Chapter 3

Active Power Filters: Applications and Design

A survey of current trends in applications and design of Active power filters for control circuit as well as power circuit is described in the chapter. Implementation of embedded controller for APF is discussed using different DSP processors

3.1 Harmonic Compensation in Power Systems

Section describes a combined system of a passive filter and a small-rating active filter, both connected in series with each other, which results in a great reduction of the required rating of the APF and eliminates the limitations of the passive filter, leading to a practical and economical system. Experimental results obtained from a prototype model [12] verify the theory developed.

With remarkable progress in the speed and capacity of semiconductors switching devices such as GTO thyristors and IGBTs, active filters consisting of voltage- or current-source PWM inverters have been studied and put into practical use [1]-[6] . It is difficult to construct a large-rated current source and initial costs and running costs are high with a rapid current response. A few approaches to rating reduction in active filters have 'been proposed on the basis of a combination of active filters and passive elements such as capacitors and reactors [7] - [10].

Fig. 3.1 shows a combination of a series active filter and a shunt passive filter [9], [10]. The APF acts as a "harmonic isolator" between the source and the load.

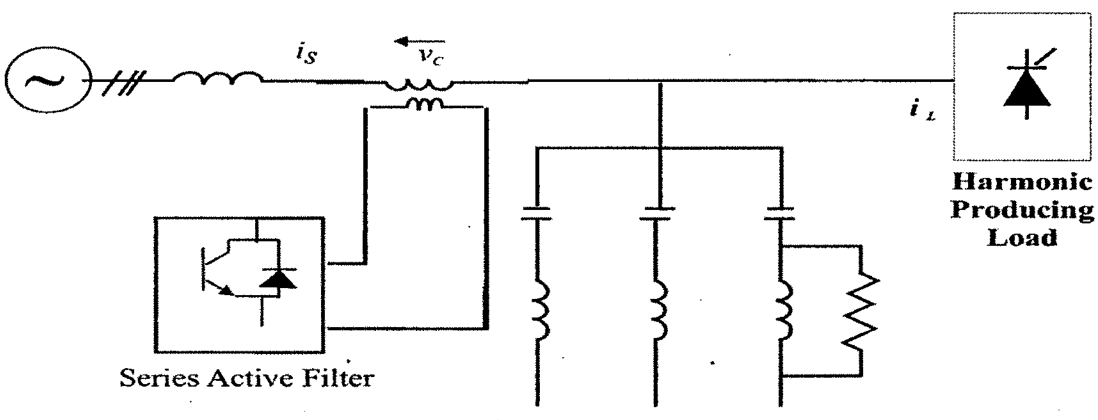

Fig 3.1: Combination of Series Active and Passive Filters

[12] Presents a combined system of a passive filter and a small-rated active filter, which are connected in series with each other.

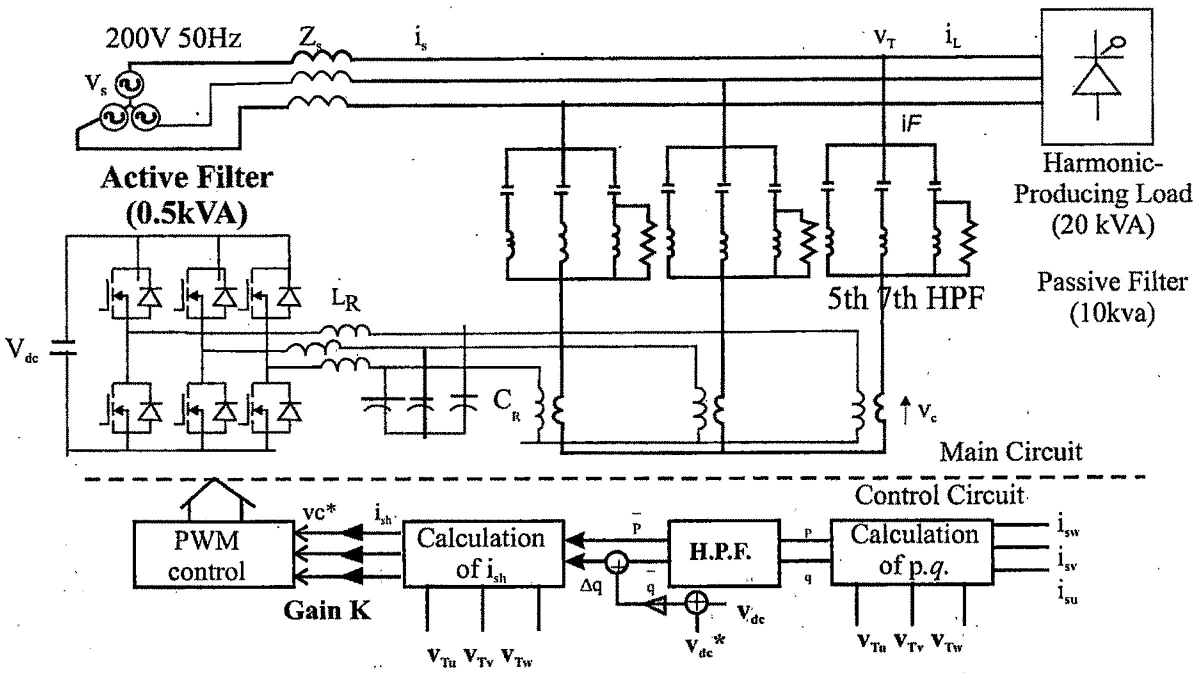

Fig 3.2 Hybrid Series Configuration

The system shown in the Fig 3.2 solves the problems inherent in the passive filter with the active filter having much smaller rating than for a conventional APF. It consists of an active filter and a passive filter, which are connected in series with each other.

The system is installed in parallel with a harmonic producing load, i.e., a three-phase thyristor bridge converter of rating 20 kVA. The passive filter of rating 10 kVA consists of a fifth- and seventh-tuned LC filter and a high-pass filter. The main circuit of the active filter with a rating of 0.5 kVA is a three-phase voltage-source PWM inverter using six MOSFET's. The PWM inverter has a dc capacitor of 1200 pF. The purpose of a small-rated LC filter *(L_R, C_R)* is to suppress switching ripples generated by the Active filter.

Table 3.1: Circuit Constants

Passive Filter			
5^{th}	L=1.2 mH	C = 340 µF	Q = 14
7^{th}	L=1.2 mH	C = 170 µF	Q = 14
HPF	L=0.26 mH	C = 300 µF	R = 3Ω
Small rated LC Filter			
	L_R= 10 mH	C_R = 0.1 µF	

Table 3.1 shows the constants of the passive filter and the small-rated LC filter used in the following experiment. Three current transformers of turn ratio 1:lO are connected to match the voltage-current rating of the active filter with that of the passive filter.

Three-phase source currents are detected and a source harmonic current in each phase i_s is calculated by applying the *p - q* theory [11]. Terminal voltages and the source currents are transformed from three- to two-phase quantities as per equations 3.1.

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_u \\ e_v \\ e_w \end{bmatrix}$$

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Su} \\ i_{Sv} \\ i_{Sw} \end{bmatrix}. \quad ...3.1$$

The e_u, e_v and e_w, are the fundamentals of the terminal voltages. The instantaneous real power p and the instantaneous imaginary power q are given by relation 3.2.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix}. \quad ...3.2$$

The current flowing through the active filter in Fig. 3.1 is the sum of the leading current of the passive filter and the fundamental of the load current, which does not contain any harmonics. But in Fig. 3.2, the harmonic current produced by the load and the leading current of the passive filter flow through the active filter. The harmonic current causes a harmonic voltage drop across the matching transformer. On the other hand, it is easy to supply electric power corresponding to the switching and conducting loss of the active filter to the dc capacitor in Fig 3.2.

Since, the fundamental current flowing through the active filter is varied by the operating conditions of the load, Fig. 3.1 requires an external power supply. The required rating of the active filter depends on the power factor of the load because the passive filter is usually designed according to the reactive power of the load to be canceled for low power factor, the required rating of the active filter Fig. 3.1 is smaller while for high power factor, ratings of APF configuration of Fig. 3.2 is smaller. In Fig. 3.1, it is difficult to isolate the active filter from the source and to protect it against a short-circuit fault because of the series connection with the source. It is easy to protect and isolate the active filter connected to the neutral point of the wye-connected passive filter Fig.3.2 is more applicable to high-voltage power systems.

3.2 APF EMPLOYING A DEAD BEAT CONTROL

The utility companies are becoming strangled with the constraints of delivering high quality energy for an every day higher and more demanding load, in most cases without the possibility of expanding their resources. A much better use of the already installed resources is then the only way out of such dilemma. Thus, the system must improve its characteristics such as speed of controllers, harmonic immunity, voltage balance, voltage regulation, and the control of reactive flow, among others, even under a reduction of its stability margin. The tools available today to achieve this goal are the ones provided by power electronics which means to control the reactive power flowing through a line. This permits the management of the power factor, voltage regulation and current harmonics filtering.

Steve Moran [13] has demonstrated the use of shunt active filter to filter out the most harmonics content of the load. In the same way, Akagi et al. [14-15], has demonstrated the advantages of employing shunt active filter to compensate the disturbance origined in the load, as harmonics and reactive power, providing improvements in the total power factor.

. The control method used is a dead beat technique, as developed and applied for inverters by Gokhale and Kawamura [16]. The control tasks are performed by a floating-point Digital Signal Processor-DSP, nevertheless it is not shown in detail in this paper and some extra information can be found in Tzou [17] and Claro [18]. This paper brings a contribution to this subject by proposing a shunt active filter with fast response to reactive disturbances and able to filter out the most harmonics content of the load. A complete design of its filter as in [19], the shunt active power filter [20] can control the displacement and the distortion factors of the load by injecting reactive power into the system, providing a near unit power factor.

3.2.1 Shunt active power filter

(Shunt A.P.F.)[21] is shown in Fig 3.3 It consists of a voltage source inverter connected in parallel to the point of common coupling (PCC) through a transformer. This allows the shunt compensator to correct most deviations of the displacement angle for a required sinusoidal reference. In order to guarantee these goals, a high performance dead beat control is employed. This real time closed loop feedback digital system measure the current signals on the load and on the source, to compare this last instantaneous current signal with a current reference signal, generated by the DSP. Thus, with the measured variables I_s and I_L and depending on the resulting errors, the control law will produce the necessary pulse width and current level in the inverter's output. This signal will be adequately shaped through the A. C. filter to become a sinusoidal waveform required. Industrial distribution systems have a impedance between 1% -5% interval with high reactance, it has a significant filtering contribution in the control law expression for the required compensating signal. Since the control law forces the source current to follow the current reference, the current signal on the source without major harmonics, which characterizes it as an in intrinsic filter and a displacement factor compensator.

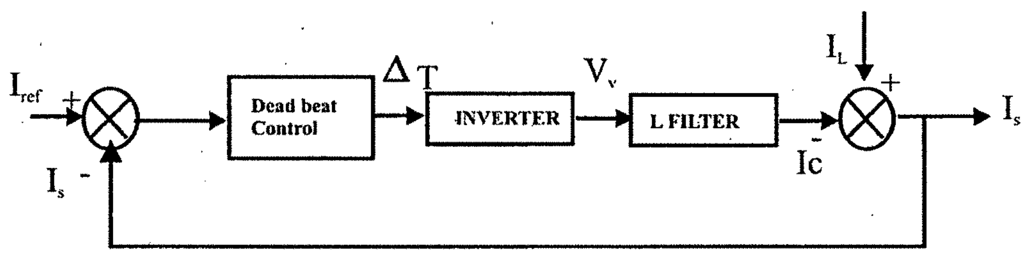

Fig 3.3 Control Diagram of Shunt APF

- *A C. **Filter:*** The shunt active power filter employs a pulse width modulation which control a voltage source inverter (VSI) that produces a modulated voltage signal. So, this inverter output signal is not sinusoidal and should be shaped through a second order LC filter added to the inverter output, filtering out the most harmonics content produced by the inverter's switching.

- ***D.C. BUS FILTER***: A D.C. bus shown in the Fig 3.4 is connected to the inverter with purpose to provide all required power for the shunt active power filter to compensate the disturbance on the load. However, this D.C. bus has a harmonics content originated from switching function ***of*** the shunt compensator inverter, as well as from the Inverter rectifier that feed energy to the D.C. bus from the utility.

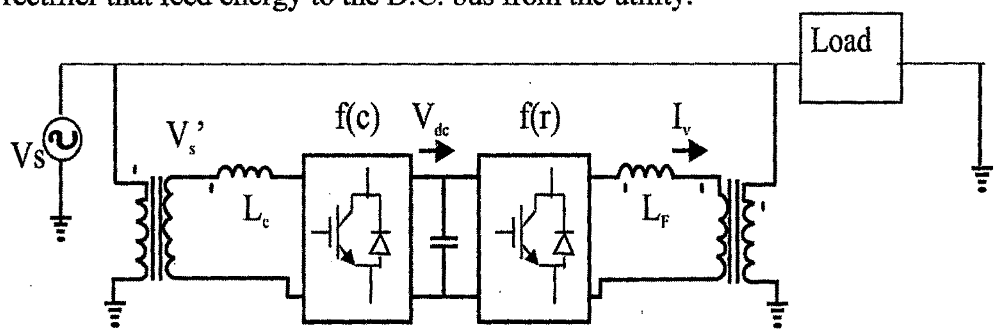

Fig 3.4 Circuit representing DC bus fed by Inverter

3.2.2 APF Implementation

The diagram presented in Fig. 3.5 shows the hardware connection between power circuit and control of the proposed system[21]. The core of it is the floating point DSP, model TMS320C31, based on a board and connected to a PC. The system variables are sampled through voltage or current transducers, isolated and conditioned by a measurement transformer and by an attenuator, before it couples to the ***A/D*** converter. Because more than one variable is required, an analog multiplexer is used to select the signal to be sampled at each moment. The ADC used [21] is a 12 bit 200 kHz model, which provides a real time fast response, stability and precision in the compensation action. The controlling signals are directly connected to the switches through high speed optocouplers.

Compensator software control: The software was executed on DSP and employed to command the two inverters. It is based on Assembler language and guarantee fast processing and compensation response as well as simplicity. Its basic steps are showed in [19] and the main structure of the program consists of: measured the required variables, control law processing *(ΔT)* and application of the command signal on the switch inverter.

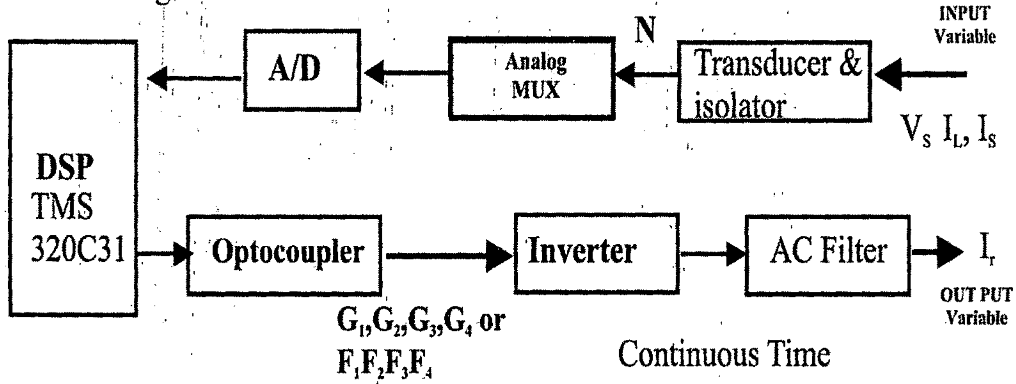

Fig 3.5 Block Diagram of Hardware setup for DSP Based APF

3.3 APF Controller: DSP Implementation

In paper [22] active power filter with the control circuit based on the TMS320C50 DSP Starter Kit is designed. The active power filter circuit was built, tested and results were also presented. To suppress harmonics in power system, an active power-harmonic-compensation filter (APF) can be connected in series or in parallel with the supply network. The series APF is applicable to the harmonic compensation of a large capacity diode rectifier with a DC link capacitor. The parallel APF (shunt active power filter) permits to compensate the harmonics and asymmetries of the mains currents caused by nonlinear loads. Harmonic compensation circuit with current-fed active power filter is depicted in Fig.3.6 Shunt APF injects AC power current I_c to cancel the main AC harmonic content.

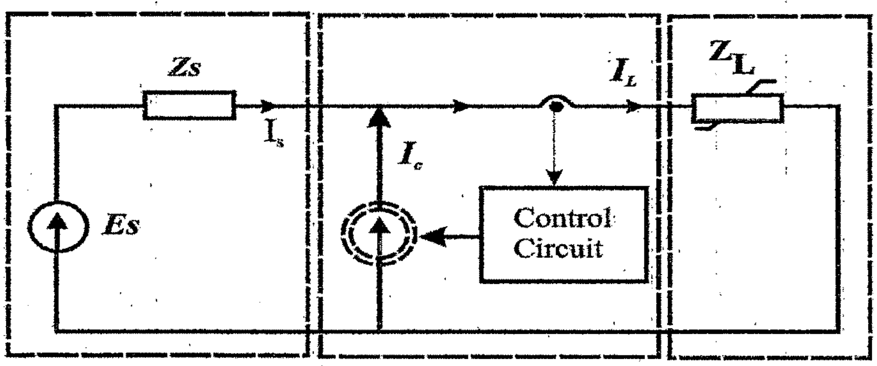

Fig 3.6Harmonic Compensation circuit with current-fed APF

Simplified block diagram of the proposed active power compensation circuit with the parallel APF for power of 75 kVA is depicted in Fig. 3.7

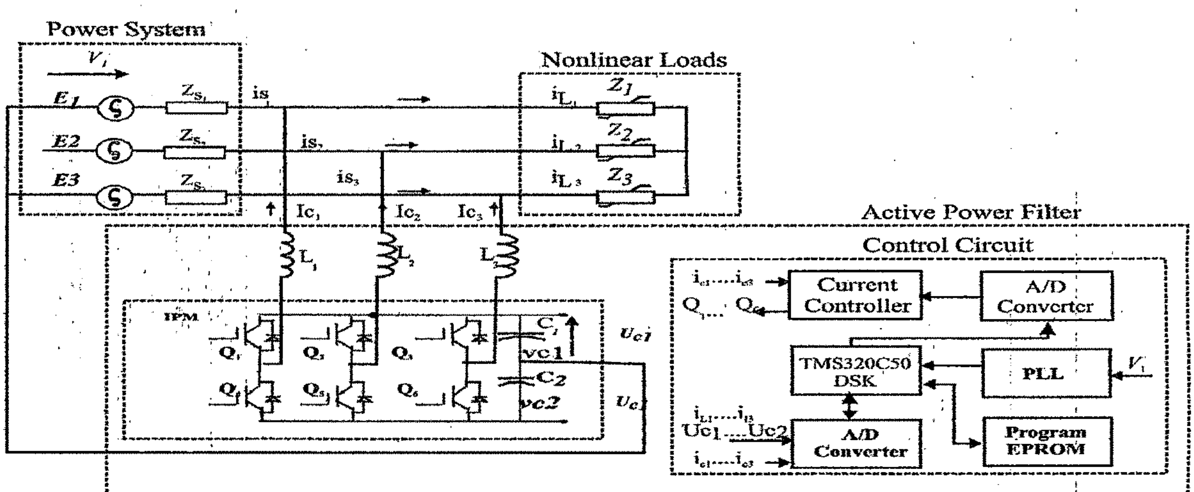

Fig 3.7 Simplified Block diagram of Active Power Compensation Circuit

The circuit consists of the power part with a three-phase IGBT power transistor bridge IPM (intelligent power module) connected to the AC mains through an inductive filtering system composed of inductors L_1, L_2, L_3. The APF circuit contains a DC energy storage, ensured by two capacitors C_1 and C_2. The control circuit is realized using the digital signal processor TMS320C50 (the TMS320C50 DSP Starter Kit). The active power filter injects the harmonic currents I_{c1}, I_{c2}, I_{c3} into the power network and offers a notable compensation for harmonics, reactive power and unbalance.

3.3.1 Control algorithm

Control algorithm for the proposed APF is based on the strategy resulting from the instantaneous reactive power theory initially developed by Akagi *et al.* [23-24]. Simplified block diagram for the active power filter control algorithm is depicted in Fig. 3.8(based on the circuit designed by Strzelecki [25-26]). It is divided into parts: the first one is realized using the digital signal processor TMS320C50 [27-28] and the second is realized using analog circuits.

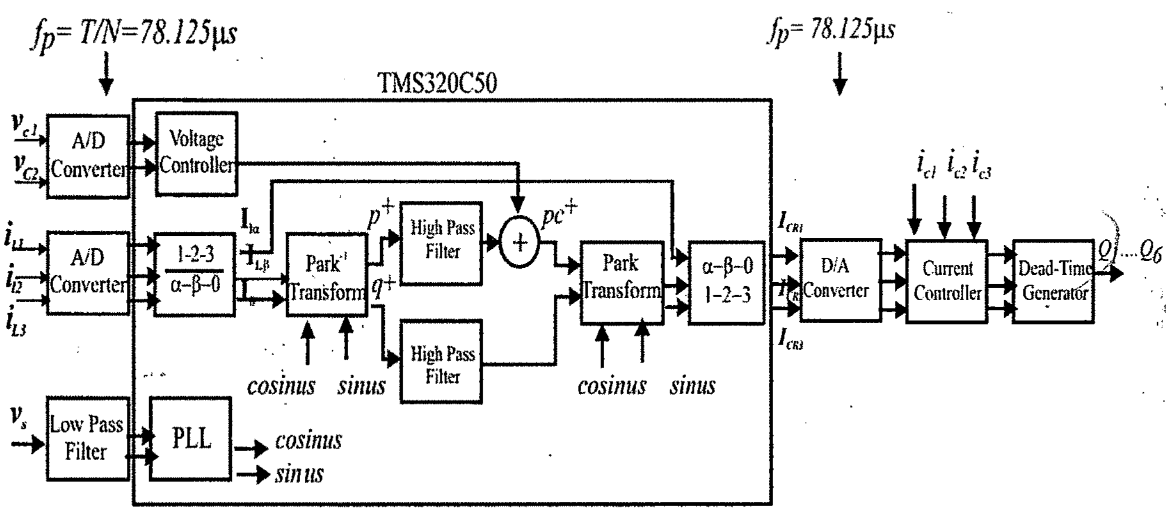

Fig. 3.8 Simplified Block Diagram for the APF Control Algorithm

In [22] the voltage frequency of mains *fs*=50 Hz is used with the number of samples N=256 having the sampling period is Tp =78.125 µs. The sampling rate *fp* =12800 samples/s is selected. Three-phase current signals can be transformed into the equivalent two-phase representation. The transformation (1-2-3 › α-β-0) from the three-phase current signals i_{L1}, i_{L2} i_{L3}, to the two-phase $i_{L\alpha}$, $i_{L\beta}$ with an additional neutral signal i_{L0} can be written in a matrix form:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \\ i_{L0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{6} & 1/\sqrt{6} & 1/\sqrt{6} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{L3} \end{bmatrix} \quad \text{...3.3}$$

The two-phase signals are transformed from the rotating to the stationary reference frame. This transformation is commonly called the reverse Park transformation and can be digitally calculated by equations:

$$\begin{cases} p^+ = i_{L\alpha}\sin\left(\frac{2\pi n}{N}\right) - i_{L\beta}\cos\left(\frac{2\pi n}{N}\right) \\ q^+ = i_{L\alpha}\cos\left(\frac{2\pi n}{N}\right) + i_{L\beta}\sin\left(\frac{2\pi n}{N}\right) \end{cases}$$

...3.4

and the digital sinusoidal reference signal is given by formula

$$\sin\left(\frac{2\pi n}{N}\right) = \sin\left(\frac{2\pi f_s n T_s}{N}\right),$$

--- 3.5

where: n – index of the current sample.

In order to generate the reference sinusoidal and cosinusoidal signals, a table containing sinus function values is allocated in the digital signal processor program memory. Signal $p+$ represents instantaneous active power and signal $q+$ instantaneous reactive power. The DC components of signals $p+$ and $q+$ are removed by a high-pass filter. This filter is described by equation

$$H(z) = \frac{b - bz^{-1}}{1 + az^{-1}}, \quad b = \frac{2\frac{T_1}{T_p}}{1 + 2\frac{T_1}{T_p}} \text{ and } a = \frac{1 - 2\frac{T_1}{T_p}}{1 + 2\frac{T_1}{T_p}},$$

where: T_1 – the reference (analog) filter time constant.

...3.6

For stabilizing the DC voltage a proportional controller is used.

Steps:

1. The response is calculated by the equation 3.7:

$$\Delta V_{C12} = k_e (V_R - (V_{C1} + V_{C2}))$$

Where: k_e – gain of voltage controller

V_R - DC reference voltage

V_{C1}, V_{C2} – voltage across capacitors c_1 and c_2 ...3.7

2. Signal ΔV_{C12} is subtracted from the component p+

$$P^+_C = P^+ - \Delta V_{C12}$$ ...3.8

3. The components p_c^+ and q^+ are calculated using park transformation equation 3.9 for the two phase representation:

$$i_{CR\alpha} = p_c^+ \sin(2\pi n/N) + q^+ \cos(2\pi n/N)$$
$$i_{CR\beta} = -p_c^+ \cos(2\pi n/N) + q^+ \sin(2\pi n/N)$$ ...3.9

4. Transform back to the three phase signal using 3.10

$$\begin{bmatrix} iCR1 \\ iCR2 \\ iCR3 \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} 2/3 & 0 & \sqrt{2/3} \\ -1/3 & 1/\sqrt{3} & \sqrt{2/3} \\ -1/3 & -1/\sqrt{3} & -\sqrt{2/3} \end{bmatrix} \begin{bmatrix} iCR\alpha \\ iCR\beta \\ iL0 \end{bmatrix} \qquad \ldots 3.10$$

5. The output compensation reference current signals I_{CR1}, I_{CR2} and I_{CR3} are transformed to an analog form in a digital to analog converter.

Prototype of the three-phase active power filter was build and tested in the laboratory. Simplified diagram of the test circuit of the paper [22] is depicted in Fig. 3.9. To model the nonlinear load a thyristor power controller RI31 (from METROL) with the resistive load was used. Oscillogram records of the various waveforms of the test circuit. the steady-state performance of the active power filter and the harmonic spectrum of the load current I_{L1} and the line current I_{S1} were studied.

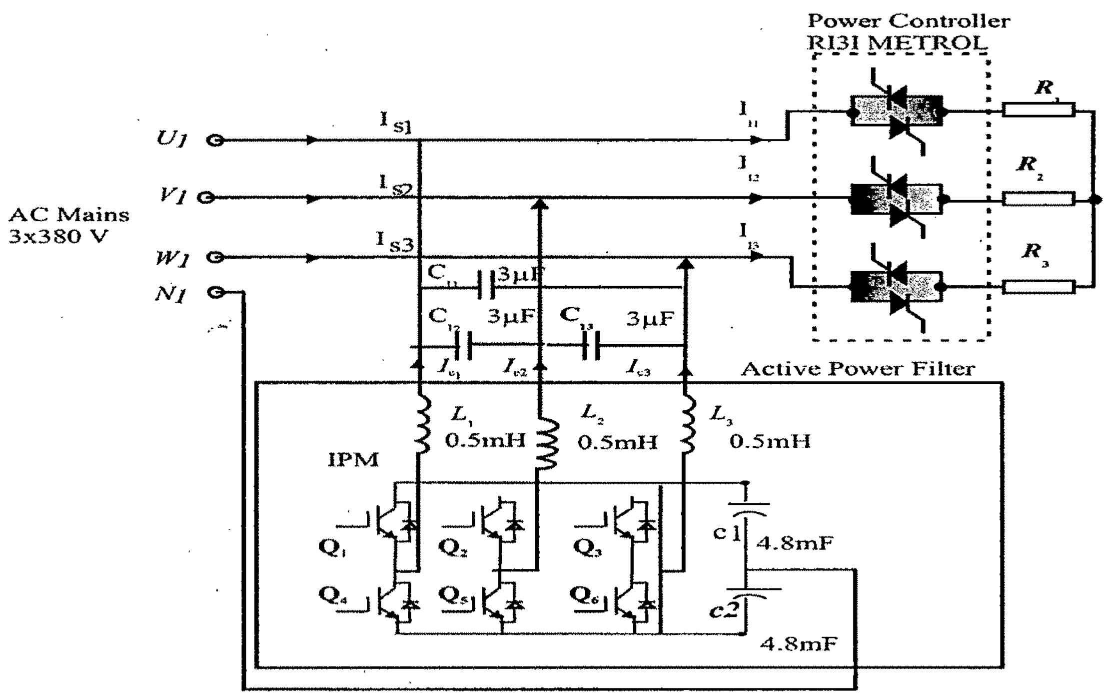

Fig 3.9 Three-Phase Active Power Filter Test Circuit

3.4 Controller for Hybrid APF: Parallel Connection

The hybrid active power filter combines the compensation characteristics of resonant passive and active power filters. The series active power filter is implemented with a three-phase pluse-width modular (PWM) voltage-source inverter. The proposed scheme [29] is able to compensate displacement power factor and current harmonics simultaneously. The combination of passive and active power filters allows a better performance compensation of high-power nonlinear loads. The principles of operations under steady-state and transient conditions as well as the design and implementation of the power and control circuits are discussed. The predicted results are verified on a 5 **kVA** prototype model.

Active power filters have been shown to be an interesting alternative to compensate power distribution systems. Series and shunt topologies have already been presented and discussed in the technical literature. Shunt active power filters are more suitable to compensate current harmonic components and the displacement power factor, while series topologies present better characteristics to compensate voltage distortions. Hybrid topologies composed of passive LC filters connected in series with an active power filter have already been proposed and discussed previously [30-34]. Hybrid topology significantly improves the compensation characteristics of simple passive filters, making the active power filter available for high-power applications, relatively at a lower cost. Moreover, compensation chtiracteristics of already installed passive filters can be significantly improved by connecting a series active power filter at its terminals.

Control schemes for the active power filter are normally based on the instantaneous reactive power reference [30] or synchronous reference frame [33], requiring complex circuitry for their implementation, or a DSP to implement digitally. Also, compensation characteristics of both schemes depend significantly on the voltage waveform distortion. A simple control scheme implemented with analogue technology was presented in [34]. Although the reported control scheme was simple and easy to implement, the compensation characteristics were not good enough due to the frequency response of the passive filter used to obtain the control reference waveforms.

The hybrid active power filter topology presented is shown in Fig. 3.10. The active power filter is implemented with a three-phase PWM voltage-source inverter, operating at fixed switching frequency. and connected in series to the passive filter through a coupling transformer. The proposed control scheme [29] shown in Fig. 3.10 generates the reference signals required to compensate current harmonic components and the displacement power factor of high power nonlinear loads. The active power filter forces the utility line currents to become sinusoidal and in phase with the respective phase to-neutral voltage, improving the compensation characteristics of the passive filter.

3.4.1 Principles of operation

Passive filters have been extensively used to compensate current harmonics and the displacement power factor in power distribution systems. The poor flexibility of passive filters to adapt to variable load compensation requirements constitutes a major disadvantage results in power Factor overcompensation in the case of low-load power operation. or in poor harmonic filtering in case the frequency spectrum of the load current changes in magnitude or in frequency.

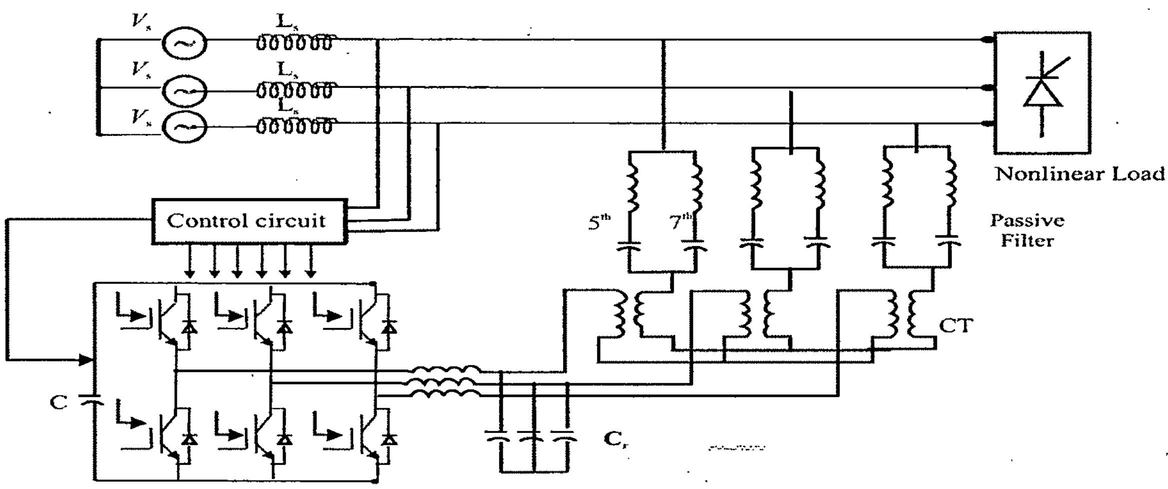

Fig 3.10 Hybrid APF Configuration

In the hybrid topology Fig. 3.10, since the active power filter is connected in series to the passive tilter through a coupling transformer, it imposes a voltage signal at its primary terminals that forces the circulation of current harmonics through the passive filter, improving its compensation characteristics independently of the variations in the selected resonant frequency of the passive filter. By changing the voltage waveform at the terminal of the primary winding of the coupling transformer, the compensation characteristics of the passive scheme are changed, By adjusting the amplitude of the voltage fundamental component, the amount of reactive power required by the load can be controlled precisely. If current harmonic compensation must be improved, the active power filter generates a voltage component at the terminal of the coupling transformer primary winding, changing the passive filter frequency response, and therefore increasing the harmonic compensation performance.

3.4.2 Control circuit

The block diagram of the proposed control scheme [29] shown in Fig. 3.11 consists of three modules: the DC voltage control, the voltage reference generator and the inverter gating signals generator. The voltage reference waveform required by the inverter control scheme is obtained by adjusting the amplitude of a sinusoidal reference waveform in phase with the respective phase-to-neutral voltage and then subtracting the respective AC line current Fig. 3.11.

The sinusoidal reference signal can he obtained from the voltage system (in the case of low voltage distortion) or it can he generated from an EPROM synchronized with the respective phase-to-neutral voltage. The amplitude of this reference waveform controls the inverter DC voltage and the AC mains displacement in power factor. The inverter DC voltage varies according to the amount of real power absorbed by the inverter, while the AC mains power factor depends on the amount of reactive power generated *by* the hybrid filter, which can be controlled by changing the amplitude of the fundamental component of the inverter output voltage.

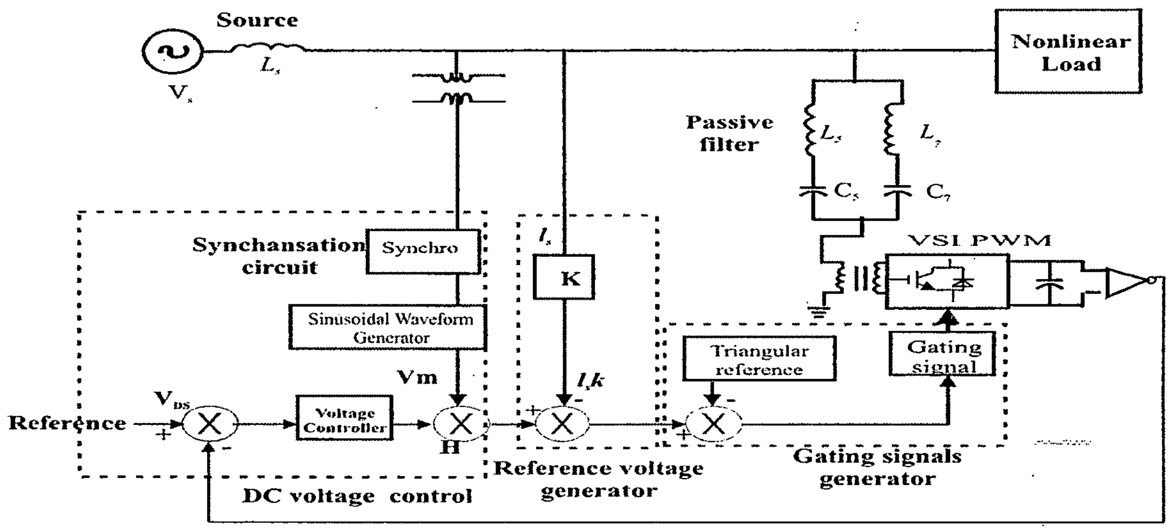

Fig 3.11 Hybrid APF: Topology & Associated Control Scheme

Simulated results [29] of the hybrid scheme indicate that the THD of the line current is reduced from 28%. in the case of a direct connection to 14.4% in the case where only the passive filter operates, *to* only 4.04%, for active compensation with the hybrid topology. Simulated results prove the good transient response of the hybrid topology and the passive filter rms current is reduced due to the connection of the active filter. Results confirm that the transient response scheme is fast enough to compensate rapid changes in the load current.

A *5* kVA laboratory prototype using IGBT [29] switches was implemented and tested in the compensation of a six-pulse controlled rectifier. The implemented passive filter has the following parameters:

- Fifth order Filter: L = 6.22 mH; C = 65 μF
- Seventh Order Filter: L = 3.17 mH; C = 65 μF

The Q factor in both filters is equal to ten. The coupling transformer tum ratio is equal to four. The active filter DC voltage is set at 200V. The inverter modulation index is 0.9. The nonlinear load used in the experimental setup is a 2.5kVA six pulse controlled rectifier. The inverter was operated at 4 kHz switching frequency. The THD of the rectifier input current is 28.1%. Once the passive filters are connected, the system line current THD is reduced to 24%. If the proposed active power filter is connected, the system line current THD is reduced to 6.9%.

3.5 APF for Harmonic Damping in a Power Distribution System

The section discusses automatic gain adjustment in a fully-digital-controlled shunt active filter. This is the first step in cooperative control of the multiple active filters based on voltage detection for harmonic damping throughout power distribution systems. In general, the active filter should be equipped with an optimal control gain corresponding to the characteristic impedance of a distribution line. However, it is difficult to know circuit parameters of a real distribution line having various shunt capacitors and loads.

The main purpose of the gain adjustment is to make the active filter damp out harmonic propagation without considering the circuit parameters. In addition, the gain adjustment can reduce the compensating currents and losses in the active filter, and moreover it can avoid over-damping performance. Experiment results [35] obtained from a 200-V, 20-kW laboratory system verify the effectiveness of the active filter equipped with automatic gain adjustment.

In recent years, harmonic problems have been serious in industrial and utility power distribution systems. One of the most serious problems in utility power distribution systems is the so-called "harmonic propagation," which contributes to a significant amplification of voltage harmonics in a distribution line [36]. The harmonic propagation is caused by harmonic resonance between line inductances and shunt capacitors for power factor correction. To solve this problem, active filters intended for installation on power distribution systems have been researched and put into a field test [37-38]. Although theoretical researches on active filters for mitigating voltage harmonics in distribution systems have been done in [39-40], they might have no intention of putting the active filters into practical use because these references make no concrete description of their hardware implementation and control system.

The shunt active filter based on harmonic- voltage detection which is intended to be installed by electric utilities are proposed in [41-43]. This active filter is characterized by behaving like a resistor for harmonic frequencies, making it possible to damp out harmonic propagation throughout a whole distribution line. Installing the active filter on the end bus of the line is effective in harmonic damping. In general, the higher the control gain of the active filter, which is in inverse proportion to a resistance value of the resistor for harmonic frequencies, the lower voltage harmonics appearing on its installation bus.

In a long distribution line having a large number of shunt capacitors, however, installing the active filter with a large gain may exhibit over-damping performance. It might make voltage harmonics on a middle bus larger than those on the same bus before installing the active filter. This problem can be solved by setting such a control gain corresponding to the characteristic impedance of the distribution line. This principle is similar to "termination" in signal transmission and/or distribution circuits.

However, it would be impossible to know the characteristic impedance in a real power distribution system. Even if it is possible in advance, it would not be a constant value because the arrangement of the distribution system would be changed according to system operation and/or fault conditions. In addition, shunt capacitors and loads in the distribution system are connected or disconnected, not by an electric power company but by individual customers.

Paper [36] presents a software implementation of automatic gain adjustment, as the first stage of cooperative control for multiple shunt active filters intended for installation on power distribution systems. According to voltage harmonics detected at its installation bus, the APF can adjust the control gain by itself so as to keep the voltage harmonics lower than a specified level, even if the characteristic impedance of the distribution line is unknown. No over-damping performance occurs during operation of the active filter so the voltage harmonics on a middle bus are not amplified after the APF is installed. The APF is on standby as long as no harmonic propagation occurs.

3.5.1 Experimental System

Fig. 3.12 shows a three-phase power distribution line simulator rated at 200 V, 60 Hz and 20 kW used for the following laboratory experiments [36]. Table 3.2 shows circuit parameters of the line simulator. The line simulator is a down-scaled model of an overhead distribution line rated at 6.6 kV, 3 MW and 3 km long in Japan. Voltage corresponds to a 6.6-kV substation voltage. An inductor corresponds to a leakage inductance of a primary distribution transformer in the substation and line inductances. Three capacitors represent shunt capacitors for power factor correction, which are installed by high-power consumers.

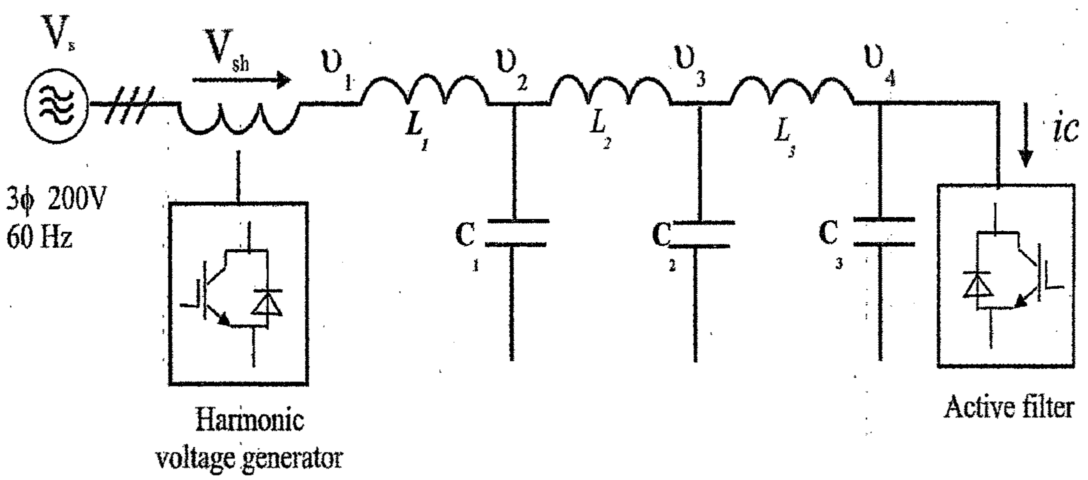

Fig 3.12: Three Phase distribution line Simulator

Table 3.2 Parameters of Line Simulator

Line Inductor	**L_1=L_2=L_3**	**0.22 mH (4.1 %)**
Resistor	**R_1**	**0.02 Ω (1.0%)**
	R_2 = R_3	**0.05 Ω (2.5%)**
Capacitor	**C_1=C_2=C_3**	**150 μF (11.3%)**
Note: 3 ϕ, 200 V, 60 Hz, 20- kVA Base		

Under no-load conditions without any active filter, the harmonic voltage at bus 4 is magnified by several times as large as that at bus 1. This phenomenon is called "harmonic propagation" resulting from series and/or parallel resonance between the inductors and the capacitors existing on the line.

Fig. 3.13 shows a fully-digital-controlled shunt active filter which is specially developed for achieving cooperative control [45]. A power circuit of the active filter consists of a three-phase voltage-fed PWM inverter using six IGBT's, a three-phase step-up power transformer with a turn ratio of 2:1, three digital controller consists of an A/D unit, a D/A unit, a DSP, a digital PWM unit, and a phase-locked-loop (PLL) unit.

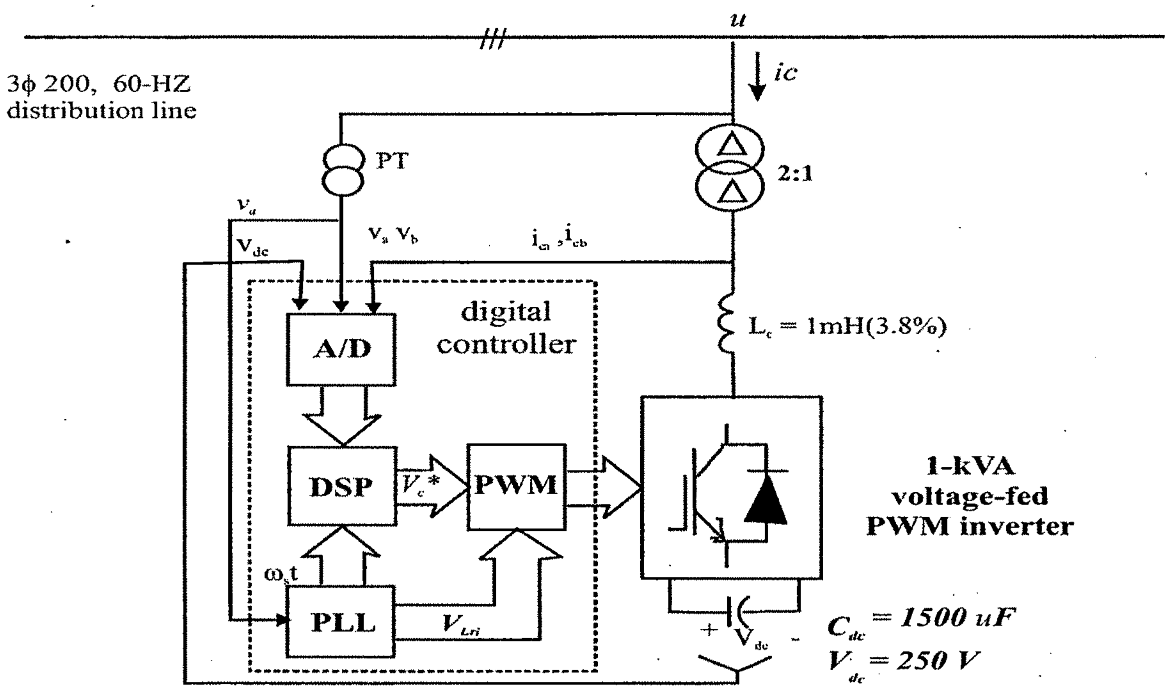

Fig 3.13: Digitally Controlled APF

A 16-bit fixed-point DSP (ADSP2101: Analog Devices) is used. The digital controller works with a sampling frequency of 20 kc/s. In order to reduce the time and phase delays inherent in the digital controller, signal sampling and PWM control processes are synchronized with the line frequency [44] and "deadbeat control" is applied to improve current control response [46-47].

In order to damp out harmonic propagation throughout power distribution systems, the active filter based on voltage detection is installed on the end bus of the distribution line. The voltage at the point of installation is detected, and then a harmonic voltage is extracted from the detected voltage. After that, is amplified by a control gain to make a compensating current reference.

In general, the higher the control gain, which is in inverse proportion to the damping resistor, the lower voltage harmonics appearing on the installation bus of the active filter. In a long distribution line having a large number of shunt capacitors, however, installing the active filter with a large gain may exhibit over-damping performance. It might make voltage harmonics on a middle bus larger than those on the same bus before installing the active filter. The dc capacitor voltage on the dc side of the active filter is detected and then compared with the dc voltage reference. The difference signal between and is amplified by a dc control gain to generate which corresponds to the fundamental current being in phase with the supply voltage. Consequently, a small amount of active power is absorbed from, or released to, the dc capacitor so as to regulate

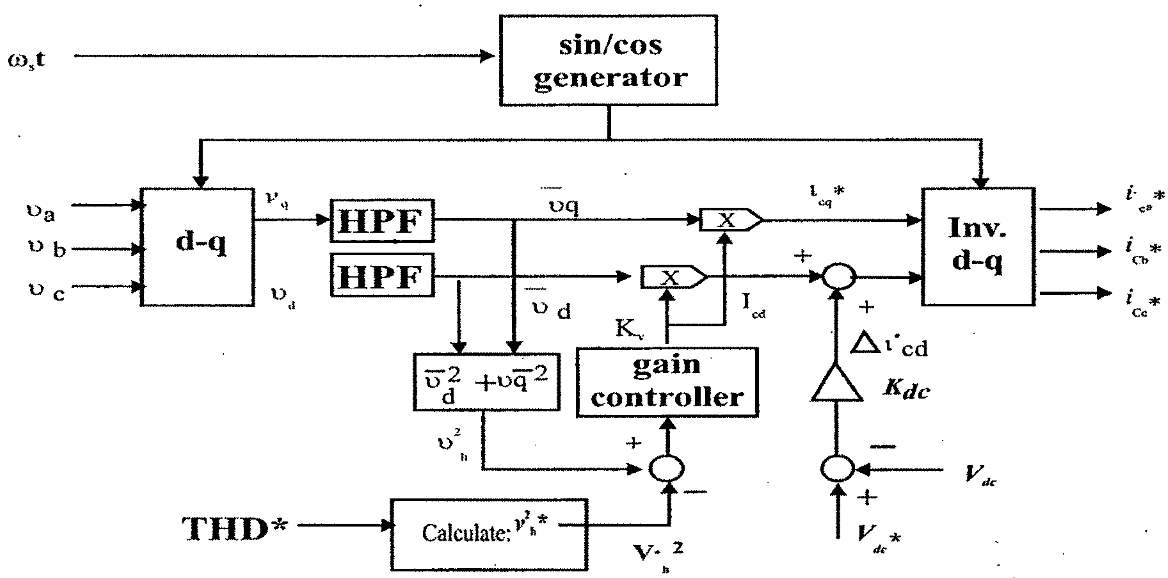

Fig 3.14: Control Block Diagram of APF

Fig. 3.14 shows a control block diagram of the active filter. Three-phase voltages at the point of installation which are detected by potential transformers, PTs are transformed to and on the coordinates with the help of the line phase in a real distribution system, individual voltage harmonics have to be calculated, thus requiring several transformation and the inverse transformations. As a result, the calculation time in the DSP increases and might exceed the sampling period generating a delay time problem.

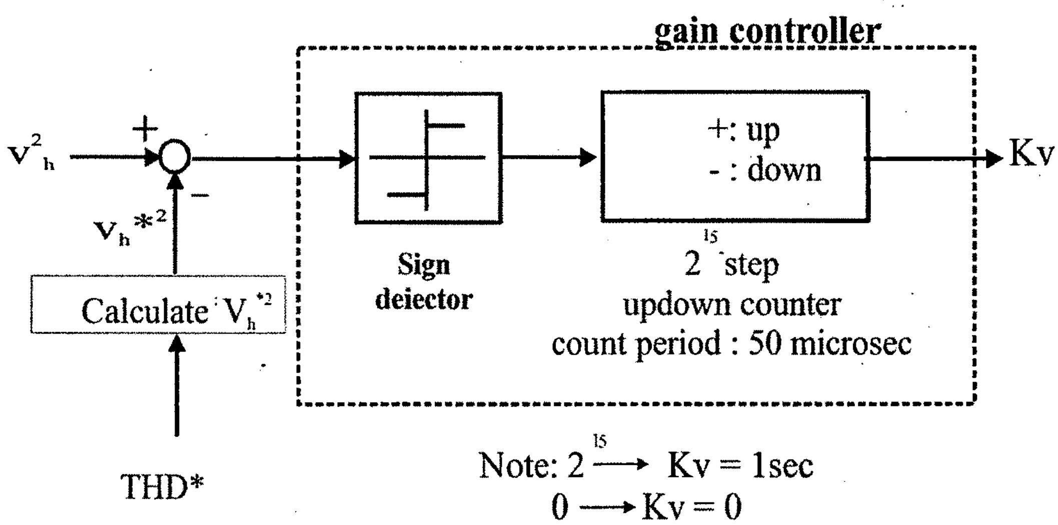

Fig 3.15: Software Implementation of Automatic Gain Adjustment

The purpose of the automatic gain adjustment is to keep the harmonic voltage at the installation bus within a specified range. The fundamental components in and correspond to the dc components, and harmonic components to the ac components Fig. 3.15 shows a block diagram of the automatic gain adjustment. The gain adjustment is composed of a sign detector and a -step updown counter to adjust a gain. It is implemented easily by the DSP programming with a calculation time of 2 sec.

3.6 Cooperative Control of Shunt APF for Harmonic Damping

Section describes cooperative control of multiple active filters based on voltage detection for harmonic damping throughout a power distribution system. The arrangement of a real distribution system would be changed according to system operation, and/or fault conditions. In addition, shunt capacitors and loads are individually connected to, or disconnected from, the distribution system. Independent control might make multiple active filters produce unbalanced compensating currents.

[49] describes the hardware and software implementations of cooperative control for two active filters and verification is done by experiment results with the help of a communication system.

A significant amplification of voltage harmonics in a distribution feeder, which is so-called "harmonic propagation" resulting from harmonic resonance between line inductances and shunt capacitors for power-factor correction, has been a serious problem in both industrial and utility power distribution systems [50-51]. It has been reported by actual measurements that harmonic propagation frequently occurs in the downtown area of a 6.6-kV power distribution system under light-load conditions at night [52]. To solve this problem, a shunt active filter intended for installation on power distribution systems has been researched and put into a field test [53]. Although theoretical researches on active filters for mitigating voltage harmonics in distribution systems have been done in [54-55], they might have no intention of putting the active filters into practical use, because these references make no concrete description of their hardware implementation and control system.

[56-59] have proposed a shunt active filter based on harmonic- voltage detection. The APF is characterized by behaving like a resistor for harmonic frequencies, thus resulting in damping out harmonic propagation throughout a distribution feeder without stability problem. Moreover, the active filter equipped with automatic gain adjustment can damp out harmonic propagation without considering the circuit parameters of the distribution feeder [60]. Installation of the single active filter with the gain adjustment on the end bus of each feeder achieves harmonic damping effectively. In a real distribution system, the feeder arrangement would be changed according to system operation, and/or fault conditions. Multiple active filters might be dispersed in the same feeder. As a result, mutual interference among the active filters may occur; the active filters might not share harmonic damping, and might produce unbalanced compensating currents because they are controlled independently. Independent control of active filters might not be efficient or effective in achieving harmonic damping.

[49] Describes cooperative control of multiple active filters based on voltage detection. The cooperative control is based on information exchanging among the active filters with automatic gain adjustment. A host computer takes in both compensating

current of each active filter and voltage total harmonic distortion (THD) at each site of installation, with the help of a communication system. Then, the computer decides each control gain, thus making the value of the voltage THD less than a specified level, and balancing the compensating currents of the active filters. The cooperative control of two active filters equipped with automatic gain adjustments are experimentally considered for the sake of simplicity. Experimental results obtained from a 200-V 20-kW laboratory setup verify the effectiveness of the cooperative control in damping out harmonic propagation [49].

3.6.1 Review of APF based on Voltage Detection

Fig. 3.16 shows a simplified radial power distribution system having active filters. The distribution system consists of four feeders rated at 6.6 kV and 3 MW/feeder. For the ease of explanation, attention is paid to feeder 1, and moreover branch lines are excluded from feeder 1.

Under light-load conditions, the fifth- and/or seventh-harmonic voltages at bus 10 are magnified several times as large as that at bus 2 when no active filter is installed. This phenomenon is called "harmonic propagation" resulting from series and/or parallel resonance between the inductors and the capacitors existing on the feeder. APF is installed on the end bus (bus 10) in order to damp out harmonic propagation throughout the feeder.

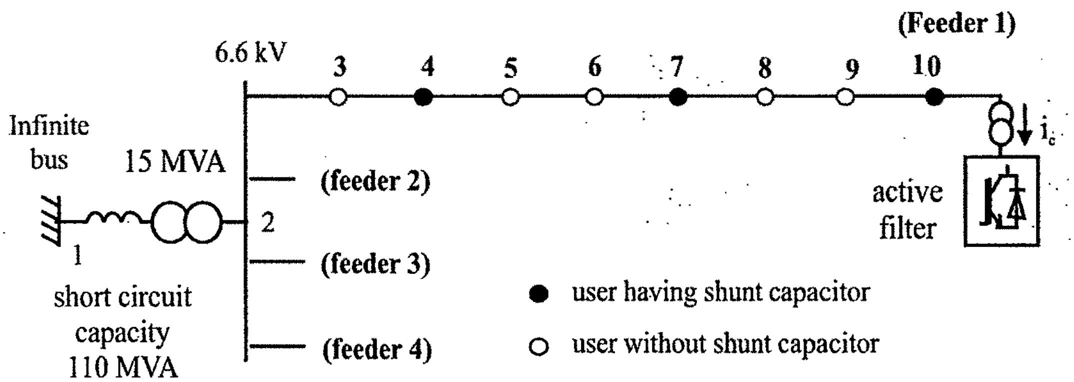

Fig 3.16 A radial Power Distribution system

Fig. 3.13 shows a shunt active filter based on voltage detection, which is characterized by fully digital control [59]. A power circuit of the active filter consists of a three-phase voltage-fed pulsewidth-modulation (PWM) inverter using six insulated gate bipolar transistors (IGBTs), a three-phase step-up power transformer, three interfacing inductors , and a dc capacitor . A digital controller consists of an A/D unit, a digital signal processor (DSP), a digital PWM unit, and a phase-locked-loop (PLL) unit. A 16-bit fixed-point DSP (ADSP2101:Analog Devices) is used. The digital controller works with a sampling period of 50 sec. of the active filter on the end bus of a feeder achieves harmonic damping or harmonic termination throughout the feeder. This principle is similar to "termination" in signal transmission and/or distribution networks.

Fig. 3.14 shows a control block diagram of the active filter based on voltage detection. Harmonic voltages are extracted from three-phase voltages at the site of installation, v_a, v_b, and

v_c, by using the d-q– and inverse d-q– transformations, and two first-order high-pass filters (HPFs) with a cutoff frequency of 13 Hz. Each harmonic voltage is amplified by a gain K_V to produce the compensating current reference.

The idea of automatic gain adjustment to the control system of an active filter based on voltage detection is used. The APF controller calculates an instantaneous value of the harmonic voltage corresponding to the actual value of voltage THD at its installation bus and the controller adjusts its gain so as to keep the actual value of voltage THD to be lower than a specified value of voltage THD, without considering the circuit parameters of the distribution feeder. The control scheme of the gain adjustment is shown in Table 3.3. The gain is automatically adjusted properly to avoid over/ under damping performance

Table 3.3 THD Control Method

	THD > THD*	THD ≤ THD*
K_V	Increment	Decrement

3.6.2 Feeders under Fault Conditions

Fig. 3.17 shows a feeder arrangement of a simplified power distribution system consisting of two feeders under fault conditions. Under normal conditions, normally-opened switches between bus 10 (the end bus of feeder 1) and bus 18 (the end bus of feeder 2) remain opened [61]. When these buses are not so far, the switches are installed for improvement of system reliability. Each feeder delivers electric power to consumers on the corresponding feeder. Since the best installation site of the active filter for achieving harmonic damping is the end bus of each feeder, two active filters equipped with automatic gain adjustment are installed on bus 10 and bus 18.

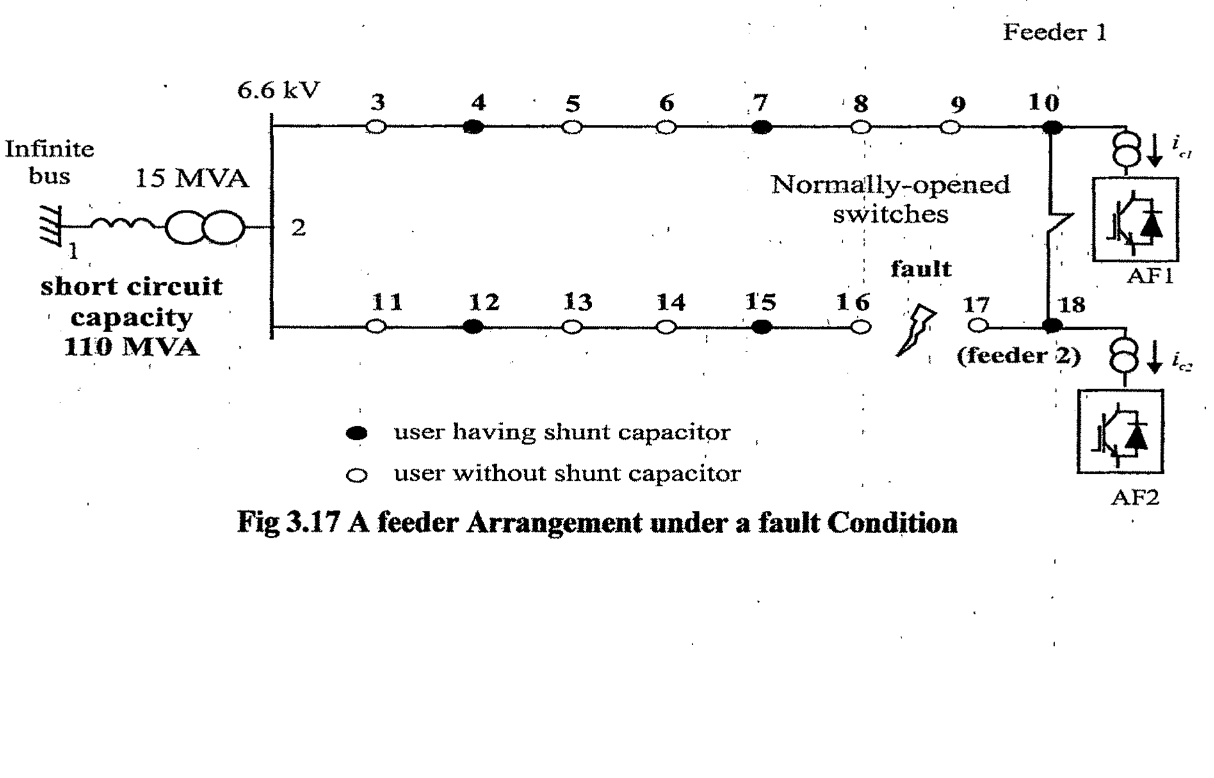

Fig 3.17 A feeder Arrangement under a fault Condition

Generally, temporary and permanent faults may occur in power distribution systems. As soon as a permanent fault occurs, for example, between buses 16 and 17 in feeder 2, a protection system is operated in order to reduce the customer impact due to the fault. Switches between buses 16 and 17 are opened, while switches between buses 10 and 18 are closed. In this case, buses 17 and 18 will be restored electric power via feeder 1.

However, when switches between buses 10 and 18 are closed, the feeder arrangement is significantly changed, thus resulting in installing the two active filters close each other. In addition, the voltage THD at bus 18 is higher than that at bus 10 because of the so-called "Ferranti effect." Therefore, only AF2 on bus 18 adjusts its gain to reduce the voltage THD at bus 18 within its reference, while AF1 on bus 10 reduces its gain to zero, and finally AF1 is out of operation. As a result, the two active filters might not share harmonic damping, thus leading to unbalanced compensating currents. Fig. 3.18 depicts the block diagram of voltage THD and compensating current calculations in each active filter.

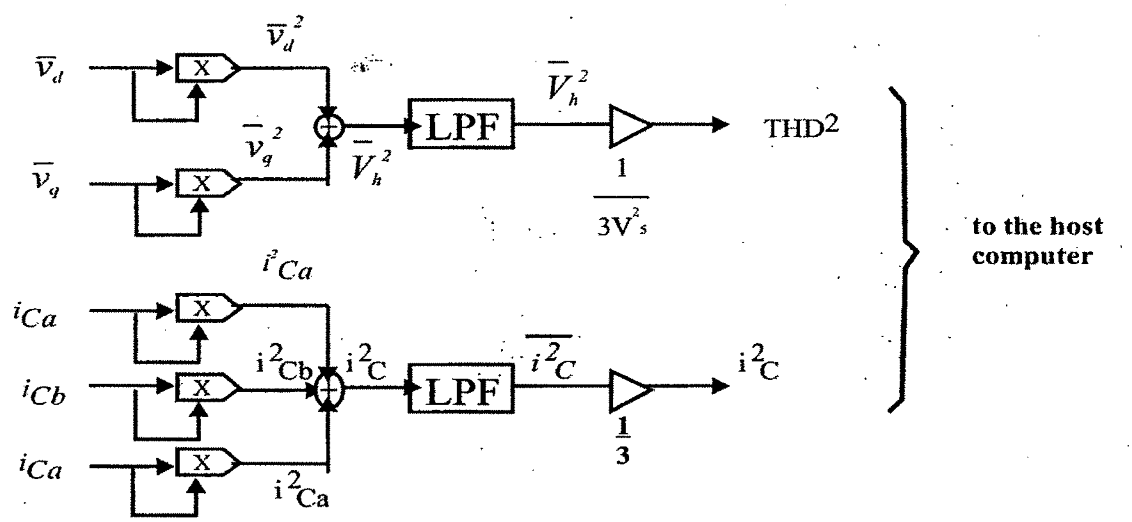

Fig 3.18: Voltage THD and Compensation Current Calculations

3.6.3 Communication System

There are many types of communication system such as a radio system, a distribution -line carrier system and so on [62], Fig. 3.19 shows a communication system developed in [49] a serial communication consisting of a 16-bit parallel common data bus, an interface controller(Z80-CPU board), a serial data bus (RS-232C), and a host computer. The active filters are linked to the common data bus. The interface controller is used to interface all active filters.

Fig. 3.20 shows a block diagram of signal processing in the host computer. The cooperative control consists of a THD controller, a current-balancing controller and a limiter. Tables 3.4 and 3.5 show the algorithm of the cooperative control. The aim of the THD controller with the highest priority is to keep the actual value of THD at the installation bus of each active filter within its reference value of THD, according to Table 3.4.

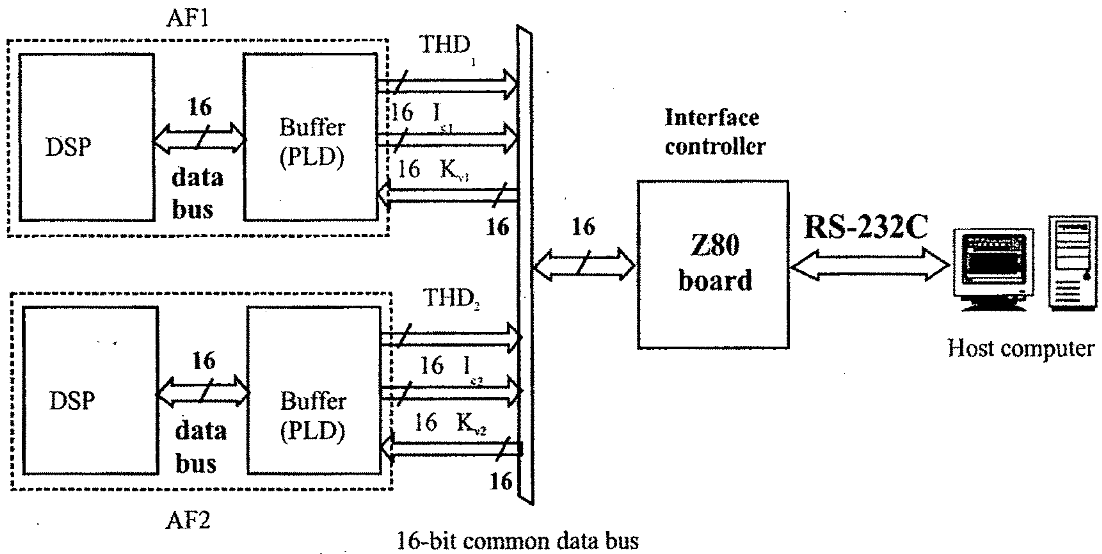

Fig 3.19 Communication System

The reference value should be typically set to 5% for a general power distribution system of 2.3–6.9 kV. However, the reference value for the following experiments is set to 2.6% in order to make more clear the effect of the active filters on harmonic damping. The function of the current-balancing controller is to balance the compensating currents between the active filters, referring to Table 3.5, while the limiter is used to restrict the control gain between 0–1 S.1 In the case of multiple active filters, the cooperative control can be achieved by modifying the control logic in Table 3.5 only.

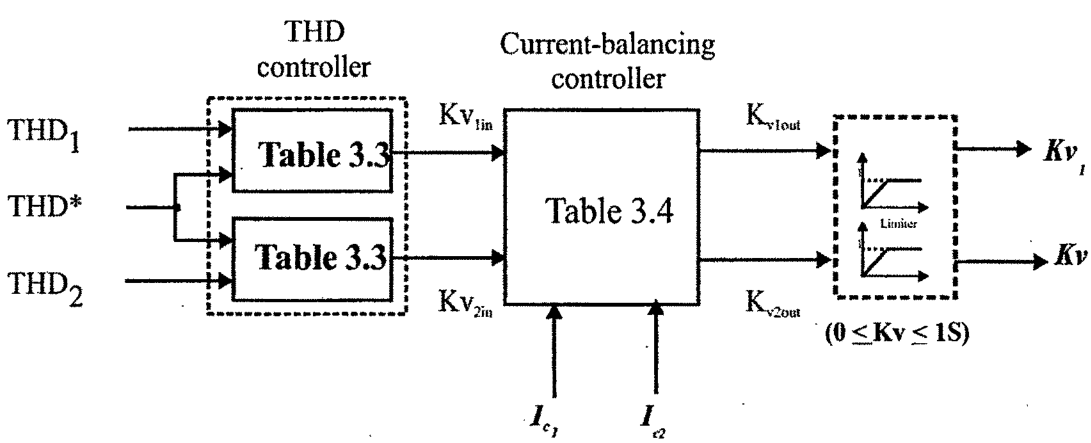

Fig 3.20 Cooperative Control in the Host Computer

Tables in Fig 3.20 are implemented by 15-bit up-down counters based on the C language. The control system of the cooperative control forms a feedback loop including a nonlinear integrator. Either inc/dec step in Table 3.3 is set to S, while incremental step in Table 3.4 is set to

S. The updated time is longer than 70 ms being 4–6 times as long as the time constant of the LPFs in Fig. 3.18, in order to avoid the "limit-cycle instability."

Table 3.4 Balancing of the Compensating Currents(Case of Two APF)

	$I_{C1} > I_{C2}$	$I_{C1} = I_{C2}$	$I_{C1} < I_{C2}$
K_{V1in}	constant	Constant	Increment
K_{V2in}	Increment	Constant	constant

Fig. 3.20 shows a block diagram of signal processing in the host computer. The cooperative control consists of a THD controller,

3.6.4 Setup: Two Active Filters on the Same Bus

Fig. 3.21 shows an experimental system when two active filters are on the same bus. It is assumed that a fault occurs near the end bus of feeder 2, as shown in Fig. 3.27 Switches near the fault are tripped while switches between buses A and B are closed to restore power via feeder 1. When buses A and B are not so far, the line impedance between these buses can be ignored.

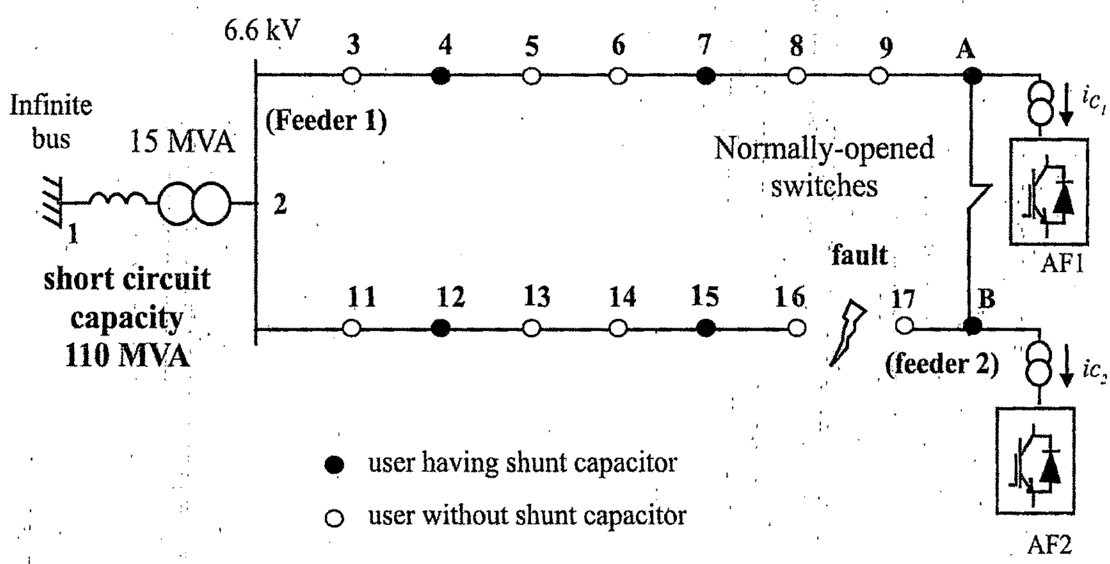

Fig 3.21 Hypothetical Test Setup

A simplified laboratory setup in Fig. 3.22 is related to the feeder arrangement in a hypothetical model under the fault condition in Fig. 3.21. Because attention is paid to the behavior of the two active filters, the line upstream of the fault point in feeder 2 is excluded from discussion. Here, a three-phase power distribution line simulator rated at 200 V, 60 Hz and 20 kW under no-load conditions is used for experiment.

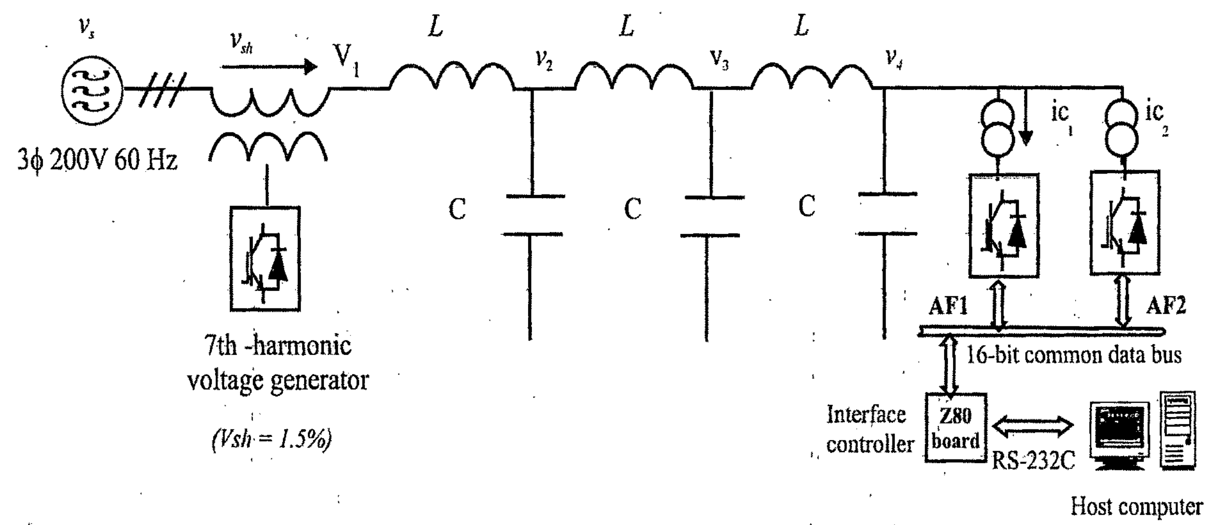

Fig 3.22 Simplified Laboratory Test Setup

Table 3.5 shows the circuit parameters of the line simulator. Note that these parameters are designed to cause the seventh-harmonic resonance. A seventh-harmonic voltage of 1.5% is injected by a harmonic voltage generator for the purpose of taking a background harmonic voltage into account.

Table 3.5 Parameters of the APF

Parameters of the Line Simulator		Parameters of the Active Filter	
Line Inductor L	0.22 mh(4.1%)	Rating	! kVA
Shunt Capacitor C	150 µF (11.3%)	Transformer Ratio a	2:1
		Interfacing Inductor L_C	1 mH (3.8%)
		dc Capacitor C_{dc}	1500 µF
		dc Voltage V_{dc}	250 V
Note: 3 ϕ, 200V, 60 Hz , 1kVA base			

3.6.5 Setup: Two Active Filters on different Buses

Fig. 3.23 shows an experimental system when two active filters are on different buses. In this case, it is assumed that the distances of two feeders are different, and a fault occurs around the middle bus of feeder 2 in a hypothetical power distribution system model, as shown in Fig. 3.23. When the fault occurs, switches near the fault are tripped while switches between buses A and B are closed.

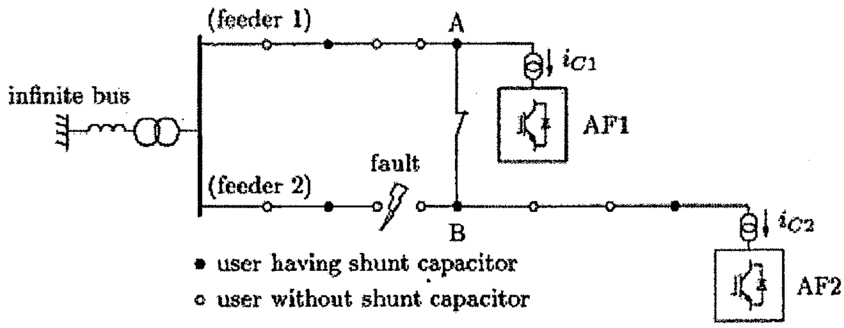

Fig 3.23 Hypothetical Test Setup

A simplified laboratory setup shown in Fig. 3.24 is related to the hypothetical model shown in Fig. 3.23. The circuit parameters of the line simulator are shown in Table 3.5. For the following experiments, AF1 is on bus 3 (the middle bus) and AF2 is on bus 4 (the end bus).

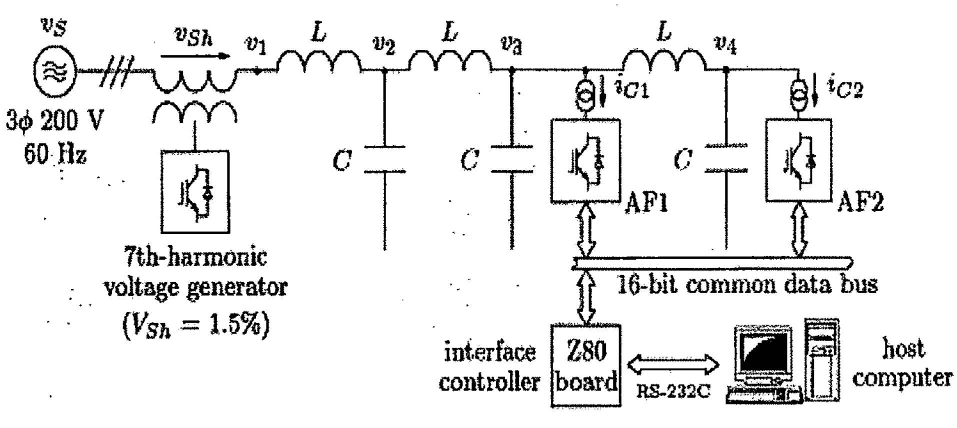

Fig 3.24 Simplified Laboratory Test Setup

The cooperative control of two active filters has been experimentally compared to independent control. It is shown in [49] that cooperative control makes each active filter reduce the voltage THD value at the bus of installation and balance the compensating currents well, irrespective of the system conditions.

3.7 APF Implementation: PWM VSI in CASCADE

A three-phase active power filter implemented with two **PWM** voltage-source inverters connected in cascade **is** presented and analyzed in [63]. The active power filter is connected in parallel to the system and can compensate the reactive power and the harmonic current components of high power nonlinear loads.

Using two **PWM** voltage-source inverters in cascade, the compensation characteristics of the active power filter are significantly improved.

- First PWM inverter can be implemented with GTOs operating at lower switching frequency
- Second inverter can used IGBTs since it has to operate at higher switching frequency.

Section discusses the scheme [63] in terms of principles of operation, and the analysis under transient and steady state operating conditions. The computer simulation for the proposed active power filter has been done and the results show excellent static and dynamic performances.

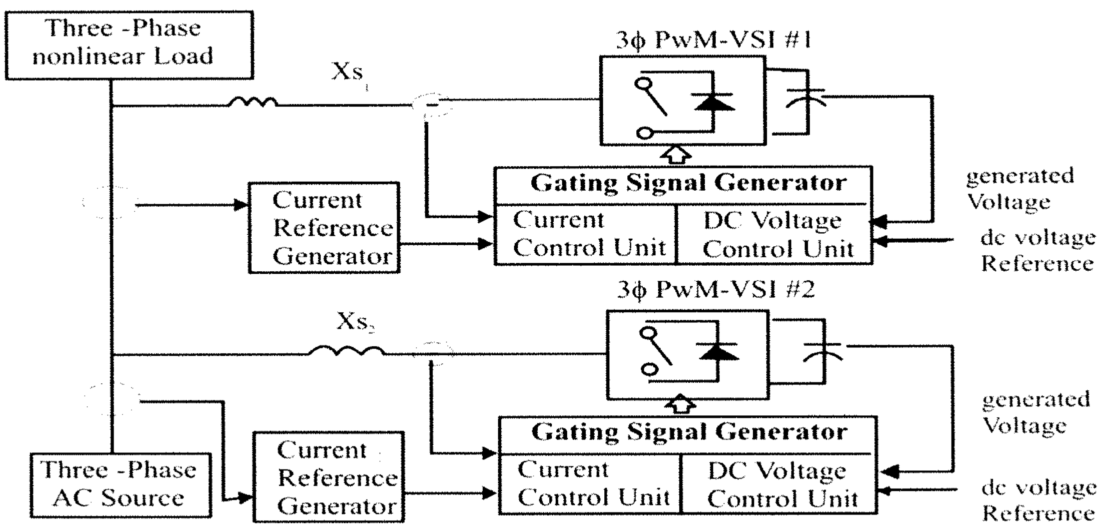

Fig 3.25 APF Configuration: TWO VSI in Cascade

The topology of the three-phase active power filter shown in Fig 3.25 is based on two three-phase force-commutated pulse-width modulation voltage-source inverters (PWM-VSI) connected in parallel to the nonlinear load. The two inverters are connected in cascade and operate with independent dc voltage and current control schemes

The control system of each PWM-VSI consists of four modules, the current generator circuit, the dc voltage control, the inverter output current control, and the gating signal generator. The current generator circuits use the concept of Instantaneous Reactive Power **[64]** to create the required reference signals. The gating signals of each inverter are generated by using a vector control techniques The proposed vector control technique allows to control the maximum switching frequency of each converter.

There are a number of articles which deal with the analysis of active power filters using force-commutated voltage-source inverters connected in parallel [65-69], the three-phase active power filter differs from previously discussed approaches in the following ways.

1. Each **PWM** voltage-source inverter operates with different switching frequency allowing the generation of specific current harmonic component of the load. In that way, the

converter connected closer to the load operates at lower switching frequency (650 Hz) and compensate the reactive power and the low frequency current components required by the load.

The second inverter operates at higher switching frequency (2 kHz) and compensates the high frequency current harmonic components that can not be generated by the first converter.

2. Since the converter connected closer to the load will generate a higher **rms** current and will operate at lower switching frequency, it can be implemented with GTOs or fast thyristors, which can stand highest rms current. The second inverter can be implemented with bipolar transistors or IGBT's since it will operate at higher switching frequency but will generate a lower rms current.

3. Current control **in** each **PWM** inverter is achieved with almost constant switching frequency

4. Current control is done in time domain allowing instantaneous compensation characteristics.

5. By connecting the two inverters in cascade a significant improvement in the active power filter compensation characteristics **is** achieved since the second inverter will generate all the current harmonic that the first converter is not able to provide.

Moreover, compared with active power filters using quad series PWM inverters **[65-66],** this topology requires less number of converters, a simple and conventional transformer, and a simpler control circuit and compared with active power filters implemented with parallel converters. APF *configuration in* [69] *has* a better compensation performance since the second converter compensates the current harmonics introduced by the low frequency PWM switching pattern used in the first converter.

3.7.1 APF Control System

It **is** well **known** that active power filters compensate current system distortion caused by nonlinear loads by injecting equal-but opposite current harmonic components at specific points of a power distribution system **[66].** The active power filter compensation characteristics depend mainly on the control strategy. The control system Fig 3.26 of each **PWM** inverter has to be able to generate the current reference waveform, maintain the dc voltage constant, and has to generate the inverter gating signals.

3.7.1.1 **Current reference generator**

Circuit defines the compensation characteristics and accuracy of the active power filter. The reference **signals** are generated by using the Instantaneous Reactive Power Concept, which allows a more flexibility in the active power filter compensation performance. Depending upon the reference signals used the active power fitter can compensate only the displacement power factor, only current harmonics or both at the same time. The instantaneous reactive power concept also allows the generation of the reference signals required to control the dc voltage.

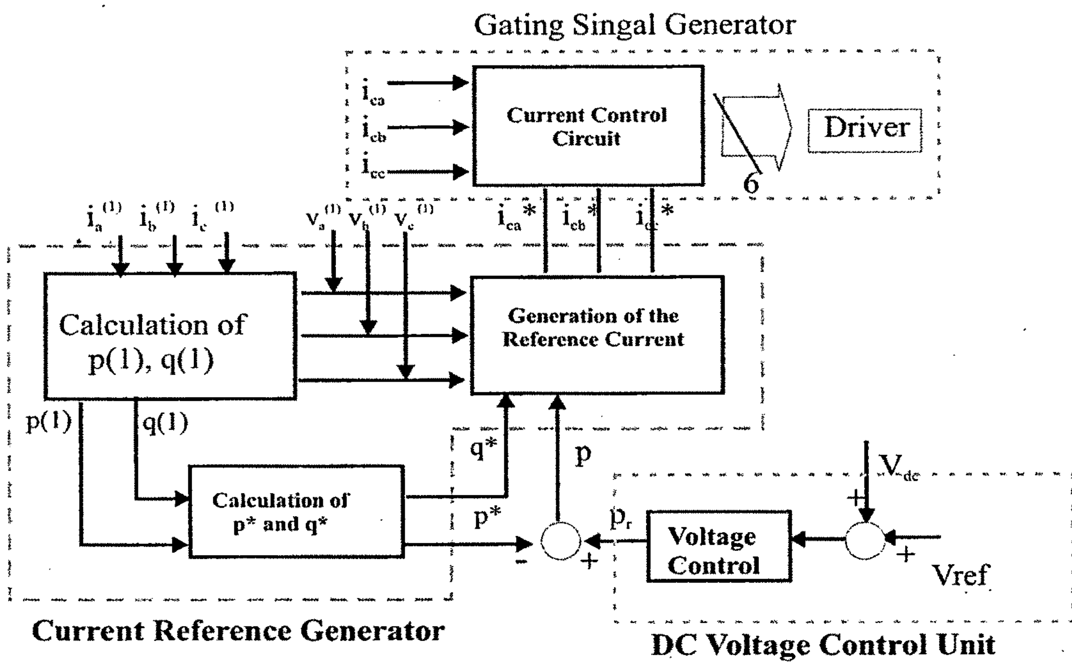

Fig 3.26 Block Diagram of APF Control System

If low frequency power variations are generated by the nonlinear load, the low pass filter used to generate p* does not allow their compensation, thus the voltage source inverter will experience low frequency dc voltage fluctuation. This problem can be solved by using a low pass filter tuned at a frequency lower than the fundamental Fig. 3.27.

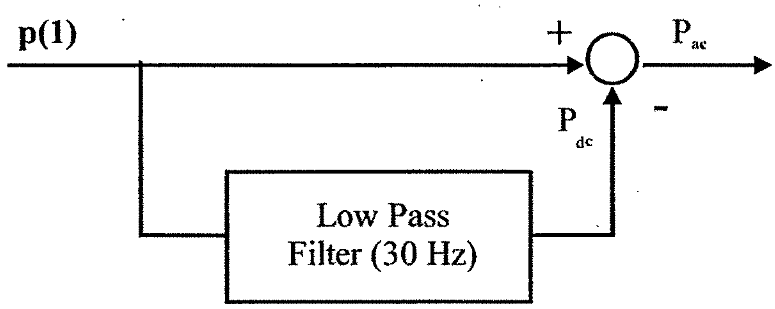

Fig 3.27 Power Reference Generator

3.7.1.2 DC Voltage Control Unit

Fig 3.25 shows that each PWM voltage source inverter is connected to a dc capacitor in the dc bus. Voltage control in the dc bus is performed by adjusting the small amount of real power absorbed by each converter. The real power flowing into each PWM voltage source inverter depends on the amplitude of the fundamental current component in phase with the respective phase to neutral voltage. The reference current of each phase contains a term in phase with the respective phase to neutral voltage, and with an amplitude proportional to P_{ave} which is obtained from the DC Voltage Control Unit Fig 3.26. By adjusting $P_{ave.}$ each inverter will absorb the real power required to cover the switching losses and to maintain the steady state dc capacitor voltage constant.

- The generation of the converter gating signals depends on the current control technique used in the PWM voltage-source inverter. The current control strategy plays an important role in active power filters. since it defines the converter switching frequency, the converter time response, and the accuracy to follow the current references. Also for high power applications it is very important to operate the inverter with a controlled switching frequency, and with a high voltage gain. Current control is achieved by using a vector control technique [70] and is not a predictive control but a feedback control, which has proved to present a better performance for active power filter applications.
- Current control is achieved by selecting the inverter output voltage that will minimize the current error signal. This control technique divides the reference frame in **six** regions Fig. 3.28 and identifies in which region the current error vector, Δi, is located and selects the inverter output voltage that will force the current error to change in an opposite direction, keeping the inverter output current closer to the reference signal. By selecting the inverter output Voltage that presents the largest opposite direction component to the current error a faster time response in the current control loop is achieved.

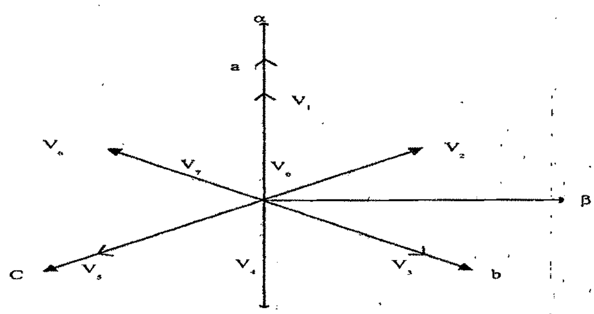

Fig 3.28 Regions of Inverter Output Voltage

In Table 3.6, all the possible switching combinations of the inverter aie shown One or zero of the switching functions **Sa, Sb,** and **Sc,** corresponds to the mode in which the upper side device or the lower side device is on respectively.

Table 3.6 PWM VSI Switching Functions

V(k)	K=0	K=1	K=2	K=3	K=4	K=5	K=6	K=7
(s_a,s_b,s_c)	000	100	110	010	011	001	101	111

Table **3.7** shows that the switching function is determined by the region in which Δi and E are located It is not necessary to know the magnitude of the error current vector, thus simplifying the current control circuit implementation. In case Δi needs to be changed faster it is necessary to determine which vector E-V(k) presents the higher component in the opposite direction to Δi

Table 3.7 Inverter Switching Mode

E Region	Δi region					
	1	2	3	4	5	6
I	V_1	V_2	V_2	$V_o - V_7$	$V_o - V_7$	V_1
II	V_2	V_2	V_3	V_3	$V_o - V_7$	$V_o - V_7$
III	$V_o - V_7$	V_3	V_3	V_4	V_4	$V_o - V_7$
IV	$V_o - V_7$	$V_o - V_7$	V_4	V_4	V_5	V_5
V	V_6	$V_o - V_7$	$V_o - V_7$	V_5	V_5	V_4
VI	V_1	V_1	$V_o - V_7$	$V_o - V_7$	V_6	V_6

If Δi is located below the δ region no commutation is applied to the inverter. If Δi is located between δ and ***h***, the switching modes shown in Table 3.7 must be applied, and if Δi passes through the ***h*** hexagon, then the control system is switched over to the faster loop and applies the switching modes defined in Table 3.8.

Table3.8 Switching Mode Combination for Larger Changes in Δi

Δi region	V(k)
1	V(1)
2	V(2)
3	V(3)
4	V(4)
5	V(5)
6	V(6)

Once the current control circuit has selected the region where **V(k)** must commutated, it verifies the time that has passed since the last commutation, and then it compares with the switching frequency selected for the inverter. If the time is higher or equal to 1/2fc a new switching function is applied to the inverter semiconductors. Figure 3.29 shows the block diagram of the inverter current control scheme

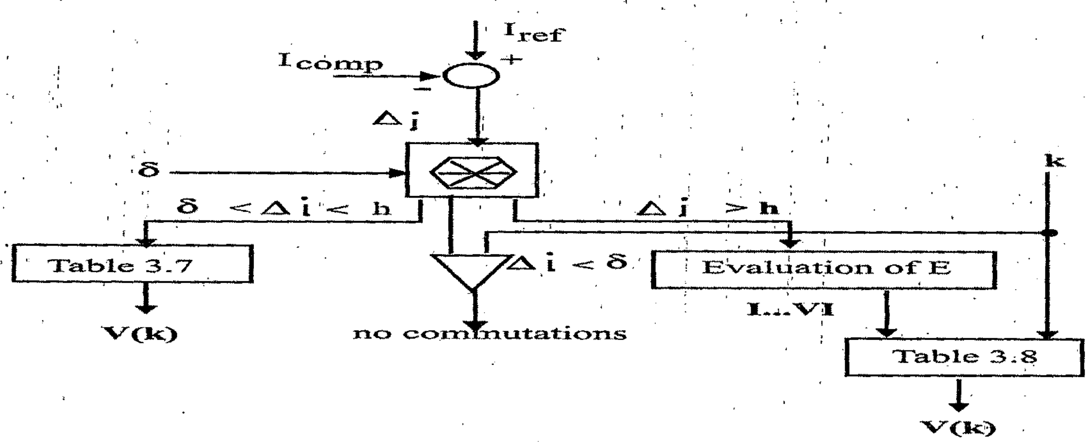

Fig 3.29 Current Control Scheme

The APF can be used in an application that requires displacement power factor correction and current harmonics compensation. The reference signals required by the active power filter were obtained by using the instantaneous reactive power concept Current control was implemented with a vector control technique each converter was operated at a different switching frequency, allowing the compensation of high power nonlinear loads.

3.8 APF Controller: Modified Instantaneous Reactive Power Control

Active power filter with the control circuit based on the modified instantaneous reactive power control algorithm is described. The control circuit uses digital signal processor ADSP-21065 to realize advanced current controller algorithm. The active power filter circuit was build and tested, experimental results are depicted in [71].

To suppress harmonics, an active power-harmonic compensation filter (APF) can be connected in series or in parallel with the supply network. The series APF is applicable to the harmonic compensation of a large capacity diode rectifier with a DC link capacitor. The parallel APF (shunt active power filter) permits to compensate the harmonics and asymmetries of the mains currents caused by nonlinear loads. Two version of harmonic compensation circuit with current-fed active power filter is depicted in Fig. 3.30. Fig. 3.30a shows APF without feedback (with unity gain), while in the Fig. 3.30b APF with feedback is shown. For better stability for realization APF without feedback was used in [71].

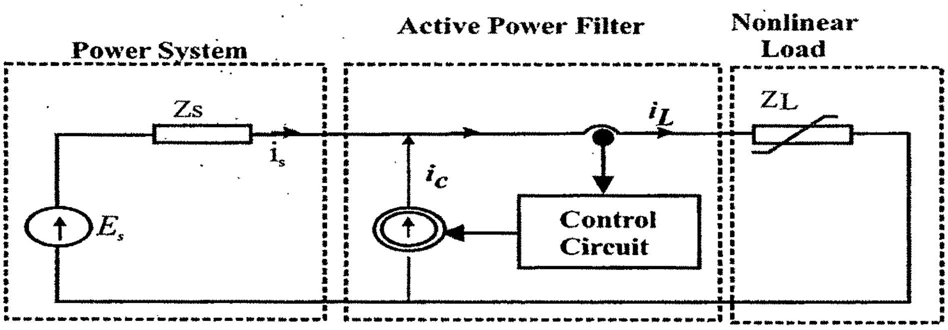

Fig 3.30 (a) Harmonic Compensation Circuit with current-fed APF without feedback (with unity gain)

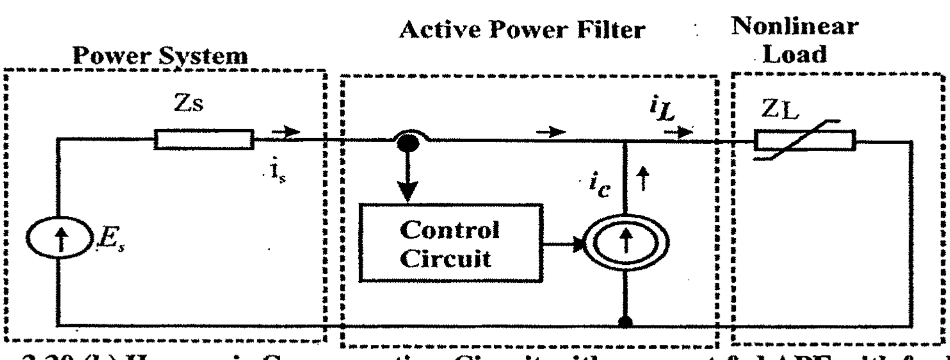

Fig 3.30 (b) Harmonic Compensation Circuit with current-fed APF with feedback

Simplified block diagram of the proposed active power compensation circuit with the parallel APF for power of 75 kVA is depicted in Fig. 3.31. The circuit consists of the power part with a three-phase IGBT power transistor bridge IPM (intelligent power module) connected to the AC mains through an inductive filtering system composed of inductors L_1, L_2, L_3. The APF circuit contains a DC energy storage, ensured by two capacitors C_1 and C_2. The control circuit is realized using the digital signal processor ADSP-21065. The active power filter injects the harmonic currents I_{C1}, I_{C2}, I_{C3} into the power network and offers a notable compensation for harmonics, reactive power and unbalance. The filter is designed for three and four wire loads.

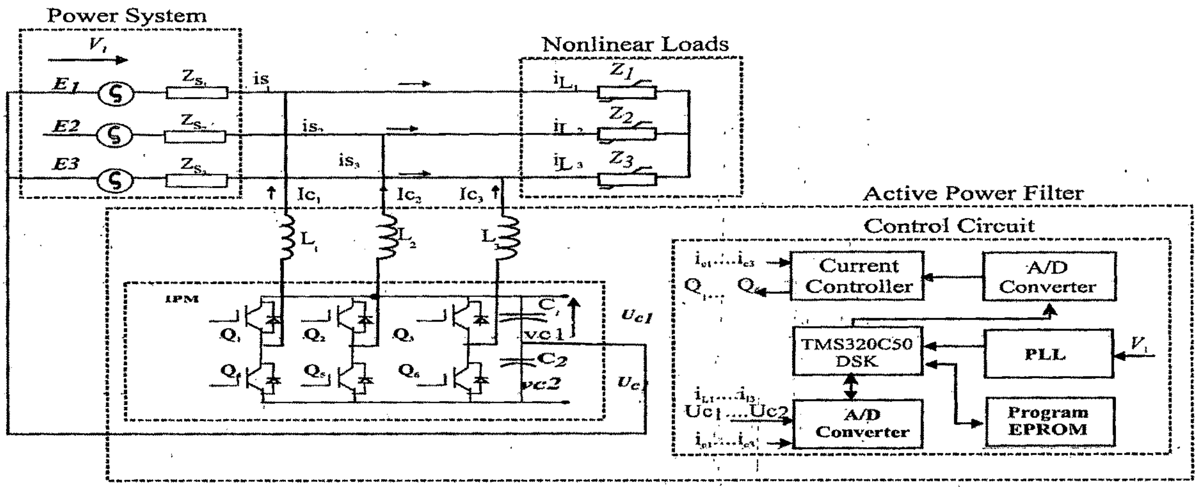

Fig 3.31 Simplified Block Schematic of Current-Fed APF

3.8.1. Control algorithm

Control algorithm for the proposed APF is based on the strategy resulting from the instantaneou reactive power theory initially developed by Akagi *et al* [72-75]). To the classical instantaneous reactive power algorithms are added as additional control parameters, they are described in Table 3.9.

Table 3.9 APF Control Parameters

Name	Value of Parameter
K_0	1- APF transistors are switch off, capacitor C1 and C2 are charged to initial voltage 510 volts 0- APF transistors are switched ON
K_1	1- APF compensator is switch off, capacitor voltage regulator is working,C1 and C2 are charged to nominal working voltage 690 V 0- APF compensator are switched ON
K_2	Value of parameter varying from 0 to 1 1- Harmonics and asymmetry are compensated 0- Full compensation of reactive power
K_3	3 wire or 4-wire circuit

The output compensation reference current signals $i_{CR1}(nTp1)$, $i_{CR2}(nTp1)$ $i_{CR3}(nTp1)$ are interpolated with oversampling ratio R=8, to signals $i_{CR1}(nTp2)$, $i_{CR2}(nTp2)$ $i_{CR3}(nTp2)$. Block diagram of the chosen polyphase interpolator based on FIR filter with periodically time-varying coefficients is depicted in Fig. 3.32

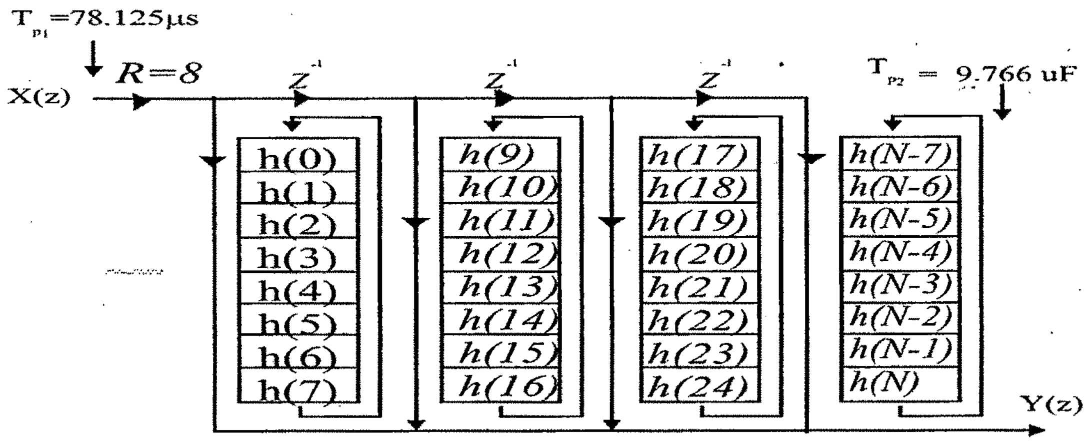

Fig 3.32 Poly phase Interpolator

Output compensation reference current\ signal are transformed to transistor controlling pulses by current controller. Initially in the proposed circuit a hysteresis current controller algorithm realized using the digital signal processor ADSP-21065 is employed. Hysteresis control algorithm is based on a nonlinear feedback loop with two-level hysteresis comparators. The inverter switching speed depends largely on the load parameters. In the proposed APF advanced hysteresis current controller with variable width of the hysteresis (Fig. 3.33) is applied.

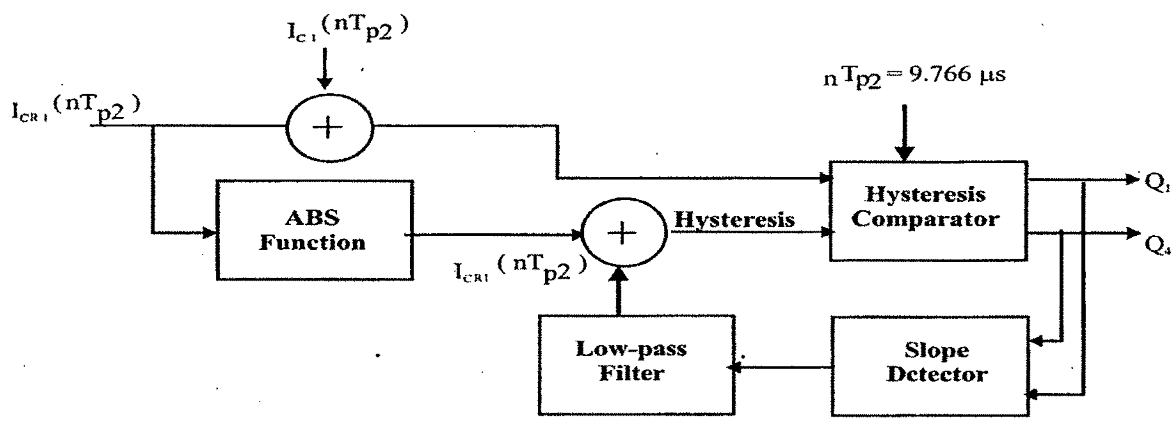

Fig 3.33 Hysteresis Current Controller Algorithm

The improvements are: maximum switching speed is limited, switching speed depends on the 'speed history' and the compensation reference current signals i_{CR1}; the higher the signal level the lower is the switching speed. The current controller algorithm, current delta sigma modulator (CDSM) [75] was implemented in[71].