Design of Passive High Pass Filter for Hybrid Active Power Filter Applications

A Thesis Submitted in Partial Fulfilment
of the Requirements for the Award of the Degree of

Master of Technology
in
Power Control & Drives

by
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May-2013

Under the guidance of

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Dedicated to my family & teachers

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CERTIFICATE

*This is to certify that the Thesis Report entitled "**Design of Passive High Pass Filter for Hybrid Active Power Filter Applications**, submitted by Mr Gourishankar Mishra bearing roll no. 211EE2134 in partial fulfilment of the requirements for the award of Master of Technology in Electrical Engineering with specialization in "Power Control and Drives" during session 2011-2013 at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance. I believe that the thesis fulfils part of the requirements for the award of degree of Master of Technology in Power Control and Drives. The results embodied in the thesis have not been submitted for award of any other degree.*

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DECLARATION

I hereby declare that the investigation carried out in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree/diploma at this or any other institution / University.

Gourishankar Mishra

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ABSTRACT

In recent years there has been considerable interest in the development and applications of active filters because of the increasing concern over power quality (PQ), at both distribution and consumer levels, and the need to control reactive power and voltage stability at transmission levels. Active filtering of electric power has now become a mature technology for harmonic and reactive power compensation in two-wire (single phase), three-wire (three phase without neutral), and four-wire (three phase with neutral) ac power networks with nonlinear loads. Active power and passive filters (APF and PF) are the traditional ways of compensating for harmonics. However, both of the two ways have some disadvantages, namely resonance and tuning problems in passive filters (PF), and capacity, initial and running cost in active power filter (APF). Hybrid Active Power Filter (HAPF) has been proposed to overcome the disadvantages of APF and PF. It is a combined system of PF and APF. Appropriate choice of passive filters and detailed design method for the same is being presented in this thesis, which when combined with APF will eliminate the higher order harmonics. A simple mathematical design procedure is derived for the passive high pass filter. In this thesis, power quality improvement based on HAPF is analyzed for a nonlinear RL-load connected to a single phase ac supply which can simultaneously improve the power quality and control the reactive power requirement of the load. The switching algorithm for the APF is also presented. The design procedure is limited to the design of passive high pass filter. However using the designed PF along with existing system consisting of APF is solely responsible for the remarkable improvement in power quality. The obtained results of the proposed hybrid APF is compared with the existing system with only APF in terms of source current and source voltage spectrums, active & reactive power flow from the filter side to the power system at the point of common coupling (PCC). The studied system is modelled and simulated in the MATLAB/Simulink environment. The performance indices included total harmonic distortion (THD) analysis of source voltage & source current.

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ACRONYMS

PQ	Power quality
HPF	High pass filter
APF	Active power filter
HAPF	Hybrid active power filter
THD	Total harmonic distortion
PCC	Point of common coupling
$\mathrm{h_k}$	RMS value of harmonic component k of quantity h
EMI	Electromagnetic interference
VSI	Voltage source inverter
PWM	Pulse width modulation
$\mathrm{i_S}(t)$	Source voltage
$\mathrm{i_S}$	Source current
$\mathrm{i_L}$	Load current
$\mathrm{i_f}$	Compensating current from APF
$\mathrm{V_{DC}}$	DC link capacitor voltage
$\mathrm{C_f}$	Filter capacitor
$\mathrm{L_f}$	Filter inductor
$\mathrm{i_r}(t)$	Reference sinusoidal signal
$\mathrm{I_x}$	Amplitude of real part of fundamental current
$\mathrm{I_{sc}}(t)$	Real part of the fundamental load current
$\mathrm{I_{cr}}(t)$	Calculated compensation current
$\mathrm{Z_f}(s)$	Filter s-domain complex impedance
$\mathrm{Z_{sys}}(s)$	System s-domain complex impedance
$\mathrm{H_f}(s)$	Filter impedance s-domain transfer function

$V_f(s)$	Single-phase equivalent filter s-domain voltage
$I_f(s)$	Filter branch s-domain current
$H_{cds}(s)$	Current divider transfer function
L_S	System inductance
R_h	Passive HPF resistance
L_h	Passive HPF inductance
C_h	Passive HPF capacitance
Q_h	Quality factor of high pass filter
ω_f	Fundamental angular frequency of source
Z_{Lf}	Impedance offered by load at fundamental frequency
Z_{HPFf}	Impedance of high pass filter at fundamental frequency
ω_{p_1} and ω_{p_2}	Parallel resonant frequencies of HPF
f_s	Switching frequency of APF

Chapter 1

INTRODUCTION

Overview

Motivation

Objective of Research

Thesis Organisation

1.1. Overview

Power electronics has three faces in power distribution: one that introduces valuable industrial and domestic equipment; a second one that creates problems; and, finally, a third one that helps to solve those problems.

On one hand, power electronics and microelectronics have become two technologies that have considerably improved the quality of modern life, allowing the introduction of sophisticated energy-efficient controllable equipment to industry and home. On the other hand, those same sensitive technologies are conflicting with each other and increasingly challenging the maintenance of quality of service in electric energy delivery.

It generates serious pollution to the quality of power supply of transmission and distribution network. Harmonic may results equipment overheating, capacitor fuse blowing, excessive neutral currents within buildings, and inaccurate power metering, etc. And, electrical equipment of modern industry, commerce and resident users is highly sensitive to power quality. Then, more high demands have been made on power supply quality [1-3].

The power equipment which include adjustable-speed motor drives (ASDs), electronic power supplies, direct current (DC) motor drives, battery chargers, electronic ballasts are responsible for the rise in related PQ problems [2-4]. These nonlinear loads are constructed by nonlinear devices, in which the current is not proportional to the applied voltage. A simple circuit as shown in Fig. 1.1 illustrates the concept of current distortion. In this case, a sinusoidal voltage is applied to a simple nonlinear load in which the voltage and current vary according to the curve shown. While the voltage is perfectly sinusoidal, the resulting current is distorted.

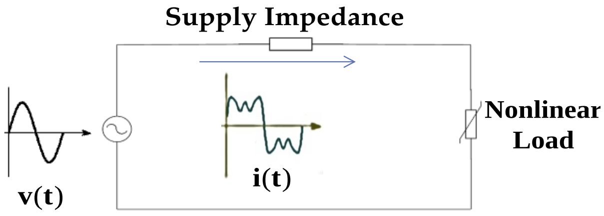


Fig. 1.1 Distorted source current due to nonlinear load

1.2. Motivation

In today’s scenario the use of modern semiconductor switching devices is becoming more prominent in a wide range of applications in distribution networks, particularly in domestic and industrial loads. Examples of such applications widely used are adjustable-speed motor drives, diode and thyristor rectifiers, uninterruptible power supplies, computers and their peripherals, consumer electronics appliances, among others. Those power electronics devices offer economical and reliable solutions to better manage and control the use of electric energy. However, given the characteristics of most power electronics circuits, those semiconductor devices present nonlinear operational characteristics, which introduce contamination to voltage and current waveforms at the point of common coupling of industrial loads. These devices, aggregated in thousands, have become the main polluters, the main distorters, of the modern power systems.

At the same time, microelectronics processors have found their way into many applications: from automated industrial assembly lines, to hospital diagnostics and measurement schemes, to home appliances such as video and DVD units. These applications are sensitive and vulnerable to power quality problems such as either electrical disturbances or power system harmonics. But microelectronics-based applications are not the only ones facing the dangers of poor power quality. Those same semiconductor-based loads, which are the major contributors to power system pollution, are also very sensitive to that pollution.

Ultimately we cannot live without the power electronics and microelectronics based instruments as these are now being very much essential looking at their uses; hence what we can do is that, by using power electronic devices; such as active or passive filter or both we can improve the power quality and compensate the reactive power requirement of the load.

1.3. Research Background

1.3.1. Passive Filters

Passive filters are widely used in power systems for harmonic mitigation. In general, they have shunt branches consisting of passive elements; such as inductors and capacitors which are respectively tuned to the predominant harmonics. Design procedure for this type of filter is also very simple. However, in practical application these passive filters have the following problems [5].

- Source impedance influences the compensation characteristics of passive filters.
- At specific frequencies there are anti-resonances between source impedance and the passive filters. Additionally, the harmonic currents generated by the distorted non-sinusoidal source voltage flow into the passive from the source.
- Frequency variation of the ac source affects the compensation characteristics of the passive filters. As a result, the size of the components in each tuned branch becomes impractical if the frequency variation is large.
- Overload occurs when the load harmonics increase.
- Due to presence of inductors and capacitors, passive filter are generally large and bulky

1.3.2. Active Power Filter

The aforesaid problems limit the use of passive filters. With remarkable progress in the speed and capacity of semiconductor switching devices, active filters have been studied and put into practical use, because they have the ability to overcome the above-mentioned disadvantages inherent in passive filters. They are more effective in harmonic compensation and improve performance. However, they are high initial costs and running costs and require comparatively high power converter ratings.

The term active filter is a generic one and is applied to a group of power-electronic circuits incorporating power switching devices and passive energy-storage-circuit elements, such as inductors and capacitors. The functions of these circuits vary depending on the applications. They are generally used for controlling current harmonics in supply networks at the low- to medium-voltage distribution level or for reactive power and/or voltage control at high-voltage distribution level [7]

1.3.3. Hybrid Active Power Filter

The idea of hybrid APF has been proposed by several researchers [7-9]. In this scheme, a low cost passive high-pass filter (HPF) is used in addition to the conventional APF. The harmonics filtering task is divided between the two filters. The APF cancels the lower order harmonics, while the HPF filters the higher order harmonics. HAPF, inheriting the advantages of both passive filter and active filter, provide improved performance and cost-effective solutions.

1.4. Objective of Research

The objective of the research is: (1) to develop a simple control strategy for APF connected in a low voltage application system. (2) to design of a passive HPF for the same system and incorporate it with APF to make a Hybrid APF. (3) to analyse and compare the performance of the system after connecting the HAPF.

To achieve the first objective, a simple control strategy is being used for a single-phase APF system connected to DC link capacitor. It not only improves the power quality of a system feeding a typical non-linear load, but also compensates for the reactive power requirement of the load.

But it is seen that the power quality achieved by the use of APF is not up to the mark. The total harmonic distortion (THD) limits are not within the limits specified by IEEE std. 519. That’s why we will go for the second objective in which a simple design procedure for a Passive HPF is proposed which when connected to the existing system (with APF), the undesirable higher order harmonics are removed and the power quality improved significantly.

The final objective is to analyse and compare the system performance in each case, i.e. I. with APF only. II. with APF as well as designed HPF.

1.5. Thesis Organisation

This thesis consists of this introductory chapter and seven other chapters arranged as follows:

Chapter 2 covers the literature survey of the project work. The details about power quality and their mitigations are studied and presented. Various filter topologies are also discussed.

Chapter 3 presents the detailed study of shunt active power filter topology. The switching algorithm used for the APF is also discussed. Important parts of the APF, i.e. control circuit and power circuit are explained. The need of energy storage element is also focused and discussed.

Chapter 4 concerns about the hybrid filters. Focusing the limitations of APF, hybrid filtering topology for power quality improvement is brought into picture. To choose appropriate high pass filter for the Hybrid APF, various types of high pass filters and their advantages, limitations are analysed by using transfer function approach. Various types of filter transfer functions are also given.

Chapter 5 describes about the mathematical design procedure of the chosen high pass filter that is to be used for the HAPF, considering resonance problem. Various parameters of the high pass filters are designed mathematically considering the filter behaviour and transfer function approach.

Chapter 6 provides the simulation results of the power system without any compensations, with only APF compensation and in the end by using the proposed hybrid filter compensation. Various parameters taken for the simulation purpose are given and from those data, the high pass filter parameters are formulated. The results are analysed and compared. The total harmonic distortion of voltage and current spectrum of each case is presented to get idea about improvement in power quality in each case. Power flow from the filter side to the distribution system side at the PCC are given to get an idea about the loading effect of filter on supply.

Chapter 7 summarises the thesis with a general conclusion and scope for future work followed by references and appendices.

Chapter 2

LITERATURE REVIEW

Electric Power Quality

Harmonic Distortion

Effect of Harmonic Distortion on Power Quality

Harmonic Distortion Mitigation Techniques

Summary

2.1. Electric Power Quality

Power system are designed to operate at a frequencies of 50 or 60 Hz. However, certain types of non-linear loads produce current and voltages with frequencies that are integer multiple of the fundamental frequency. These frequency components known as harmonic pollution and is having adverse effect on the power system network. This is generally a consumer driven issue, so PQ problem is defined as,

“any occurrence manifested in voltage, current, or frequency deviations that results in damage, upset, failure, or misoperation of end use equipment.”

2.2. Harmonic Distortion

Due to increased use of nonlinear loads, one of the PQ issues that has been gaining continuous attention is the harmonic distortion. The nonlinear loads control the flow of power by drawing currents only during certain intervals of the fundamental period. Hence the current supplied by the source becomes non-sinusoidal and contains higher percentage of harmonic components.

Fig. 2.1 shows that any non-sinusoidal signal can be expressed as sum of pure sinusoids. The sum of sinusoids is referred to as a Fourier series. By using Fourier analysis, a periodic distorted waveform can be decomposed into an infinite series containing DC component, fundamental component (50/60 Hz for power systems) and its integer multiples called the harmonic components. The harmonic number (h) usually specifies a harmonic component, which is the ratio of its frequency to the fundamental frequency [2].

The total harmonic distortion is the most common measurement index of measuring harmonic distortion [2-3], [10-11]. THD applies to both current and voltage and is defined as the root-mean-square (rms) value of harmonics divided by the rms value of the fundamental, and then multiplied by 100% as shown in the following equation:

$$THD = \frac{\sqrt{\sum_{k=2} h_k^{\ 2}}}{h_1} \times 100$$

where h_k is the rms value of harmonic component k of the quantity h.

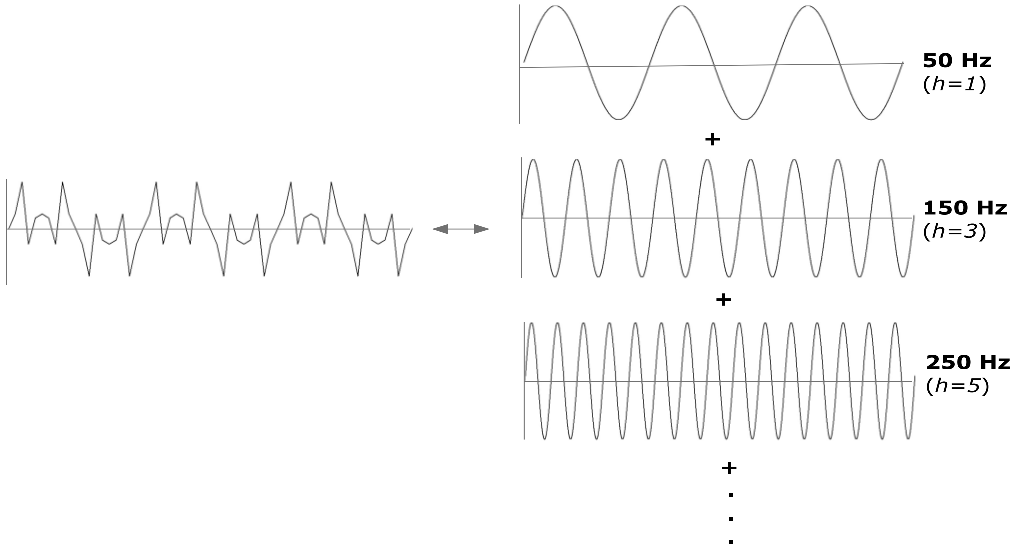


Fig. 2.1. Non-sinusoidal signal expressed as sum of sum of sinusoidal signals

2.3. Harmonic Distortion Effects on Power Quality

When a nonlinear load is fed from a sinusoidal supply, non-sinusoid, distorted current containing harmonics will be drawn from the supply. A voltage drop for each harmonic will be produced when this harmonic current will pass through the source impedance resulting in harmonic voltage at the PCC. The amount of voltage distortion depends on the source impedance and current.

Harmonics has numerous undesirable effects on electric PQ. Unexplained computer network failures, premature motor burnouts, humming in telecommunication lines, and transformer overheating are only a few of the damages that quality problems may bring into home and industrial installations. What may seem like minor quality problems may bring whole factories to a standstill. Table 2.1 illustrates various effects of poor PQ on power system components.

Table 2.1. Effect of poor PQ on power system components

Sl. no.	Item	Impact
1	Rotating machines	Overheating, loss of efficiency, pulsating torque, shaft fatigue, reduced life, acoustic noise emission
2	Transformer	Overheating, reduced life, acoustic noise emission
3	Neutral wire	Overloading
4	Power factor capacitor	Overloading, reduced life, fuse disconnection
5	Fuses and circuit breaker	Nuisance tripping, reduced life
6	Cables and conductors	Increased temperature, inability to provide full current rating without overheating, reduced life
7	Meters	Erroneous reading
8	Residential equipment	Increased acoustic noise emission, loss of life, overheating
9	Electronic equipment	Defective operation, radio interference
10	Power distribution network	Excitation of system resonance, increased level of voltage distortion
11	Telephone network	Increased levels of noise, safety problem
12	Data cable	Interference and noise

2.4. Harmonic Distortion Mitigation Techniques

Harmonic distortion in power system can be minimized through three basic approaches [12].

They are

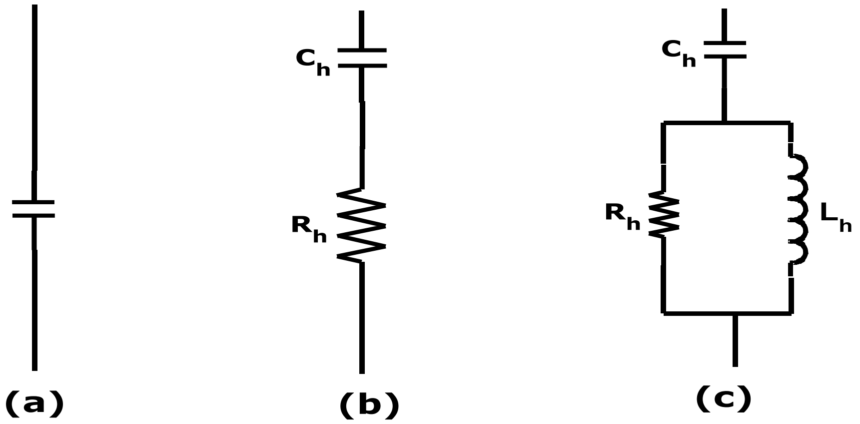
i. Passive filter
ii. Active power filter
iii. Hybrid active power filter

In this section we will discuss about various harmonic distortion mitigation techniques and advantages, disadvantages and limitations of these techniques.

2.4.1. Passive Filter

This is the most conventional method of mitigating harmonic components and is the first to come into picture. It is the simplest method of all to suppress harmonics from power system [2], [12-16]. This type of filter is constructed from simple passive elements (resistor, inductor and capacitor) and is tuned to eliminate particular frequency component. The single tuned filter is connected in shunt with the power system and is series tuned to present low impedance to a particular harmonic current. Hence the harmonic currents will be diverted from its normal path through the filter.

High pass filter is one of the type of passive filter which allow large percentage of harmonics to pass through it above its corner frequency [2], [14]. It is typically one of the three types as shown in Fig. 2.2.



a. First order HPF
b. Second order HPF
c. Third order HPF

Fig. 2.2. Passive high pass filters of different orders

Resonance problem of first order HPF limits the use of it. However connecting a resistance in series with the capacitor solves a part of the resonance problem, but at a cost of high power loss, which is also undesirable. The second order filter is the most effective to use considering both design complexities and harmonic distortion mitigation capacity. It is having reduced fundamental frequency loss. The third order filter gives improved performance as compared to the second order filter, but due to the design complexity and reliability & economic factors, use of third order filter is limited for low/medium voltage application system.

Though passive filters are simple to design and operate, they do not always respond to dynamics of power system. The other disadvantages of passive filters are: (1) size of these type of filters are quite heavy and bulky due to the presence of passive elements. The harmonics that are to be suppressed are usually of low order [2], [16]. (2) resonance or tuning problem effecting the stability of power system network [12], [16-17]. (3) filtering characteristics gets affected by the frequency variation in power system and tolerances in components, size of components become unrealizable in a varying frequency environment (4) fixed compensation (5) noise (6) increased loss [16].

2.4.2. Active Power Filter

Remarkable advances in the field of power electronics had sparked interest in APF for harmonic distortion mitigation [6], [12], [17-19]. The basic technology of APF is to use power electronics technologies to produce the harmonic current components such that the source will supply only the fundamental part of current required by the load.

The total system is basically comprising of two circuits, i.e. power circuit and control circuit. The reference current estimator of control circuit is fed with the information regarding harmonic current and other system variable to generate the control signal which will drive the APF of the power circuit to generate required compensation current.

The major advantages of APFs over the passive filters are: (1) they can suppress not only the supply current harmonics, but also the reactive currents, (2) unlike passive filters, they do not cause harmful resonances with the power distribution systems, (3) the APFs performances are independent of the power distribution system properties [12], [17], (4) Fast acting (5) Good filtering action for large range of frequencies.

APF is basically of two types. They are (i) Shunt APF (ii) Series APF

2.4.2.1. Shunt APF

This type of configuration is widely used in active filtering applications. A shunt APF has a controllable voltage or current source. Fig. 2.3 demonstrates principal configuration of a voltage source inverter based APF which the most common type of shunt APF today. It is based on the principle of injection of harmonic current equivalent to the distorted current waveform,

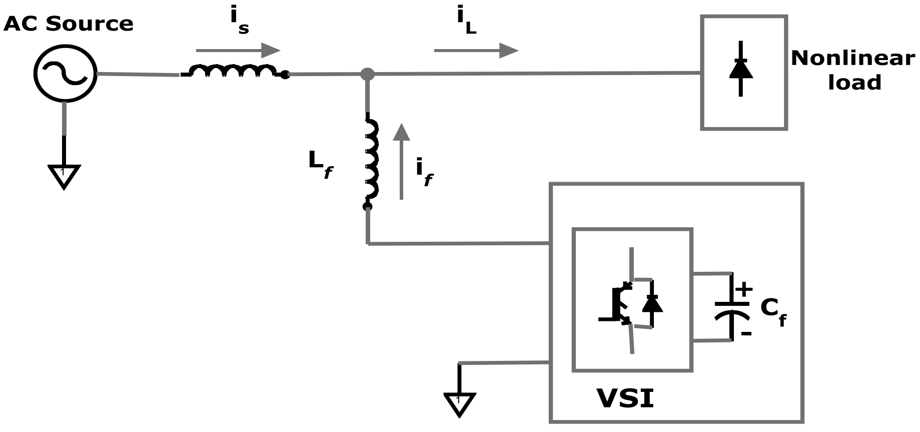


Fig 2.3. Basic configuration of Shunt APF

thus eliminating the original distorted current. This is connected in shunt with the distribution line through an interfacing inductor.

2.4.2.2. Series APF

Basic principle of this type of configuration is isolation of harmonics in between nonlinear load and source. The basic configuration is similar with shunt APF, except that interfacing inductor is replaced by an interfacing transformer, where the injection of harmonic voltage occurs. It is otherwise known as a harmonic isolator, which offers zero impedance to the fundamental and infinite impedance to the harmonic frequency components. Fig. 2.4 demonstrates the basic configuration of a series APF. Series APF is suitable for improving the quality of the distribution source voltage.

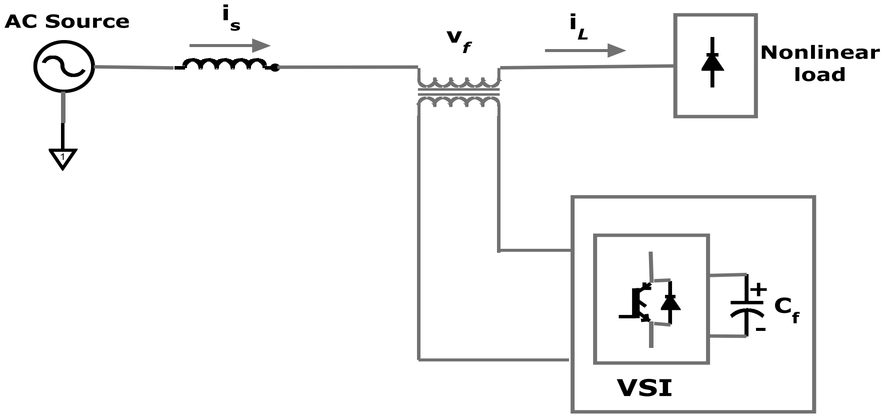


Fig. 2.4. Basic configuration of Series APF

2.4.3. Hybrid Active Power Filter

The APF supplies the compensating current which comprises the reactive component of the fundamental current and the harmonic current demanded by the load. Though it is very much capable of improving the power quality better than passive filters, it has some shortcomings. Modern shunt APFs are found to compensate current harmonics dynamically (typically till 25th order). Current distortion still exists due to high frequency current harmonics present because of the following reasons (i) uncompensated harmonics of the load current (ii) switching harmonics introduced due to high switching rate of APF [20]. Due to the presence of source inductance, these higher order current harmonics introduces higher order voltage harmonics of high magnitude in the source voltage. This results in a high frequency noise that may cause an electromagnetic interference (EMI) in the power distribution systems [21].

The limitations of conventional APFs discussed above can be overcome with hybrid APF configurations [7-9], [23]. They are typically the combination of basic APFs and passive HPFs tuned to filter out the high frequencies beyond a particular value. Hybrid APF, inheriting the advantages of both passive filter and active filter, provide improved performance and cost-effective solutions [23]. HAPF aimed to act as a “harmonic isolator” and present zero impedance to the external circuit at the fundamental frequency and a high resistance to source or load harmonics. The idea behind this scheme is to simultaneously reduce the switching noise and electromagnetic interference [12].

There are many configuration for Hybrid APF is possible as given in literature [6], [19]. But two most prominent configurations are hybrid shunt APF and hybrid series APF. Basically it is the combination of APF with a passive high pass filter. Advantages of both types of filter can be drawn by using these type of filters. The function of hybrid APF can be divided into two parts. The APF will eliminate the lower order harmonics, whereas the passive filter is meant for elimination of higher order harmonics.

2.5. Summary

In this chapter, power quality issues, its measure and its effect on power system components are discussed. In today’s scenario, power system has not only to become reliable one, but also has to ensure about the quality of power supply. Due to few of the load side equipment only, the quality of power supply worsens. But that affects the whole power system as well as many consumer side appliances and some sensitive equipment which cannot be afforded to be malfunctioned leading to even loss of life. Then harmonic distortion mitigation techniques are discussed and the positive and negative sides of each are highlighted. From the discussion above, we get idea that hybrid active power filter should be preferred to have good power quality at an optimum cost.

Chapter 3

SHUNT ACTIVE POWER FILTER

Introduction

Power Filter Topologies

Working of Shunt Active Power Filter

Basic Compensation Principle

Control Strategy

Control Ciruit

Power Circuit

Summary

3.1. Introduction

From previous chapter we saw that passive filter can be designed easily, more reliable, simpler; but it has many limitations like heavy and large size, effectiveness, used to remove particular harmonic frequency component, slow response, resonance problem and uncontrollability. That's why active power filter came into picture. In spite of higher initial installation cost as compared to its counterpart; it has faster response, no resonance problem, good filtering action for a large range of frequency and independent of the distribution system to which it is connected. Due to all these advantages APF is preferred over passive filters. As previously discussed APF is again of two types. Among them shunt APF is mostly used in distribution power system.

The configurations of APF developed include three phase and single phase systems. The three phase system implemented by a three phase bridge inverter is suitable for large capacity. But using three single phase bridge inverter is more suitable for serious unbalanced loads rather than using a single three phase inverter. In other words each phase is being independently compensated [24].

In this chapter we will discuss in detail about power filter topologies, single phase shunt APF, the control scheme followed, switches used, and switching algorithm used, and limitations of shunt APF.

3.2. Power Filter Topologies

Voltage source converters, which have a voltage source at the dc bus, usually a capacitor, as an energy storage device is used by most of the power filter topologies. For gating of the power semiconductor switches pulse width modulation technique is used now-a-days. PWM techniques applied to a voltage source inverter consist of chopping the dc bus voltage to produce an AC voltage of an arbitrary waveform. There are a large number of PWM techniques available to synthesize sinusoidal patterns or any arbitrary pattern. With PWM techniques, the AC output of the filter can be controlled as a current or voltage source device.

3.3. Working of Shunt Active Power Filter

The shunt-connected active power filter, with a self-controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal-but-opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase-shifted by 180°. Fig. 3.1 shows the connection of a shunt active power filter and Fig. 3.2 shows how the active filter works to compensate the load harmonic currents.

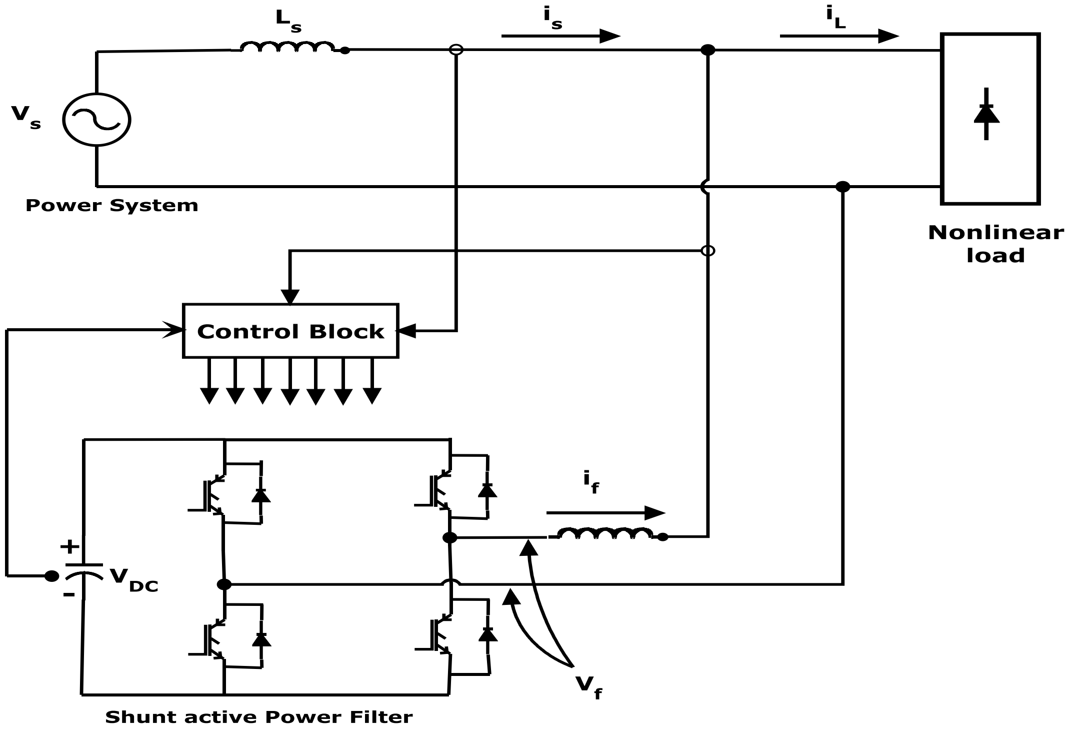


Fig. 3.1. Shunt active power filter topology

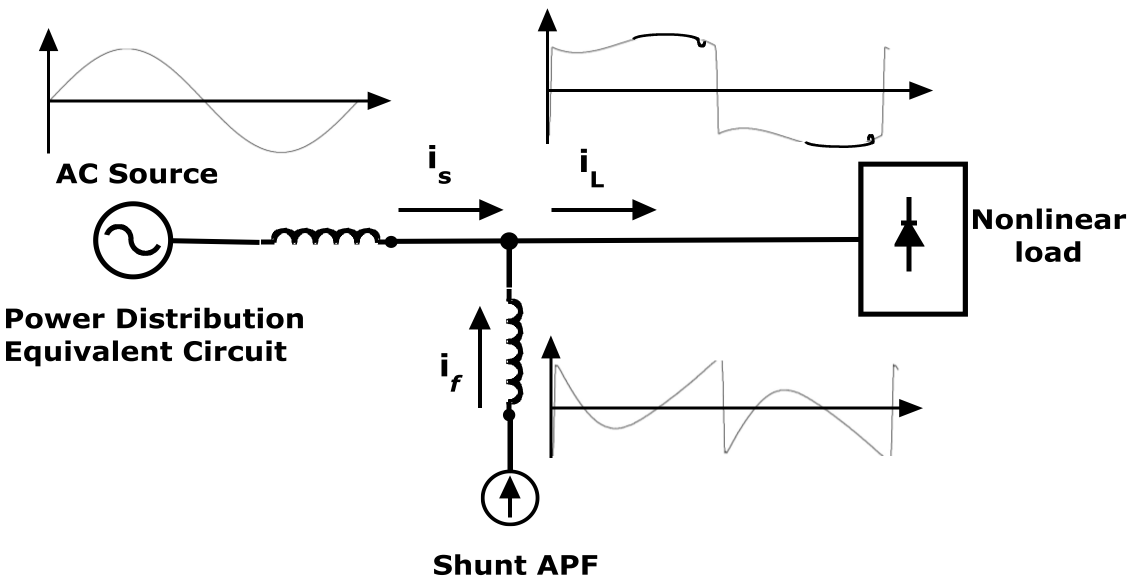


Fig. 3.2. Working of a shunt APF

3.4. Basic Compensation Principle

Fig. 3.2 shows the basic compensation principle of a shunt active power filter. It is controlled to draw / supply a compensating current i_c from/ to the utility, so that it cancels current harmonics on the AC side, and makes the source current in phase with the source voltage. Fig.3.3 shows the different waveforms. (a) shows the load current, (b) shows the desired source current and (c) shows the compensation current to be fed from the APF to make mains current sinusoidal.

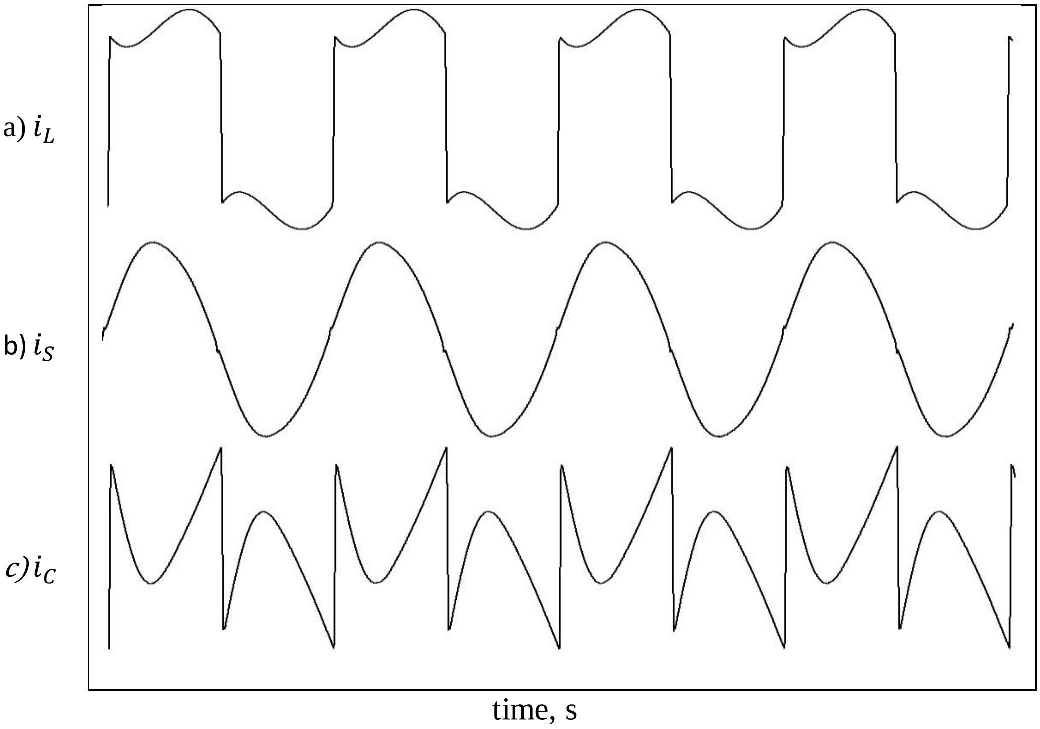


Fig 3.3. Basic current waveforms for a Shunt APF

a. Load current b. Source current c. Compensation current

3.5. Control Strategy

We will discuss about single phase shunt APF and its switching strategy.

There exist many single phase algorithm for APF, but performance of few still needs to be improved. The half-cycle integration algorithm is having inherent problem of giving large error when the load current contains even-order harmonics. The current sampling detection too fails to compensate effectively. Under distorted mains voltage few more algorithms like full-cycle detection algorithm and synchronous detection algorithm fail. We will follow a simple algorithm proposed in literature [24].

Fig. 3.4 shows the power circuit of the active power filter. The load in this diagram may be a rectifier or other nonlinear load. The mains voltage is assumed to be purely sinusoidal in nature and is represented as

$$v_s(t) = V_p\, sin(\omega t) \tag{1}$$

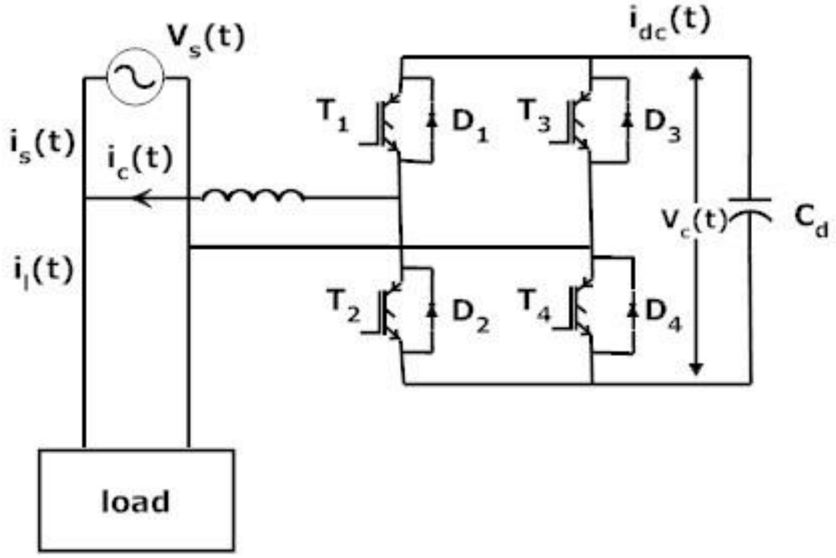


Fig. 3.4. Power circuit of APF

The nonlinear load current can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \theta_n) \tag{2}$$

The load current can be subdivided into the fundamental and harmonic components as

$$i_L(t) = I_1 \sin(\omega t + \theta_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \theta_n) \tag{3}$$

Let a reference sinusoidal signal is represented as

$$i_r(t) = \sin(\omega t) \tag{4}$$

The amplitude of the real part of the fundamental load current can be extracted using the Fourier algorithm and represented as

$$\begin{aligned} I_x &= \frac{1}{T}\int_0^T i_L(t) i_r(t)\, dt \\ &= I_1\, cos\, \theta_1 \end{aligned} \tag{5}$$

Then, the real part of the fundamental load current can be obtained by multiplying I_x by $i_r(t)$, and it is represented as

$$\begin{aligned} I_{sc}(t) &= I_x i_r(t) \\ &= I_1 \, cos\, \theta_1 \end{aligned} \tag{6}$$

Hence, the calculated compensation current can be obtained by subtracting (2) from (6). It is shown as

$$\begin{aligned} I_{cr}(t) &= i_L(t) - I_{sc}(t) \\ &= \sum_{n=1}^{\infty} I_n \sin(n\omega t + \theta_n) - I_1 \cos\theta_1 \sin\omega t \end{aligned} \tag{7}$$

3.6. Control Circuits

3.6.1. Compensation Current Control

The block diagram for implementing the proposed active power filter is shown in Fig. 3.5.

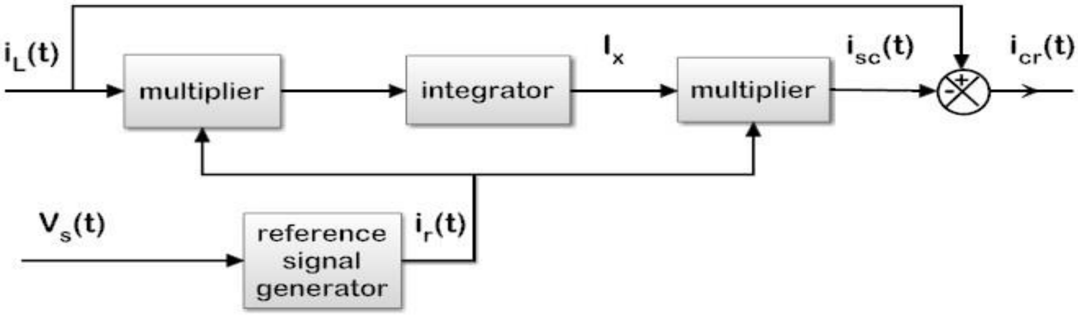


Fig. 3.5. Block diagram of the compensation current calculated circuit for the APF

The mains voltage is fed to the reference sinusoidal signal generator to generate a reference signal $i_r(t)$. The load current and the reference signal are fed to the input terminals of a multiplier. Then, the output of the multiplier is fed to a linear integrator. The output of the integrator is the amplitude of the real part of the fundamental load current if the parameters of the integrator are designed suitably. The output of the integrator and the output of the reference signal are fed to the input terminals of a multiplier. As the reference signal is in phase with the mains voltage, the output of the multiplier is the real part of the fundamental load current. Finally, the compensation current $I_{cr}(t)$ can be obtained by a subtract circuit that subtracts $I_{sc}(t)$ from the load current $i_L(t)$.

3.6.2. DC bus bar voltage control

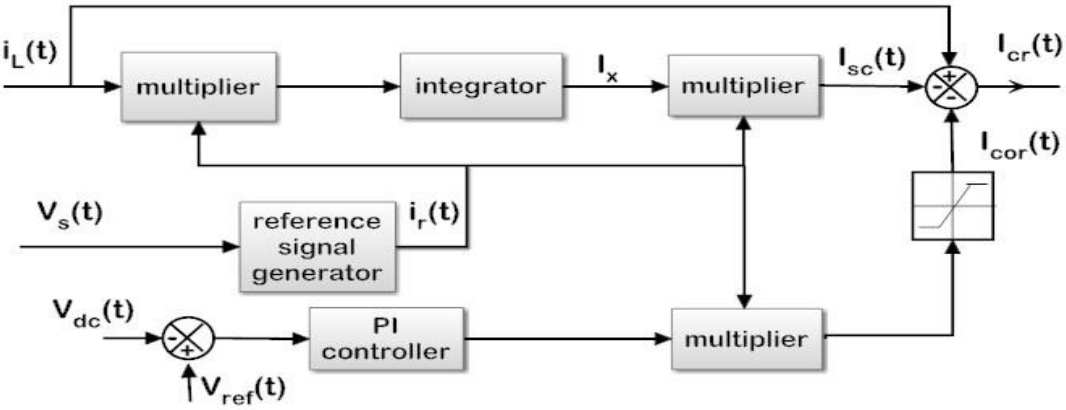


Fig. 3.6. Block diagram for compensation circuit along with dc link voltage controller

Now we can get the sinusoidal source current, but it can be seen that the the DC bus bar voltage of the APF too needs to be controlled so that it matches the dc reference voltage. This can be done by controlling amplitude of mains current. A PI controller is used to control the DC capacitor voltage. Hence the error between the capacitor voltage and the dc refernece voltage is multiplied by the reference sinusoidal signal after passing through a PI controller and is then fed to the subtract circuit that subtract the corrected error signal along with $I_{sc}(t)$. So the control block is now as given in Fig. 3.6 and the compensation current becomes

$$I_{cr}(t) = i_L(t) - I_{sc}(t) - I_{cor}(t) \tag{8}$$

3.7. Power Circuit

Fig. 3.4 shows the power circuit for the APF. It is comprised of a single phase full bridge converter, a DC bus capacitor and a filter inductor. The desired compensation and reactive power is supplied by using the converter. The DC bus capacitor is used to store the energy to maintain the constant DC voltage and to reduce the voltage fluctuation under load variation. The filter inductor is used to smoothen the compensation current supplied from the converter by filtering out switching ripple. The size of inductor should be made optimum; as very small size of inductor leads to good dynamic response, but at the same time it is unable to suppress the switching ripple.

3.7.1. Single-phase full bridge converter

A full bridge converter is used in active power filter. Unipolar PWM is used as control strategy, and insulated gate bipolar transistor (IGBT) is used as switching device. The converter is basically a multifunctional converter. It supplies real power to the DC bus bar of the converter to maintain a constant DC voltage and generates a compensation current to compensate for the load current.

3.7.2. Energy storage element

To have a simple analysis of DC bus bar fluctuation, following assumption are made.

(i) Energy stored in the filter inductor is negligible.
(ii) In steady state the, the fluctuating voltage of the DC capacitor is very small compared with the average voltage of the DC capacitor.
(iii) The power converter is lossless.
(iv) Because of the high switching frequency, the voltage fluctuation of the DC capacitor due to the higher order harmonics is very small. Though it can be neglected.

The voltage fluctuation of the DC busbar must be regulated to an acceptable level to obtain a good compensating accuracy and high operation frequency. The voltage fluctuation of DC capacitor depends upon the voltage of DC capacitor and the capacity of DC capacitor. However the capacitor required will be larger if the frequency is lowered or the AC power magnitude is raised. The capacity of DC capacitor depends on the power rating of the active power filter and the load type.

3.8. Summary

In this chapter various aspects of shunt active power filter were discussed. Switching algorithm for APF, details about the control circuit and power circuit that are going to be used in the following chapters were discussed. Various aspects of storage elements present in APF were also studied.

Chapter 4

CHOICE OF PASSIVE FILTER FOR HYBRID ACTIVE POWER FILTER

Introduction

Need for Hybrid Filter

Passive High Pass Filter Analysis

Summary

4.1. Introduction

Modern active power filters are capable to compensate high order harmonics (typically, the 25th) dynamically [19]. Even though, shunt active power filter maintains source current nearly sinusoidal, considerable distortion is observed in source current due the presence of high order harmonics (greater than 25th). A passive high pass filter can be used to filter out these harmonics (of order more than 25). Hence a combination of APF and passive HPF is one of the most effective way to filter out harmonics present in the power system. In this chapter we will focus on the various aspects of passive filters, then appropriate passive filter will be designed for shunt active power filter application.

4.2. Need for Hybrid Filter

Shunt APF plays an important role in improving power quality by maintaining sinusoidal voltage and current at the source with unity power factor. Shunt APF supplies the compensating current which comprises the reactive component of the fundamental current and the harmonic current demanded by the load. Modern shunt APFs are found to compensate current harmonics dynamically (typically till 25th order). Current distortion still exists due to high frequency current harmonics present because of the following reasons (i) uncompensated harmonics of the load current (ii) switching harmonics introduced due to high switching rate of APF [20]. Due to the presence of source inductance, these higher order current harmonics introduces higher order voltage harmonics of high magnitude in the source voltage. As per IEEE Std. 519, the limits for the individual voltage harmonics and the Total Harmonic Distortion (THD) of the voltage are 3% and 5% respectively [25]. Hence reduction in higher order current harmonics is essential to maintain good quality of voltage. A properly designed High Pass Filter (HPF) connected parallel to APF as shown in Fig. 4.1, bypasses the high frequency currents [13], [15], [17], [21], [26].

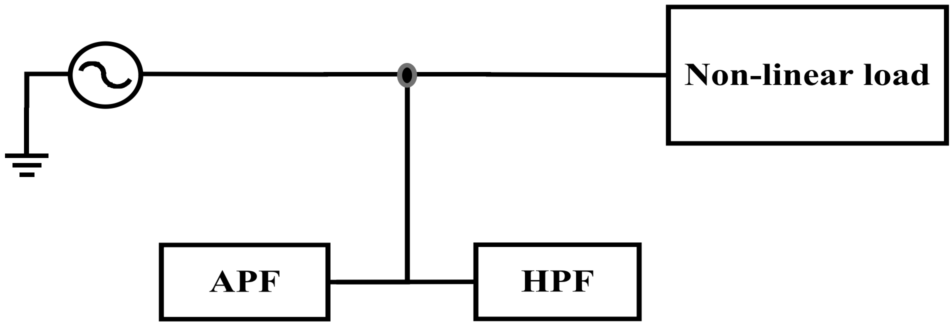


Fig. 4.1. Parallel connection of HPF with APF in a power circuit

4.3. Passive High Pass Filter Analysis

In this section, a detailed study of passive high pass filter is given. Possible representations for the filter transfer function are given and by using the transfer function analysis few basic passive filters will be analysed and pros & cons of those filters will be discussed.

4.3.1. Filter Transfer Function

In any case, the analysis begins with the generalized frequency dependent filter system impedance representation Z_f. The impedance can take on several forms depending on the desired response, and it is the basic building block on which several useful filter system design transfer function can be defined.

There are a number of important transfer functions that can be derived for filter design and system modelling purposes. In case a filter is to be designed for a three-phase system, the following transfer functions are based on single-phase equivalent is designed and operated under balanced load condition [15].

4.3.2. Filter impedance transfer function

This transfer function is the basic building block on which the modeling begins. It is defined to be the complex impedance frequency response of the filter system expressed in the s-domain of the individual filter circuit elements. As shown in Fig. 4.2, if a general filter branch is defined at its terminals, (1) can be defined as follows

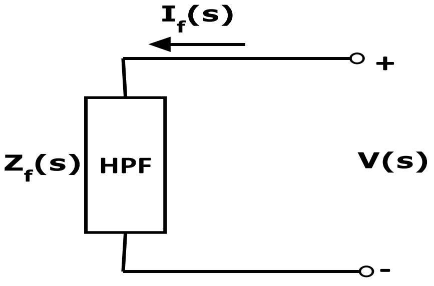


Fig.4.2. Filter impedance representation

$$H_f(s) = Z_f(s) = \frac{V_f(s)}{I_f(s)} \tag{1}$$

where

$H_f(s)$ = Filter impedance s-domain transfer function

$Z_f(s)$ = Filter s-domain complex impedance

$V_f(s)$ = Single-phase equivalent filter s-domain voltage

$I_f(s)$ = Filter branch s-domain current

$H_f(s)$ can be used to design and tune the filter as a separate system before it is modeled in the power system network Depending on the type and complexity of the filter configuration, Z_f (s) can be factored into a combination of denominators (poles) and numerators (zeros) substituting

$$s = j\omega \tag{2}$$

to derive the particular tuning and damping relations between component variables.

4.3.2.1. Filter/System Impedance Transfer Function

After the filter system is configured and $Z_f(s)$ is known, this impedance can be connected to the power system network to derive the filter/system impedance transfer function H_{fs} (s) where Z_s(s) is represented as the system Thevenin equivalent system network impedance as given in Fig. 4.3.

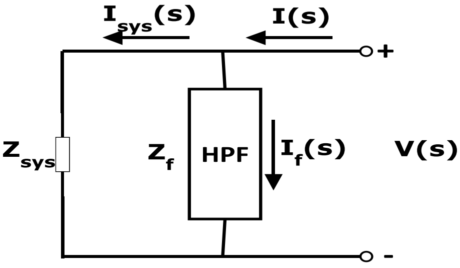


Fig.4.3. Filter/System impedance representation

$$H_{fs}(s) = Z_{fs}(s) = \frac{V(s)}{I(s)} = \frac{V(s)}{I_f(s) + I_{sys}(s)} = \frac{1}{\frac{1}{Z_f(s)} + \frac{1}{Z_{sys}(s)}} \tag{3}$$

If other energy storage elements such as capacitances and/or inductances exist in the power system network, they will affect the overall performance of the filter system when it is installed. $H_{fs}(s)$ is a powerful tool that can be used to gain insight into the combined frequency response of the filter connected to the system.

4.3.2.2. Current divider transfer function

Referring to Fig. 4.3, current divider transfer functions for the filter system connected to the power system network is the ratio of system current to injected current.

$$H_{cds}(s) = \frac{I_s(s)}{I(s)} = \frac{Z_f(s)}{Z_f(s) + Z_{sys}(s)} \tag{4}$$

When the filter system is being designed, the impedances of the transfer functions can be used to assess the overall system performance After the filter system is installed and operational, the harmonic current flows can be measured and the appropriate current divider ratios can be computed and plotted on the same graph for a filter performance comparison of designed vs. measured response. Equation (4) is useful for designing and determining harmonic current distortion limit compliance with IEEE- 519 limits.

4.3.3. Different Configuration of HPF And Their Analysis

Traditionally three types of passive high pass filters are used as shown in Fig. 2.2 [13], [15], [17].

Now these basic filters will be analysed by transfer function approach and the suitable filter will be chosen for higher order harmonic filtering.

4.3.3.1. First order HPF

A first-order filter is very simple to design. It consists of a capacitor bank connected directly to the power system bus and it is typically intended to filter high frequency harmonics from the system. To provide damping characteristics to the HPF, a series resistance is connected as shown in Fig. 4.4, with the system impedance assumed to be a simple inductance, $Z_s(s)=sL_s$.The "order" of the filter, in this case the 1st, is taken as the highest exponent of the characteristic s-domain polynomial of $H_f(s)$.

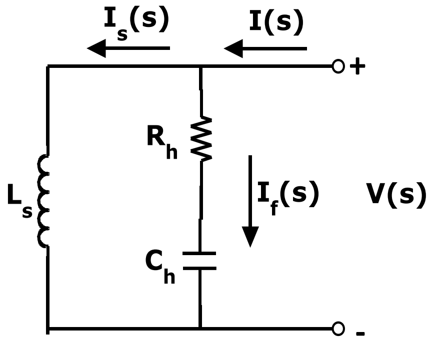


Fig. 4.4. Thevenin equivalent of first order damped high pass filter with system reactance

$$H_f(s) = R_h + \frac{1}{C_h s} \tag{5}$$

When used intentionally, the primary application of this type filter is to attenuate high frequency harmonic current components that cause telephone interference and reduce the voltage notching caused by SCR rectifier commutation as well as provide partial power factor correction of the fundamental load current When used unintentionally, as in the case of 50 Hz power factor correction capacitor banks, the system natural parallel resonant frequency may fall near one or more critical driving harmonic current frequencies, and significant voltage distortion may result.

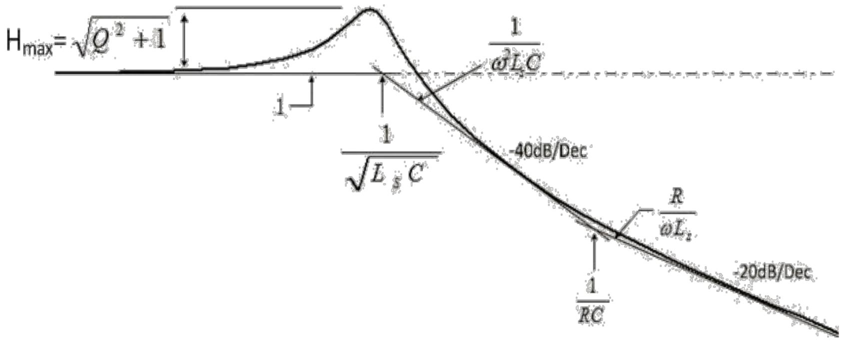


Fig. 4.5. Frequency response for first order filter

For 1st order HPF, current divider transfer function is given as

$$\mathrm{H}_{cds}(\mathrm{s}) = \frac{\mathrm{I}_s(\mathrm{s})}{\mathrm{I}(\mathrm{s})} = \frac{\mathrm{R}_h + \frac{1}{\mathrm{C}_h \mathrm{s}}}{\mathrm{R}_h + \frac{1}{\mathrm{C}_h \mathrm{s}} + \mathrm{sL}_s} \tag{6}$$

At very low frequency,

$$\mathrm{H}_{cds}(\mathrm{s}) = \frac{\mathrm{R}_h + \frac{1}{\mathrm{C}_h \mathrm{s}}}{\mathrm{R}_h + \frac{1}{\mathrm{C}_h \mathrm{s}}} \approx 1, \text{ slope is 0 dB/Dec} \tag{7}$$

At very high frequency,

$$H_{cds}(s) \approx \frac{R_h}{L_s s}, \text{ slope is -20 dB/Dec} \tag{8}$$

Resonant peak occurs at parallel resonant frequency $\omega = \frac{1}{\sqrt{L_s C_h}}$

$$H_{max} = \left|H_{cds}(s = j\omega)\right|_{\omega = \frac{1}{\sqrt{L_s C_h}}} = \left|1 - j\frac{1}{R_h}\sqrt{\frac{L_s}{C_h}}\right| = \sqrt{\left(\frac{1}{R_h}\sqrt{\frac{L_s}{C_h}}\right)^2 + 1} \tag{9}$$

Fig. 4.5 shows the frequency response of a basic 1st order HPF. As shown by (8), the roll-off of the high frequency components above the frequency 1/(RC) is only -20 dB per decade Hence, the application of the series damping resistance significantly limits high frequency performance over that of the undamped first-order high-pass This tends to make it less desirable.

In certain instances, when the parallel resonant frequency resulting from the cancellation of the system inductive reactance by the high-pass filter capacitive reactance falls on or near a critical harmonic frequency, a high-pass damping resistance can be connected in series with the capacitance to control and reduce the amplification Such a resistance, however, increases the fundamental frequency power loss and reduces the effectiveness of the high-pass attenuation above the frequency l/(RC) as shown by $H_{cds}(s)$.

Use of 1st order filter is limited, because

i. Power loss occurs due to R_h.
ii. If R_h decreases, resonant peak increases and current harmonics near resonance amplify.
iii. If R_h much more, filter performance decreases.

4.3.3.2. Second order filter

It consists of a series combination of a capacitance, inductance, and a resistance to bypass the inductance at high frequency as shown in Fig. 4.6. Value of R_h should be low to have less power loss.

At very low frequency, filter is dominantly capacitive and is open circuited. Hence the filter does not allow the low frequency current harmonics to pass through.

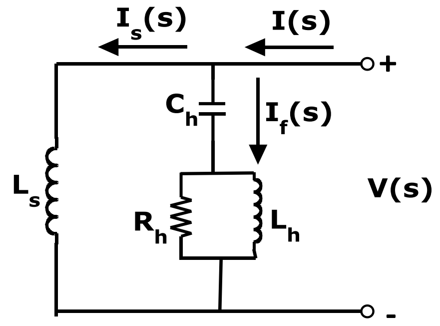


Fig. 4.6. Thevenin equivalent of second order damped high pass filter with system reactance

At very high frequency, capacitor is short circuited and as $R_h \ll \omega L_h$, high frequency current will pass through the resistance, so the HPF has almost negligible resistance for high frequency currents.

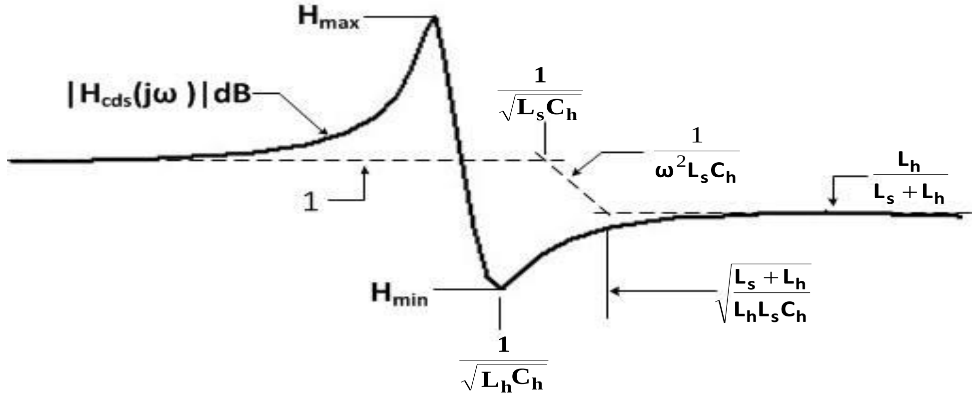


Fig. 4.7. Frequency response for second order filter

From Fig. 4.7, it is seen that the HPF has two resonant peaks, H_{max} and H_{min}. The bypass resistance is chosen based on the desired high-pass response and the series resonant attenuation. Bypass quality factors $0.5 < Q < 2.0$ are typical [15].

Where
$$Q = \frac{1}{R_h}\sqrt{\frac{L_s}{C_h}} \tag{10}$$

Higher Q factors allow more series resonant attenuation and less high-pass; by contrast, lower Q factors provide less series resonant attenuation and greater high-pass response. Hence, a trade-off between the series-resonant and high-pass responses exists.

The main application of this filter is to provide attenuation for harmonic frequency components over a wide frequency range.

The merits of second order filter are:

i. Simple design
ii. Attenuation for harmonic frequencies over wide frequency range
iii. Less power loss as low resistance is used

4.3.3.3. Third and higher order filters

In second order filter, if the resistance used has high value, then to minimize the power loss an additional capacitor is connected in series with bypass resistor. The filter is now called as 3rd order filter. Fig. 4.8 demonstrates a simple Thevenin equivalent of 3rd order HPF in a system.

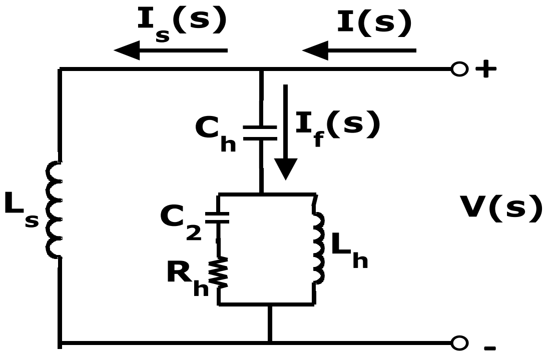


Fig. 4.8. Thevenin equivalent of third order damped high pass filter with system reactance

The filter energy efficiency increases. This however makes the design complicated without any significant filter performance.

Generally for low and medium voltage applications, it is not preferred because of economic, complexity and reliability factors.

4.4. Summary

From above discussion, it is seen that first order filter is not reliable and third order filter is used only when power loss is more. Moreover third and higher order filter design is too complex and unreliable. So second order filter is widely used for reducing the higher order harmonics in current and hence higher order harmonics in source voltage. Hence the design procedure to be followed is limited to second order filter only, as shown in Fig. 2.2 (b)

Chapter 5

PASSIVE HIGH PASS FILTER DESIGN

Introduction

Passive High Pass Filter Design Procedure

Summary

5.1. Introduction

In the previous chapter various aspects of passive filter are discussed. Different types of high pass filters were analysed by transfer function approach. Frequency response of the filters were also given. In the end it was concluded that constructing of hybrid filter by choosing a second order HPF along with shunt APF will perform affectively with satisfying the economic and reliability factors. The APF will eliminate harmonics of order till 25th whereas the passive HPF will eliminate the higher order harmonics. The higher order harmonics present in source current as well as source voltage will be reduced by the use of HPF.

In this chapter the proposed step-by-step design procedure for the 2nd order high pass filter is presented. At the end we will get some simple expressions for finding the filter parameters.

5.2. Passive High Pass Filter Design Procedure

The single line diagram shown in Fig.4.1 is represented as a circuit in Fig.5.1 which consists of a second order HPF and a voltage source V_S with a source inductance L_s. A full wave bridge rectifier with RL load is widely used in practical applications. Hence it is employed here in place of nonlinear load with load terminals ‘a’ and ‘b’. It is assumed that APF shown in Fig. 3 is designed to compensate till 25th harmonic. Hence higher order (> 25) harmonic current is required to be filtered by proper design of HPF. The equations required to design the HPF are derived based on following conditions

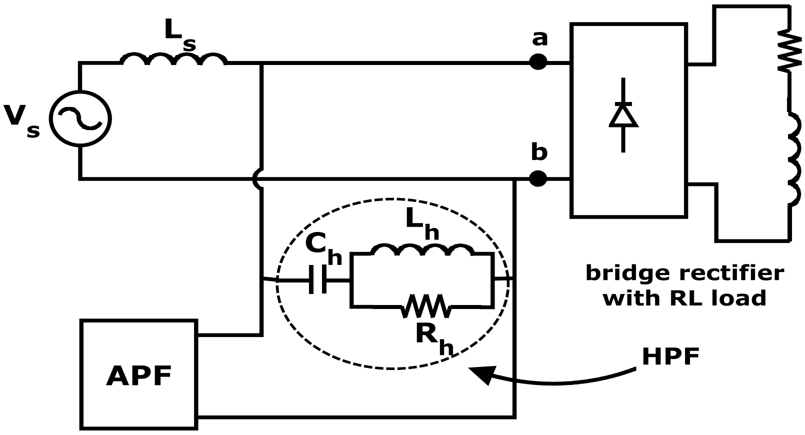


Fig. 5.1. Active power filter model with second order HPF

i. Loading effect of the filter on the source

ii. Location of resonant frequencies and resonant magnitude of peak of the high frequency model of circuit shown in Fig. 5.1.

iii. Attenuation at switching harmonic frequencies to maintain distortion level as per IEEE Std. 519.

Considering the above conditions, a step by step design procedure is illustrated.

Step-1: An equation is derived considering the load impedance and HPF impedance at fundamental (power) frequency. If V_f, I_f and ω_f are the fundamental voltage, fundamental current and angular frequency of the source respectively, the impedance (Z_{Lf}) offered by the load to this fundamental frequency is given by

$$Z_{Lf} = \frac{V_f}{I_f} \tag{1}$$

At fundamental frequency, inductance L_h acts like a short circuit and bypasses R_h and capacitive reactance dominates. Hence the impedance of the HPF at fundamental frequency is given by

$$Z_{HPFf} = \frac{1}{\omega_f C_h} \tag{2}$$

To avoid loading effect of HPF, Z_{HPFf} is taken 'k' times higher than Z_{Lf} given by (3). For example if k > 20, fundamental current of less than 5% passes through HPF.

$$Z_{HPFf} = kZ_{Lf} \tag{3}$$

From (1), (2) and (3), the required value of capacitance is approximately given by (4),

$$C_h = \frac{1}{kZ_{Lf}\omega_f} \tag{4}$$

Step-2: One of the important factor needs to be considered while designing a filter is the system natural resonant frequencies. If the resonant frequency falls near one or more critical driving harmonic frequencies, the latter tend to be amplified. The amount of amplification of these harmonics depends on the magnitude of resonant peak.

Proper location of system resonant frequency is possible by careful selection of inductor and capacitor in HPF. Similarly the magnitude of resonant peak can be adjusted by proper selection of resistor (R_h) in HPF.

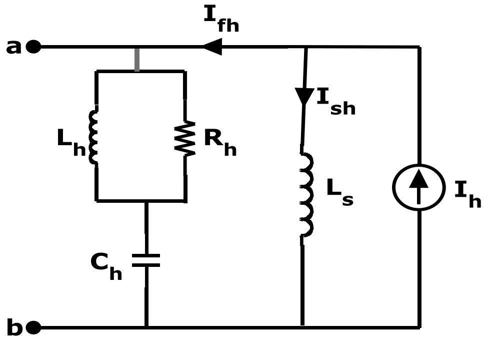


Fig. 5.2. High pass filter with source impedance

Considering the circuit shown in Fig. 5.1, the inductance of the load is very high compared to the source inductance. Hence at high frequency, the load across the terminals ‘a’ and ‘b’ is assumed to be open circuit. The high frequency model of the circuit shown in Fig. 5.2 is obtained by representing the load by an open circuit and other part of the circuit by its Norton’s equivalent across the terminals ‘a’ and ‘b’ is shown in Fig. 5.2. I_h is the equivalent Norton’s current and subscript ‘h’ denotes that the current contain high frequency harmonics (required to be filtered by HPF). For an ideal HPF, all the current I_h passes through HPF, thus filtering the high frequency harmonics in the source current (passing through L_s). I_{sh} and I_{fh} denote the current passing through source inductance and HPF respectively.

The current divider transfer function (H_{cds}) with respect to source current I_{sh} is [15]

$$H_{cds} = \frac{I_{sh}}{I_h} \tag{5}$$

Fig. 5.3 is the bode plot of the circuit shown in Fig. 5.2. The resonant frequencies depend on the values of L_h, C_h, L_s and R_h. Due to series resonance the source current harmonics near series resonant frequency are attenuated but due to parallel resonance the source current harmonics near parallel resonant frequency are amplified. Hence, only parallel resonance is considered here. The value of filter resistance R_h may vary from 0 to ∞. Initial analysis is carried out by considering the two limiting values of R_h.

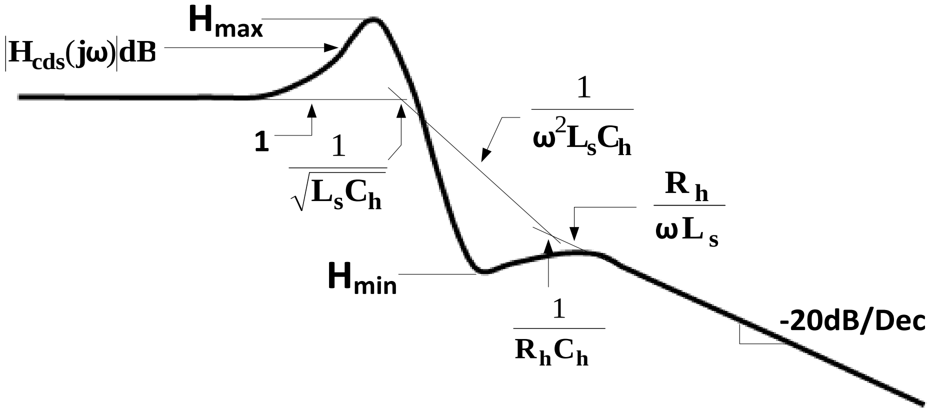


Fig. 5.3. Frequency response of current divider transfer function for HPF shown in Fig. 5.2

Case I: If $R_h \rightarrow \infty$, the transfer function is

$$H_{cds} = \frac{\frac{1}{C_h s} + L_h s}{\frac{1}{C_h s} + (L_h + L_s)s} \tag{6}$$

The parallel resonant frequency is given by ω_{p_1}, where

$$\omega_{p_1} = \frac{1}{\sqrt{(L_h + L_s)C_h}} \tag{7}$$

Case II: If $R_h \rightarrow 0$, the transfer function is

$$H_{cds} = \frac{\frac{1}{C_h s}}{\frac{1}{C_h s} + L_s s} \tag{8}$$

In this case the parallel resonant is given by ω_{p_2}, where

$$\omega_{p_2} = \frac{1}{\sqrt{L_s C_h}} \tag{9}$$

$$C_h = \frac{1}{{\omega_{p_2}}^2 L_s} \tag{10}$$

From (7) and (9)

$$\frac{{\omega_{p_2}}^2}{{\omega_{p_1}}^2} = 1 + \frac{L_h}{L_s} \tag{11}$$

So

$$L_h = L_s \left(\frac{{\omega_{p_2}}^2}{{\omega_{p_1}}^2} - 1 \right) \tag{12}$$

From (4) and (9)

$$\frac{1}{k Z_{Lf} \omega_f} = \frac{1}{{\omega_{p_2}}^2 L_s}$$

So

$$k = \frac{{\omega_{p_2}}^2 L_s}{Z_{Lf} \omega_f} \tag{13}$$

Case III: If $0 \leq R_h < \infty$

Let ω_p be the parallel resonant frequency for a given value of R_h between 0 and ∞. It is seen from (7) and (9) that $\omega_{p_1} \leq \omega_p \leq \omega_{p_2}$.

As already discussed, parallel resonance of HPF with source inductance causes amplification of harmonics in source current that fall near parallel resonant frequency. So, one of the design constraints is the location of ω_p and other is to limit the magnitude of resonant peak. This is achieved by

1. analyzing the source current harmonics and selecting ω_{p_1} and ω_{p_2} in a frequency band where no critical source current is present.
2. tuning damping resistance (R_h) to reduce the resonant peak

It can be observed from (10) and (12) that the values of the capacitor and inductor are obtained by proper selection of ω_{p_1} and ω_{p_2}.

Selection of ω_{p_1} *and* ω_{p_2}

a. From (13), it is observed that loading effect due to HPF is reduced by increasing the value of k and hence ω_{p_2}. This defines the lower limit of ω_{p_2}.

$$\omega_{p_2} \geq \sqrt{\frac{k Z_{Lf} \omega_f}{L_s}} \tag{14}$$

Modern APFs are capable of compensating harmonics typically till 25th order [19]. So HPF is required to filter all the high harmonics that APF is not able to compensate. From Fig. 5.3, it is observed that attenuation of the HPF starts approximately from parallel resonant frequency. Hence the upper limit for parallel resonant frequency ω_{p_2} is

$$\omega_{p_2} < 25\omega_f \tag{15}$$

From (14) and (15),

$$\sqrt{\frac{kZ_{Lf}\omega_f}{L_s}} \le \omega_{p_2} < 25\omega_f \tag{16}$$

From (16)

$$k < \frac{625L_s\omega_f}{Z_{Lf}} \tag{17}$$

This shows the constraint on ‘k’. To avoid loading effect as discussed in Step-1, the value of ‘k’ is selected as high as possible.

b. From (12), it is observed that L_h depends on square of the ratio of $\omega_{p_2}$to ω_{p_1}. By choosing the ω_{p_1} nearer to ω_{p_2}, the value of L_h reduces. Thus decreases the cost of designed inductor. However if the ω_{p_2} and ω_{p_1} are too near, the frequency response of HPF becomes more sensitive to the changes in R_h. Hence a compromise must be made in choosing the value of ω_{p_1}.

Thus $\omega_{p_1}$and $\omega_{p_2}$are selected in a frequency band whose upper limit lies below $25\omega_f$.

Step-3: As frequency tends to be very high (near switching frequency),

$$H_{cds}=\frac{R_h}{L_s s} \tag{18}$$

From (18), it can be observed that high value of R_h results in low attenuation near switching frequency and low magnitude resonant peak at parallel resonance. The HPF will show good performance when peak at resonance is low and attenuation at switching frequency is high. Hence an optimum value is to be selected. The limits of R_h can be obtained by taking the typical values of quality factor used for HPF in the literature [17], [26].

Selection of R_h

The value of R_h is obtained by selecting the quality factor Q_h. The quality factor is represented as

$$Q_h=R_h\sqrt{\frac{C_h}{L_h}} \tag{19}$$

Typical values of quality factor are $0.5 \leq Q_h \leq 2$. The limits of R_h are defined based on the limits of Q_h. By selecting quality factor close to 0.7, the series resonance and high pass performances are satisfactory.

5.3. Summary

In this chapter a step-by-step design procedure was presented. Various parameters of a second order passive HPF for APF applications can be found out by using the derived equations.

Chapter 6

SIMULATION AND RESULTS

6.1. System parameters

To demonstrate the performance of the proposed high pass filter in APF application, a single phase APF circuit is developed in MATLAB/Simulink with the parameters as given in Table 6.1. A sinusoidal voltage source of 220 V rms (50 Hz) is connected to a full wave bridge rectifier with RL load having the value R =10 Ω, L = 50 mH. The complete model consists of a single phase voltage source, a nonlinear load, a voltage source PWM converter, control circuit for triggering.

Table 6.1. Major parameters of the MATLAB/Simulink model

Parameters	***Symbol***	***Value***
Source Voltage	V_s	220 V
Source Frequency	f	50 Hz
Source inductance	L_s	1 mH
DC bus voltage	V_{dc}	600 V
DC bus capacitor	C_{dc}	2000 μF
DC link inductance	L_f	5 mH
Switching frequency	f_s	10 kHz

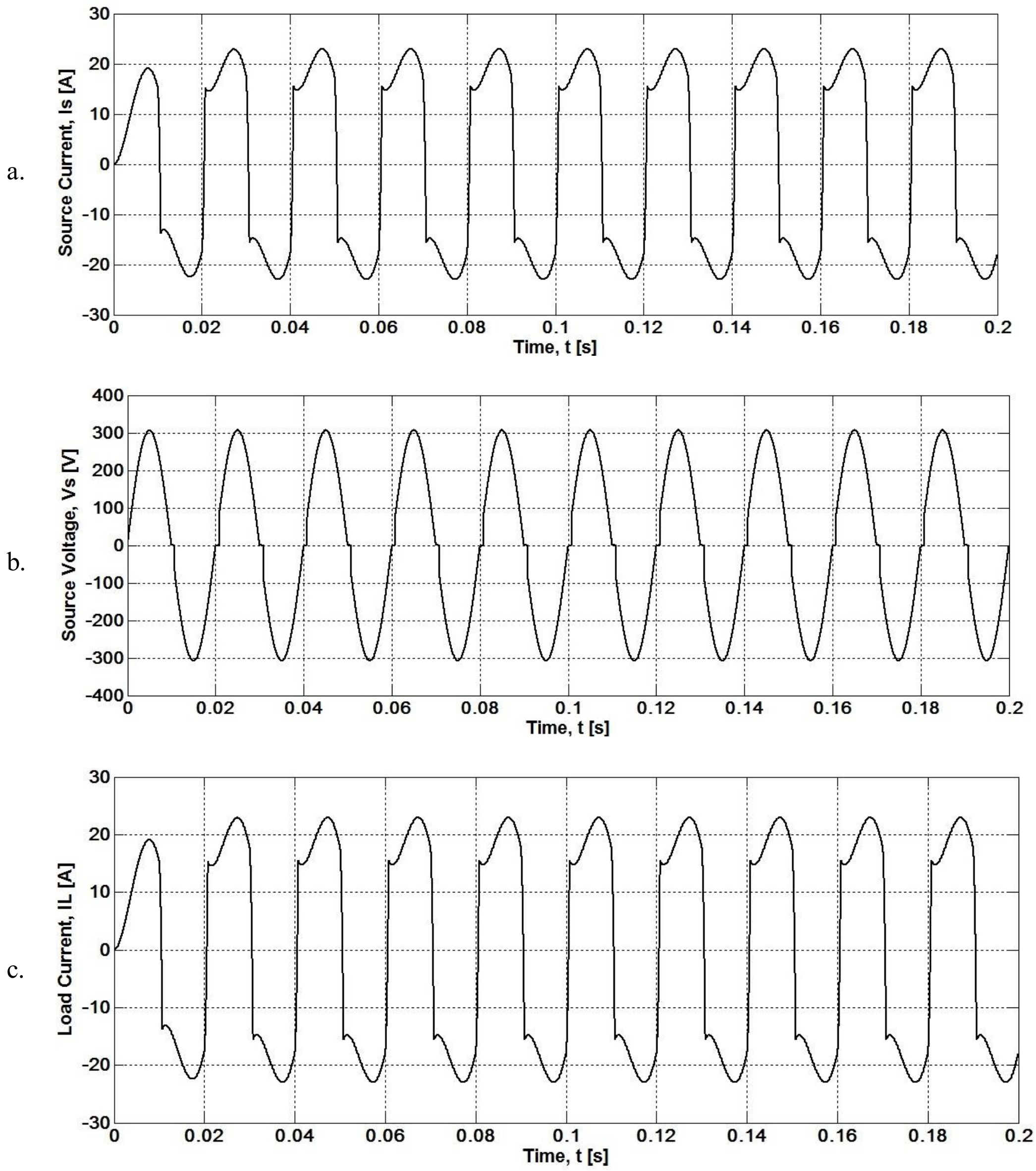
6.2. Performance of the System

First we will observe the load behavior without any compensation provided. Then we will connect an APF and see the various waveforms. We will analyse the purity in source current and voltage waveforms with spectrum analysis. Then we will design the high pass filter model with the proposed design method and connect it to the existing model to see the improvement in the power quality.

We will also see the active reactive power flow from the filter side and will check whether the filter is fed active power.

6.2.1. Without any Compensation

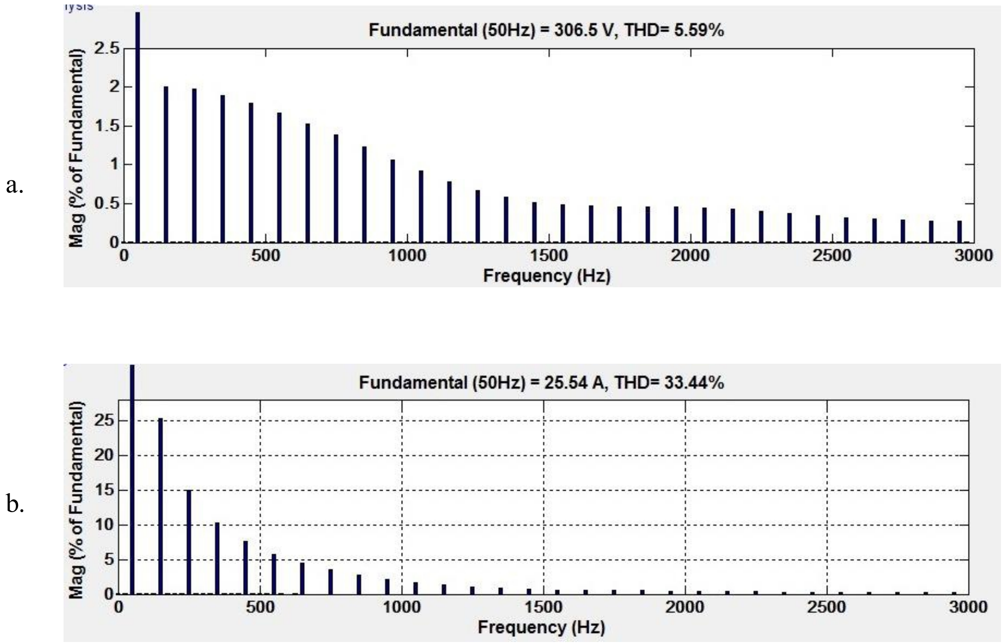
Fig. 6.1 shows the waveforms of the distribution model without any compensation provided. We can clearly observe that the load current is not at all sinusoidal, and hence the source current. The motive is to make this source current sinusoidal by some compensation method.



a. Source current b. Source voltage c. Load current

Fig. 6.1. Simulation results of the model without any compensation

Fig. 6.2 shows the voltage and current spectrum when no compensation is provided. We can clearly see that that the current waveform is totally distorted whereas the voltage waveform is having very less amount of harmonics.



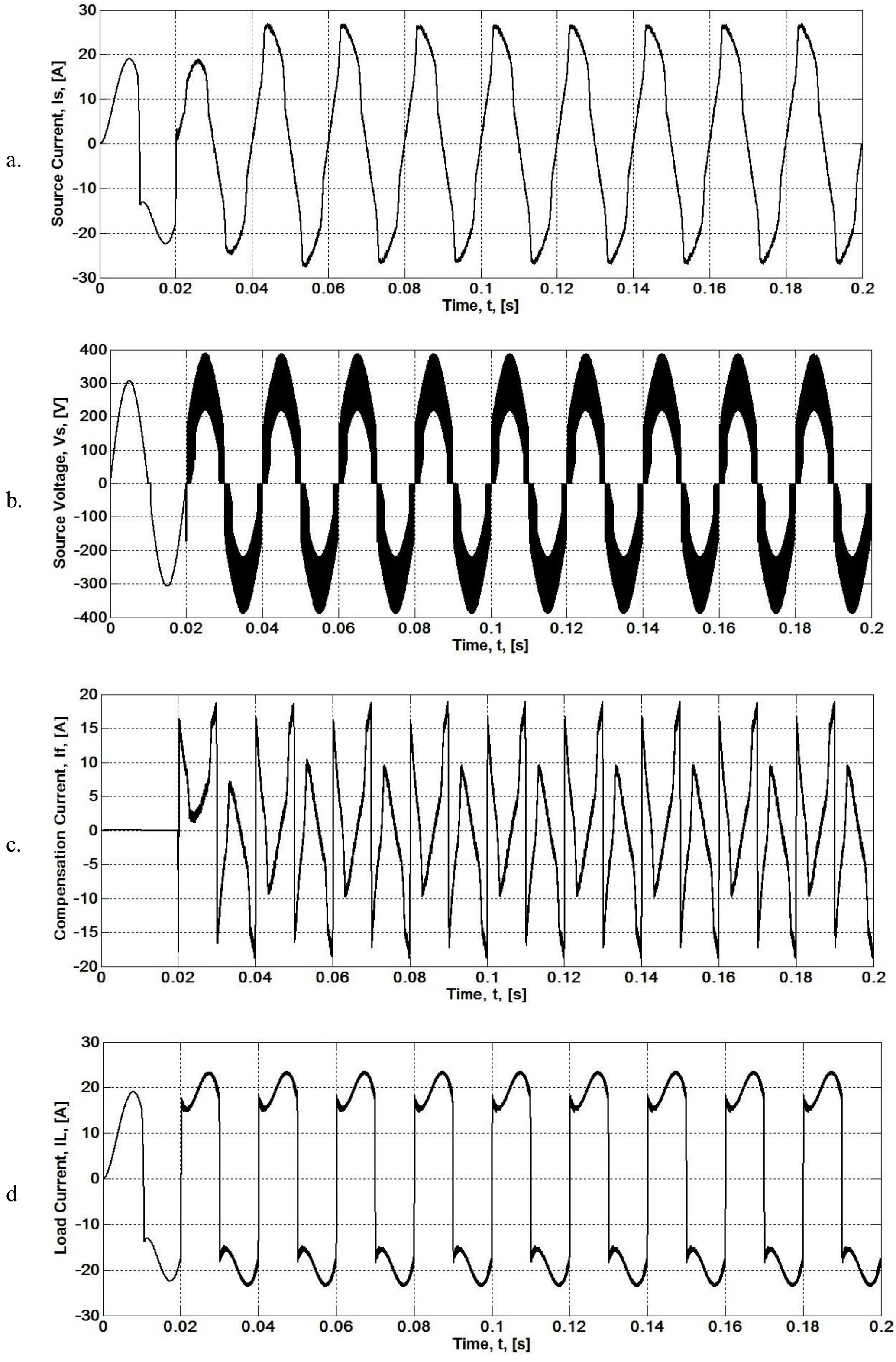
a. Voltage spectrum b. Current spectrum

Fig. 6.2. Spectrum analysis of the distribution system without any compensation

6.2.2. With APF Compensation

Now an APF compensation is being provided with the distribution system. The MATLAB/Simulink model of the complete system is as shown in Fig. A.1 in appendix. The control circuit for the APF is as shown in Fig. A.2 in appendix. The APF is being connected to the distribution system at time, t=0.02 s. Hence the compensation is starting after that time. Fig. 6.3 shows the different waveforms of the model. From Fig. 6.3 (a) we can see that the source voltage waveform is getting distorted after the APF compensation is used. This is because of the high value of switching frequency involved in APF switching.

Fig. 6.4 shows the spectrum analysis of the source voltage and source current. We can see that the source current is improved as compared to the previous case, though it is not coming within the limits specified by the standard specified by IEEE Std. 519.



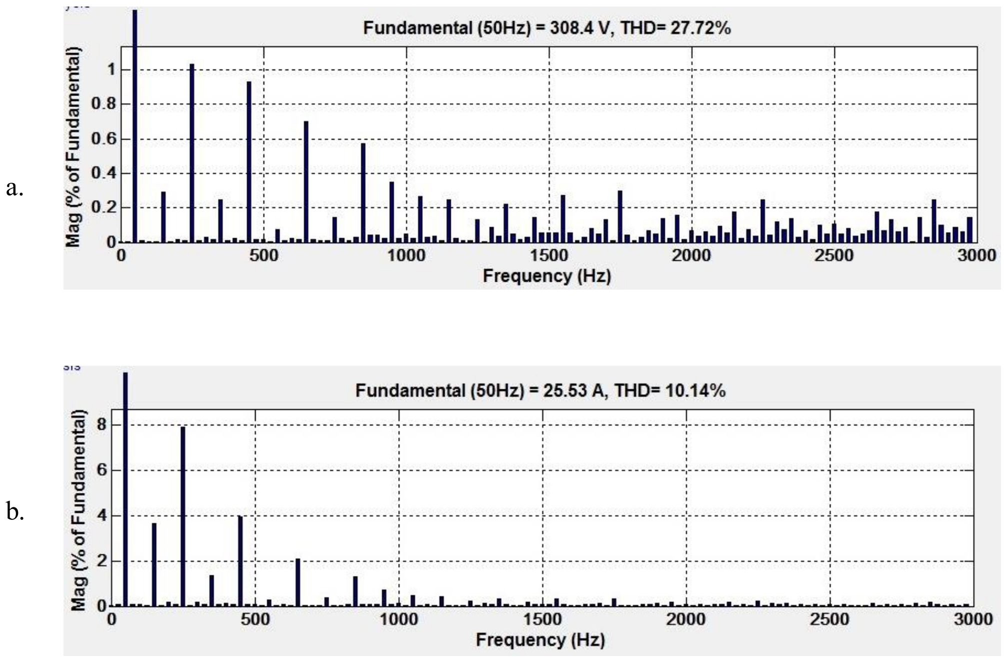
a. Source current

b. Source Voltage

c. Compensation current

d. Load current

Fig. 6.3. Simulation results of the model with APF compensation



c. Voltage spectrum d. Current spectrum

Fig. 6.4. Spectrum analysis of the distribution system with APF compensation

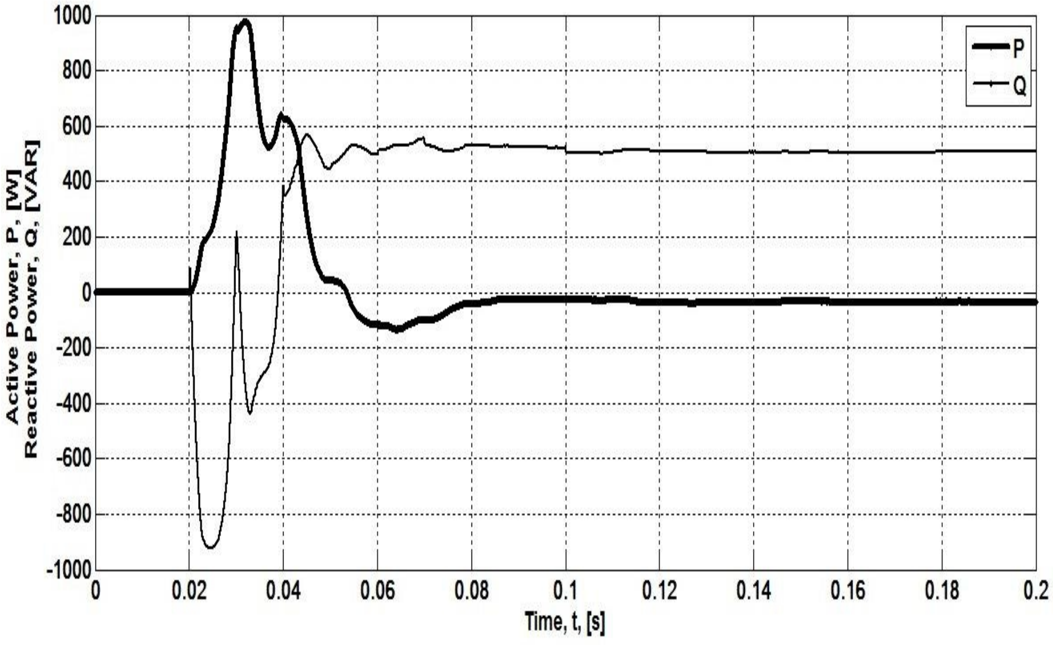


Fig. 6.5. Power flow from the filter side at the PCC

Fig. 6.5 shows the power flow from the filter side to the distribution system at the PCC. For a compensation for harmonics, the active power absorbed by the filter should be zero, i.e. the APF should not be fed from the source.

Now we will design the passive HPF for this distribution system to eliminate the higher order harmonics from the source current by using the proposed design method as discussed in the previous chapter.

6.3. Design of Passive HPF

From simulation of the given model without any compensation, it is seen that load impedance at fundamental frequency is $Z_{Lf} = \frac{V_f}{I_f} = 12\Omega$.

In chapter (5), equations were derived for the design of passive HPF. Briefly some important equations we will recall and they are given as follows,

i. The upper limit of cut-off frequency,

$$\omega_{p_2} < 25\omega_f \tag{15}$$

ii. The value of HPF capacitor,

$$C_h = \frac{1}{\omega_{p_2}{}^2 L_s} \tag{10}$$

iii. The value of HPF inductor,

$$L_h = L_s \left(\frac{\omega_{p_2}{}^2}{\omega_{p_1}{}^2} - 1 \right) \tag{12}$$

iv. The value of HPF resistor can be got from,

$$Q_h = R_h \sqrt{\frac{C_h}{L_h}} \tag{19}$$

Where, typical value for quality factor will be considered, i.e. $0.5 < Q_h < 2$. Here we will take the value of quality factor $Q_h = 0.7$.

6.3.1. *Choice of* ω_{p_1} *and* ω_{p_2}

Corresponding cut-off frequencies in Hz be f_{p_1} and f_{p_2}.

From (15) $f_{p_2} < 1250$ Hz

Hence frequencies f_{p_1} and f_{p_2} are chosen near to 1250 Hz; such that at those frequencies the magnitude of frequency component of source current is less than 2% of the fundamental. Fig. 6 shows the current spectrum of the source current prior to connecting HPF. By observing

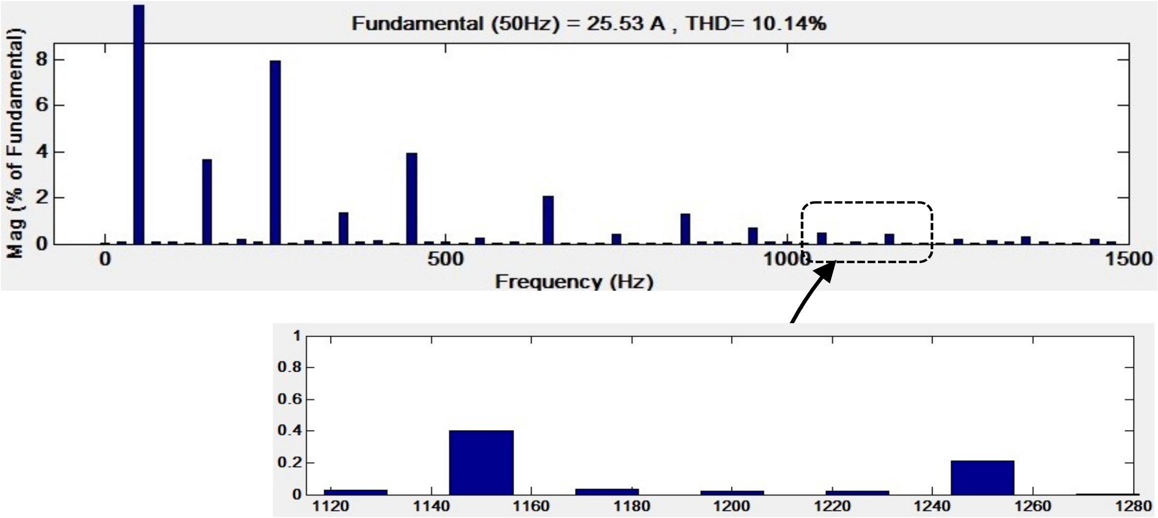


Fig. 6.6. Choice of parallel resonant frequencies from current spectrum analysis of model without HPF

Fig. 6.6, f_{p_1} and f_{p_2} are chosen as 1160 Hz and 1240 Hz respectively where the harmonic content is totally absent. Hence the frequency components in rad/s are as follows,

$$\omega_{p_1} = 2320\pi \text{ rad/s and } \omega_{p_2} = 2480\pi \text{ rad/s}$$

6.3.2. *High pass filter parameters*

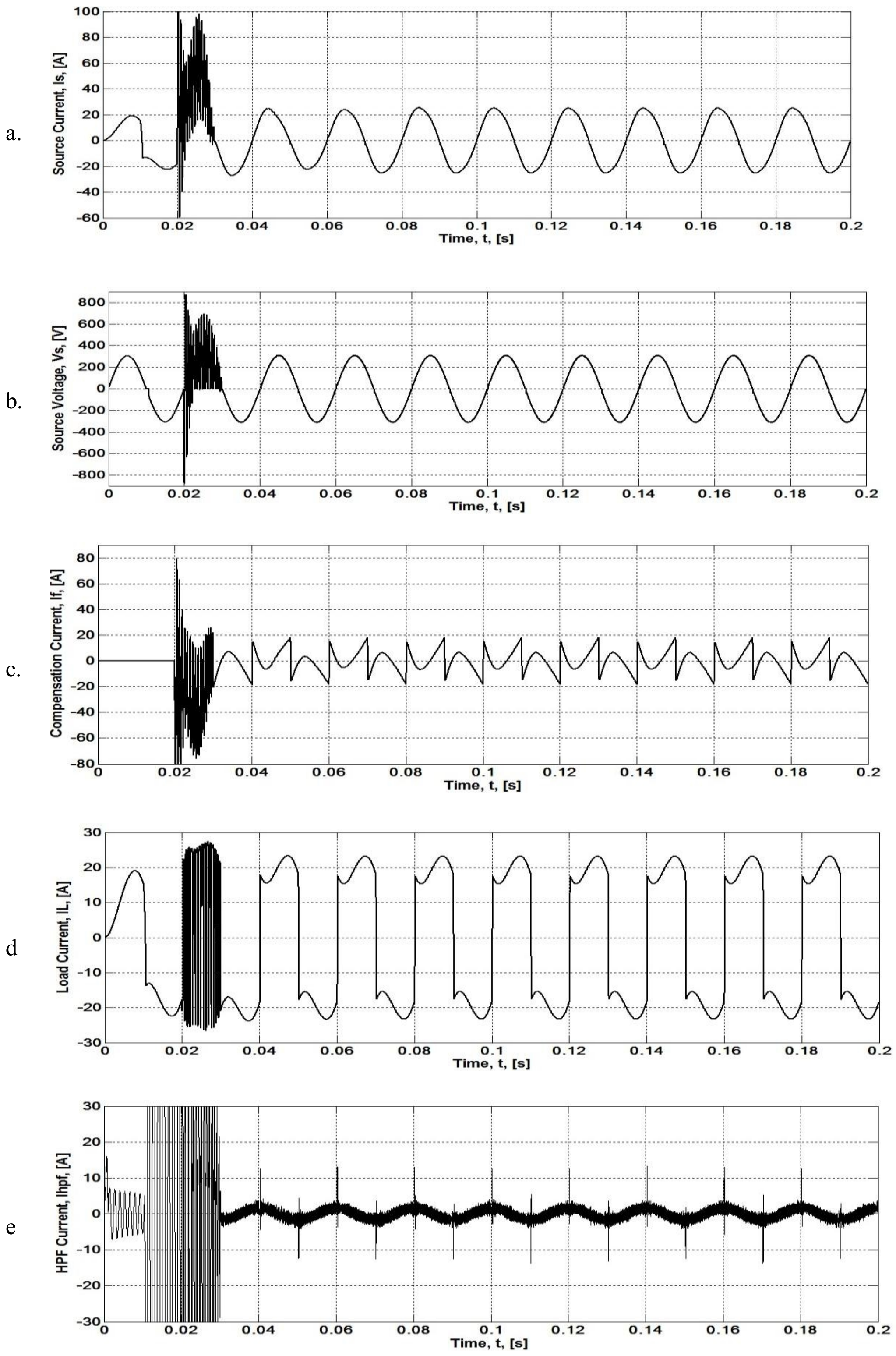
Now the various HPF parameters are found out by using equations (10), (12) and (19) as follows,

$$L_h = 0.124 \text{ mH}, C_h = 16.75\ \mu\text{F}, R_h = 1.90\ \Omega$$

6.4. Performance of the system after connecting of designed HPF

Simulated results after connecting HPF are shown in Fig. 6.7. It is observed that the distortion of the mains current and voltage decreased to a level as mentioned in the standards IEEE Std. 519. Fig. 6.7(e) shows the current passing through the HPF. Fig. 6.8 shows the harmonic content in the source voltage and source current with HPF. THD of the voltage and current are lying below 1.2% and 4% respectively, whereas the limit specified by IEEE Std. 519 is 3% and 5% respectively. At the time of switching (t=0.02 s) for less than half period, transient rise in all the waveform can be seen, elsewhere both the voltage and current wave are completely sinusoidal.

Fig. 6.9 and Fig. 6.10 are showing the power flow at PCC from filter side and through the designed HPF respectively.



a. Source current

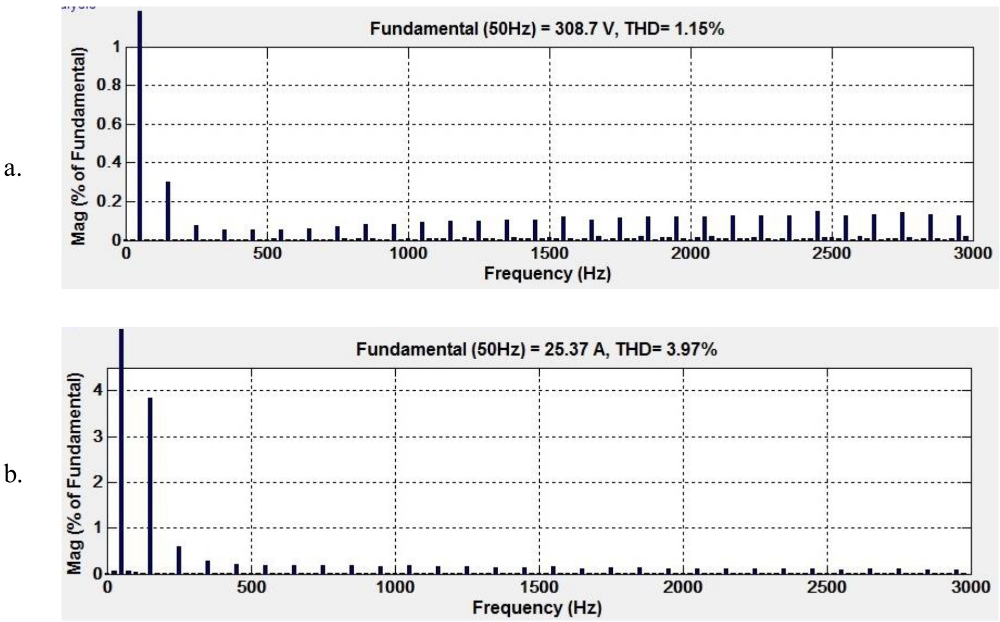
b. Source Voltage

c. Compensation current

d. Load current

e. Current through HPF

Fig. 6.7. Simulation results of the model with APF compensation



a. Voltage spectrum b. Current spectrum

Fig. 6.8. Spectrum analysis of the distribution system with HAPF compensation

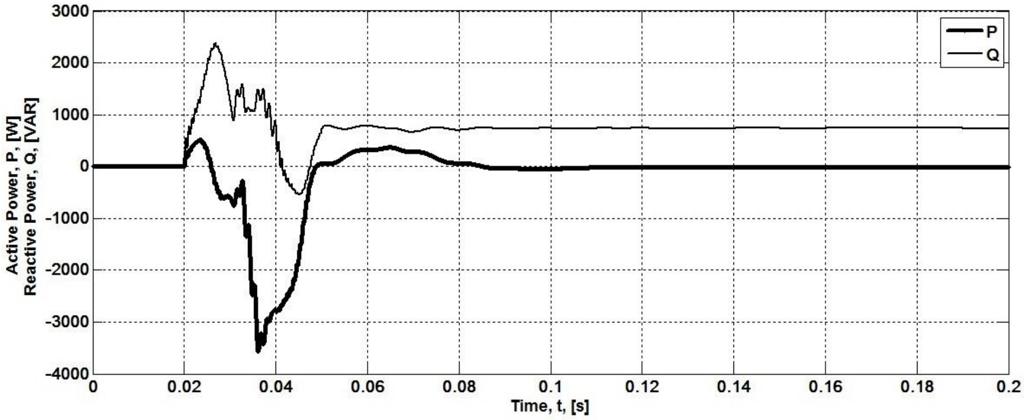


Fig. 6.9. Power flow from the filter side at the PCC in hybrid APF

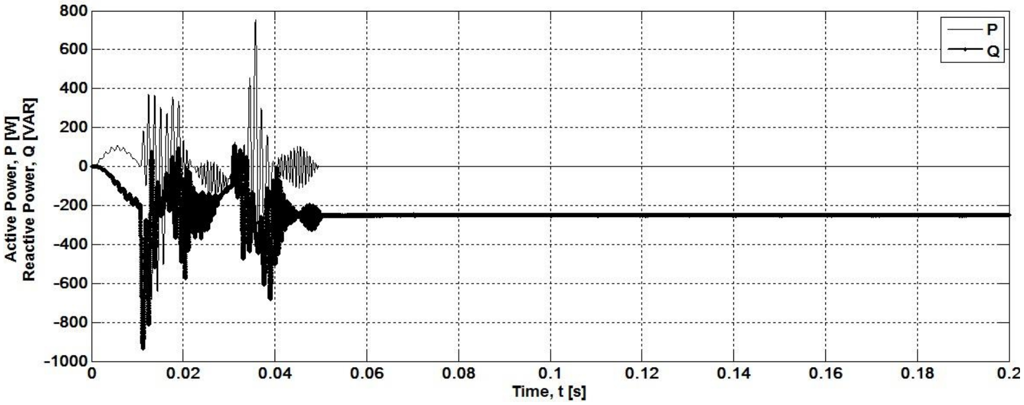
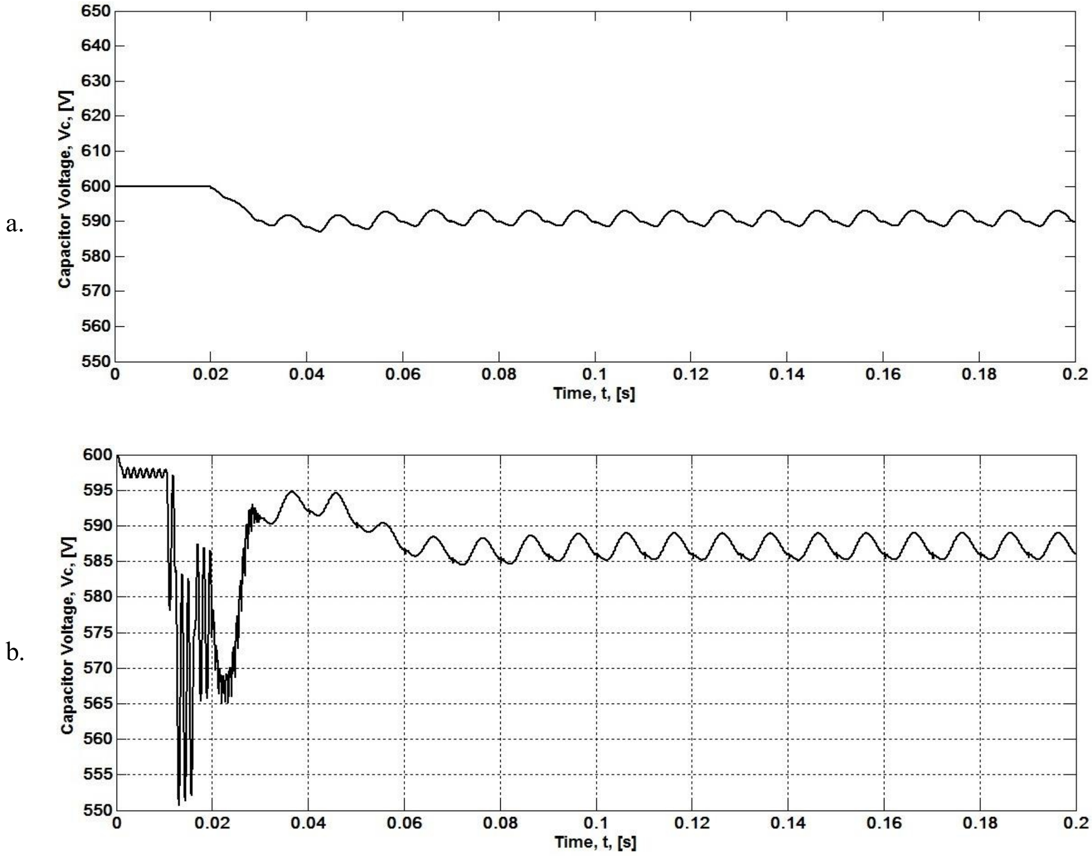


Fig. 6.10. Power flow through the designed HPF

From Fig. 6.9, it can be seen that filter side is supplying reactive power to the distribution system at the PCC and except for a transient period, the filter side is rarely consuming any active power which is the case of ideal compensation. From Fig. 6.10 it is seen that the HPF is absorbing a fixed amount of reactive power, but the active power transaction with the rest of the system is almost zero except a small duration at the time of switching.

6.5. DC link capacitor voltage waveform

Fig. 6.11 shows the DC link capacitor voltage variation for the system before and after connecting the designed high pass filter. It can be seen that after connecting the designed HPF, the DC link voltage is having transient behavior during switching (0.02s) which comes to almost steady state after half cycle. A very small oscillation of nearly 4 V is seen which can be considered as constant voltage being at very high level.



a. Before connecting HPF b. After connecting HPF

Fig. 6.11. DC link capacitor voltage variation waveform

6.6. Summary

In this chapter the performance of the distribution system without any compensation is first seen. Then the system performance with shunt APF compensation is observed, where it was seen that the shunt APF improves the performance of source current at the cost of source voltage waveform which is having harmonic components. Then a passive HPF is designed as per the procedure presented in previous chapter and was connected to the existing system. This hybrid combination rectified both the source voltage and current to make them perfect sinusoid. The THD also lied with in the limit specified as per IEEE Std. 519.

Chapter 7

CONCLUSION & FUTURE WORK

Conclusion

Power quality problem in power system is a very serious problem now-a-days. It is interesting to know that due to power electronics devices it is introduced and the same power electronic equipment are used to mitigate them. Performance of shunt APF was analysed and it was seen that power quality of the distribution system improved, but the total harmonic distortion is not coming within the specified limit. Though lower order harmonics was compensated from the system, the higher order harmonics were still prominent.

Then intensive study was done about different passive high pass filter configurations and second order HPF was chosen among them. A step-by-step design procedure was followed to design the second order HPF which was then used along with the existing system with APF.

This designed hybrid filter performed quite satisfactorily with the THD limits for both current as well as voltage lied below the limits specified by IEEE Std. 519. Power flow from filter to distribution system from the filter side at the PCC and power flow through the 2nd order HPF was observed. It was found that there is no transaction of active power at the PCC from filter side, whereas the filter side is compensating for the reactive power requirement of the load.

Moreover the parameters of HPF are of very low rating (R_h=1.9 Ω, L_h= 0.124 mH, C_h=16.75μF) leading to economical design of the passive filter. The designed hybrid filter is found to be efficient enough to supply very good quality of power.

Scope for Future Work

Experimental model can be developed for this hybrid filter to verify the performance of the designed filter. The HPF performance can be examined by using a programmable source which can generate harmonics. For switching of the inverter, DSP 2812 kit can be used. Voltage and current sensors are also needed for the control signal generation.

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Publication (s)

1. **Gourishankar Mishra** and S. Gopalakrishna, “Design of passive high pass filter for shunt active power filter application,” *Proc. of IEEE International Conference on Circuit, Power and Computing Technologies 2013*, ICCPCT 2013, Nagercoil, pp. 17-21
2. **Gourishankar Mishra** and S. Gopalakrishna, “Design of hybrid active power filter with first order passive high pass filter,” *Proc. of National Conference on Power Electronics Systems and Applications 2013*, PESA 2013, NIT Rourkela, pp. 351-355

Appendix

MATLAB/Simulink Model of the Power System with Hybrid APF

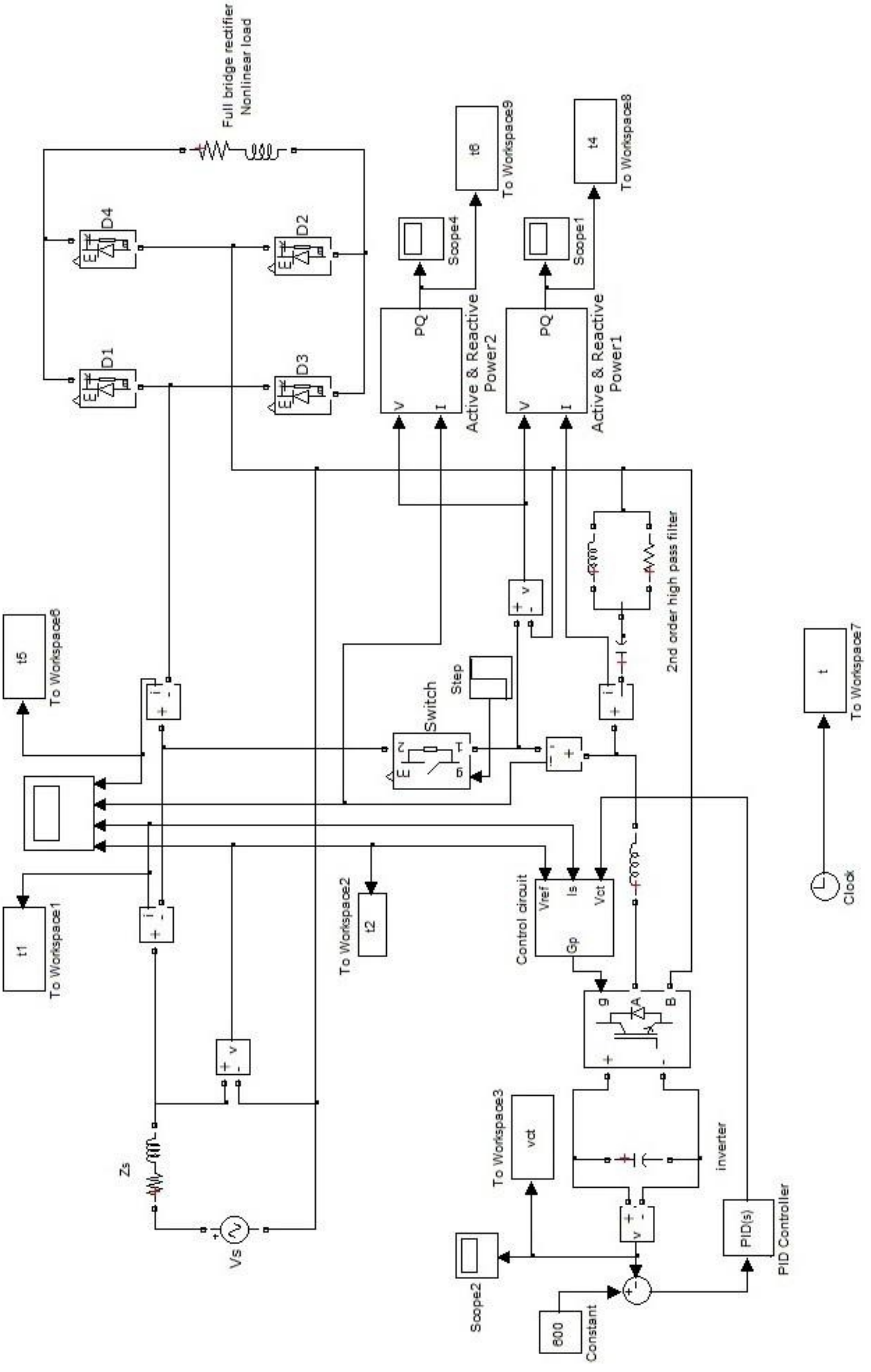

Fig. A.1. MATLAB/Simulink model of the complete system

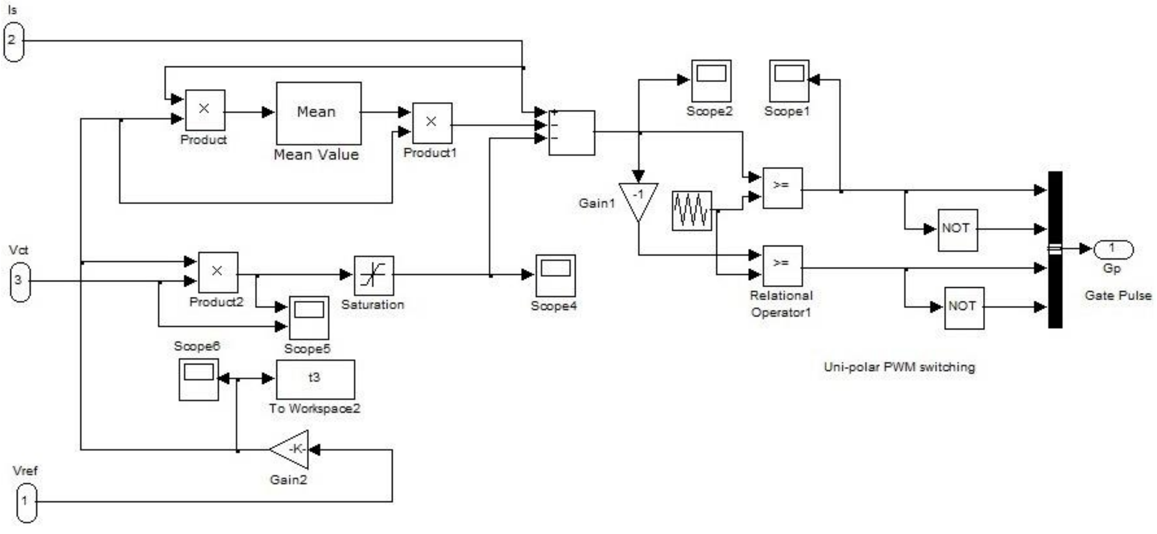

Fig. A.2. MATLAB/Simulink model of the inverter gate driver circuit