CHAPTER-II

PASSIVE & ACTIVE FILTER

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2.1 INTRODUCTION

Over the year there has been a continuous proliferation of nonlinear type of loads due to intensive use of power electronic control in all branches of industry as well as by the general consumers of electric energy. These modern equipments are designed to offer optimum performance at low running costs, but in turn they play havoc with the supply system and hence affect the performance of other equipment connected in the system. These disturbances include harmonic distortion, voltage unbalance, voltage surges, increased reactive power demand and power system fluctuations etc. Harmonic contamination has become a major concern of power system specialist due to its effects on sensitive loads and on power distribution system. Harmonic current component increase power system losses, causes excessive heating in rotating machinery, can create significant interference with the commutation circuits that shared common right of ways with AC power lines, can generate noise on regulating and control circuits causing erroneous operation of such equipment. The effect of voltage and current harmonics can be noted at far of places in equipment connected to the same circuit.

2.2 HARMONIC SOURCES:

Two types of harmonics exist in the AC system voltage and current waveforms, characteristic harmonics and non-characteristic harmonics. Characteristic harmonics are generated due to characteristic of the harmonic producing equipment or subsystem and magnitude of these harmonics is much higher compared to magnitude of non-characteristic harmonics. The magnitude of characteristic harmonics decreases with increase in the harmonic order. Non-characteristic harmonics are generated due to all sorts of asymmetries in various parameters of the subsystem and the AC system.

Following equipment or subsystems are source of harmonics in the AC system. These sources of harmonics are already discussed in detail in chapter-I.

- Thyristor controlled devices, e.g.
- Rectifier and inverter stations of HVDC scheme.
- Thyristor Controlled Reactor (TCR)
- Thyristor Switched Capacitor (TSC)
- Cyclo-Converters
- Non-linear loads, e.g.
- Induction furnace and arc furnace
- Steel mills and rolling mills
- Welding machine
- Single phase uncompensated railways loads
- Switching equipment and various electronic circuits.
- Different type of loads at low level, e.g. house hold equipment and computers
- Non-linearity and core saturation of transformers and reactors.
- Combined effect of various harmonic producing equipment and subsystems.
- Cross modulation across the converters.

Even though magnitude of non-characteristic harmonics are very small, however parallel resonance within the AC system at any harmonic frequency can increase the magnitude significantly.

2.3 DIFFERENT METHODS OF DEALING WITH POWER QUALITY:

Harmonic present in the AC network causes following problems in the power system equipment.

1) Overheating in transformers and reactors
2) Overheating in capacitor bank and rotating machines
3) Additional losses in the transmission lines
4) Telephonic noise due to higher order harmonics
5) Higher stresses on the circuit breaker
6) Malfunctioning of control and protection equipment because of displacement of the zero crossing and increase in peak voltages
7) Third harmonic, which is of zero phase sequence, can flow through neutral wires into electricity distribution network causing overheating in the neutral wires.

As an alternative to harmonic reduction, it has been suggested to derate transformers and oversize cables. This could be an adequate solution in some cases, but since system configurations change, and thereby the harmonic profile of the system, the required amount of derating or over sizing could be difficult to predict. Also, this option does not prevent harmonies from entering the supply system. Therefore, a more appropriate method for harmonic mitigation is the use of filters.

Harmonic injected by the consumer loads into the AC system are required to be limited to the acceptable values. The simplest means of limiting harmonic at the AC bus is by installing harmonic filter at the load itself where harmonics are generated. Installation can be done either by the consumer or by the utilities.

Harmonic filters in power systems are used primarily to mitigate the harmonics generated by various kind of non-linear load. Depending on the configuration, filters are either of passive type or active type.

Conventionally, passive LC filters have been used to eliminate line current harmonics and to increase the load power factor.

2.4 PASSIVE FILTERS:

Filters are either series connected or shunt connected in the AC system. The concept of series connected filter is parallel resonating electrical circuit, which offers very high impedance at tuning frequencies. The high impedance offered by the filter allows very little harmonics to pass through it. The disadvantage of this type of connection is that all the filter components are required to be rated for full line current, which makes installation very expensive.

Most commonly the filters are shunt connected to the AC system. This type of filters use series resonating electrical circuit offering negligible impedance compared to the AC system harmonic impedance at tuning frequencies. The low impedance path, provided by the filters, attract major portion of the harmonics and allows very small portion of the harmonics to flow into the AC systems. Components in the shunt connected filter branch are designed for graded insulation levels, which make component cheaper than those used for series connected filters.

Combination of series and shunt-connected branch is used in the design of Power Line Carrier (PLC) and Radio Interference (RI) filters. The series connected branch blocks the harmonics and the shunt-connected branch allows the harmonics to flow in to the ground. The combination cannot be used for low order harmonics because high blocking impedance at low order tuning frequency will have significant voltage drop at fundamental frequency as well, which will reduce the AC bus voltage.

2.4.1. TYPES OF PASSIVE FILTERS:

Passive filters are series resonating or parallel resonating electrical circuit, which offer very high or very low impedance at tuning frequency. The filters are resistive at tuning frequency, capacitive below tuning frequency and inductive beyond tuning frequency. Filters have two important characteristics: impedance and bandwidth. Low impedance is required to ensure that harmonic voltages have a low magnitude and certain bandwidth is needed to limit the consequences of filter detuning.

2.4.1.1 SINGLE TUNED FILTER:

Single tuned filters as name suggests, are tuned to only one frequency and are simplest of all filters.

CONFIGURATION:

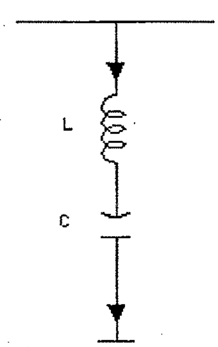

Figure 2.4.1.1-1: Single Tuned Filter

ADVANTAGE:

1) Simple configuration with only two components, capacitor and reactor.
2) Quality factor of the filter is high which provides maximum attenuation of one harmonic
3) Negligible losses as there are no resistor for damping etc.
4) Low maintenance requirements because of fewer components.

DISADVANTAGE:

1) Many filters will be required to filter several harmonics since one filter can be used for one harmonic only
2) High quality factor of the filter gives low bandwidth, which makes filter sensitive to variations in the fundamental frequency as well as the component values.
3) Accurate tuning is required at site because of which provision of taps on the reactor is essential. This increases the cost of the reactor.

FORMULAE FOR COMPONENT VALUE CALCULATION:

$$C_H = \frac{Q}{(V^2 * 2\pi f)} \quad (2.4.1.2\text{-}1)$$

$$L = \frac{1}{\{(2\pi f_r)^2 * C_H\}} \quad (2.4.1.2\text{-}2)$$

$$R = q * 2\pi f_r * L \quad (2.4.1.2\text{-}3)$$

$$C_L = \frac{1}{\{(2\pi f)^2 * L\}} \quad (2.4.1.2\text{-}4)$$

Where Q= reactive power to be generated by the filter at fundamental frequency (assumed)

V=voltage level at which filters are to be installed

f= Fundamental frequency

f_r= Tuning frequency (assumed)

q= Quality factor of the filter (assumed)

2.4.1.2 DOUBLE TUNED FILTERS :

Double tuned filters are equivalent to two single tuned filters connected in parallel. These filters use series as well as parallel resonating circuits, which makes it complex. C_H & L_H correspond to first tuning frequency and high voltage section whereas C_L& L_L corresponds to second tuning frequency and low voltage section.

CONFIGURATION:

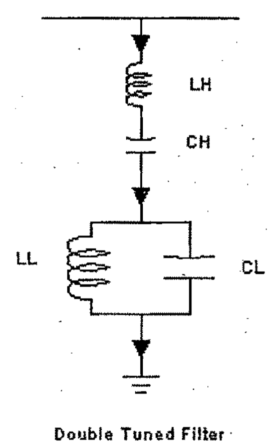

Figure 2.4.1.2-1: Double Tuned Filter

ADVANTAGES:

1) Quality factor the filter is high which provides maximum attenuation of two harmonic
2) Negligible losses as there are no resistors for damping etc.
3) There is only one high voltage capacitor and high voltage reactor because of which it is cheaper than two single tuned filters connected in parallel.

DISADVANTAGES:

1) High quality factor of the filter give low bandwidth, which makes filter sensitive to variations in the fundamental frequency as well as the component values.
2) Accurate tuning is required at site because of which provision of taps on the reactor is essential. This increases the cost of the reactor.
3) Rating of low voltage component is decided mainly by transient behavior of the filter circuit.

FORMULA FOR COMPONENT VALUE CALCULATION

$$C_H = \frac{Q}{\left(V^2 * 2\pi f\right)} \qquad (2.4.1.3\text{-}1)$$

$$L_H = \frac{1}{\left\{(2\pi f_1)^2 * C_H\right\}} \qquad (2.4.1.3\text{-}2)$$

$$C_L = \frac{1}{\left\{(2\pi f_L)^2 * L_L\right\}} \qquad (2.4.1.3\text{-}3)$$

Where Q= reactive power to be generated by the filter at fundamental frequency (assumed)

V=voltage level at which filters are to be installed

f= Fundamental frequency

f_1= First tuning frequency (assumed)

f_2= Second tuning frequency (assumed)

The filter circuit being complex in nature, the component values are finalized only after analysis of impedance versus frequency plots. Adjustment in the component values are made based on the desired filter characteristics.

2.4.2. GUIDELINES FOR PASSIVE FILTER SELECTION:-

The choice of techno-economical filter circuit depends on site conditions and AC system parameters. Detailed performance and rating studies only can establish an optimum solution. From the advantages and disadvantages described in section 2.4.1 following can be used for selection of filters

Damped filters are not very sensitive to frequency variations. When variation in the AC system fundamental frequency is large then damped filter shall be preferred to tuned filters.

1) Combination of damped filters can be used for limiting telephonic interference problem
2) Double tuned and triple tuned filters can be used for economical solutions in high voltage low MVAR filters.
3) For accurate tuning at sites, taps on the reactor shall be specified.
4) Where there is a wide ambient temperature range, tuned filters may not be right choice. However if seasonal tuning is permitted then taps on the reactor can be used for returning in summer and winter conditions.
5) Second order-damped filters can provide the optimum solution for characteristic harmonic groups.
6) Low harmonic order filter shall be realized either tuned or damped filters.
7) When limitation of voltage distortion can achieved by either tuned or damped filters.
8) When limitation on reactive power exchange in conjunction with TIF limitation is required double tuned high pass filters may be the optimum solution.

However, in practical application these passive filters present following disadvantages.

1) The source impedance strongly affects filtering characteristics.
2) As both the harmonics and the fundamental current components flow into the filter, the capacity of the filter must be rated by taking into account both currents.
3) When the harmonic current components increase, the capacity of the filter can be overloaded.
4) Parallel resonance between the power system and the passive filter causes amplification of the harmonic currents on the source side at a specific frequency.
5) The passive filter may fall into series resonance with the power system so that voltage distortion produces excessive harmonic currents flowing into the passive filter.

In order to overcome these problems, active filters have been researched and developed. Since then basic compensation were proposed around 1970 much research has been done on active filters and their practical application [l1]-[l3]. In addition, state of art power electronics technology has enabled engineers to put active filters into practical use.

2.5 ACTIVE FILTERING

Passive filters can prevent harmonics from entering a supply system, and are also useful in increasing power factor, but there are a number of considerations that are critical in this approach [10] [11]. For instance parallel and series resonance with ac line impedance may produce amplification in the harmonic current and voltage of the line at certain frequencies. Also the effectiveness in attenuating harmonics is not dictated only by the passive filter itself, but depends on the source impedance. Moreover, it is difficult to decouple the effects of one load from those of other loads connected to the line and compensate only for harmonic currents produced by this one load. Thus, it is often necessary to oversize passive filters in order to avoid overheating. The classic solution of tuned passive filters therefore has serious limitations. Furthermore, with the widespread use of variable distorting electronic loads, harmonic tracking is not adequately achieved. Also the probability of encountering resonant conditions increases with the number of installed filtering units. Active filtering techniques have therefore been proposed to overcome the problems associated with passive filters.

Much research has been performed on active filters for power conditioning and their practical applications since their basic principles of compensation were proposed around 1970 (Bird et al., 1969; Gyugyi and Strycula, 1976; Kawahira et al., 1983). In particular, recent remarkable progress in the capacity and switching speed of power semiconductor devices such as insulated-gate bipolar transistors (IGBTs) has spurred interest in active filters for power conditioning. In addition, state-of-the-art power electronics technology has enabled active filters to be put into practical use. More than one thousand sets of active filters consisting of voltage-fed pulse-width-modulation (PWM) inverters using IGBTs or gate-turn-off (GTO) thyristors are operating successfully in Japan.

Active filters for power conditioning provide the following functions:

1) Reactive-power compensation
2) Harmonic compensation,
3) harmonic isolation,
4) harmonic damping and harmonic termination,
5) negative-sequence current and voltage compensation,
6) Voltage regulation.

The term "active filters" is also used in the field of signal processing. In order to distinguish active filters in power processing from active filters in signal processing, the term "active power filters" is used in normal practice.

2.5.1. CLASSIFICATION OF ACTIVE FILTER:

Various types of active filters have been proposed in many technical literatures. Classification of active filter is made from different point view. Active filters are divided into AC and DC filters. Active DC filters have been designed to compensate for current and/or voltage harmonics on the DC side of thyristor converters for HVDC systems [4] and on the DC link of a PWM rectifier/inverter for traction system. But the term "active filter" refers to the AC filters in most cases.

2.5.1.1 CLASSIFICATION BY SYSTEM CONFIGURATION

2.5.1.1.1 Shunt active filters:

Figure 2.5.1-1 shows a system configuration of a shunt active filter used alone, which is one of the most fundamental system configurations. The shunt active filter is controlled to draw a compensating current i_{AF}, from the utility, so that it cancels current harmonics on the AC side of a general-purpose thyristor rectifier with a DC link inductor or a PWM rectifier with DC link capacitor for traction systems. The shunt active filter has the capability of damping harmonic resonance between an existing passive filter and the supply impedance.

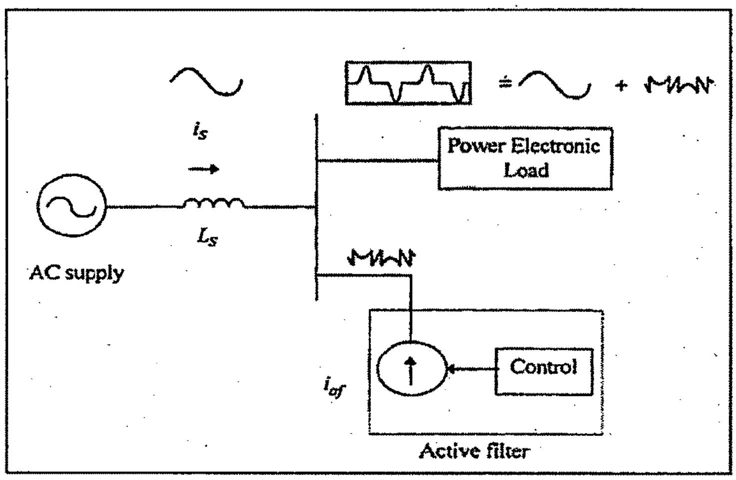

Figure 2.5.1-1: Shunt Active Filter

2.5.1.1.2 Series active filters:

Figure 2.5.1-2 shows a system configuration of a series active filter used alone. The series active filter is connected in series with a utility through a matching transformer, so that it is applicable to harmonic compensation of a large capacity diode rectifier with a DC link capacitor. Comparisons between the shunt and series active filters show that series active filter has a "dual" relationship in each item with the shunt active filter.

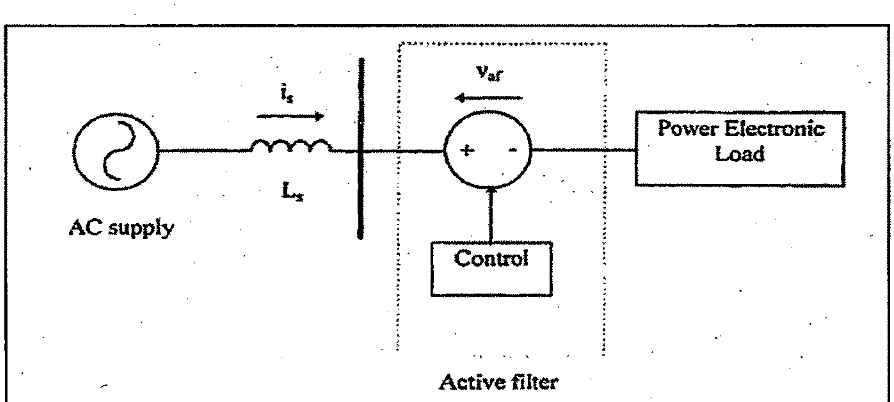

Figure 2.5.1-2: Series Active Filter

Comparison of shunt and series active filter used alone:

	Shunt active filter	**Series active filter**
System configuration	Figure 2.5.1-1	Figure 2.5.1-2
Power circuit of	Voltage-fed PWM inverter with	Voltage-fed PWM inverter
Active filter acts as	Current source: i_{af}	Voltage source: V_{af}
Harmonic producing	Cyclo-Converters & thyristor	Diode rectifiers with
Additional function	Reactive power compensation	AC voltage regulator
Present situation	Commercial stage	Laboratory level

2.5.1.1.3 Hybrid Active Filter:

(1) Hybrid active/passive filters:

Figure 2.5.1-3 to Figure 2.5.1-5 show three types of hybrid active/passive filters, the main purpose of which is to reduce initial costs and to improve efficiency. The shunt passive filter consists of one or more tuned LC filters and/or a high-pass filter. The difference among the three hybrid filters, in which, the active filters are different in function from the passive filters.

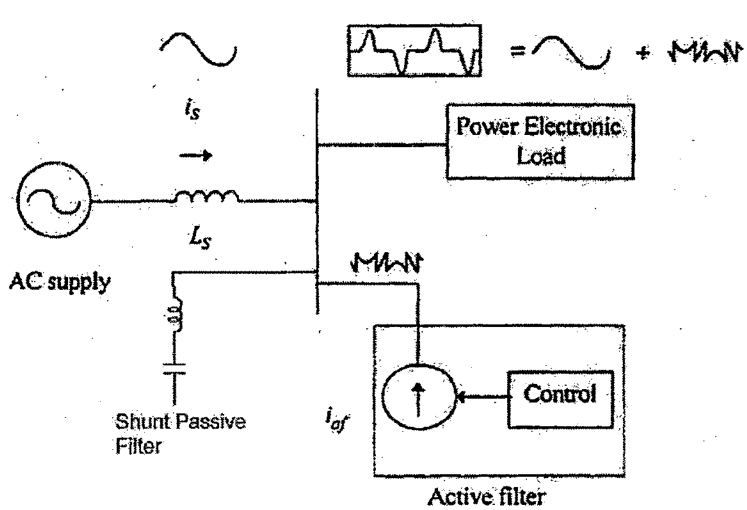

Figure 2.5.1-3: Combination of shunt active filter and shunt passive filter

(2) Hybrid shunt/series active filters:

The combination of shunt and series active filter will be applied in near future, not only for harmonic compensation but also for harmonic isolation between supply and load, and for voltage regulation and imbalance compensation. They are considered prospective alternatives to shunt or series active filters used alone.

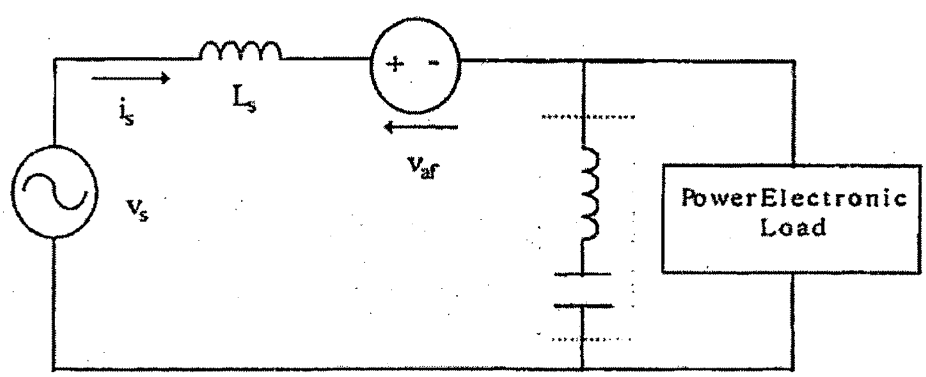

Figure 2.5.1-4: Combination of series active filter and shunt passive filter

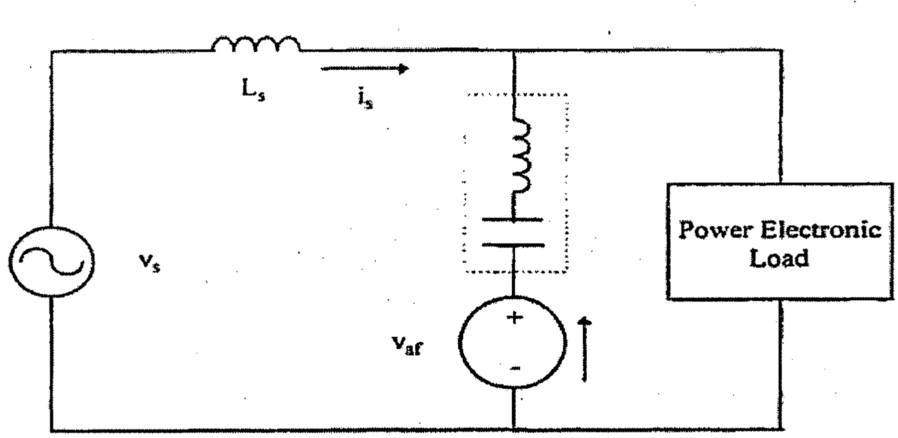

Figure 2.5.1-5: Combination of series active filter connected in series with and shunt passive filter

Comparison of hybrid active /passive filters

	Shunt active filter plus shunt passive filter	**Series active filter plus shunt passive filter**	**Series active filter connected in series with shunt passive filter**
System configuration	Figure 2.5.1-3	Figure 2.5.1-4	Figure 2.5.1-5
Power circuit of active filter	Voltage-fed PWM inverter with current minor loop	Voltage-fed PWM inverter without current minor loop	Voltage-fed PWM inverter with or without current minor loop
Function of active filter	Harmonic compensation or harmonic damping	Harmonic isolation and harmonic damping	Harmonic damping or harmonic compensation
Advantages	General shunt active filters applicable Reactive power controllable	Already existing shunt passive filters applicable No harmonic current flowing through active filter	Already existing shunt passive filters applicable Easy protection of active filter
Problem or issues	Share compensation in frequency domain between active filter and passive filter	Difficult to protect active filter against over current No reactive power control	No reactive power control
Present situation	Commercial stage	Field testing	Coming into market

2.5.1.2 CLASSIFICATION BY POWER CIRCUIT:

There are two type of power circuit used for active filters a voltage-fed PWM inverter and a current fed PWM inverter. These are similar to the power circuit used for AC motor drives. They are, however, different in their behavior because active filters act as non-sinusoidal current or voltage source. The voltage fed PWM inverter is preferred compare to the current fed PWM inverter because the voltage fed PWM inverter is higher in efficiency and lower in initial costs than the current fed PWM inverter. In fact, almost all active filters, which have been put into practical applications, have adopted the voltage fed PWM inverter as the power circuit.

2.5.1.3 CLASSIFICATION BY CONTROL STRATEGY:

The control strategy of active filters has great impact not only on the compensation objective and required kVA rating of active filters, but also on the filtering characteristics in transient state as well as in steady state.

2.5.1.4 FREQUENCY DOMAIN AND TIME DOMAIN:

There are mainly two kinds of control strategies for extracting current or voltage harmonics from the corresponding distorted current or voltage; one based on frequency domain i.e."Fourier analysis" and the other is based on time domain i.e. "instantaneous reactive power theory" in three phase circuits, which is called " p-q theory",. "synchronous reference theory" and "sine multiplication theory". The concept of the p-q theory in the time domain has applied to the control strategy of almost all the shunt active filters installed by individual high power consumer.

2.5.1.5 HARMONIC DETECTION METHODS:

Three kinds of harmonic detection methods in the time domain has been proposed for shunt active filters acting as a current source i_{AF}

load current detection $i_{AF} = i_{Lh}$

supply current detection $i_{AF} = Ks * i_{Sh}$

voltage detection $i_{AF} = Kv * v_h$

load current detection and supply current detection are suitable for shunt active filters installed in the vicinity of one or more harmonic producing loads by individual high-power consumer. Voltage detection is suitable for shunt active filter to be used as shunt device of the "unified power quality conditioner" which will be installed in primary distribution substations by utilities.

Supply current detection is the most basic harmonic detection method for series active filters acting as a voltage source v_{AF}

Supply current detection $v_{AF} = G * i_{SH}$

Series active filter are based on supply current detection. It is also suitable for a series active filter to be used as the series device of the unified power quality conditioner.

2.6 PULSE WIDTH MODULATION SCHEMES:

Pulse width modulation (PWM) techniques have been the subject of intensive research during the last few decades. A large variety of methods, different in concept and performance, have been newly developed and described. However, the main objective is to shape the output AC voltages to be as close to a sine wave as possible and hence to reduce current harmonics and to improve the harmonic spectrum. However while achieving the above, the switch utilization factor, losses and complexity of control is also kept in mind and is tried to be optimized.

The voltage source converter type of inverters can be divided into following two general categories.

1) Pulse-width modulated inverters. In these inverters, the DC voltage is essentially kept constant in magnitude, where a diode rectifier is used to rectify the line voltage. Therefore, the inverter must control the magnitude and the frequency of the AC output voltages. This is achieved by PWM of the inverter switches and hence such inverters are called PWM inverters. There are various schemes to pulse-width modulate the inverter switches in order to shape the output AC voltages to be as close to a sine wave as possible. Out of these various PWM schemes, a scheme called sinusoidal PWM and Space vector modulation (SVM) are the most popular.
2) Square-wave inverters. In these inverters, the input DC voltage is controlled in order to control the magnitude of the output AC voltage, and therefore the inverter has to control only the frequency of the output voltage. The output AC voltage has a waveform similar to a square wave, and hence these inverters are called square-wave inverters.

2.6.1. SQUARE WAVE OPERATION IN THREE-PHASE INVERTERS

If the input DC voltage V_d is controllable, the inverter in Figure 2.6.1-1a can be operated in a square-wave mode. Here, each switch is on for 180° (i.e., its duty ratio is 50%). Therefore, at any instant for time, three switches are on.

In the square-wave mode of operation, the inverter itself cannot control the magnitude of the output AC voltages. Therefore, the DC input voltage must be controlled in order to control the output in magnitude. Here, the fundamental-frequency line-to-line rms voltage component in the output can be obtained as,

$$V_{LL_{1(rms)}} = \frac{\sqrt{3}}{\sqrt{2}}\frac{4}{\pi}\frac{V_d}{2} \qquad (2.6.1\text{-}1)$$

$$= \frac{\sqrt{6}}{\pi}V_d \qquad (2.6.1\text{-}2)$$

$$= 0.78V_d \qquad (2.6.1\text{-}3)$$

The line to line output voltage waveform does not depend on the load and contains harmonics ($6n\pm1$; n = 1, 2 ...), whose amplitudes decrease inversely proportional to their harmonic order, as shown in Figure 2.6.1.1c:

$$V_{LL_h} = \frac{0.78}{h}V_d \qquad (2.6.1\text{-}4)$$

where $h = 6n\pm1$ (n = 1, 2, 3 ...)

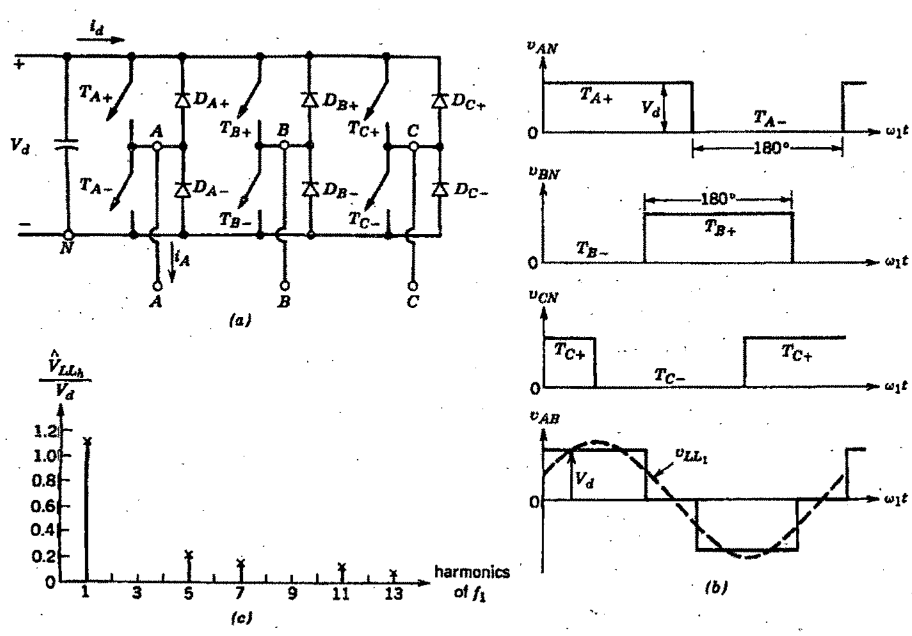

Figure 2.6.1-1: Square Wave inverter

2.6.2. SINUSOIDAL PULSE WIDTH MODULATION

To obtain balanced three-phase output voltages in a three-phase PWM inverter, triangular voltage waveform is compared with three sinusoidal control voltages that are 120° out of phase, as shown in Figure 2.6.2-1a.

It should be noted from Figure 2.6.2-1b that an identical amount of average DC component is present in the output voltages v_{AN} and v_{BN}, which are measured with respect to the negative DC bus. These DC components are cancelled out in the line-to-line voltages, for example in v_{AB} shown in Figure 2.6.2-1b. This is similar to what happens in a single-phase full-bridge inverter utilizing a PWM switching.

In general, the harmonics in the inverter (sinusoidal PWM control) output voltage waveform appears as sidebands, centered around the switching frequency and its multiples, that is, around harmonics m_f, $2m_f$, $3m_f$, and so on. Where m_f is the frequency modulation ratio. This general pattern holds true for all values of m_a (modulation index) in the range 0-1. Theoretically, the frequencies at which voltage harmonics occur can be indicated as,

$$f_h = (jm_f \pm k)\, f1$$

that is, the harmonic order *h* corresponds to the k^{th} sideband of *j* times the frequency modulation ratio m_f.

$$h = j\,(m_f) \pm k$$

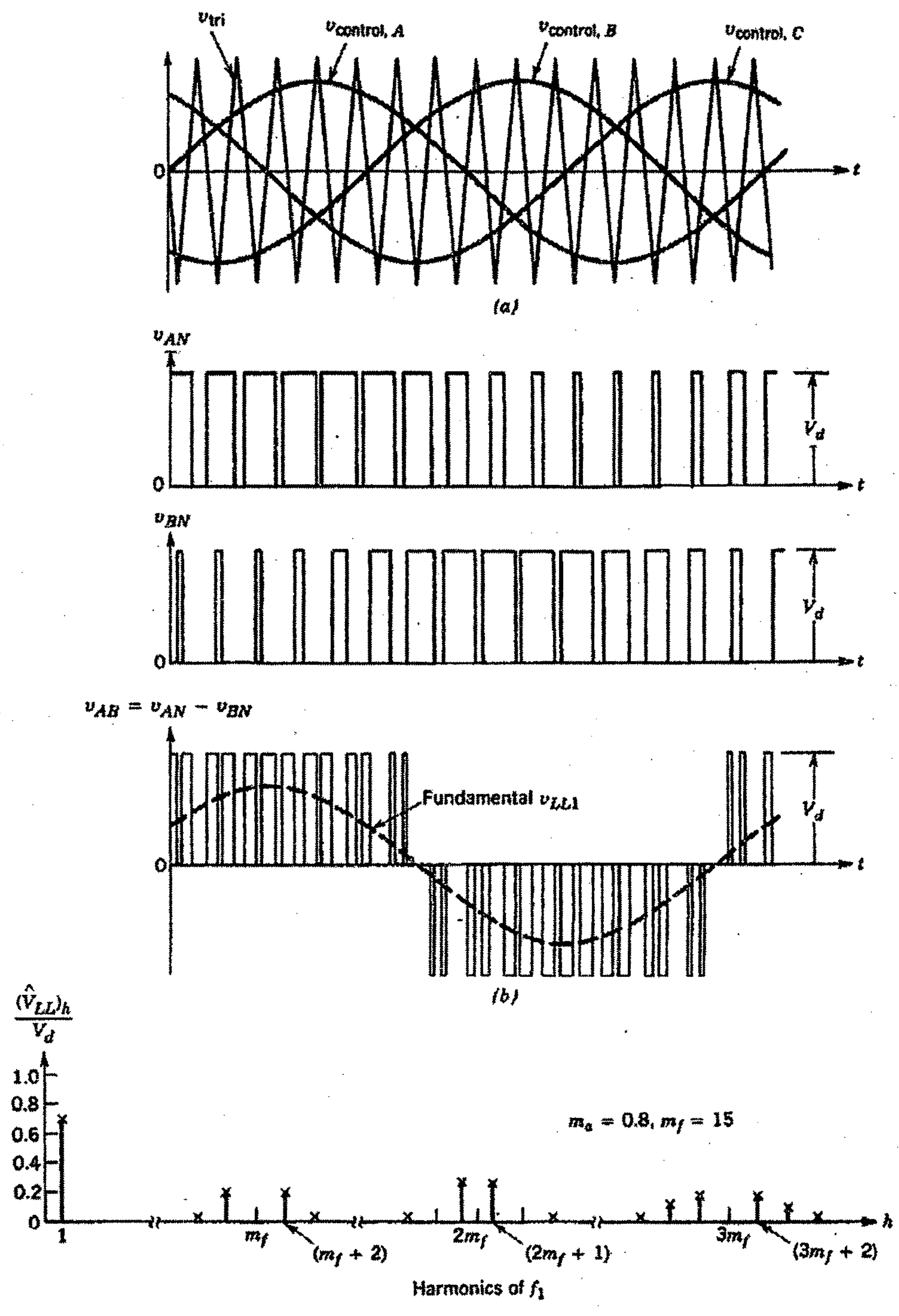

Figure 2.6.2-2: Three Phase PWM Waveforms and harmonics Spectrum

where the fundamental frequency corresponds to h=1. For odd values of *j*, the harmonics exist only for even values of *k*. For even values of *j*, the harmonics exist only for odd values of *k*.

However in three-phase inverters, only considering the harmonics at m_f (the same applies to its odd multiples), the phase difference will be equivalent to zero (a multiple of 360°) if m_f is odd and a multiple of 3. As a consequence, the harmonics at m_f is suppressed in the line-to-line voltage v_{AB}. The same argument applies in the suppression of harmonics at the odd multiples of m_f to be an odd multiple of 3 is to keep m_f odd and, hence, eliminate even harmonics). Figure 2.6.2-2d shows the variation of line-to-line output voltage (normalized with respect to DC link voltage v_d) of three sinusoidal pulse width modulated inverter for different values of modulation index. Figure also shows the linear and over modulation operating region.

If modulation index is defined as,

$m = \frac{u^*}{u_{1six-step}}$ where u^* = normalized fundamental reference vector

and $u_{1six-step}$ is the fundamental voltage of a six-step waveform.

Then, in case of sinusoidal pulse width modulation the maximum value of the modulation index, m = 0.785, is reached at a point where the amplitudes of the reference and the carrier signal become equal. However a distorted reference waveform, containing only triplen harmonics to an extent that its maximum assumes a flattop like shape as shown in Figure 2.6.2-2d increases the maximum modulation index, m=0.907. The added triplen harmonics modify the switched voltage waveform, increasing their fundamental content; they do not produce harmonic currents in a three-phase system.

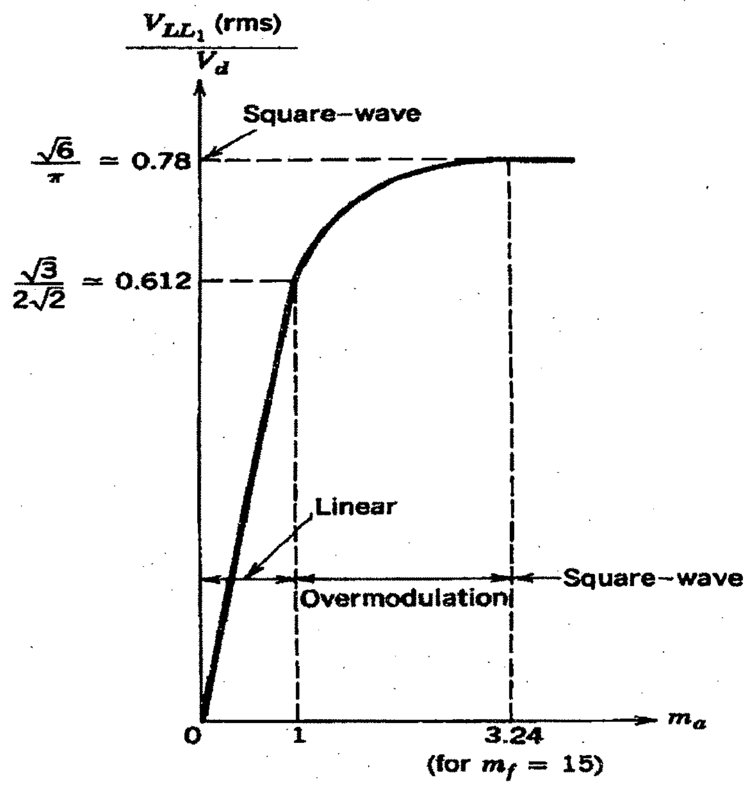

Figure 2.6.2-3: Three Phase Inverter V_{LL1}(rms)/V_d as a function of m_a

2.7 PWM CONVERTER FOR THREE PHASE FOUR WIRE ACTIVE FILTER SYSTEM:

In this section two configurations of voltage source inverters (VSI), which can be used in three-phase four wire systems are discussed. The fundamental difference between the VSI of Figure 2.7-1 and Figure 2.7-1 is the number of power semiconductor device.

A conventional three leg converter is used in Figure 2.7-1 and the AC neutral wire are connected directly to the mid-point of the DC bus, while in Figure 2.7-2 the AC neutral is provided through a fourth leg. Since the configuration has PWM current control, they behave as controlled current source. The AC current generated by the VSI has some high-order harmonics at the switching frequency, which can be easily filtered using a small passive filter (R and C in Figure 2.7-1. Ideally the currents track accurately their reference i_{ck}^* (k = a, b, c).

The controllability of the "four switch-leg" inverter topology Figure 2.7-2 is better than the "split-capacitor" inverter topology Figure 2.7-1. However the conventional three-leg converter is preferred because of its lower number of power semiconductor devices. The problems related to the DC capacitor voltage control by using the topology of "split-capacitor" will be discussed below.

Figure 2.7-3 shows a typical motion of the a-phase VSI current, controlled by hysteresis-based PWM current controller. If the current reference i_{ck}^* are assumed to be composed from zero sequence component, the line current i_{fk} (k = a, b, c) will return through the AC neutral wire. This forces, in the "split-capacitor" inverter topology, the current of each phase to flow either through C1 or through C2 and to return through the AC neutral wire.

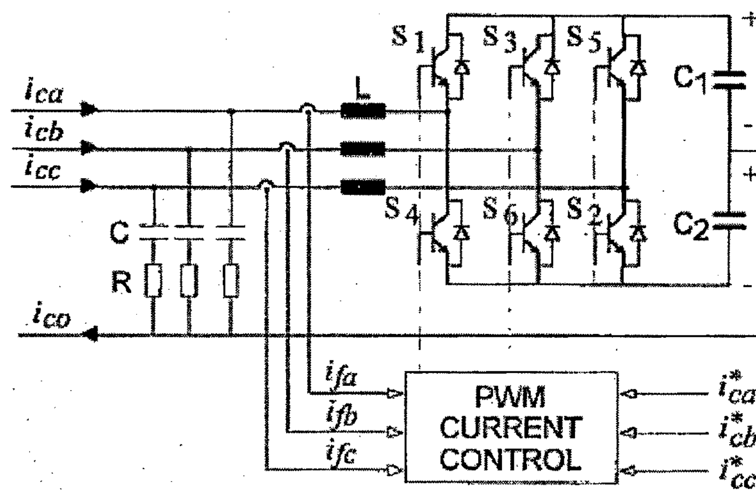

Figure 2.7-1: Three Phase Four Wire Three Leg Converter

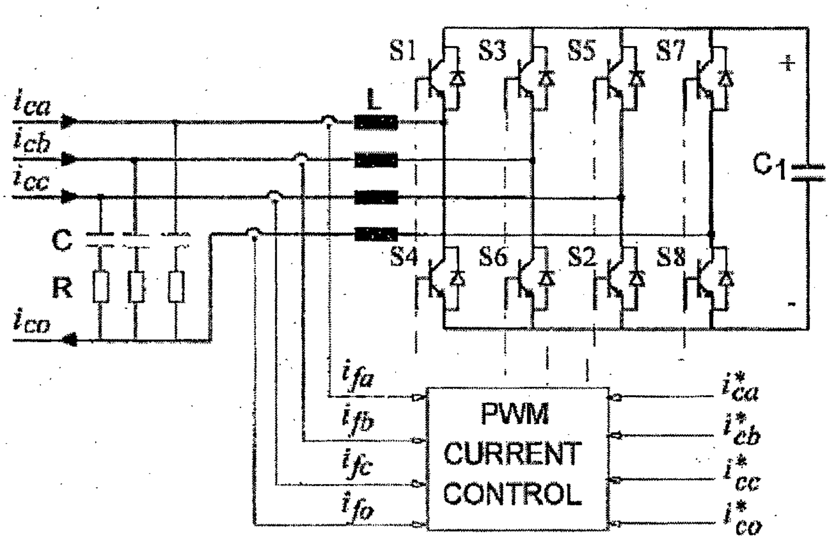

Figure 2.7-2: Three Phase Four Wire Four Leg Converters

The current can flow in both directions through the switches and capacitors. Table 2.7-1 summarizes the conditions that cause voltage variations in the capacitor C_1 and C_2 for a zero sequence current reference in the "split-capacitor" inverter topology.

Table 2.7-1: Conditions for the capacitor voltage Variation V_{c1} and V_{c2}

$i_{fk} > 0$ and $di_{fk} / dt < 0$	Increase the voltage in C_1
$i_{fk} < 0$ and $di_{fk} / dt < 0$	Decrease the voltage in C_1
$i_{fk} < 0$ and $di_{fk} / dt > 0$	Increase the voltage in C_2
$i_{fk} > 0$ and $di_{fk} / dt > 0$	Increase the voltage in C_2

When $i_{fk} > 0$, V_{c1} rises and V_{c2} decreases, but not with equal ratio because positive and negative values of di_{fk} / dt are different and depend on the instantaneous values of the AC phase voltages. The inverse occurs when $i_{fk} < 0$ the DC voltage variation depends also on the shape of the current reference and the hysteresis bandwidth.

Therefore, the total DC voltage as well as the voltage difference (V_{c2}-V_{c1}) will oscillates not only at the switching frequency, but also at the corresponding frequency of i_0 that is being generated by the VSI.

In the example given in Figure 2.7-3 the phase current i_{fa} causes voltage variations such that at the end of the period the voltage V_{c1} is higher and Vc2 lower. If a dynamic offset level is added to both limits of the hysteresis band, it is possible to control the capacitor voltage difference and to keep it within an acceptable tolerance margin. For instance, a negative offset in Figure 2.7-3 counteracts the above voltage variation

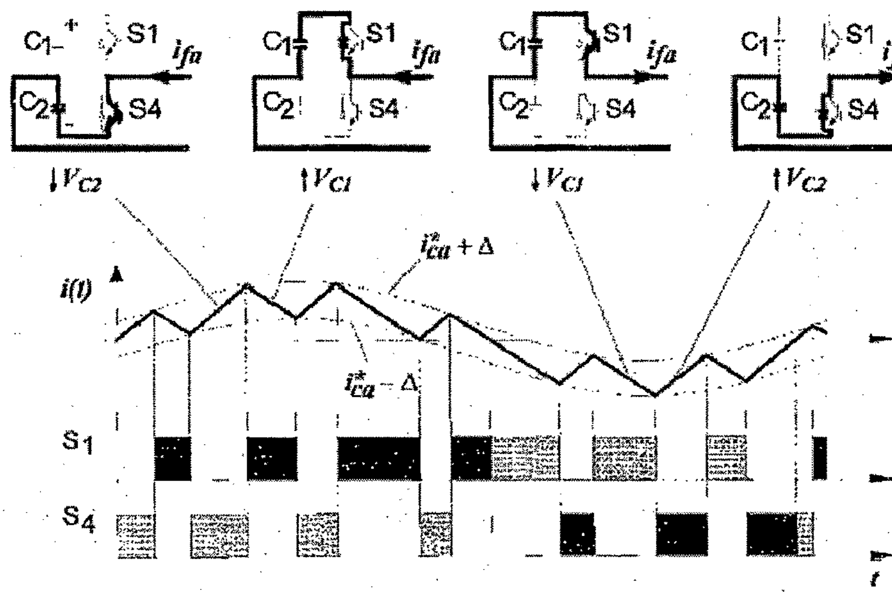

Figure 2.7-3: Hysteresis Band Current Control

2.8 SHUNT ACTIVE FILTER CONTROL APPROACH:

There are numerous approaches by which realization of shunt active filter control is possible. Instantaneous active reactive power theory was used to implement the shunt active filter. Instantaneous active reactive power theory based on which the active filter was designed is discussed below

2.8.1. INSTANTANEOUS ACTIVE REACTIVE POWER THEORY

The instantaneous power in three-phase is defined on the basis of instantaneous concept for arbitrary voltage and current waveforms including transient states. The detailed description of this theory is as follows.

To deal with instantaneous voltages and current in three phase circuits mathematically, it is adequate to express these quantities as the instantaneous space vectors. For simplicity, the three phase voltages and currents excluding zero sequence components will be considered in the following. The derivation with zero sequence is given in Appendix-II-B.

Figure 2.8.1-1 shows a three-phase three-wire system on the a-b-c coordinates, where no zero-sequence voltage is included in the three-phase three-wire system.

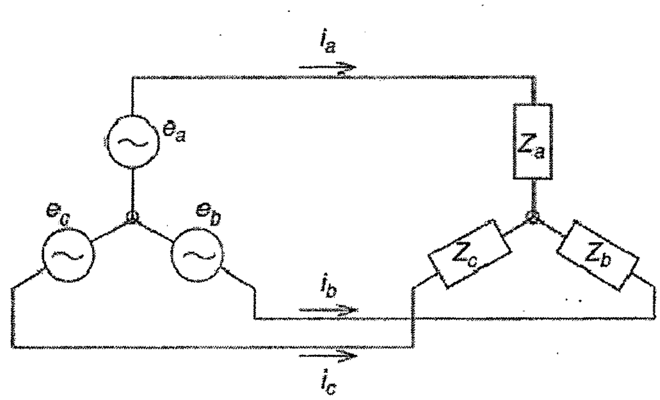

Figure 2.8.1-1: Three-phase three-wire system

In a-b-c coordinates, the a, b and c axes are fixed on the same plane, apart from each other by $2\pi/3$, as shown in Figure 2.8.1-2 The instantaneous space vectors, e_a and i_a are set on the a axis, and their amplitude and (+,-) direction vary with passage of time. In the same way, e_b and i_b are on the b axis, and e_c and i_c are on the c axis.

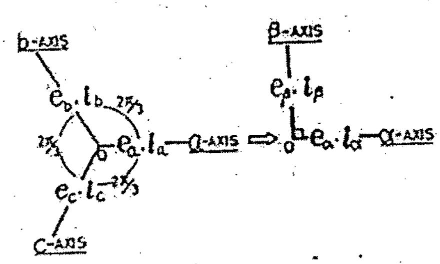

Figure 2.8.1-2: α-βCoordinates Transformer

These space vectors are easily transformed into α-β coordinates as follows:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (2.8.1\text{-}1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (2.8.1\text{-}2)$$

Where the α and β axes are the orthogonal coordinates. Necessarily, e_α and i_α are on the α axis, e_β and i_β are on the β axis. Their amplitude and (+,-) direction vary with passage of the time.

Figure 2.8.1-2 shows the instantaneous space vectors on the α-β coordinated. As is well known, the instantaneous real power either on the a-b-c coordinates or on the α-βcoordinates is defined by

$$p = e_\alpha i_\alpha + e_\beta i_\beta = e_a i_a + e_b i_b + e_c i_c \tag{2.8.1-3}$$

Where p is equal to the conventional power.

In order to define the instantaneous reactive power, the space vector is defined by

$$q = e_\alpha i_\beta - e_\beta i_\alpha \tag{2.8.1-4}$$

As shown in Figure 2.8.1-3 this space vector is the imaginary axis vector and is perpendicular to the real plane on the α-β coordinates, to be in compliance with right hand rule.

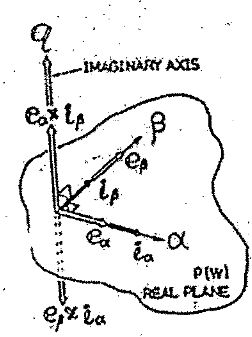

Figure 2.8.1-3: Instantaneous Space Vector

Taking into consideration that e_α is parallel to i_α, and that e_α is perpendicular to i_β and e_β to i_α, the conventional instantaneous imaginary power q, which of amplitude q, are expressed by

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2.8.1-5}$$

In Equation (2.8.1-5) $e_\alpha i_\alpha$ and $i_\beta e_\beta$ obviously mean instantaneous power because they are defined by the product of the instantaneous voltage in one axis and the instantaneous current in the same axis. Therefore, "p" is the real power in the three-phase circuit, and its dimension is (W). Conversely, $e_\alpha i_\beta$

and $e_\beta i_\alpha$ are not instantaneous power because they are defined by the product of the instantaneous voltage in the in one axis and the instantaneous current not in the same axis but in the perpendicular axis.

Accordingly q cannot be dealt with conventional quantity. "q" is quite different from "p" in dimension and electric property although "q" looks similar in formulation to "p". A common dimension for "q" should be introduced from both theoretical and practical points of view. A good candidate is [IW], that is, "imaginary watt."

Definition and physical meaning of instantaneous reactive power in Equation (2.8.1-5) is changed into the following equation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \qquad (2.8.1\text{-}6)$$

Note that the determinant with respect to e_α and e_β in Equation (2.8.1-5) is not zero. The instantaneous currents on the α-β coordinates, i_α and i_β are divided into two kinds of instantaneous current components, respectively:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ q \end{bmatrix} \qquad (2.8.1\text{-}7)$$

$$= \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} \qquad (2.8.1\text{-}8)$$

α - axis instantaneous active current

$$i_{\alpha p} = \frac{e_\alpha}{e_\alpha^{2} + e_\beta^{2}} p \qquad (2.8.1\text{-}9)$$

α axis instantaneous reactive current

$$i_{\alpha q} = \frac{-e_\beta}{e_\alpha^2 + e_\beta^2} q \qquad (2.8.1\text{-}10)$$

β axis instantaneous active current

$$i_{\beta p} = \frac{e_\beta}{e_\alpha^2 + e_\beta^2} p \qquad (2.8.1\text{-}11)$$

β axis instantaneous reactive current

$$i_{\beta q} = \frac{e_\alpha}{e_\alpha^2 + e_\beta^2} q \qquad (2.8.1\text{-}12)$$

Both physical meaning and reason for the naming of the active and the reactive currents are clarified in the following.

Let the instantaneous powers in the α axis and the β axis is p_α and $p_\beta$respectively, they are given by the conventional definition as follows.

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha i_\alpha \\ e_\beta i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha i_{\alpha p} \\ e_\beta i_{\beta p} \end{bmatrix} + \begin{bmatrix} e_\alpha i_{\alpha q} \\ e_\beta i_{\beta q} \end{bmatrix} \qquad (7.1.13)$$

The instantaneous real power in the three phase circuit p is given as follows using Equation (2.8.1-7) and (2.8.1-13),

$$p = p_\alpha + p_\beta \quad = e_\alpha i_{\alpha p} + e_\beta i_{\beta p} + e_\alpha i_{\alpha q} + e_\beta i_{\beta q}$$

$$= \frac{e^2{}_\alpha}{e_\alpha^2 + e_\beta^2} p + \frac{e^2{}_\beta}{e_\alpha^2 + e_\beta^2} p + \frac{-e_\alpha e_\beta}{e_\alpha^2 + e_\beta^2} q + \frac{e_\alpha * e_\beta}{e_\alpha^2 + e_\beta^2} q \qquad (2.8.1\text{-}14)$$

Note that the sum of the third and fourth term of the right hand side is always zero from Equation (7.1.13) and (7.1.14) following equations are obtained

$$p = e_\alpha i_{\beta p} + e_\beta i_{\beta p} = p_{\alpha p} + p_{\beta p} \qquad (2.8.1\text{-}15)$$

$$0 = e_\alpha i_{\alpha q} + e_\beta i_{\beta q} = p_{\alpha q} + p_{\beta q} \qquad (2.8.1\text{-}16)$$

where,

α axis reactive power = $$p_{\alpha p} = \frac{e^2{}_\alpha}{e_\alpha{}^2 + e_\beta{}^2} p$$

α axis instantaneous active current = $$p_{\alpha q} = \frac{-e_\alpha e_\beta}{e_\alpha{}^2 + e_\beta{}^2} q$$

β axis instantaneous active current = $$p_{\beta p} = \frac{e^2{}_\beta}{e_\alpha{}^2 + e_\beta{}^2} p$$

β axis instantaneous reactive power = $$p_{\beta q} = \frac{e_\alpha e_\beta}{e_\alpha{}^2 + e_\beta{}^2} q$$

Equation (2.8.1-15) & (2.8.1-16) leads to the following conclusion

1. The sum of the power components, $p_{\alpha p}$ and $p_{\beta p}$, coincides with the three-phase instantaneous real power, "p", which is given by Equation (2.8.1-3).Therefore, $p_{\alpha p}$ and $p_{\beta p}$ are referred to as the α-phase and β-phase instantaneous active powers.
2. The other power components, $p_{\alpha q}$ and $p_{\beta q}$, cancel each other and make no contribution to the instantaneous power flow from the source to the load. Therefore, $p_{\alpha q}$ and $p_{\beta q}$ are referred to as the α-phase and β-phase instantaneous reactive powers.
3. Thus, a shunt active filter without energy storage can achieve instantaneous compensation of the current components, $i_{\alpha q}$ and $i_{\beta q}$ or the power components, $p_{\alpha q}$ and $p_{\beta q}$. In other words, the Akagi-Nabae theory based on Equation (2.8.1-5) exactly reveals what components the active filter without energy storage can eliminate from the α-phase and β-phase instantaneous currents, i_α and i_β or the α-phase and β-phase instantaneous real powers, $p_\alpha$and p_β as shown in Figure 2.8.1.4.

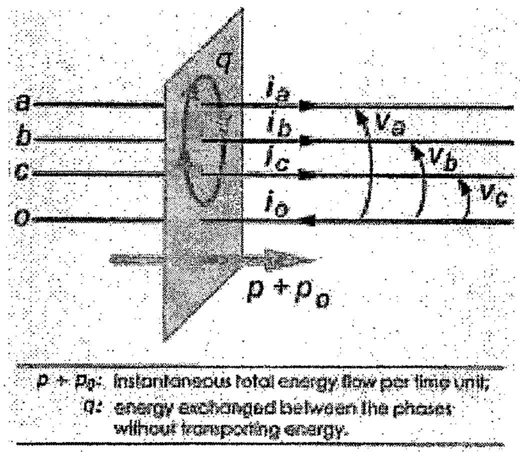

Figure 2.8.1-4 (a): physical meaning of the instantaneous power defined in the α-β-o reference frame

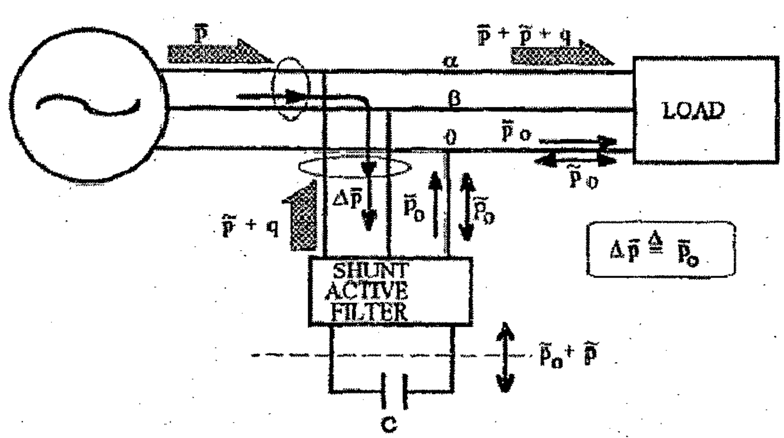

Figure 2.8.1-4 (b): Compensation of all undesirable power of the load by using a shunt active filter

2.8.1.1 CONTROL STRATEGY:

Figure 2.8.1.1-1 shows the basic compensation scheme of the instantaneous reactive power, where p_s and q_s are the instantaneous real and imaginary powers on the source side p_c and q_c are those on the active filter side.

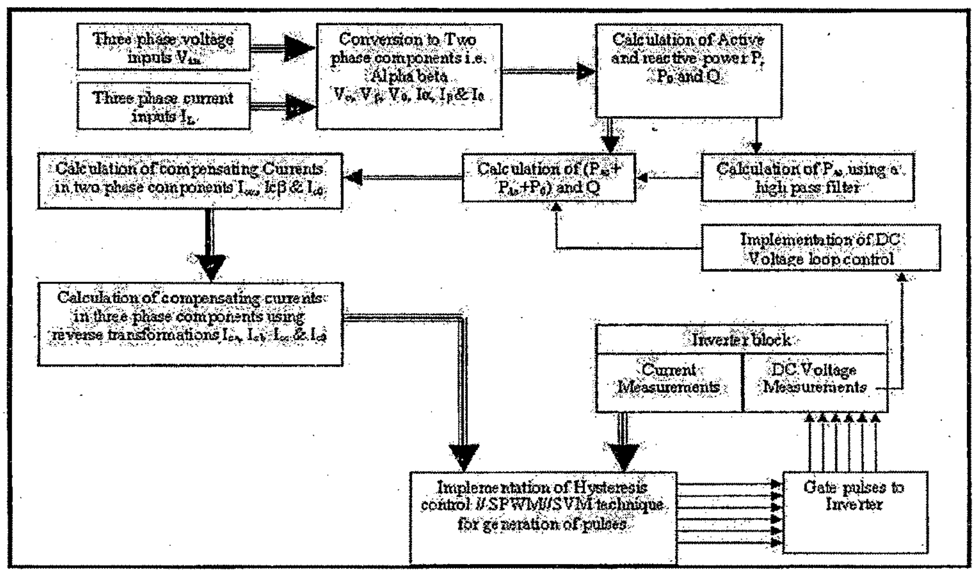

Figure 2.8.1.1-1: Shunt Active Power Filter control scheme using IARP theory

The active filter eliminates the instantaneous reactive power on the source side and harmonics, which are caused by the instantaneous power on the load side. The active power filter consists of only switching devices without energy storage components, because pc is always zero. The instantaneous compensating currents on the α-β coordinates ic_{α} and $i_{c\beta}$ are given by

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \begin{bmatrix} e_{\alpha} & e_{\beta} \\ -e_{\beta} & e_{\alpha} \end{bmatrix}^{-1} \begin{bmatrix} -p_{ac} \\ -q \end{bmatrix} \tag{2.8.1}$$

The basic principle of the active filter will not be considered, concerning the α axis instantaneous current on the load side. The instantaneous active and the reactive currents are divided into the following two kinds of instantaneous currents respectively:

$$i_\alpha = \frac{e_\alpha}{e_\alpha^2 + e_\beta^2} p_{dc} + \frac{e_\alpha}{e_\alpha^2 + e_\beta^2} p_{ac} + \frac{-e_\beta}{e_\alpha^2 + e_\beta^2} q_{dc} + \frac{-e_\beta}{e_\alpha^2 + e_\beta^2} q_{ac}$$

(2.8.2)

where p_{dc} and p_{ac} are the DC and AC components of the instantaneous real power and q_{dc} and q_{ac} are the DC and AC components of the instantaneous imaginary power. The first term of the right hand side of Equation is the instantaneous value of the conventional fundamental active current. The third term is the instantaneous value of the conventional fundamental reactive current. The second term is the instantaneous value of the harmonic current which represents the AC component of the instantaneous real power. The fourth term is the instantaneous value of the harmonic currents, which represents the AC components of the instantaneous imaginary power. Accordingly, the sum of the second and fourth terms is the instantaneous value of the conventional harmonic currents.

Equation (7.2.2) leads to the following conclusions:

1). The active filter eliminates both the third and fourth terms. For this reason, the displacement factor is unity not only in steady states but also in transient states.

2). The harmonic currents represented by the second and fourth term can be eliminated by the active filter comprising switching devices without energy storage components.

2.8.1.2 SIMULATION RESULTS

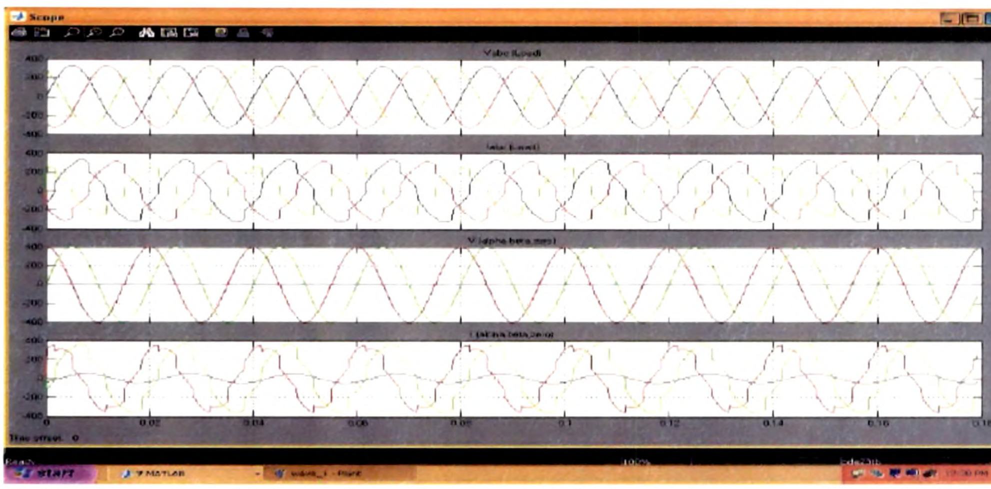

Figure 2.8.1.2-2: Source voltages and Load currents alpha beta components for voltage and current

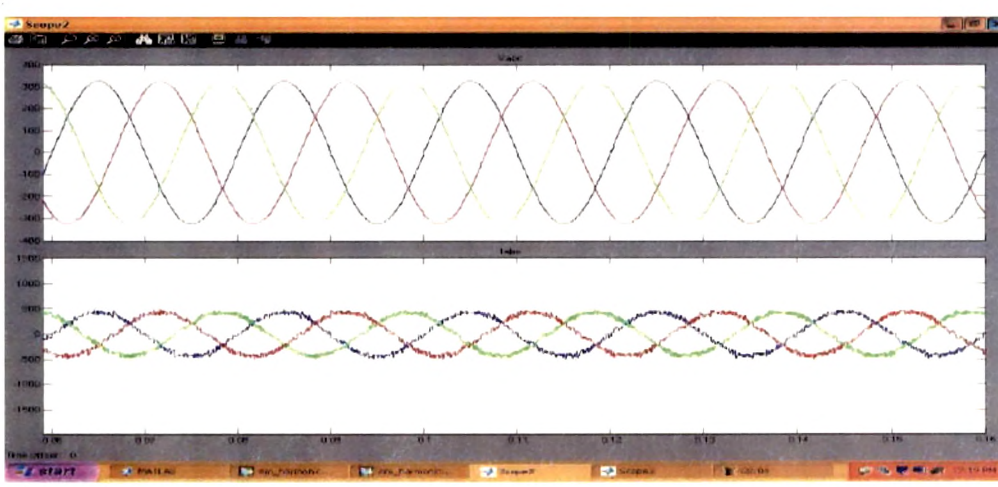

Figure 2.8.1.2-3: source voltages and currents

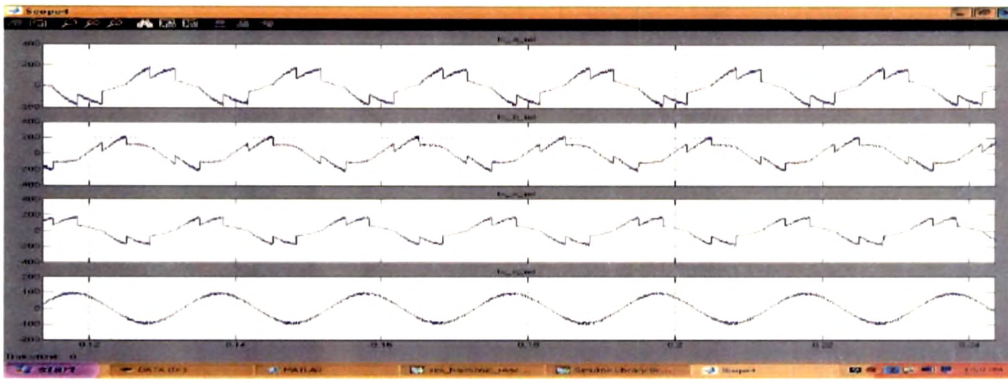

Figure 2.8.1.2-4: Filter currents

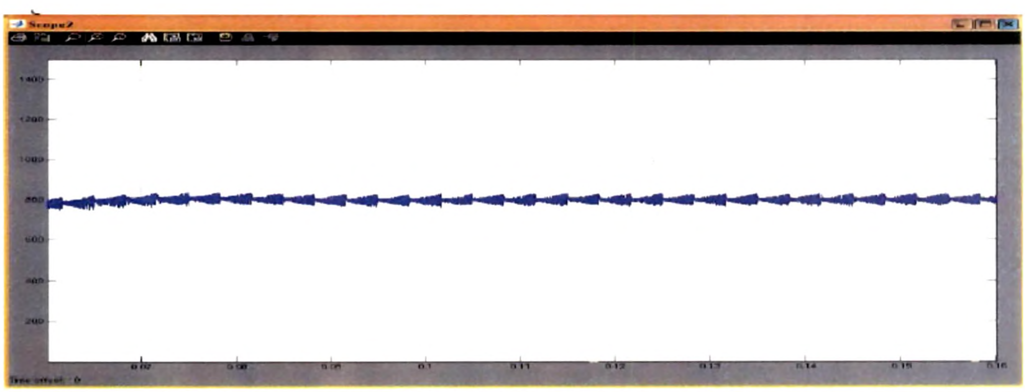

Figure 2.8.1.2-5: DC Bus Voltage

Figure 2.7.1 shows the schematic of three-phase four-wire active filter. A three-phase diode rectifier system with resistive load as harmonic producing loads for experimental purpose is used.

The corresponding waveforms of three phase compensated load currents and waveform at different places are shown at the end of this chapter

Detail simulation as well experimental results for shunt active power filter using instantaneous active reactive power theory are given in Annexure-II-C

2.8.2. SINE MULTIPLICATION THEORY

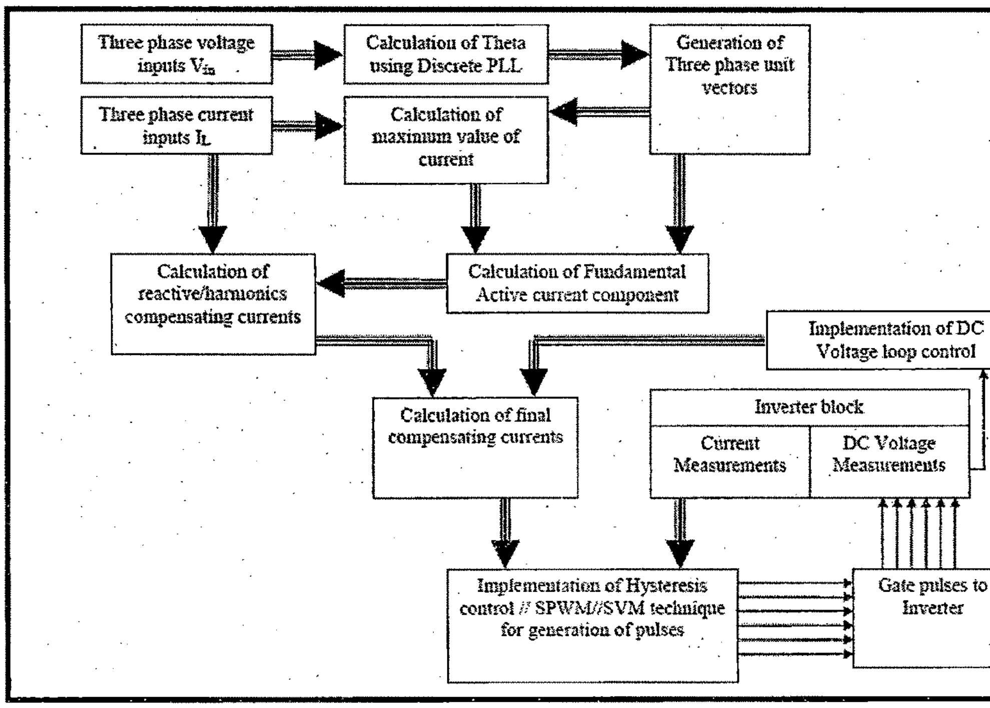

Figure 2.8.2-1: Shunt Active Power Filter control scheme using Sine Multiplication theory

Step I: Calculate sin(*t), cos(*t), *t using three phase lock loop

Step II: Calculate the Maximum value of the Fundamental active current using the sine multiplication method. Initially it is required to multiply phase load currents with corresponding sinusoidal unit vectors as follows:

$$\boxed{\begin{array}{l} I_{La} * \sin \omega t \\ I_{Lb} * \sin\left(\omega t - 2\pi/3\right) \\ I_{Lc} * \sin\left(\omega t + 2\pi/3\right) \end{array}}$$

Integrating the above set of equations over a cycle will generate maximum value of the current I_m

Multiplying the value of I_m with three phase unit vectors will generate three phase fundamental active currents supplied by the source as follows:

$$\begin{aligned} I_{1a} &= I_m * \sin \omega t \\ I_{1b} &= I_m * \sin\left(\omega t - \frac{2\pi}{3}\right) \\ I_{1c} &= I_m * \sin\left(\omega t + \frac{2\pi}{3}\right) \end{aligned}$$

Harmonics and reactive current components of the source currents can be calculated by subtracting the fundamental active current from the load currents. The resultant currents are the compensating reference currents for the active filter.

$$\begin{aligned} \vec{I}_{ca} &= \vec{I}_{La} - \vec{I}_{af} \\ \vec{I}_{cb} &= \vec{I}_{Lb} - \vec{I}_{bf} \\ \vec{I}_{cc} &= \vec{I}_{Lc} - \vec{I}_{cf} \end{aligned}$$

The unbalance in load currents in is compensated introducing forth leg in the three-leg inverter. The compensating reference current for this leg is calculated using three phase load currents.

$$\vec{I}_{cn} = -\left(\vec{I}_{La} + \vec{I}_{Lb} + \vec{I}_{Lc}\right)$$

The capacitor DC bus voltage is controlled using a proportional control. The output of the control is multiplied with the three phase voltage unit vectors and thus the resultant would be three current signals (one for each phase) required for maintaining DC bus voltage at desired levels.

Hysteresis current control technique is used for switching of the IGBTs of the inverter so as to make the inverter currents follow the reference compensating signals.

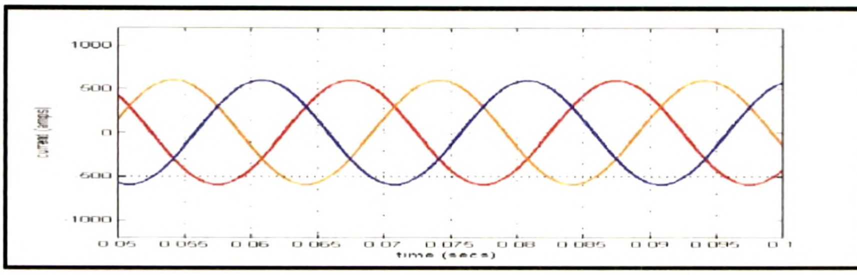

Figure 2.8.2-2: Input Source Voltages

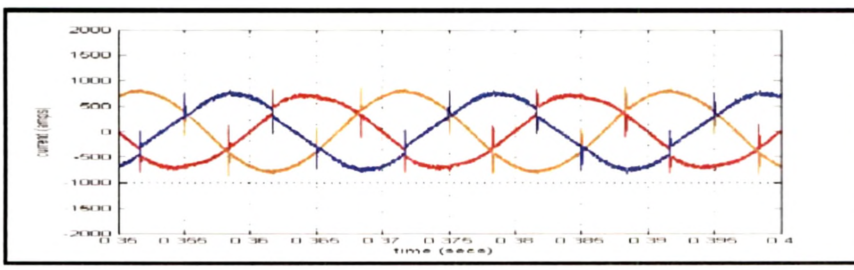

Figure 2.8.2-3: Input Source Currents

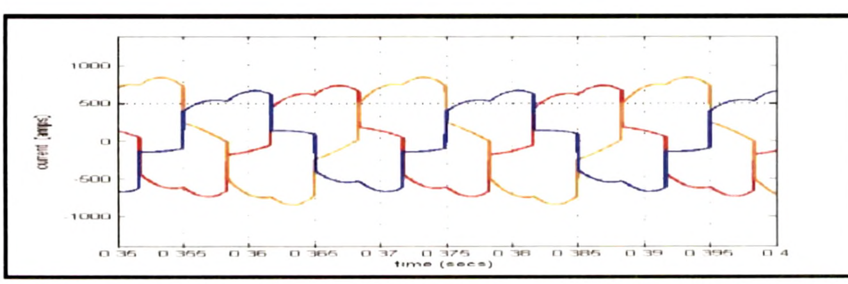

Figure 2.8.2-4: Load Currents

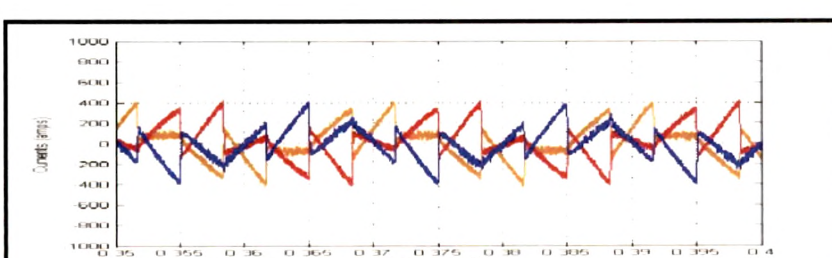

Figure 2.8.2-5: Filter Currents

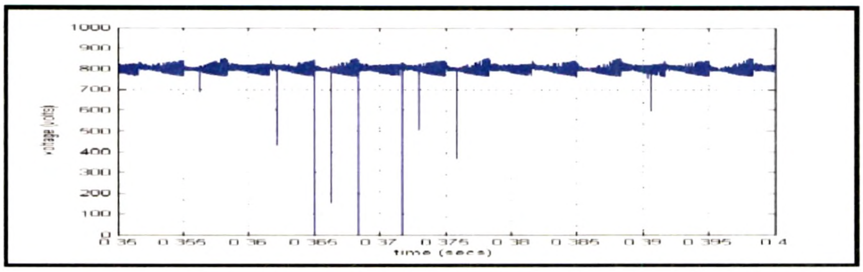

Figure 2.8.2-6: DC Bus voltage

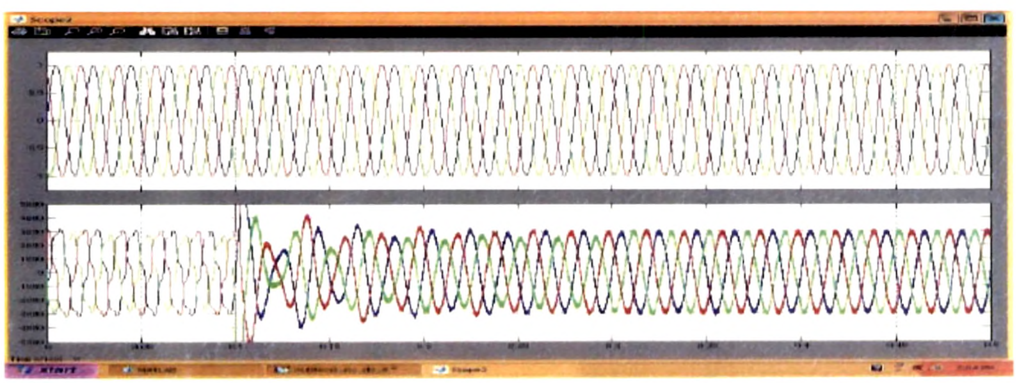

Figure 2.8.2-7 Input Source Voltages and Currents

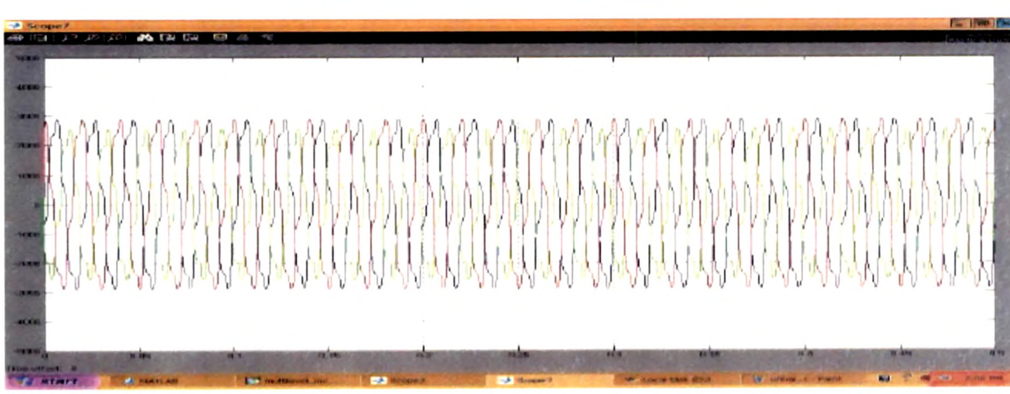

Figure 2.8.2-8: Load Currents

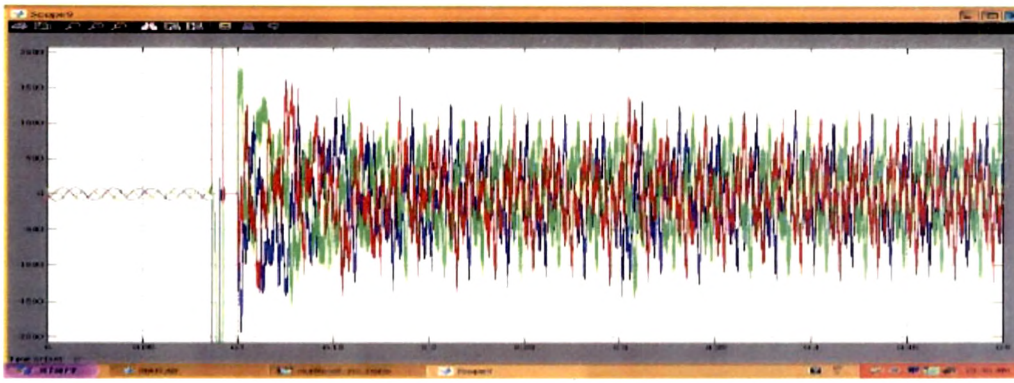

Figure 2.8.2-9: Filter Currents

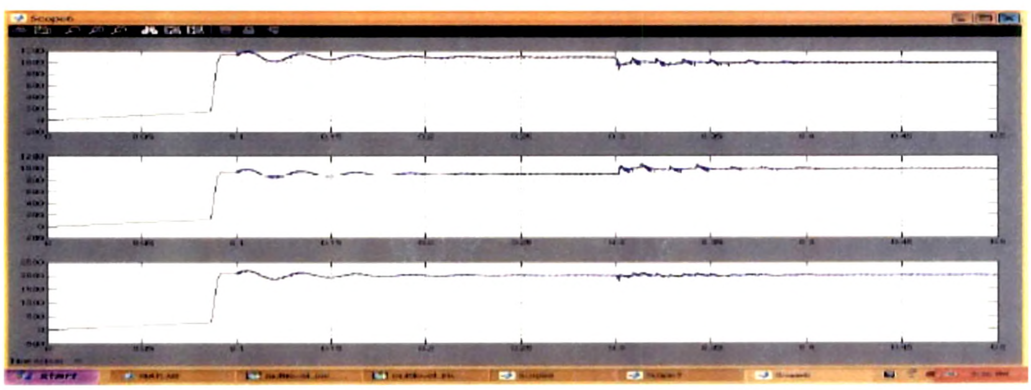

Figure 2.8.2-10: DC Bus Voltages

2.8.3. SYNCHRONOUS REFERENCE FRAME THEORY

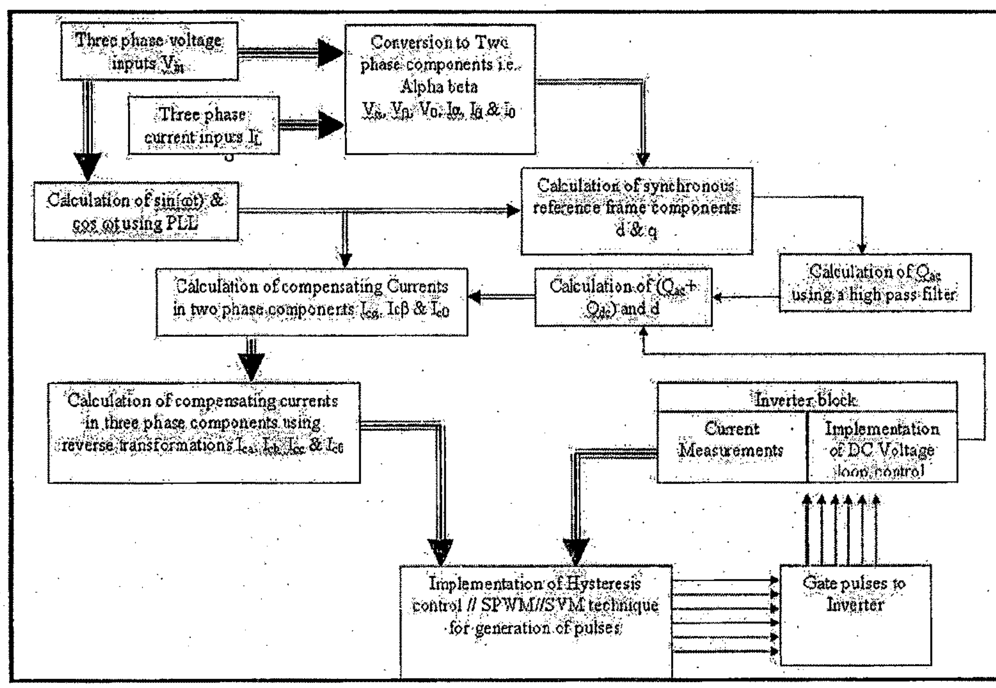

Figure 2.8.3-1: Shunt Active Power Filter control scheme using Synchronous Reference Frame Theory

Step 1. Conversion of three-phase coordinates to two-phase alpha beta coordinates

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Step 2. Conversion of stationary reference frame components to rotating reference frame components

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

Step 3. Extraction of components required for compensation

$$\begin{aligned} i_d &= \overline{i_d} + \tilde{i}_d \\ i_q &= \overline{i_q} + \tilde{i}_q \end{aligned}$$

Out of these, id & i_{qac} are components of interest. Along with these components, the reference required to maintain the DC voltage across the capacitor is calculated using a PI control applied to the DC loop. The output of the PI loop is added to the iqac.

Step 4. Calculation of compensating reference signals in two-phase stationary frame from

rotating reference frame

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_d \\ \tilde{i}_q + e_{dc} \end{bmatrix}$$

$$\boxed{i_{c0} = i_0}$$

Step 5. Calculation of compensating reference signals in three-phase a, b, c components

$$\boxed{\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2}\,0 & -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_{c0} \\ i_{c\alpha} \\ i_{c\beta} \end{bmatrix}}$$

The reference-compensating signal for neutral currents is calculated as

$$\boxed{i_{cn} = i_{ca}^{*} + i_{cb}^{*} + i_{cc}^{*}}$$

A hysteresis controller with +/-5% band is used for generating the switching pulses for the inverter.

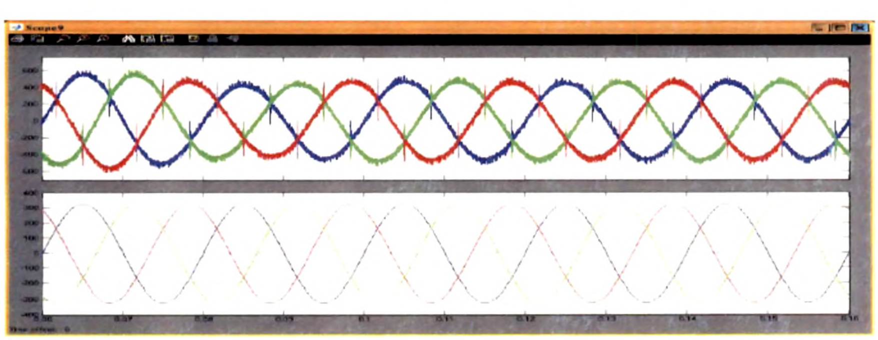

Figure 2.8.3-2: Source Currents and Voltages

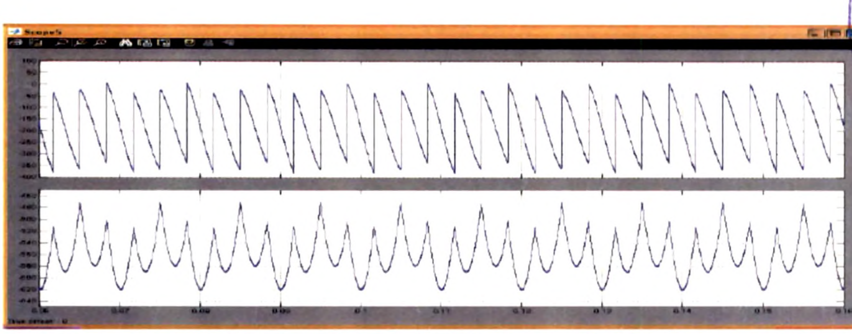

Figure 2.8.3-3: I_d-I_q components

Figure 2.8.3-4: Load Currents

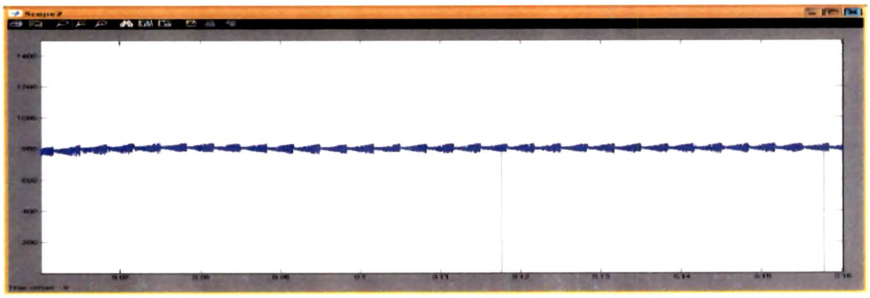

Figure 2.8.3-5: DC Bus Voltage

2.9 ACTIVE POWER FACTOR CORRECTION INTEGRATED TO THE INPUT STAGE OF THE EQUIPMENT

Power quality problems posed by single-phase rectifier load are well known. Such loads distort the supply voltage waveform, causing overheating of transformers & neutral conductors and ultimate equipment malfunction. There have been several solutions to the problems proposed in the recent years and various equipment and system standards [5]-[6] such as the IEEE 519:1999 have been published. Also with imposed of harmonic standards such as IEC 61000-3-2 by international communities, it would be much important aspect to consider in every design of the appliances.

Solutions such as (a) passive filter at input side (b) active filter for eliminating current harmonics, (c) active filter for eliminating voltage harmonics, negative sequence voltage, zero sequence voltage (d) DVR have been proposed to improve power quality [2]-[4].

Solution to improve power quality for single phase appliance include (a) passive filter at input side (b) Ferro resonant transformer, (c) active power factor correction integrated to the input stage of the rectifier, and (d) isolation transformer with third harmonic trap. These techniques improve the input current waveform and the power factor and hence power quality.

Due to advancement in power electronics technology, energy saving electronic ballasts is becoming more popular. Lighting load is more in domestic application and therefore power quality problems are much concern in distribution system. This paper presents the use of boost converter in HPSV electronic ballast to improve its performance so that input supply current becomes sinusoidal & power factor improves to unity and hence the power quality of the system will improve.

The operation of the proposed single-phase boost converter is described in 2.9.1. In section 2.9.2 analysis & simulation along with the design of current & voltage control loops are presented. In section IV experimental setup & comparison of current waveform with & without boost converter are explained which is followed by conclusion.

2.9.1. PRINCIPLE OF OPERATION

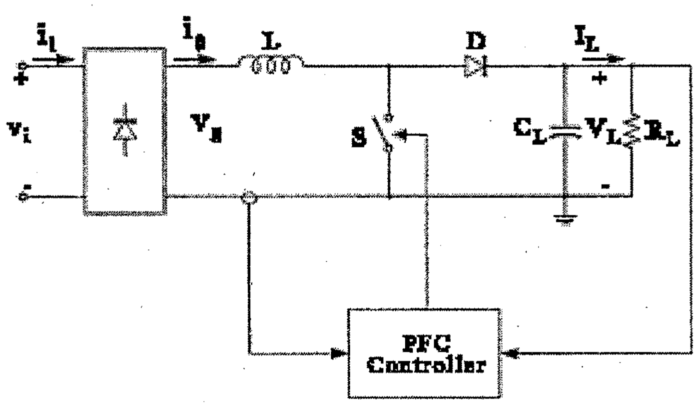

Figure 2.9.1-1: Principal scheme of a boost PFC converter

Figure 2.9.1-1shows the principle scheme of a boost PFC converter. The boost topology is very simple and allows low distorted input currents an almost unity power factor with different control techniques. Moreover, the switch is connected to ground, which simplifies the drive circuit. The main draw backs of this topology are: (1) startup over currents, due to the charge of the large output capacitor, (2) lack of current limitation during overload and short circuit condition due to direct connection between line and load, (3) lack of isolation and (4) higher output voltage always greater than peak input voltage.

In spite of these limitations many PFC's based on the boost topology have been proposed in the literature. Various control strategies have also been implemented. In the following, borderline control scheme, which is implemented to improve harmonics & power factor, is discussed.

Borderline Control:

In this approach the switch on time is held constant during the line cycle & the switch is turned ON when the inductor current falls to zero, so that the converter operates at the boundary between continuous and discontinues inductor current mode (CCIM-DCIM) [7].

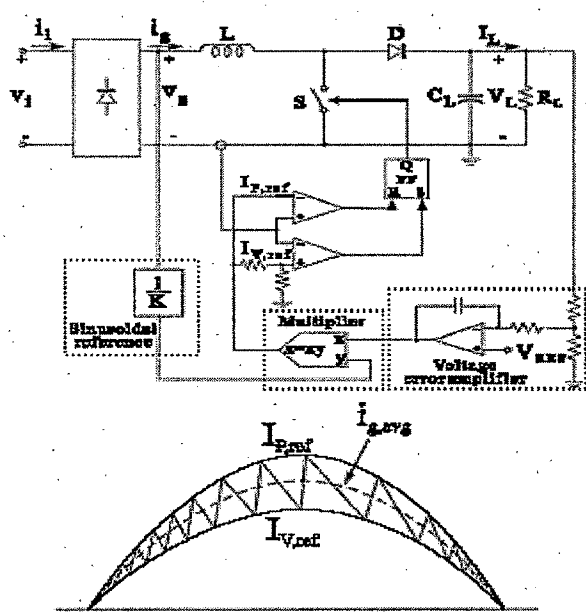

Figure 2.9.1-2: Hysteresis Control Scheme.

In this way, the freewheeling diode is turned off softly (no recovery losses) and the switch is turned ON at zero current, so the commutation losses are reduced. On the other hand, the higher current peaks increase device stresses and conduction losses and may call for heavier input filters (for some topologies).

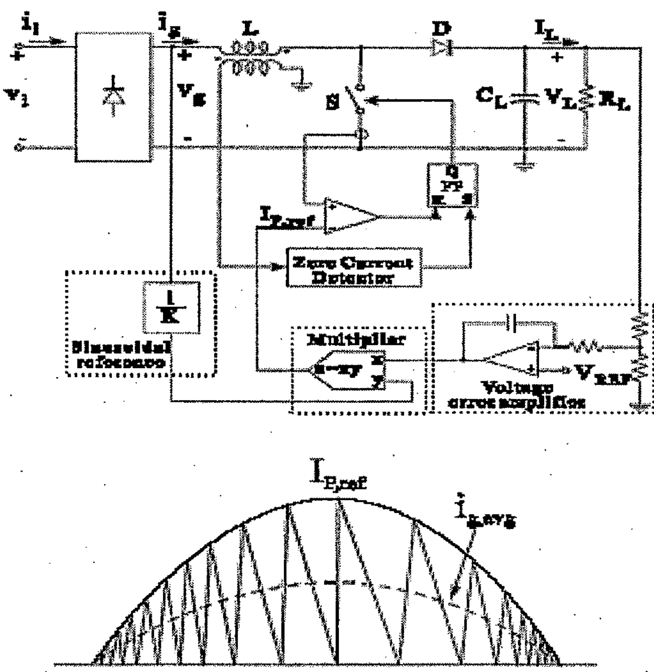

Figure 2.9.1-3: Borderline Control Scheme.

This type of control is a particular case of hysteresis control, in which the lower reference Iv, ref is zero anywhere, which is shown in Figure 2.9.1-2. The principle scheme of borderline control is shown in Figure 2.9.1-3.

The instantaneous input current is constituted by sequence of triangles whose peaks are proportional to the line voltage without duty-cycle modulation during the line cycle. This characterizes this control as an "automatic current shaper" technique.

2.9.2. DESIGN ANALYSIS & SIMULATION

The output of the boost converter [1] is given by,

$$V_o = V_{in}(\frac{1}{1-D}) \; \& \; I_o = I_d(1-D) \quad (2.9.2\text{-}1)$$

Average value of the inductor current I_{LB} at the boundary between continuous & discontinuous conduction is

$$I_{LB} = \frac{T_s V_o}{2L} D(1-D) \tag{2.9.2-2}$$

Average output current I_{oB} at the edge of continuous current is

$$I_{oB} = \frac{T_s V_o}{2L} D(1-D)^2 \tag{2.9.2-3}$$

$$I_{LB,\max} = \frac{T_s V_o}{8L} \quad when \quad D = 0.5$$

$$I_{oB,\max} = \frac{2}{27}\frac{T_s V_o}{L} \qquad \text{when} \quad D = 0.333 \tag{2.9.2-4}$$

To design the boost converter

The maximum power required is calculated using

$$p_o = V_o I_o \tag{2.9.2-5}$$

Similarly, the Peak inductor current at minimum required ac line voltage for output regulation.

$$I_{l(pk)} = \frac{2\sqrt{2}P_o}{\eta V_{ac(LL)}} \tag{2.9.2-6}$$

If the switching frequency for input voltage of 85 to 265 Vac is 25 kHz, the inductance L can be calculated as

$$L_p = \frac{t\left(\frac{V_o}{\sqrt{2}} - V_{ac(LL)}\right)\eta\left(V_{ac(LL)}\right)^2}{\sqrt{2}V_o Po} \tag{2.9.2-7}$$

Switching ON time t_{on} for this scheme is nearly constant, therefore switch OFF time t_{off} which varies through the cycle can calculated as

$$T_{off} = \frac{T_{on}}{\left(\frac{V_o}{\sqrt{2}V_{ac}|Sin\theta|} - 1\right)} \qquad (2.9.2\text{-}8)$$

Where θ represents the angle of the ac line voltage, Ton represents switch on time, T_{off} represents switch off time and L represents boost inductor.

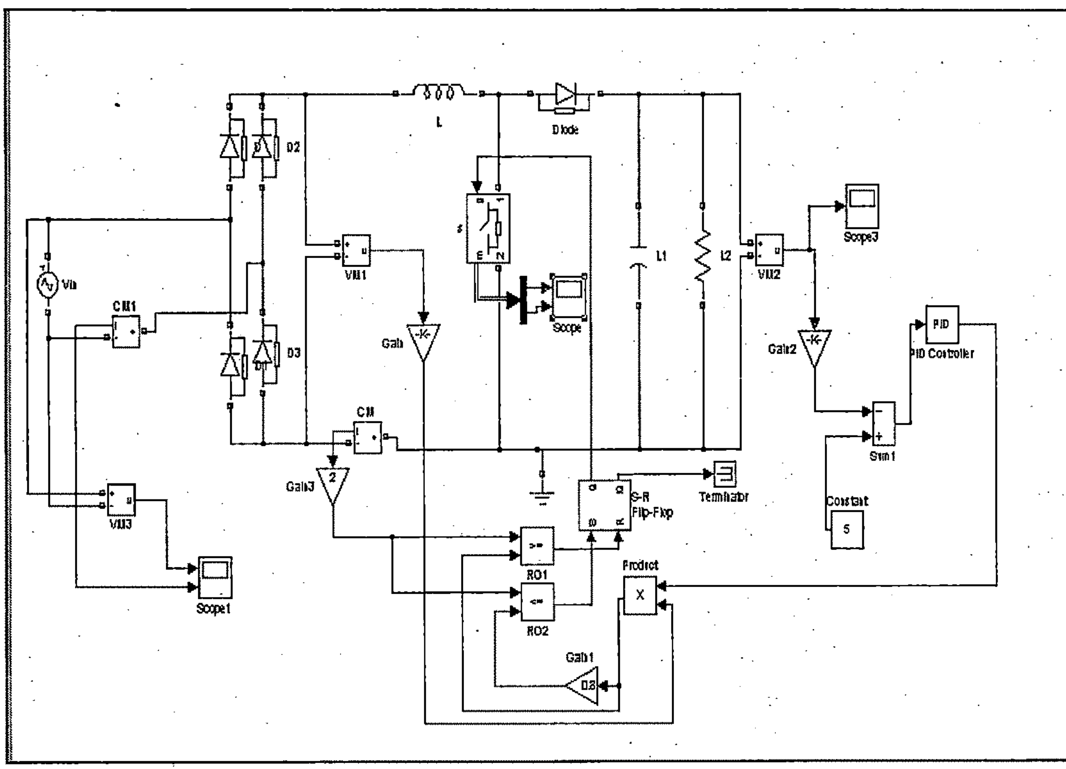

Figure 2.9.2-4: Simulated system using MATLAB for UPF boost converter

The mains AC supply voltage is rectified and supplied to the boost converter that mainly consists of inductor, a power MOSFET, a high frequency power diode and a Bulk Capacitor.

The simulation of the single-phase boost converter with low THD & unity power factor was done using MATLAB-SIMULINK software for its performance. The Block diagram of UPF boost converter simulated is shown in Figure 2.9.2-4.

The input voltage, input current, DC output voltage & voltage across inductor respectively are shown in Figure 2.9.2-5. The waveforms show that the input current & voltage waveform are in phase with minimum distortion.

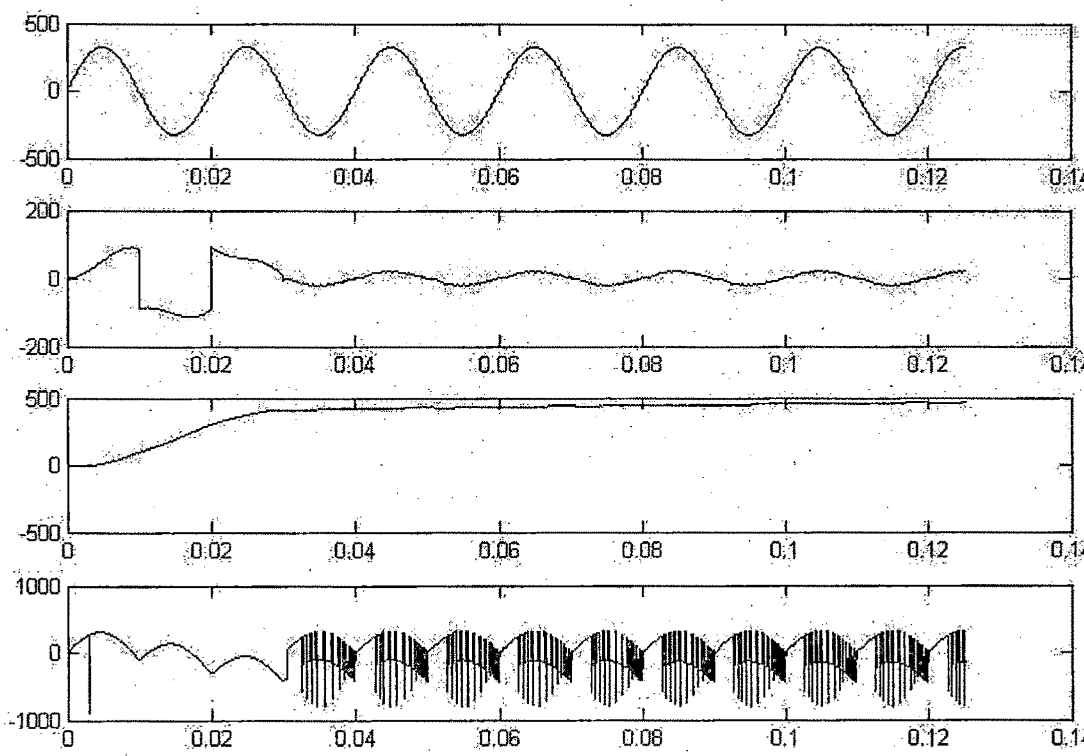

Figure 2.9.2-5: Simulated waveform of input voltage, input current, output DC voltage & voltage across inductor respectively.

2.9.3. EXPERIMENTATION & RESULTS

Input current show heavy inrush while starting, due to initially bulk capacitor is charged. Inductor was fabricated using two EE ferrite core of standard size EE 42 x 21 x 20 having the value of inductance 1.86 mH.

The number of Turns is 66 with air gap of 1.8 mm. To detect the zero current, separate winding was inserted in the inductor. The polarity of the second winding is such that when the main winding voltage is positive the second winding voltage is of reverse polarity. The numbers of Turns in the second winding is 6.

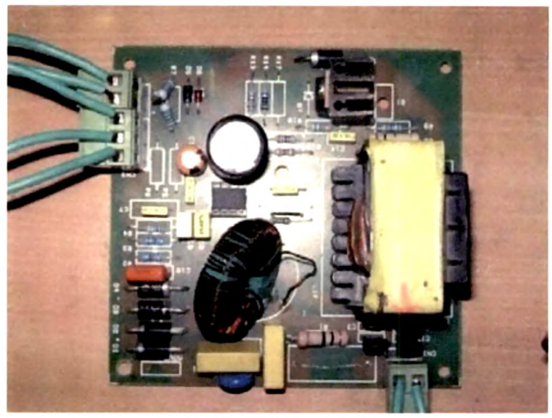

Figure 2.9.3-6: Rectifier with PFC assembled on PCB

IRF 840 MOSFET is used as switch to operate at 25 kHz. Bulk capacitor of the value 220 μF, 450 volts is used to filter out the output ripple. Ultra High frequency diode MUR 460 with very low t_{rr} is used in the boost converter.

To limit the initial inrush current to charge the bulk capacitor NTC-15 are used as shown in the Figure 2.9.3-7. A small π filter is used to filter out high frequency ripple in input current which is due to switch of MOSFET.

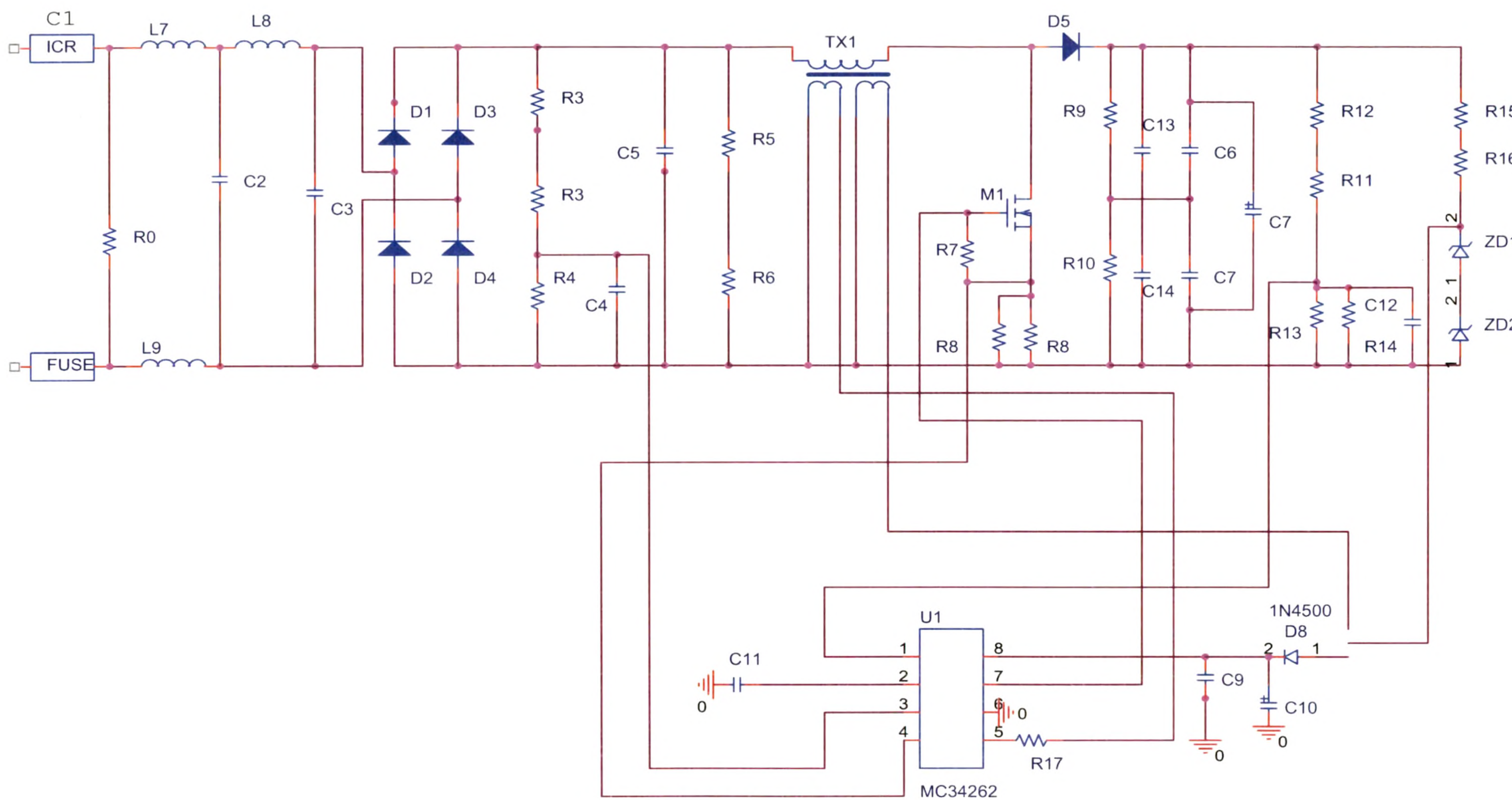

Figure 2.9.3-7: Schematic of PFC circuit

The actual waveform of the PFC correction is shown is Figure 2.9.3-8 to Figure 2.9.3-10.

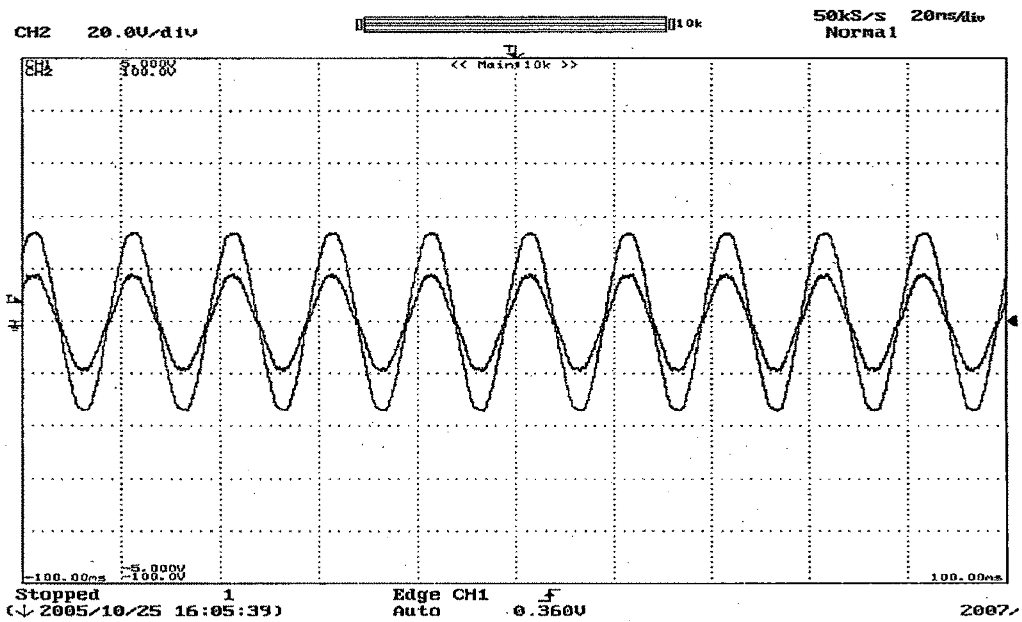

Figure 2.9.3-8: Input voltage and current

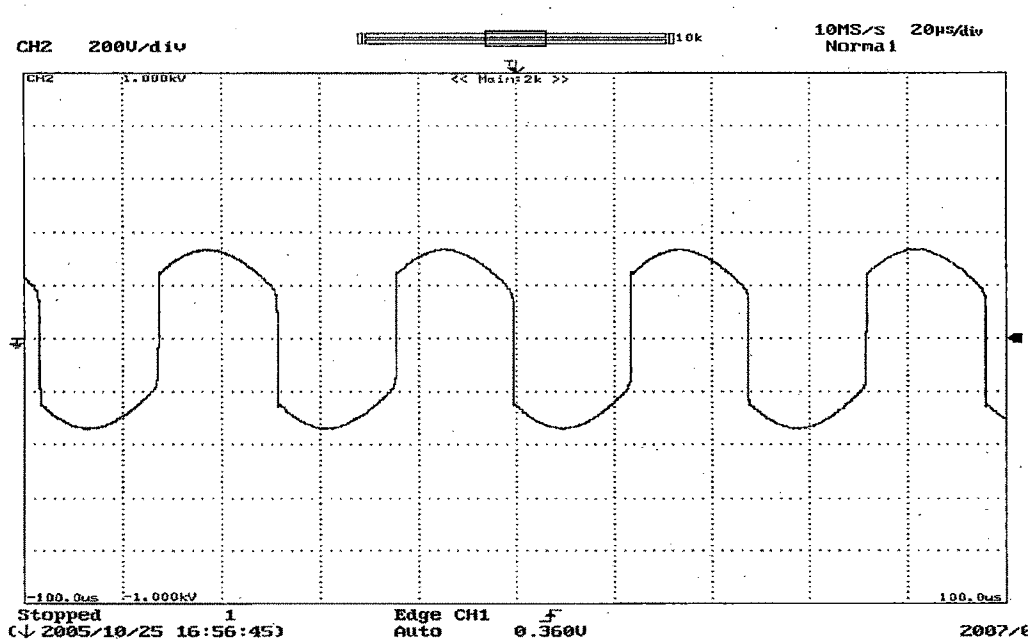

Figure 2.9.3-9: Voltage across device

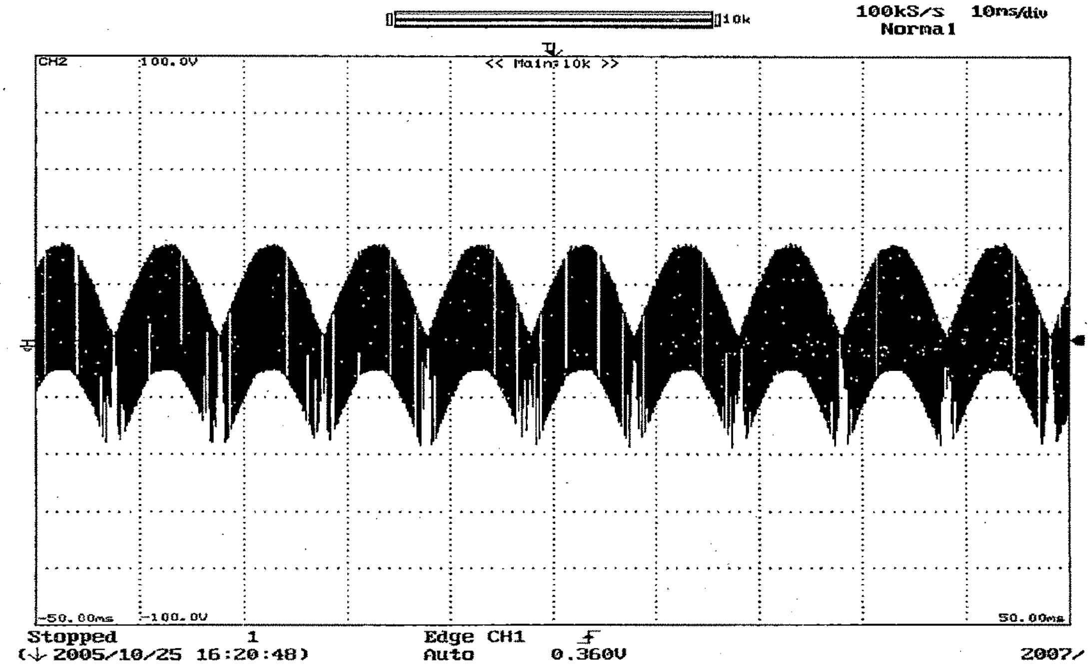

Figure 2.9.3-10: Voltage across inductor

The waveform of the rectifier without PFC circuit is shown in Figure 1.9.3-10.

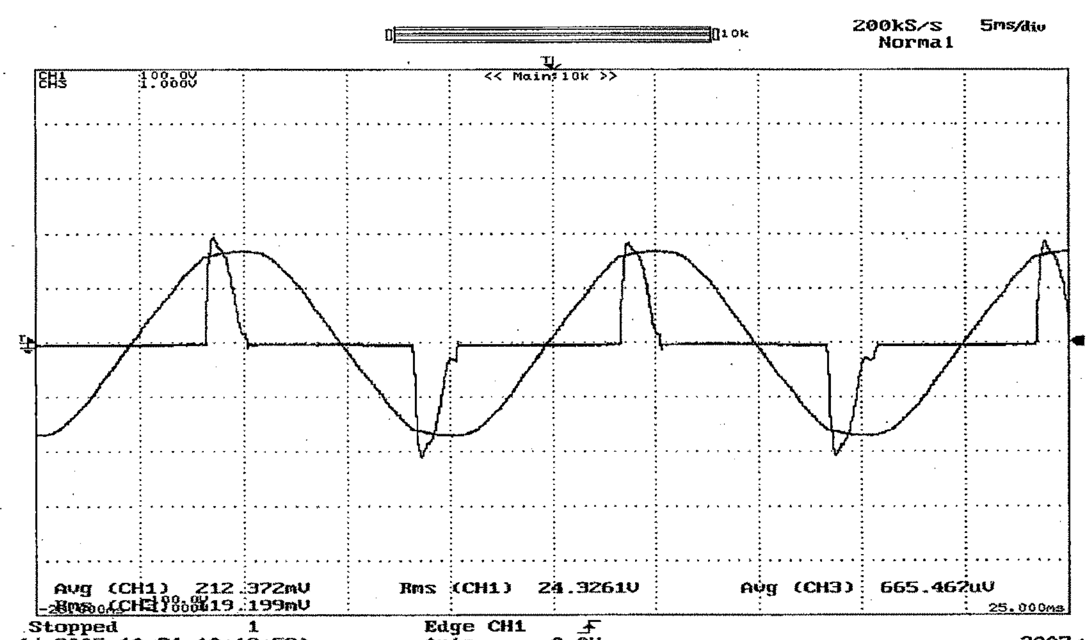

Figure 2.9.3-11: Voltage & current waveform of rectifier without PFC

The PFC was checked with the load of 150 watt HPSV electronic ballast. The performance results of 150 watt HPSV ballast without & with PFC circuit are as follows:

Table 2.9.3-1: 150 watt HPSV Ballast Without PFC Circuit

Input Volt	**Input Amp**	**Input Watt**	**Input PF**	**% THD**	**Lumens**
[V]	[A]	[W]	[λ]	[%]	Lumens
240.0	1.187	152.1	0.533 lead	150.4%	12449

Table 2.9.3-2: 150 watt HPSV Ballast With PFC Circuit

Input Volt	**Input Amp.**	**Input Watt**	**Input PF**	**% THD**	**Lumens**
[V]	[A]	[W]	[λ]	[%]	Lumens
240.0	0.784	187.7	0.998	6.02%	15724

The above results show improvement in PF from 0.533 lead to 0.998 which is closed to unity & % Total Harmonics Distortion reduces from 150% to 6.02%, which is even much better than the limits specified limits in IEC 61000-3-2 standard.

Single-phase boost converter circuit reduces the THD to 6% and improves the PF close to unity. This is much better than the limit specified by international standard IEC 61000-3-2. By improving the THD & power factor, boost converter helps to improve the power quality of the distribution system by reducing the generation of harmonics.

2.10 CONCLUSION:

In this chapter different techniques for elimination of current harmonics are discussed. It started with Passive filter design having different configuration of tuned filter. Its advantage and disadvantage along with its limitation was presented.

Different type of Shunt active filter based on application was discussed along with its control schemes. Shunt active filter to eliminate current harmonics in the system using IARP theory was presented along with simulation as well as experimental result. For detection of harmonic in the power system, mainly three techniques 1) IARP theory 2) Sine multiplication theory 3) Synchronous Reference Frame theory are used. These theories in brief was discussed but IARP theory was discussed in detail as this theory is used for other novel power quality improvement tool which are presented in subsequent chapter.

Also other techniques to improve power quality by incorporating in the power electronics tool, which are the major source of harmonic, so that this limits the generation of harmonics was presented along with simulation as well as experimental results.