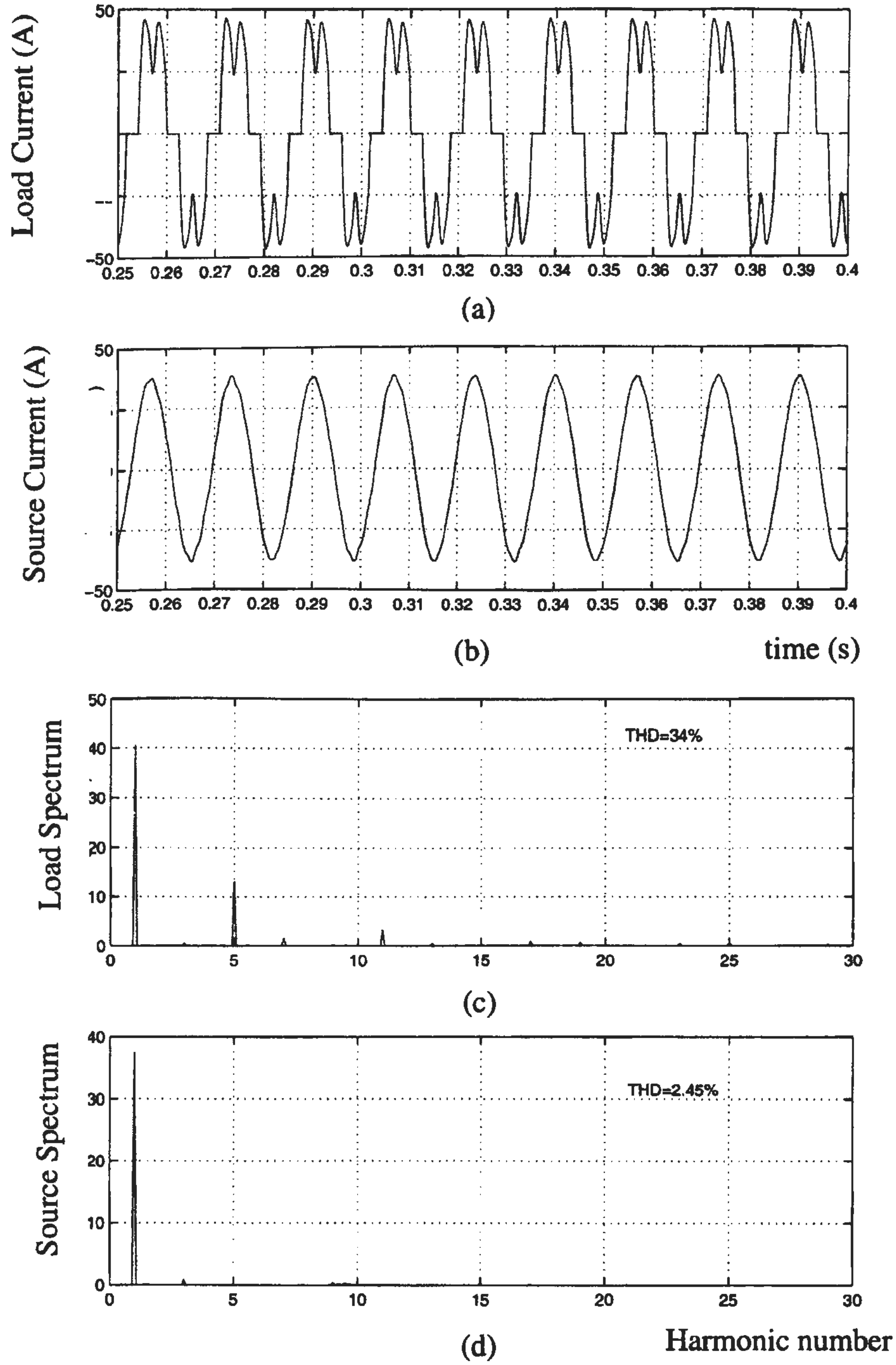

Fig 3.8: (a) Total load current; (b) Source current; (c) Harmonic spectrum of the total load current; (d) Harmonic spectrum of the source current

The total load current harmonic distortion is determined from Fig. 3.8c as 34% while the total source current distortion is obtained from Fig 3.8d as 2.45% a figure which meets the recommended harmonic specifications of IEEE 519.

To further investigate the performance of Type A Compensation System under different nonlinear load conditions, the total harmonic distortions of the nonlinear load current was varied so as to determine the resulting THD of the source voltage and current.

The results of this study are displayed in Table 3.2, where it can be observed that the load voltage THD increases with the load current THD and fails to meet specifications for large nonlinear loads with high THD in their input current.

Table 3.2: Source and load total harmonic distortion for Type A

Load current THD%	Source current THD%	Load voltage THD%	Source voltage THD%
107.59	6.04	8.97	2.58
83.15	4.49	7.35	2.30
55.05	3.05	6.54	1.78
37.62	2.31	5.40	1.20
26.23	2.01	4.11	0.9

From the results obtained, Type A Compensation System has the capability of compensating for nonlinear load current harmonics and voltage distortions resulting from the supply end. Its weakness is its inability to effectively mitigate load end voltage harmonics and the high voltage rating of the shunt active filter as a result of having to withstand the line voltage. This is shown in Fig 3.9. The figure shows that the supply voltage is undistorted having a very low total harmonic distortion of 1.5%, while the load end voltage contains distortion components. The load voltage is determined from Fig 3.9d to be 5.6%, a figure that exceeds the required specification.

The system is thus able to prevent harmonic distortion at the point of common coupling, but unable to keep the load end voltage free of harmonic distortion. Figure 3.10a shows the compensating current generated by the shunt active filter to cancel out the harmonic currents resulting from the nonlinear load operations. Fig 3.10b is the generated distortion voltage from the series active filter.

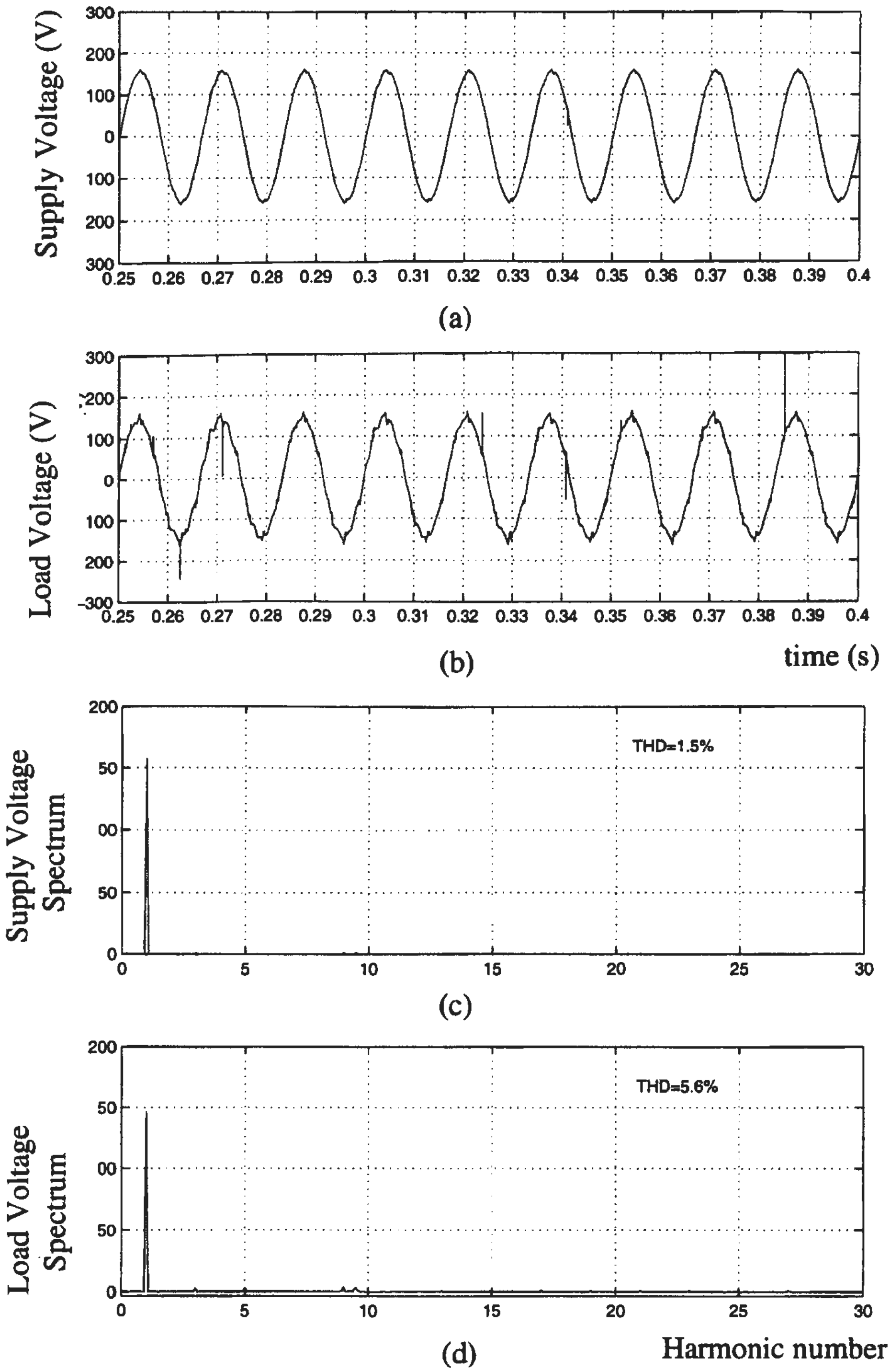

Fig 3.9: (a) Supply voltage; (b) Load voltage; (c) Harmonic spectrum of the supply voltage; (d) Harmonic spectrum of the load voltage.

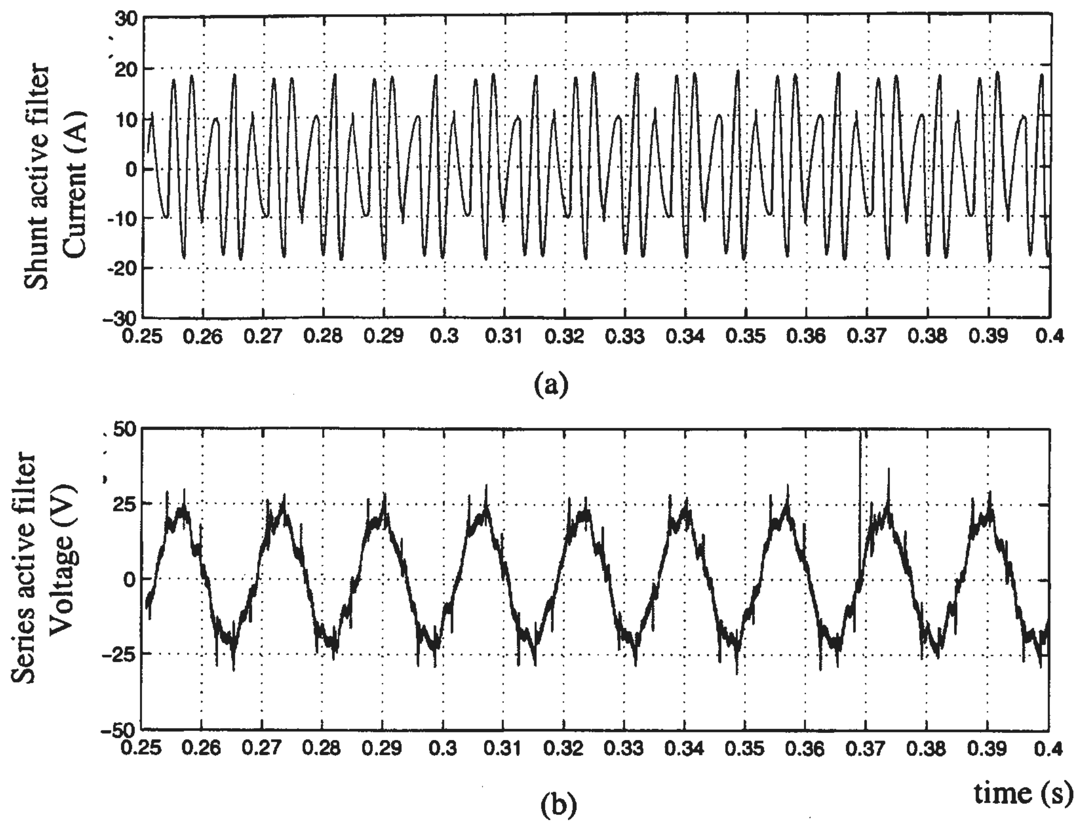

Fig 3.10: Active filter outputs. (a) Shunt active filter compensating currents, (b) Series active filter output voltage.

3.4.2 Performance under voltage sag, swells and flicker conditions

Although Type A Compensation System is unable to compensate for voltage distortions resulting from the operation of the load, it is capable of compensating voltage distortions resulting from the supply end. Figure 3.11 show the performance of the system under source end distortion undergoing 30% sag at 0.1second and a 17% swell at 0.2 second. Fig 3.11b shows that the load voltage is held constant with the sag and swell condition present in the supply. Fig 3.11c shows the response of the series active filter in correcting for the deviation of the supply from its fixed reference.

Figure 3.12 and 3.13 shows an expanded part of Fig 3.11 i.e. the interval between 0.07 and 0.13 seconds and between 0.17 and 0.23 seconds. These figures show that series active filter using the adopted multiple loop control scheme has a fast dynamic response. It is capable of responding to quick changes in the supply voltage such as sudden sags occurring along the line hence keeping the load voltage near constant. Figure 3.14 shows the system response to supply voltage sag of 50% and swell of 30%. It shows again that the system is capable of compensating for the high values of voltage sags and swells. The amount of voltage sag and swell that can be compensated is limited only by the DC supply voltage in the inverter and the ratings of the semiconductor switches.

Figure 3.15 shows a 30% amplitude modulation of the supply end voltage by an 8Hz sinusoid resulting in voltage flicker at the load end, the resulting steady load voltage and the response of the series active filter, dynamically restoring the load end voltage to a fixed value. This demonstrates that the active compensation system is capable of compensating for slow variation in the supply voltage and hence results in voltage flicker elimination at the load voltage.

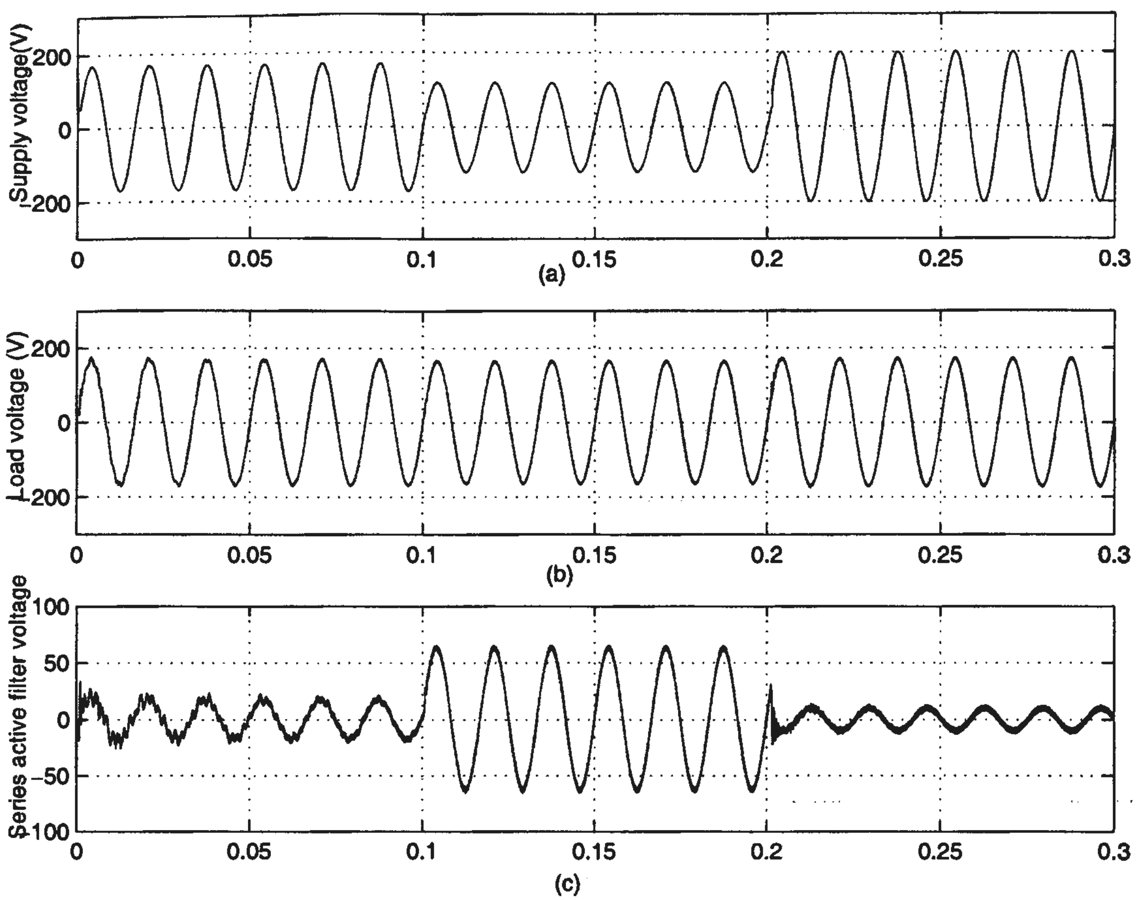

Fig 3.11: Voltage sag and swell compensation

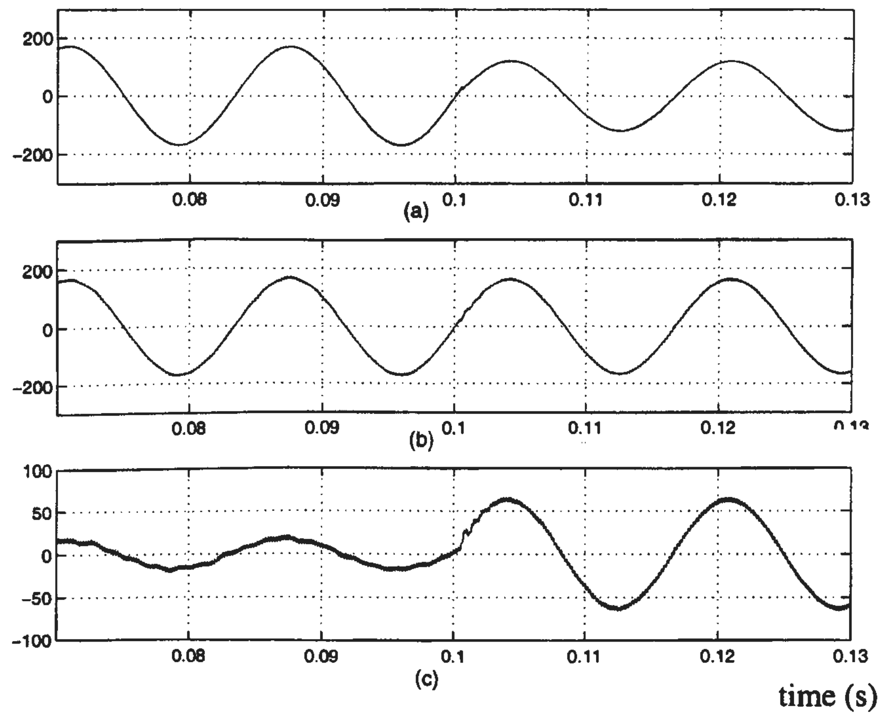

Fig 3.12: (a) Supply voltage; (b) Load voltage; (c) Compensating voltage

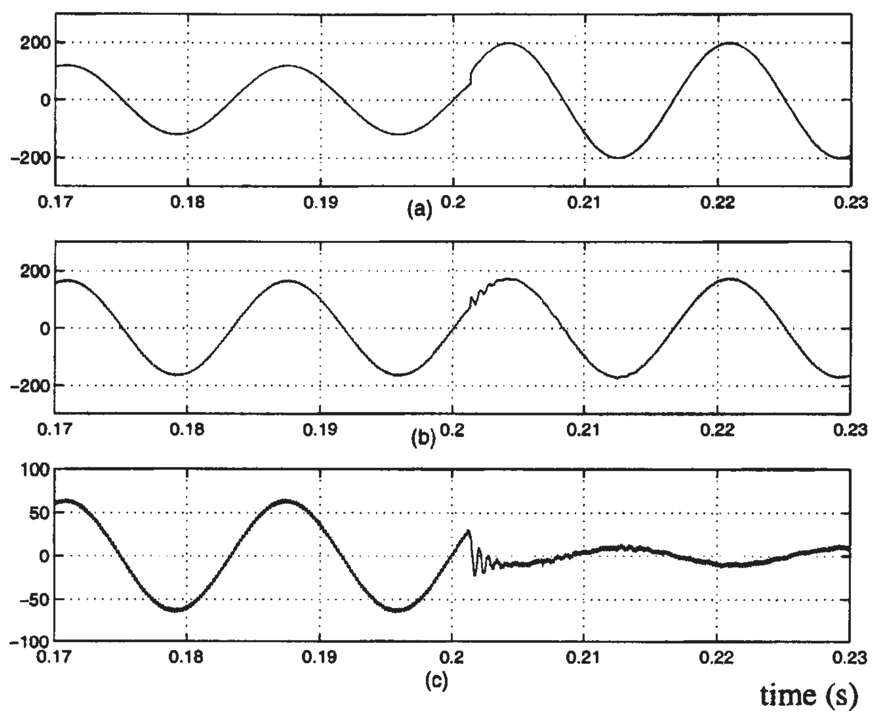

Fig 3.13: (a) Supply voltage; (b) Load voltage; (c) Compensating voltage

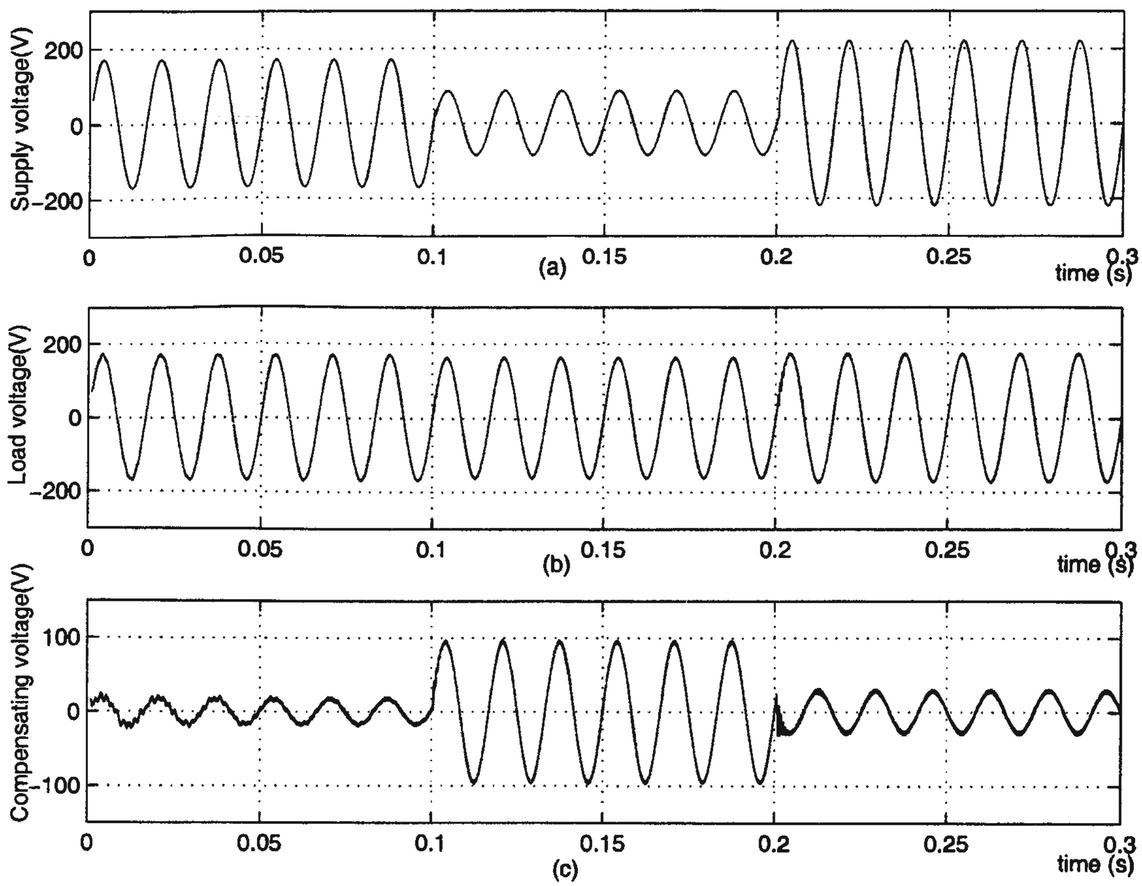

Fig 3.14: Voltage sag and swell compensation for higher sag and swell value

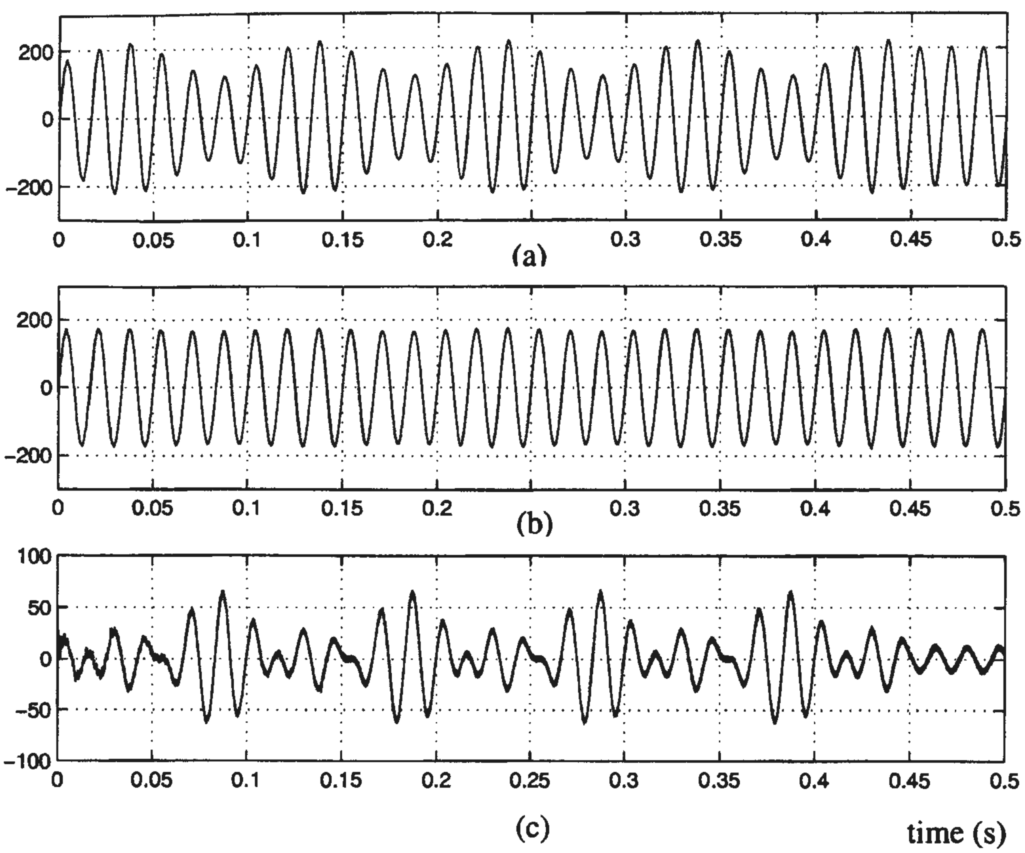

Fig 3.15: Voltage flicker compensation: (a) Supply voltage with flicker; (b) Load voltage; (c) Series active filter compensating voltage

3.4.3 Simulation results for more complex models for Type A

Simpler load and inverter models (Appendix A.1, A.5 and A.6) were used in obtaining the results of the previous sections 3.4.1 and 3.4.2 in order to reduce the number of equations to be solved and to speed up the simulation time. More complex models (Appendix A.15 and A.16) were then used to present a more realistic view of the system performance. The results are presented in this section. Figure 3.16 and 3.17 shows that the system is just as effective with more complex simulation models.

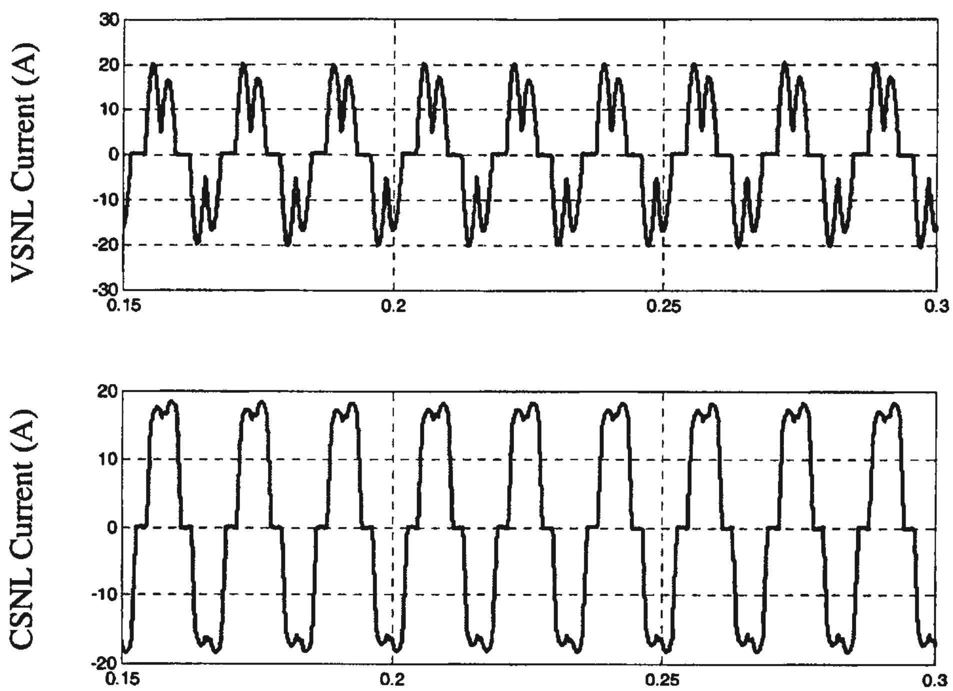

Fig 3.16: Load currents with more complex models for type A

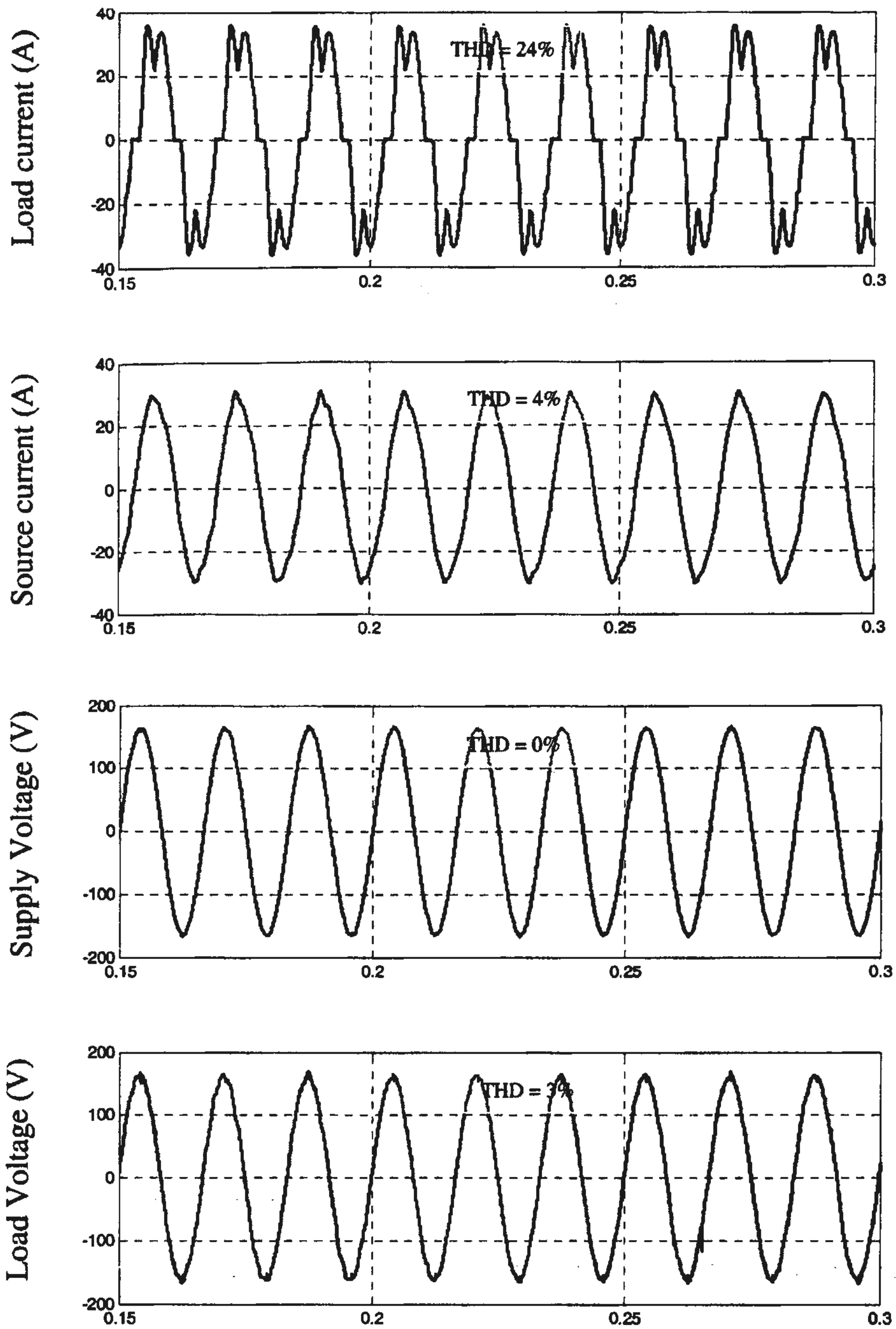

Fig 3.17: Currents and Voltages with more complex models for type A

3.5 Type B Compensation System

Type A Compensation System shown in figure 3.5 has a disadvantage of requiring the use of several current sensors in the control scheme since it is necessary to sense the load currents in the three phases and the passive filter currents in the three phases as well. This results in increase in cost. A series arrangement of the shunt active filter and the passive filter can solve the problem of high voltage rating of the shunt active filter and the requirement of high number of current sensors. This results in Type B Compensation System shown in Fig 3.18 with a single-phase equivalent model shown in figure 3.19.

3.5.1 System description and analysis

This compensation system is similar to Type A Compensation System except that the shunt compensator is a series type instead of a parallel type as in Type A Compensation System. The series active compensator is controlled as a voltage controlled voltage source, while the shunt active compensator is controlled as a current controlled voltage source. The reference signal for the series active compensator is the extracted distortion voltage at the point of common coupling, obtained by comparing the voltage at the PCC with a reference signal of the same phase. The error signal is the distortion voltage. The reference signal for the shunt active filter is obtained by the extraction of the load current harmonics by the synchronous reference frame method discussed in Chapter 2.

By the application of the circuit law of superposition and Kirchhoff's laws, the control equations are obtained as

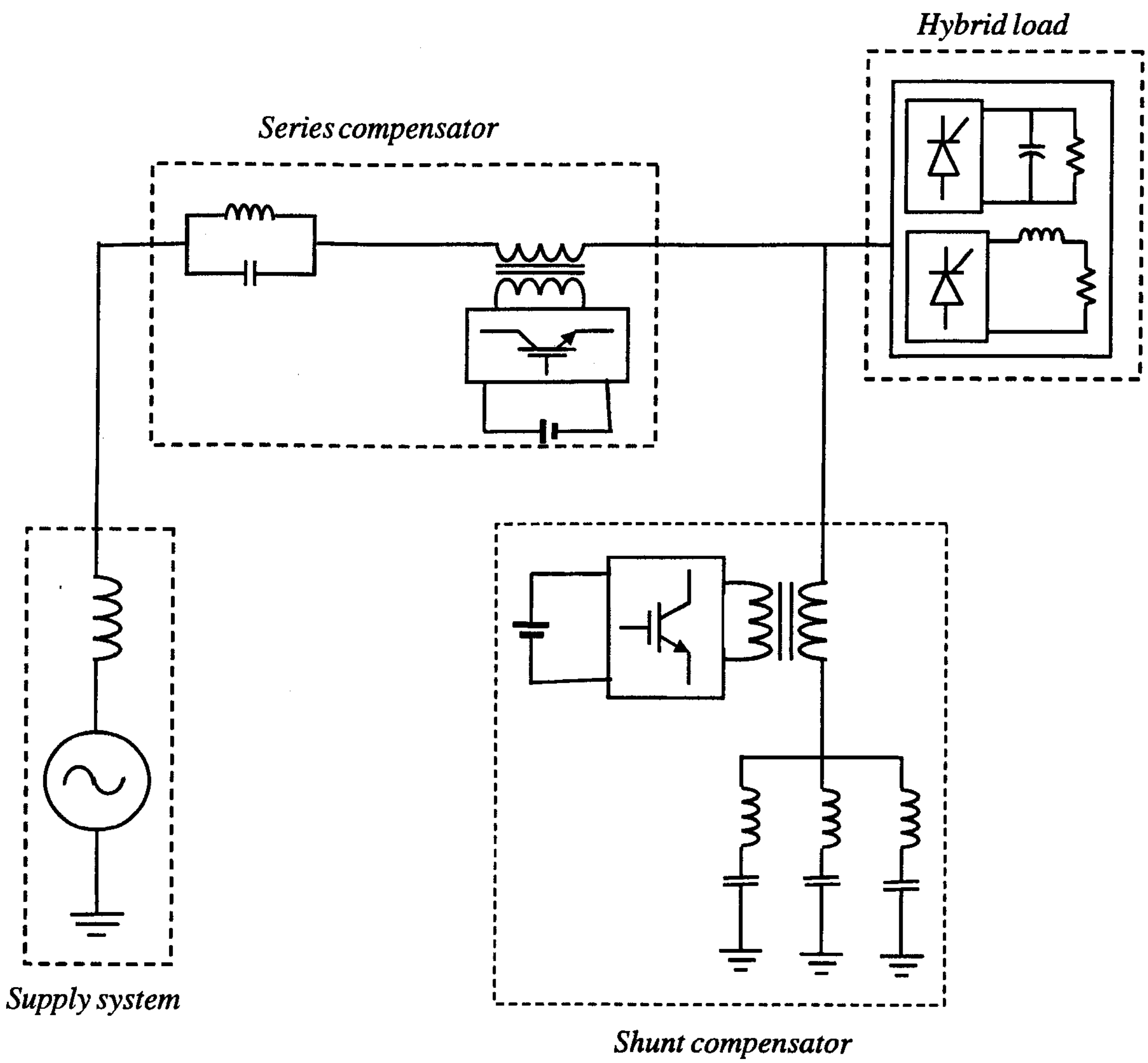

Fig 3.18: Type B Compensation System Configuration

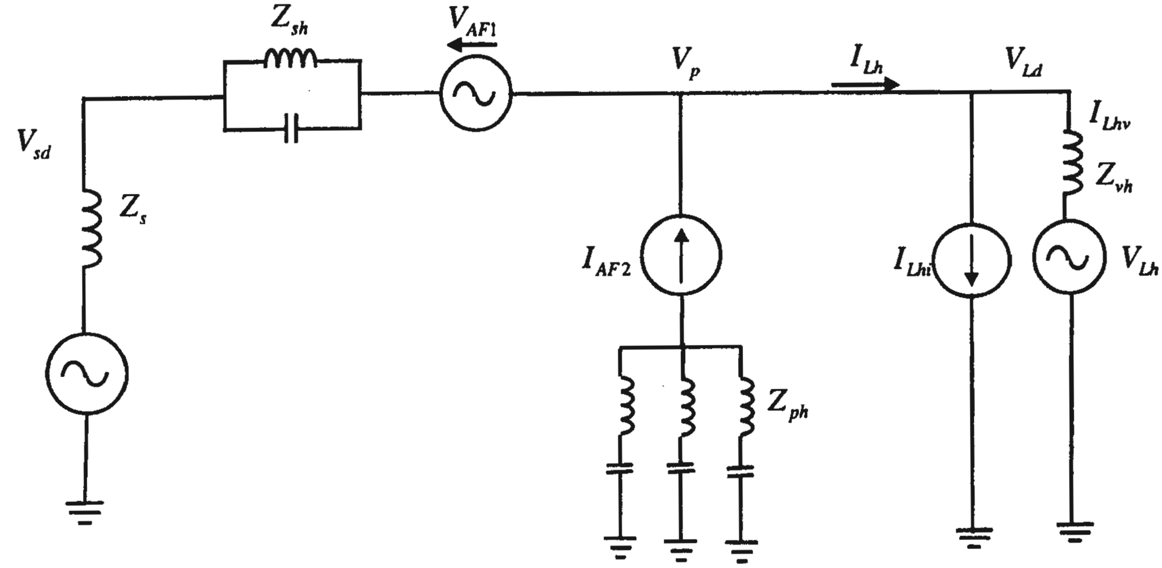

Fig 3.19: Single-phase equivalent model of Type B Compensation System

$$I_{sh} = \frac{V_{sd}(1-k_1)}{Z_s + Z_{sh}} + I_{Lh}(1-k_2) \tag{3.10}$$

The equation shows that for the inverter gains of unity, the harmonics can be cancelled from the source end, due to the load or from source end distortion.

The load end voltage has two components, one due to source end distortions and the other due to harmonic voltage drop across the shunt compensating devices. This is expressed in equation 3.11 as

$$V_{Ld} = \frac{V_{sd}(1-k_1)Z_{ph}}{Z_{ph} + Z_{sh} + Z_s} + I_{Lh}Z_{ph} \tag{3.11}$$

For a unity gain of the series active compensator, only the source end voltage distortions can be cancelled. The load end voltage will have distortions due to the harmonic voltage drop across the passive filter which is proportional to the harmonics in the load current and hence to the total harmonic distortion.

3.6 Performance of Type B Compensation System

A simulink model of the system was built and used to investigate its performance under non-linear load sag, and swell conditions. The system parameters are the same as in compensation system 1. (See Appendix A for the model).

3.6.1 Performance under normal load conditions

Figure 3.20 shows the simulation results of the system for the condition when the system is loaded with the VSNL and CSNL, in the absence of voltage sags or swells or other abnormal voltage condition.

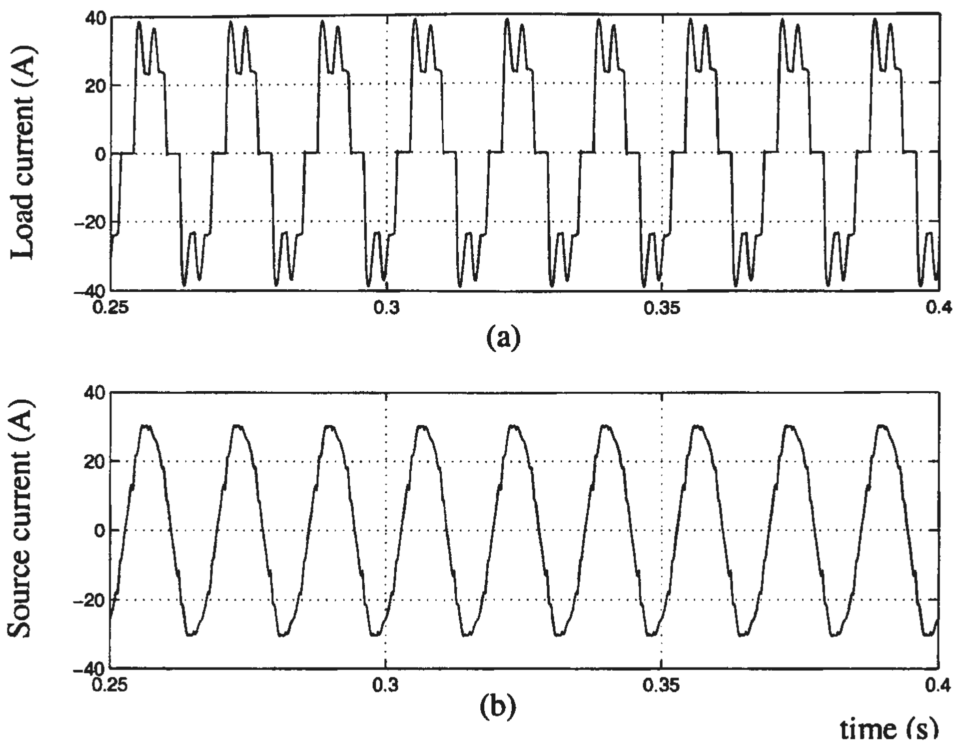

Fig 3.20: (a) Combined load current; (b) source current

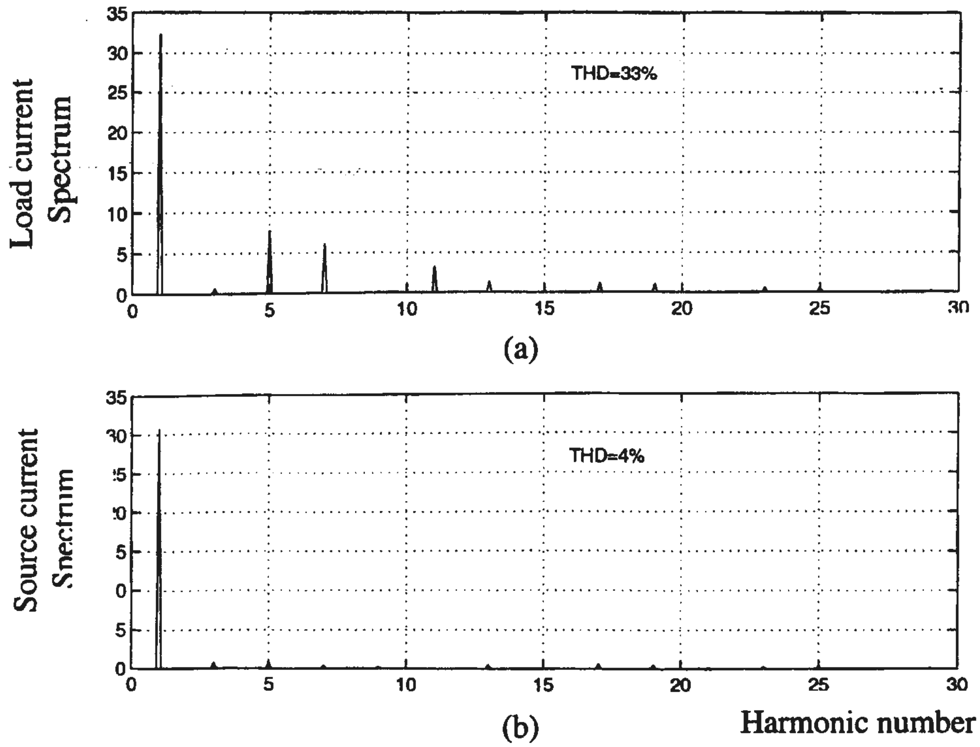

Fig 3.21: Harmonic spectrum of (a) load and (b) source currents

Figure 3.20 shows the simulated results of the load currents of the combined nonlinear load and the current drawn from the supply. Figure 3.21 shows the harmonic spectrum of the load current with a THD of 33%, and the spectrum of the source current with a THD of 4%, an 88% improvement which meets IEEE 519 specifications. The VSNL and CSNL currents are shown in Fig 3.22 and their frequency spectra showing their THD is shown in Fig 3.23. Figures 3.24 and 3.25 shows the waveform and frequency spectra of the source and load terminal voltage. It shows that the load terminal voltage has a high total harmonic distortion of 14%. The compensating voltage and current generated by the active filters is shown in Fig 3.26. The current and voltage are injected into the line in opposite phase to cause a cancellation of existing distortion and harmonics.

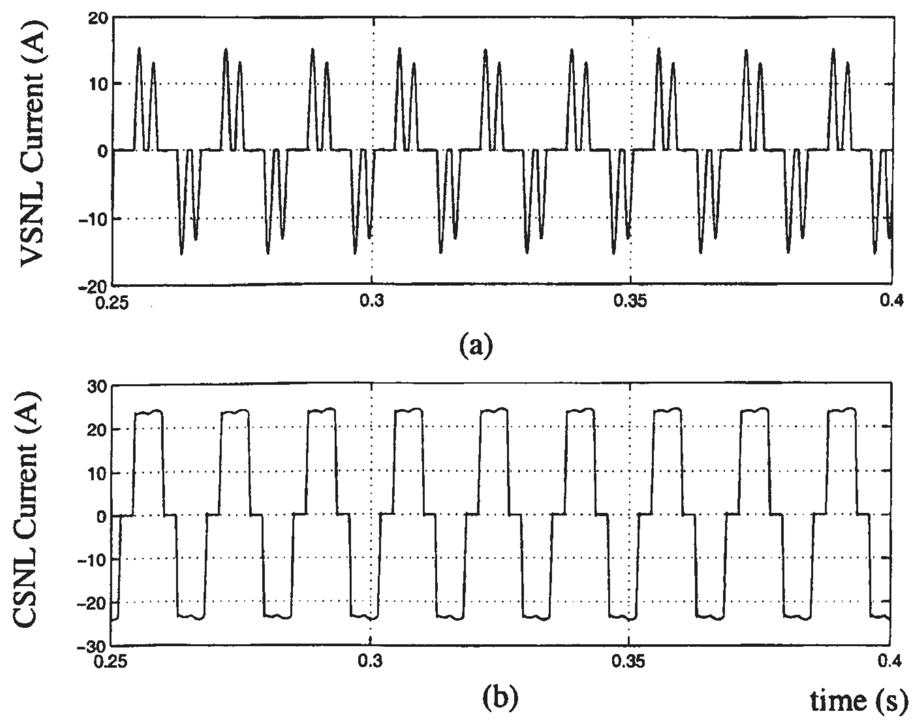

Fig 3.22: VSNL and CSNL currents

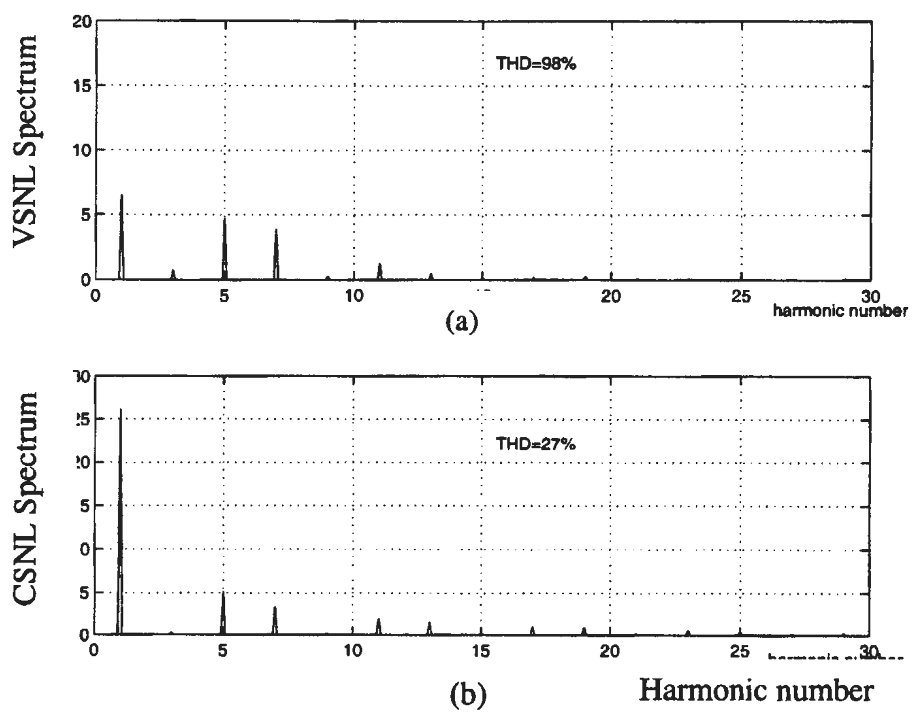

Fig 3.23: Harmonic spectrum of (a) VSNL and (b) CSNL currents.

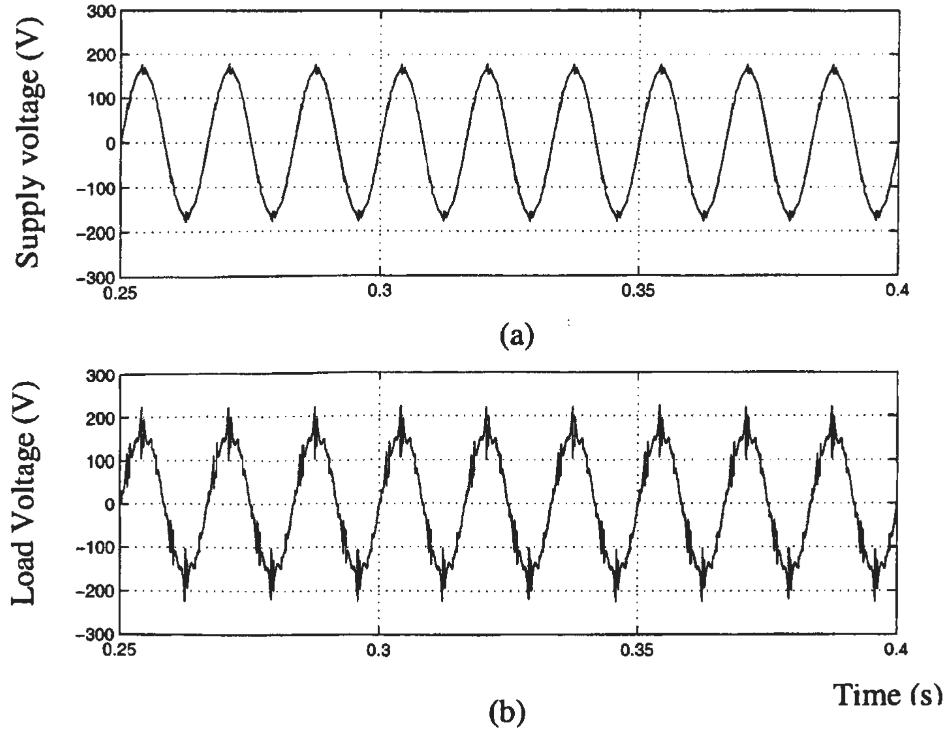

Fig 3.24: (a) Supply voltage waveform and (b) Load voltage waveform

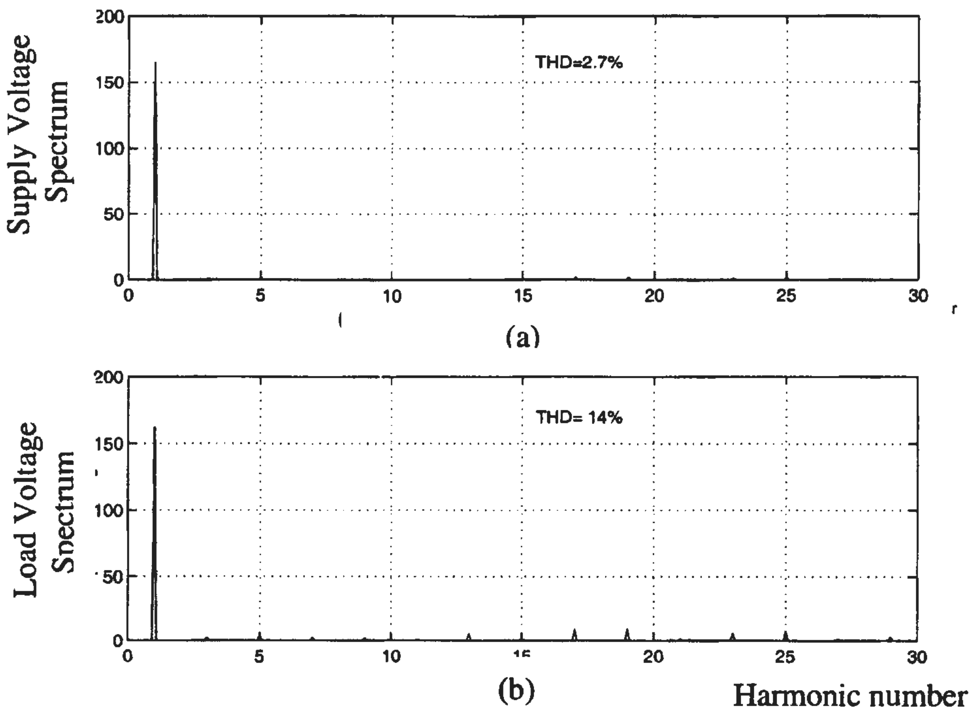

Fig 3.25: (a) Spectrum of supply voltage and (b) Spectrum of load voltage

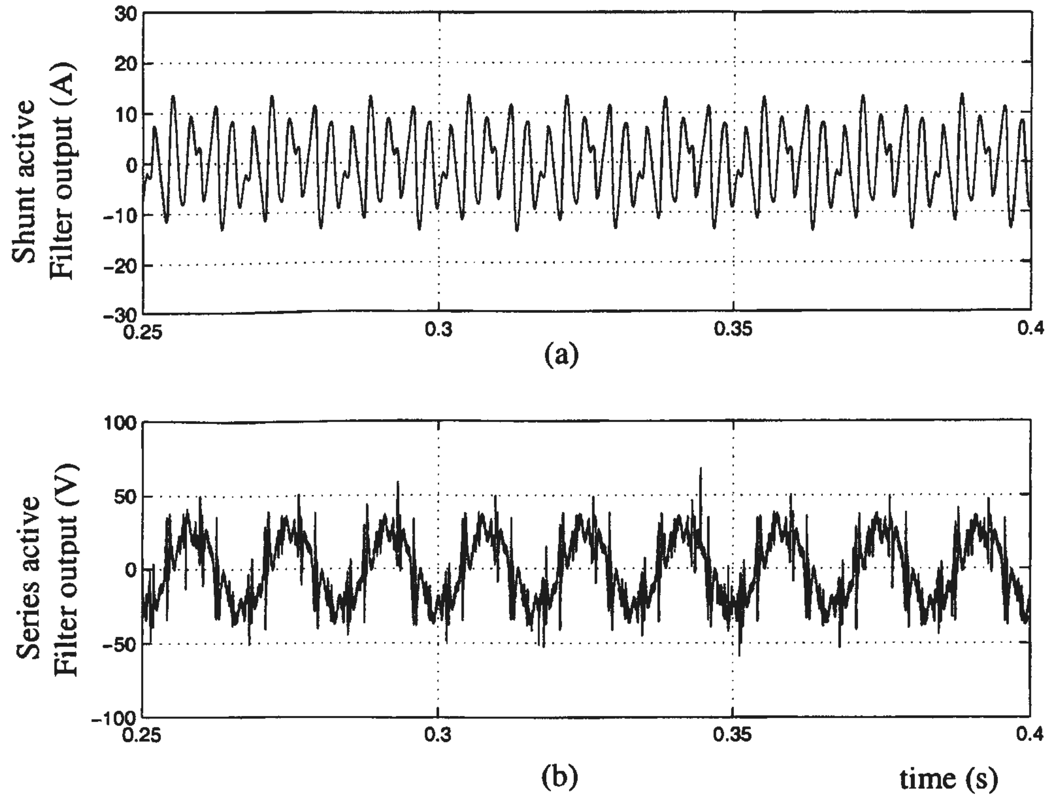

Fig 3.26: (a) Injected harmonics by the shunt active filter and (b) compensating voltage by the series compensator

To further investigate the performance of Type B Compensation System, the load current total harmonic distortion was varied so as to observe the effect on the source current and voltage THD levels as well as the load voltage THD level.

Table 3.3 shows the performance in terms of total harmonic distortion of the source current, voltage and load end voltage as a result of variations in the total harmonic distortion of the load current. The results in the Table were obtained by simulation.

Table 3.3: Source and load Total harmonic distortion for Type B

Load current THD%	Source current THD%	Load voltage THD%	Source voltage THD%
105	11.0	8.7	12.1
74	8.0	4.0	8.0
40	4.5	1.5	6.3
32	3.0	1.2	6.0
23	2.7	1.1	5.1

The simulation result shows that the load end voltage total harmonic distortion consistently fails to meet the recommended limits for normal operation of critical loads. It is also noted that the load end voltage contains more distortion compared to Type A Compensation System. This is a result of the limitation caused by the series connection of passive and active filter, preventing effective compensation of harmonics that are not at the tuned frequencies of the passive filters. Also the second component of (4.11) results in load voltage distortion and cannot be canceled by the active filters.

The results show that Type B Compensation System is capable of harmonic cancellation and correction of voltage distortion. The performance of the shunt active filter is more dependent on the characteristics of the passive filter than in Type A because of the series arrangement. This imposes a constraint on the active filter performance, since the passive filters are usually tuned to specific frequencies. Other frequencies extracted by the synchronous reference frame control scheme and generated by the shunt active filter will be subjected to relatively high attenuation by the passive filter impedance at those frequencies.

For harmonic producing nonlinear loads where the harmonic orders are known and well defined, such as adjustable speed drives using three-phase diode or thyristor converters, Type B Compensation System will be more efficient because of the reduction in the voltage rating of the active devices used in the shunt active filter. However, if the dominant harmonic order is unknown or varies rapidly as in arc furnace loads during the striking of the arc, Type A Compensation System will be more effective, since the shunt active filter is not constrained by the passive filter. Therefore there is a tradeoff between the voltage rating of the active devices and the order of harmonics that can be effectively compensated.

3.6.2 Performance in the presence of voltage flicker

Figure 3.27a shows the supply voltage with a 30% modulation by a low frequency sinusoid, resulting in voltage flicker conditions. Figure 3.27b shows the load-end voltage, which is held constant and 3.27c is the compensation voltage generated by the series active compensator. As in Type A Compensation System, Type B Compensation System is also able to dynamically restore the load end voltage to predefined reference value, making the load end voltage immune to system disturbances such as voltage sags, swell, flicker and other voltage distortion that may be undesirable at the load end. Due to the fact the compensator is constantly online, response to variation in the voltage is fast and dynamic. The multiple loop control scheme used in the inverter circuit ensures that the inverter output voltage follows the reference and that a stable operation results.

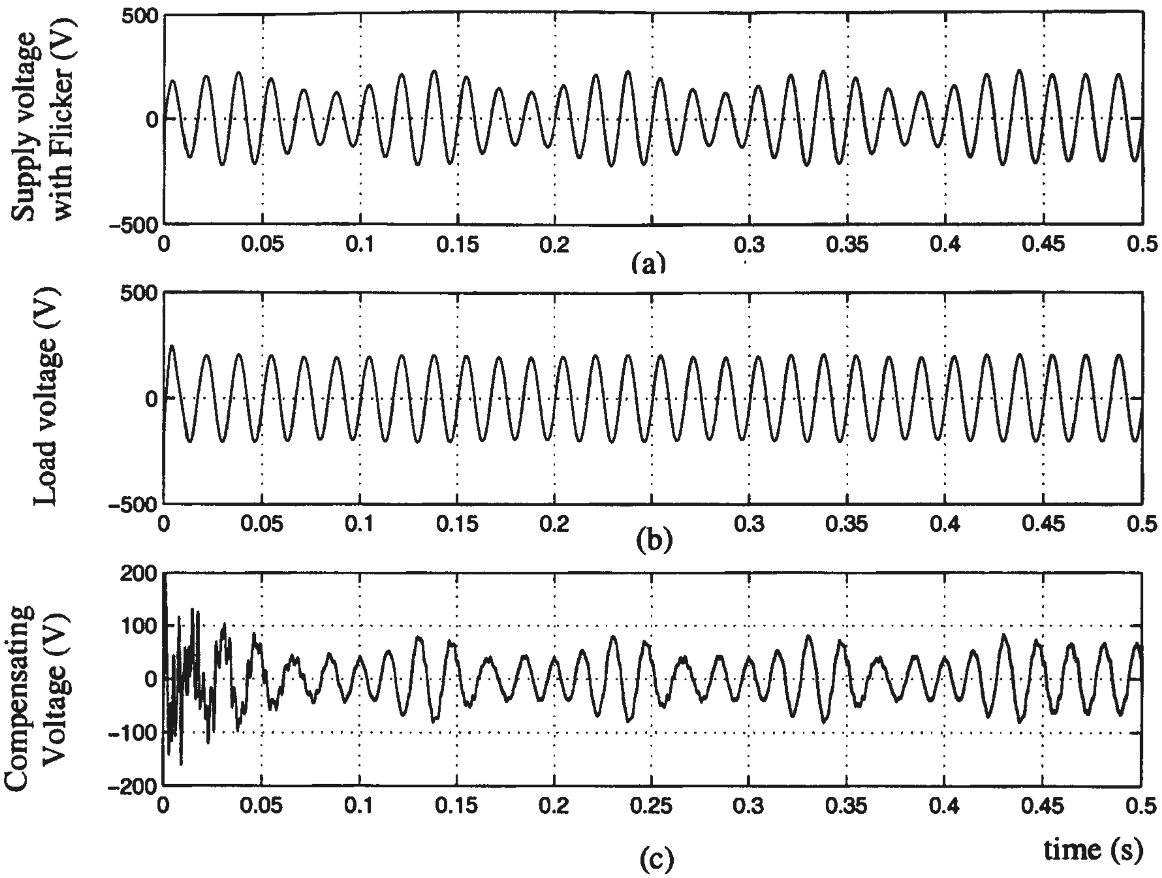

Fig 3.27: (a) Supply voltage with flicker; (b) Compensated load end voltage (c) Series active compensator output voltage

3.6.3 Simulation results for more complex models for Type B

More complex models were also used to present a more realistic view of the system performance. The results are presented in this section. Figures 3.28 and 3.29 shows that the system is just as effective with more complex simulation models. The results are consistent with that of the simpler models.

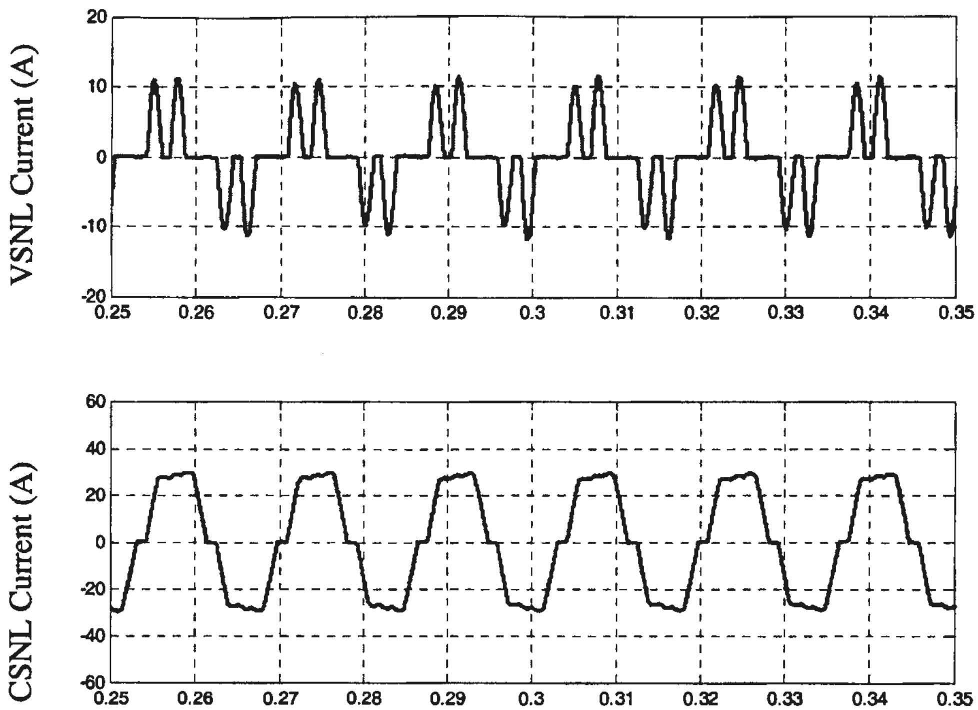

Fig 3.28: Nonlinear load currents with more complex models for type B

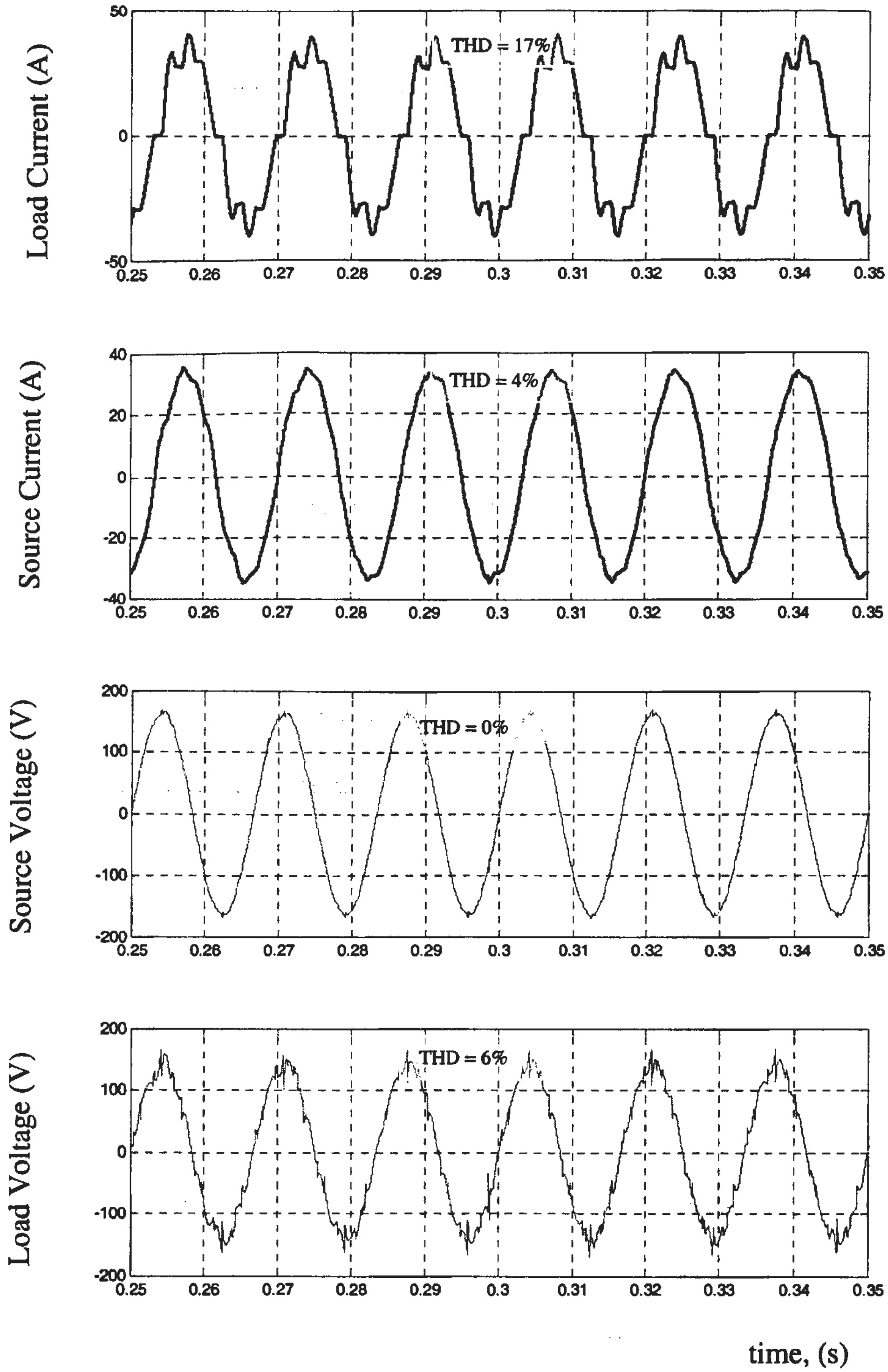

Fig 3.29: Currents and Voltages with more complex models for type B

3.7 Summary

In this chapter, two different types of load, the current source type nonlinear load and the voltage source type nonlinear load were introduced and discussed. Their harmonic effects were also considered as well as the harmonic and distortion mitigation methods.

Two compensation systems suitable for a combination of both kinds of loads were investigated. Type A Compensation System consisted of a parallel tuned passive filter in series with an active filter using multiple loop control method as the series hybrid compensator. It also has a series tuned passive filter in parallel with an active filter using the synchronous frame based harmonic extraction method as the shunt compensator. Type B Compensation System had the same series compensator as in Type A, but a shunt compensator with the passive filter in series. The performance of both compensation systems was investigated under various load conditions as well as source variation. Both systems were effective in mitigating source end distortions resulting from sags, swell or flicker. However, Type A Compensation System was more effective in reducing the total harmonic distortion of the load end voltage and its source end current had a lower level of harmonic distortion. However the voltage rating of the active filter can be high. Type B Compensation System results in lower rating of the active filter, but the range of harmonics covered by the passive filter limits its performance. This results in a tradeoff between bandwidth in Type A Compensation System and rating in Type B.

Chapter 4

Load-end Voltage and Current Compensation Systems

In the previous chapter, the performance and characteristics of two compensation systems were examined and it was shown that both systems were effective in compensating for harmonics caused by the operation of nonlinear loads in the system. However, it was also shown that because of the position of the series active compensator, which in both systems is between the supply and the shunt hybrid filter, it is unable to compensate for voltage distortions in the load terminals caused by the flow of current harmonics in the shunt filter. In order to compensate for this drawback, it is proposed that the series active compensator be positioned between the passive filter and the load terminals. This will allow for the voltage distortions due to source-end variations and the shunt filter to be compensated. This topology is expected to result in better voltage compensation than the two systems previously considered. In this chapter, the analysis and performance of this compensation system will be investigated with the aim of demonstrating that the total harmonic distortion in the load terminal voltage is improved compared to the previous systems. Single-phase equivalent circuit model is used to carry out the analysis as in the previous chapter.

4.1 Type C Compensation System

The first proposed compensation system referred to as Type C Compensation System is shown in schematic form in Fig 4.1 and its single-phase equivalent circuit model is shown in Fig 4.2.

The system topology is comparable to that of Type A Compensation System, with the exception that the series active compensator is positioned at the load terminal voltage for better voltage compensation. The functions of the active compensators are described as follows:

- As in the previously considered systems, the shunt hybrid compensator is used for current compensation since current compensation and voltage compensation are carried out separately. The active and passive filters connected in parallel to the load complement each other in the harmonic bandwidth covered. The injected harmonics by the inverter is given by $I_{AF2} = k_2(I_{Lh} - I_{pfh})$.
- The series active compensator acts as a distortion voltage generator serving to produce the voltage distortion at the passive filter terminals and injecting it in opposite phase in the line, hence canceling it out. The output voltage is given by $V_{AF1} = V_P(1-k_1)$ where V_p is the distortion voltage at the passive filter terminals ob-

tained by subtracting the actual passive terminal voltage from a reference i.e. $V_p = V_p^* - V_{ref}$, where V_p^* is the actual distorted voltage, consisting of the fundamental sinusoidal voltage that may be due to sags, swells and distortion voltage.

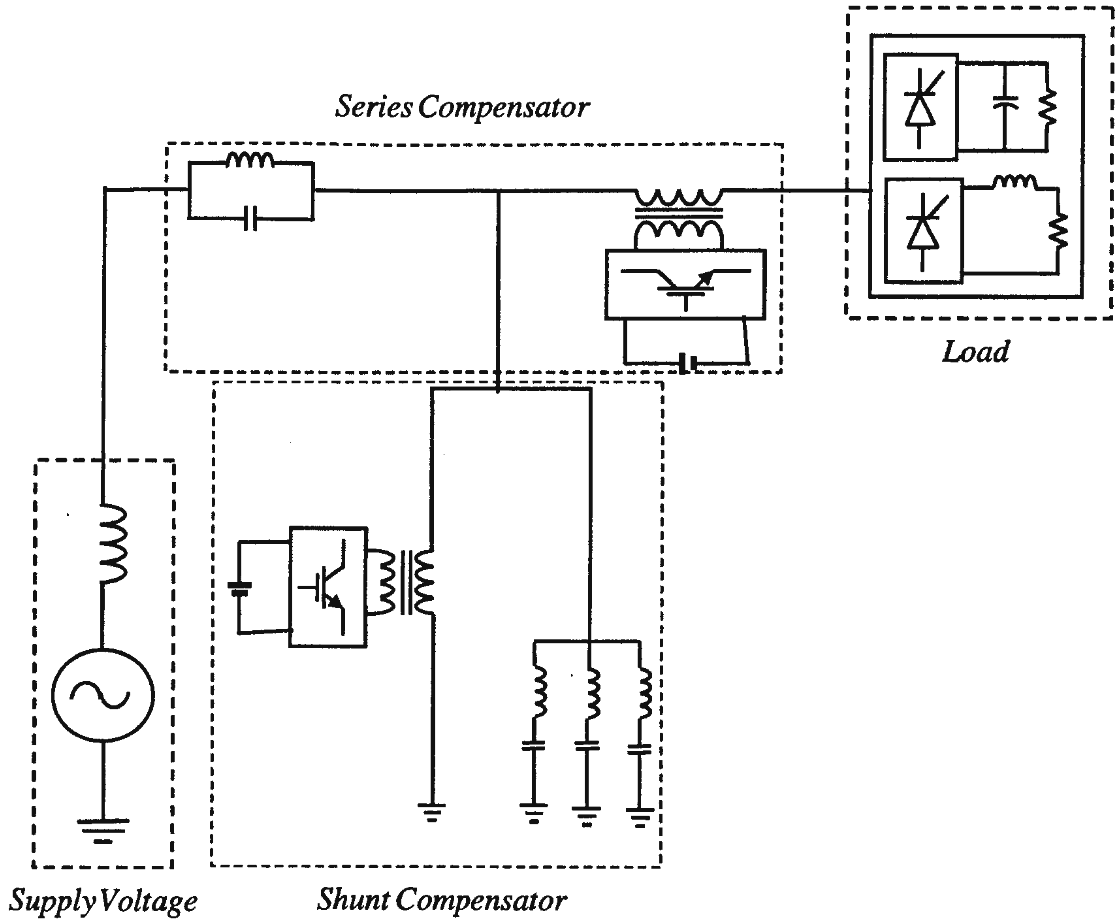

Fig 4.1: Type C Compensation system

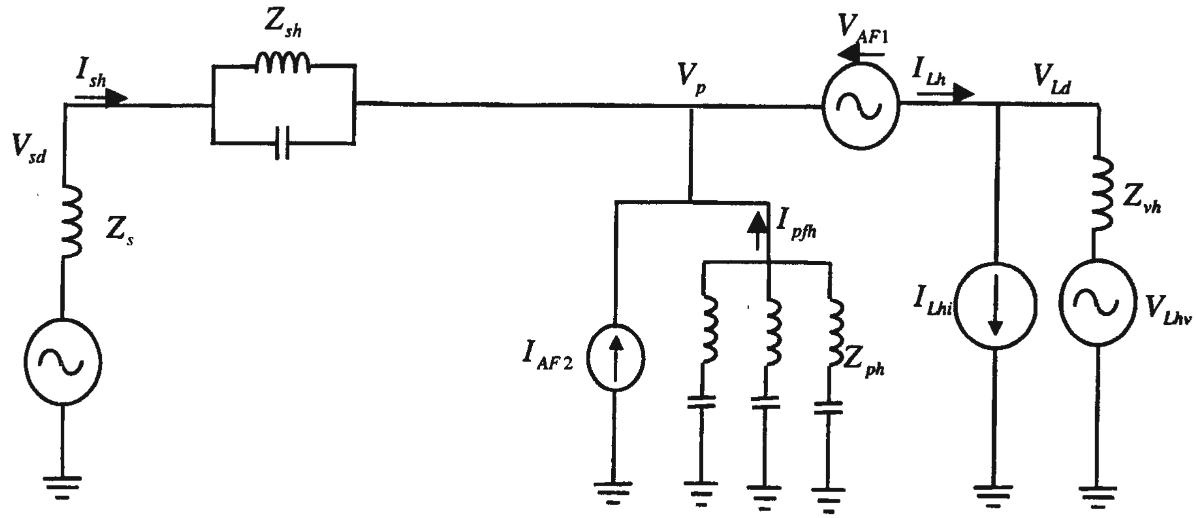

Fig 4.2: Single-phase equivalent circuit of Type C compensation system

By applying KCL to the shunt filter terminals in the circuit of Fig 4.2, the harmonic current flowing into the supply terminals is given as

$$I_{sh} = \frac{V_{sd} - V_p}{Z_s + Z_{sh}} + I_{Lh} - I_{pfh} - k_2(I_{Lh} - I_{pfh}) \tag{4.1}$$

where I_{sh} has two components; one due to load current harmonics and the other due to source end distortion. With the gain of the shunt active filter set to unity, the component due to the load current harmonics is cancelled. The components due to the supply distortion are not compensated for actively. However, the high impedance of the series passive filter at the tuned harmonic frequencies serves to limit the supply harmonics that can flow into the shunt filter. Comparing (4.1) to (3.5), it is observed that the series active compensator has no effect on current compensation in Type C Compensation System, unlike in Type A Compensation System, where it serves to cancel out supply end distortion current. This can also be seen intuitively since the position of the series active compensator in Type C requires the full load current to flow though it. Hence it cannot compensate for load current harmonics. Its placement between the load terminals and the passive filter also prevents it from being able to compensate for supply current distortion. Hence current compensation and voltage compensation are achieved independently in Type C Compensation System, the shunt active and passive filter being entirely responsible for mitigation of the load current harmonics.

The series active filter is used to provide voltage compensation for the load terminals.

The voltage distortion at the load terminals without the series active filter is the superposition of supply voltage distortion and the distortion voltage component due to distortion current flowing in the passive filter. The load terminal voltage can be written as

$$V_{Ld} = \frac{V_{sd} Z_{ph}}{Z_{ph} + Z_s + Z_{sh}} + I_{pfh} Z_{ph} \tag{4.2}$$

With the series active filter inserted between the passive filter terminals and the load, the passive filter terminal voltage becomes different from the load terminal voltage.

$$V_p = \frac{V_{sd} Z_{ph}}{Z_{ph} + Z_s + Z_{sh}} + I_{pfh} Z_{ph} \tag{4.3}$$

and the load terminal voltage becomes

$$V_{Ld} = V_p (1 - k_1) \tag{4.4}$$

Equation (4.4) shows that the insertion of the series active filter in the position between the passive filter terminals and the load terminals allows for a more comprehensive voltage correction as it allows for correction of both the supply end distortion as well as the distortion caused by the passive filter. This constitutes a significant improvement of the load terminal voltage profile over the previous systems considered.

The significant improvement in the load voltage profile in terms of its harmonic and distortion content comes at the cost of a poorer harmonic compensation of the supply current if the supply voltage is distorted. However, the series passive filter contributes to limit the harmonic current flowing into the shunt passive filter since it blocks the harmonics it is tuned to, which usually are the dominant harmonics. This can be seen in (4.1).

4.2 Simulation results for Type C Compensation System

As in Type A and Type B Compensation Systems, the validation of Type C Compensation System performance was accomplished via computer simulation in the Power System Block set of Simulink. The simulation model is presented in Appendix A. For the purpose of consistency and comparison, the simulation was carried out under the same load and supply conditions as for the previous two systems in chapter 3.

Figure 4.3a shows the input current drawn by the combination of the voltage source type nonlinear load and the current source type nonlinear load. Figure 4.4a is the harmonic spectrum of the load current, with a total harmonic distortion of 43%. Figures 4.3b and 4.4b show the resulting source current and its harmonic spectrum, with a total harmonic distortion of 4.3%. Figures 4.5 and 4.6 show the individual nonlinear load currents and their harmonic contents. Figure 4.7 shows the supply voltage and the load terminal voltage when the supply voltage has low distortion as shown by their harmonic spectrum in Fig 4.8. Figure 4.9 shows the supply voltage with harmonic distortion, and the compensated load voltage with no distortion. The compensating harmonic current is shown in Fig 4.10a. The current is generated by the shunt active filter and injected into the line forcing the load current harmonics to flow in the shunt filter path instead of the source. Figure 4.10b is the generated voltage by the series active filter. It compensates for the voltage drop resulting from the flow of fundamental current in the series passive filter. Figure 4.11 shows that the system compensates for voltage flicker in the source terminal, keeping the load terminal voltage constant.

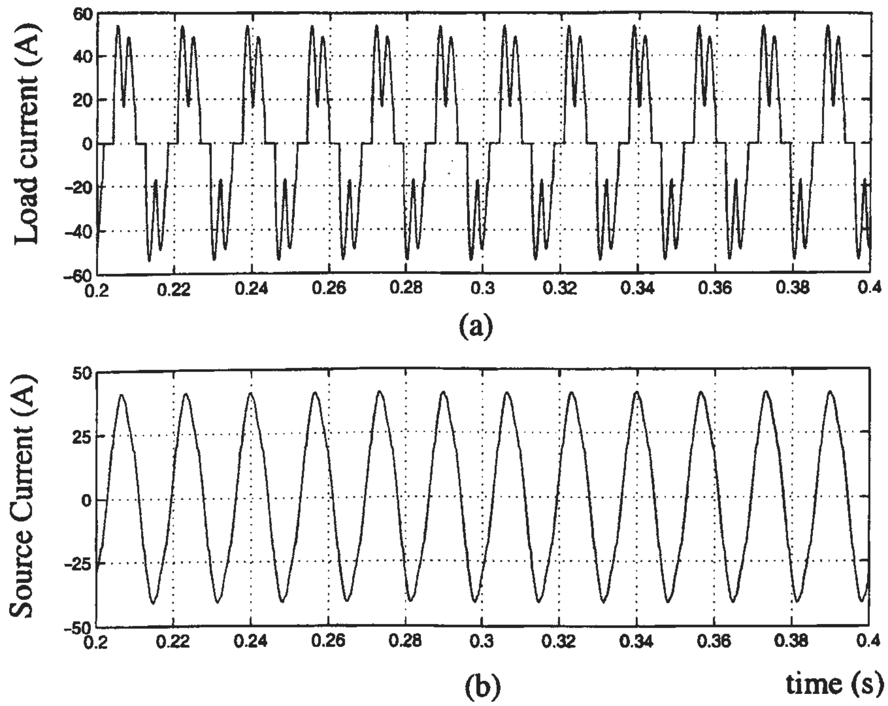

Fig 4.3: (a) Load current; (b) Source currents

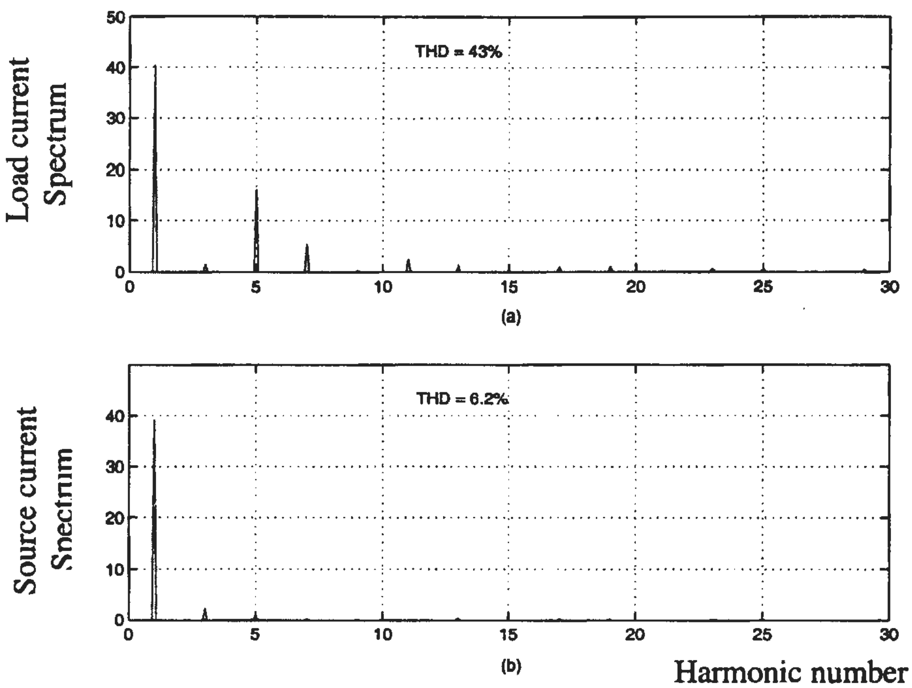

Fig 4.4: Harmonic spectrum of (a) load current; (b) source current

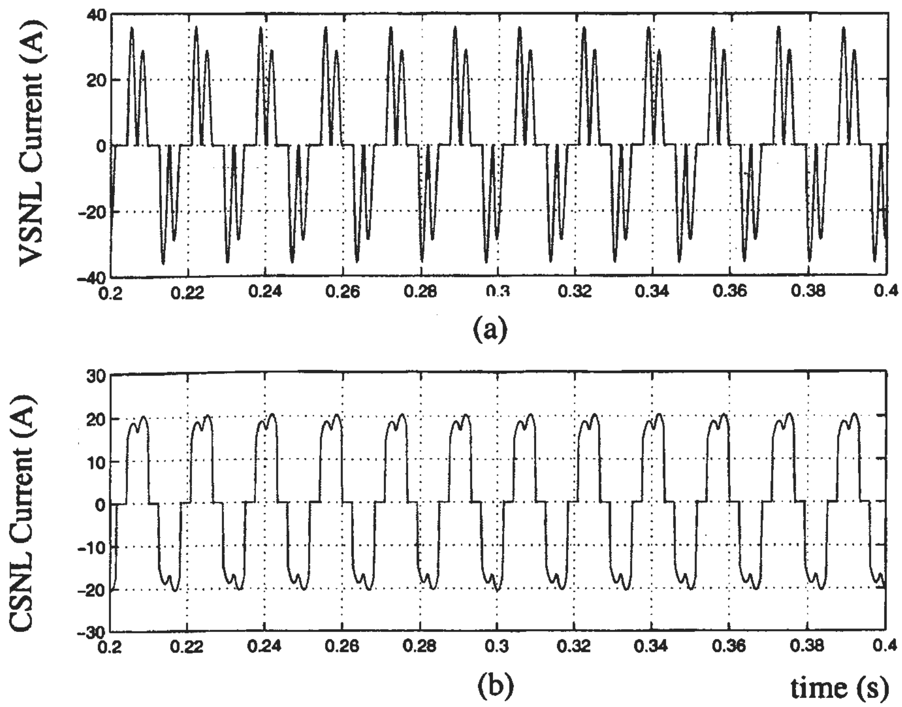

Fig 4.5: (a) VSNL current; (b) CSNL current

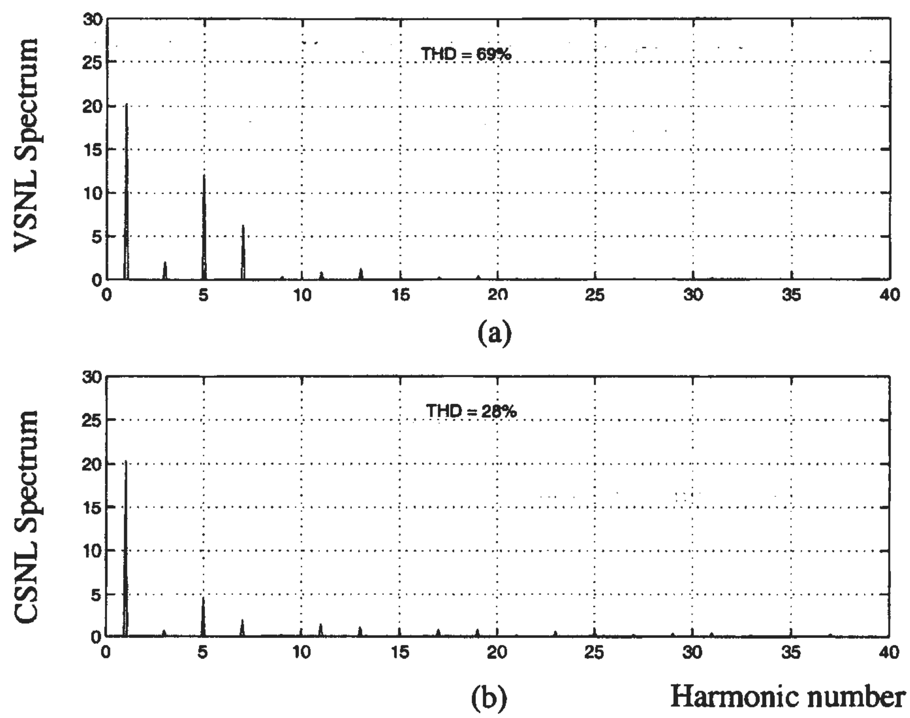

Fig 4.6: Harmonic spectrum of (a) VSNL Current; (b) CSNL Current

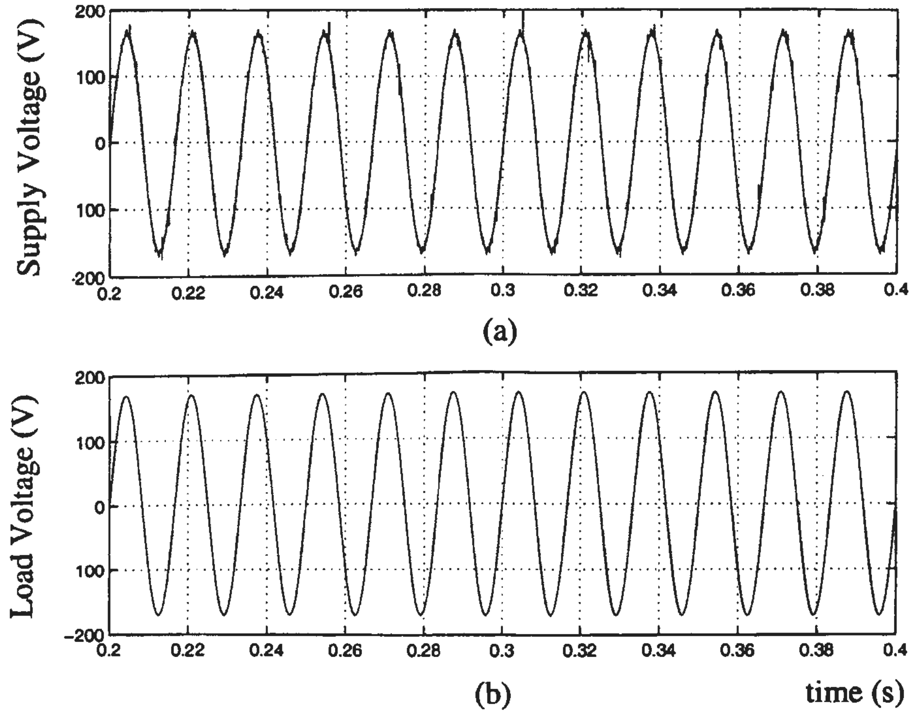

Fig 4.7: (a) Supply voltage; (b) Load voltage

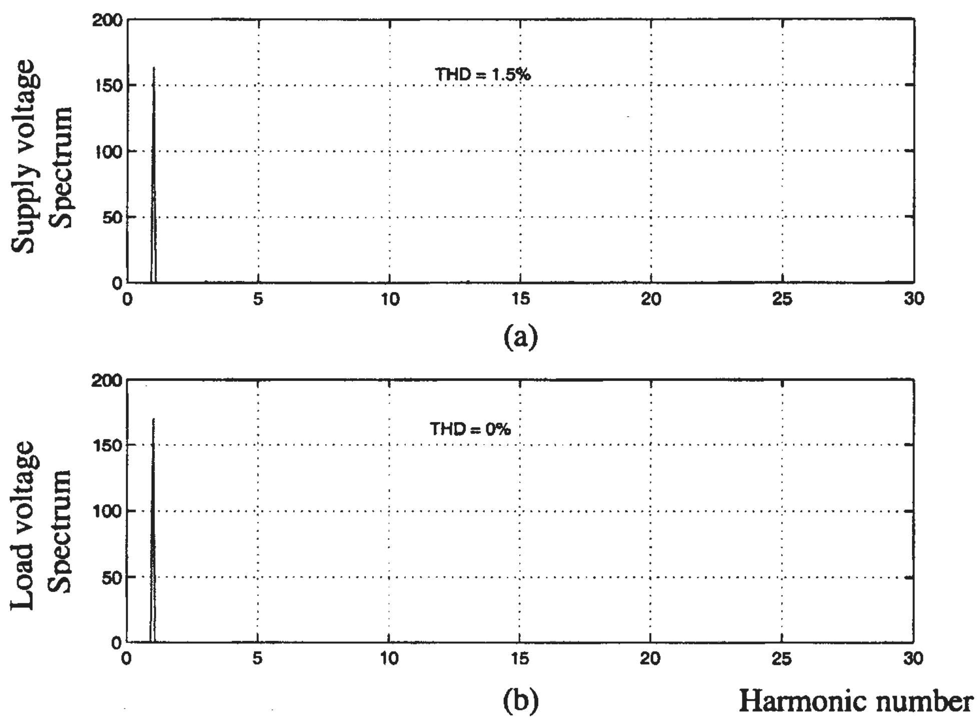

Fig 4.8: Harmonic spectrum of (a) Supply voltage; (b) Load voltage

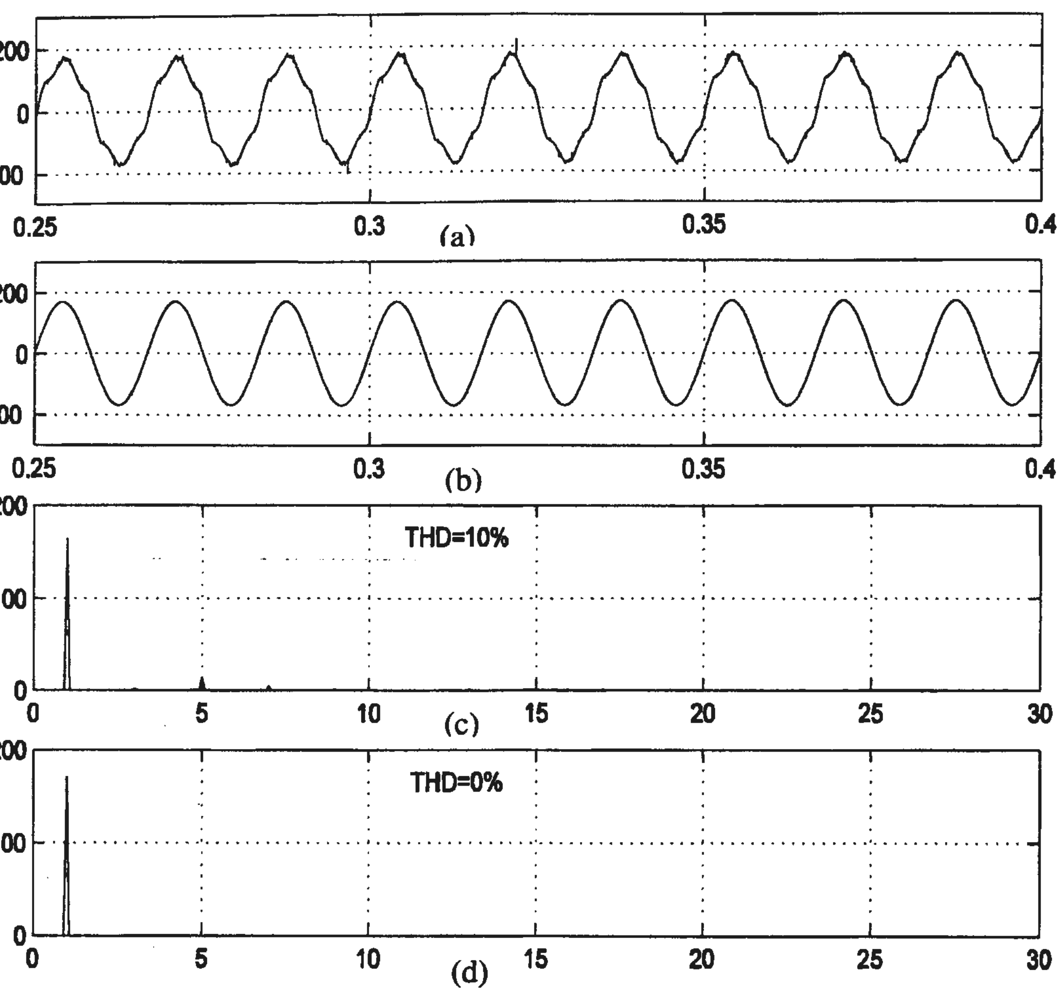

Fig 4.9: (a) Distorted supply voltage; (b) Compensated load voltage; (c) Spectrum of supply voltage; (d) Spectrum of load voltage

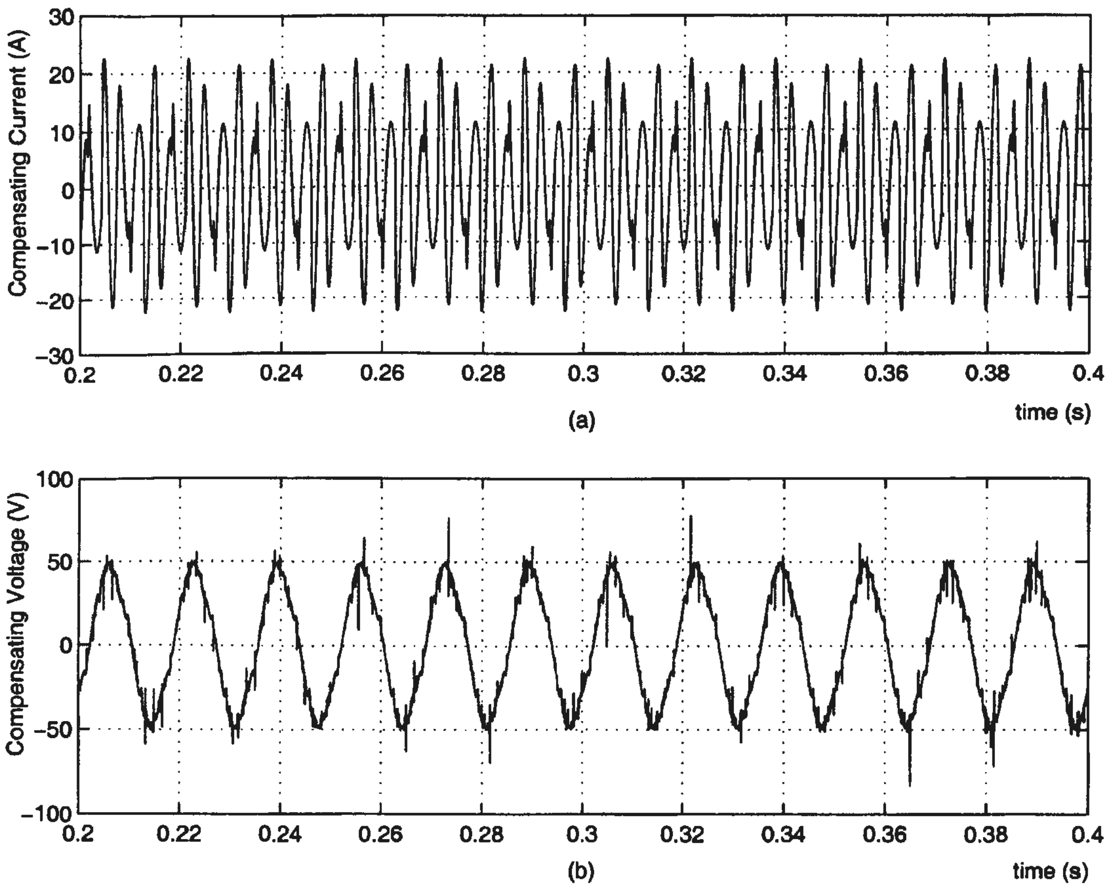

Fig 4.10: (a) Compensating currents generated by the shunt active filter; (b) Compensating voltage generated by the series active filter

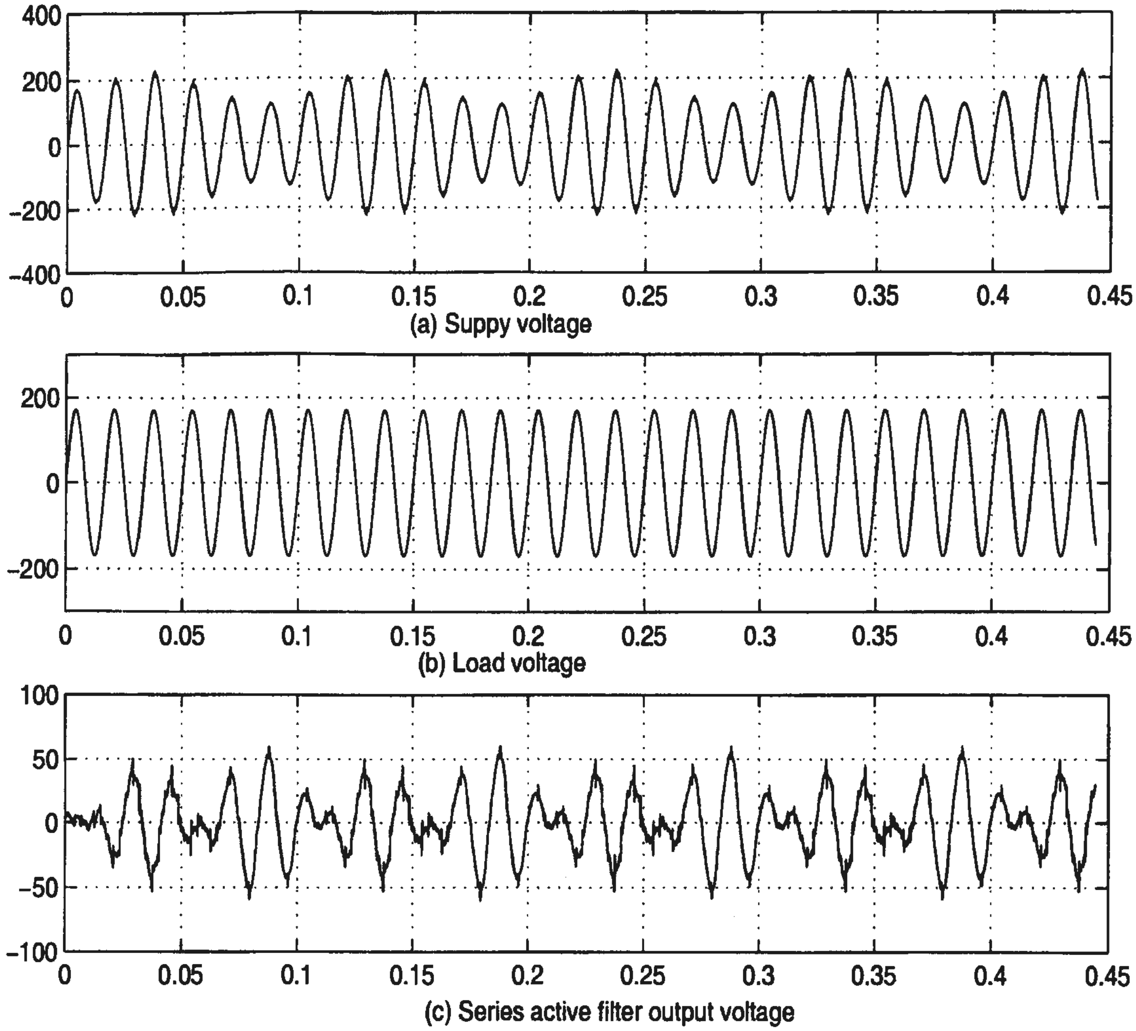

Fig 4.11: Response to voltage fluctuation and flicker.

To further investigate the performance of the compensation system, the total harmonic distortion of the load current was varied to observe the effect on the THD of the source current and the THD of the load voltage. The result is shown in Table 4.1. The results show that the compensation system is particularly effective in the elimination of load voltage distortion. This is expected due to the position of the series active compensator in the topology.

Table 4.1: Source and load total harmonic distortion for Type C

Load current THD%	Source current THD%	Load voltage THD%	Source voltage THD%
110	4.12	0.76	3.20
74	2.89	0.50	2.90
40	1.72	0.43	2.70
32	1.46	0.31	2.10
23	1.22	0.15	1.40

The Table also shows that the system is able to correct for harmonic distortion in the source current and in the source voltage. Type C Compensation System is thus able to compensate for current distortions caused by the nonlinear load, and it also has the advantage of excellent load terminal voltage compensation as indicated by the near zero vantage of excellent load terminal voltage compensation as indicated by the near zero total harmonic distortion.

Due to the parallel connection of the shunt active filter with the passive filter, the harmonic current compensation is accomplished on a complementary basis, since the active filter control reference currents are the passive filter harmonics subtracted from the load current harmonics. This results in lower current ratings, but has a disadvantage of requiring relatively large number of current sensors. A series connection of the shunt active filter and passive filter should remove the need for large number of current sensors, and large voltage rating due to direct line connection. This results in a new topology, Type D Compensation System.

4.2.1 Simulation results for more complex models for Type C

Again, in this compensation system, more complex models were also used to present a more realistic view of the system performance. The results are presented in this section. Figures 4.12 shows the nonlinear load currents resulting from the operation of the two types of nonlinear loads considered, the combined load currents and the resulting source currents having a low total harmonic distortion. The source and load terminal voltage waveforms are shown in Fig 4.13. The results show that the system is just as effective with more complex simulation models.

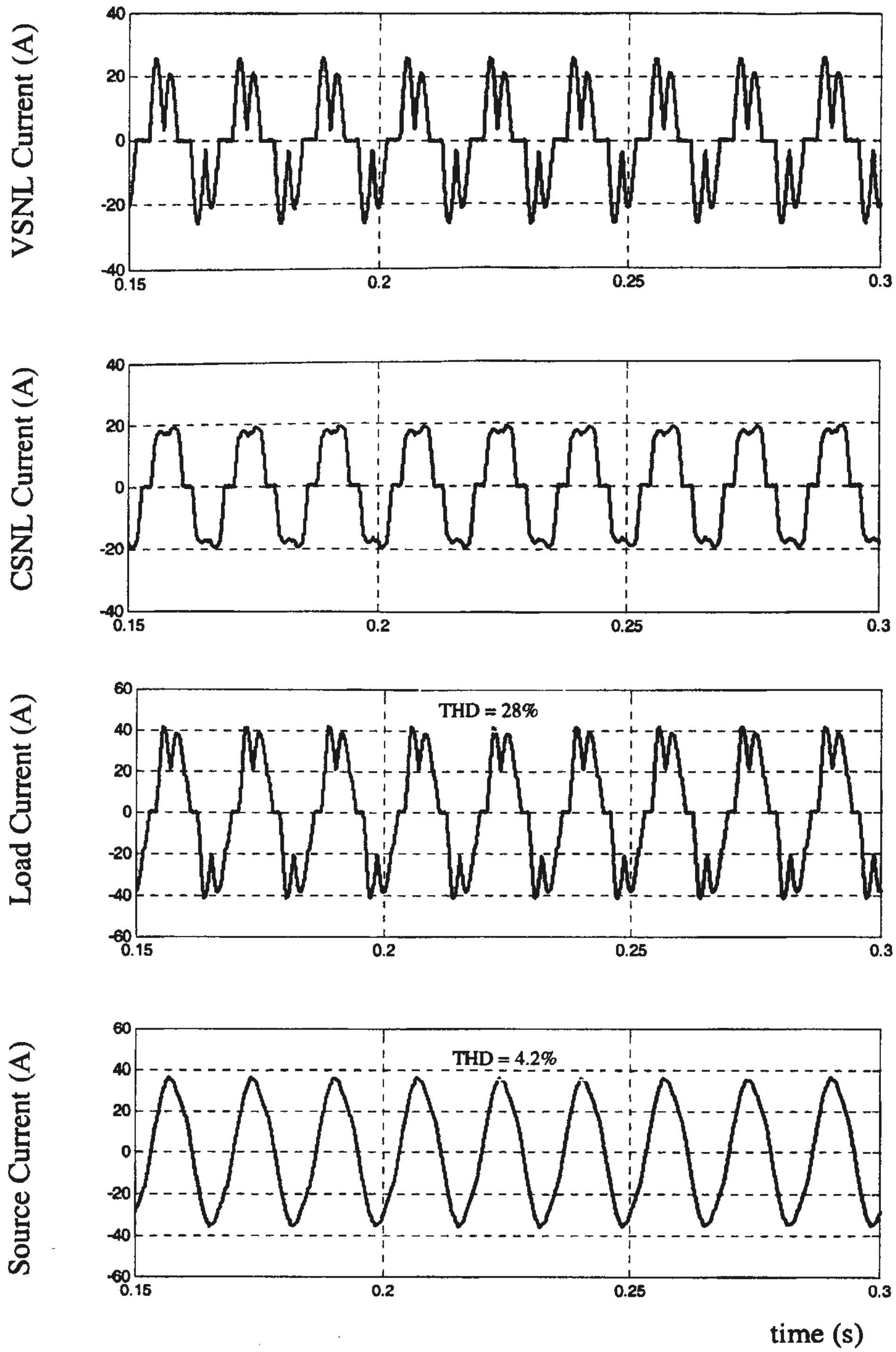

Fig 4.12: Load and source currents for more complex models for Type D compensation system

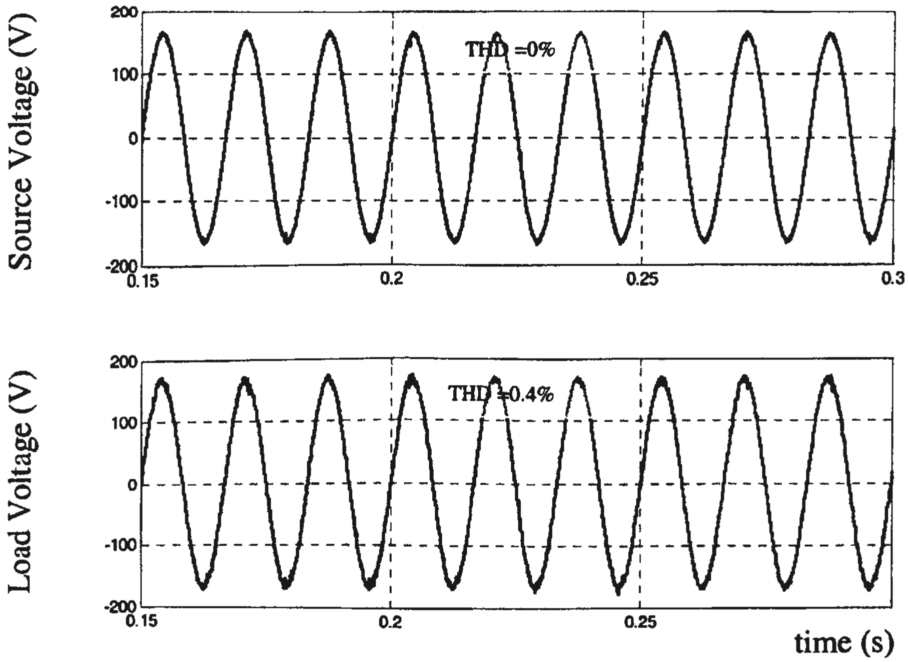

Fig 4.13: Source and load voltage for more complex models for Type C

4.3 Type D Compensation System

This harmonic and distortion compensation system is similar to the Type C Compensation System except that the parallel passive filter and the shunt active filter are placed in series. This arrangement ensures that the same harmonic current flow in both filters, but the line voltage is shared. This is advantageous in that it limits the voltage stress on the semiconductor switches used in the active filter, resulting in reduced ratings and cost. As in the previous systems, a single-phase approach is used in deriving the compensation equations. Figure 4.14 shows a singe phase diagram of the compensator and Fig 4.15 shows the single-phase equivalent model.

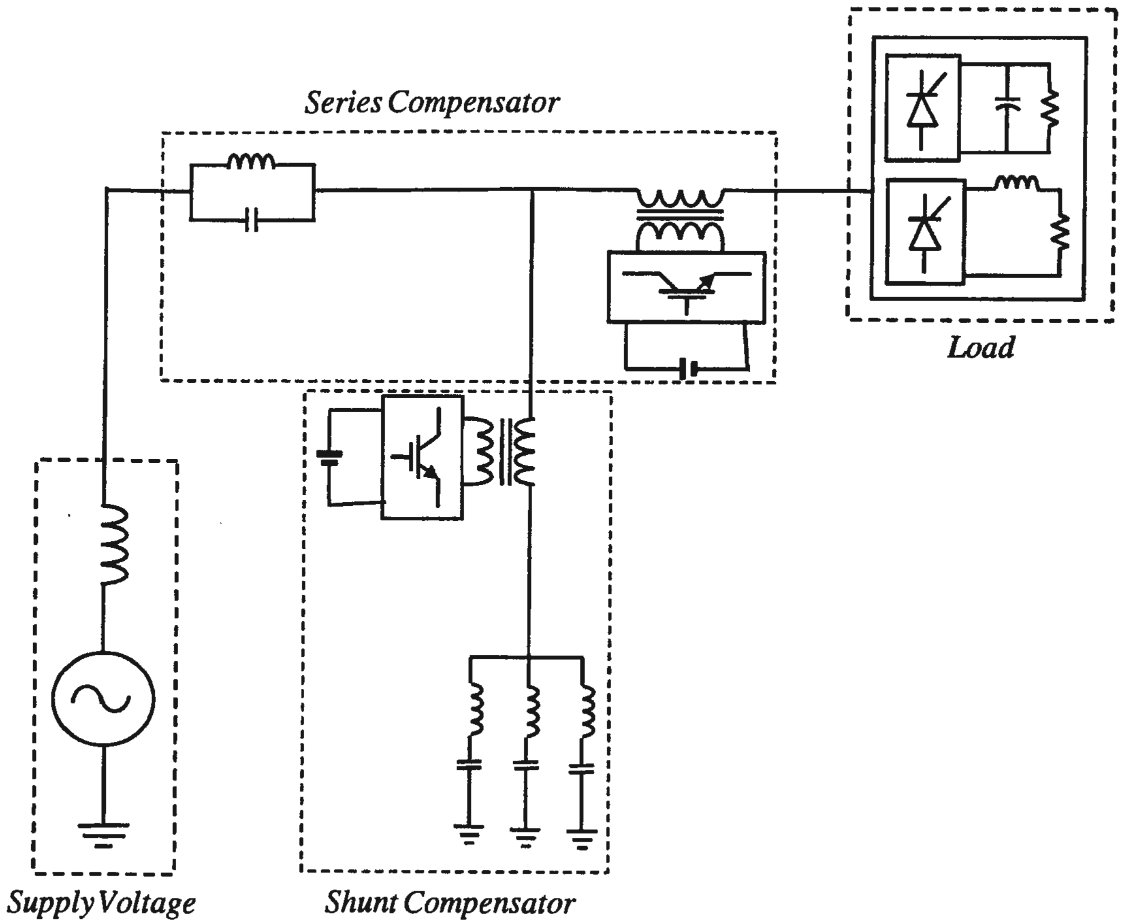

Fig 4.14: Type D Compensation System

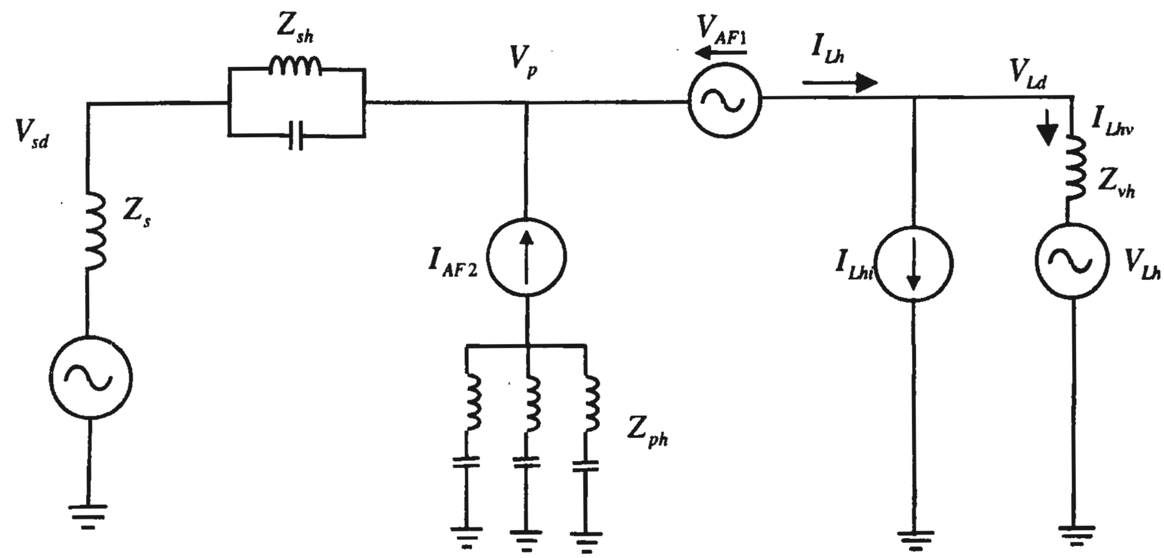

Fig 4.15: Single phase equivalent model of Type D compensation system

From the circuit of Fig 4.15, the harmonic current flowing in the source is obtained as

$$I_{sh} = \frac{V_{sd} - V_p}{Z_{sh}} + I_{Lh}(1 - k_2) \tag{4.5}$$

Equation (4.5) shows that with a tight control of the shunt active filter, the harmonics produced as a result of the nonlinear loads can be cancelled. However, harmonics produced as a result of supply voltage distortion will tend to flow into the shunt passive filter, which has low impedance at tuned frequencies. The series passive filter therefore serves to limit the flow of supply end harmonics into the shunt compensator at the dominant harmonic frequencies.

The voltage compensation principles are the same as for the Type C Compensation System; hence (4.2), (4.3) and (4.4) apply.

4.4 Simulation results for Type D Compensation System

The system was simulated under the same conditions as for the previous systems. Matlab was used for the simulation and the Simulink model is shown in Appendix A. Figure 4.16 shows the load and source current and their harmonic spectra. The load current total harmonic distortion of 33% has been reduced to 1.5% in the source current. Fig 4.17 is the VSNL and CSNL currents and their harmonic spectra, showing the magnitude of the individual frequency contents. Fig 4.18 is the supply and load voltage and their frequency spectrum showing an undistorted supply and load voltage.

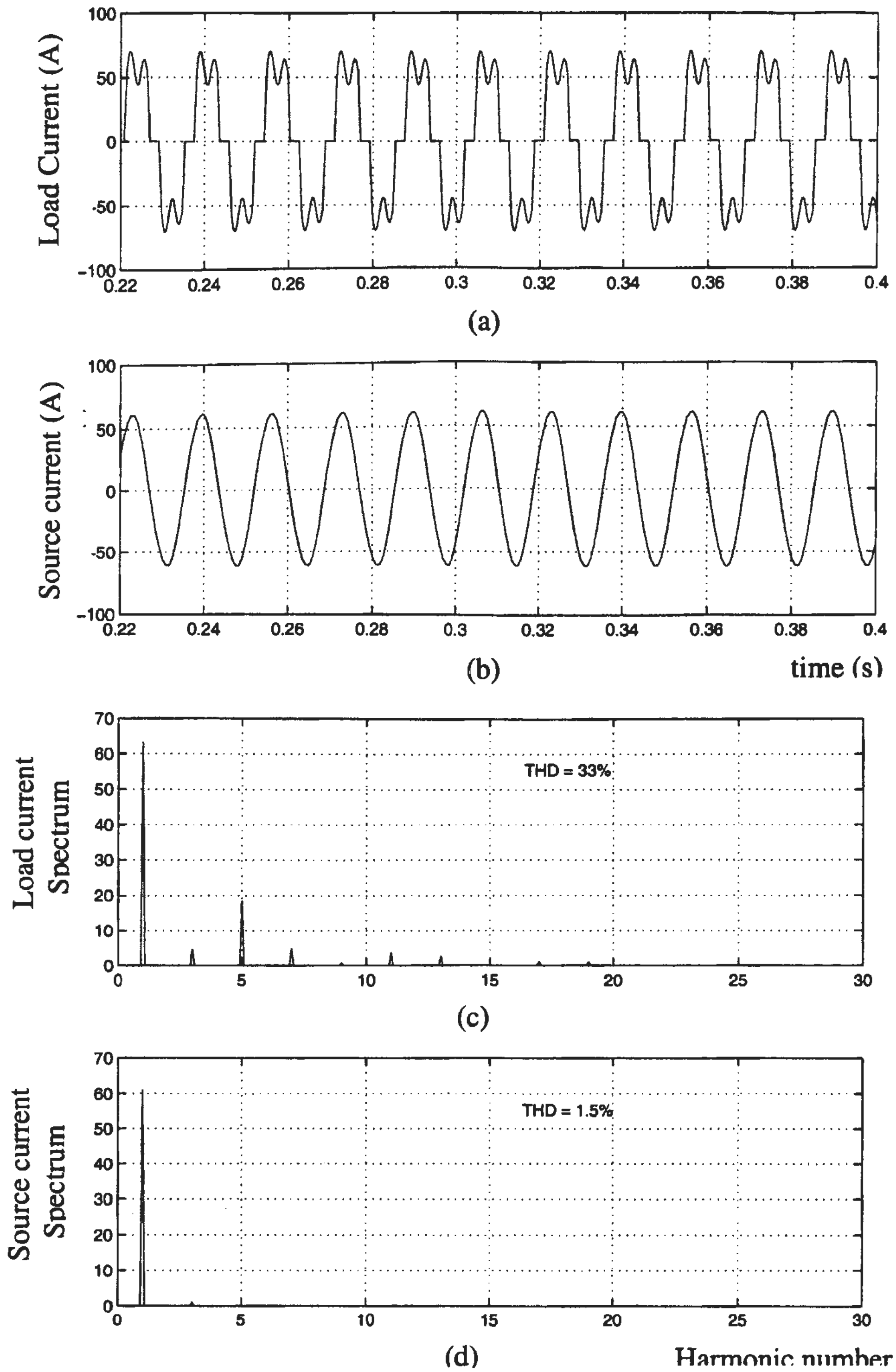

Fig 4.16: (a) Combined load current; (b) source current; (c) Harmonic spectrum of the load current; (d) Harmonic spectrum of the source current

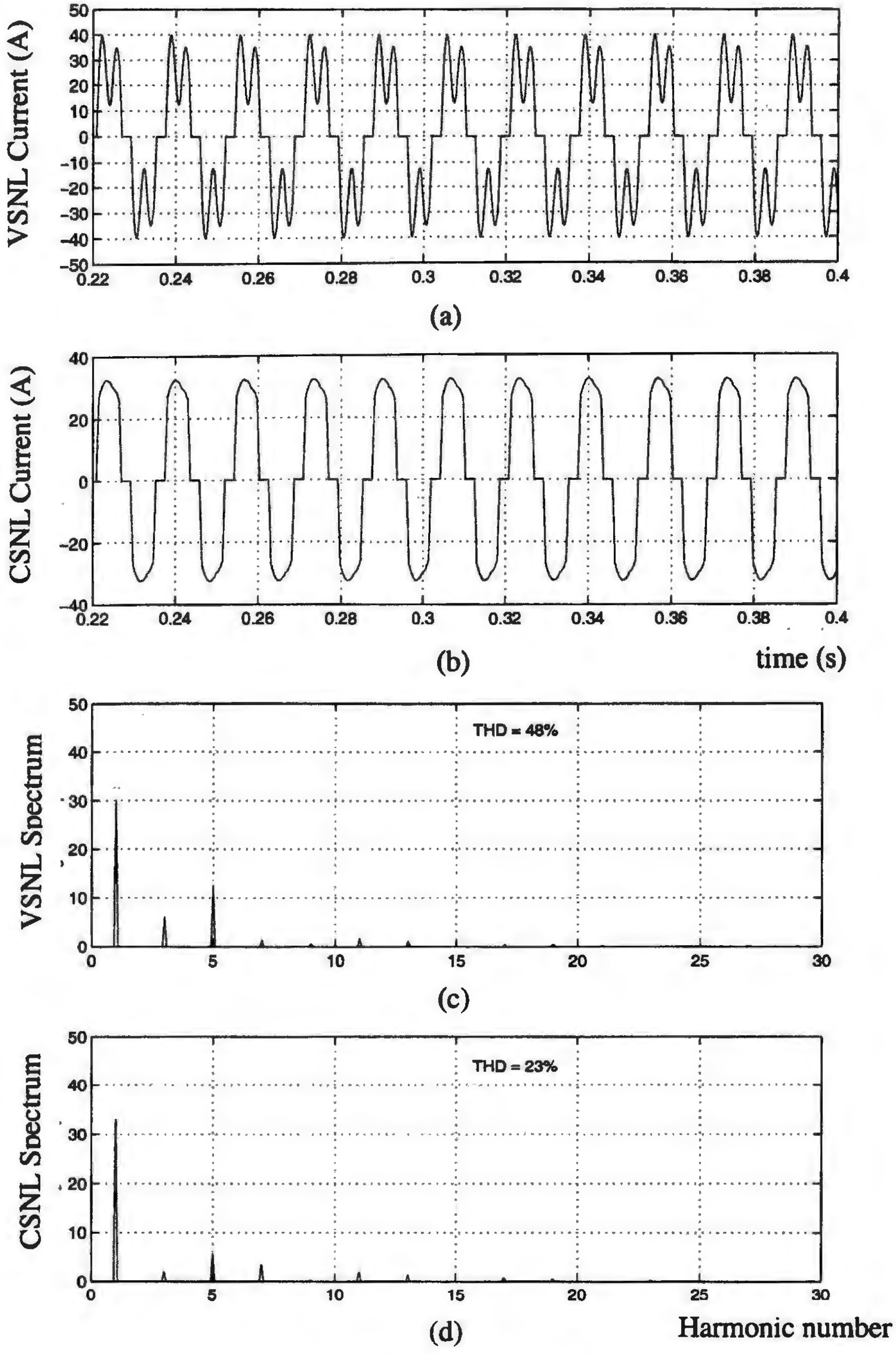

Fig 4.17: (a) VSNL current; (b) CSNL current; (c) Harmonic spectrum of the VSNL current; (d) Harmonic spectrum of the CSNL current

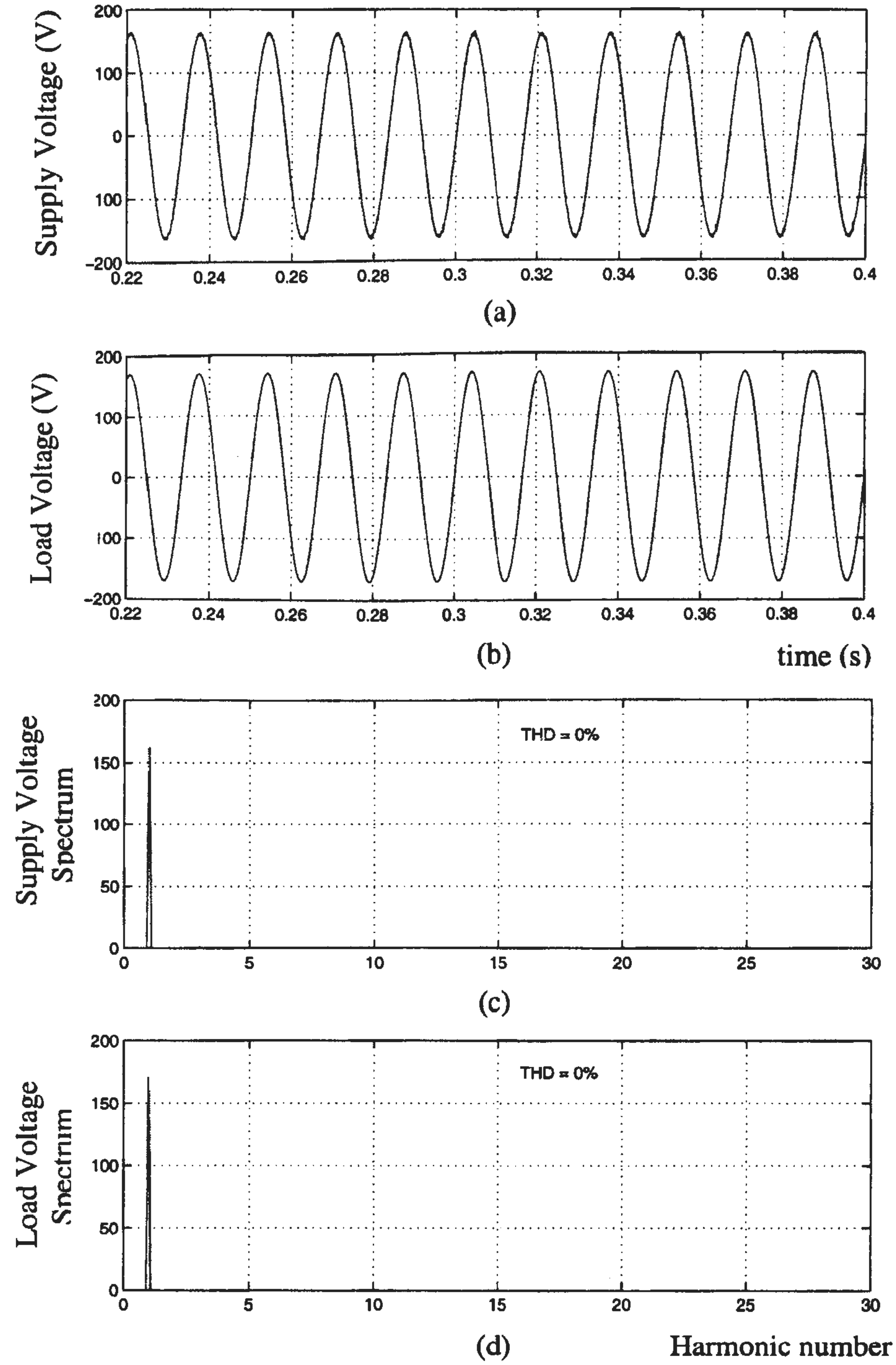

Fig 4.18: (a) Supply voltage; (b) Load voltage; (c) Harmonic spectrum of the supply voltage; (d) Harmonic spectrum of the load voltage

The capability of the system to correct for supply end distortions such as voltage flicker, sag and swell is shown by Fig 4.19. The figure shows an undulating supply voltage that would result in the flickering of lamps, the load terminal voltage and the compensating voltage generated by the active filter. The result shows that the system is able to correct for distortion in the supply voltage hence keeping the load voltage constant.

Table 4.2 shows the performance of the compensation system when the total harmonic distortion of the load current was varied to observe the effect on the source current and on the load voltage. The results show that the system is very effective in mitigating load voltage distortion caused by nonlinear load operation.

Table 4.2: Source and load Total harmonic distortion for Type D

Load current THD%	Source current THD%	Load voltage THD%	Source voltage THD%
94.6	5.21	0.17	3.17
80.4	4.21	0.12	2.75
66.3	3.72	0.10	1.91
35.5	1.94	0.09	1.40
22.7	1.65	0.04	0.93

The total harmonic distortion in the source current and the load voltage decrease with decreasing load current THD.

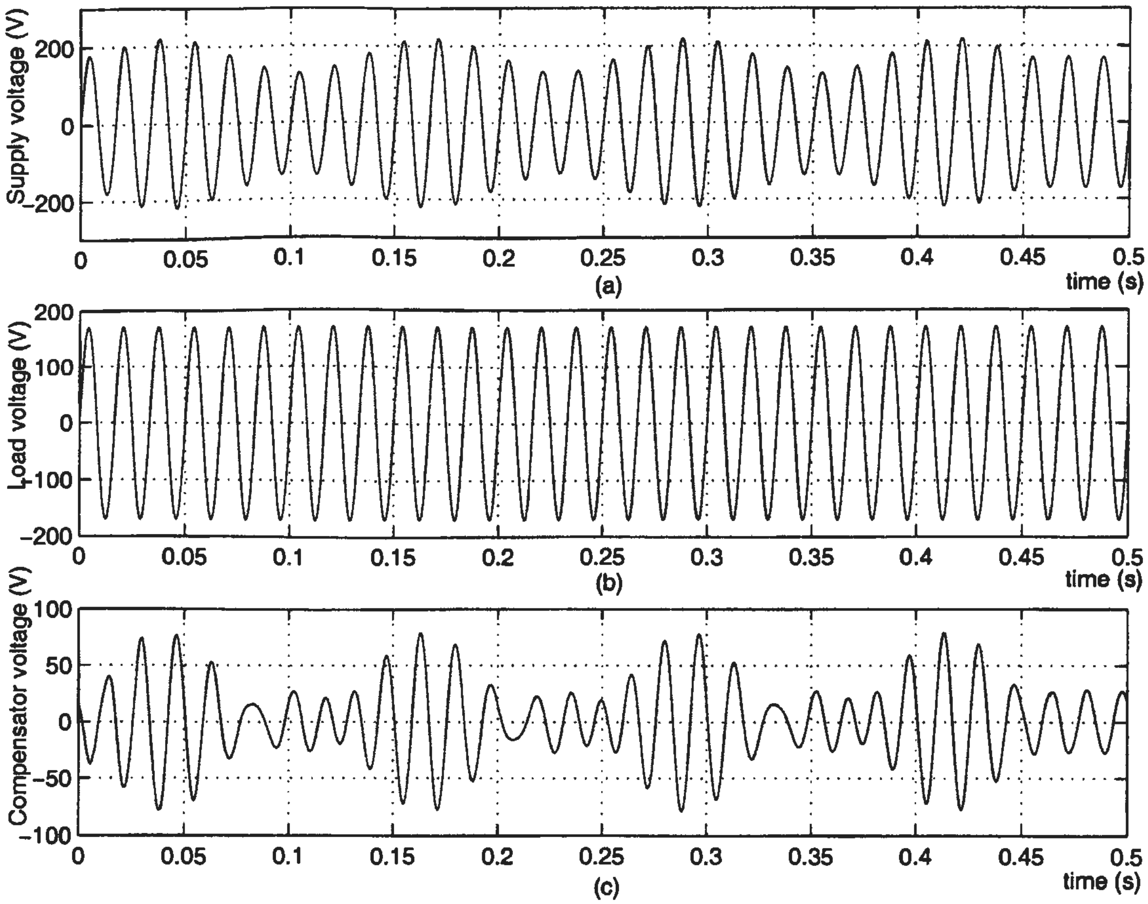

Figure 4.19: Response to voltage fluctuation and flicker.

4.4.1 Simulation results for more complex models for Type D

More complex models were also used to obtain more simulation results for Type D compensation system. The result shows that the system is also effective in canceling harmonics and correcting voltage distortion, as in simpler models. The VSNL and CSNL currents are shown in Fig 4.20. The combined load currents, the supply voltage and the load terminal voltage are shown in Fig 4.21. The resulting total harmonic distortion in the waveforms for the source currents and voltages demonstrates the functionality of the system in harmonic compensation.

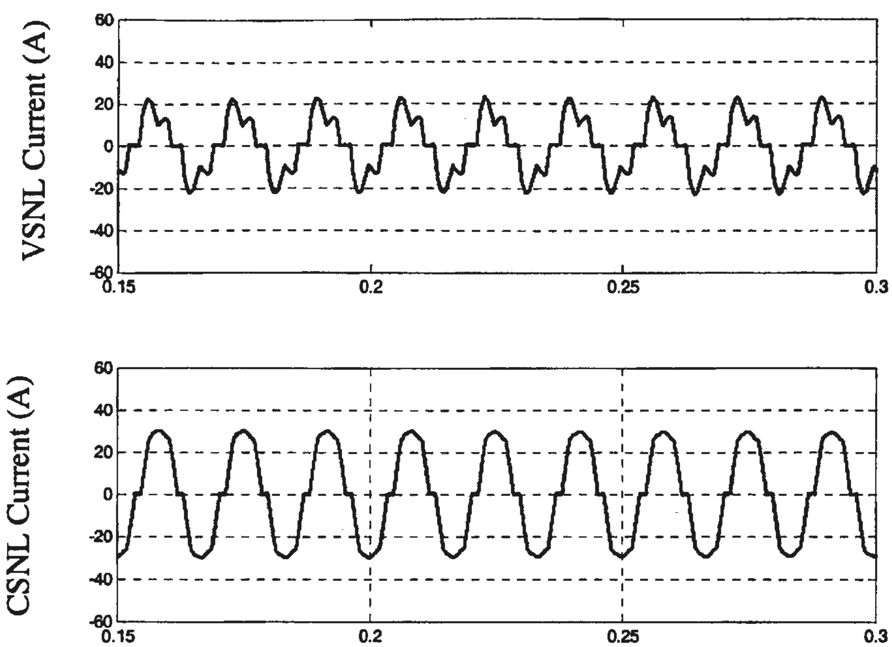

Fig 4.20: Nonlinear load currents for more complex models for Type D compensation system

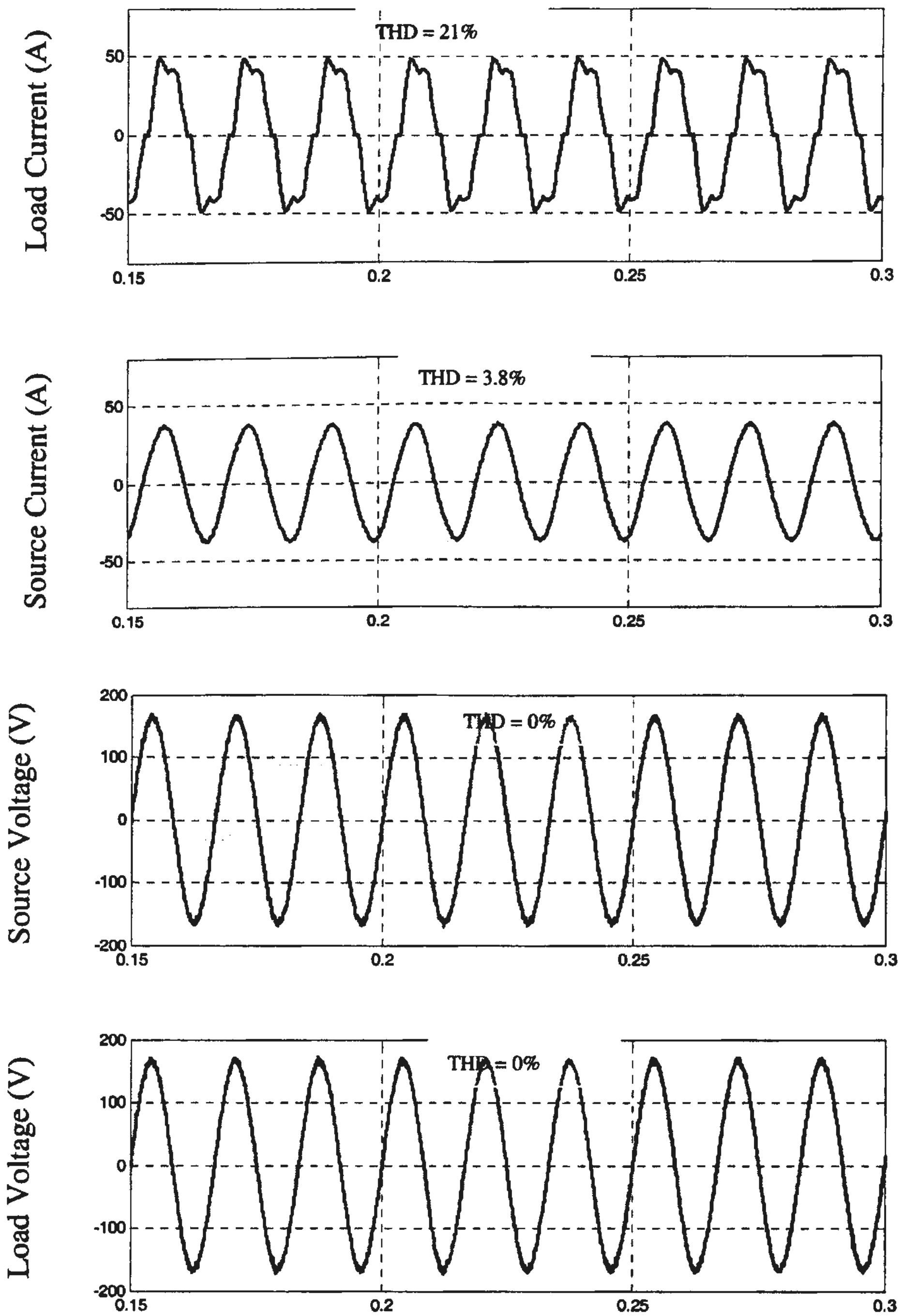

Fig 4.21: Currents and voltages for more complex models for Type D

4.5 Summary

This chapter has focused on two compensation systems having the series active compensator on the load terminals, between the load and the shunt compensators. Type C Compensation System has a parallel-based shunt compensator while Type D Compensation System has a series based shunt compensator. The principal objective of both topologies is the mitigation of the load voltage distortion. The simulated performance of both systems shows that they are effective in the elimination of load voltage distortion and source current harmonics. They are also effective in compensating for voltage flicker from the supply such that the load voltage is held constant. As in the previous two systems, due to the parallel arrangement of the shunt compensator elements and the method of generating the current reference for the shunt active filter, Type C Compensation System will have a higher bandwidth than that of Type D. However, due to the high voltage stresses the shunt active filter is subjected to, its voltage rating and hence cost is increased with respect to Type D Compensation System.

Chapter 5

Ratings of the Active Filters in the Hybrid Compensators

A major limitation on the use of the active filter is the cost of the device. The cost of the semiconductor switches increases with their ratings so does the size and ratings of associated circuits components such as drives and snubber circuits. Hybrid topologies were developed and proposed by researchers partly to help reduce the cost as opposed to using pure active filters in the compensation systems and also to improve the performance of passive filtering schemes. In this chapter, the ratings of the active compensators in the compensation topologies presented in the preceding chapters are investigated.

In the four compensation configurations presented in the previous two chapters, the active filters have been arranged as follows:

- The series active and passive filters are on the supply side of the shunt filter. With a tight control of the harmonics, this means only the fundamental current will flow through the active filter. This filtering arrangement is labeled type 1.

- The series active filter is on the load end while the series passive filter is on the supply end. In this case, the series active filter is rated for the full load current, which includes the load harmonics. This is labeled is type 2.
- The shunt active and passive filters are in parallel. In this configuration, the full line voltage appears across both the active and passive filters. However, the active filter shares the harmonic currents with the passive filter. This is labeled type 3.
- The shunt active filter and passive filter are in series. This configuration ensures that the active filter is subjected to a reduced voltage as a result of the voltage sharing. On the other hand, both filters carry the same harmonic currents. This arrangement is labeled type 4.

The compensation systems described in the previous chapters are a combination of the various hybrid active types. Type A Compensation system consists of type 1 and type 3 hybrid filters while Type B Compensation System is a combination of type 1 and type 4 hybrid filters. Type 2 and 3 hybrid filters are employed in Type C Compensation system while type 1 and 4 hybrid filters are used in Type D Compensation system.

5.1 Rating of Type 1 Hybrid Series Filter

Figure 5.1 shows the type 1 series hybrid filter used in Type A and B Compensation systems. The analysis of the system is carried out with the aim of determining the rating of the active filters for a reference load. All voltages and currents are in rms.

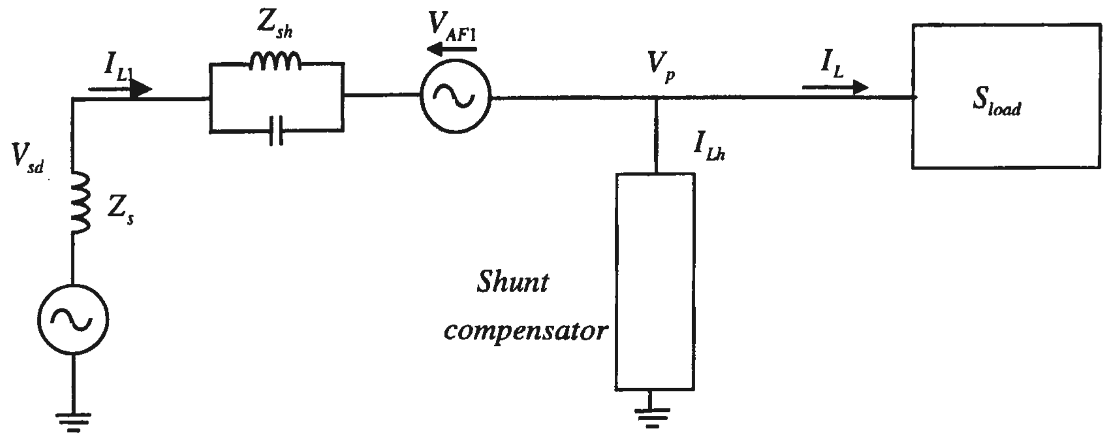

Fig 5.1: Type 1 Hybrid series filter

S_{load} is the total KVA rating of the non-linear load having or causing a known amount of distortion. It is important that the distortion level caused by the non-linear load be known since it determines the level of compensation that would be needed and hence the rating of the active filters. Let S_{load} have an input current of I_L with a total current harmonic distortion of THD_i

From Fig 5.1

$$S_{load} = V_p I_L \tag{5.1}$$

Using KCL on the shunt filter terminals, (5.1) can be written as

$$S_{load} = V_p (I_{L1} + I_{Lh}) \tag{5.2}$$

The total harmonic distortion in the load current is given by

$$THD_i = 100\frac{\sqrt{\sum_{n\neq 1}^{\infty} I_{Ln}^2}}{I_{L1}} \tag{5.3}$$

The fundamental component of the load current I_{L1} is drawn from the supply while the harmonic currents I_{Lh} flow in the shunt compensator.

$$I_{Lh} = \sqrt{\sum_{n\neq 1}^{\infty} I_{Ln}^2} \tag{5.4}$$

Equation (5.2) can therefore be expressed as

$$S_{load} = V_P I_{L1}(1+\frac{THD_i}{100}) \tag{5.5}$$

The KVA rating of the series active filter is given as

$$S_{AF1} = I_{L1} V_{AF1} \tag{5.6}$$

where V_{AFl} is the compensating distortion voltage output of the series active compensator. Equation (5.6) can be written as

$$S_{AF1} = I_{L1} k_1 V_{sd} \tag{5.7}$$

where V_{sd} is the deviation of the supply voltage from a set reference. From (5.5) and (5.7), the rating of the series active compensator can be determined in per unit of the load as

$$\frac{S_{AF1}}{S_{load}} = \frac{k_1 V_{sd}}{V_p(1+\frac{THD}{100})} \tag{5.8}$$

Assuming that the dominant component of the distortion voltage is voltage sags and swells, and further assuming a sag (s) mitigation of the line voltage, (6.8) becomes

$$\frac{S_{AF1}}{S_{load}} = \frac{s}{(1+\frac{THD}{100})} \tag{5.9}$$

Figure 5.2 shows that the rating of the series active compensator in per unit of the load decreases with increasing total current harmonic distortion. This is expected because increasing the distortion of the load currents for a fixed load implies increasing the higher order harmonics and a corresponding decrease in the fundamental. The figure also shows that the rating of the series active filter increases with the voltage sag magnitude as expected.

Figure 5.3 shows the variation of the rating of the series active compensator for increasing load rating and various sag magnitudes. The plot shows that the active filter rating increases for increasing load rating. This is the result of the increasing fundamental component in the load currents; the rating also increases for increasing sag magnitude.

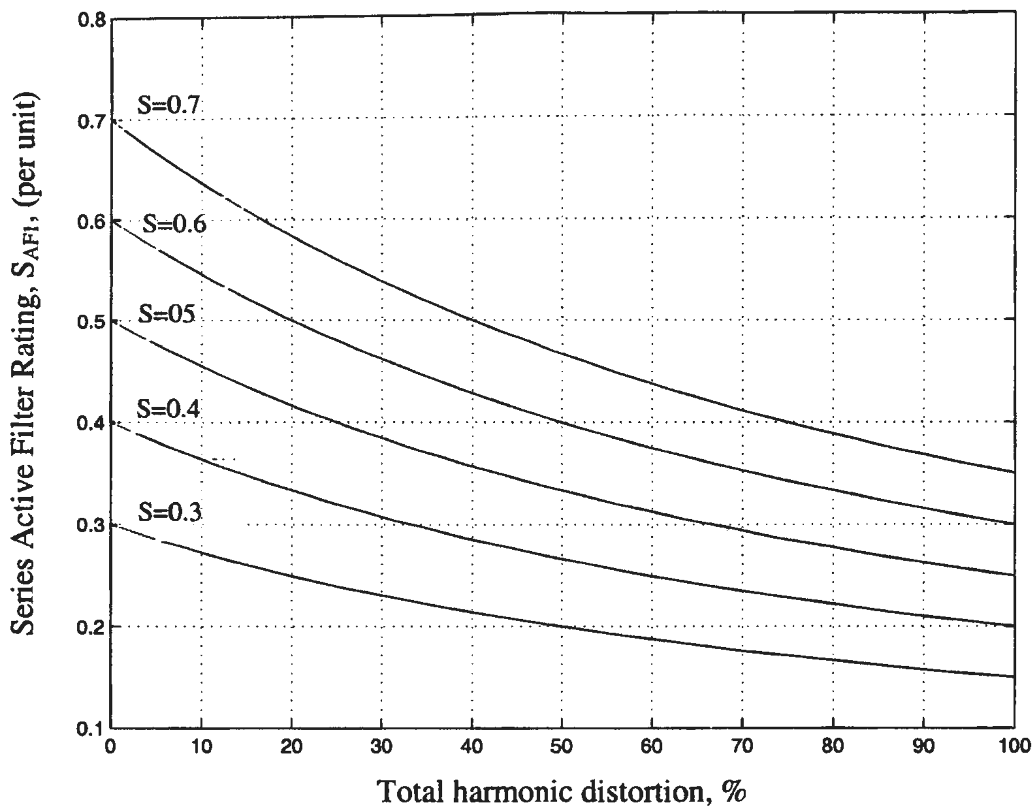

Fig 5.2: Variation of the rating of the series active compensator with total harmonic distortion of the load current for various sags s and for a fixed load of 1 per unit. $k_1 = 1$

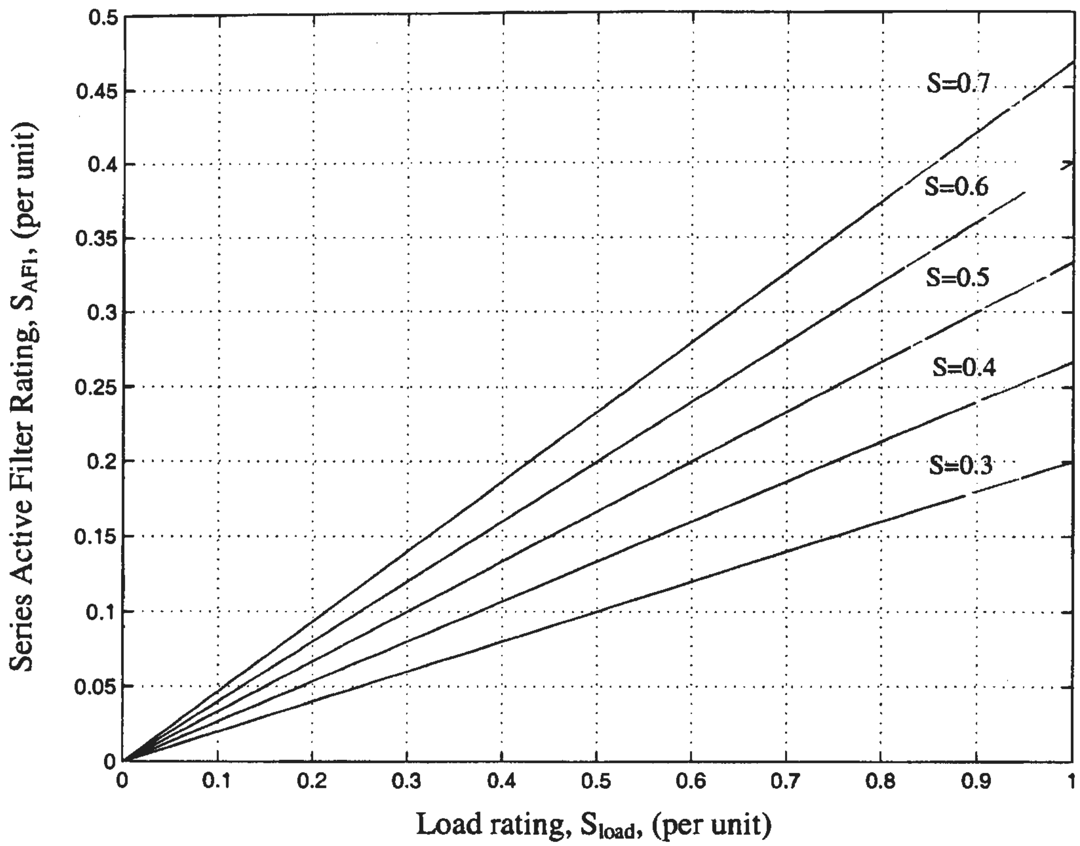

Fig 5.3: Variation of the Series active compensator rating with the load rating for a fixed THD of 50% and for various sags s. $k_1 = 1$

5.2 Rating of Type 2 Hybrid Series Filter

This hybrid compensator type has the series passive filter on the source side of the shunt compensator and the active filter on the load side. Due to the positioning of the series active filter, it is subjected to the full load current that is, the fundamental and the harmonics flow through it; hence it must me rated to carry the full load current. Figure 5.4 shows the single-phase equivalent circuit of the type 2 compensator.

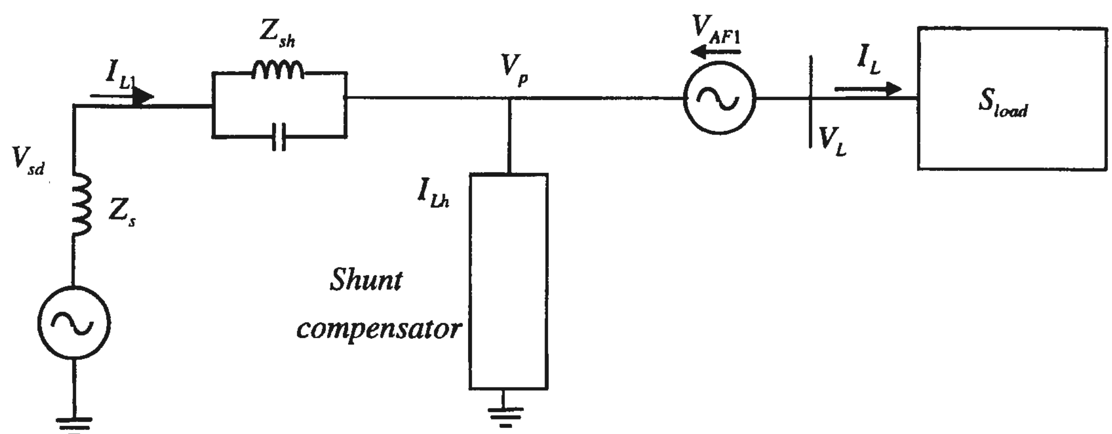

Fig 5.4: Type 2 Hybrid series filter

From Fig 5.4, the series active filter rating is

$$S_{AF1} = I_L V_{AF1} \tag{5.10}$$

where V_{AF1} is the compensating voltage generated by the series active filter to cancel the distortion in V_p , at the shunt compensator terminals.

If it is assumed that the dominant voltage distortion likely to occur is voltage sags and swells, and allowing for a sag and swell mitigation factor of s, the active filter rating per unit of the load rating becomes

$$\frac{S_{AF1}}{S_{load}} = \frac{s k_1 V_s I_L}{V_L I_L} = s k_1 \tag{5.11}$$

$$\frac{S_{AF1}}{S_{load}} = s \tag{5.12}$$

for $k_1 = 1$, since the compensator ensures that $V_L = V_s$. Equation (5.12) indicates that the rating of the series active filter in this compensator type is independent of the load current total harmonic distortion, but is solely dependent on the load rating and the voltage distortion compensation factor allowed.

5.3 Rating of Type 3 Hybrid Shunt Filter

In this hybrid filter type, the shunt passive filter and shunt active filter are in parallel with the load. Figure 5.5 is a schematic of the hybrid shunt filter. Both the active and passive filters are subjected to the same load terminal voltage. However, they share the compensating harmonic currents. The control is carried out by first extracting the harmonic currents of the load (I_{Lh}). The harmonic currents flowing through the tuned shunt passive filters (I_{pf}) are then sensed, measured and subtracted from the load harmonic currents. The resulting harmonic current is then used as a reference for the shunt active filter.

Since the passive filters are tuned to known fixed frequencies and are inflexible once they are tuned and installed, the active filters can then be used to compensate for the other frequencies that may be present resulting in increased flexibility, wider range of harmonics compensation, and a lower rating for the active filter.

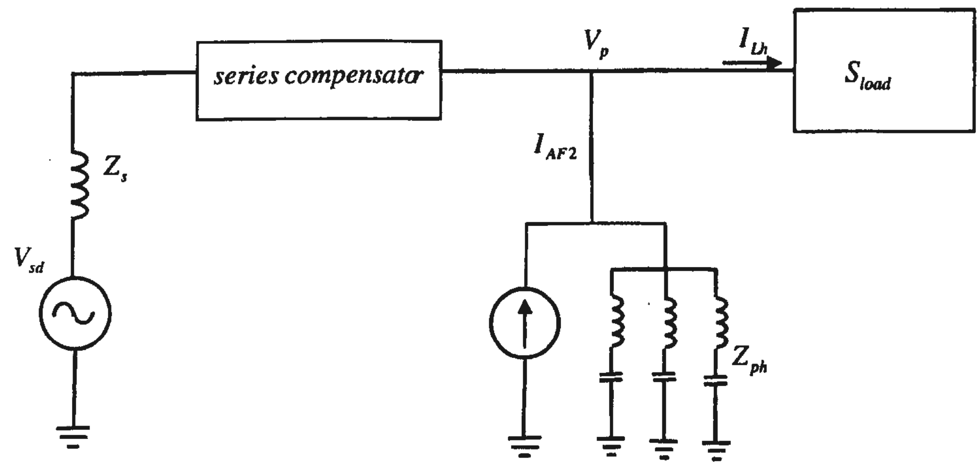

Fig 5.5: Type 3 hybrid shunt filter

From Fig 5.8

$$S_{AF2} = k_2(I_{Lh} - I_{pf})V_P \tag{5.13}$$

Equation (5.15) can be written in terms of the load current THD and the fundamental as

$$S_{AF2} = k_2(\frac{THD_I I_{L1}}{100} - I_{pf})V_P \tag{5.14}$$

Since the passive filters are usually tuned to specific harmonics for a reference load having a total harmonic distortion of THD% in its input current, it follows that the harmonic current through the passive filters are constant. From (5.14), the rating of the active filter decreases for increasing values of passive filter current.

Expressing the rating of the active filter in per unit of the load rating, (5.14) becomes

$$\frac{S_{AF2}}{S_{load}} = \frac{(\frac{THD_i}{100} - \frac{I_{pf}}{I_{L1}})k_2}{1 + \frac{THD_i}{100}} \tag{5.15}$$

From (5.3) and (5.4)

$$I_{L1} = \frac{100}{THD_i} I_{Lh} \tag{5.16}$$

Substituting in equation 5.15 gives

$$\frac{S_{AF2}}{S_{load}} = \frac{k_2 \frac{THD_i}{100}(1 - I_r)}{(1 + \frac{THD_i}{100})} \tag{5.17}$$

where $I_r = \frac{I_{pf}}{I_{Lh}}$

For any value of load current total harmonic distortion for a reference load, the ratio of the passive filter current to the total load current harmonics I_r, strongly influences the rating of the active filter. Increasing I_r implies that the passive filter compensating current is increasing; hence the rating of the active filter falls.

Figure 5.6 shows the variation of the active filter rating with load current THD for a reference load with the active filter rating expressed as per unit of the load rating. The figure shows that the active filter rating increases with the load current total harmonic distortion and decreasing current ratio, I_r. Figure 5.7 shows that the active filter rating increases with the load rating for a specific value of load current total harmonic distortion and also decreases with increasing current ratio

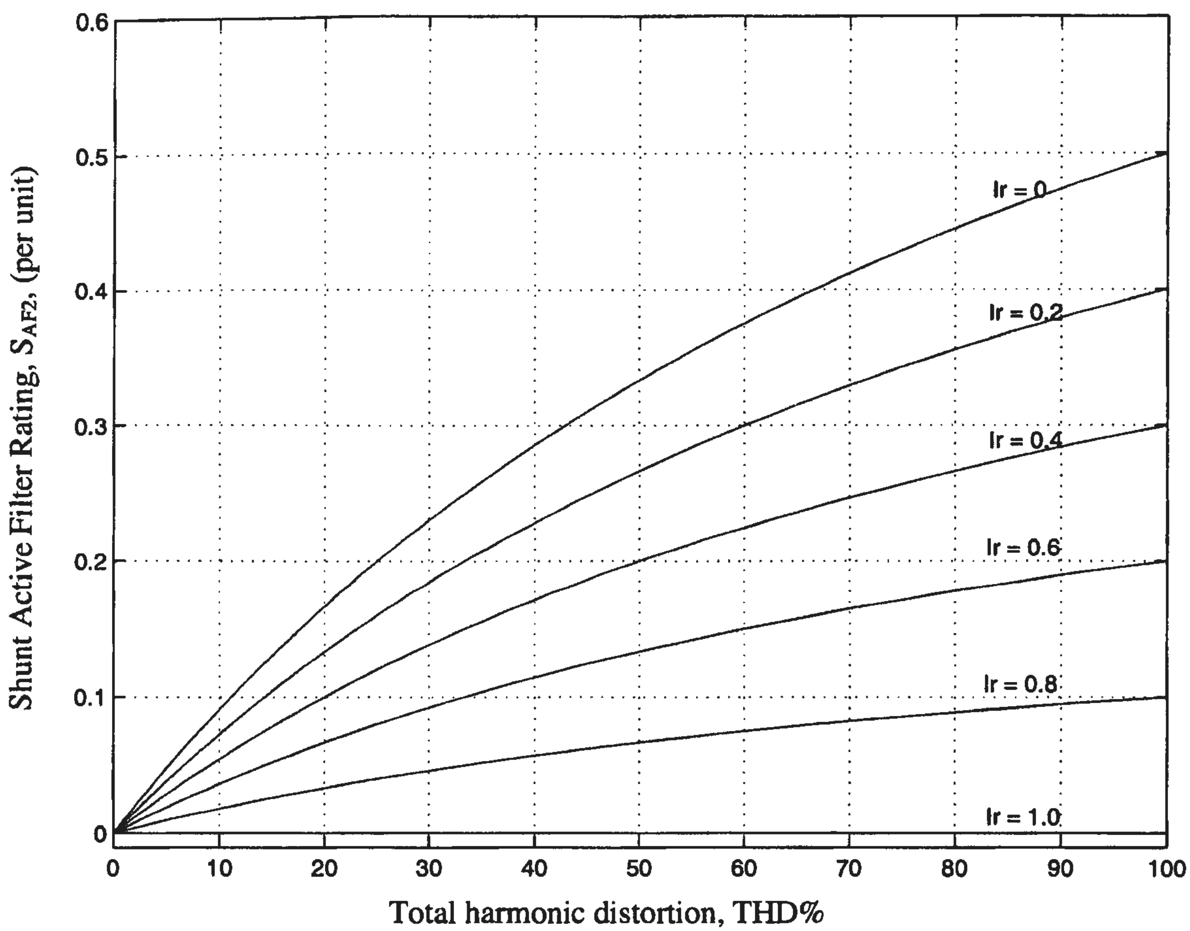

Fig 5.6: Variation of active filter rating with load current THD for a fixed reference load

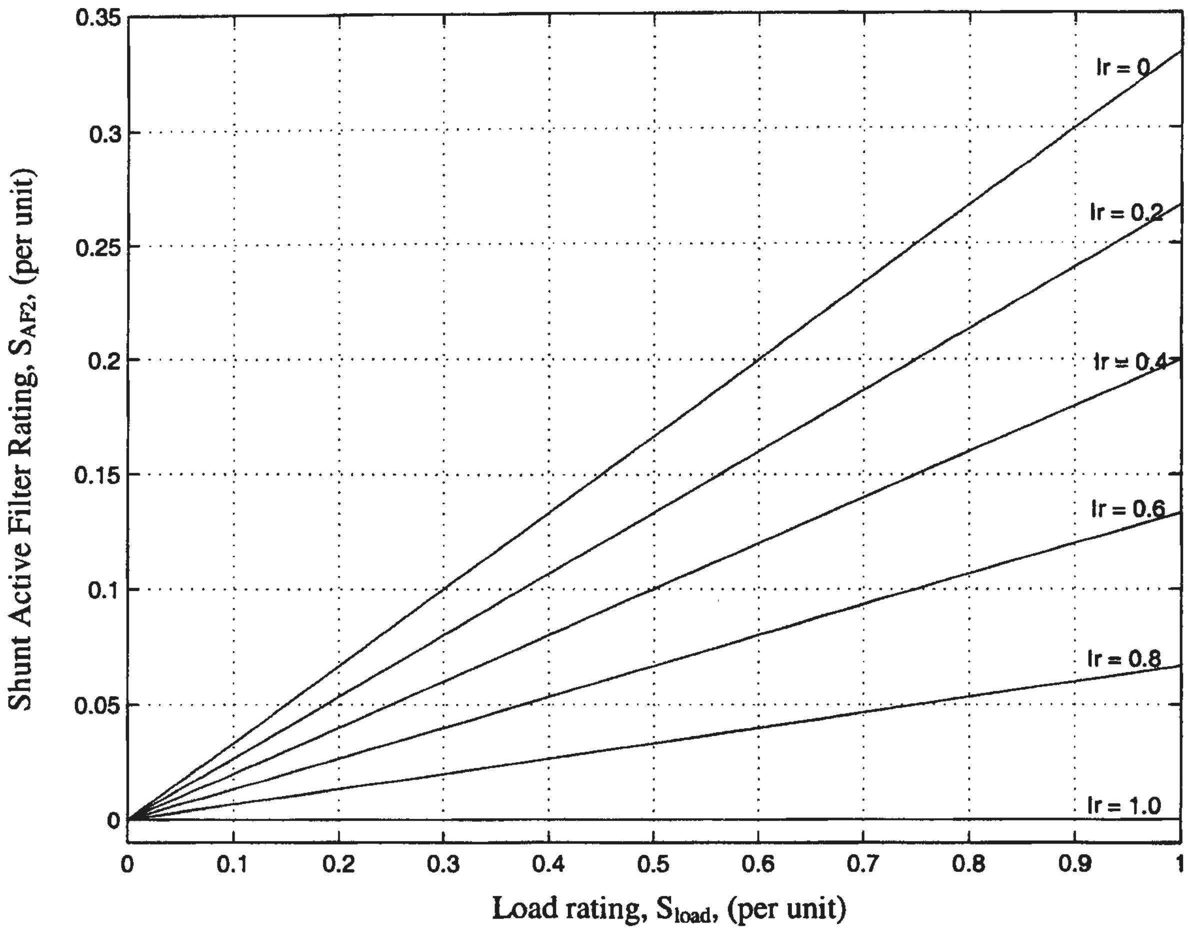

Fig 5.7: Variation of the shunt active filter rating with load rating having a current THD of 50%

5.4 Rating of Type 4 Hybrid Shunt Filter

In these compensation system topologies, the shunt active and passive filters are in series. The type 4 hybrid shunt filter arrangement is used to reduce the rating of the active device, since the line voltage divides between the passive filter and the active filter. This is the result of the voltage drop across the small leakage impedance of the coupling transformer. Figure 5.8 shows a single-phase representation of the type 4 hybrid shunt filter

Since the active and passive filters are in series, the active filter rating can be written as

$$S_{AF2} = k_2 I_{Lh} V_p \frac{Z_{taf2}}{Z_{pf} + Z_{taf2}} \tag{5.18}$$

where Z_{taf2} is the per unit leakage impedance of the matching transformer and Z_{pf} is the passive filter impedance at the line voltage frequency.

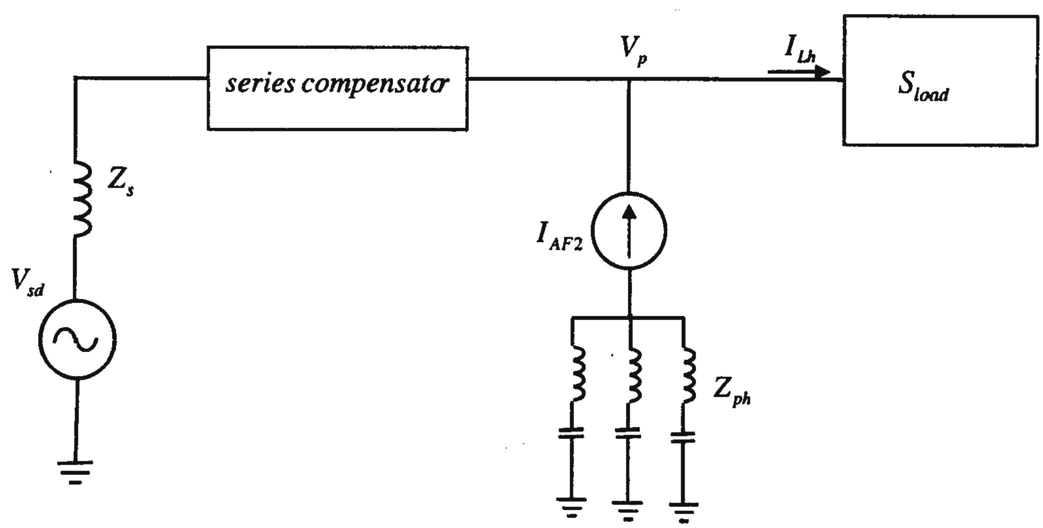

Fig 5.8: Type 4 hybrid shunt filter.

Equation (5.18) shows that the rating of the shunt active filter is proportional to the transformer impedance, hence for small ratings; it is desirable to have the leakage impedance as small as possible. Equation (5.18) can be written as

$$S_{AF2} = k_2 I_{Lh} V_p Z_r \tag{5.19}$$

where $$Z_r = \frac{Z_{taf2}}{Z_{pf} + Z_{taf2}} \tag{5.20}$$

Equation (5.19) can be written in terms of the fundamental current and the total harmonic distortion of the load current as

$$S_{AF2} = k_2 \frac{THD_i I_{L1}}{100} V_p Z_r \tag{5.21}$$

Hence the rating of the shunt active filter expressed as per unit of the load rating is

$$\frac{S_{AF2}}{S_{load}} = \frac{\frac{THD}{100} Z_r}{1 + \frac{THD}{100}} \tag{5.22}$$

Equation (5.22) shows that the VA rating of the shunt active filter is proportional to the load rating and also proportional to the amount of harmonic distortion caused by the load input current. This is expected because for a fixed reference load, increasing the harmonic distortion of its input current results in increased shunt compensating current injected in the line. Also for a given load with a fixed THD, increasing its rating also results in higher harmonic levels that need compensation. Figures 5.9 and 5.10 are a graphical representation of the increasing rating of the shunt active filter with THD and load. The plots show that the shut active filter rating increases with the load rating, the load current total harmonic distortion and Z_r.

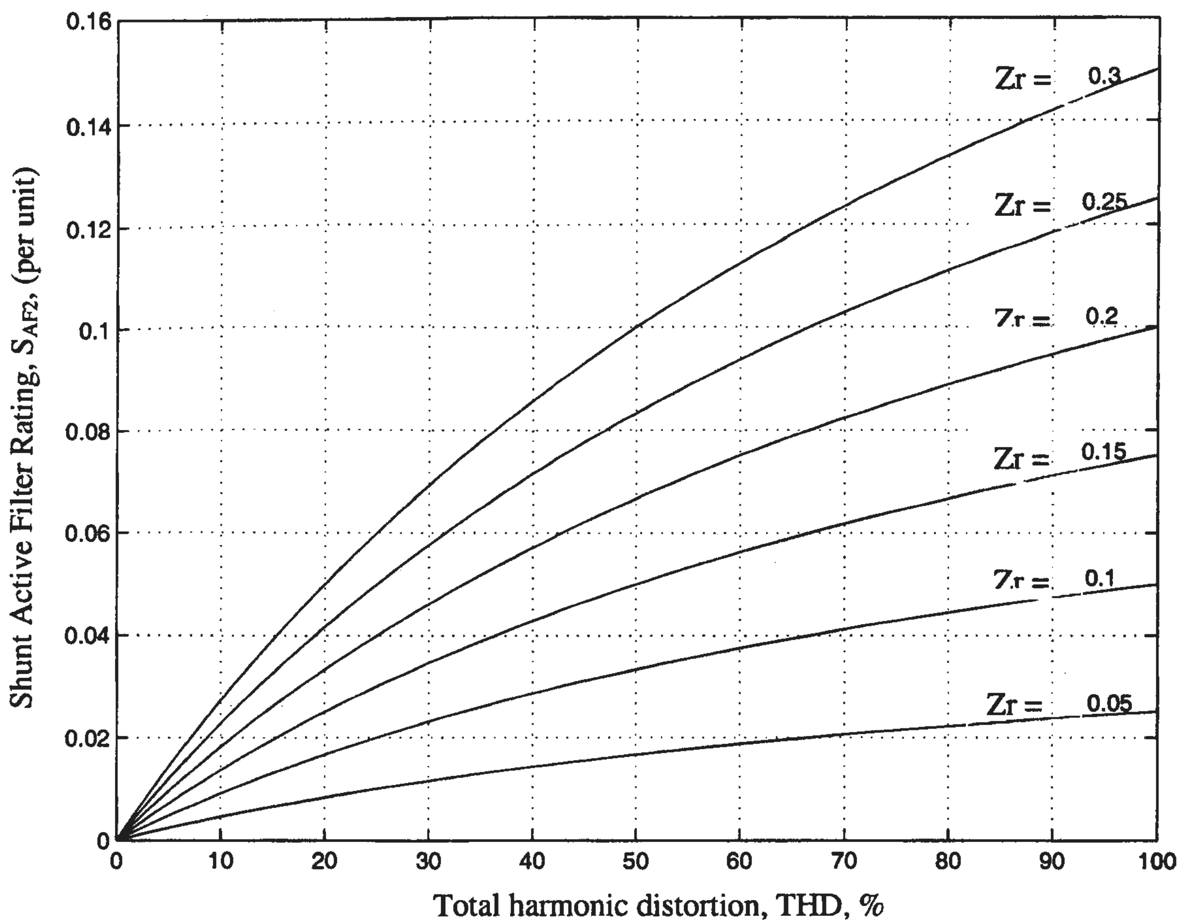

Fig 5.9: Increase of shunt active filter rating with load current THD

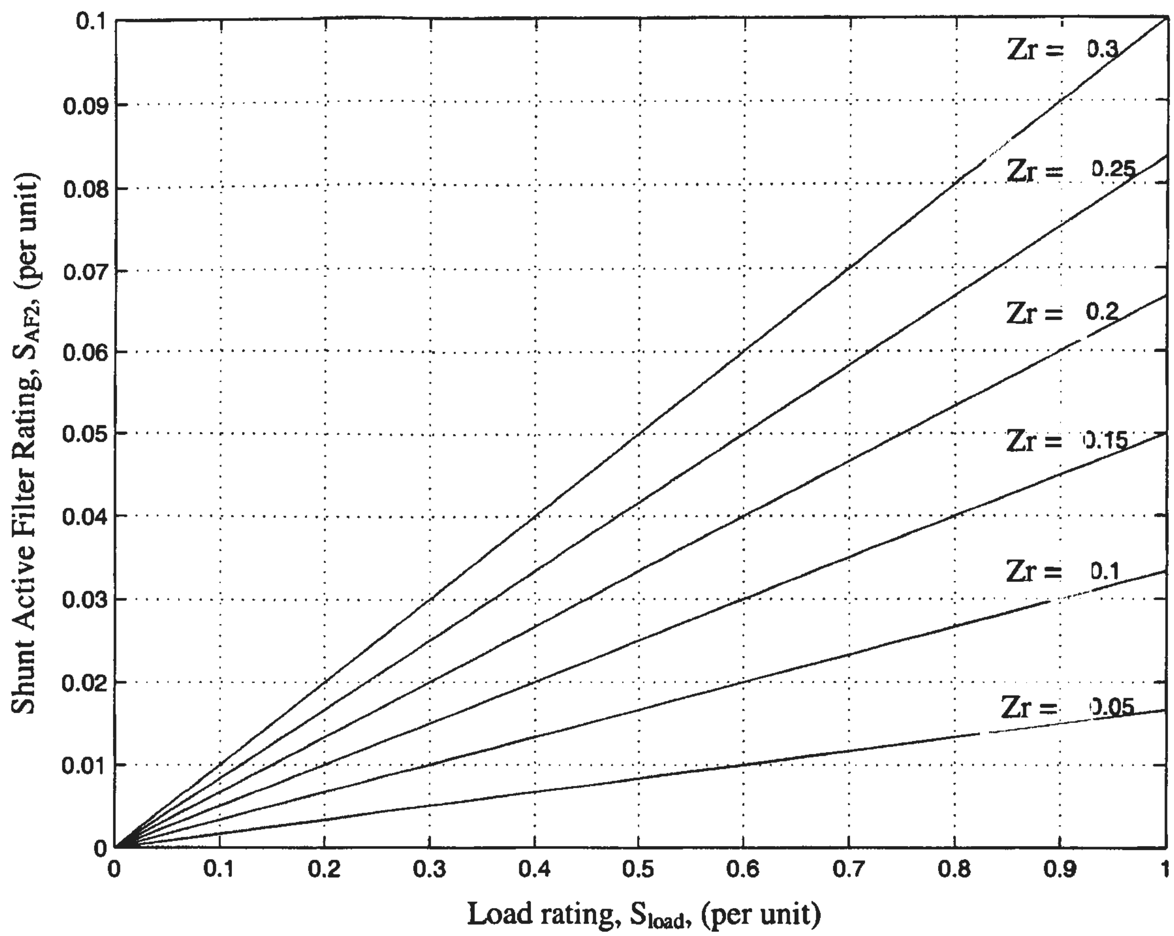

Fig 5.10: Variation of the shunt active filter rating with load rating for a fixed load current harmonic distortion of 50%. ($k_2 = 1$)

5.5 Performance Comparison of the Compensation Systems

The four compensation systems under consideration in previous chapters are composed of the four hybrid filter types arranged in various configurations. In this section, the performance comparison of the compensation systems is carried out with the aim of determining, with respect to a fixed reference load with a known total harmonic distortion in the load current, the current compensation level achieved by each system as well as the level of voltage distortion cancellation attained. This is done with a view of providing recommendation for the best potential application of each system.

The current compensation performance of the compensation systems was investigated for similar levels of total harmonic distortion in the load current. From the results shown in Fig 5.11, and also illustrated in tables 3.1, 3.2, 4.1, and 4.2 in the previous chapters, Types A and C Compensation Systems offers better performance in preventing the load current harmonics from contaminating the source. This is due to the parallel arrangement of the shunt compensator elements, i.e. the shunt passive and shunt active filters are in parallel. The control is also carried out to allow for the active filter to complement the passive filter. This arrangement is also better for loads whose harmonic components are unknown or is rapidly changing such as arc furnace loads. However, for loads with well-known and unvarying harmonic components such as six-pulse drives, the reduction in the rating of the shunt active as a result of the voltage dividing between the active and passive filter of Types B and D Compensation Systems may be of more significance than their slightly higher total harmonic distortion.

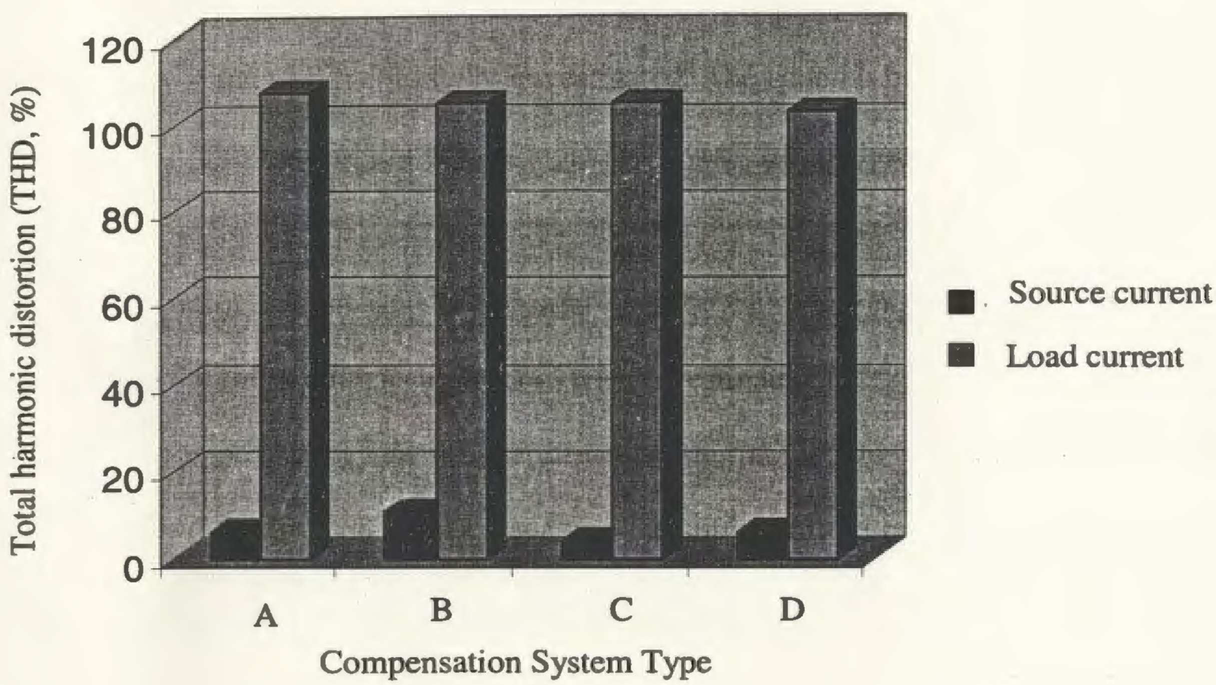

Fig 5.11: Harmonic compensation in Compensation Systems A-D

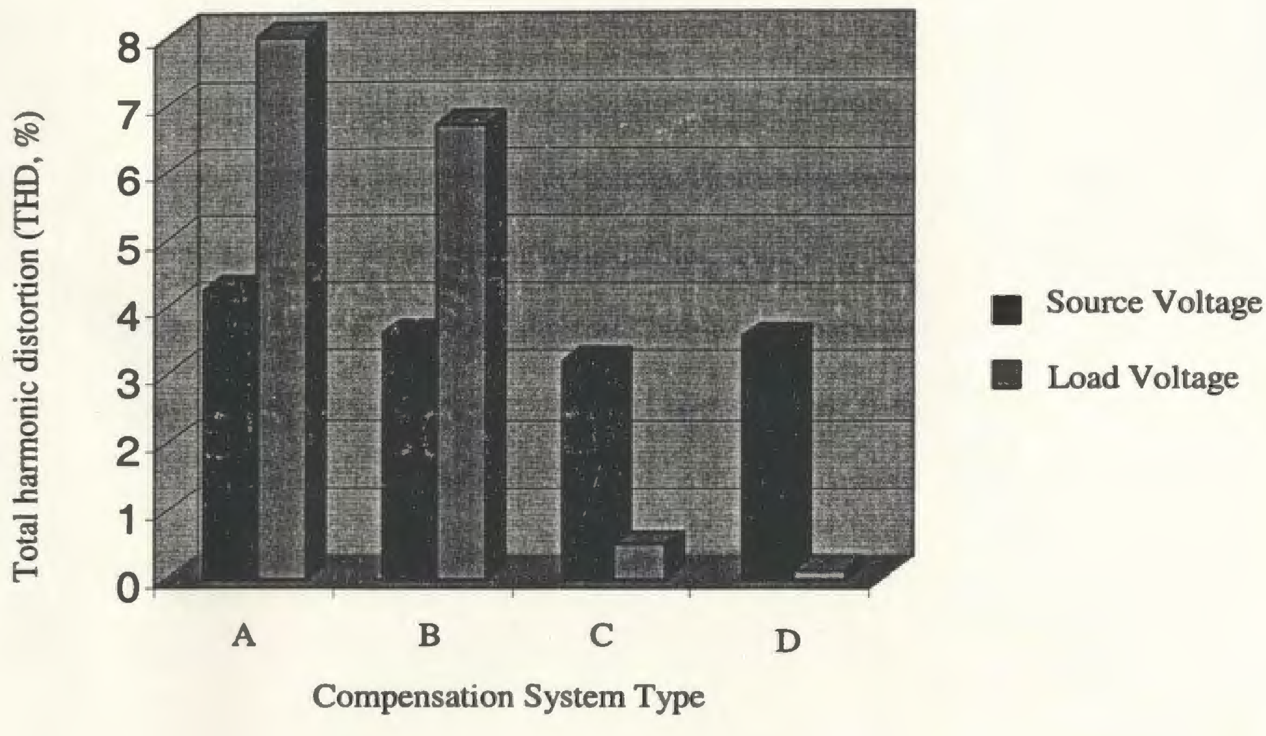

Fig 5.12: Load voltage distortion compensation in Compensations Systems A-D

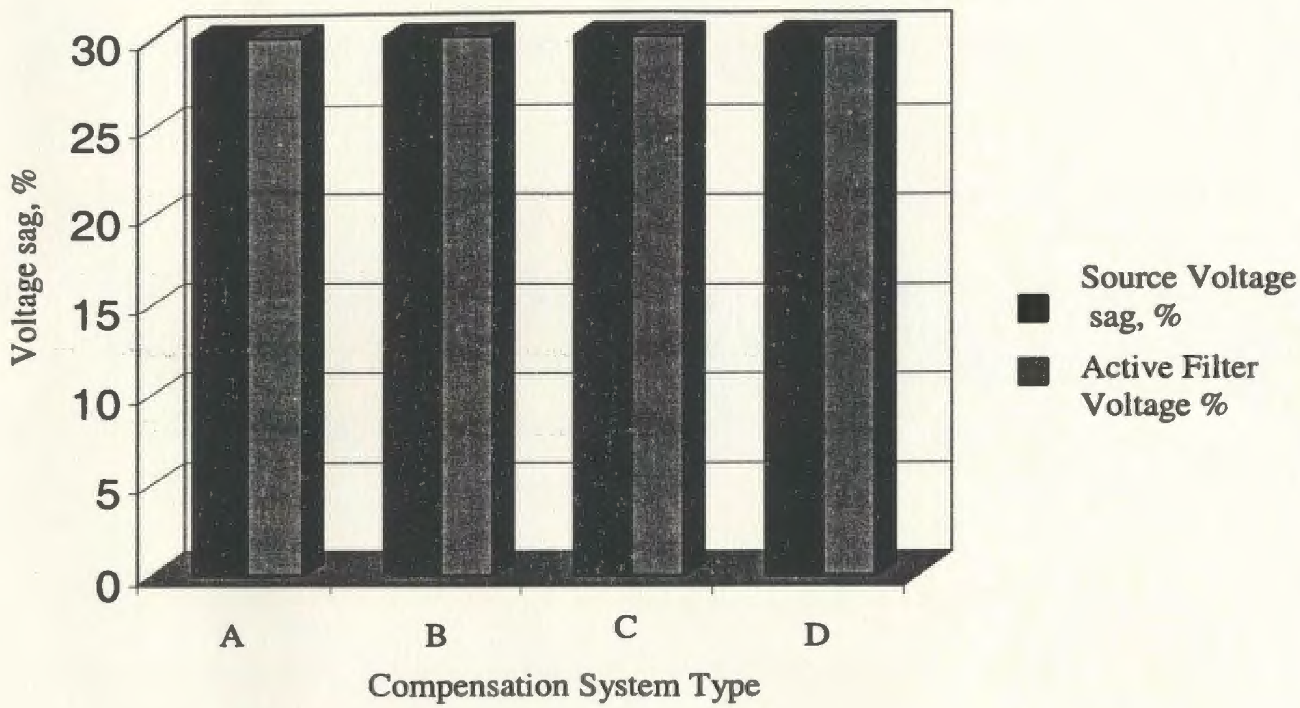

Fig 5.13: Supply voltage sag compensation in Compensations Systems A-D

In all the compensation systems, the voltage distortion at the load terminals is a superposition of the source end distortion and passive filter caused distortion. Figure 5.12 shows the performance of the compensation systems in the elimination of the voltage distortion caused by the flow of harmonics in the passive filter. The figure illustrates that Types C and D Compensation Systems are more effective in this regard as a result of the position of the series active filter in the topologies. When the voltage distortion is from the supply end as in voltage sag, swell and flicker, all the compensation topologies are effective in correcting the deviation from the reference. This is illustrated in Fig 5.13.

5.6 Summary

In this chapter, the various types of basic compensator topologies used in the hybrid active compensation systems of the previous two chapters have been described. The rating of the active compensators with respect to the rating of the load and the total harmonic distortion of the load current has also been determined. It was shown that the rating of the active compensators strongly depends on the applicable topology, the load rating and the total harmonic distortion of the load current. In all types, the active compensator rating increased for increasing load. Type 1 series active filter rating decreased with increased load current THD for a fixed reference load, while type 4 series active filter rating is unaffected by the THD of the load current. For the shunt active compensators, the ratings in both types 2 and 3 follows a similar pattern, increasing with the load rating and the load current THD. The various compensation systems were also compared in terms of their harmonic current mitigation with respect to a harmonic rich load current. Similarly, the voltage distortion compensation of the four systems was also compared with each other, with load caused distortion and the source end distortion as the comparison factors.

Chapter 6

Conclusions and Scope for Future Work

In this thesis, the analysis and performance of four hybrid compensation topologies have been carried out. The performance characteristics were determined and quantified using the total harmonic distortion of the compensated source current with respect to the load current. The load voltage and the source voltage distortion levels were also used as indicators of the performance of the compensation topologies.

The multiple feedback loop control scheme, developed for use in UPS applications, was first investigated to determine its suitability for use in active filtering applications. The following basic features of the scheme made it attractive for active filtering applications.

The inner current loop of the control scheme has been shown to provide a peak current limit in the capacitor of the output filter, hence limiting current surges at start up. It has also been shown to be capable of predicting and correcting near future variation in the output voltage, hence resulting in fast dynamic response in the inverter. The outer voltage loop ensures that the inverter output voltage is a replica of the reference. It was shown that the control scheme is capable of:

- Generating sinusoidal voltages at the line frequency for injection into the line for compensation of voltage sags, swells and flicker.
- Generating non-sinusoidal voltages and currents for harmonic compensation in the line.

Having established the functionality of the control scheme for active filter applications, the harmonic current extraction method was investigated. The scheme based on the synchronous reference frame controllers was adopted. It was also demonstrated that the scheme is capable of extracting the harmonic currents that may be present in the load current. The inverter control scheme and the harmonic current extraction method adopted were then applied to the four compensation topologies investigated.

The capacity of the compensation systems to mitigate the harmonic and distortion caused by the operation of two kinds of nonlinear loads was the subject of the investigation. The hybrid load considered consisted of a voltage source and a current source type nonlinear load. A single-phase model of Type A Compensation System was developed and used to determine the compensation requirements. Simulation results demonstrating the capacity of the system to mitigate load current harmonics and voltage distortion were presented. The parallel connection of the shunt hybrid filter in the topology resulted in very good harmonic compensation as a result of the complementing effect in the harmonic extraction and control between the active and the passive filters.

Type B Compensation System was also investigated. It was an attempt to reduce the rating of the active filter in the shunt hybrid filter by a series arrangement as opposed to a parallel arrangement. The price paid is the loss of the advantages of complementation in the control. The system was found to result in higher values of total harmonic distortion in the source current. Both systems were effective in supply voltage distortion correction since they both employ the same type of hybrid series filter.

Due to the positioning of the series hybrid filter in the previous compensation systems, voltage distortions caused by the flow of load current harmonics through the passive filter were not compensated for, resulting in relatively high total harmonic distortions in the load terminal voltage. To overcome this load voltage distortion, the series active filter was positioned at the load side of the shunt hybrid filter. This resulted in Type C and D Compensation System. It was shown that the total harmonic distortion in the load voltage improved significantly compared to the previous two systems. A disadvantage of the topologies of Types C and D Compensation Systems is that the series active filter has to be rated for the full load current, increasing its size and cost.

The rating of the active filters in the various types of hybrid configurations was determined. For type 1 hybrid filter, the rating depended on the THD of the load current, the VA rating of the load and the level of voltage sag/swell compensation allowed. While the rating of type 1 increased with the load rating and the sag compensation factor, it decreases with increasing load current THD. The rating of type 2 filter on the load side of the shunt hybrid filter is independent of the load current THD as it is rated for the full load current. The ratings of type 3 and 4 were also determined to increase with the load rating and the total harmonic distortion in the load current.

The contributions of this work can be summarized as follows:

- An investigation of the performance of different hybrid filtering topologies and their comparison leading to recommendations about their most suited applications. This is significant because it allows the designers to make an informed choice regarding the type of compensation system depending on the loads in the system.
- A determination of the rating of the active filters with respect to the load rating, the total harmonic distortion of the load current and factors such as voltage sag. This is also necessary since the cost increases in proportion to the rating, hence to keep cost down; there is the need for a proper choice of the compensation system.
- A simple voltage distortion extraction method was used. This eliminates the need for complicated extraction circuits and large computation time.
- A successful adaptation of the multiple feedback control scheme for active filtering application. The control scheme guarantees accurate generation of the extracted reference current harmonics and voltage distortion.

6.1 Suggestions for Future Work

- The effectiveness of any compensation systems depends on the capability of the control system used to accurately extract the harmonics. The extraction scheme used in this work is the synchronous reference frame method. The method is cumbersome and requires that the system be three-phase, making it difficult for single-phase applications. It is also difficult to use when there is unbalance voltage or currents in the system. One possible solution to this problem is to use an extraction method based on the discrete wavelet transform algorithm. A general overview of the method has shown that it is fast, accurate and does not require the system to be three-phase. Further study is required to confirm its feasibility for active filtering application

- Ideal coupling transformers were assumed in the models used in this work. A study where such an assumption is not made would be interesting, as the effect of the transformer parameters on the inverter output voltage maybe significant.
- It may also be advantageous to investigate other control methods such as fuzzy logic and neural network based controllers for determining the inverter switching times.
- An experimental verification of the compensation systems and the control method investigated in this work is recommended.

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Appendix A

Simulation Models

The simulation results presented in this thesis were obtained with the aid of Matlab (version 6) and Simulink (version 4). The models were constructed using the control systems and simulink toolboxes as well as the power system block set. The resulting system models are stiff and hence require integro-differential equation solvers suitable for stiff systems. ODE 23tb, a variable step continuous solver was found to result in the convergence of the solution with minimum simulation time.

Since the models required elements from the simulink and power systems block set, Controlled voltage and current sources were used to interface between simulink signals and Power system blocks signals. Voltage and current measurement blocks were used to sense power system voltages and current for input into simulink and control system tools for the necessary control actions.

A.1 Active filter Inverter

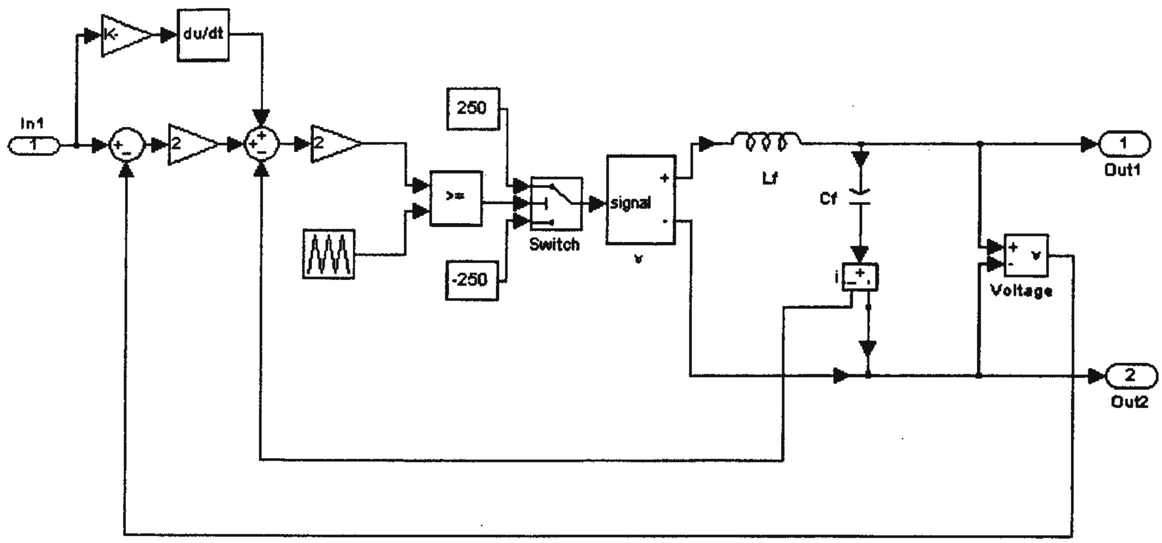


Fig A.1: Model of the active filter inverter control (Active filter subsystem)

A.2 Supply and Passive filters

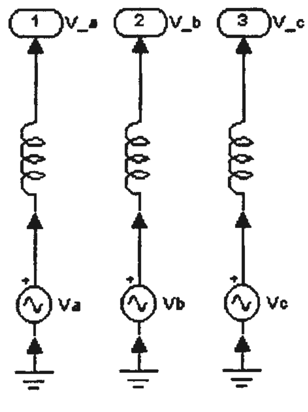


Fig A.2: Three-phase supply (voltage sources subsystem)

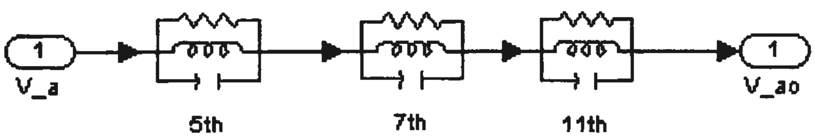


Fig A.3: The series passive filter subsystem

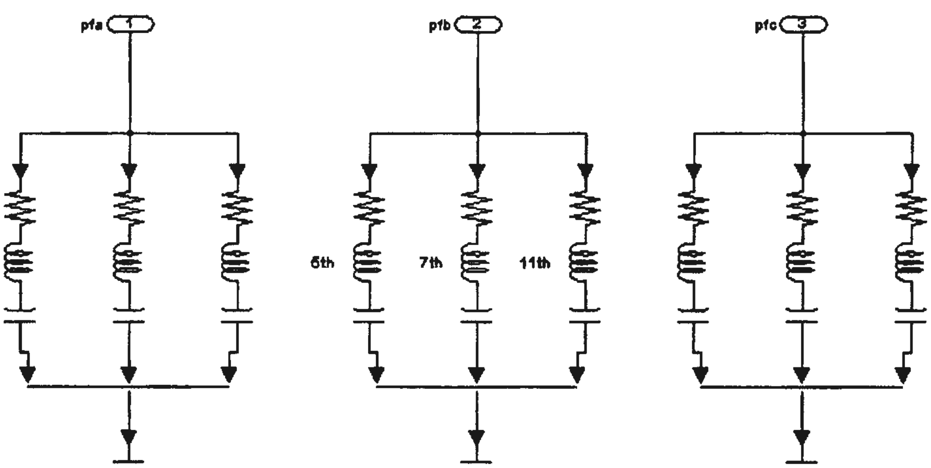


Fig A.4: The shunt passive filter subsystem

A.3 Load

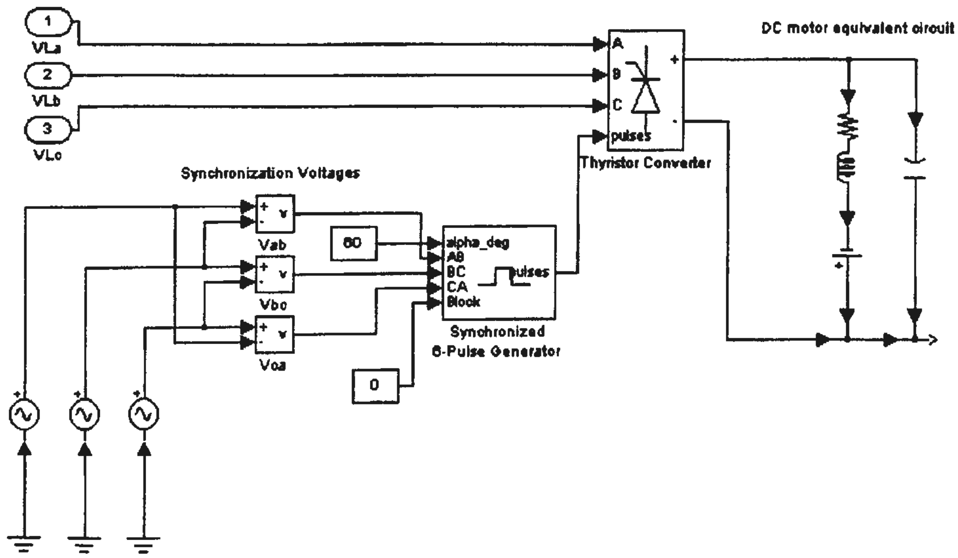


Fig A.5: The voltage source non-linear load (VSNL) subsystem

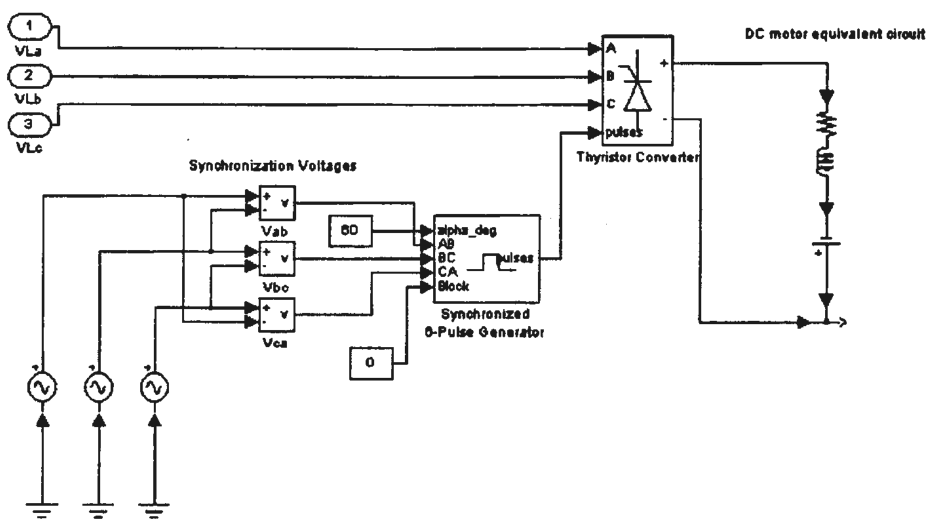


Fig A.6: The current source non-linear load (CSNL) subsystem

A.4 Harmonic current extraction

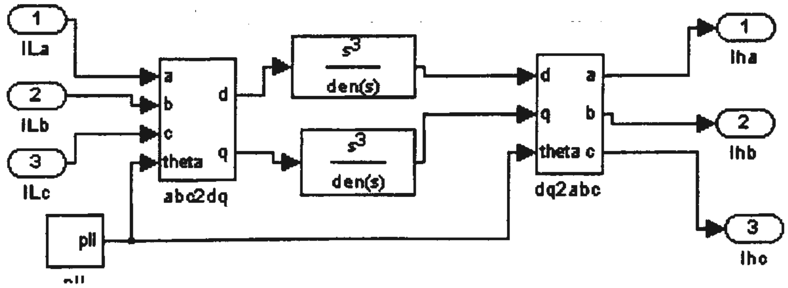


Fig A.7: Harmonic current extraction unit

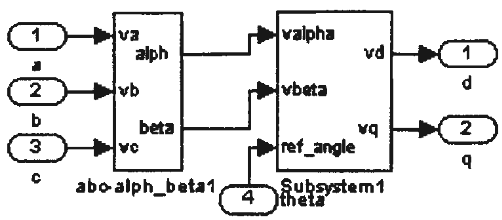


Fig A.8: abc-to-dq transformation block – subsystem of the harmonic current extraction unit

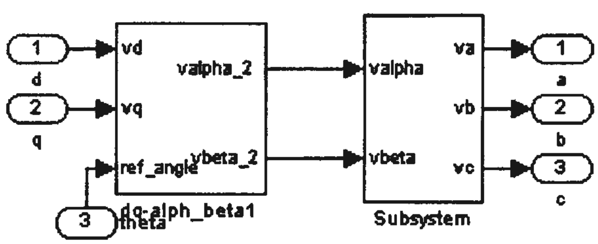


Fig A.9: dq-to-abc transformation block - subsystem of the harmonic current extraction unit

A.5 Distortion voltage extraction

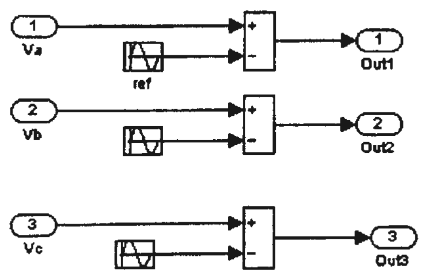


Fig A.10: Distortion voltage extraction subsystem

A.6 Compensation systems

The four compensation system models were constructed using the various subsystems in a modular setup. The active filters are shown in Fig A.11-A.14, only in phase a to avoid clutter in the figures. The result of the simulation are written to the matlab workspace using the "to workspace block" where calculations and fft analysis are carried out and the results plotted where appropriate. "Goto and from" blocks are used to transfer data from one point in the subsystems to another to allow for modularity of the systems.

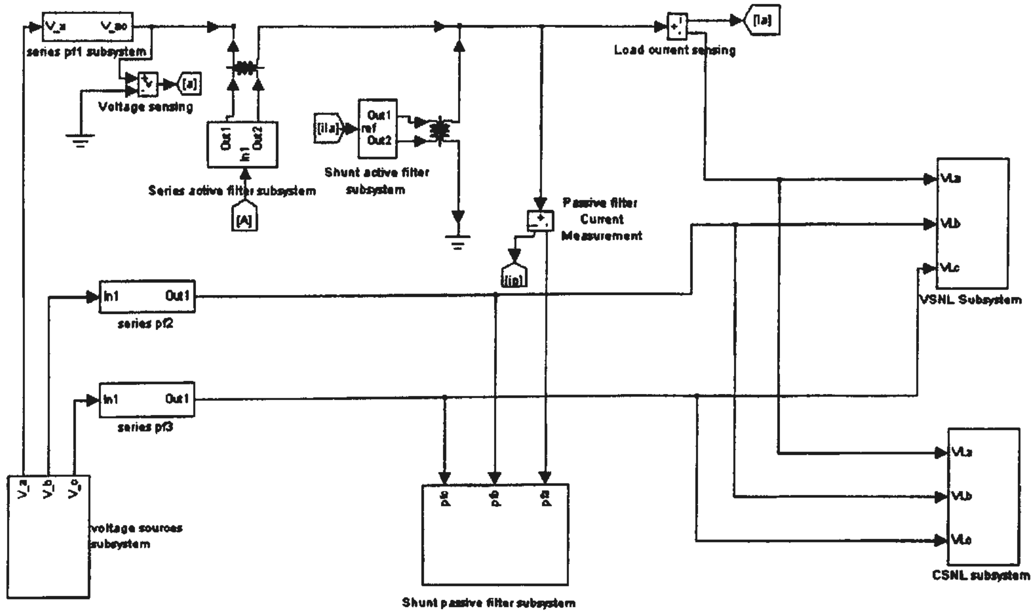


Fig A.11: Type A Compensation System

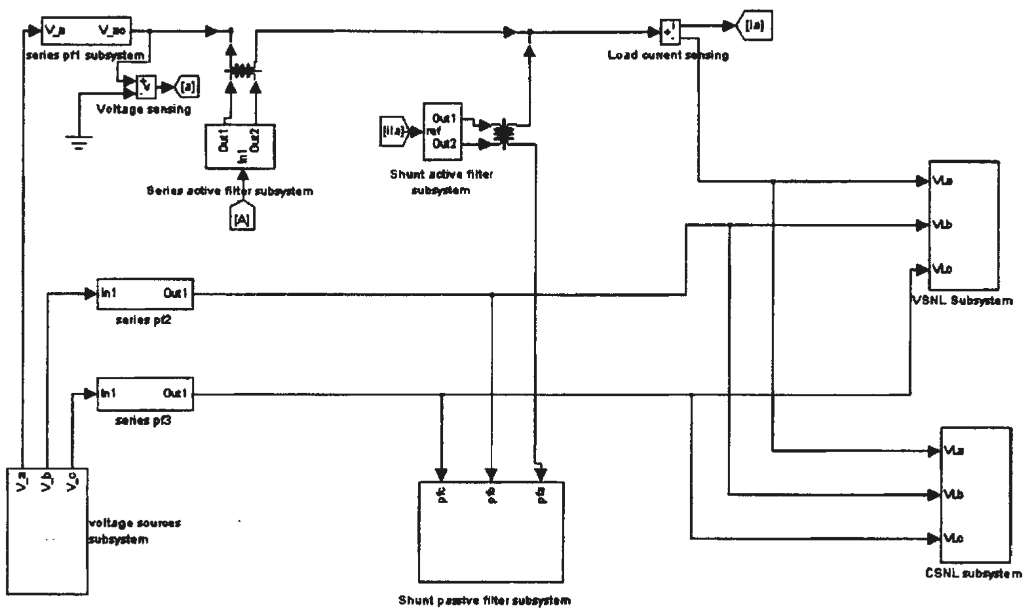


Fig A.12: Type B Compensation System

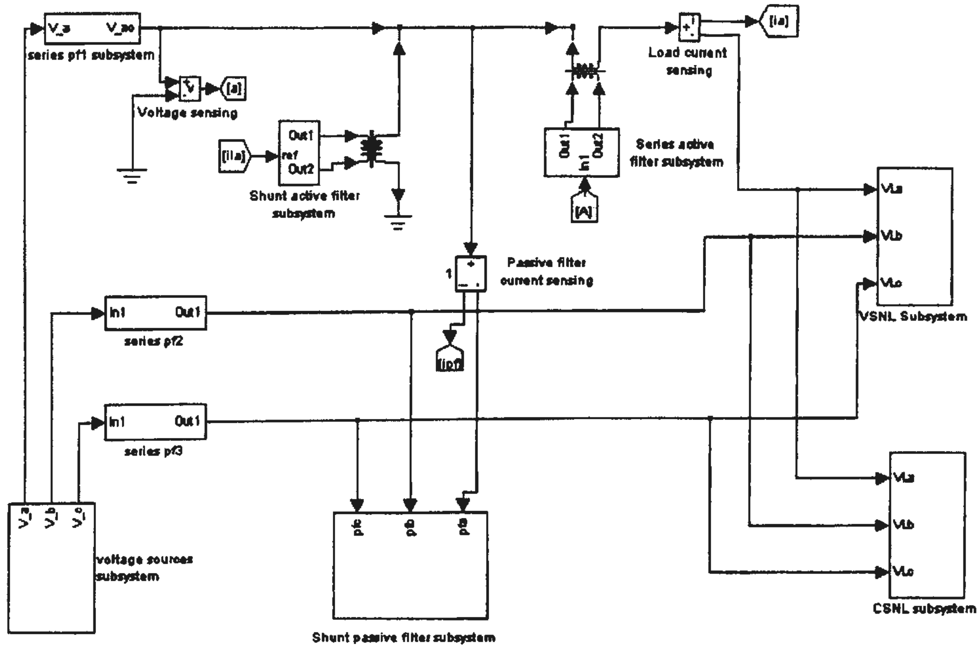


Fig A.13: Type C Compensation System

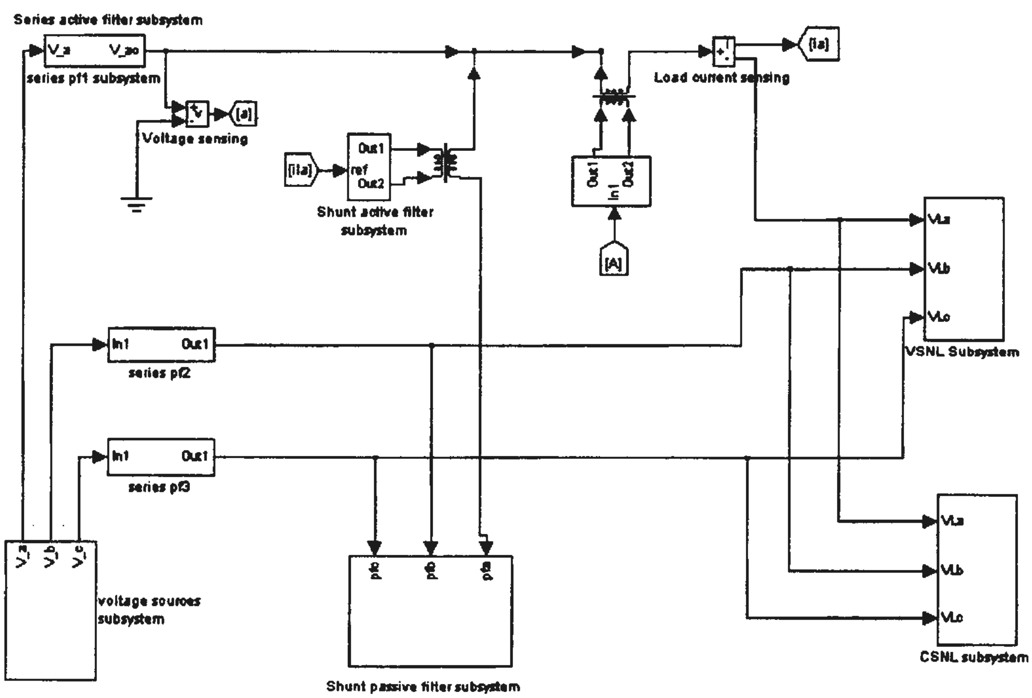
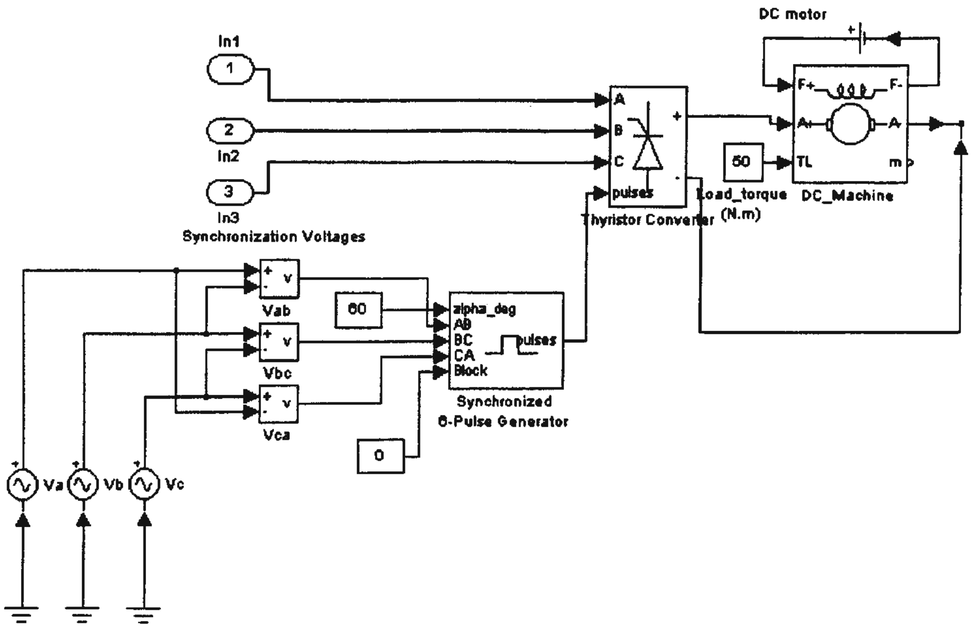
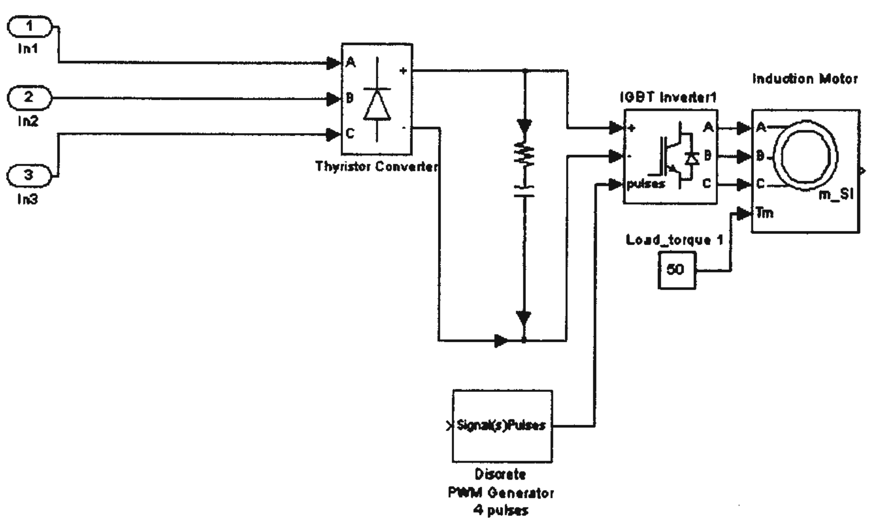


Fig A.14: Type D Compensation System



A.15: Separately excited DC motor load



A.16: PWM based Induction motor drive

Appendix B

Matlab Programs

B.1 Basic fft function routine called by the programs

```
function [mag, f]=specFFT(x,dt)

% This function returns the magnitude and frequencies

% of the sinusoidal signals that make up the function x. The function

% x should have an even number of points.

% Frequency (f) is in Hz.


xfft = fft(x);

N = length(xfft);

mag = abs(xfft(1:((N/2)+1)));

f = (0:(N/2))/(N*dt);
```

B.2 Main analysis and plot program

%This program accepts the data written into the workspace by the simulink models and computes the frequency spectrum by calling the basic function "specFFT", plots the data and calculates the total harmonic distortion.

```
dt=0.00001;  % sampling frequency
n=length(t);
subplot(2,1,1)
plot(t,iload_a);
grid on
subplot(2,1,2)
plot(t,ia)
grid on
figure
[ILA,freq1]=specFFT(iload_a,dt); % load current analysis
ILA=ILA*2/n;
subplot(2,1,1)
plot(freq1/60,ILA)
grid on
%axis([0 2000 0 40])
Thd=0;
for f=37:24:10000
  Thd=Thd+ILA(f)*ILA(f);
```

```
end
  Thd=sqrt(Thd)/(ILA(13));
disp('the load current thd is')
disp([Thd])


% axis([0 2000 0 40])
[IAS,freq2]=specFFT(ia,dt); % source current analysis
IAS=IAS*2/n;
subplot(2,1,2)
plot(freq2/60,IAS)
%axis([0 2000 0 40])
grid on
Thd=0;
for f=37:24:10000
  Thd=Thd+IAS(f)*IAS(f);
end
  Thd=sqrt(Thd)/(IAS(13));
disp('the source current thd is')
disp([Thd])
figure
subplot(2,1,1)
plot(t,va)
```

```
subplot(2,1,2)
plot(t,vload_a)
figure
[VAS,freq5]=specFFT(va,dt); %Source voltage analysis
VAS=VAS*2/n;
subplot(2,1,1)
plot(freq5/60,VAS)
grid on
 axis([0 1200 0 200])
Thd=0;
for f=37:24:10000
  Thd=Thd+VAS(f)*VAS(f);
end
  Thd=sqrt(Thd)/(VAS(13));
disp('the source voltage thd is')
disp([Thd])
[VAL,pha,freq6]=specFFT(vload_a,dt); %Load voltage analysis
VAL=VAL*2/n;
subplot(2,1,2)
plot(freq6/60,VAL)
grid on
 axis([0 1200 0 200])
```

```
Thd=0;
for f=37:24:10000
  Thd=Thd+VAL(f)*VAL(f);
end
  Thd=sqrt(Thd)/(VAL(13));
disp('the load voltage thd is')
disp([Thd])
figure
subplot(2,1,1)
plot(t,iload_a1)
subplot(2,1,2)
plot(t,iload_a2)
figure
[IAL1,freq6]=specFFT(iload_a1,dt); %VSNL load current analysis
IAL1=IAL1*2/n;
subplot(2,1,1)
plot(freq6/60,IAL1)
grid on
 axis([0 1200 0 200])
Thd=0;
for f=37:24:10000
  Thd=Thd+IAL1(f)*IAL1(f);
```

```
end
  Thd=sqrt(Thd)/(IAL1(13));
disp('the thd of the VSNL is')
disp([Thd])
[IAL2, freq6]=specFFT(iload_a2,dt); %CSNL load current analysis
IAL2=IAL2*2/n;
subplot(2,1,2)
plot(freq6/60,IAL2)
grid on
 axis([0 1200 0 200])
Thd=0;
for f=37:24:10000
  Thd=Thd+IAL2(f)*IAL2(f);
end
  Thd=sqrt(Thd)/(IAL2(13));
disp('the thd of the CSNL is')
disp([Thd])
figure
subplot(211)
plot(t,ipaf)
subplot(212), plot(t,vs)
```

B. 3 Ratings evaluation program

B.3.1 Type 1 rating

```
% Series active filter rating for a reference load of 1p.u and sag of 0.3-0.7   % percent

for s = 0.3:0.1:0.7

sload=1;

THD=0:100;

saf1=(s./(1+THD/100)).*sload;

plot(sload, THD)

hold on

xlabel('Total harmonic distortion, THD%')

ylabel('series active compensator rating, per unit')

grid on

%title('increase of series compensator rating for a sag of 50% and various THD')

end

% Variation of series active filter rating for increasing load and a fixed THD of 50 per-

cent

for x=0.3:0.1:0.7

sload=0:0.1:1;

THD=50;

saf1=(x./(1+THD/100)).*sload;

plot(sload,saf1)
```

```
hold on
xlabel('load rating')
ylabel('series active compensator rating per unit')
grid on
%title('increase of series compensator rating for a sag of 50% and various THD')
end
```

B.3.2 Type 3 rating

```
% This part calculates the rating of the active filter for increasing THD and a fixed refer-
ence load of 1p.u for various levels of passive filter compensation
Ilh=1;
for Ir=0:0.2:1;
sload=1;
THD=0:100;
saf2=(((THD/100)*(1-Ir))./(1+THD/100)).*sload;
plot(THD,saf2)
hold on
end
xlabel('Total harmonic distortion, %')
ylabel('Active filter rating, pu')
grid on
figure
```

%This part calculates the rating of the active filter for increasing load %and total harmonic distortion.

```
for Ir=0:0.1:1
sload=0:0.01:1;
THD=50;
saf2=(((THD/100)*(1-Ir))/(1+THD/100)).*sload;
plot(sload,saf2)
hold on
end
grid on
xlabel('Load rating, pu')
ylabel('Active filter rating, pu')
```

B.3.3 Type 4 rating

%This part calculates the shunt active filter rating for increasing THD and and a reference load of 1p.u

```
for zr=0.0:0.1:0.7;
THD=0:100;
saf2=(THD/100)*zr./(1+THD/100);
plot(THD,saf2)
hold on
end
```

```
xlabel('total harmonic distortion, %')

ylabel('shunt active filter rating, pu')

grid on

figure

%This part computes the rating of the shunt active filter for a fixed THD and increasing

load.

for zr=0.0:0.1:0.5;

THD=50;

sload=0:0.01:1;

saf2=((THD/100)*zr./(1+THD/100)).*sload;

plot(sload,saf2)

hold on

end

xlabel('Load rating, %')

ylabel('Shunt active filter rating, pu')

grid on
```