Chapter 2

Active Power Filter: Configurations and Control Strategies

The increasing use of power electronics based loads (adjustable speed drives, switch mode power supplies, etc.) to improve system efficiency and controllability is increasing the concern for harmonic distortion levels in end use facilities and on the overall power system.

Active filters have the advantage of being able to compensate for harmonics without fundamental frequency reactive power concerns. This means that the rating of the active power filter can be less than a conquerable passive filter for the same nonlinear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another.

The active filter concept uses power electronics to produce harmonic components which cancel the harmonic components from the nonlinear loads. These active filters are relatively new and a number of different topologies are being proposed. Within each topology, there are issues of required component ratings and methods of rating the overall filter for the loads to be compensated. Development of a detailed model for the active filter using the Electro- Magnetic Transients Program (EMTP) facilitates the evaluation of these design and application considerations without extensive field tests

Active power filter (APF) is a power electronics system that can dynamically suppress harmonics and compensate reactive power regardless of their frequencies and amplitudes. The three-phase three-wire active power filter has been successfully developed. But the development of three-phase four-wire active power filter has a long way to go [1,2]. Like compensating methods to zero sequence current, the three-phase four-wire active power filters have different topologies.

Active power line conditioners, which are classified into shunt and series ones, have been studied with the focus on their practical installation in industrial power systems. In 1986, a combined system of a shunt active conditioner of rating 900 kVA and a shunt passive filter of rating 6600 kVA was practically installed to suppress the harmonics produced by a large capacity cycloconverter for steel mill drive. The largest one is 20 MVA, which was developed for flicker compensation for an arc furnace with the help of a shunt passive filter of 20 MVA. Many times the term "active power line conditioners" is used instead of that of "active power filters" because active power line conditioners cover a wider sense than active power filters.

2.1 UCI Control

Fig.2.1 shows two kinds of voltage source inverter (VSI): four-leg inverter and three-leg inverter. The four-leg inverter uses one switch leg specially to compensate zero sequence current. It can be looked as four-phase compensating device, so its controllability is better. The three-leg inverter has the zero line directly connected to the middle point of the dc bus. Compared with the four-leg inverter, it has lower number of semiconductor devices, so the control circuit is simpler. For the sake of capacity and cost, three-leg active power filter is preferred. But how to balance the voltage of two capacitors is a key problem.

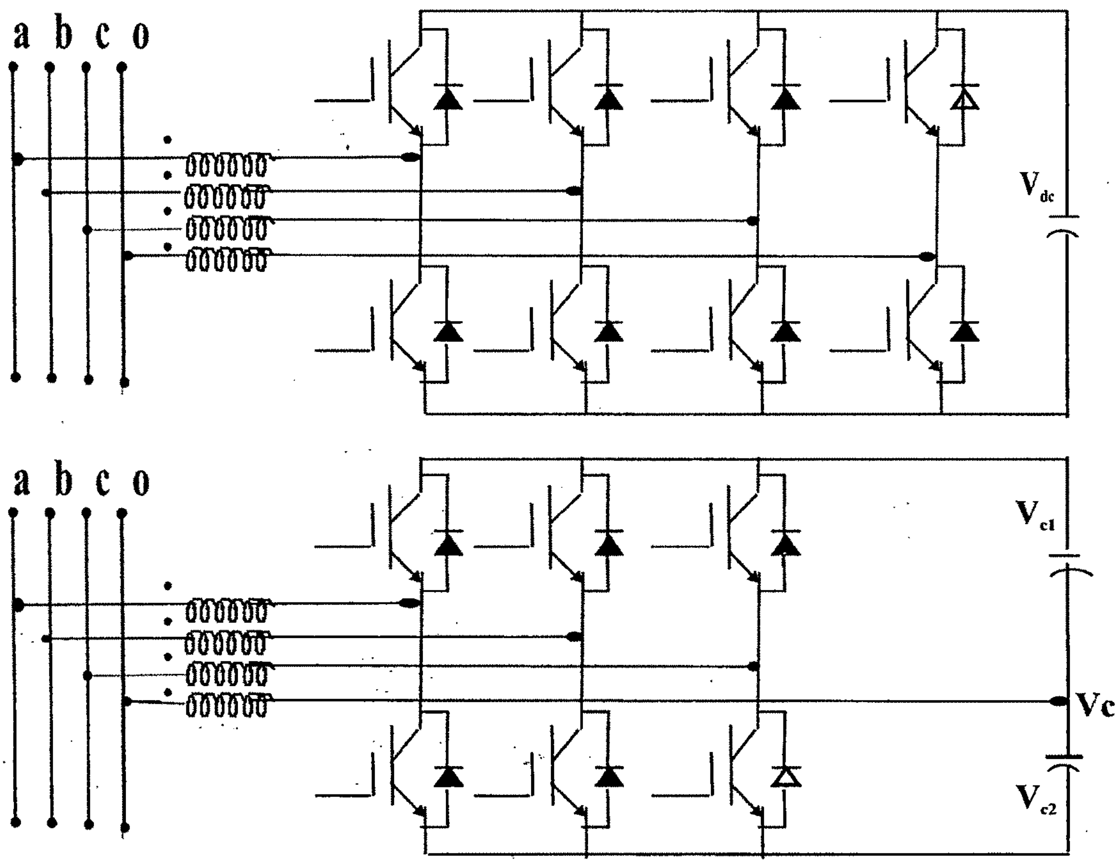


Fig 2.1 Three-leg and Four wire Inverter

UCI control is a nonlinear control method proposed by Keyue M.Smedley and Slobodan Cuk[3,4,5]. Its principle is to control the duty-ratio d to make the average value of a switched variable of the switching converter equal to or proportional to the control reference in each cycle. Compared with other methods, UCI has the constant switching-frequency of modulation, simple control circuit and no need to generate controlling reference. It does not require voltage and current sensors. It rejects power source perturbations.

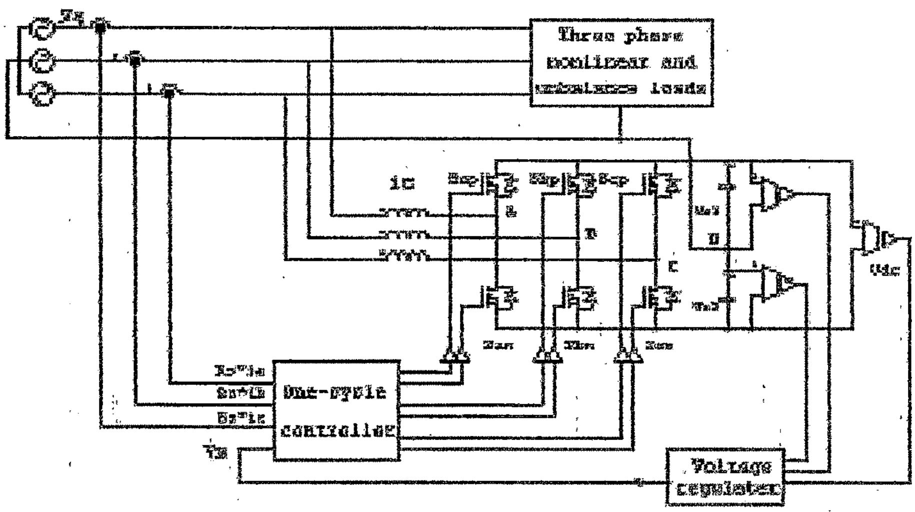


Fig 2.2 APF with UCI control

An APF with UCI control is shown in Fig.2.2. Its main structure is a three-level inverter, and the system is three-phase four-wire. D_{ap} , D_{an}...D_{cn} are the drive signals for switches S_{ap} , S_{an}...S_{cn} respectively. The two switches in the same leg always have different states, one is open the other is closed, so the duty ratios, for example, S_{ap}, S_{an} are d_{an} and $1/d_{an}$ respectively. The energy flows in both the direction between AC mains and inverter [6].

2.2 SLMC and PI Controller

Over the recent years, power quality has been given attention due to the intensively use of power electronic controlled applications in all branches of industry, such as controlling or converting AC power to feed electrical loads. As a result, harmonics were generated from the power converters or non-linear loads that caused the power system operate with low power factor, low efficiency, voltage and current distortions, and increased losses in transmission and distribution lines. Due to inability of passive filers to compensate random frequency variations in currents, tuning problems and parallel resonance, active power filters (APFs) are used.

The research and development of various APF configurations with their respective control strategies have been proposed, and have been gradually recognized as a viable solution to the problems created by high-power non-linear loads [1-4]. Active filters have been divided into AC and DC filters, DC filters compensate for voltage and current harmonics on the DC side of the converters for HVDC systems and on the DC link of a PWM inverter for traction systems [7].

Since, most of the active filters are often referred to as active AC filters, based on shunt APF with VSI-PWM configuration, [11] emphasizes on active AC filters. The reactive power compensation presented in this proposed APF system is achieved without the need of sensing the reactive current component of the load and the current compensation is done in the time domain allowing fast time response. Further more, the current control is achieved with constant switching frequency, producing a better switching pattern than the hysterisis current control [12-13]. This reduces the high-frequency current harmonics of the DC capacitor voltage.

The non-linear loads have led to the concerns over the allowable amounts of harmonic distortion injected into the supply system. Standards such as IEEE-519 have emerged to set and impose limits and recommended practices so that the harmonic distortion levels are kept in check, thereby promoting better practices in the design and operation of power system and electric equipment [14]. Based on observations from various references, a practical limit of less than 5% of the total harmonic distortion (THD) must be employed by any system designers and/or end-users to ensure compliance with the established standards [7,14].

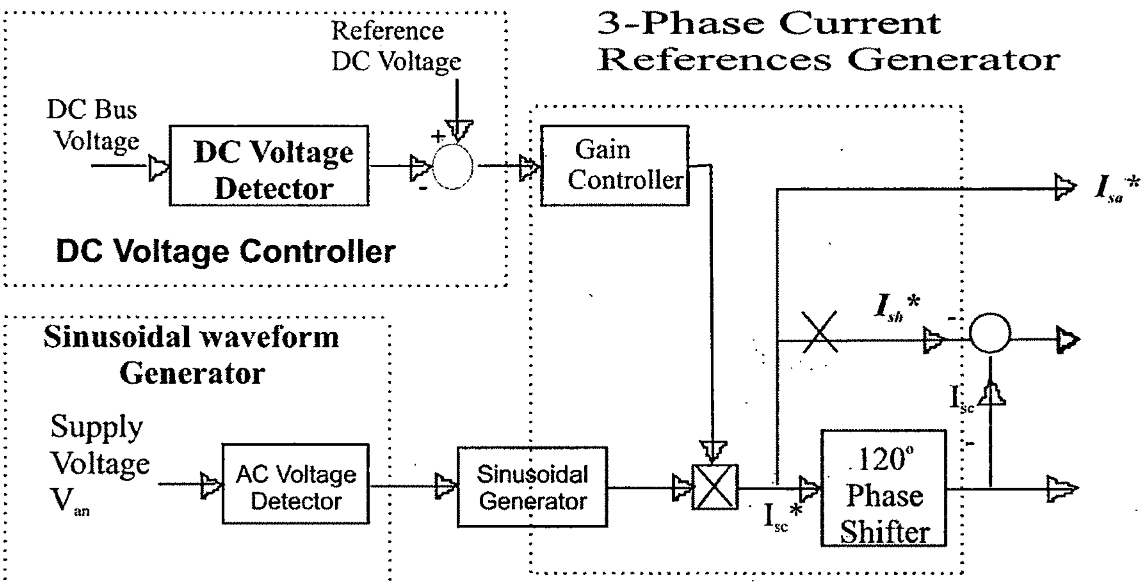


Fig 2.3 Block Diagram of Voltage Control Loop

The Time Domain Harmonic Detection Strategy of the supply current is utilized in this proposed three-phase APF system. Generally, there are two control loops, voltage control loop (VCL) and current control loop (CCL).

The proposed scheme [6]is mainly composed of a DC-voltage controller and a three-phase sinusoidal wave- form generator, as shown on Fig 2.3. In this circuit, the detected DC-capacitor voltage is subtracted from the reference DC voltage and its error is fed into the sliding mode controller (SLMC). The detail description of SLMC theory has been given in [14]. The generated output signal of the SLMC controller is the desired amplitude of the supplies current. By multiplying the DC signal with the sinusoidal waveform produced from the sinusoidal waveform generator, the reference current signal is obtained. The amplitude of this reference current is equal to the amplitude of the fundamental component of the load current plus or minus the error signal obtained from the VCL. If the detected amplitude of the DC capacitor is less than the reference DC voltage, this implies that the supplied real power from the mains has to be increased in order to compensate the demand from the load, and vice versa.

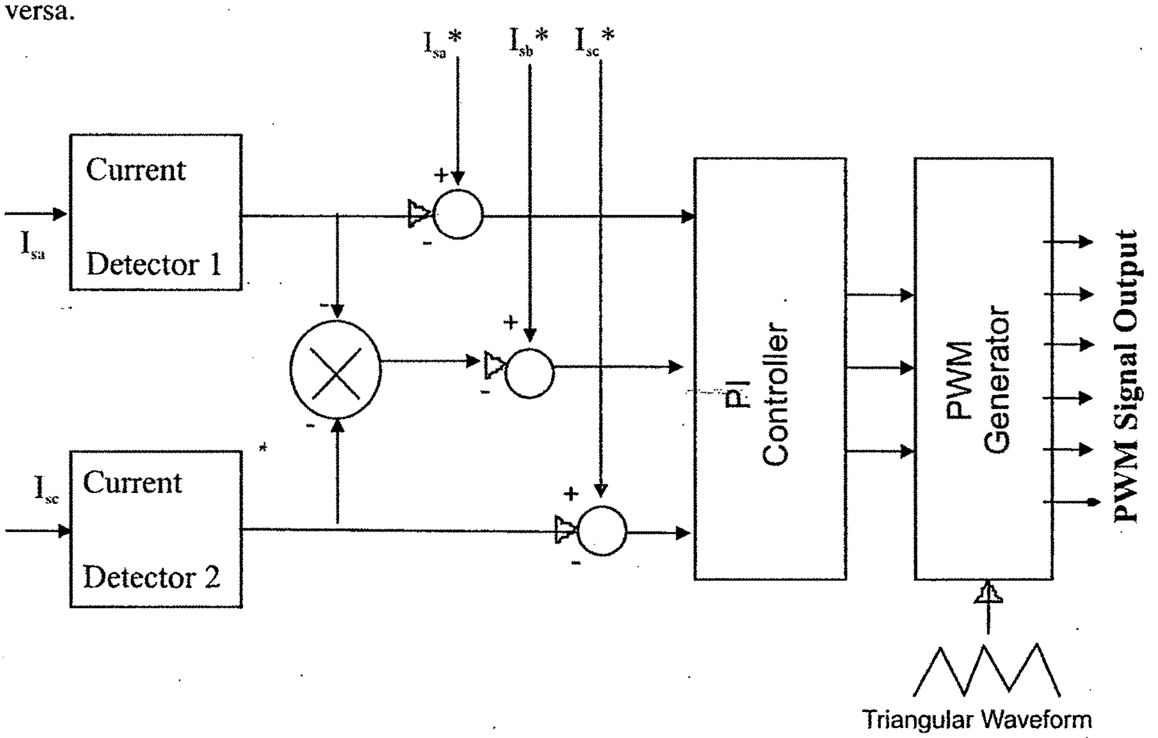


Fig 2.4 Block Diagram of Current Control Loop

Fig 2.4 shows the block diagram of CCL. In this circuit, the supply currents are first detected through the current detectors. Using a negative adding circuit, i_{sb} can be obtained. These currents (actual) are then compared with the generated three-phase reference currents obtained from the VCL. The difference (error) is then sent to the PI-controller.

A constant switching frequency is achieved by comparing the PI-controller's output signal with the reference triangular waveform. This method can be explained by considering the bang-bang hysteresis technique plus the addition of a fixed frequency triangular waveform inside the imaginary hysteresis window [15].

The purpose of using the triangular waveform is to stabilize the converter switching frequency by forcing it to be constant and equal to the triangular waveform frequency. If the variation of the generated current error from the PI-controller is larger than the peak of the reference triangular waveform, there will not be an intersection between the current error and the triangular waveform. The switching pattern will remain unchanged until the current error signal is decreased and a new intersection occurs.

The stability of the APF is reflected by its ability to keep the capacitor voltage as close as possible to the DC reference value. However, the DC capacitor voltage variation cannot be prevented due to the real power and reactive power injections and/or absorptions. The reactive power injections result in the ripple of the DC capacitor voltage and the active power absorptions from the mains also change the averaged DC capacitor voltage. This DC capacitor acts as an energy storage element and maintains the DC voltage as constant as possible in the steady state.

2.3 3D Space Vector Modulation

Distribution systems will typically have a great deal of single-phase load connected to them. Therefore distribution systems are inherently unbalanced. The load is also very dynamic and varies with time, theses factors contribute to increase dificulties in controlling the distribution voltage within certain limits. If the phases are unequally loaded, they produce undesired negative and zero sequence currents. The negative sequence will cause excessive heating in machines, saturation of transformers and ripple in rectifier [16,17]. The zero sequence currents cause not only excessive power losses in neutral lines [18], are undesirable or unacceptable for certain commercial and industrials users.

Efforts have been concentrated in the development of active power filter [19,20]. Using three-legged power converters to deal with unbalanced load and source has been addressed in [21, 22]. By engaging a feed forward control, the negative-sequence component caused by unbalanced source/load can be cancelled out so that the input power becomes a constant and the DC link voltage is free of low frequency even harmonic ripples. However, a three-legged power converter is incapable of dealing with zero-sequence unbalance. To solve the limitation, normally split DC link capacitors are used. The zero-sequence current path is provided by connecting the neutral point to the middle point of the two DC link capacitor [23]. The drawback of this scheme is that excessively large DC link capacitors are needed; therefore the cost is high, especially, for high voltage applications. To handle the zero-sequence component, the four-legged inverter [24] can substantially reduce the DC link capacitance.

Handling the voltage balancing using a four-legged inverter under balanced and unbalanced load condition in three phase four wires to consider zero sequence component and three-dimension space vector modulation is presented in [25]

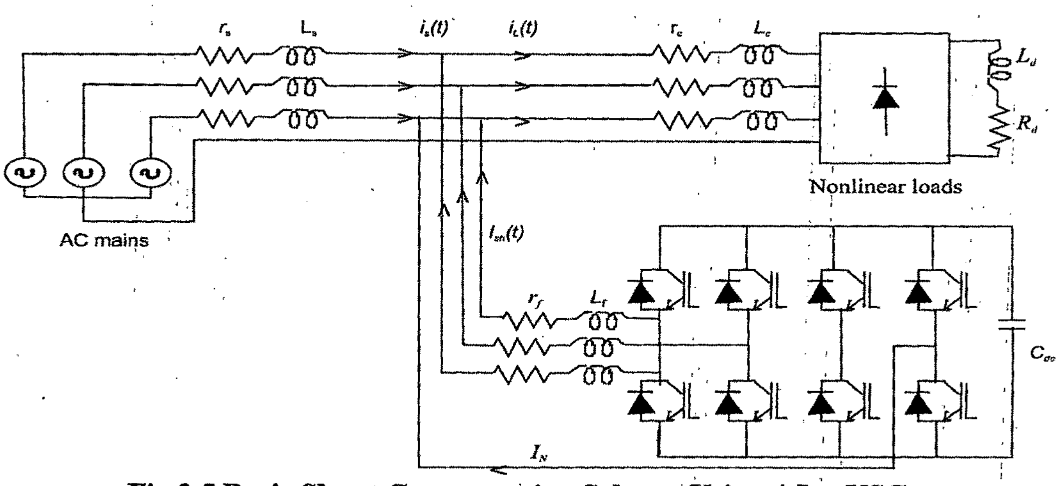


Fig 2.5 Basic Shunt Compensation Scheme Using 4-LegVSC

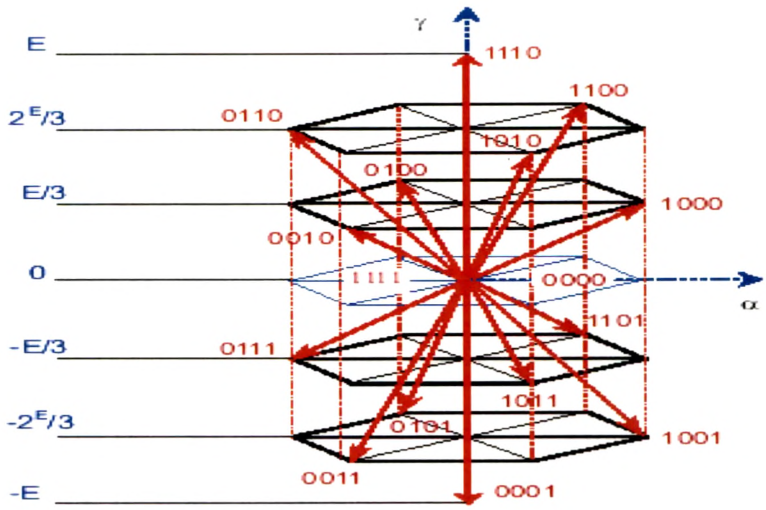


Fig 2.6 Switching Vectors of a three-phase four legged Inverter

In the conventional inverter, there are eight possible switch combinations. With an additional leg, the total number of switch combinations increases to sixteen. Table 2.1

States	Vα	Vβ	Vγ
1111	0	0	0
0001	0	0	- E
1001	(2/3)E	0	- (2/3)E
1101	(1/3)E	- (1/√3)E	- (2/3)E
0101	- (1/3)E	1/√3)E	- (2/3)E
0111	- (2/3)E	0	- (1/3)E
0011	- (1/3)E	- (1/√3)E	- (2/3)E
1011	(1/3)E	- (1/√3)E	- (1/3)E
1110	0	0	E
0000	0	0	0
1000	(2/3)E	0	(1/3)E
1100	(1/3)E	(1/√3)E	(2/3)E
0100	- (1/3)E	(1/√3)E	(1/3)E
0110	- (2/3)E	0	(2/3)E
0010	-- (1/3)E	- (1/√3)E	(1/3)E
1010	-- (1/3)E	- (1/√3)E	(2/3)E

Table 2.1: Switching Combination in the α-β-γ Coordination

- Current control: The APF based on the 4-leg VSC topology is presented in Fig. 2.5 variable $g_i(k)$, where i = 1; 2; 3 stand for the phase number and k is the VSC state number, are the switching functions. A value $g_i(k) = 0 /1$ means that the lower/upper IGBT is conducting. Obviously, in any leg, the IGBT's conduction is non simultaneous .The variable $g_4(k)$ is also a switching function, related with the fourth leg which is connected to the neutral wire. The 4-leg VSC topology enable to generate sixteen, k = (0…15) voltage space vectors,

$e_{\alpha\beta0}(k)$. The current control in the APF is achieved with space vector based current controller shown in Fig.2.7. This current controller is implemented with hysteresis comparators acting in the current errors.

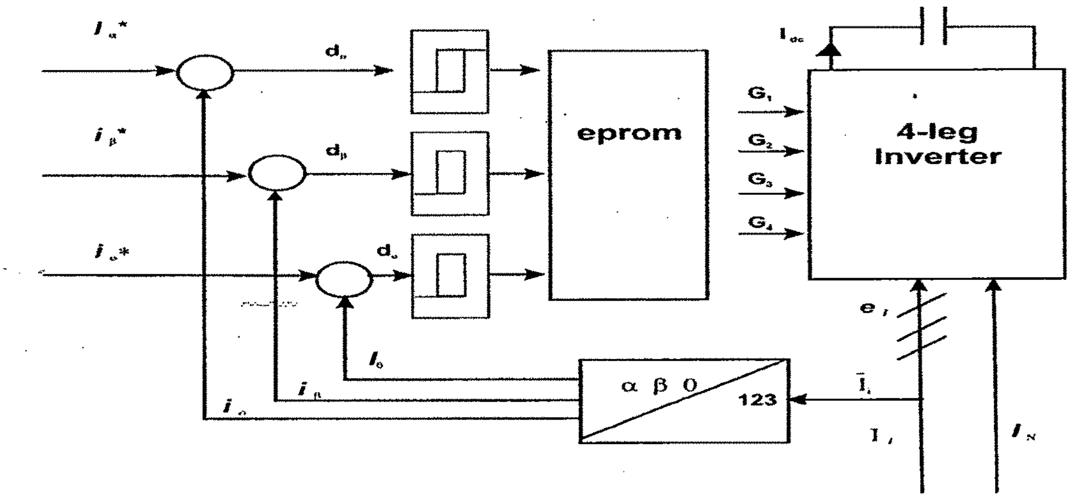


Fig 2.7: Control Circuit: A Three Phase Four Legged APF

Table 2.2 presents the switching variables $d_{\alpha\beta0}$, VSC state number and voltages, $e_{\alpha\beta0}(k)$ used in the space vector based current controller for the 4-leg VSC. Using this control strategy only eight (k = 2; 3; 5; 6; 10; 11; 13; 14) of sixteen possible states are used. However, there is always an approximated state k that satisfies all the voltage components required.

d_α	d_β	d_0	k	$e_\alpha(k)$	$e_\beta(k)$	$e_0(k)$
0	0	0	2	$e_{dc}/\sqrt{6}$	$e_{dc}/\sqrt{2}$	$2.e_{dc}/\sqrt{3}$
0	0	1	13	$e_{dc}/\sqrt{6}$	$e_{dc}/\sqrt{2}$	$-e_{dc}/\sqrt{3}$
0	1	0	6	$e_{dc}/\sqrt{6}$	$-e_{dc}/\sqrt{2}$	$2.e_{dc}/\sqrt{3}$
0	1	1	11	$e_{dc}/\sqrt{6}$	$-e_{dc}/\sqrt{2}$	$-e_{dc}/\sqrt{3}$
0	0	0	3	$-e_{dc}/\sqrt{6}$	$e_{dc}/\sqrt{2}$	$e_{dc}/\sqrt{3}$
0	0	1	14	$-e_{dc}/\sqrt{6}$	$e_{dc}/\sqrt{2}$	$-2.e_{dc}/\sqrt{3}$
0	1	0	5	$-e_{dc}/\sqrt{6}$	$-e_{dc}/\sqrt{2}$	$e_{dc}/\sqrt{3}$
0	1	1	10	$-e_{dc}/\sqrt{6}$	$-e_{dc}/\sqrt{2}$	$-2.e_{dc}/\sqrt{3}$

Table 2.2: Switching Variables used in the Space

The three-phase 4-wire APF control circuit proposed in Fig 2.8, is based on the above VSC topology. The space vector based current control [25] is used to achieve the current injection of the reference currents $i_{c\alpha\beta0}$ or $ic_{\alpha\beta0}{}^*$. The dynamic response of the control strategy (and overall active power filter) was studied [25, Fig 2.8] by switching the three single phase inverter feeding unbalanced load with the same commutation angle: $\alpha = 30^0$, under the following parameters:
Ac source 220V/50 Hz, $R_s = 1.2m\Omega$, $L_s = 32.8\ \mu H$, $R_c = 2.6m\Omega$, $L_c = 25\ \mu H$, $R_{L1} = 0:2$, $L_{L1} = 1$ mH, $R_{L2} = 0.66$, $L_{L2} = 2.6$ mH and $R_{L3} = 3$, $L_{L3} = 4$ mH

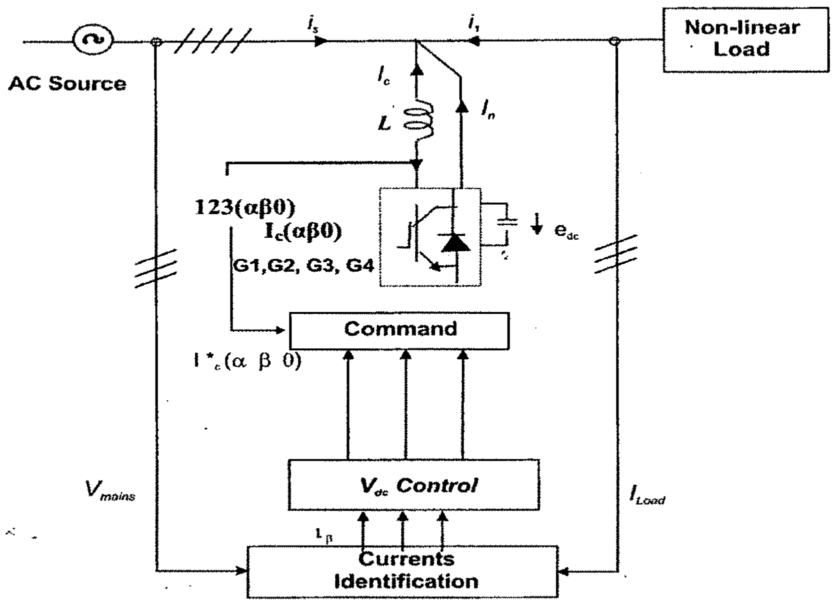


Fig 2.8: Control Circuit: A Three Phase Four Legged APF

2.4 Hybrid Active Filter

Non-linear loads such as diode or thyristor rectifiers and cycloconverters draw non-sinusoidal currents from utility grids, thus contributing to the degradation of power quality in utility or industrial power systems. Notably, voltage distortion or voltage harmonics in the power systems are becoming so serious that 5th and 7th harmonic voltages are barely acceptable at the customer-utility point of common coupling [26]

As reported in [27,28], the maximum value of 5th harmonic voltage in the downtown area of a 6.6kV power distribution system exceeds 7% under light-load conditions at night. The 5th harmonic voltage increases on the 6.6 kV bus in the secondary of the primary distribution transformer installed in a substation, whereas it decreases on the 77-kV bus in the primary under light-load conditions at night. These facts based on the actual measurement suggest that the increase of 5th harmonic voltage on the 6.6kV bus at night is due to harmonic resonance between line inductors and shunt capacitors for power factor correction installed on the distribution system. This harmonic resonance may occur, not only in utility power systems, but also in industrial power systems for factories, plants, office buildings and so on. Harmonic damping, therefore, would be as cost-effective in mitigating harmonic voltages and currents as harmonic compensation [29].

Hybrid filters consisting of active and passive filters connected in series or parallel with each other combines the advantages of both filters, thus leading to the best effectiveness in cost/performance [30-36]. Control schemes for the active filter have been presented to provide the required functions such as harmonic compensation, harmonic damping and/or harmonic isolation.

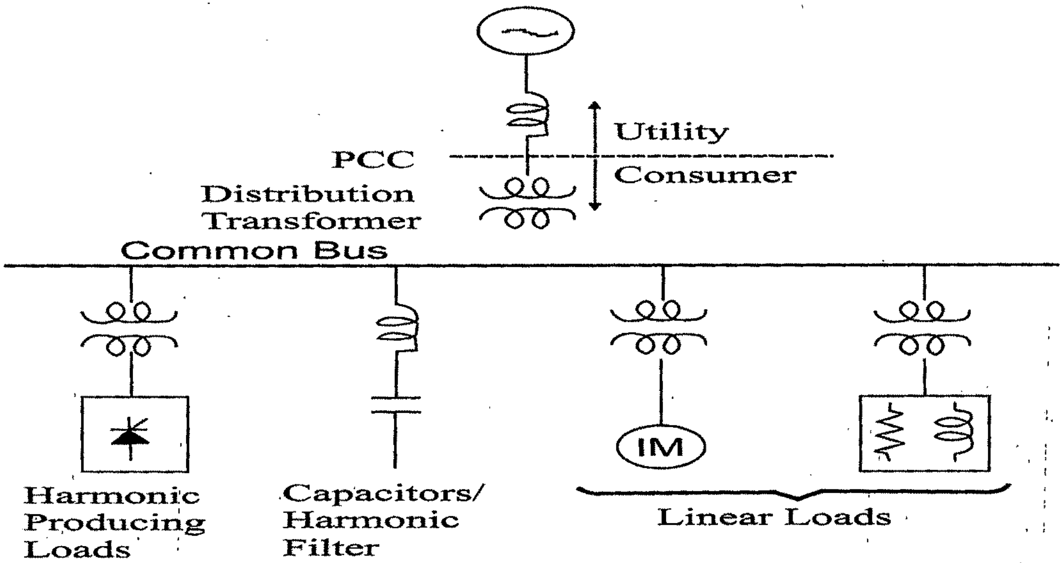


Fig 2.9: Industrial Power System

Hybrid active filter Fig 2.9 consisting of a small-rated active filter and a specially designed passive filter is proposed in [37]. The active and passive filters are connected in series with each other. The hybrid filter is connected in parallel with other loads in the vicinity of the secondary of a distribution transformer installed at the utility-consumer point of the common coupling (PCC). It is, therefore, different in the point of installation from pure active filters and hybrid active filters which have been installed in the vicinity of harmonic-producing loads. The purpose of installing the hybrid filter proposed in this paper is to damp the harmonic resonance in industrial power systems, as well as to mitigate harmonic voltages and currents. It also describes the principle of operation of the hybrid filter and discusses three different harmonic detection methods for the active filter used in the hybrid filter. Experimental results obtained from a 20-kW laboratory model Fig 2.10 verify the viability of the hybrid filter and its effectiveness in harmonic damping and harmonic mitigation.

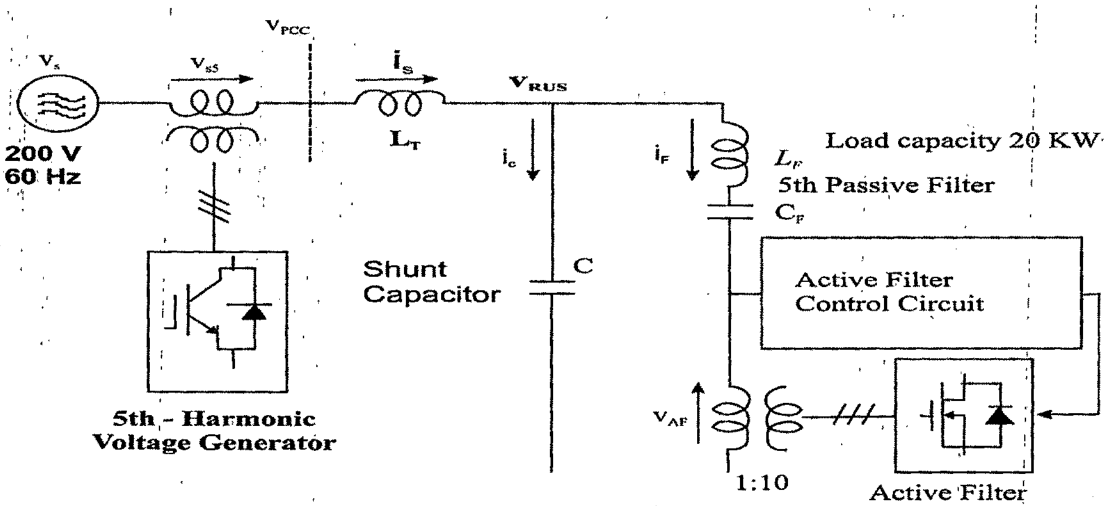


Fig 2.10: Experimental System

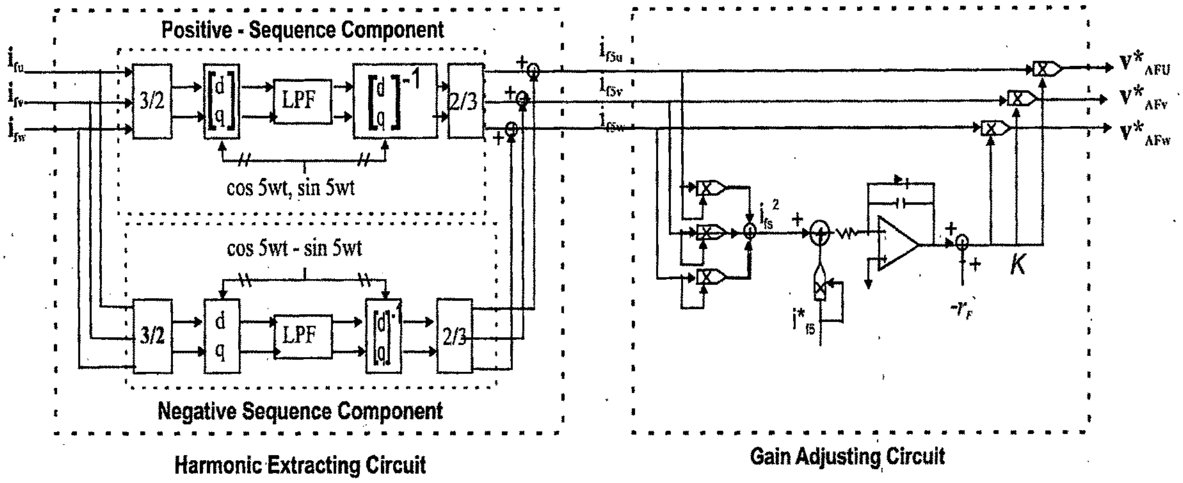


Fig 2.11: Block Diagram of Control Circuit

Fig. 2.11 show a block diagram of the control circuit for the active filter. It consists of two parts; a circuit for extracting the 5th harmonic current from the passive filter current i_F and a circuit for automatically adjusting the gain K. The reference voltage for the active filter, V_{AF}* is given by V_{AF}* $K * i - 5$: where the gain K is determined in the gain-adjusting circuit.

A. Harmonic-extracting circuit: The extracting circuit detects three phase currents flowing into the passive filter through three AGCTs, and then the two phase currents on the a-β coordinates are transformed to those on the d - q coordinates by using a unit vector (*cos 5wt,* sin *5wt)* with a rotating frequency of five times as high as the line frequency. As a result, only 5th- harmonic positivesequence currents on the d - q coordinates are converted into two dc components, and the fundamental current and other harmonic currents into ac components. Therefore, the 5th harmonic positive sequence currents can be extracted from the currents on the d - q coordinates through two first-order low-pass filters (LPFs) with a corner frequency of 0.1 Hz. The inverse d - q transformation is applied to the extracted 5th-harmonic positive sequence currents, producing three-phase positive sequence 5th harmonic currents. To extract 5th-harmonic negative sequence currents, the same signal processing as the 5th-harminc positive sequence currents is performed except for employing another unit vector (cos *5wt,* -sin *5wt)* with the opposite rotating direction. Finally, the extracted positive and negative sequence currents in each phase are added to obtain three-phase 5th harmonic currents.

B. Gain-adjusting *circuit:* The gain-adjusting circuit calculates a square of the extracted 5th harmonic current for every phase, and then sums all of the three, producing i_{FS}^2 **as** follows:

$$i_{FS}^2 = i_{F5u}^2 + i_{F5v}^2 + i_{F5w}^2.$$

5th harmonic voltage is injected upstream of the **PCC** by the harmonic voltage generator, **as** shown in Fig. 2.10, 1.3% 5th harmonic voltage is injected, in order to reduce the 5th harmonic; current flowing into the capacitor for power factor correction.

The circuit compares i_{F5}^2 with a square of a limitation value i^*_{p5} When i_{F5}^2 is smaller than the square of i_{F5}^*, the circuit sets the gain in such a way as K = $-r_F$. When i_{F5}^2 is larger, an integral feedback controller in the circuit adjusts the gain in such a way as to make i_{F5}^2 equal $i^*_{F5}{}^2$. The purpose of the gain-adjusting circuit is to prevent the passive filter and the active filter from overheating and over current, and therefore the circuit requires a control response as slow as 1-4 seconds.

2.5 Combined Configuration: Shunt Passive and Series Active Filters

Harmonic interference problems generated by bulk thyristor converters become increasingly serious as they are widely used in industrial applications and transmission/distribution systems. So far, shunt passive filters have been used to suppress harmonics in power systems. As shown in Fig 2.12, a shunt passive filter exhibits lower impedance at a tuned harmonic frequency than the source impedance to reduce the harmonic currents flowing into the source. In principle, filtering characteristics of the shunt passive filter are determined by the impedance ratio of the source and the shunt passive filter. The shunt passive filter has the following problems.

- The source impedance, which is not accurately known and varies with the system configuration, strongly influences filtering characteristics of the shunt passive filter.
- The shunt passive filter acts as a current sink to the harmonic voltage included in the source voltage, Vs. In the worst case, the shunt passive filter falls in series resonance with the source impedance. At a specific frequency: $f_0 = 1/2\pi\ [(L_s + L_F).C_F]^{1/2}$ a parallel resonance occurs between the source impedance and the shunt passive filter, which is the so-called harmonic amplifying phenomenon.

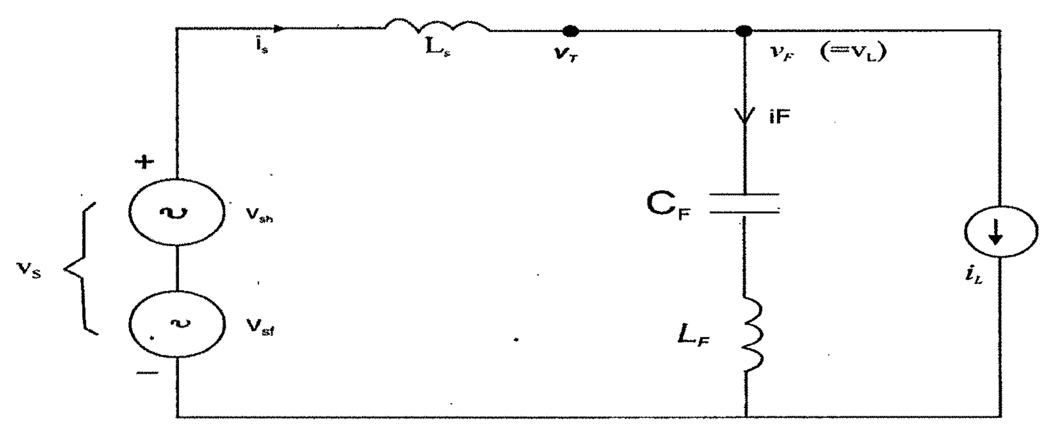


Fig 2.12: Basic Principle of Shunt Passive Filter

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 [38]. As shown in Fig.2.13, a shunt active filter is controlled in such a way as to actively shape the source current, i_s into sinusoid by injecting the compensating current, i_c. This is considered as the arch 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 [38] presented a family of shunt and series active filters, and established the concept of the active filters consisting of PWM inverters using power transistors [38]. 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.

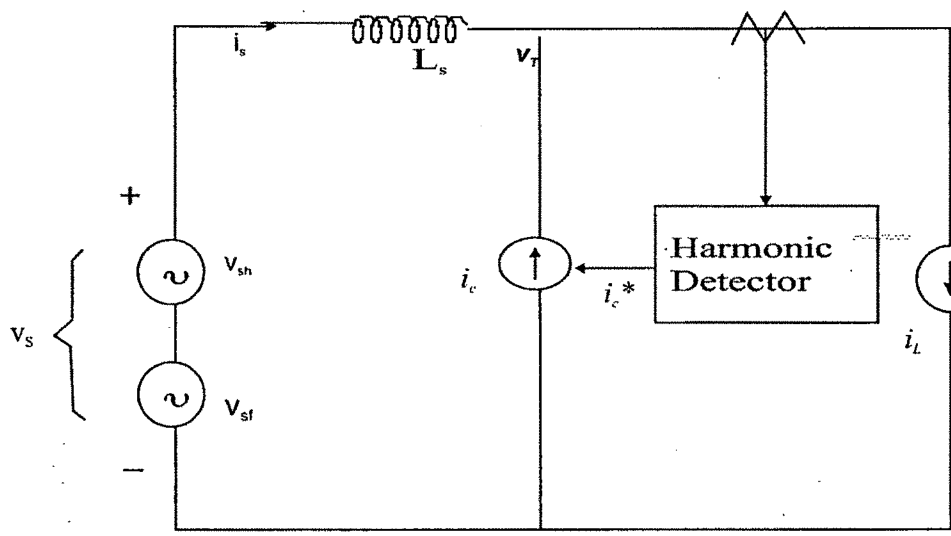


Fig 2.13: Basic Principle of Shunt Passive Filter

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. [39] presented a practical means for injecting the compensating current, which was implemented using naturally commutated thyristor inverters with a specially designed 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 [40-50]. At the same time, the following problems of shunt active filters have been pointed out, delaying their practical uses [41-43].

- 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 to 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[44]

Conventional shunt passive and active filters have the problems described above, which make their practical applications difficult

It is known that filtering characteristics of a shunt passive filter partially depend 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.

1. Higher the source impedance, the better the filtering characteristics.
2. 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. [51] combines the use of a shunt passive filter and a small rated series active filter as shown in Fig 2.14.

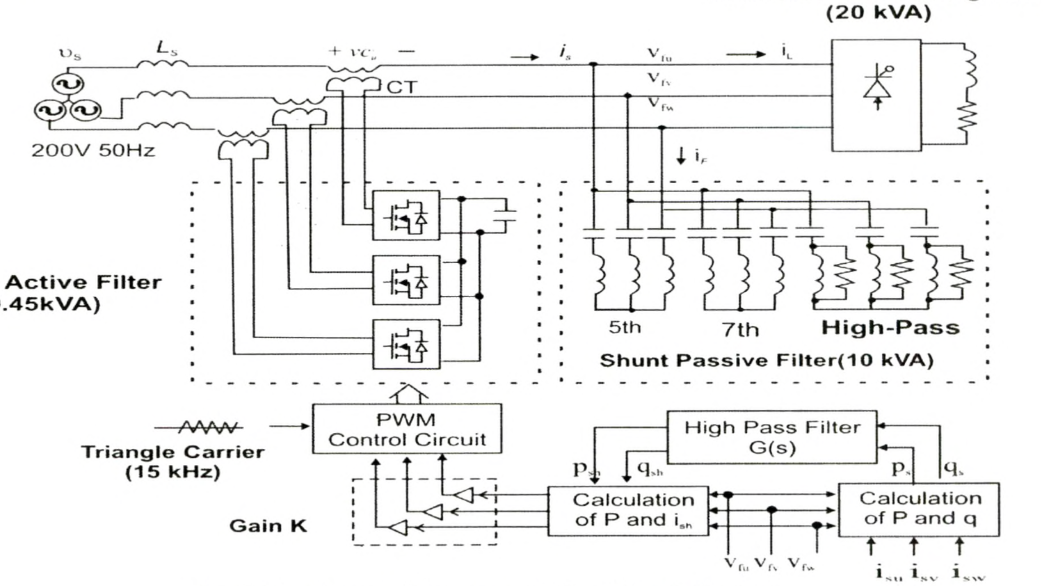


Fig 2.14: Circuit Diagram of Combined System

2.6 The unified power quality conditioners (UPQC)

A specially designed 12-pulse thyristor rectifier of 5–8 MVA is required to generate a strong magnetic field with high stability as a low-voltage high-current dc power supply for super-conductive material tests, proton synchrotron accelerators, and so on.

The thyristor rectifier has to be equipped with a filter consisting of reactors and capacitors on its dc terminals to prevent current ripples from flowing into electromagnet. The filter can easily eliminate high-frequency current ripples accompanying ac/dc power conversion. It is, however, difficult to reduce low-frequency current ripples caused by a supply voltage flicker with a frequency range from 1 to 20 Hz. It is pointed out that such a voltage flicker appearing at the point of common coupling (PCC) results from large capacity arc furnaces and/or cycloconverters installed on the same or upstream power system.

The unified power quality conditioners (UPQC's) aims at the integration of series-active and shunt-active filters. The main purpose of a UPQC is to compensate for voltage flicker/imbalance, reactive power, negative sequence current, and harmonics. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The control strategy of the UPQC, with a focus on the flow of instantaneous active and reactive powers inside the UPQC. Experimental results obtained from a laboratory model of 20 kVA, along with a theoretical analysis, are shown to verify the viability and effectiveness of the UPQC. [51] deals with unified power quality conditioners (UPQC's) [52-54], which aim at the integration of series active [55-61] and shunt-active filters. The UPQC, therefore, is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage flicker/imbalance.

[51] presents two types of UPQC's. One is a general UPQC for power distribution systems and industrial power systems. The other is a specific UPQC for a supply voltage- Flicker/imbalance-sensitive load, installed by electric power consumers on their own premises. Much attention is paid in [52] to the specific UPQC consisting of a series active and shunt-active filter. The series-active filter eliminates supply voltage flicker/imbalance from the load terminal voltage, and forces an existing shunt-passive filter to absorb all the current harmonics produced by a nonlinear load. Elimination of supply voltage flicker, however, is accompanied by low frequency fluctuation of active power flowing into or out of the series-active filter. The shunt-active filter performs dc-link voltage regulation, thus leading to a significant reduction of capacity of the dc capacitor. [52] Reveals the flow of instantaneous active and reactive powers inside the UPQC and shows experimental results obtained from a laboratory model of 20 kVA.

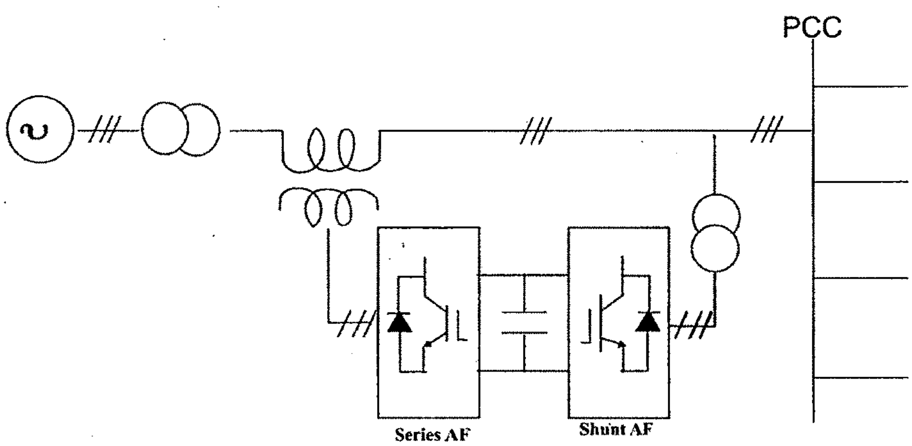


Fig 2.15: unified power quality conditioners (UPQC)

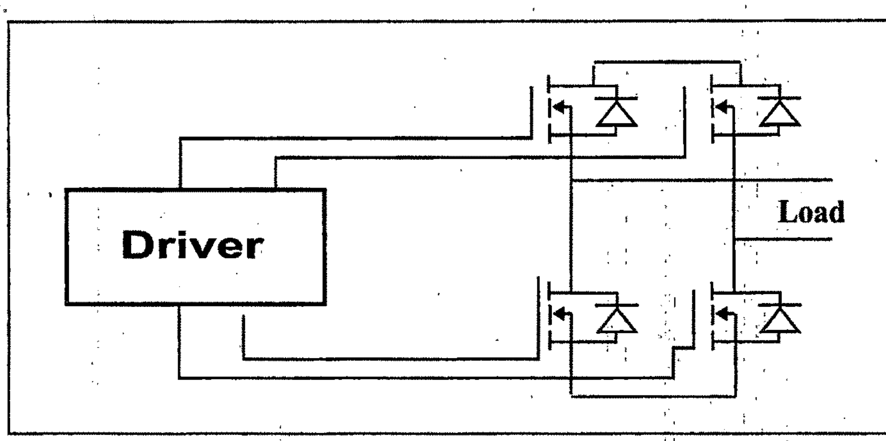
2.7 VS-APF using MULTI-STAGE CONVERTER and DC-LINK.

Multi-stage converters [62-64] work more like amplitude modulation rather than pulse modulation, and this fact makes the outputs of the converter very much cleaner. This way of operation allows having almost perfect currents, and very good voltage waveforms, eliminating most of the undesirable harmonics. And even better, the bridges of each converter work at a very low switching frequency, which gives the possibility to work with low speed semiconductors, and to generate low switching frequency losses.

The performance advantages of a multi-stage converter used as an active filter and VAR compensator are depicted in [65]. The filter is used to compensate a contaminated load with small power factor and to feed the load during voltage dips. The results are compared with conventional PWM modulators working at a switching frequency of 10 kHz. All the load parameters of both types of converters are set at the same values.

- **BASICS OF MULTI-STAGE CONVERTERS**

The circuit of fig.2.16 shows the basic topology of one converter used for the implementation of multi-stage converters. It is based on the simple, four switches device, used for single phase inverters. These converters are able to produce three levels of voltage in the load: +Vdc, -Vdc, and Zero.



2.16: Three-level Module for building Multiconverters

References [66-68] have proposed a per phase power conversion scheme for synthesizing multilevel waveforms, connecting many converters like the one shown in figure 2.1 in series, but with all the dc voltages equal to "Vdc". Such a multilevel inverter with 'n' equal dc voltage levels can offer only 2n+1 distinct voltage levels at the phase output. The references [69-70] go one step ahead with dc voltages varying in binary fashion, which gives an exponential increase in the number of levels. For 'n' such cascaded inverters, with dc voltage levels varying in binary fashion, one can achieve (2^{n+1}-1) distinct voltage levels. In this paper, the outputs of the modules are connected thorough transformers whose voltage ratios are scaled in power of three, allowing 3^n levels of voltage. Then, with only four converters (n=4), 81 different levels of voltage are obtained: 40 levels of positive values, 40 levels of negative values, and zero. As a comparison, the first topology only achieves 9 levels with four converters, and the second topology just 81 levels.

Fig. 2.17 displays the main components of the four-stage converter which is being used in this paper as an active filter. The figure only shows one of the three phases of the complete system.

As can be seen, an Ultra capacitor of 1F is used in the DC link. The transformer located at the bottom of the figure has the highest voltage ratio, and will be called Master. The rest of the modules will be the Slaves. The Master works at the lowest switching frequency, which is an additional advantage of this topology.

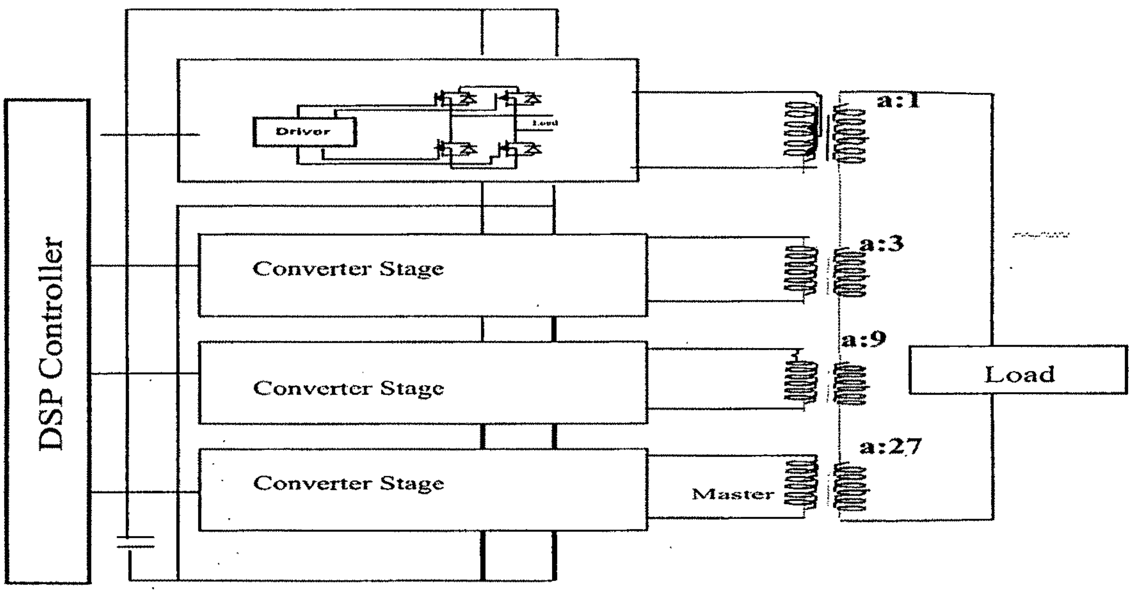


Fig 2.17: Main Components of the Four-Stage Multiconverter

With 81 levels of voltage, a four-stage converter can follow a sinusoidal waveform in a very precise way and can control the load voltage as an AM device (Amplitude Modulation) or, if the DC voltage varies, it can maintain a constant sinusoidal voltage at the load, compensating the DC variations by changing the amplitude modulation. This change in the modulation is easily done by changing the amplitude of the sinusoidal reference by the ratio of the actual DC voltage to the ideal voltage. The same amplitude voltage wave can be achieved with different voltages at the DC Ultra capacitor, which are obtained through the control of the gates of the power transistors in each one of the four converters. This allows using the energy stored at the Ultra capacitor to feed the load during voltage Dips. All the AM control of the voltage is done using DSP control.

- Active Filter Configuration: Fig. 2.18 shows a typical configuration for a shunt active power filter, using PWM strategy. The source is feeding a contaminating load, such as a power rectifier, and the active filter, connected in parallel, injects the harmonics to the load needs, and the power system sees a cleaner sinusoidal current waveform. Nevertheless this filter produces significant switching looses, electromagnetic noise and its output voltage has high frequency noise content.

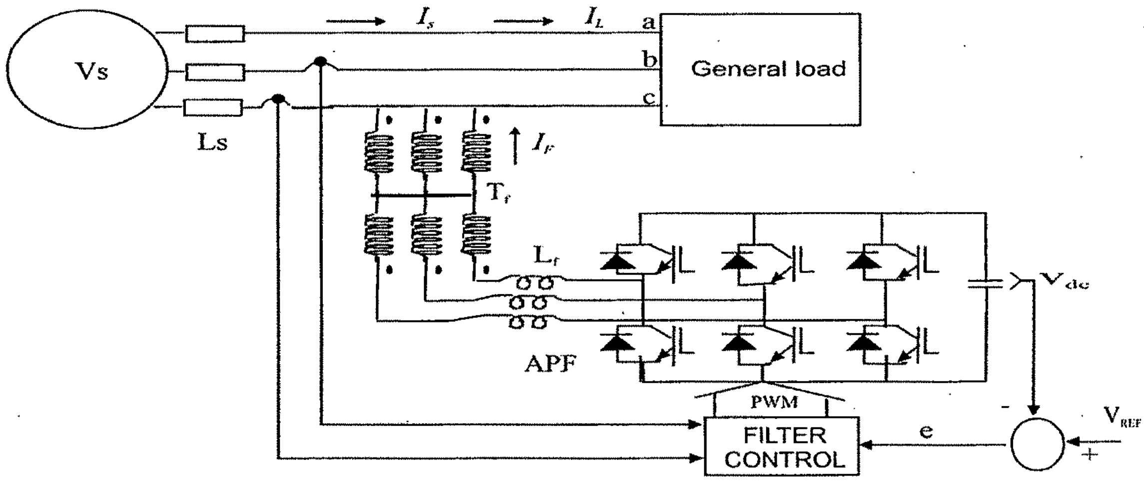


Fig 2.18: Shunt Active Filter using PWM Techniques

The same filter can be constructed replacing the classic PWM-driven converter by a multiconverter like the one mentioned before, achieving low switching looses and low electro-magnetic noise. Fig 2.19 shows the topology and its main components.

Three converters, like the one shown in Fig. 2.17 are connected to the same capacitor at the DC side and in star at the AC side. The capacitor voltage is simply controlled by shifting the angle of the voltage wave at the filter's output. The output voltage is practically sinusoidal; therefore all harmonic currents consumed by the load are fed by the filter.

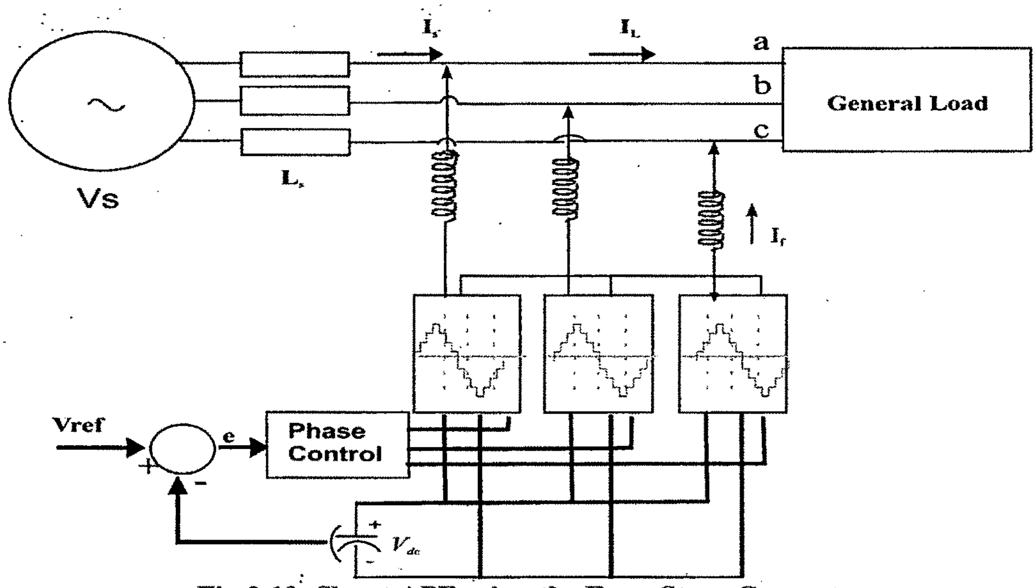


Fig 2.19: Shunt APF using the Four-Stage Converter

Fig 2.20 shows a comparison between PWM and multilevel converter methodologies obtained using PSIM [71],

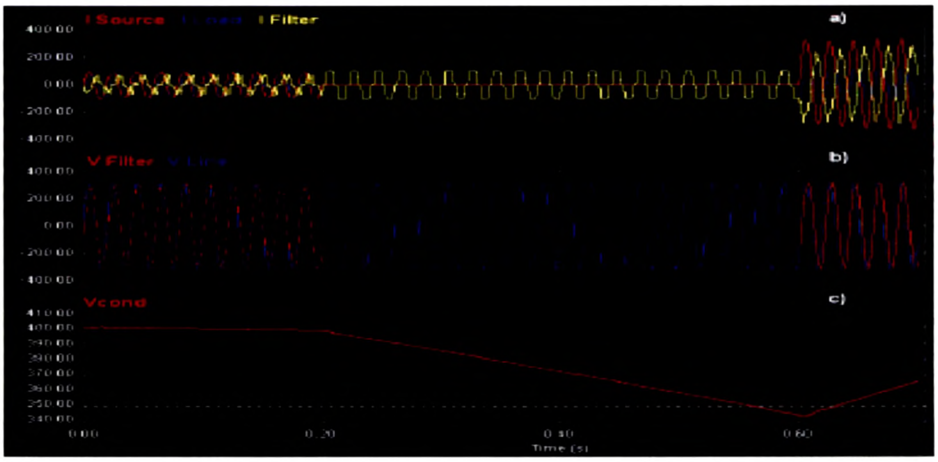


Fig. 2.20 Results from simulation: (a) Source, load and filter currents. (b) Filter (load) and line voltages. (c) Ultra capacitor voltage.

Fig. 2.20 shows a plot of the line, load and filter currents during the simulation. Also the filter's output voltage and the DC Ultra capacitor's voltage are shown. Ultra capacitors' voltage drop represents the energy supplied by the capacitor during the Voltage Dip. After the voltage from the source is re-established, the control modifies the filter's voltage angle to inject active current to the filter and recover the capacitor's voltage level. As can be seen in Fig. 2.20, the source currents are perfectly sinusoidal, and with unity power factor. Also, the load currents are completely fed by the filter during the voltage Dip. This demonstrates that this kind of multiconverter works perfectly as Voltage-Dip-proof filter delivering quasi-sinusoidal voltages.