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Shunt Active Filter for Power Quality Improvement

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ABSTRACT: In the present work a new control algorithm based on Instantaneous power theory (p-q theory) for three phase four wire is taken for a Shunt Active Power Filter (SAPF) to compensate harmonics and reactive power and power factor of a three phase nonlinear load, uncontrolled bridge rectifier . Sensing load currents, dc bus voltage and source voltages compute reference currents of the SAPF. Driving signals of SAPF are produced by feeding reference and actual output currents of APF, to hysteresis band current controller. As proposed model contains three phase four wire system neutral current compensation also taken care by SAPF. Here in this dissertation two cases are considered of different load situation at rectifier side, such as nonlinear load alone and unbalance load with nonlinear load. It is found that under both the load cases the SAPF is very effective solution for current harmonics, reactive power compensation and power factor correction. MATLAB / SIMULINK ® power system toolbox is used to simulate the proposed system

INTRODUCTION

Recently, wide application of nonlinear and time-varying devices has led to distortion of voltage and current waveforms in ac networks. Consequently, harmonics, sub-harmonics and inter-harmonics are often present in voltage and current spectra. Passive filters are conventional solutions to mitigate harmonics but the limitation of passive filters for compensating has made active filters attractive. The passive filters have been used as a conventional solution to solve harmonic currents problems, but they present some disadvantages: they only filter the frequencies they were previously tuned for; its operation cannot be limited to a certain load or group of loads; resonance can occur due to the interaction between the passive filters and others loads, with unexpected results. To cope with these disadvantages, recent efforts have been concentrated on the development of active power filters. In this paper the development of a shunt active filter is proposed, with a control system based on the p-q theory. With this filter it is possible to effectively compensate the harmonic currents and the reactive power (correcting power factor to the unity), and also to balance the power supply currents (distributing the loads for the three-phases in equal form, and compensating zero-sequence current).

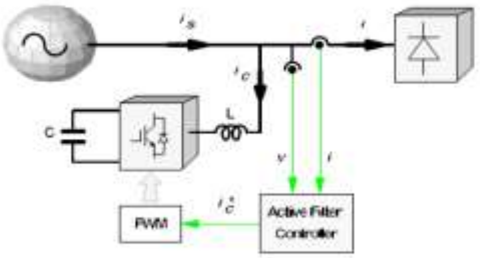


Fig.1 Schematic diagram of shunt active filter

Active power filters are flexible and versatile solution to voltage quality problems. Improvement of technologies devoted to ac induction machine drive and, in particular, realization of fast electronic switches has developed the use of active filters for harmonic and power factor compensation. Several works on active filter controllers based on synchronous reference frame transformation are implemented . Shunt active filters using traditional control methods have successfully been used to compensate for basic power quality problems such as current harmonics, reactive power and load imbalance.

Shunt active power filters are normally implemented with pulse-width modulated voltage source inverters. In this type of applications, the pwm-vsi operates as a current controlled voltage source and compensates current harmonics by injecting equal-but opposite harmonic compensating current. A fundamental topic for shunt active filter design is the selection of a compensating strategy, thatis, the procedure for evaluating the reference compensating current. Various current control methods were proposed for shunt active filter. Hysteresis current control method is the most popular one in terms of quick current controllability, versatility and easy implementation.

1. Classification of Active Filters

A. Classification based on objective:

Who is Responsible for Installing Active filters? The objective of "who is responsible for installing active filters" classifies them in to the following two groups:

A) Active filters of installed by individual consumer on their own premises near one or more identified harmonic producing loads:

B) Active filters installed by electrical power utilities in substation and /or on distribution feeders.

The main purpose of the active filter installed by individual consumers is to compensation for current harmonics and/or current imbalance of their own harmonic producing loads.On the other hand ,the primary purpose of active filter installed by utilities in the near future is to compensate for voltage harmonics and voltage imbalance ,or to provide "harmonic damping "throughout power distribution system. In addition active filters have the function of harmonic isolation at the utility –consumer point of common coupling in power distribution system.

B. Classification by System Configuration

Shunt Active Filters and Series Active Filters:

fig 2 shows a system a system configuration of a shunt active filter used alone, presents the electrical scheme of a shunt active filter for a three-phase power system with neutral wire, which is able to compensate for both current harmonics and power factor. Furthermore, it allows load balancing, eliminating the current in the neutral wire. The power stage is, basically, a voltage-source inverter with only a single capacitor in the DC side (the active filter does not require any internal power supply), controlled in a way that it acts like a current-source. From the measured values of the phase voltages (va, vb, vc) and load currents (ia, ib, ic), the controller calculates the reference currents (ica*, icb*, icc*, icn*) used by the inverter to produce the compensation currents (ica, icb, icc, icn). This solution requires 6 current sensors and 4 voltage sensors, and the inverter has 4 legs (8 power semiconductor switches).For balanced loads without 3rd order current harmonics (three-phase motors, three-phase adjustable speed drives, three-phase controlled or non-controlled rectifiers, etc) there is no need to compensate for the current in neutral wire. These allow the use of a simpler inverter (with only three legs) and only 4 current sensors.It also eases the controller calculations.

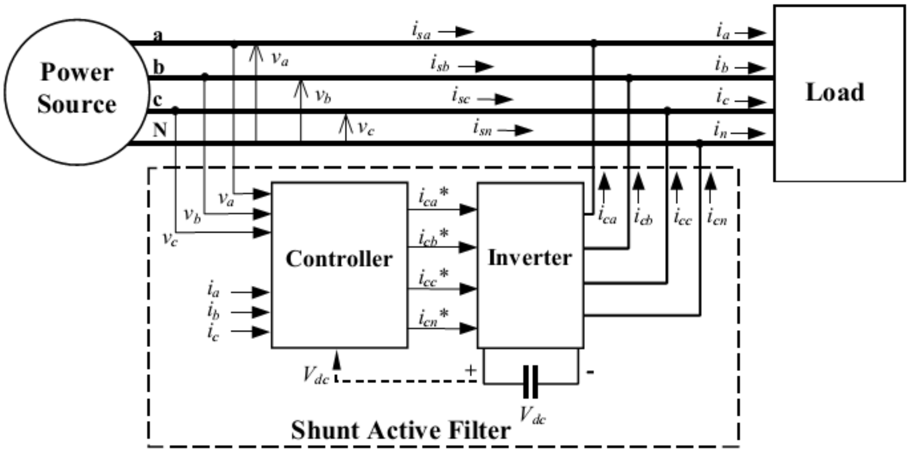


Fig. 2 - Shunt active filter in a three-phase power system.

Fig. 3 shows the scheme of a series active filter for a three-phase power system. It is the dual of the shunt active filter, and is able to compensate for distortion in the power line voltages, making the voltages applied to the load sinusoidal (compensating for voltage harmonics). The filter consists of a voltage-source inverter (behaving as a controlled voltage source) and requires 3 single-phase transformers to interface with the power system. The series active filter does not compensate for load current harmonics but it acts as high-impedance to the current harmonics coming from the power source side. Therefore, it guarantees that passive filters eventually placed at the load input will not drain harmonic currents from the rest of the power system.

Another solution to solve the load current harmonics is to use a shunt active filter together with the series active filter (Fig. 4), so that both load voltages and the supplied currents are guaranteed to have sinusoidal waveforms.

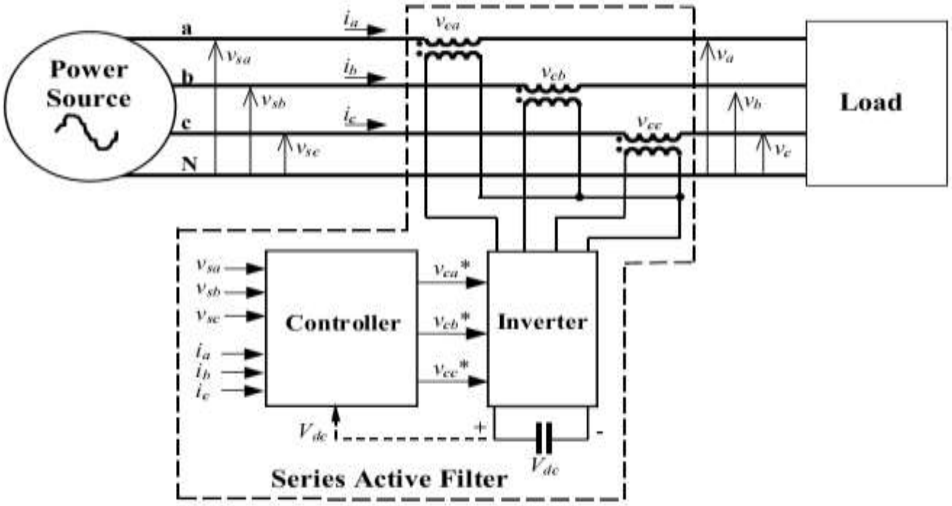


Fig. 3- Series active filter in a three-phase power system.

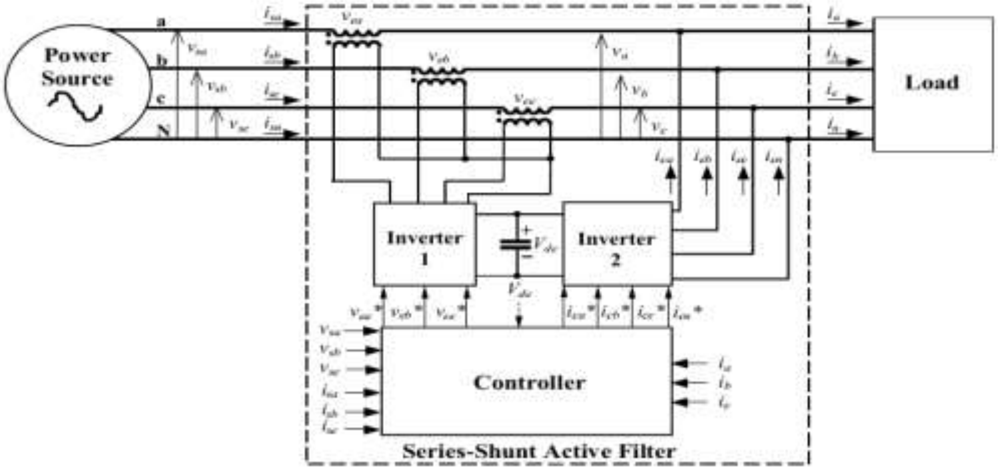
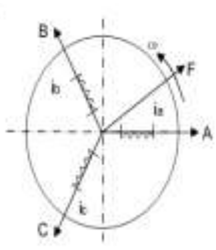
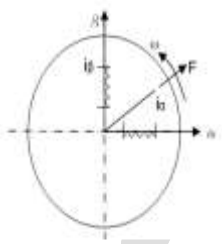


Fig. 4– Series-shunt active filterin a three-phase power system.

2.Instantaneous power theory

In three-phase circuits, instantaneous currents and voltages are converted to instantaneous space vectors. In instantaneous power theory, the instantaneous three-phase currents and voltages are calculated as following equations.





These space vectors are easily converted into the α–β orthogonal coordinates

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

…………………………(1)

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\mathrm{a} \\ i_\mathrm{b} \\ i_\mathrm{c} \end{bmatrix}$$

……………………………(2)

Considering only the three-phase three-wire system, the three-phase currents can be expressed in terms of harmonic positive, negative and zero sequence currents. In Equations (1) and (2), α and β are orthogonal coordinates. Vα and iα are On α axis, vβ and iβ are on β axis. In three-phase conventional instantaneous power is calculated as follows:

$$p = v_\alpha i_\alpha + v_\beta i_\beta$$

……..………(3)

In fact, instantaneous real power (p) is equal to following equation:

$$p = v_a i_a + v_b i_b + v_c i_c$$

…………(4)

Instantaneous real and imaginary powers are calculated as Equations(5):

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

………………(5)

In Equation(5),vα iα and vβ iβ are instantaneous real (p) and imaginary (q) powers. Since these equations are products of instantaneous currents and voltages in the same axis. In three-phase circuits, instantaneous real power is p and its unit is watt. In contrast vα iβ and vβ iα are not instantaneous powers. Since these are products of instantaneous current and voltages in two orthogonal axes, q is not conventional electric unit like W or Var.qis instantaneous imaginary power and its unit is Imaginer Volt Ampere (IVA) . These power quantities given above for an electrical system represented in a–b–c coordinates and have the following physical meaning.

¯ p, the mean value of the instantaneous real power corresponds to the energy per time unity which is transferred from the power supply to the load, through a–b–c coordinates, in a balanced way.

˜ p, alternated value of the instantaneous real power—it is the energy per time unity that is exchanged between the power supply and the load through a–b–c coordinates.

¯ q, instantaneous imaginary power—corresponds to the power that is exchanged between the phases of the load. This component does not imply any exchange of energy between the power supply and the load, but is responsible for the existence of undesirable currents, which circulate between the system phases.

˜q, the mean value of the instantaneous imaginary power that is equal to the conventional reactive power. The instantaneous active and reactive power includes ac and dc values and can be expressed as follows:

$$\begin{aligned} p &= \bar{p} + \tilde{p} \\ q &= \bar{q} + \tilde{q} \end{aligned}$$

…………………(6)

dc values of the p and q (¯ p,¯ q) are created from positive-sequence component of the load current. ac values of the p and q (˜p,˜ q) are produced from harmonic components of the load current. Equation(5)can be written as Equation(7):

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix}$$

……………………………………(7)

From Equation(7), in order to compensate harmonics and reactive power instantaneous compensating currents (icα and icβ) on α and β coordinates are calculated by using − ˜ p and −q as given below

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} -\tilde{p} \\ -q \end{bmatrix}$$

………………………………………(8)

In order to obtain the reference compensation currents in the a–b–c coordinates the inverse of the transformation given in expression (9) is applied:

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}$$

……………(9)

Method

3. Selected Method for Study

The p-q theory based shunt APF is implemented for Harmonic compensation and power factor correction.

3.1 Specification of the design:

Simulation is performed on 2 types of **Three phase Balanced Non –Linear Load** as follows:

System Parameters

Source Voltage	Vsa, Vsb, Vsc	220v
System Frequency	f	50 Hz

APF

Load 1 Thyristor Rectifier (of rating 4 KVA)supplying to DC motor equivalent of 2.5KW

AC side inductance	L Lac	1 mH
AC side resistance	R Lac	0.01 Ω
DC side Resistance	R Ldc	18 Ω
DC side Inductance	L Ldc	85mH

Load 2 Diode rectifier (of rating around 3KVA) supplying to purely resistive load

DC side Resistance	R L dc	18 Ω

3.3 Calculation of $\bar{p}$

According p-q theory real and imaginary power can be separated into two parts: Real power: $p = \bar{p} + \tilde{p}$

Imaginary Power : $q = \bar{q} + \tilde{q}$

Where $\bar{p}$ and $\bar{q}$ are average power due to component $i_{\overline{ap}} and\ i_{\overline{aq}}$ respectively $\tilde{p}$ and $\tilde{q}$ are oscillating power due to components $i_{\widetilde{ap}} and\ i_{\widetilde{aq}}$ respectively.

And $i - (i_{\widetilde{ap}} + i_{\widetilde{aq}})$ will produces a purely sinusoidal waveform. But in order to achieve unity power factor APF must compensate for $\bar{q}$ from component $i_{\overline{aq}}$. Thus, i- $(i_{\widetilde{ap}} + i_{\widetilde{aq}} + i_{\overline{aq}})$

will produce purely sinusoidal waveform with unity power factor.

Thus, inverse transformation $i_{\overline{ap}}$ will produce reference current i_S^* for each phase. $i_{\overline{ap}}$ can deduced from $\bar{p}$ which is filtered out using low pass filter from p.

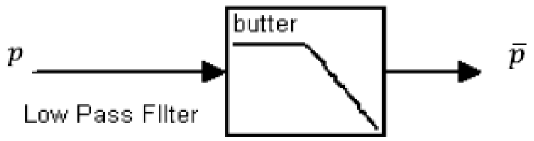


Fig 3.5 $\bar{p}$ from p using Low Pass filter

3.4 DC-Bus Voltage Control

Under a loss free situation, the shunt APF need not provide any active power to cancel the reactive and harmonic currents from the load. These currents show up as reactive power. Thus, it is indeed possible to make the DC-bus capacitor delivers the reactive power demanded by the proposed shunt APF. As the reactive power comes from the DC-bus capacitor and this reactive energy transfers between the load and the DC-bus capacitor (charging anddischarging of the DC-bus capacitor), the average DC-bus voltage can be maintained at a prescribed value.

However, due to switching loss, capacitor leakage current, etc., the distribution source must provide not only the active power required by the load but also the additional power required by the VSI to maintain the DC-bus voltage constant. Unless these losses are regulated, the DC-bus voltage will drop steadily.

A PI controller used to control the DC-bus voltage is shown in Figure6.6. Its transfer function can be represented as

$$H(s) = K_p + \frac{K_I}{s}$$

Where Kp is the proportional constant that determines the dynamic response of the DC-bus voltage control, and KI is the integration constant that determines its settling time.

It can be noted that if Kp and KI are large, the DC-bus voltage regulation is dominant, and the steady-state DC-bus voltage error is low. On the hand, if Kp and KI are small, the real.

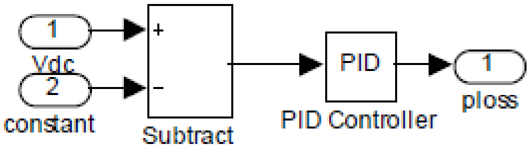


Fig 3.6 PI controller for DC-bus voltage control.

Power unbalance give little effect to the transient performance. Therefore, the proper selection of Kp and KI is essentially important to satisfy above mentioned two control performances.

3.5 Reference Current Calculation:

Reference Currents are calculated from inverse clark transformation.

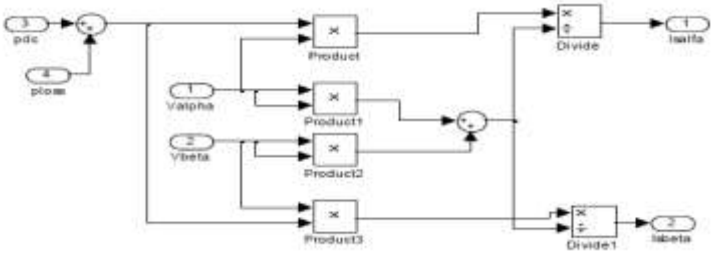


Fig 3.7 Block diagram for calculation of Isα, Isβ

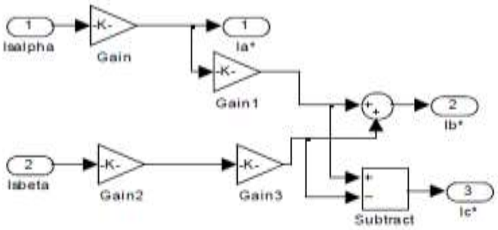


Fig 3.8 Reference Current calculation Ia*,Ib*and Ic*

3.6 Compensator:

Switching is done according to gating signals from Hysteresis Band Current Controller. Capacitor Voltage is continuously measured and fed to PI controller as explained earlier.

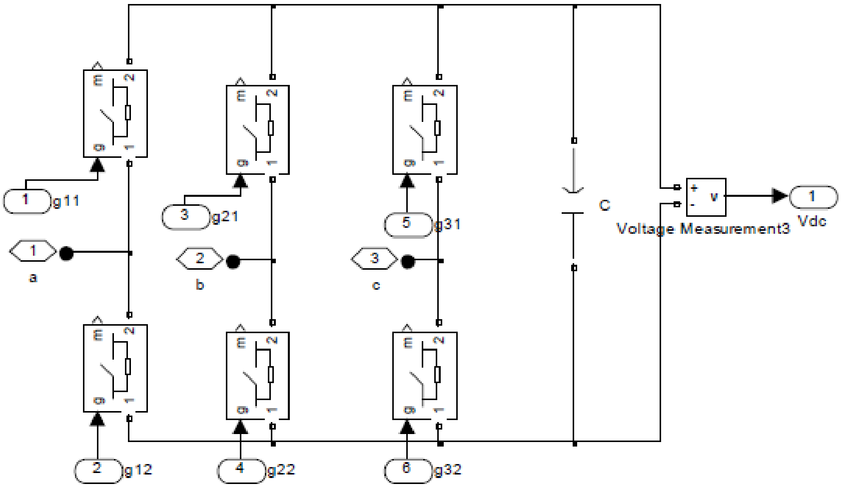


Fig 3.9 Compensator

3.7 Non-Linear Loads Case:1

Thyristor Converter Supplying to DC motor equivalent

Using PI controller DC motor current value is maintained at 20 Amps. PI controller varies alpha of thyristor until motor current match reference current. Pulse width is takes as $15\ ^{0}$.

Case2: Diode Rectifier supplying to pure resistive load

Fig 3.11 Block diagram for Diode rectifier supplying to pure Resistive Load

A pure resistive load is taken in order to APF performance. As in this load phase current varies in abrupt manner on the contrary to RL load where load phase current is smooth varying curve.

4. Hysteresis band current controller

The actual active power filter line currents are monitored instantaneously, and then compared to the reference currents generated by the control algorithm. In order to get precise instantaneous current control, the current control method must supply quick current controllability, thus quick response. For this reason, hysteresis band current control for active power filter line currents can be implemented to generate the switching pattern the inverter. There are various current control methods proposed for such active power filter configurations, but in terms of quick current controllability and easy implementation hysteresis band current control method has the highest rate among other current control methods such as sinusoidal PWM. Hysteresis band current control is the fastest control with minimum hardware and software but even switching frequency is its main drawback. The hysteresis band current control scheme, used for the control of active power filter line current, is shown inFig. 2, composed of a hysteresis around the reference line current.

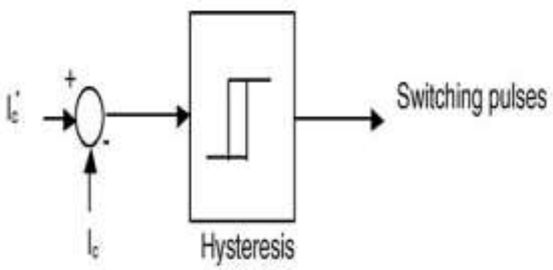


Fig:4.1 Hysteresis band current controller.

The reference line current of the active power filter is referred to as ic*and actual line current of the active power filter is referred to as ic. The hysteresis band current controller decides the switching pattern of active power filter. The switching logic is formulated as follows:

Ifica<(i∗ca−HB) upper switch is OFF and lower switch is ON for leg "a" (SA = 1).

Ifica>(i∗ca+ HB) upper switch is ON and lower switch is OFF for leg "a" (SA = 0).

The switching functions SB and SC for phases "b" and "c" are determined similarly, using corresponding reference and measured currents and hysteresis bandwidth (HB).

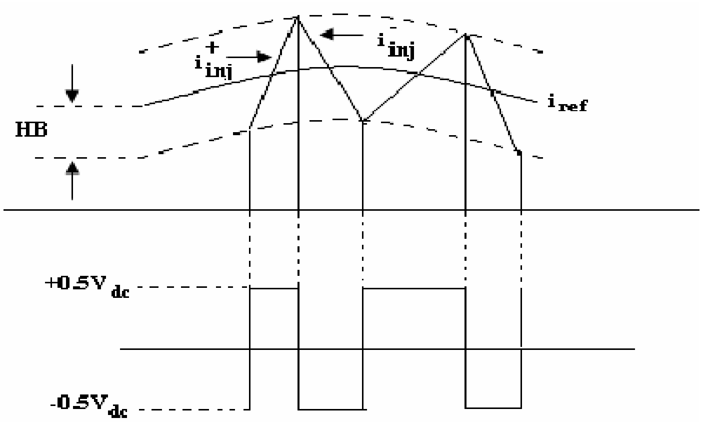


Fig: 4.2 Hysteresis current control

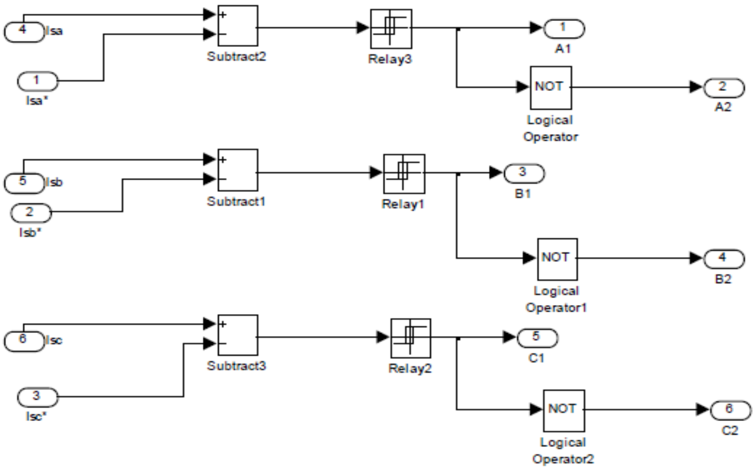


Fig 4.3 Hysteresis Band Current Controller

5. Work Done

Here for two loads, that is resistive load connected through a three phase diode rectifier without connecting a shunt Active Filter. And thyristor connected DC motor load. Their harmonic analysis is done and found out total harmonic distortion

Case:1 Thyristor Converter Supplying to DC motor equivalent

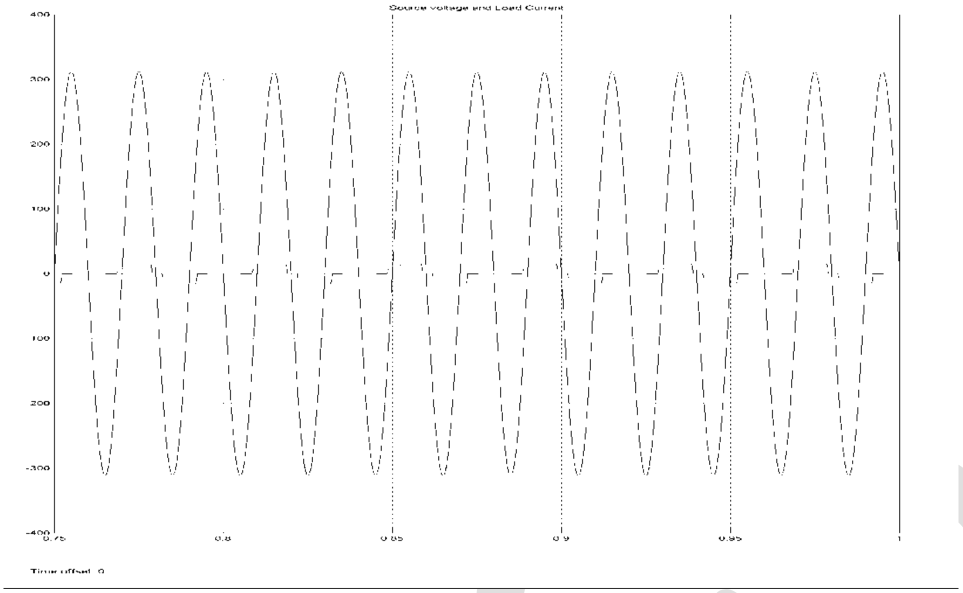


Fig:5.2 Supply Voltage and load current

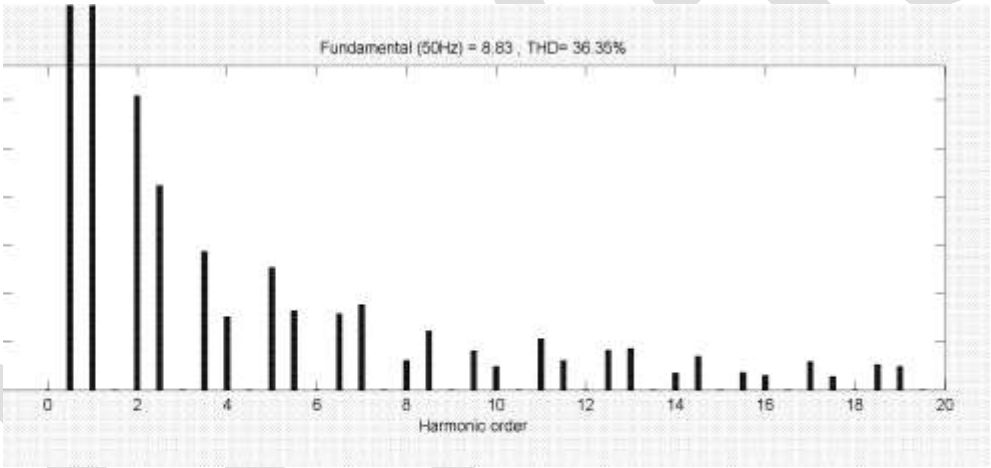


Fig:5.3 Harmonic Analysis of Load Current (Case 1)

Case:2 Resistive load through three phase diode rectifier.

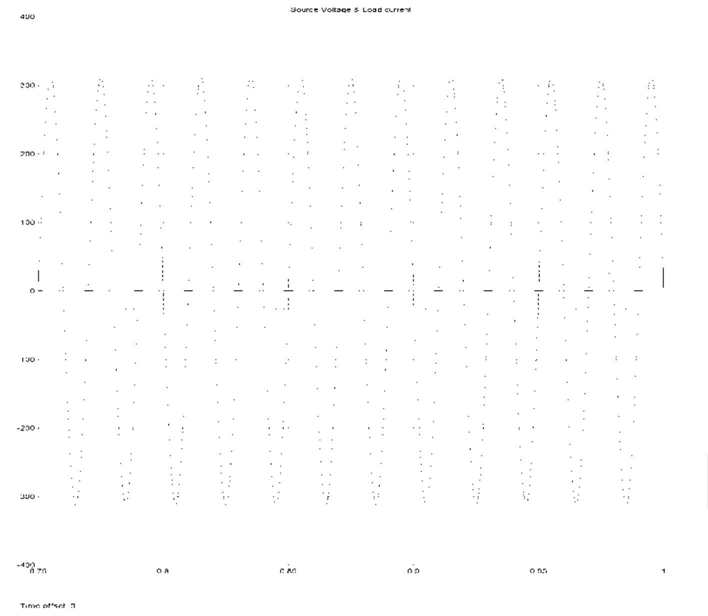


Fig 5.5 load Source Voltage & Load Current with APF

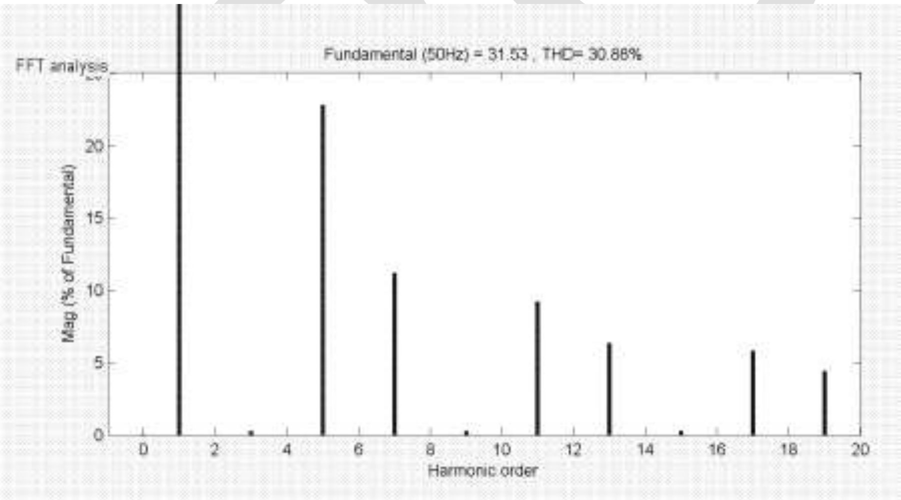


Fig :5.6 Harmonic Analysis of Load Current (case-2)

Conclusion

In this method, a new APF control scheme has been proposed to improve the performance of APF under non-ideal mains voltage conditions. The computer simulations in MATLAB has to verify the effectiveness of the proposed control scheme. Active power filters, based on the proposed theory, give satisfactory operation even when the system phase voltages are unsymmetrical and distorted, because no distortion appears in the line currents.

In non-ideal mains voltage condition, the source currents by the instantaneous power (p–q) theory are distorted, but the source currents by the proposed method have no distortion. The increased performance of the APF under different non-sinusoidal mains voltage conditions is extensively demonstrated. The APF is found effective to meet IEEE 519 standard recommendations on harmonics levels in all of the non-ideal voltage conditions. The performance of the proposed algorithm is therefore superior to that of conventional three-phase APF control algorithm. Its control circuit is also simpler that those of published non-ideal mains voltage algorithms. The unsymmetrical distorted voltage system is the most severe condition. However, good results can be obtained by the proposed theory.

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