Chapter-III

Series Active Filter – Solution To Voltage Harmonics And Distortion

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3.1 INTRODUCTION

This chapter introduces the technique to develop a novel three-phase series active filter to eliminate voltage harmonics and compensate reactive power based on instantaneous active reactive power theory (p-q theory). A 3-phase voltage source inverter with DC bus capacitor (center tapped) is used as a 3-phase active filter. A SPWM based control technique is employed to generate the gating signal for devices of the 3-phase active filter. Three distorted voltages are generated by putting the reactor at input side in series with Diode Bridge. Because of the current drawn by the diode bridge, the voltage drops across the series reactor. This drop in series reactor, distort the voltage at input of the diode bridge. If any linear load is connected in parallel to Diode Bridge, this load also experiences the harmonic; hence performance of the same is deteriorated. The 3-phase active filter generates the compensating voltages in the close vicinity of the desired reference voltages. The performance characteristics of the active filter is simulated and tested experimentally. The experimental result establishes the validity.

New advancement in power electronics has driven the development of ever more flexible, cost effective, high performance electrical equipment. However, such increasingly sophisticated equipment draws non-sinusoidal current from the source. Every source has an inherent impedance characteristic. There is a non linear voltage drop due to the harmonic current flowing from the source which in turn distorts the network power supply voltage. The currents harmonics, which cause the voltage distortion, lead to malfunctions, abnormal heating and vibrations in equipment, connected to network.

Power quality and reliability are essential for proper operation of industrial processes, which involve critical and sensitive loads. With the growing usage of solid-state converters in application such as adjustable speed drives and computer supplies, there has been a considerable increase in the voltage/current harmonic congestion and distortion on the power network. Short-duration power disturbances, such as voltage sags, swells and short interruptions, are major concern for industrial customer. Due to wide usage of sensitive electronic equipment in process automation e.g. semiconductor industry, traction signaling etc, even voltage sags which last for only few tenths of second may cause serious problems such as Production stoppages with considerable associated costs; Equipment restarting, Damaged or lower-quality product and customer satisfaction Malfunctioning of relays and sensors The high costs associated with these disturbances explain the increasing interest towards power quality & reliability problems mitigation techniques. The cost of mitigation intervention has to be compared with the loss of revenue and takes into account all economic factors involved. Also the proliferation of Non-linear loads such as static power converter and arc furnaces results in a variety of undesirable phenomena in the operation of power system. The most important among these are harmonic contamination, increased reactive power demand and power system fluctuations. 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 components 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 equipments.

Electric power generated by the utilities is distributed to the consumer in the form of 50/60 Hz ac voltage. The utilities have a tight control on the design and operation of the equipment used for transmission and distribution, and can therefore keep frequency and voltage delivered to their customers within close limits. Unfortunately, an increasing portion of loads connected to the power system are comprised of power electronic converters. These loads are non linear and inject distorted currents in the network and consequently, through line drops, they generate harmonic voltage waveforms. Power converters such as rectifiers, power supplies and at a higher power level, arc furnaces are ideal sources of distortion. According to the survey conducted by ERDA [A16] in 2000 and 2007, 35-40% of ideal electric power flows through electronic converters. This is expected to increase to 60% by the year 2020. The distortion, whether it is produced by a large single source or by the cumulative effect of many small loads, often propagates for miles along distribution feeders.

As the use of non linear power equipment is spreading, the degradation of the power quality in the utility networks is increasing and is becoming a major problem. Limiting the voltage distortion is therefore a concern for both utilities and consumers. For these reasons international agencies like IEEE and IEC (worldwide) and CEA/BIS (India) are proposing or enforcing distortion limits [G26] [G27]. The simple block diagram of Figure 3.1-1 illustrates the distortion problem due to harmonic at low and medium power levels.

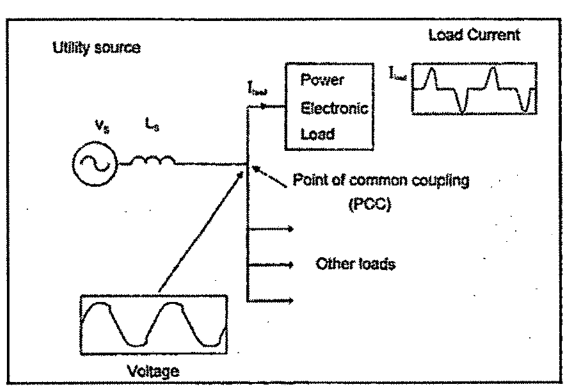


Figure 3.1-1: Harmonic distortion at PCC

The utility is represented by an ideal ac voltage source in series with lumped impedance representing lines and transformers. The voltage waveform at the point of common coupling is distorted due to harmonic current generated by the power electronic load or the load. This results in the following effects on the power system components:

(i) Malfunction of harmonic sensitive loads;

(ii) Increased losses in parallel connected capacitor, transformers, and motors;

(iii) Improper operation of protection relays and circuit breakers.

3.2 EFFECT OF HARMONICS ON SYSTEM VOLTAGES

Every source has a definite impedance characteristic and this impedance plays important role. Consider the Figure 3.2-1, which shows the impedance (lumped) of 5% with the source voltage Vac. Two different cases are explained wherein one is having linear load and other is having load. The case in which the linear load is connected, the current drawn from the source is sinusoidal in nature. This leads to sinusoidal voltage drop across the source impedance. Hence at the point of common coupling of source and load, the voltage is in sinusoidal form having no distortion.

In the second case, the Non-linear load draws non sinusoidal harmonic current (distorted current) from the source. As a result, there is a Non-linear distorted voltage drop [C17] across the source impedance. Hence the net voltage developed at the point of common coupling gets distorted. The percentage of source voltage distortion depends in the percentage of source impedance.

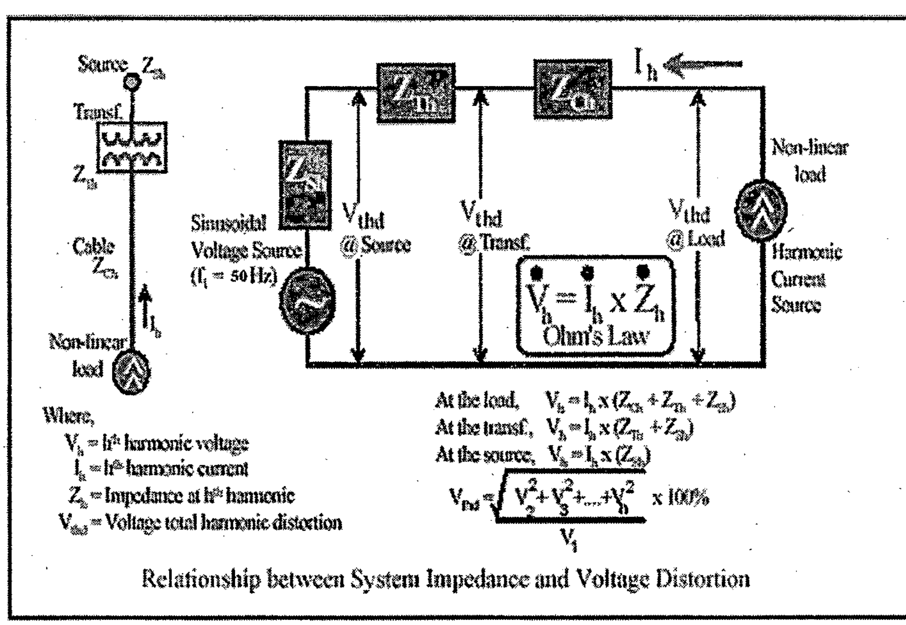


Figure 3.2-1: Relationship between system impedance and voltage distortion

3.3 SOLUTION TO SYSTEM VOLTAGE HARMONIC PROBLEMS

3.3.1 PASSIVE FILTER

Conventionally, series passive L inductor can be used to eliminate the voltage harmonics to be propagated to the load. Being connected in series in the system, the filters are to be designed at the line voltage and current ratings. However, in practical applications this also drops the fundamental voltage hence effective rms voltage to the load reduces. These 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 will be overloaded

4) Resonance between the power system and the passive filter causes amplification of the harmonic contents on the source side at a specific frequency

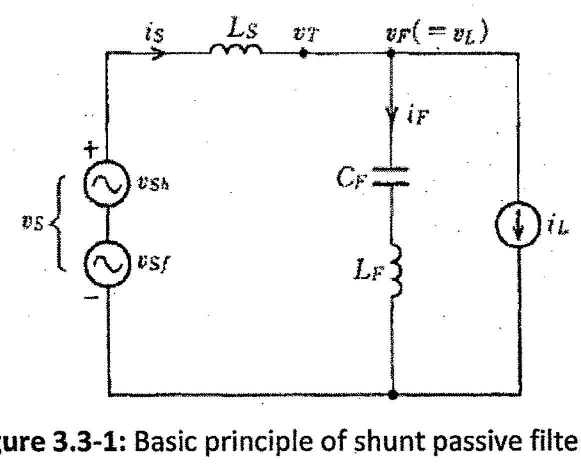


Figure 3.3-1: Basic principle of shunt passive filter

3.3.2 SERIES ACTIVE POWER FILTER

To solve the preceding problems of the shunt passive filter, shunt active filters using PWM inverters have been studied and developed in recent years. The basic principle of shunt active filters was originally presented by H. Sasaki and T. Machida in 1971 [l]. As shown in Figure 3.3-2, a shunt active filter is controlled in such a way as to actively shape the source current, *Is,* into sinusoid by injecting the compensating current, I_c. This is considered the arche type of shunt active filters. Since a linear amplifier was used to generate the compensating current, its realization is unreasonable due to low efficiency. In 1976, L. Gyugyi and E. C. Strycula [G26] presented a family of shunt and series active filters, and established the concept of the active filters consisting of PWM inverters using power transistors [G26]. However, no attention has been paid to series active filters and no experimental result has been shown in any papers, because there is no available way to shape the source current into sinusoid.

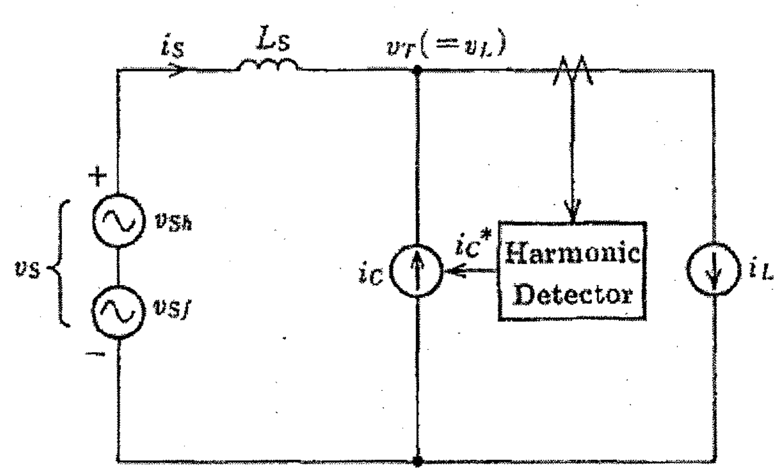


Figure 3.3-2: Basic principle of shunt active filter

In the beginning, shunt active filters were proposed to suppress the harmonics generated by large rated thyristor converters and inverters used in HVDC transmission systems. However, they could not be realized in real power systems because high-power high-speed switching devices were unavailable in the 1970's. Then N. Mohan et al. [G26] presented a practical means for injecting the compensating current, which was implemented by using naturally commutated thyristor inverters with a specially tuned passive circuit to reduce the fundamental voltage rating of the shunt active filter. However, the thyristor inverters generate undesirable high-order harmonics, which thus discourages their practicability. With remarkable development and advances in switching speed and capacity of power semiconductor devices in the 1980's, shunt active filters using PWM inverters have been studied, with a focus on their practical applications in real power systems [G27]-[G35]. At the same time, the following problems of shunt active filters have been pointed out, delaying their practical uses.

- It is difficult to realize a large rated PWM inverter with rapid current response and low loss for use as a main circuit of shunt active filters.
- The initial cost is high as compared with that of shunt passive filters, and shunt active filters are inferior in efficiency to shunt passive filters.
- Injected currents by shunt active filters may flow into shunt passive filters and capacitors connected on the power system [G28].

As is known, filtering characteristics of a shunt passive filter partially depends on the source impedance, which is not accurately known and is predominantly inductive. The impedance of the shunt passive filter should be lower than the source impedance at a turned frequency to provide the attenuation required. Hence the higher the source impedance, the better the filtering characteristics. However, the source impedance should exhibit a negligible amount of impedance at the fundamental frequency so that it does not cause any appreciable fundamental voltage drop. These two requirements, which contradict each other, can be satisfied only by inserting active impedance in series with the ac source. Also, series and parallel resonances in the shunt passive filter, which are partially caused by the inductive source impedance, can be eliminated by inserting active impedance. The active impedance can be implemented by a series active filter using voltage-source PWM inverters. Hence a new approach, which combines the use of a shunt passive filter and a small rated series active filter, is the answer to the question.

Series active filters work as isolators, instead of generators of harmonics and, hence, they use different control strategies.

3.4 A SERIES ACTIVE POWER FILTER COMBINED WITH SHUNT PASSIVE FILTER BASED ON A SINUSOIDAL CURRENT-CONTROLLED VOLTAGE-SOURCE INVERTER

The circuits of Figure 3.4-1 (a) and (b) show the block diagram and the main components, respectively, of the proposed system: the shunt passive filter, the series active filter, the current transformers (CT's), a low-power pulse width modulation (PWM) converter, and the control block to generate the *sinusoidal template* I_{ref} for the series active filter. The shunt passive filter, connected in parallel with the load, is tuned to eliminate the fifth and seventh harmonics and presents a low-impedance path for the other load current harmonics. It also helps to partially correct the power factor. The series active filter, working as a sinusoidal current source in phase with the line voltage supply V_L, keeps "unity power factor," and presents very high impedance for current harmonics.

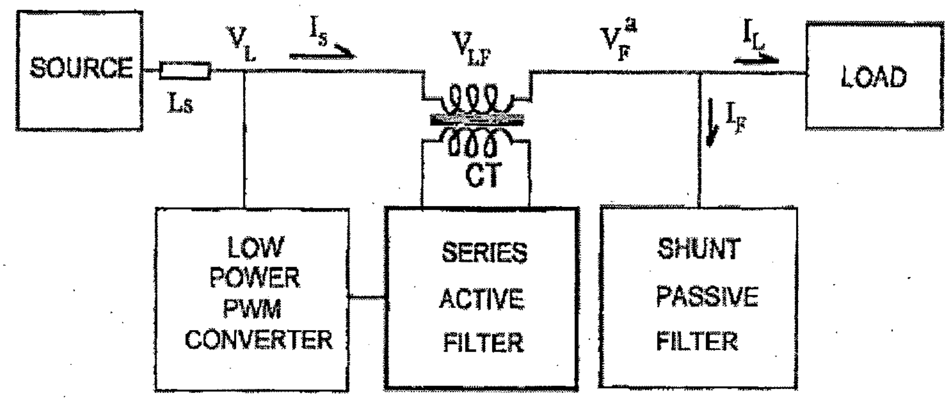


Figure 3.4-1: Block diagram showing main components of the series active filter.

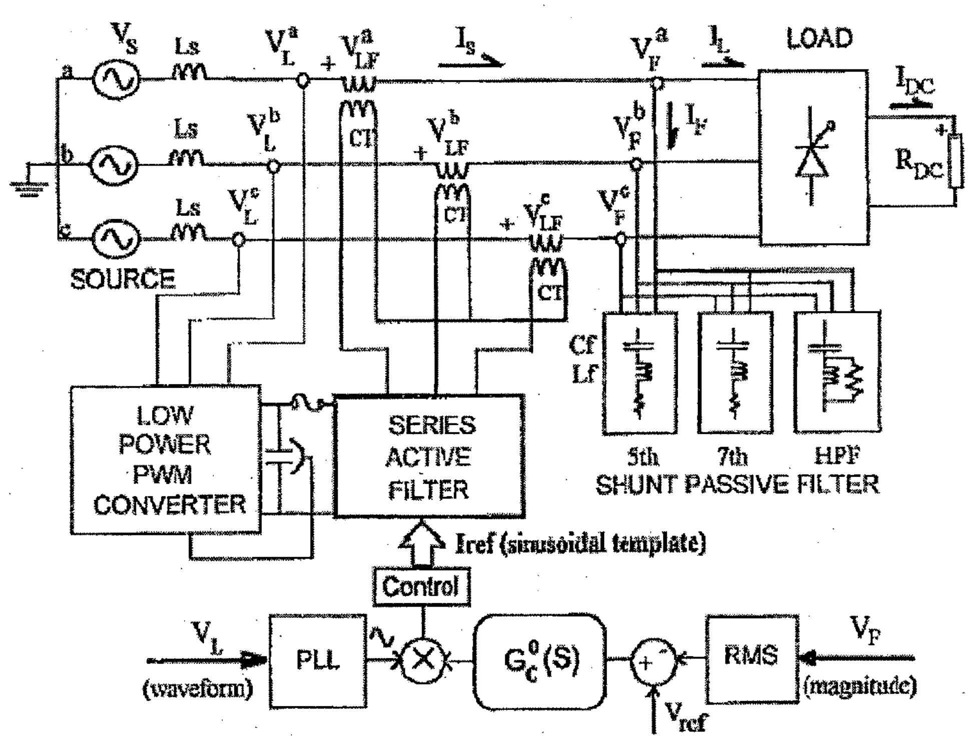


Figure 3.4-2: Components diagram of the series active filter

The CT's allow for the isolation of the series filter from the mains and the matching of the voltage and current rating of the filter with that of the power system. In Figure 3.4-2, I_L represents the *load current*, I_F the current passing through the *shunt passive filter*, and the I_S *source current*. The source current I_S is forced to be sinusoidal because of the PWM of the series active filter, which is controlled by I_{ref}. The *sinusoidal waveform* of I_{ref} comes from the line voltage V_L, which is filtered and kept in phase with the help of the PLL block Figure 3.4-1 (b).

By keeping the load voltage V_F constant, and with the same magnitude of the nominal line voltage V_L, a "zero regulation" characteristic at the load node is obtained. This is accomplished by controlling the magnitude of I_{ref} through the error signal between the load voltage V_F and a reference voltage V_{ref}. This error signal goes through a PI controller, represented by the block $G_c^0(S)$. V_{ref} is adjusted to be equal to the nominal line voltage V_L.

The two aforementioned characteristics of operation ("unity power factor" and "zero regulation"), produce an automatic phase shift between V_F and V_L, without changing their magnitudes.

3.4.1 POWER-FACTOR COMPENSATION

To have adequate power-factor compensation in the power system, the series active filter must be able to generate a voltage V_{LF} the magnitude of which is calculated through the circle diagram of Figure 3.4.1-1 according to

$$V_{LF} = 2 . V_L . \sin\frac{\emptyset}{2} \qquad (3.4.1\text{-}1)$$

Assuming, for example, a series filter able to generate a voltage V_{LF}, the magnitude of which is 50% of the fundamental amplitude V_L, the maximum phase shift should be approximately Φ=29°, which poses a limit in the ability to maintain unity power factor. The larger the value of V_{LF}, the larger the rating of the series active filter (kVAr). From Figure 3.4.1-1:

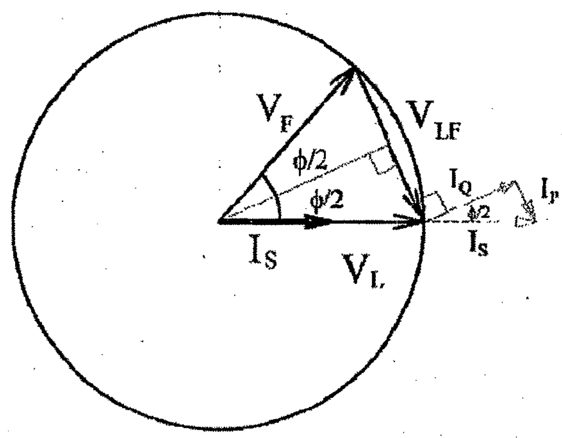


Figure 3.4.1-1: Circle diagram of the series filter

$$Q_{FILTER} = V_{LF}.I_S.\cos\frac{\emptyset}{2} \quad (3.4.1\text{-}2)$$

Replacing (3.4.1-1) into (3.4.1-2)

$$Q_{FILTER} = 2V_F.I_S.\sin\frac{\emptyset}{2}\cos\frac{\emptyset}{2}$$

$$= V_F.I_S.\sin\emptyset \quad (3.4.1\text{-}3)$$

Then, (3.4.1-2) corresponds to the total reactive power required by the load to keep unity-power-factor operation from the mains point of view.

It can be observed from the circle diagram of Figure 3.4.1-1 that, in order to obtain unity power factor at the line terminals (V_L), a little amount of active power has to go through the series filter.

$$P_{FILTER} = V_{LF}.I_P$$

$$= V_{LF}.I_S.\sin\frac{\emptyset}{2} \quad (3.4.1\text{-}4)$$

However, most of this active power is returned to the system through the low-power PWM converter shown in Figure 3.4-1. The amount of active power that has to go through the series active filter, according to Figure 3.4.1-1, is given by

P_{FILTER} can also be obtained through

$$P_{FILTER} = P_{LINE} - P_{LOAD}$$

$$= V_F . I_S (1 - \cos\emptyset) \qquad (3.4.1\text{-}5)$$

Equations (3.4.1-4) and (3.4.1-5) are equivalent. They are related through (3.4.1-1) and the trigonometric identity $2\, sin^2(\emptyset/2) = 1 - cos(\emptyset)$

For cost considerations, it is important to keep as low as possible. Otherwise, the power ratings of both the series filter and the small PWM rectifier shown in Figure 3.4-1 become large. This means that the capability to compensate power factor of the series filter has to be restricted. The theoretical kilovolt ampere ratings of the series filter and the low-power PWM converter can be related to the kilovoltampere rating of the load (S_{LOAD}). The kilovoltampere rating of the series filter, from Figure 3.4.1-1 or from Equation (3.4.1-2) and (3.4.1-4), is

$$S_{FILTER} = V_{LF} . I_S$$

$$= 2 . V_F . I_S . \sin\frac{\emptyset}{2} \qquad (3.4.1\text{-}6)$$

As

$S_{LOAD} = V_F . I_S$, it yields

$$\frac{S_{FILTER}}{S_{LOAD}} = 2 \sin\frac{\emptyset}{2}$$

$$= \frac{V_{LF}}{V_S} \qquad (3.4.1\text{-}7)$$

On the other hand, the relative kilovoltampere rating of the low-power PWM converter comes from (3.4.1-5) and is

$$\frac{S_{CONV}}{S_{LOAD}} = \frac{P_{CONV}}{S_{LOAD}}$$

$$= \frac{P_{FILTER}}{S_{LOAD}}$$

$$= 1 - \cos\emptyset \qquad (3.4.1\text{-}8)$$

If it is again consider Φ=29°, it yields S_{CONV} = 12.5% of that of the power load. It can be noticed that when no power factor compensation is required, both the series filter and the small PWM converter become theoretically null. However, the small converter has to supply the power losses of the series filter (which are very small), and the series filter needs to compensate the harmonic reactive power. The low-power PWM converter is a six-pack insulated-gate-bipolar-transistor (IGBT) module, inserted into the box of the series filter.

3.4.2 HARMONIC COMPENSATION

The *kVAr* requirements of the series filter for harmonic compensation are given by

$$Q^h_{FILTER} = V^h_{LF} \,.\, I_S \qquad (3.4.2\text{-}1)$$

where V^h_{LF} is the rms harmonic voltage at the series filter terminals and I_S is the fundamental current passing through the filter. As the series filter is a fundamental current source, harmonic currents through this filter do not exist.

The harmonic compensation is achieved by blocking the harmonic currents from the load to the mains. As the series filter works as a fundamental sinusoidal current source, it automatically generates a harmonic voltage V^h_{LF} equal to the harmonic voltage drop V^h_F at the shunt passive filter. In this way, harmonics cannot go through the mains. Then, the rms value of V_{LF}^{h} can be evaluated through the harmonic voltage drop at the shunt passive filter:

$$V_{LF}^{h} = V_{F}^{h}$$

$$= \sqrt{\Sigma (V_{F}^{j})^{2}} \qquad (3.4.2\text{-}2)$$

where V_{F}^{j} represents the rms value of the voltage drop produced by the jth harmonic in the shunt passive filter. This voltage drop is related with the jth harmonic impedance of the filter and the jth harmonic current:

$$V_{F}^{j} = I_{F}^{j} . Z_{F}^{j} \qquad (3.4.2\text{-}3)$$

Assuming a *six-pulse thyristor rectifier load,* with a shunt passive filter like the one shown in Figure 3.4-1, the jth harmonic current can be evaluated in terms of the fundamental I_{s}:

$$I_{F}^{j} = \frac{I_{S}}{j} \text{ (j = 6n} \pm 1\text{, with n = 1, 2, 3 ...)} \qquad (3.4.2\text{-}4)$$

Replacing (3.4.2-2)–(3.4.2-4) into (3.4.2-1) yields

$$Q_{FILTER}^{h} = (I_{S})^{2} . \sqrt{\Sigma \left(\frac{Z_{F}^{j}}{j}\right)^{2}} \qquad (3.4.2\text{-}5)$$

The impedanceZ_{F}^{j}, will depend on the parameters of the filter (C_f , L_f, R_f), and is very small for the fifth and seventh harmonics. On the other hand Z_{F}^{j}, takes a constant value for high-order harmonics (high-pass filter) and, for this reason, when j is large, the terms $(Z_{F}^{j}/j)^{2}$ in the summation in (3.4.2-5) can be neglected (j>60). With these assumptions, the term represented by the square root in (3.4.2-5), can be as small as 3%–10% of the load base impedance. Then,

$$\frac{Q_{FILTER}^{h}}{S_{LOAD}} = 3\% - 10\% \quad (3.4.2\text{-}6)$$

The small size of series filters, compared with the shunt active filters (30%-60% of S_{LOAD}), is one of the main advantages of this kind of solution. The small size of series filters also helps to keep the power losses at low values.

3.4.3 POWER LOSSES

The power losses of the series active filter depend on the inverter design. In this paper, the series filter was implemented using a three-phase PWM modulator, based on IGBT switches. With this type of power switches, efficiencies over 96% are easily reached. Then, 4% power losses can be considered for the series filter, based on its nominal kilovoltampere. Now, if the filter works only for harmonic compensation, its rating power will be between 3%–10% of the nominal load rating. Then, power losses of the series filter represent only 0.12%–0.4% (less than 1%) of that of the kilovoltampere rating of the load [4]. However, if the series filter is also designed for power-factor compensation ($\cos\Phi_{MAX} = 0.875$ or $S_{FILTER} = 0.5\ S_{LOAD}$), the relative power losses can be as high as 2%.

3.5 A SERIES ACTIVE POWER FILTER COMBINED WITH SHUNT PASSIVE FILTER BASED ON VOLTAGE-SOURCE INVERTER

Figure 3.5-1 shows a system configuration of the above approach to harmonic compensation.

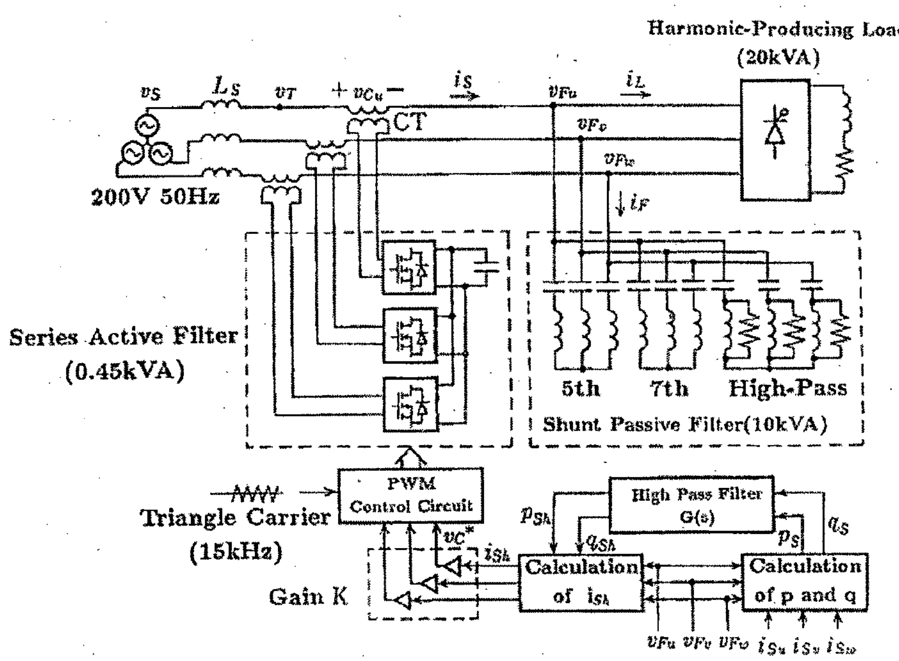


Figure 3.5-1: Circuit configuration of combined system.

Figure 3.5-2 shows a detailed circuit of a series active filter on a per-phase base. A passive filter consisting of a 5th and 7th-tuned ***LC*** filter and a high-pass filter is shunted with a three-phase six-pulse thyristor converter, which is considered a typical harmonic-producing load. The circuit constants of the shunt passive filter of rating 10 kVA are shown in Table 3.5-1. Three single-phase voltage-source PWM inverters are inserted in series with the source impedance through three single-phase current transformers (CT's; turns ratio = 1:20), thus forming a series active filter. A single-phase diode rectifier is connected on the dc side of the inverters, supplying the energy corresponding to the switching and conducting losses in the inverters.

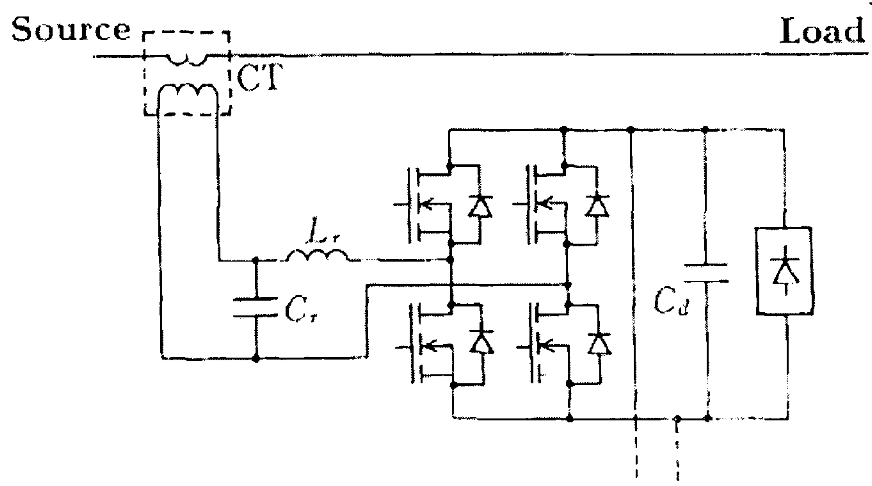


Figure 3.5-2: Detailed circuit configuration of series active filter on per-phase base

Table 3.5-1: CIRCUIT CONSTANTS OF THE SHUNT PASSIVE FILTER

Order of Harmonics Filter	Inductance	Capacitance	Quality Factor
5th	L=1.20mH	C=340 pF	14
7th	L=1.20mH	C=170 pF	14
HPF	L=0.26mH	C=300pF	R = 3Ω

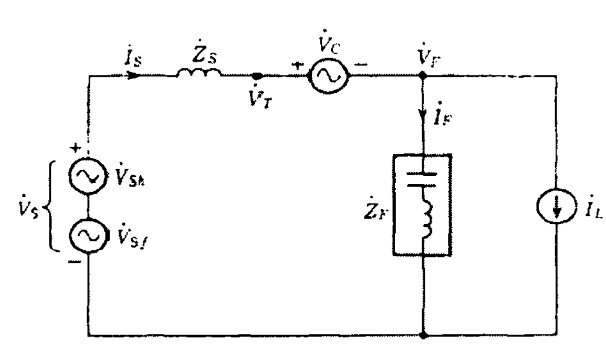


Figure 3.5-3: Equivalent circuit on per-phase base for Figure 3.5-1

The purpose of the CT's is not only to isolate the **PWM** inverters from the power system, but also to match the voltage and current rating of the **PWM** inverters with that of the power system. The function of the series active filter is not to directly compensate for the harmonics of the rectifier, but to improve the filtering characteristics of the shunt passive filter and to solve the problems of the shunt passive filter used alone. In other words, the series active filter acts not as a harmonic compensator but as a harmonic isolator. Hence the required rating of the series active filter is much smaller than that of a conventional shunt active filter.

3.5.1 COMPENSATION PRINCIPLE

Assuming for simplicity's sake that the voltage-source **PWM** inverter is an ideal controllable voltage source v_c Figure 3.5-1 is represented on a per-phase base by Figure 3.5-3. The three phase thyristor converter is also assumed to be a current source i_L due to the presence of sufficient inductance on the dc side. Here, $\dot{\boldsymbol{Z}}_F$ is the equivalent impedance of the shunt passive filters, the constants of which are shown in Table 3.5-1, and $\dot{\boldsymbol{Z}}_S$ is the source impedance.

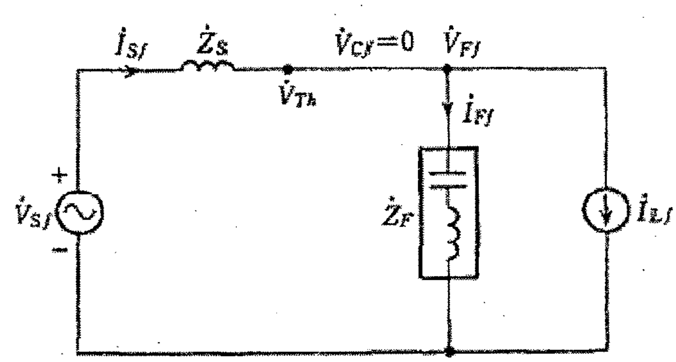


Figure 3.5-4: Equivalent circuit for fundamental frequency.

The series active filter is controlled in such a way as to present zero impedance to the external circuit at the fundamental frequency and a high resistance *K* to source or load harmonics.

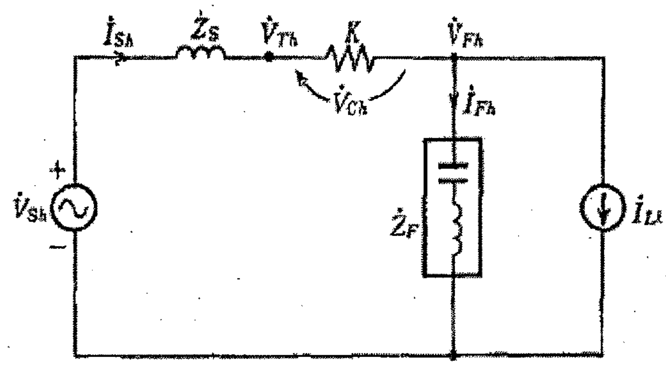


Figure 3.5-5: Equivalent circuit for harmonic frequencies.

For the fundamental and harmonics, application of the law of superposition to Figure 3.5-3 gives us two equivalent circuits, as shown in Figure 3.5-4 and Figure 3.5-5, respectively. Here, $\dot{V}_{Sf}$ is the source fundamental voltage and $\dot{I}_{Lf}$ is the load fundamental current in Figure 3.5-4, while $\dot{V}_{Sh}$ is the source harmonic voltage and $\dot{I}_{Lh}$ is the load harmonic current in Figure 3.5-5. As is seen in Figure 3.5-4, the shunt passive filter behaves as a capacitor for power factor improvement, but the series active filter does not play any role. Figure 3.5-5 shows that the series active filter acts as a harmonic isolator between the source and load.

To demonstrate the compensation principle of the combined system, some important equations are derived on the basis of Figure 3.5-5.

3.5.2 SOURCE HARMONIC CURRENT: $\dot{I}_{Sh}$

The harmonic current flowing in the source, which is produced by both the load harmonic current $\dot{I}_{Lh}$ and the source harmonic voltage $\dot{V}_{Sh}$,is given as follows:

$$I_{Sh} = \frac{Z_F}{Z_S + Z_F + K} \cdot I_{Lh} + \frac{V_{Sh}}{Z_S + Z_F + K} \qquad (3.5\text{-}1)$$

$$I_{Sh} \simeq 0 \text{ if } K \gg Z_S, Z_F \qquad (3.5\text{-}2)$$

Here, Z_S is the amplitude of $\dot{Z}_S$ and Z_F is that of $\dot{Z}_F$. The first term on the right side of (3.5-1) means that the series active filter acts as a "damping resistance," which can eliminate the parallel resonance between the shunt passive filter and the source impedance, while the second term means that the series active filter acts as a "blocking resistance," which can prevent the harmonic current produced by the source harmonic voltage from flowing into the shunt passive filter. If the resistance K is much larger than the source impedance, variations in the source impedance have no effect on the filtering characteristics of the shunt passive filter, thus reducing the source harmonic current to zero, as shown in (3.5-2).

3.5.3 OUTPUT VOLTAGE OF SERIES ACTIVE FILTER: $\dot{V}_C$

The output voltage of the series active filter, which is equal to the harmonic voltage appearing across resistance K in Figure 3.5-5, is given by

$$V_C = KI_{Sh} = K \cdot \frac{Z_F I_{Lh} + V_{Sh}}{Z_S + Z_F + K} \tag{3.5-3}$$

$$V_C \simeq Z_F I_{Lh} + V_{Sh} \quad \text{if } K \gg Z_S, Z_F \tag{3.5-4}$$

Equation (3.5-4) implies that the voltage rating of the series active filter is given as a vector sum of the first term on the right side, which is inversely proportional to the quality factor of the shunt passive filter, and the second term, which is equal to the source harmonic voltage.

3.5.4 FILTER HARMONIC VOLTAGE: $\dot{V}_{Fh}$

The filter harmonic voltage, which is equal to the harmonic voltage appearing across the shunt passive filter, is given by

$$\dot{V}_{Fh} = -\frac{\dot{Z}_S + K}{\dot{Z}_S + \dot{Z}_F + K} \cdot \dot{Z}_F \dot{I}_L + \frac{\dot{Z}_F}{\dot{Z}_S + \dot{Z}_F + K} \cdot \dot{V}_{Sh} \tag{3.5-5}$$

$$\dot{V}_{Fh} \simeq -\dot{Z}_F \dot{I}_{Lh} \quad \text{if } K \gg Z_S, Z_F \tag{3.5-6}$$

Equation (3.5-6) tells us that the source harmonic voltage does not appear on the load side because it applies across the series active filter.

3.5.5 CONTROL CIRCUIT

To control the series active filter in such a way as to present zero impedance for the fundamental and pure resistance for the harmonics, the reference output voltage of the series active filter is given by

$$v_c^* = K i_{Sh} \tag{3.5-7}$$

where is, is the source harmonic current, which can be calculated by applying the instantaneous real and imaginary power theory, the so-called "p-q theory" developed by H. Akagi et al. [G24].

Transformation of the phase voltages u_{Lu} , u_{Lv} , and u_{Lw} on the load side and source currents i_{su} , i_{sv}, and i_{sw}, into α-β orthogonal coordinates gives the following expression:

$$\begin{bmatrix} v_{L\alpha} \\ v_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{Lu} \\ v_{Lv} \\ v_{Lw} \end{bmatrix} \tag{3.5-8}$$

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{Su} \\ i_{Sv} \\ i_{Sw} \end{bmatrix} \tag{3.5-9}$$

According to [G24], the instantaneous real power *p* and the instantaneous imaginary power *q* can be defined as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_{L\alpha} & v_{L\beta} \\ -v_{L\beta} & v_{L\alpha} \end{bmatrix} \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} \tag{3.5-10}$$

Note that the dimension of *q* is not watt, volt-ampere, or VAr because $v_{L\alpha}$ $i_{S\beta}$ and $v_{L\beta}$ $i_{S\alpha}$ are defined by the product of the instantaneous voltage in one phase and the instantaneous current in the other phase.

The harmonic components p_h and q_h are extracted from p and q by using a high pass filter. A first-order high pass filter, the cutoff frequency of which is 35 Hz, is used. In the calculation circuit of i_{sh}, the following calculations are performed:

$$\begin{bmatrix} i_{Shu} \\ i_{Shv} \\ i_{Shw} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{L\alpha} & v_{L\beta} \\ -v_{L\beta} & v_{L\alpha} \end{bmatrix}^{-1} \begin{bmatrix} p_h \\ q_h \end{bmatrix} \tag{3.5-11}$$

The reference output voltage given by (3.5-7) is compared with a triangle carrier, producing the PWM switching patterns. Here the frequency of the triangle carrier is 6 kHz. Therefore the series active filter operates as a controllable voltage source, while a conventional active filter operates as a controllable current source. Hence a voltage-source PWM inverter is suitable for the series active filter rather than a current-source PWM inverter. The voltage-source PWM inverter used in the series active filter can be protected against overvoltage and over current by the following means. All the power IGBT/MOSFET's of the upper legs are turned off to release the dc capacitor from the secondary of the CT's, while those of the lower legs are turned on to short the secondary of the CT's through the on-state power IGBT/MOSFET's and diodes.

3.6 SERIES ACTIVE POWER FILTER COMBINED WITH SHUNT PASSIVE FILTER BASED ON VOLTAGE-SOURCE INVERTER

As per the section 3.2.1 the series active filter references for compensating the harmonics are generated through indirect method. More over assumption is made that source voltage is pure sine wave which is not the case in practical application, where as the series active filter explained in section 3.2.2 is aim to reduce the rating of the active filter in combination with shunt passive filter.

However there are the case as shown in Figure 3.6-1, where substation a small feeder having linear but important load are affected due to voltage harmonic the above method is not cost effective. Normally, Feeder having linear load is drawing sinusoidal current but due the bus voltage are distorted it draws nonsinusoidal current. In such case a series active filter which can isolated linear load from voltage harmonics is the only solution which is presented in this thesis.

To simplify the control strategy for series active filters, a simple approach is presented, i.e., the series filter is controlled as a voltage source whose reference is get through *" p-q theory". This approach presents the following advantages.*

1) The control system is simpler & instantaneous compensation is possible for elimination of the voltage harmonics.

2) Rating of the active filter is small as it restricted for particular feeder only.

3) It controls the voltage at the load node, to compensate the effect of blocking the voltage harmonics, allowing excellent regulation characteristics.

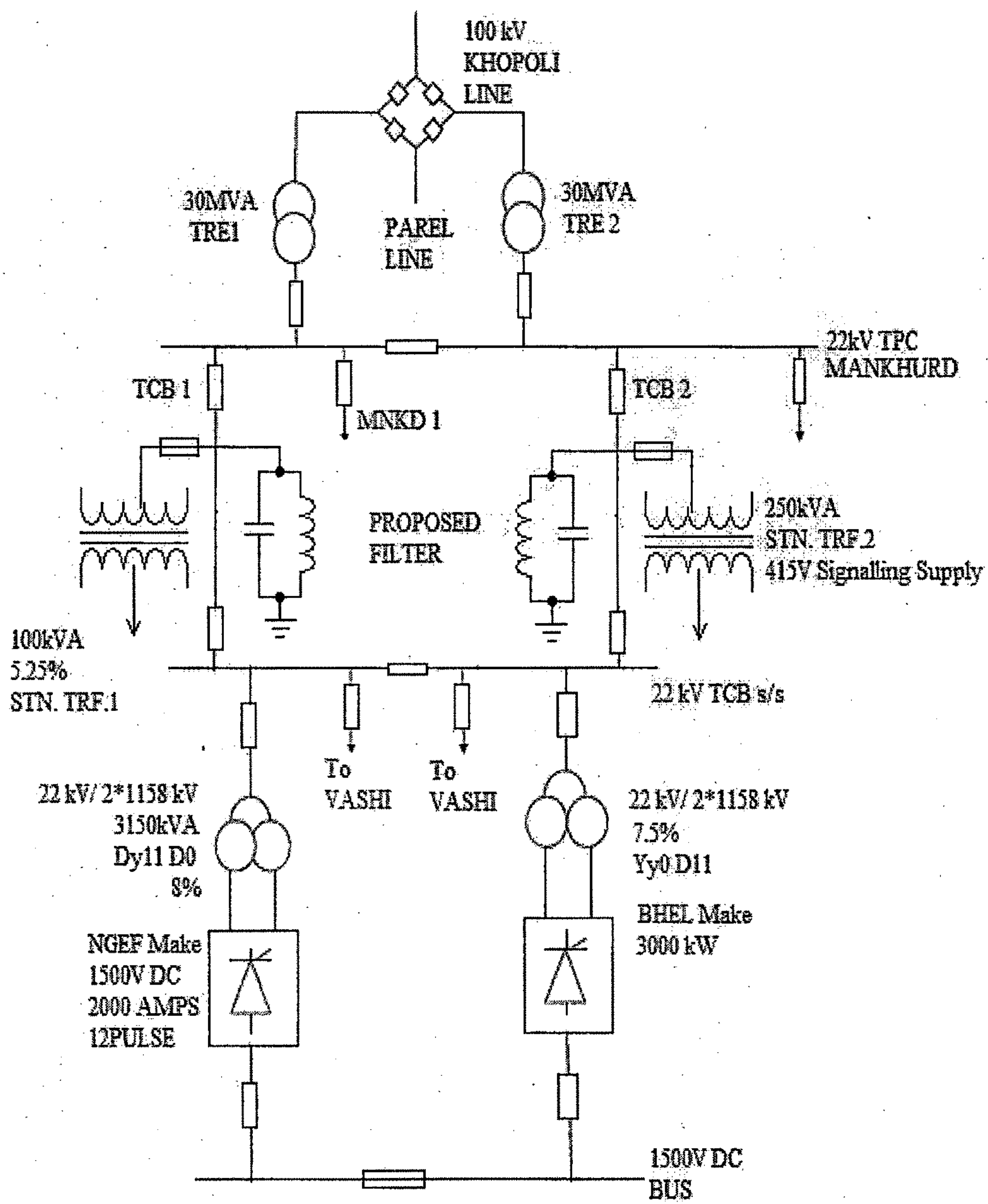


Figure 3.6-1: Traction substation having small linear load

3.7 NOVEL SERIES ACTIVE POWER FILTER COMBINED WITH SHUNT PASSIVE FILTER BASED ON VOLTAGE-SOURCE INVERTER USING ANALOG APPROACH

In this section, detailed description of control and power circuit realized using analog approach is described. Each block describes working principle and actual circuit realization. As previously described the system is based on instantaneous reactive power theory.

According to instantaneous reactive power theory six signals (three reference voltages and three distorted voltages) are required for the calculation of the three compensation voltages. These voltages signals are derived from the phase voltage using potential transformers.

3.7.1 CONTROL CIRCUIT APPROACH & IT'S REALIZATION

3.7.1.1 SIGNAL CONDITIONING CIRCUIT

Three-phase distorted source voltages are fed as input to the control cards through PT's. These signals are required to be conditioned to make them compactible for the calculation of compensating reference voltages. The reference voltages are generated by filtering all other components except the fundamental component at the control level. Due to the filtering of the distorted signal, a little phase shift is generated between the distorted input and the output sinusoidal signal. This phase difference is eliminated using phase shifter circuit.

3.7.1.2 TRANSFORMATION OF SIGNALS INTO ORTHOGONAL COORDINATES:

By p-q theory these voltages (v_a , v_b , & v_c) and (v_{ar} , v_{br} , & v_{cr}) are transformed into α-β coordinates (orthogonal coordinates) by following relations.

$$\begin{bmatrix} v_{0r} \\ v_{\alpha r} \\ v_{\beta r} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{ar} \\ v_{br} \\ v_{cr} \end{bmatrix} \quad (3.7.1\text{-}1)$$

$$\begin{bmatrix} v_{0} \\ v_{\alpha} \\ v_{\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{a} \\ v_{b} \\ v_{c} \end{bmatrix} \quad (3.7.1\text{-}2)$$

After solving matrices following was obtained

$$v_{0r} = 0.5773\, v_{ar} + 0.5773\, v_{br} + 0.5773\, v_{cr}$$

$$v_{\alpha r} = 0.8165\, v_{ar} - 0.4082\, v_{br} - 0.4082\, v_{cr}$$

$$v_{\beta r} = 0.0\, v_{ar} - 0.7071\, v_{br} - 0.7071\, v_{cr} \quad (3.7.\ 1\text{-}3)$$

Further same approach can be used to determine v_α and v_β Therefore, following was obtained

$$v_0 = 0.5773\, v_a + 0.5773\, v_b + 0.5773\, v_c$$

$$v_\alpha = 0.8165\, v_a - 0.4082\, v_b - 0.4082\, v_c$$

$$v_\beta = 0.0\, v_a - 0.7071\, v_b - 0.7071\, v_c \quad (3.7.1\text{-}4)$$

These transformation equations are used for the practical circuit realization. The corresponding circuit using operational amplifiers for each Equation is shown in Figure 3.7.1-1

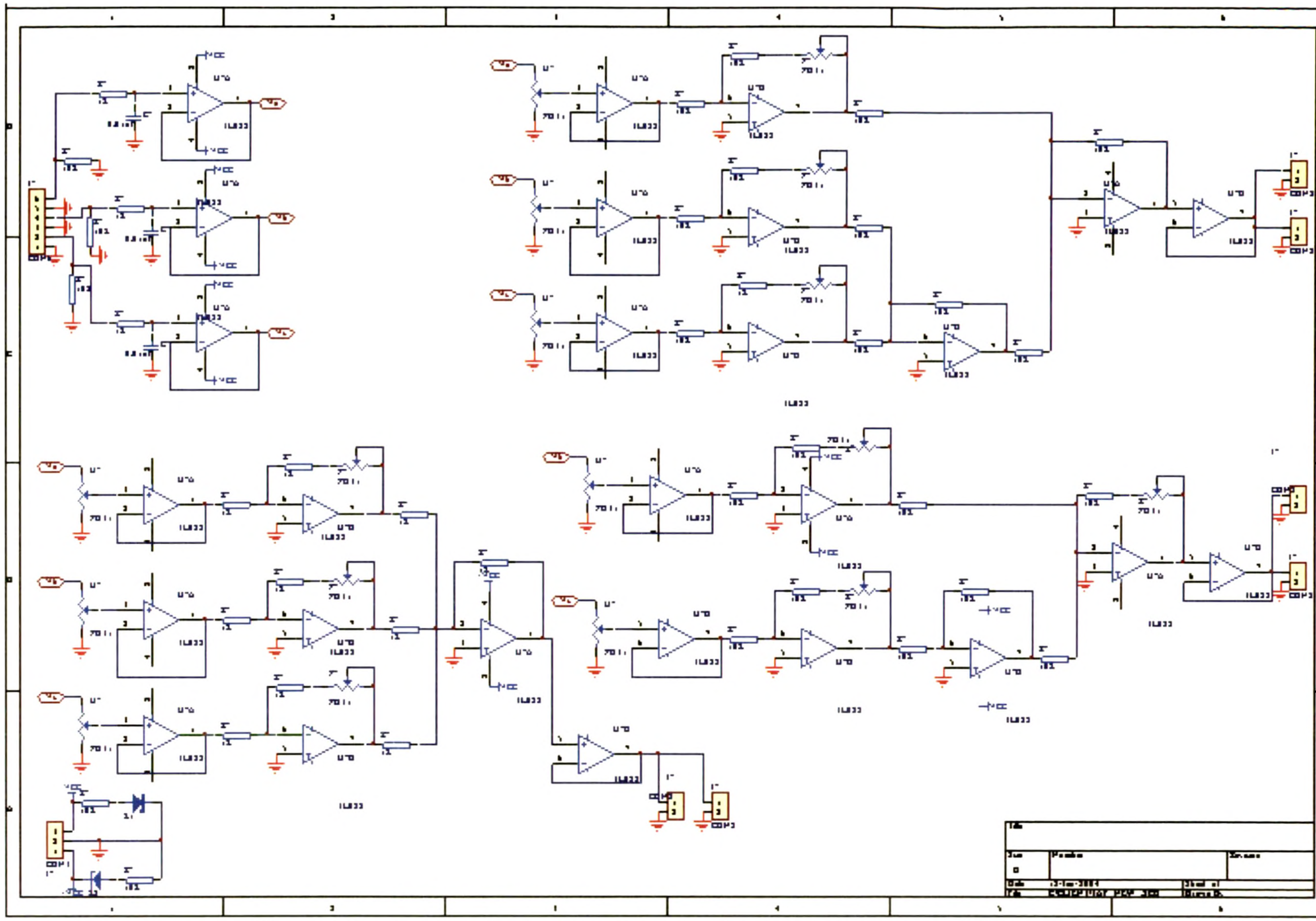


Figure 3.7.1-1: Transformation of voltage Signals into Orthogonal Coordinates

3.7.1.3 INSTANTANEOUS REAL AND IMAGINARY POWER CALCULATIONS

The resultant of these equations i.e. orthogonal reference voltages and distorted voltages are used to define instantaneous real and power.

By p-q theory instantaneous real and imaginary power are defined as

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_{0r} & 0 & 0 \\ 0 & v_{\alpha r} & v_{\beta r} \\ 0 & -v_{\beta r} & v_{\alpha r} \end{bmatrix} \begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} \tag{3.7.1-5}$$

Solving following was obtained,

$$p_0 = v_{0r}\, v_0$$

$$p = v_{\alpha r}\, v_\alpha + v_{\beta r}\, v_\beta$$

$$q = v_{\alpha r}\, v_\beta - v_{\beta r}\, v_\alpha \tag{3.7.1-6}$$

In these equations distorted voltage is multiplied with reference voltage so for practical multiplication purpose AD633JN multiplier is used and remaining addition and subtraction is done by Op-Amps. The diagram of practical circuit is shown in Figure 3.7.1-2.

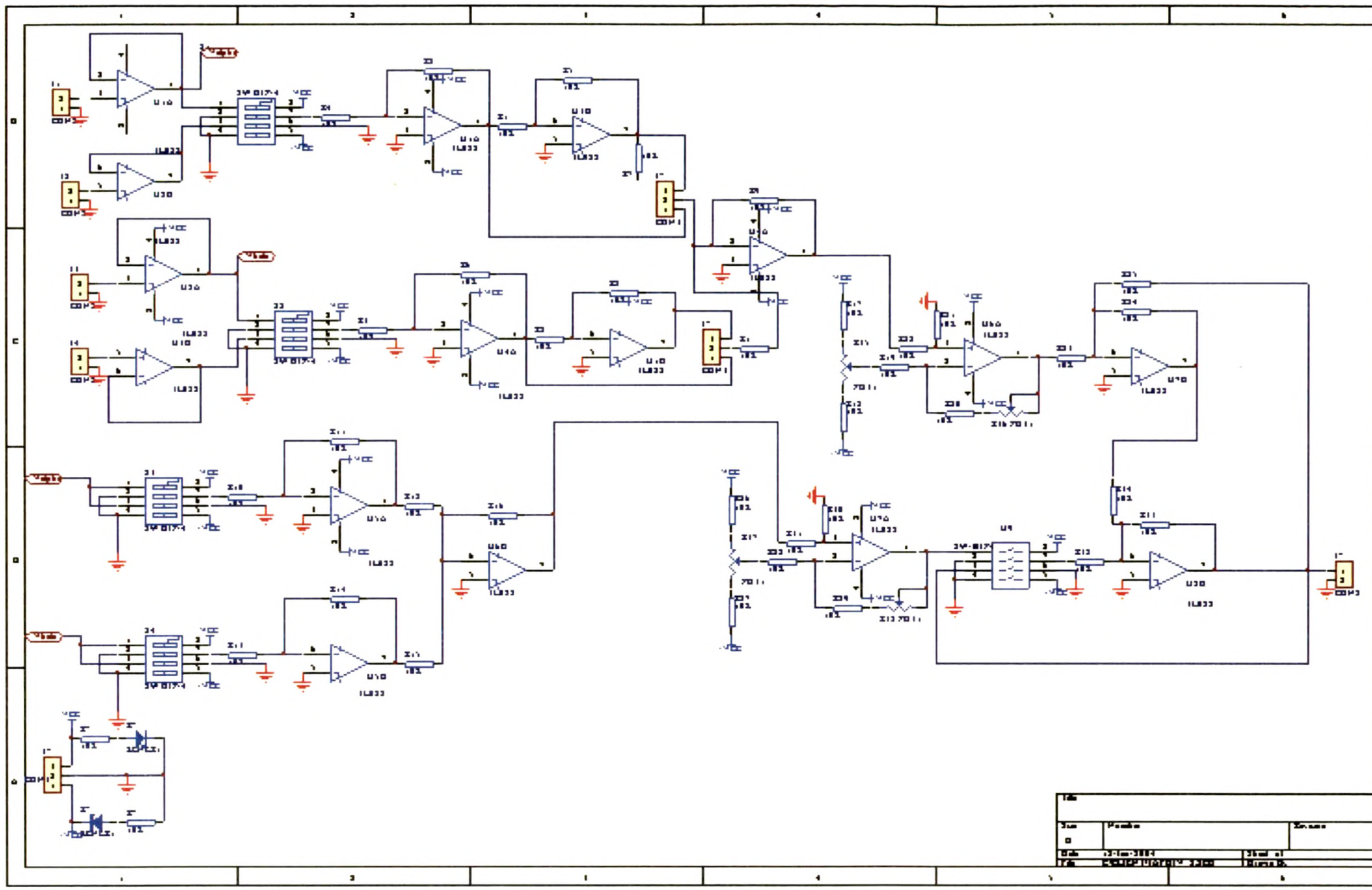


Figure 3.7.1-2: Instantaneous Real And Imaginary Power Calculations

3.7.1.4 FILTER CIRCUIT CONSIDERATION AND ORTHOGONAL COMPENSATION VOLTAGES

To eliminate harmonics and the calculated real power p is passed through high pass second order Butterworth filter. The cutoff frequency for the filter is 45Hz. In this system cascading two first order filters makes this second order filter. The corresponding circuit is shown in Figure 3.7.1-3. By using the filter the AC component is eliminated giving,

$$p_{ac} = p - p_{dc}$$

$$q_{ac} = q - q_{dc} \qquad (3.7.1\text{-}7)$$

The filter used introduces phase in the input and output signal. To compensate this phase shift a phase shifter is used in the system. Further, to compensate reactive power must be made negative in matrix equations,

$$\begin{bmatrix} v_{\alpha c} \\ v_{\beta c} \end{bmatrix} = \begin{bmatrix} v_{\alpha r} & v_{\beta r} \\ -v_{\beta r} & v_{\alpha r} \end{bmatrix}^{-1} \begin{bmatrix} -p_{ac} \\ -q_{ac} \end{bmatrix}$$

$$\begin{bmatrix} v_{\alpha c} \\ v_{\beta c} \end{bmatrix} = \frac{1}{(v_{\alpha r}{}^2 + v_{\beta r}{}^2)} \begin{bmatrix} v_{\alpha r} & -v_{\beta r} \\ v_{\beta r} & v_{\alpha r} \end{bmatrix} \begin{bmatrix} -p_{ac} \\ -q_{ac} \end{bmatrix} \qquad (3.7.1\text{-}8)$$

Thus, to cancel harmonics in the power system and reactive power the p_{ac} and q_{ac} is made negative. Further solving following was obtained,

$$v_{\alpha c} = \frac{1}{(v_{\alpha r}{}^2 + v_{\beta r}{}^2)} \left(-v_{\alpha r}\, p_{ac} + v_{\beta r} q_{ac}\right)$$

$$v_{\beta c} = \frac{1}{(v_{\alpha r}{}^2 + v_{\beta r}{}^2)} \left(-v_{\beta r} p_{ac} - v_{\alpha r} q_{ac}\right) \qquad (3.7.1\text{-}9)$$

Where $v_{c\alpha}$ and $v_{c\beta}$ are compensating voltages in the orthogonal coordinates. The corresponding realization is shown in Figure 3.7.1-3.

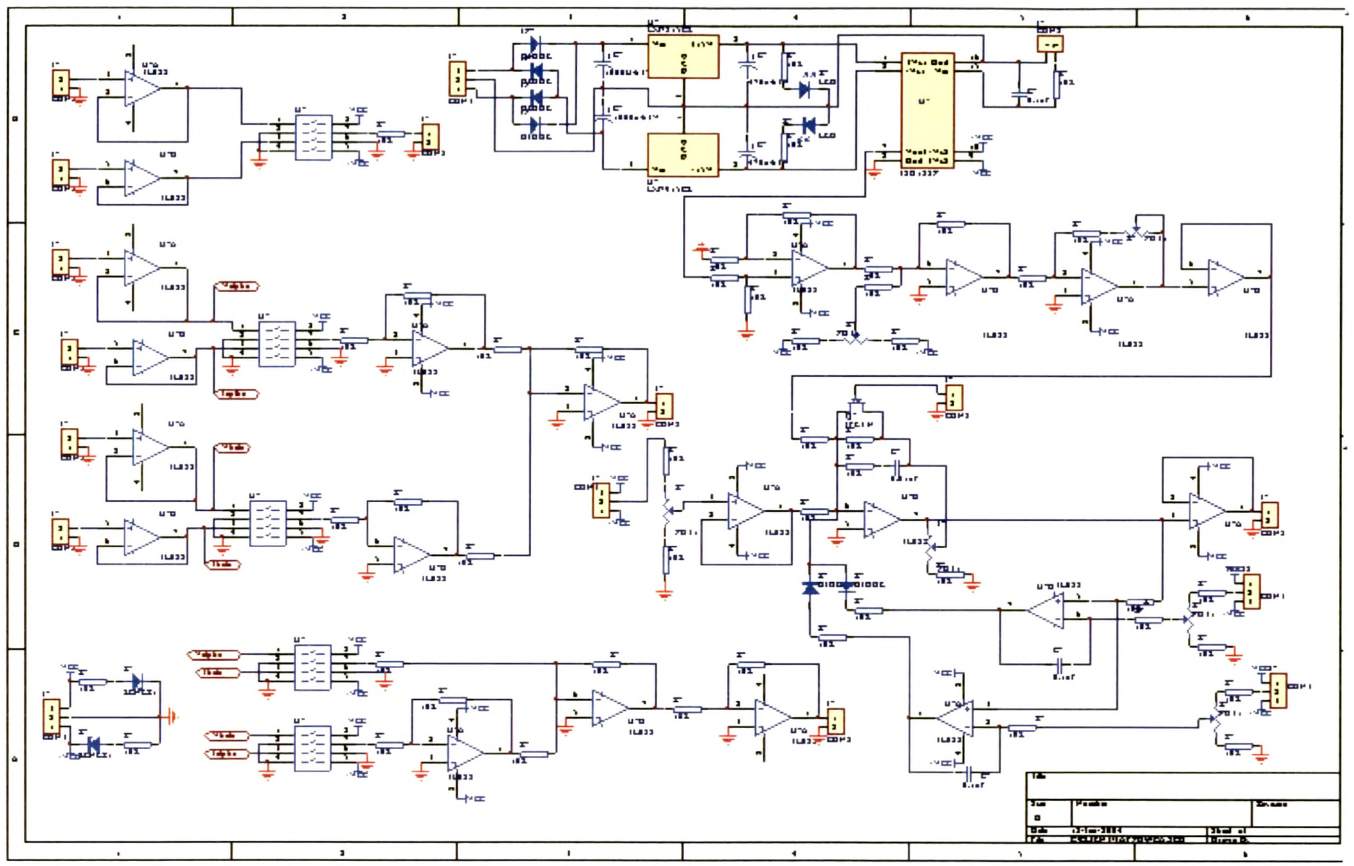


Figure 3.7.1-3: $v_{c\alpha}$ and $v_{c\beta}$ calcultation

3.7.1.5 TRANSFORMATION OF ORTHOGONAL VOLTAGES BACK INTO THREE PHASE VOLTAGES

This $e_{c\alpha}$ and $e_{c\beta}$ compensated orthogonal voltages are transformed back into three phase voltages by reverse transformation of matrix as

$$\begin{bmatrix} v_{ac} \\ v_{bc} \\ v_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_0 \\ v_{\alpha c} \\ v_{\beta c} \end{bmatrix} \qquad (3.7.1\text{-}10)$$

By solving these Equation following was obtained

$$v_{ac} = 0.5773\, v_{0c} + 0.8165\, v_{\alpha c} + 0.0000\, v_{\beta c}$$

$$v_{bc} = 0.5773\, v_{0c} - 0.4082\, v_{\alpha c} + 0.7071\, v_{\beta c}$$

$$v_{cc} = 0.5773\, v_{0c} - 0.4082\, v_{\alpha c} - 0.7071\, v_{\beta c} \qquad (3.7.1\text{-}11)$$

These e_{ac}, e_{bc}, e_{cc} are compensated three phase reference compensating voltages. The corresponding realization is shown in Figure 3.7.1-4

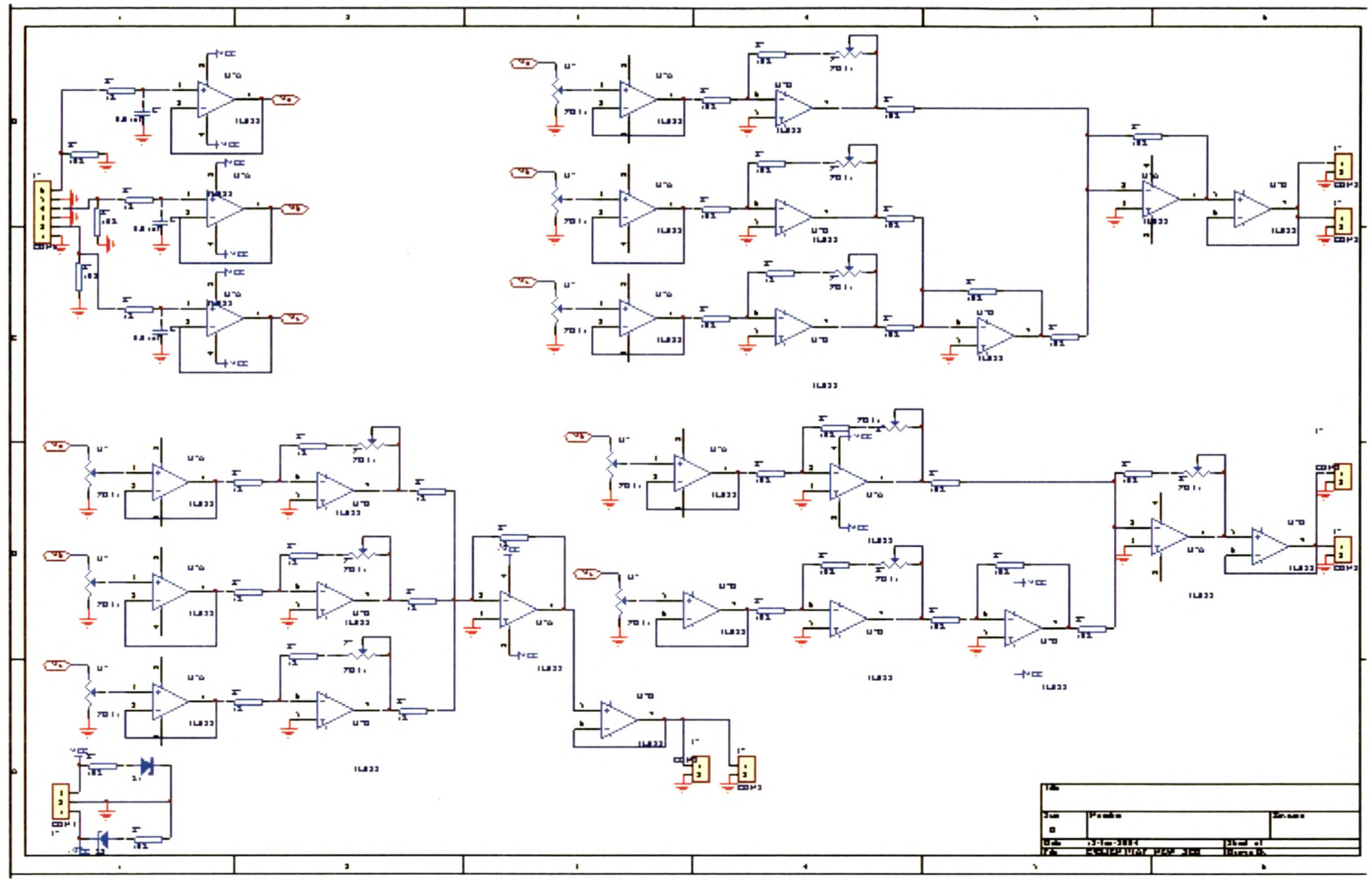


Figure 3.7.1-4: Transformation of Orthogonal voltage Back into Three Phase voltage

3.7.1.6 COMPENSATING VOLTAGE GENERATION

The compensation voltages derived from previous block is used to generate gate signals to eliminate harmonics.

The implementation of series type active filter is simpler if the type of inverter used is "SPWM Voltage Source" type. The SPWM voltage source inverter employs a SPWM switching technique in which the output voltage of the inverter is pulse width modulated type and is due to switching pattern formed due to the comparison of the reference compensating voltages and triangular wave of 4.8 kHz.

3.8 ISOLATION AND DRIVER CIRCUIT

The gate pulses, which are to be given to, the power device goes through two stages: isolation and driver stage. The isolation is must when gate pulses are given to power devices when connected in inverter configuration. Otherwise there is possibility of short circuit in low power circuitry by entering high power from power circuit when device gets short-circuited. The isolation is normally provided to gate pulses through opto-couplers, which isolates power circuit and low power circuit optically. Further these optically coupled signals are given to the driver circuit. The gate pulse, which is given to the IGBT, is with respect to the source terminal .So to avoid short circuit of drivers four separate power supplies are designed for each driver.

Since the power circuit consists of six devices and lower DC bus is common to all devices in lower limbs of inverter so only single power supply is necessary for lower limb drivers but it must have current rating thrice than the upper limb driver power supply.

The driver circuit consists hybrid IC, opto-coupler and isolated power supply. The main advantage of using hybrid IC driver is that it is made as per IGBT specification and all protection is provided in the same IC. IC M57962L is used as the hybrid driver IC and has the provision to sense the V_{ce} of the IGBT and monitor continuously voltage across the collector and emitter. When gate pulse applied to the hybrid IC and within 10 μ second if the device is not turn ON then this gives a signal which is useful for instantaneous over current protection. The Vce rises in the IGBT when access current is flow through it.

3.9 POWER CIRCUIT

The schematic diagram of series converter is shown in Figure 3.10-1 with load circuitry. This converter consists of six power IGBT, capacitor (C1). The filter capacitor has the function of suppressing the harmonic currents generated by the switching operation of IGBT. The capacitors (C1) maintain the DC bus voltage constant. These passive components size depends on the switching frequency and rating of the active filter. Diode bridge rectifier with resistive load is considered as Non-linear load (harmonic generating source). The RC snubber circuit is used for dv/dt protection of the IGBT. The value of the same is 10 ohm and 0.01 micro -farad capacitor. These snubbers are connected across each device. This snubber absorbs the peak voltage generated due to stray inductance and limits the dv/dt of the IGBT during turn off. Same way RC snubber is connected across the diode bridge module which is used to charge the DC bus capacitor and supply the active energy absorbs by the IGBT of voltage source inverter, reactor and snubber. Bleeder resistor is connected across the DC bus capacitor to balance the voltage within the voltage rating. The bleeder resistor are necessary as two capacitor of 6900μF, 450V DC, with ripple current of 10 amp are connected in series to increase the voltage rating up to 900V DC. The series active filter consists of three dual modules each module having two IGBT hence total six IGBTs in three-phase three-wire inverter configuration.

The values of components used along with active filter are :

C1, C2 = 6900 μF (4700 μF, 450 VDC Capacitor two in series and such three branch connected in parallel ALCON make with center point of each branch common)

IGBT= SKM50 GB123 B (50 amp, 1200 V, dual Module, with anti-parallel diode)

Driver IC = M57962L

The series active power filter is tested at 5 amp, 415Vac, and 50Hz three-phase supply and DC voltage of 350 V_{dc}.

The power circuit mainly consists of inverter, a high frequency transformer, LC filter. The high frequency transformer plays important role in the series compensation. The secondary of this transformer is connected in series between the source and the linear load. Generally it is found that the THD content in the source cannot be more than 20%. Actual measurements show that the harmonic content is not more than 10%. Considering this as a base for deciding the voltage of harmonic content, the rating of the high frequency transformer are fixed as follows:

Voltage ratings	:0-110-150//0-110-150volts per phase
Current rating	:15 amps per phase
Configuration	:three phase
VA ratings	:2250 VA per phase

Insulation Level :3 kV

Leakage reactance :10%

The frequency of switching is kept 4.8 kHz. The PWM signals (generated as a result of comparison of triangular wave with reference compensating voltages) are fed as gate signals to the IGBTs through the driver circuit. Thus the output of the inverter contains the components of harmonic contents plus the switching frequency. As the switching frequency component is not required, it is filtered out using the tuned LC filter.

3.10 EXPERIMENTAL SET-UP FOR TESTING

For the testing of the series active filter, artificial voltage harmonics are generated in the laboratory using a inductor and a diode bridge rectifier. The point of coupling of inductor and the diode bridge is the source of generating voltage harmonics. These distorted waveforms are utilized as input for the verification of p q theory. The PTs with 440/3.0 Volt ratio and burden of 0.2 VA are used for sensing the distorted voltages. The control circuit and power circuit are tested under the harmonic conditions. The THD was 20% approximately. The results are given in section 3.12 of this chapter

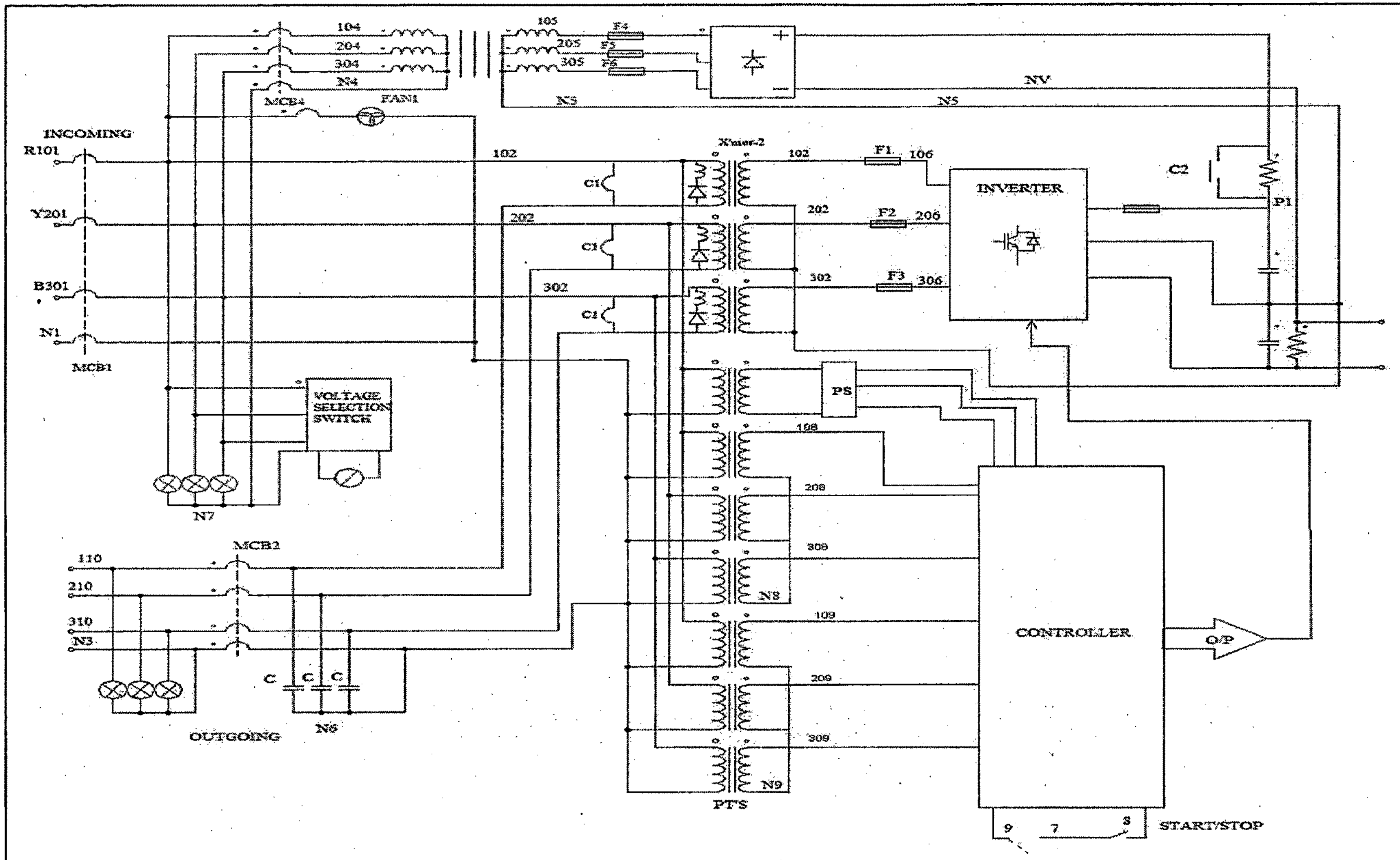


Fig 3.10-1: Schematic diagram of Series Active Filter developed

3.11 BRIEF DESCRIPTION OF WORKING OF SERIES ACTIVE FILTER

Initially the series active filter was checked for compensation of voltage harmonics at low current. First the artificial voltage harmonics are generated using the inductor and diode combination. The THD content of the source voltage is measured using the wave analyzer and these signals are fed to the control cards for generation of compensating voltages for elimination of harmonics. Bipolar triangular wave of 4.8 kHz frequency is generated using IC 8038 to imply the SPWM technique for switching of the inverter. The reference compensating voltages are compared with the triangular wave of 4.8 kHz frequency and accordingly the switching pulses are generated. Thee pulses are then fed to the driver card.

A separate three-phase transformer is used for generating DC for charging the capacitor with the help of a three phase diode bridge. A toggle switch is kept for giving and removing the gate pulse for the inverter. The output voltage of the inverter is dependent on the magnitude of the reference compensating voltages. This output of the inverter serves as the input to the transformer. The internal impedence of the transformer is kept 10%. This impedence in addition to the tuned LC filter serves the purpose of filter for eliminating the switching frequency component from the output of the transformer. The secondary side of this transformer is connected in series between the source and the linear load. The output of this transformer compensates the voltage harmonics in the source by injecting the negative of the harmonic signals.

The sequence of switching on and off and the protection scheme for inrush of currents during turning on of the active filter is explained henceforth.

Timer-relay logic has been developed to switch on the active filter. The inrush of currents during the sudden application of the DC voltages to the inverter damages the inbuilt freewheeling diodes of the IGBTs modules. To avoid these inrush currents, ERDA has implemented a soft charging circuit using resistors and timer-contactor combination. The timer is set to operate after six seconds and the charging resistor (R) is so selected that the charging time is equal to RC time constant. After six seconds the resistor is bypassed through a contractor.

The mode of operation of start/ stop of the active filter is as follows:

1) Manual mode
2) Auto mode

When SW1, SW2, and SW3 (please refer the schematic diagram and diagram of logic for switching on of active filter) is in ON position, the manual start / stop logic is bypassed. Whenever mains supply fails, whole system is switched off. At that time, position of all MCB's is in ON condition as the system is in operating condition. When the mains supply resumes, this energizes transformer-1 and transformer-2 and control logic gets ac supply. The DC capacitor of the inverter is energized through Resistor. After 6 sec, which is the time set in the timer; the contactor C2 gets energized and by passes the charging resistor. The contactor C2A is used to separate the DC and AC arc interruption. The contactors C2 and C2A both energizes simultaneously. The C2A contactor enables the start logic and as the SW1 is in ON position the RL1 gets energized which gives start command to Series Active filter and then energizes the C1 contactor. The C1 contactor is normally closed contactor and hence when C1 contactor energizes, all the contact becomes open this enables the Series active filter, which is already started, to compensate for voltage harmonic.

This sequence can be bypassed to manual mode depending upon the position of the SW1, SW2 and SW3. The detail control and power logic is given in the attached drawing. Figure 3.11-1 shows the control logic diagram of switching on series active filter. Figure 3.11-2 shows the front view of the panel developed at ERDA. Figure 3.11-3 & 3.11-4 shows the general allocation of components within the developed panel.

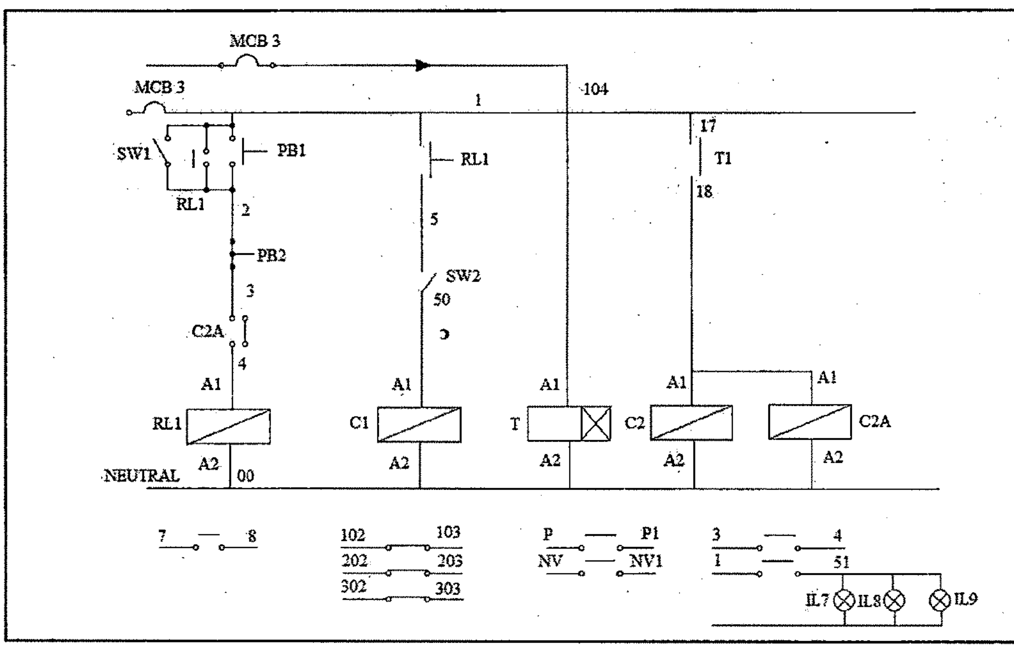


Figure 3.11-1: Control logic diagram of switching sequence of series active filter

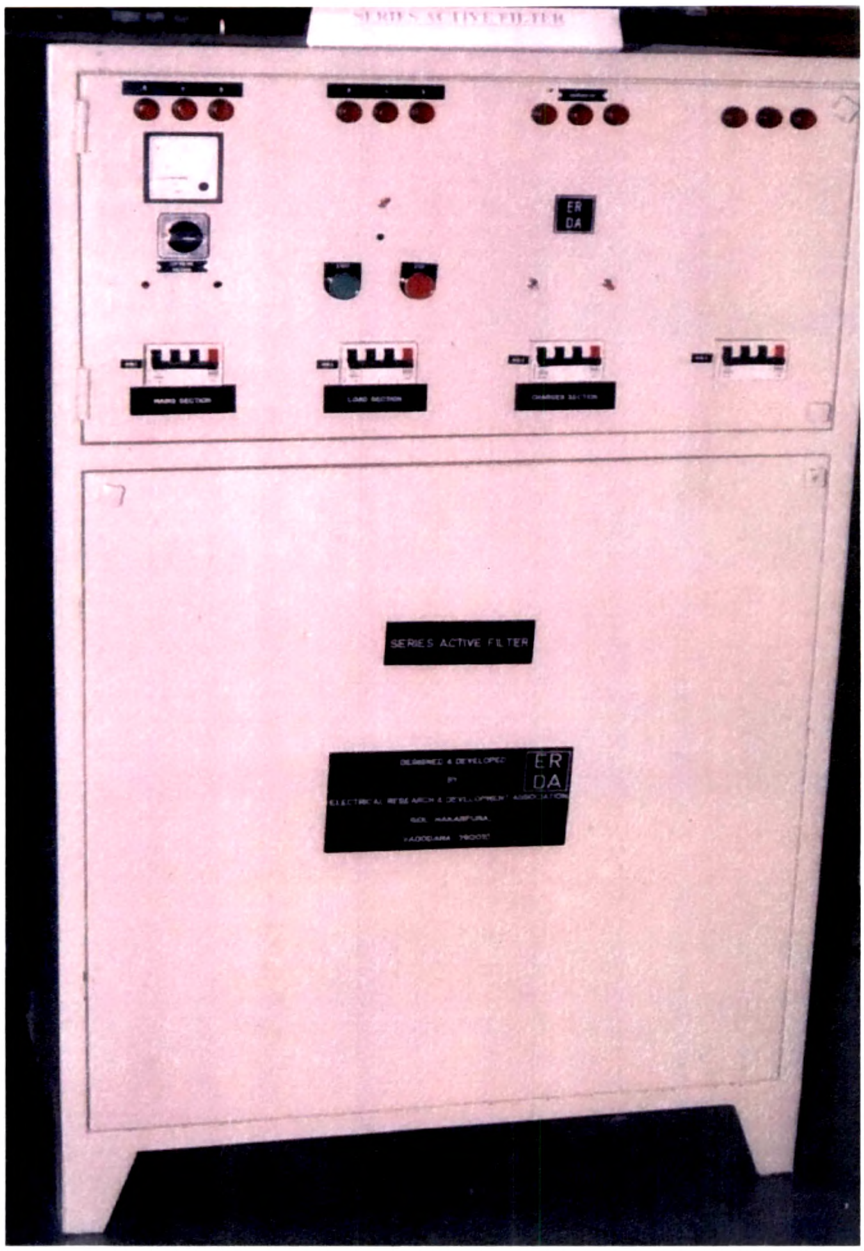


Figure 3.11-2: Photograph of front view of the panel

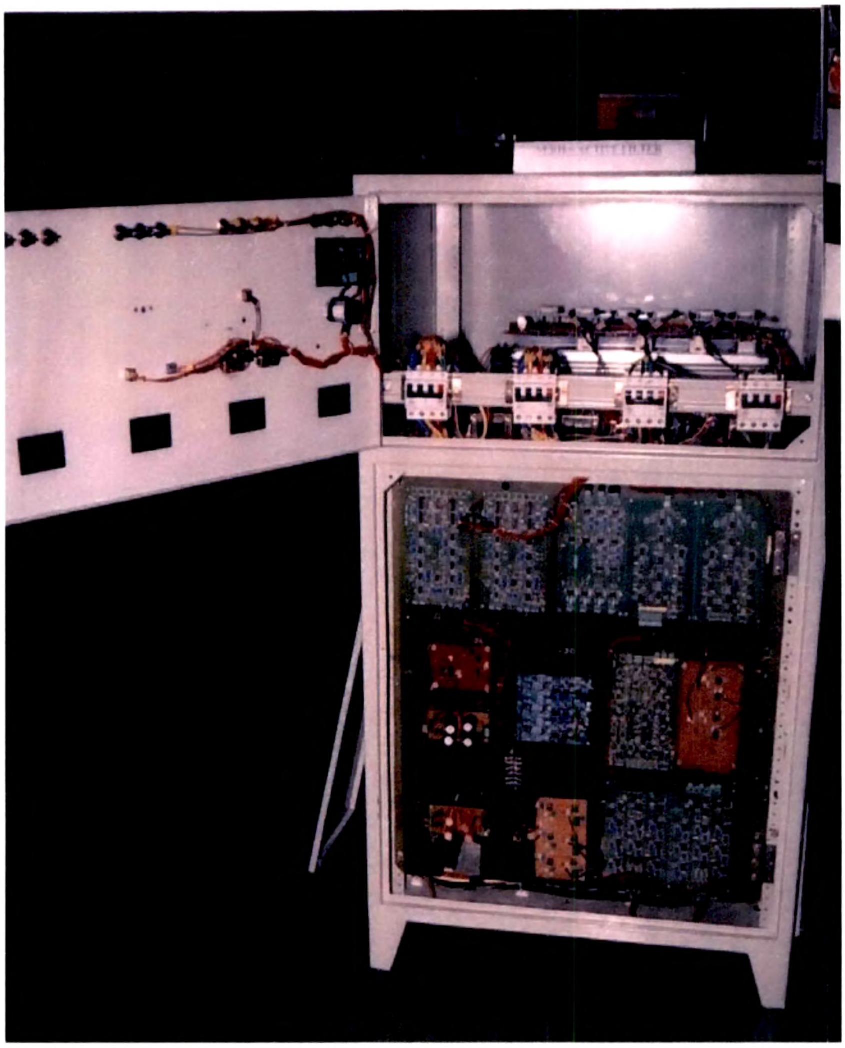


Figure 3.11-3: Photograph of components on the front side of the panel

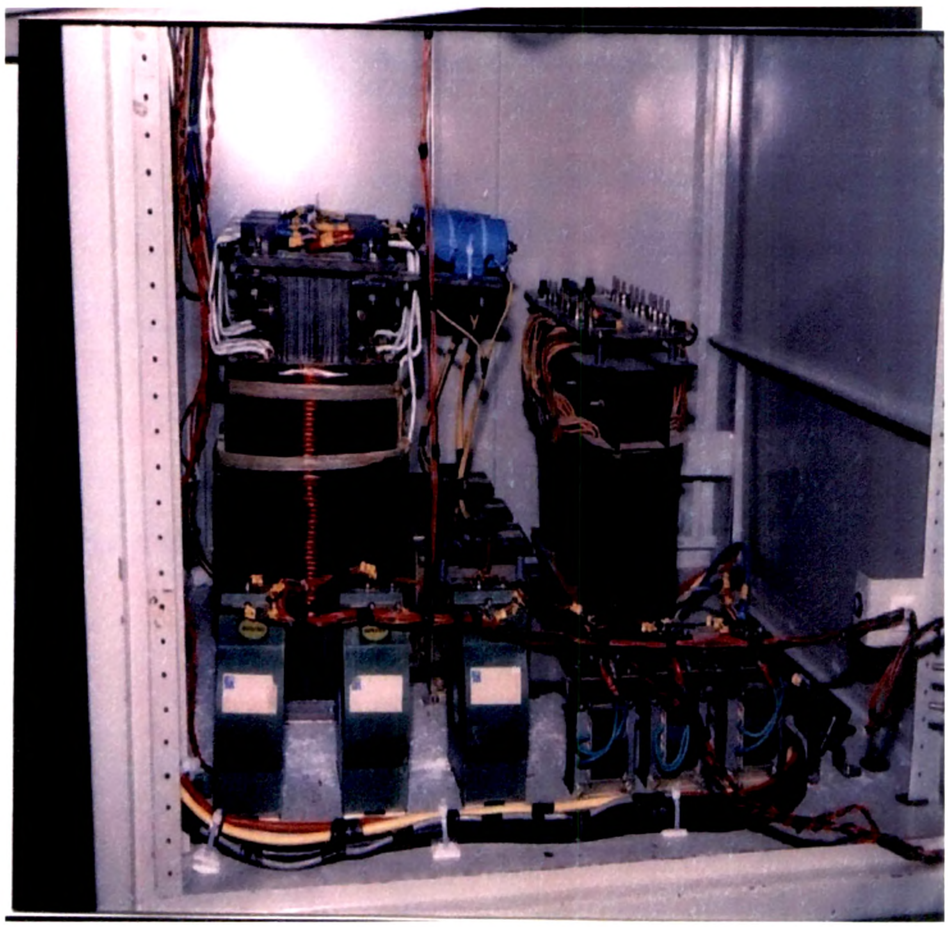


Figure 3.11-4: Photograph of the components mounted on bottom flange

3.12 RESULT

The simulations as well as experimental results are given here.

3.12.1 SIMULATION RESULTS

A complete model of the series active filter for 5 amps, 350V DC with input voltage of 440V and 5-amp load was implemented using MATLAB (SIMULINK) and the most important results will be presented to compare actual and simulated results. The fundamental frequency of the system is 50 Hz. The wave-form of source voltage, source voltage, load current and compensating voltage is observed for a-phase, b-phase, & c-phase using scope available in the simulation tools. These results shows that series active filter inject compensating voltage in series with load such that total harmonic voltage of the load becomes zero.

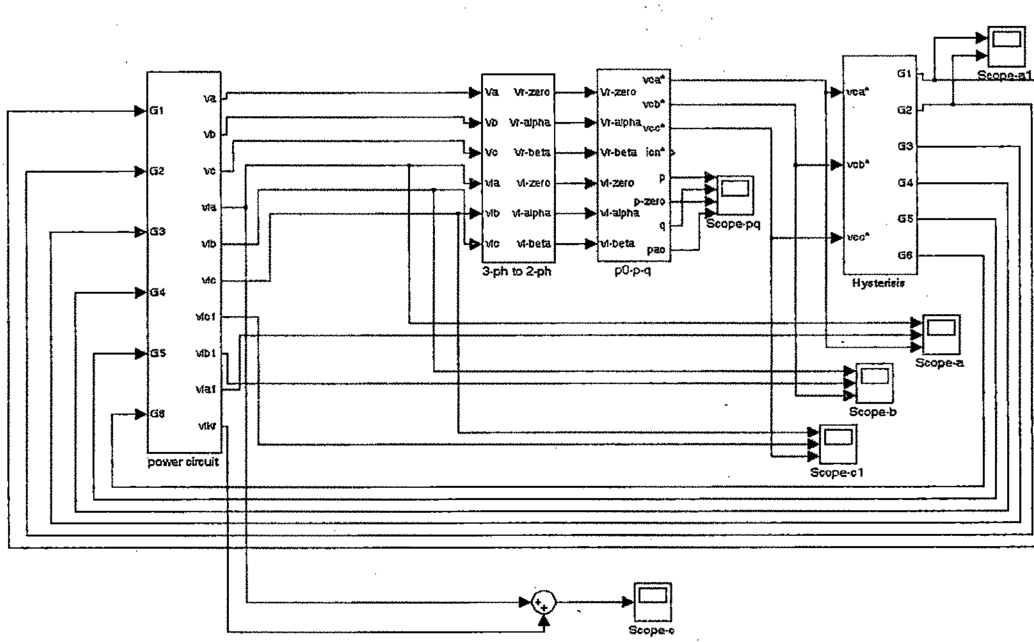


Figure 3.12.1-1: Simulation Block Diagram Used For Series Active Filter Simulation

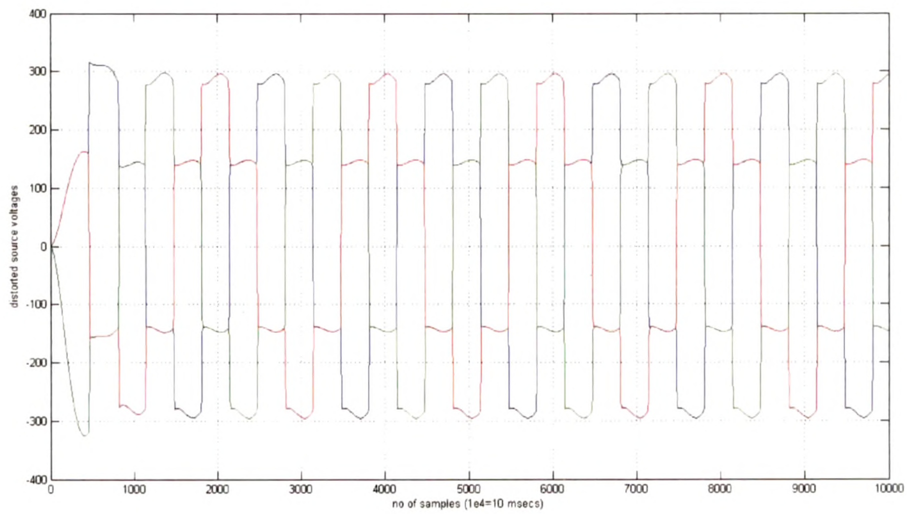


Figure 3.12.1-2: Distorted waveform at load bus before compensation

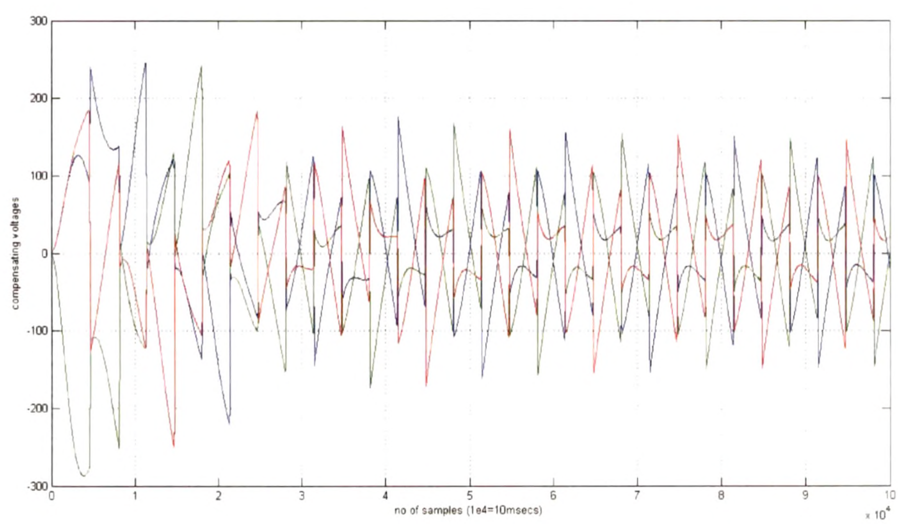


Figure 3.12.1-3: compensation waveform of series active filter to compensate the distortion in voltage

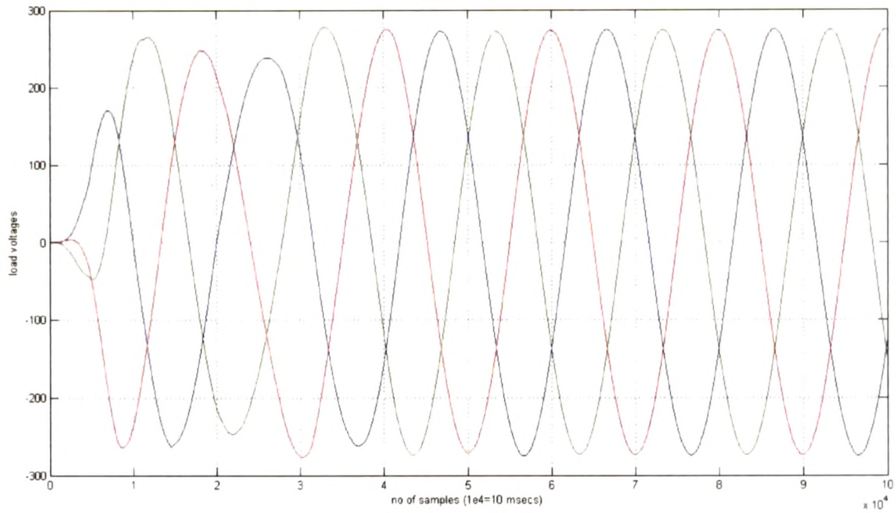


Figure 3.12.1-4: waveform at load bus after compensation through series active filter

In ideal case the capacitor voltage should remain constant but in practice every components have some losses hence DC capacitor voltage reduces. So DC Bus voltage needs to be controlled. In this scheme DC bus voltage are not controlled through inverter. To control the DC bus voltage a separate isolated rectifier having output DC voltage of 800 volts is connected in parallel to DC bus capacitor. Input of rectifier is having step up transformer with step up ratio of 1.3. The input of rectifier transformer is connected at input of series active filter as shown in Figure 3.10-1

3.12.2 EXPERIMENTAL RESULTS

Figure 3.10-1 shows the complete experimental setup of three-phase series active filter module. Three inductors of 25 mH each in series with three-phase diode rectifier system with resistive load are used as harmonic affected source for experimental purpose.

The initial testing results indicate that there is decrease in RMS value of the load voltage due to harmonic elimination from the load voltage after filtration. To avoid this decrement in the output load voltage, some percentage of the fundamental voltage is added along with harmonic compensation voltage at the control level.

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

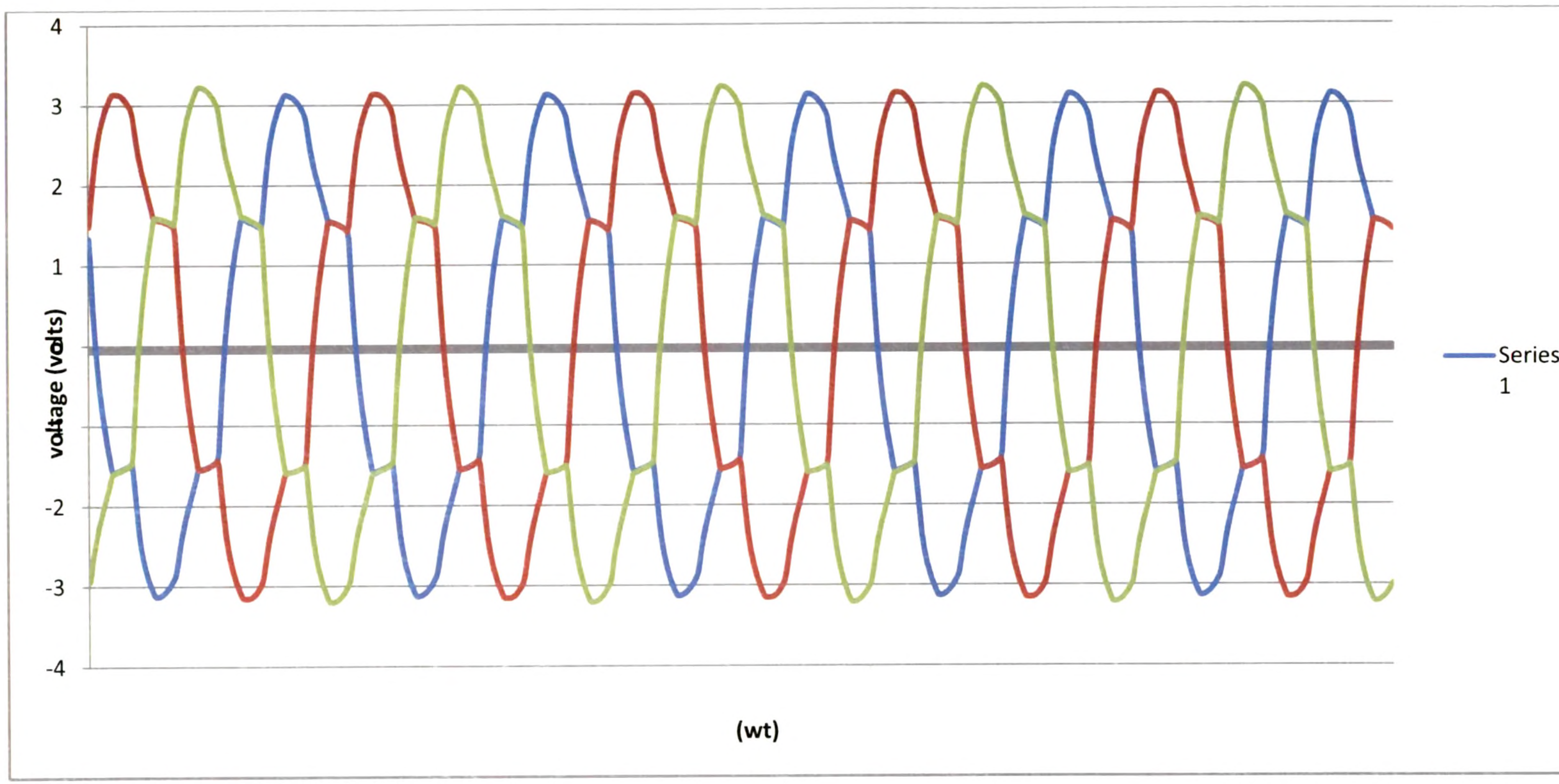


Fig 3.12.2-1 Load voltage waveform for r-y-b phase (without compensation)

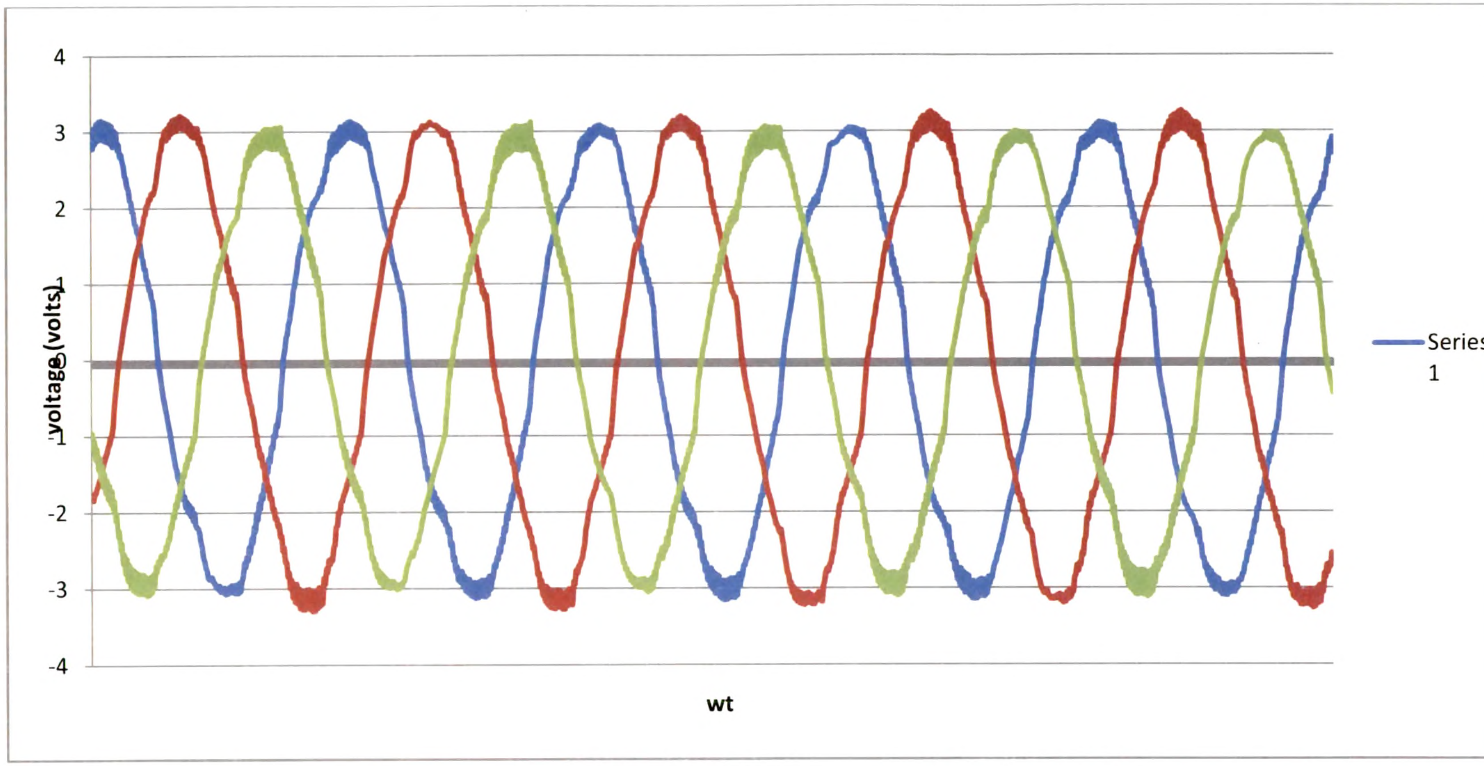


Fig 3.12.2-2 Load voltage waveform for r-y-b phase (with compensation)

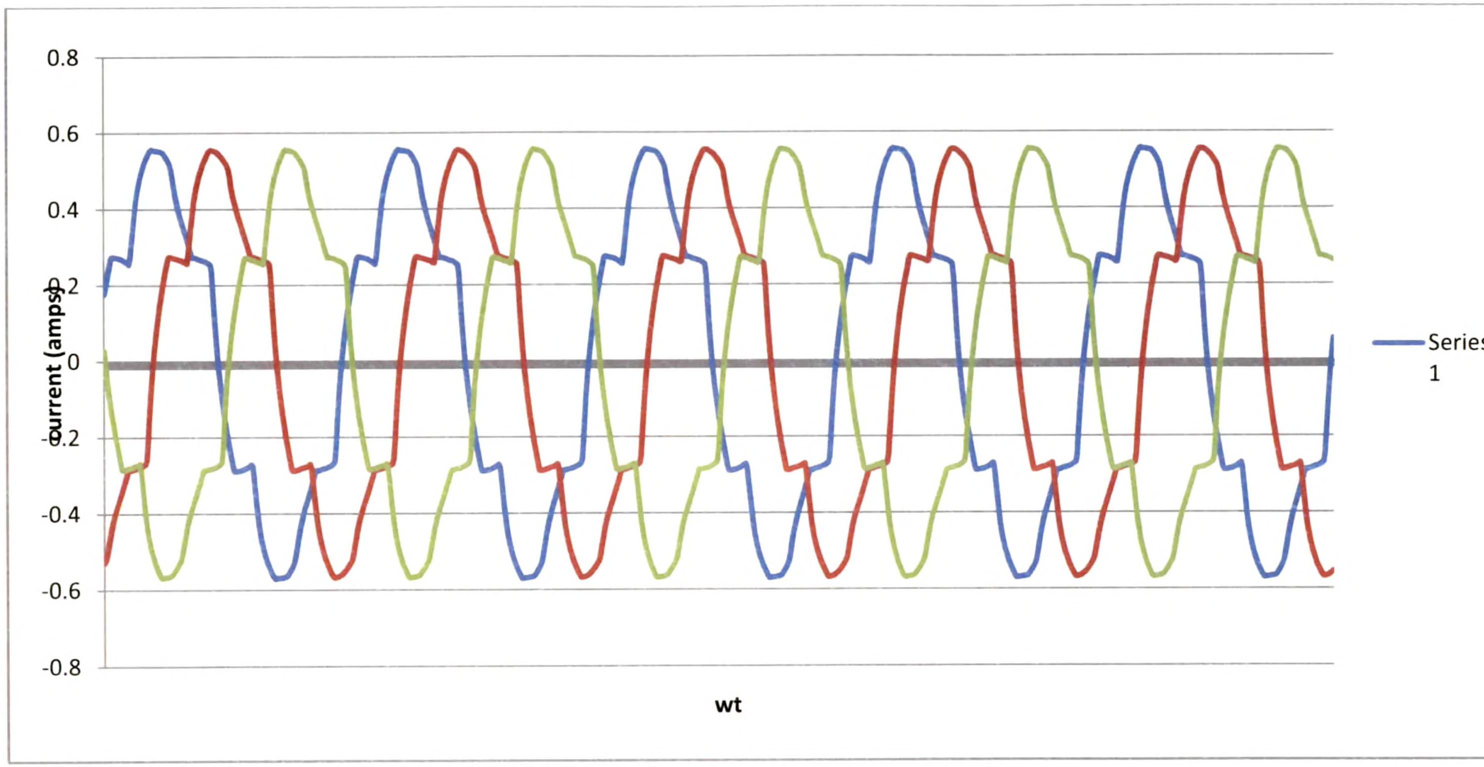


Fig 3.12.2-3 Load current waveform for r-y-b-phase (without compensation)

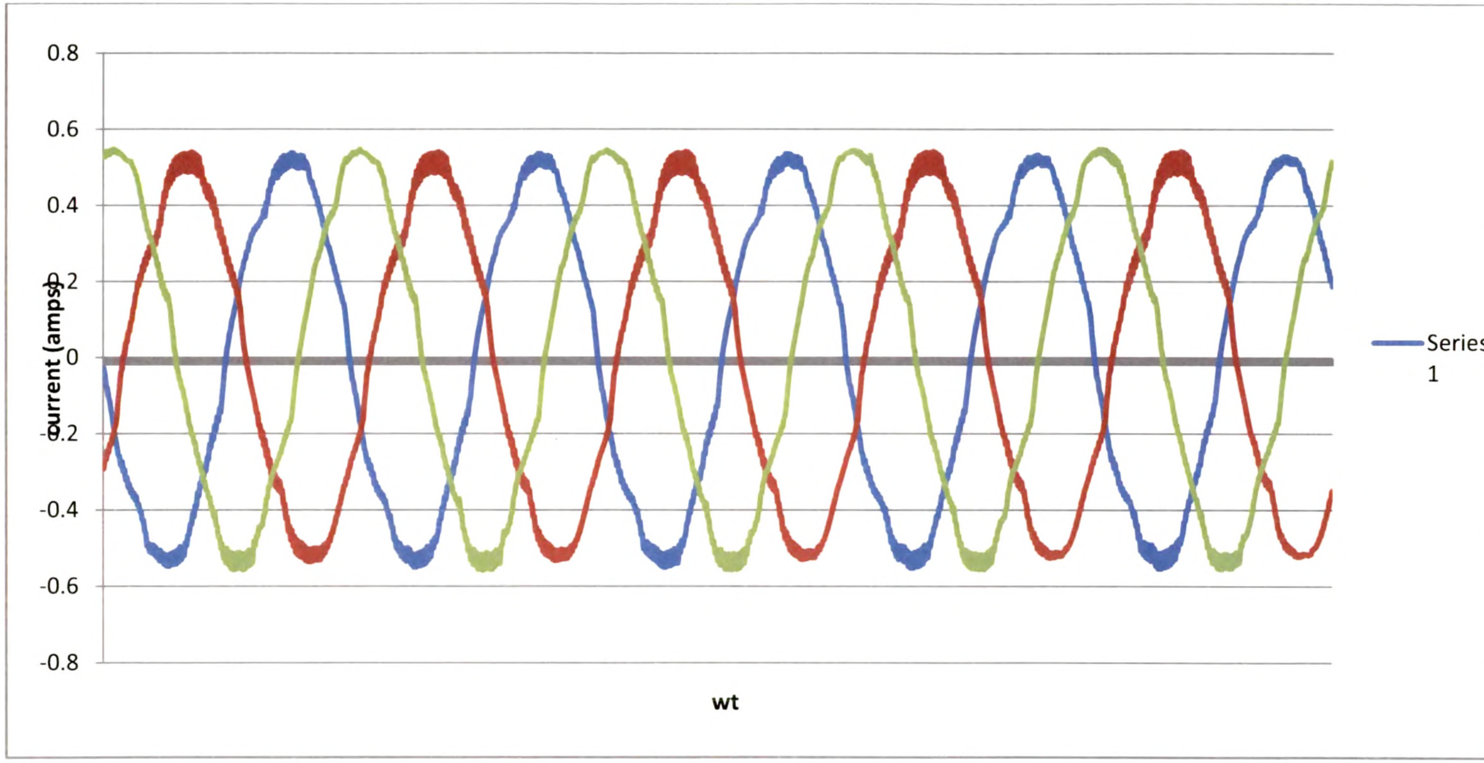


Fig 3.12.2-4 Load current waveform for r-y-b-phase (with compensation)

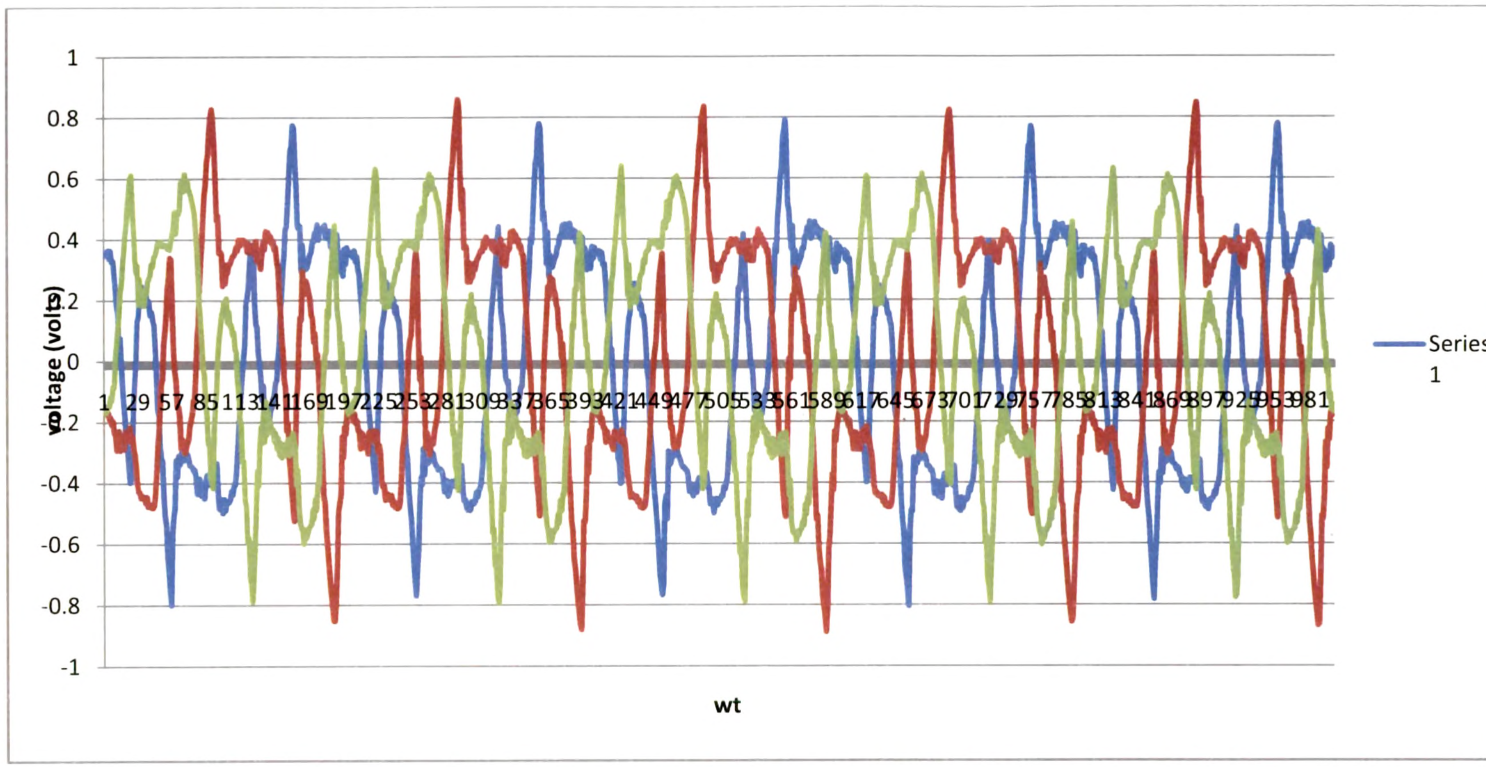


Fig 3.12.2-5 Transformer output voltage waveform for r-y-b phase (with fundamental added)

3.12.3 ANALYSIS OF RESULTS

Table 3.12.3-1: Harmonic analysis of the load voltages with series active filter Bypass

Harm no.	Voltage magnitude VRN Volts	Voltage VRN %	Voltage magnitude VYN Volts	Voltage VYN %	Voltage magnitude VBN Volts	Voltage VBN %
	208.00	100.00	212.00	100.00	206.00	100.00
2	0.40	0.19	0.40	0.19	0.10	0.05
3	0.80	0.38	0.40	0.19	1.00	0.49
4	0.00	0.00	0.00	0.00	0.00	0.00
5	30.00	14.42	30.00	14.15	29.60	14.37
6	0.00	0.00	0.00	0.00	0.00	0.00
7	16.00	7.69	16.00	7.55	15.70	7.62
8	0.00	0.00	0.00	0.00	0.00	0.00
9	8.00	3.85	0.80	0.38	0.30	0.15
10	0.00	0.00	0.00	0.00	0.00	0.00
11	4.80	2.31	5.20	2.45	5.20	2.52
12	0.00	0.00	0.00	0.00	0.00	0.00
13	3.60	1.73	3.60	1.70	3.60	1.75
14	0.00	0.00	0.00	0.00	0.00	0.00
15	0.40	0.19	0.00	0.00	0.10	0.05
16	0.00	0.00	0.00	0.00	0.00	0.00
17	3.20	1.54	3.20	1.51	3.30	1.60
18	0.00	0.00	0.00	0.00	0.00	0.00
19	2.80	1.35	2.80	1.32	2.60	1.26
20	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.10	0.05
22	0.00	0.00	0.00	0.00	0.00	0.00
23	0.80	0.38	0.80	0.38	1.00	0.49
24	0.00	0.00	0.00	0.00	0.00	0.00
25	0.80	0.38	0.80	0.38	0.90	0.44
VOLT/THD	211.05	17.18	214.85	16.45	208.85	16.70

Table 3.12.3-2 : Harmonic analysis of load voltages with series active filter in operation

Harm no.	Voltage magnitude VRN Volts	Voltage VRN %	Voltage magnitude VYN Volts	Voltage VYN %	Voltage magnitude VBN Volts	Voltage VBN %
1	221.60	100.00	208.80	100.00	217.30	100.00
2	3.20	1.44	2.00	0.96	2.20	1.01
3	2.80	1.26	5.20	2.49	9.60	4.42
4	1.60	0.72	1.20	0.57	0.90	0.41
5	4.40	1.99	6.40	3.07	6.40	2.95
6	1.20	0.54	1.20	0.57	0.50	0.23
7	6.00	2.71	5.20	2.49	4.90	2.25
8	0.40	0.18	0.80	0.38	0.70	0.32
9	2.40	1.08	0.80	0.38	1.70	0.78
10	0.80	0.36	0.80	1.34	0.80	0.37
11	2.00	0.90	2.80	0.00	1.90	0.87
12	1.20	0.54	0.00	0.57	0.30	0.14
13	0.80	0.36	1.20	0.38	1.50	0.69
14	0.80	0.36	0.80	0.38	0.50	0.23
15	0.80	0.36	0.80	0.00	1.20	0.55
16	0.00	0.00	0.00	0.77	0.20	0.09
17	1.60	0.72	1.60	0.19	1.20	0.55
18	0.80	0.36	0.40	0.38	0.20	0.09
19	0.80	0.36	0.80	0.19	0.70	0.32
20	0.40	0.18	0.40	0.00	0.00	0.00
21	0.40	0.18	0.00	0.19	0.60	0.28
22	0.40	0.18	0.40	0.19	0.30	0.14
23	0.40	0.18	0.40	0.00	0.20	0.09
24	0.00	0.00	0.00	0.00	0.20	0.09
25	0.40	0.18	0.00	0.00	0.20	0.09
VOLT/THD	221.82	4.42	209.08	5.19	217.71	6.13

Table 3.12.3-3 : Harmonic analysis of the load currents with series active filter Bypass

Harm no.	Current magnitude IRN Amps	Current IRN %	Current magnitude IYN Amps	Current IYN %	Current magnitude IBN Amps	Current IBN %
1	3.74	100.00	3.69	100.00	3.70	100.00
2	0.02	0.53	0.01	0.27	0.03	0.81
3	0.02	0.53	0.02	0.54	0.02	0.54
4	0.01	0.27	0.01	0.27	0.02	0.54
5	0.50	13.37	0.52	14.09	0.49	13.24
6	0.01	0.27	0.02	0.54	0.02	0.54
7	0.28	7.49	0.26	7.05	0.24	6.49
8	0.01	0.27	0.00	0.00	0.01	0.27
9	0.02	0.53	0.02	0.54	0.01	0.27
10	0.01	0.27	0.00	0.00	0.00	0.00
11	0.08	2.14	0.09	2.44	0.09	2.43
12	0.01	0.27	0.01	0.27	0.01	0.27
13	0.06	1.60	0.06	1.63	0.05	1.35
14	0.00	0.00	0.00	0.00	0.01	0.27
15	0.01	0.27	0.00	0.00	0.01	0.27
16	0.01	0.27	0.00	0.00	0.01	0.27
17	0.04	1.07	0.05	1.36	0.03	0.81
18	0.00	0.00	0.01	0.27	0.01	0.27
19	0.04	1.07	0.03	0.81	0.02	0.54
20	0.00	0.00	0.00	0.00	0.01	0.27
21	0.00	0.00	0.00	0.00	0.01	0.27
22	0.00	0.00	0.00	0.00	0.00	0.00
23	0.01	0.27	0.01	0.27	0.01	0.27
24	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.01	0.27	0.01	0.27
VOLT/ THD	3.74	15.67	3.74	16.14	3.74	15.12

Table 3.12.3-4 : Harmonic analysis of the load currents with series active filter in operation

Harm no.	Current magnitude IRN Amps	Current IRN %	Current magnitude IYN Amps	Current IYN %	Current magnitude IBN Amps	Current IBN %
1	3.78	100.00	3.66	100.00	3.80	100.00
2	0.06	1.59	0.02	0.55	0.04	1.05
3	0.17	4.50	0.10	2.73	0.03	0.79
4	0.03	0.79	0.04	1.09	0.03	0.79
5	0.11	2.91	0.11	3.01	0.09	2.37
6	0.03	0.79	0.01	0.27	0.02	0.53
7	0.08	2.12	0.09	2.46	0.10	2.63
8	0.01	0.26	0.01	0.27	0.00	0.00
9	0.03	0.79	0.02	0.55	0.04	1.05
10	0.00	0.00	0.01	0.27	0.01	0.26
11	0.03	0.79	0.05	1.37	0.04	1.05
12	0.01	0.26	0.01	0.27	0.02	0.53
13	0.02	0.53	0.02	0.55	0.02	0.53
14	0.01	0.26	0.01	0.27	0.02	0.53
15	0.01	0.26	0.01	0.27	0.02	0.53
16	0.00	0.00	0.01	0.27	0.00	0.00
17	0.01	0.26	0.02	0.55	0.04	1.05
18	0.00	0.00	0.01	0.27	0.01	0.26
19	0.01	0.26	0.01	0.27	0.01	0.26
20	0.00	0.00	0.00	0.00	0.01	0.26
21	0.00	0.00	0.00	0.00	0.01	0.26
22	0.00	0.00	0.00	0.00	0.01	0.26
23	0.00	0.00	0.00	0.00	0.01	0.26
24	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.01	0.26
VOLT/THD	3.79	6.24	3.67	5.24	3.80	4.49

Table 3.12.3-5 : Harmonic analysis of the output of the inverter

Harm no.	Voltage magnitude VRN Volts	Voltage VRN %	Voltage magnitude VYN Volts	Voltage VYN %	Voltage magnitude VBN Volts	Voltage VBN %
1	28.80	100.00	28.40	100.00	30.30	100.00
2	4.40	15.28	2.40	8.45	2.00	6.60
3	4.00	13.89	4.40	15.49	3.00	9.90
4	2.00	6.94	2.00	7.04	1.50	4.95
5	16.40	56.94	15.60	54.93	13.70	45.21
6	0.80	2.78	0.40	1.41	0.40	1.32
7	13.60	47.22	11.20	39.44	11.60	38.28
8	0.80	2.78	0.80	2.82	0.40	1.32
9	0.40	1.39	1.20	4.23	0.20	0.66
10	0.80	2.78	0.40	1.41	0.50	1.65
11	4.40	15.28	3.60	12.68	3.50	11.55
12	0.00	0.00	0.00	0.00	0.10	0.33
13	2.40	8.33	2.00	7.04	2.50	8.25
14	0.80	2.78	0.80	2.82	0.60	1.98
15	0.40	1.39	0.40	1.41	0.10	0.33
16	0.40	1.39	0.00	0.00	0.40	1.32
17	1.20	4.17	1.20	4.23	1.20	3.96
18	0.00	0.00	0.00	0.00	0.20	0.66
19	1.20	4.17	1.20	4.23	1.30	4.29
20	0.40	1.39	0.40	1.41	0.30	0.99
21	0.40	1.39	0.00	0.00	0.20	0.66
22	0.40	1.39	0.40	1.41	0.20	0.66
23	1.20	4.17	0.80	2.82	1.20	3.96
24	0.00	0.00	0.00	0.00	0.10	0.33
25	0.80	2.78	0.80	2.82	0.80	2.64
VOLT/THD	36.83	79.70	35.06	72.38	35.79	62.84

3.13 CONCLUSION

This whole control system is realized with analog approach. The reason behind for selecting analog approach is to make control faster. Here in this system various high speed analog IC's are used to make system faster. If this system is realized in digital way it takes lot of time to work out calculation, particularly matrix calculation. If load is like arc furnace in which load current is changing number of times in one cycle, it is very difficult to generate corresponding compensation currents for particular harmonic current. For digital approach, the possible realization is made by using either 16 bit or more processor or by using DSP. This can be taken as future extension of this project. This approach is very useful for harmonic elimination in distribution system as now a day most of the home appliance are equipped with modern sophisticated power electronic control which affect the performance of the nearby equipment connected in the same bus. Also same circuit with small modification can be used as a STATCOM, Static Reactive Power Compensator, for reactive power compensation. For high voltage application hybrid active power filter is used for harmonic elimination, which can be also taken as future project.

With this novel approach on line & instantaneous voltage harmonics detection is possible which is simple and easily implementable. The harmonics in the load bus is reduced from 17 % to 6% at rated voltage of 415 volts & load of 10 Amp. Experimental waveform taken at site along with FFT are shown in section 3.13.1

3.13.1 EXPERIMENTAL WAVEFORMS TAKEN AT SITE ALONG WITH FFT

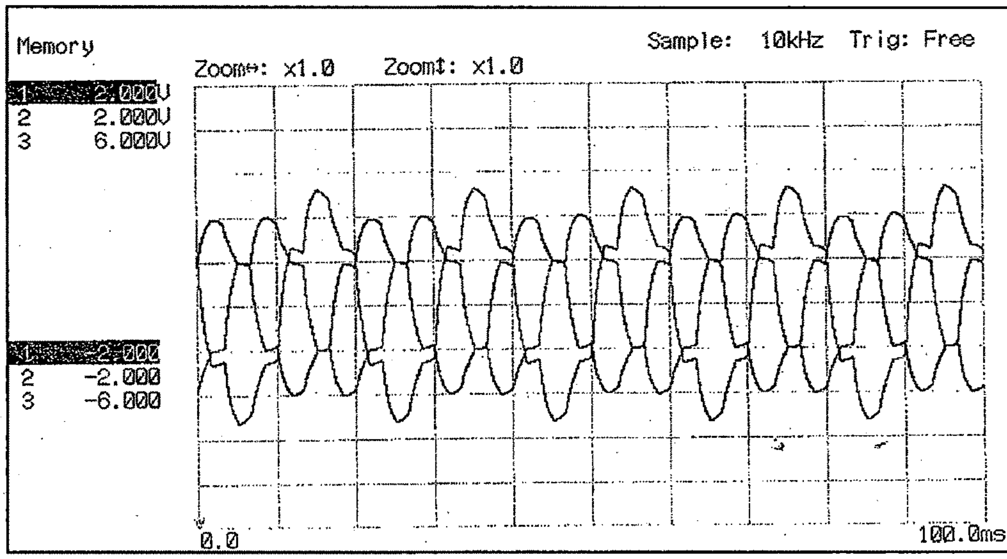


Figure 3.13.1-1 Load voltage waveform for R-Y-B phase (without compensation)

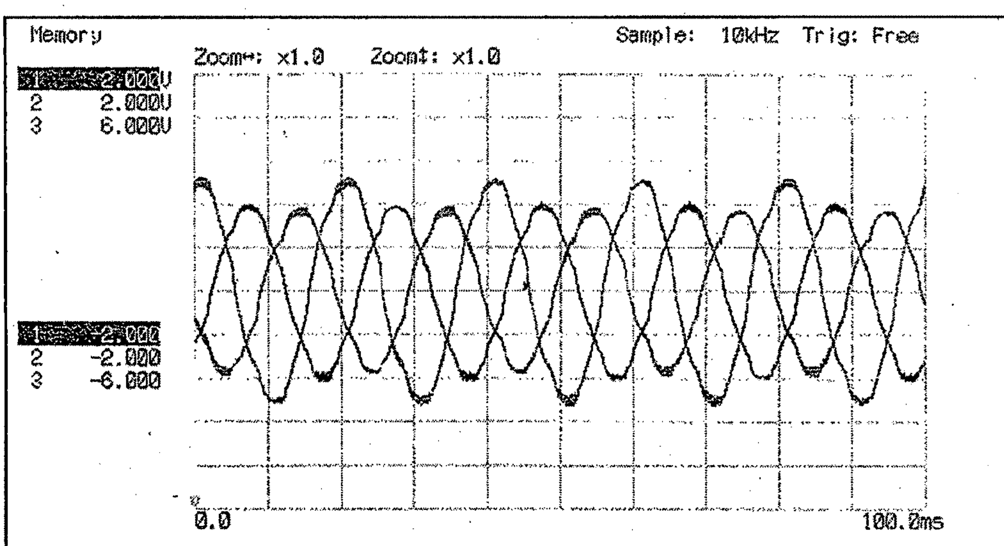
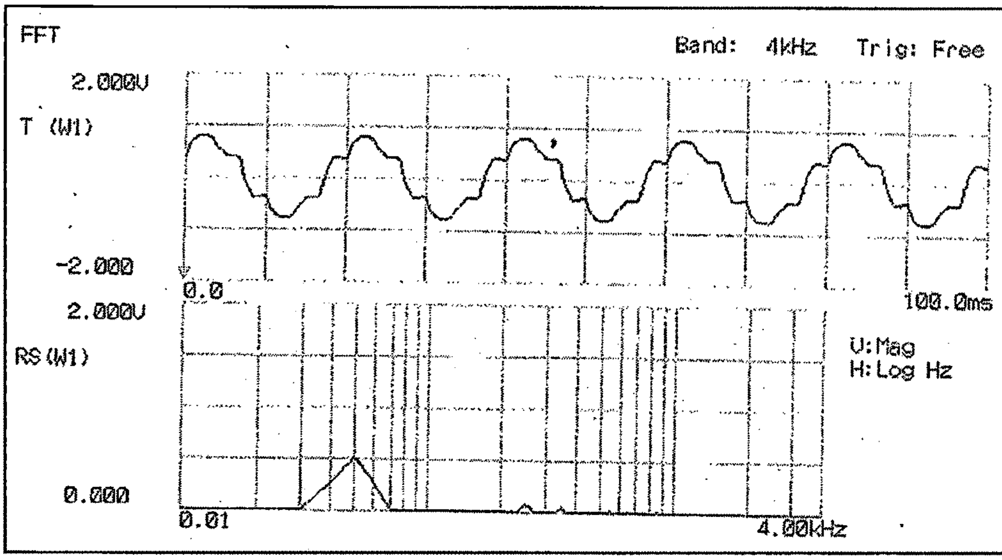
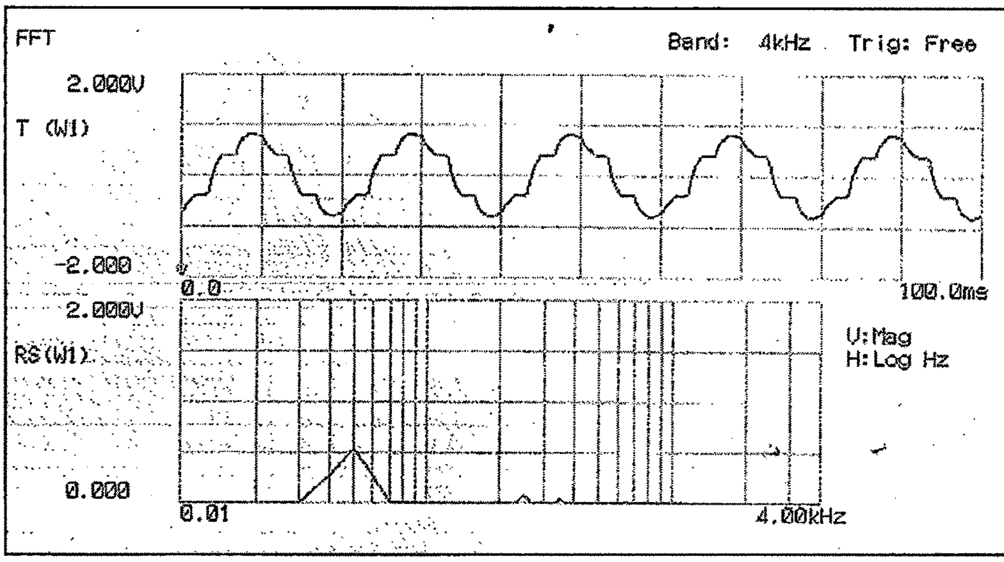


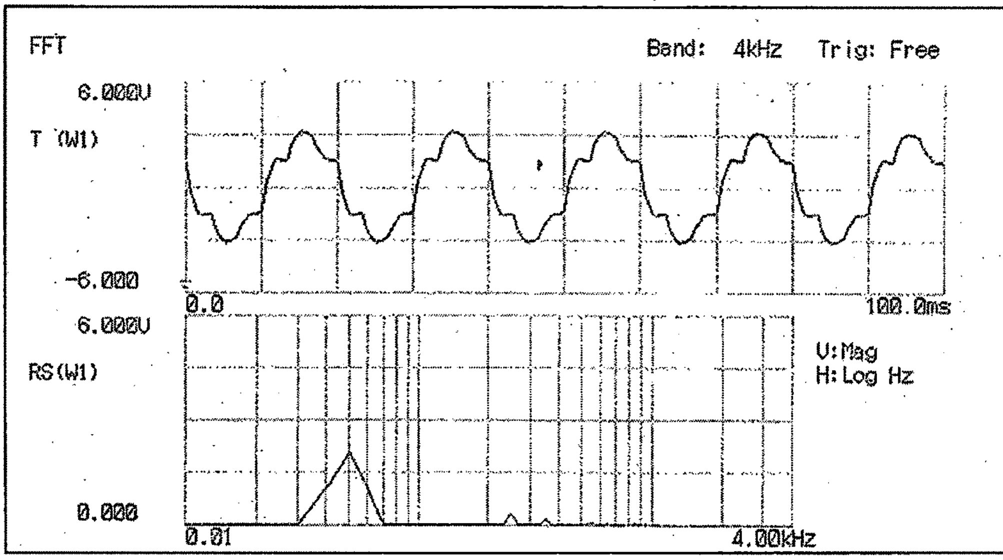
Figure 3.13.1-2 Load voltage waveform for R-Y-B phase (with compensation)



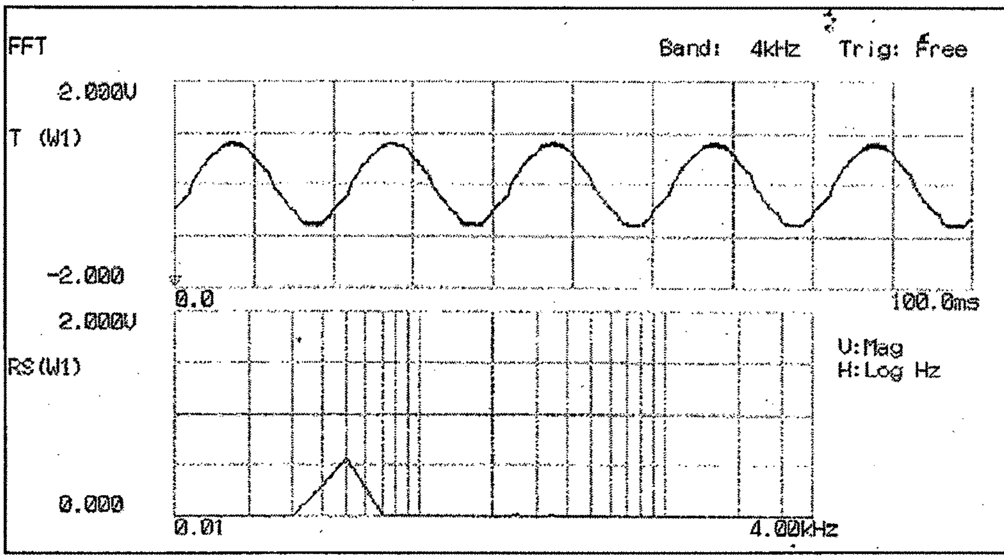
Harm No.	Voltage V in %	Voltage V In Volts
1	100.00	208.00
2	0.19	0.40
3	0.38	0.80
4	0.00	0.00
5	14.42	30.00
6	0.00	0.00
7	7.69	16.00
8	0.00	0.00
9	0.38	0.80
10	0.00	0.00
11	2.31	4.80
12	0.00	0.00
13	1.73	3.60
14	0.00	0.00
15	0.19	0.40
16	0.00	0.00
17	1.54	3.20
18	0.00	0.00
19	1.35	2.80
20	0.00	0.00
21	0.00	0.00
22	0.00	0.00
23	0.38	0.80
24	0.00	0.00
25	0.38	0.80
THD %	16.74	
Parameter measured	210.90	



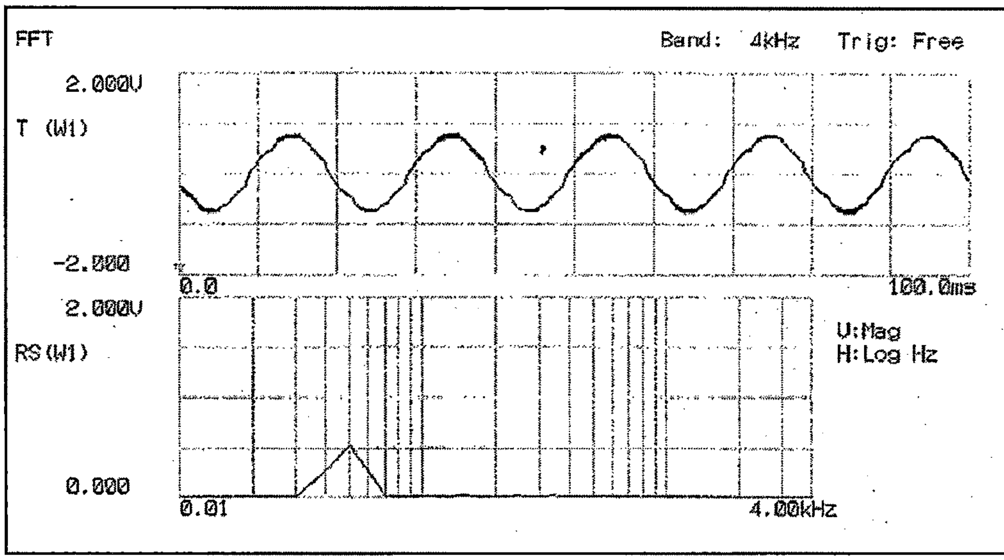
Harm No.	Voltage V in %	Voltage V In Volts
1	100.00	212.00
2	0.19	0.40
3	0.19	0.40
4	0.00	0.00
5	14.15	30.00
6	0.00	0.00
7	7.55	16.00
8	0.00	0.00
9	0.38	0.80
10	0.00	0.00
11	2.45	5.20
12	0.00	0.00
13	1.70	3.60
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	1.51	3.20
18	0.00	0.00
19	1.32	2.80
20	0.00	0.00
21	0.00	0.00
22	0.00	0.00
23	0.38	0.80
24	0.00	0.00
25	0.38	0.80
THD %	16.45	
Parameter measured	214.85	



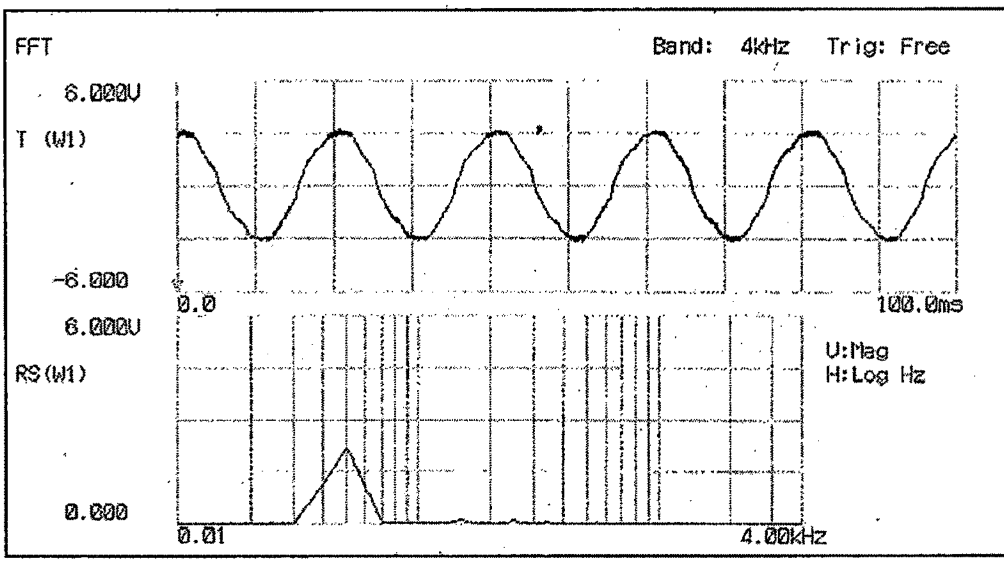
Harm No.	Voltage V in %	Voltage V In Volts
1	100.00	206.00
2	0.05	0.10
3	0.49	1.00
4	0.00	0.00
5	14.37	29.60
6	0.00	0.00
7	7.62	15.70
8	0.00	0.00
9	0.15	0.30
10	0.00	0.00
11	2.52	5.20
12	0.00	0.00
13	1.80	3.70
14	0.00	0.00
15	0.05	0.10
16	0.00	0.00
17	1.60	3.30
18	0.00	0.00
19	1.26	2.60
20	0.00	0.00
21	0.05	0.10
22	0.00	0.00
23	0.49	1.00
24	0.00	0.00
25	0.44	0.90
THD %	16.70	
Parameter measured	208.85	



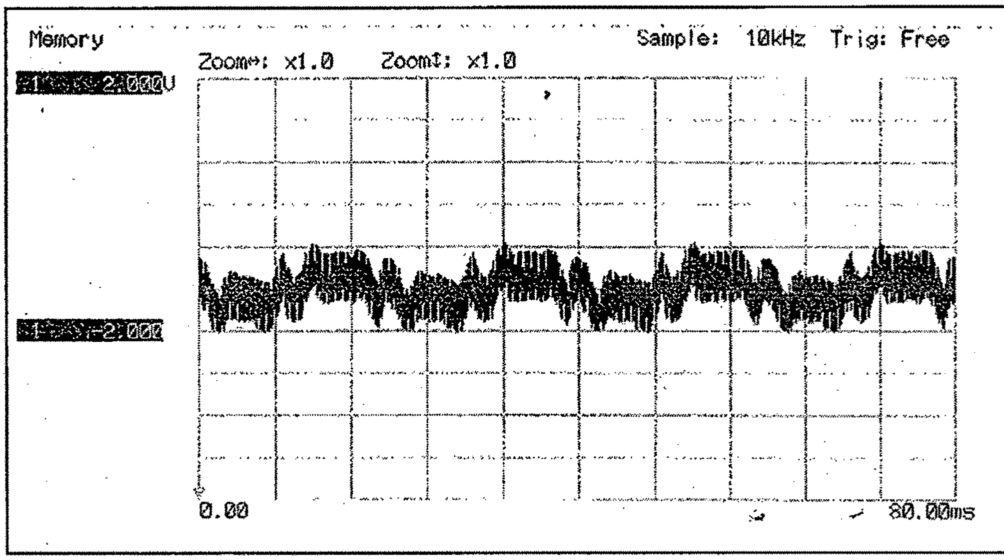
Harm No.	Voltage V in %	Voltage V In Volts
1	100.00	221.60
2	0.90	2.00
3	0.90	2.00
4	0.90	2.00
5	1.99	4.40
6	0.72	1.60
7	2.89	6.40
8	0.18	0.40
9	0.90	2.00
10	0.18	0.40
11	0.90	2.00
12	0.54	1.20
13	0.36	0.80
14	0.36	0.80
15	0.54	1.20
16	0.00	0.00
17	0.90	2.00
18	0.36	0.80
19	0.36	0.80
20	0.18	0.40
21	0.18	0.40
22	0.18	0.40
23	0.18	0.40
24	0.00	0.00
25	0.18	0.40
THD %	4.36	
Parameter measured	221.81	



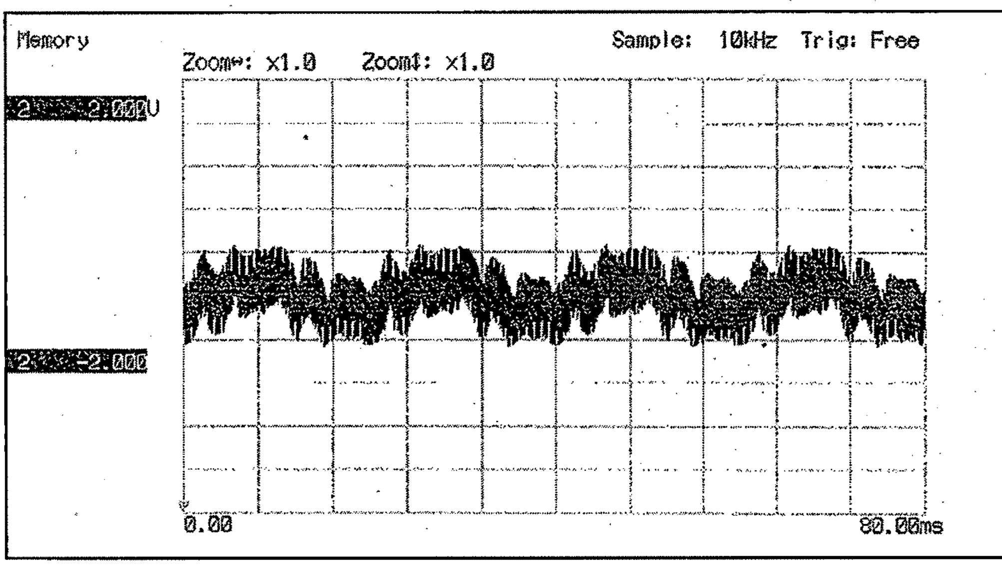
Harm No.	Voltage V in %	Voltage V In Volts
1	100.00	208.40
2	0.38	0.80
3	2.69	5.60
4	0.96	2.00
5	3.07	6.40
6	0.38	0.80
7	2.50	5.20
8	0.19	0.40
9	0.58	1.20
10	0.38	0.80
11	1.54	3.20
12	0.19	0.40
13	0.58	1.20
14	0.38	0.80
15	0.38	0.80
16	0.19	0.40
17	0.96	2.00
18	1.92	4.00
19	0.58	1.20
20	0.19	0.40
21	0.00	0.00
22	0.19	0.40
23	0.19	0.40
24	0.00	0.00
25	0.19	0.40
THD %	5.72	
Parameter measured	208.74	



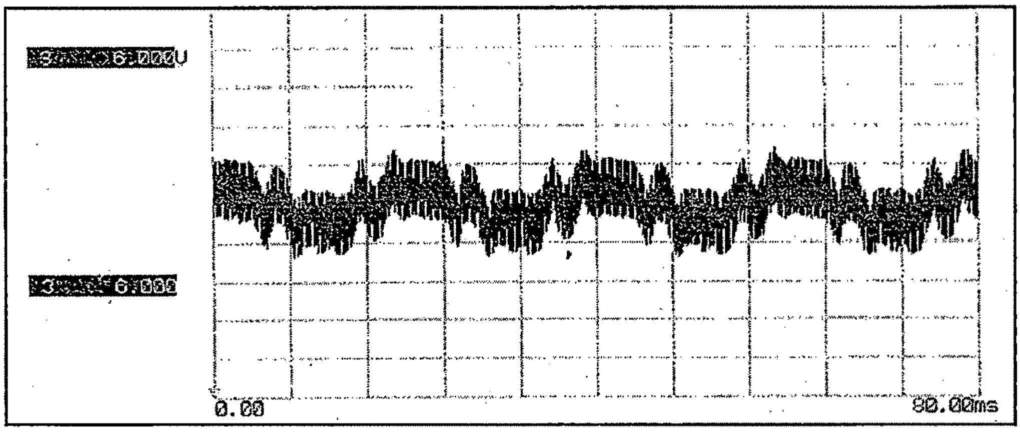
Harm No.	Voltage V in %	Voltage V In Volts
1	100.00	217.90
2	0.83	1.80
3	4.54	9.90
4	0.32	0.70
5	2.89	6.30
6	0.18	0.40
7	2.34	5.10
8	0.37	0.80
9	0.73	1.60
10	0.37	0.80
11	0.96	2.10
12	0.09	0.20
13	0.78	1.70
14	0.23	0.50
15	0.64	1.40
16	0.05	0.10
17	0.64	1.40
18	0.09	0.20
19	0.46	1.00
20	0.00	0.00
21	0.37	0.80
22	0.14	0.30
23	0.14	0.30
24	0.09	0.20
25	0.09	0.20
THD %	6.24	
Parameter measured	218.32	



Harm No.	Voltage V in %	Voltage V In Volts
1	100.00	2.00
2	20.00	0.40
3	40.00	0.80
4	0.00	0.00
5	0.00	0.00
6	20.00	0.40
7	20.00	0.40
8	40.00	0.80
9	80.00	1.60
10	1780.00	35.60
11	40.00	0.80
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00
19	80.00	1.60
20	400.00	8.00
21	20.00	0.40
22	20.00	0.40
23	0.00	0.00
24	0.00	0.00
25	0.00	0.00
THD %	1829.75	
Parameter measured	36.65	



Harm No.	Voltage V in %	Voltage V In Volts
1	100.00	4.40
2	36.36	1.60
3	9.09	0.40
4	9.09	0.40
5	9.09	0.40
6	9.09	0.40
7	9.09	0.40
8	18.18	0.80
9	54.55	2.40
10	1227.27	54.00
11	9.09	0.40
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	9.09	0.40
19	45.45	2.00
20	200.00	8.80
21	27.27	1.20
22	9.09	0.40
23	0.00	0.00
24	0.00	0.00
25	0.00	0.00
THD %	1246.71	
Parameter measured	55.03	



Harm No.	Voltage V in %	Voltage V In Volts
1	100.00	4.30
2	34.88	1.50
3	6.98	0.30
4	4.65	0.20
5	13.95	0.60
6	9.30	0.40
7	11.63	0.50
8	11.63	0.50
9	39.53	1.70
10	746.51	32.10
11	6.98	0.30
12	4.65	0.20
13	2.33	0.10
14	4.65	0.20
15	0.00	0.00
16	4.65	0.20
17	0.00	0.00
18	2.33	0.10
19	48.84	2.10
20	348.84	15.00
21	9.30	0.40
22	6.98	0.30
23	0.00	0.00
24	2.33	0.10
25	2.33	0.10
THD %	827.66	
Parameter measured	35.85	