# HYBRID FILTERS FOR HARMONIC COMPENSATION IN DISTRIBUTION SYSTEMS

*A Project Report*

*submitted by*

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*in partial fulfilment of the requirements*
*for the award of the degree of*

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# THESIS CERTIFICATE

This is to certify that the thesis titled HYBRID FILTERS FOR HARMONIC COMPENSATION IN DISTRIBUTION SYSTEMS, submitted by KOTHINTI SANDEEP REDDY, to the Indian Institute of Technology, Madras, for the award of the degree of **BACHELOR OF TECHNOLOGY and MASTER OF TECHNOLOGY**, is a bona fide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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# ABSTRACT

KEYWORDS: DSTATCOM, DVR, harmonics, THD, hybrid filters, passive filters, VA rating minimzation, harmonic compensation, reactive power compensation

Quality of power supply is a major concern for modern day electrical equipment. Harmonic distortion in supply voltage of distribution system has adverse effects on sensitive equipment. IEEE 519 standards provide limits on voltage and current distortions for reliable power supply. Conventionally passive filters are used for harmonic compensation because of low cost. Passive filters perform satisfactorily only for small distortions in currents. Resonance of passive filters with system impedance causes distortion to increase. To avoid these problems and for better compensation performance active filters are being used. Active filters proved to be very efficient in compensating for harmonics and unbalances but high cost limits usage of active filters. Hybrid filters which are combinations of active and passive filters overcome problems faced by active and passive filters. In the present work three hybrid filter topologies are presented. Two of these filters are found in existing literature. A new hybrid filter topology that has similar performance as active filters and lower cost is proposed in the present work. Simulation results of these three filter topologies are also discussed to compare the performance.

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# ABBREVIATIONS

| | |
|---|---|
| **AC** | Alternating Current |
| **DC** | Direct Current |
| **DVR** | Dynamic Voltgae Regulator |
| **THD** | Total Harmonic Distortion |
| **IHD** | Individual Harmonic distortion |
| **TDD** | Total Demand Distortion |
| **FIR** | Finite Impulse Response |
| **IEEE** | Institute of Electrical and Electronics Engineers |
| **PCC** | Point of Common Coupling |
| **VA** | Voltage Ampere |
| **VSI** | Voltage Source Inverter |
| **IGBT** | Insulated Gate Bipolar Thyristors |
| **RMS** | Root Mean Square |
| **SCR** | Short Circuit Ratio |
| **FFT** | Fast Fourier Transform |

# NOTATION

| | |
|---|---|
| $v_{sa}, v_{sb}, v_{sc}$ | Instantaneous source voltages of a, b, c phase |
| $i_{sa}, i_{sb}, i_{sc}$ | Instantaneous source currents of a, b, c phase |
| $I_{lh}, I_{sh}$ | Harmonic components in load and source currents |
| $V_{lh}, V_{sh}$ | Harmonic components in load and source voltages |
| $P_{lavg}$ | Average power consumed by the load |
| $S_a$ | binary switch variable |
| $h$ | Hysteresis constant |
| $C_{dc1}, C_{dc2}$ | DC-link capacitance values |
| $v_{012}, i_{012}$ | Instantaneous zero, positive, negative sequence voltages and currents |
| $THD_v$ | THD in voltage |
| $THD_i$ | THD in current |
| $C_f, R_f, L_f$ | Filter parameters in RLC filters |
| $I_{sc}$ | Short circuit current at PCC |
| $Z_s$ | Source impedance |
| $v_{fa}, v_{fb}, v_{fc}$ | Instantaneous filter voltages of a, b, c phase |
| $i_{fa}, i_{fb}, i_{fc}$ | Instantaneous filter currents of a, b, c phase |

# CHAPTER 1

# INTRODUCTION

The recent increase in power demand is not just in quantity of power but the advances in technologies demand quality in power. There are many issues affecting quality of power supply. Harmonics are one of the major problems in power quality. The increase in harmonics in voltages and currents in the system is due to the advent of electronic devices which require some form of AC to DC conversion. Distributed generation systems provide improved power resource management but the quality of the power provided by the various sources should be monitored to avoid quality issues. The effect of the harmonics has economical problems that range from equipment damage to defective manufacturing of expensive products such as electronic ICs. Automation of manufacturing in many areas has increased productivity, but it is very vulnerable to quality of power supply. Reliable solutions should provided for solving power quality problems to encourage such developments.

Harmonic compensation using passive filters is an option but due to variations in system parameters designing these filters is difficult and involves risk. Application of active filters for harmonic compensation was proposed in 1971 by H. Sasaki and T. Machida [1], but these filters used linear amplifiers to generate voltage and currents. The improvement in power electronic device switching speeds and capacity has provided more robust solutions with better control over switching harmonics. The high cost of active filters motivated research on hybrid filters and many differenet topologies were proposed [2]. Most of these topologies are dependent on type of load connected. The filter topologies that are installed at utilities should be load independent.

## 1.1 Power Quality Problems

Power Quality is a term used to express the fitness of the power supplied to consumer. The basic power quality problems that arise in distribution systems are unbalance in source voltage magnitude or phase-angle, unbalance in source current magnitude and harmonic content in both source voltage and current. . Harmonics in load currents occur due to non-linearity in loads, i.e. non-linear dependence between voltage and current. One such example is given in Fig. 1.1. The non-linear load shown in Fig. 1.1 draws harmonic current and source current is also distorted. This distortion in source current will produces drop across source impedance leading to distorted voltage at PCC and the balanced linear load experiences unbalances and distortion due to the drop across the source impedance.

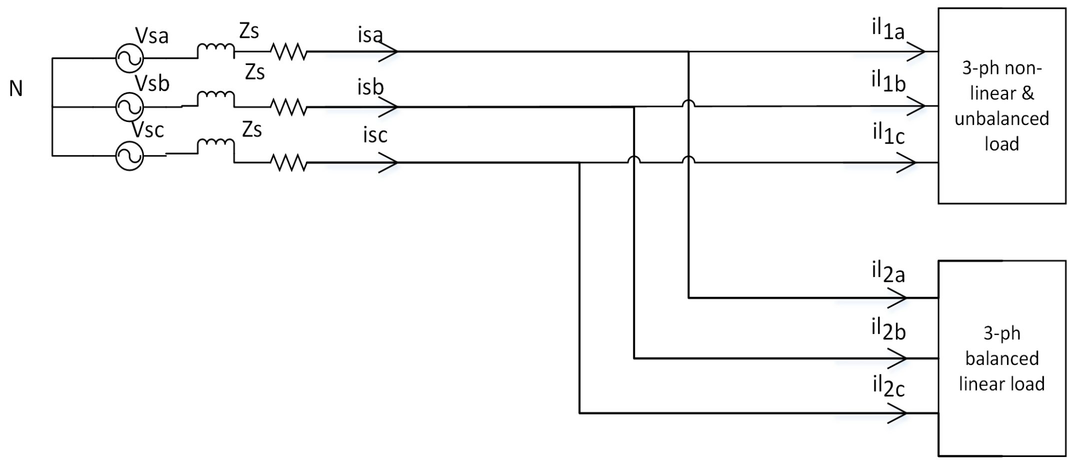


Figure 1.1: Three-phase distribution system with non-linear load

### 1.1.1 Sources of harmonics

Harmonics in currents are caused by non-linear loads that draw non-sinusoidal currents. In the early days the distortion in voltage or current waveforms were typically caused by saturation of transformers and industrial loads such as arc furnaces, arc welders. In the recent times, there is increase in usage of power electronic appliances like personal computers, speed drives, electric powered vehicles, etc., These appliances use power electronic devices such as diodes, thyristors, and transistors due to the control and flexibility these devices offer. The power electronic devices are switching devices, which draw distorted currents and make voltage waveforms distorted. Even if the distortion caused by a single power electronic load such as a personal computer is small, due to large number of such loads, the overall distortion caused is not negligible.

Harmonics in current due to rectifier loads depend on pulse number of the rectifier and are predictable. But loads such as cyclo-converters, arc-furnaces produce harmonics with frequencies that vary with time. The harmonics in source current are not only dependent on load but also on system parameters. The resonance between shunt capacitance installed at load for power factor correction and system impedance is such an example where harmonics produced by load might get amplified due to such resonance and large harmonic currents are drawn from source.

Harmonics in voltage are caused by harmonics in load current. Non-linear loads can be assumed as harmonic current sources, thus the voltage drop due to these currents depends on system impedance frequency response. If the system impedance forms resonance with some shunt element then the voltage harmonic closer to resonance frequency might get amplified causing severe voltage distortion for other loads. Harmonics in voltage is caused not only due to harmonics in load currents, but also due voltage notching caused by commutation of currents between phases in rectifier loads.

### 1.1.2 Effect of harmonics

The effects of harmonics on consumers depend on the sensitivity of the load to harmonics. In heating loads such as ovens, furnaces the harmonics are also utilized for heating and hence do not cause any problems to the load. There are loads which are very sensitive to harmonics such as communication systems, data processing equipment, automated manufacturing etc., and the effect of the harmonics on these types of loads is very severe. The problems caused on various types of electrical equipment are discussed below.

1. In rotating machinery, increased iron and copper losses at harmonic frequencies cause heating and affect the efficiency. In induction machines clogging or crawling are observed because of resultant flux in the air gap caused by harmonics. Harmonics in voltage induce harmonics in stator current. These harmonic currents cause heating additional to the fundamental frequency current.

2. In transformers, current harmonics cause increased copper losses and stray-flux losses and voltage harmonics cause increased iron losses resulting in overheating. Higher frequency harmonics cause more losses and heating compared to lower frequency harmonics.

3. Harmonics cause dielectric heating in cables and damage the insulation.

4. Capacitor banks used for reactive power compensation are affected by any resonances they form with system impedance. These resonances result in more currents flowing in the capacitors.

5. Computer controlled machine tools, digital controllers used for automation are very sensitive to harmonics in voltage. These equipments may get erroneous results because of harmonics in the voltage.

6. Power electronic equipments are also victim of harmonics in voltage. Harmonics cause shifting in zero crossings or phase-phase voltage comparisons resulting in errors in control. Errors in thyristor firing angles, false tripping of protective devices are examples of such effects.

7. Inductive metering is affected by harmonics.

8. Harmonics in line currents cause interference with communication lines which run closely with power lines.

### 1.1.3 Power quality definitions

The qualitative description of effects due to harmonics explains the need for controlling harmonic distortion in power system voltages and currents. IEEE 519 standards provide guidelines to consumers and utilities on harmonic limits in voltage and currents for a reliable operation. Before looking at the standards, the quantitative terms which are used in the standards are discussed.

**Total harmonic distortion (THD)** The total harmonic distortion is used to define the effect of harmonics on low voltage, medium-voltage and high-voltage systems. It is defined as

$$THD = \sqrt{\frac{sum\ of\ squares\ of\ amplitude\ of\ all\ harmonics}{square\ of\ amplitude\ of\ fundamental}}.100\% \tag{1.1}$$

THD in voltage is given by

$$THD_V = \sqrt{\frac{V_2^2 + V_3^2 + V_4^2 \dots}{V_1^2}}.100\% \tag{1.2}$$

THD in current is given by

$$THD_I = \sqrt{\frac{I_2^2 + I_3^2 + I_4^2 \dots}{I_1^2}}.100\% \tag{1.3}$$

**Individual harmonic distortion (IHD)** Individual harmonic distortion is used to define limits on particular harmonic to avoid effects pertinent to that harmonic. It is defined in percentage of maximum demand load current. The limits on IHD are generally imposed on currents to guide consumers. IHD in load is current is defined as

$$IHD_I(n) = \frac{I_n}{I_L}.100\% \quad n\,is\,the\,harmonic\,number \tag{1.4}$$

where $I_L$ is the fundamental component of the maximum load demand current. and it is a parameter used to define size of the load with respect to system parameter.

**Total demand distortion (TDD)** Total demand distortion (TDD) is used to examine distortion due to a particular load when compared to system parameters. TDD is different from THD as it is used to measure distortion when compared to maximum load and not to absolute load.

$$TDD = \frac{\sqrt{I^2 - I_1^2}}{I_L}.100\% \tag{1.5}$$

here, I is the rms current and $I_1$ is fundamental rms current.

### 1.1.4 IEEE 519 specifications

There are various standards on harmonics in power proposed by different scientific societies like IEEE, IEC. This work follows IEEE 519 standards on harmonics in power systems. IEEE 519 provides guidelines for consumers and utilities to contain the harmonics within limits. IEEE 519 standards impose limitations based on two criteria, first is the amount of harmonic currents that a consumer can inject and second is limit on voltage distortion in the voltage provided by the utility.

#### Guidelines for individual consumers

The limit is placed on harmonic distortion in the current that the consumer can inject in to the system. This limit takes size of the consumer power with respect to size of the supply power in to consideration. Consumers with larger power demand are restricted more when compared to small demand consumers. To determine the relative size of the load, a parameter called short circuit ratio (SCR) is used and it is defined as

$$SCR = \frac{I_{sc}}{I_L} \tag{1.6}$$

$I_{sc}$ is the short circuit current at point of common coupling (PCC) and $I_L$ is the maximum demand fundamental current of a particular consumer. For smaller SCR the effect of distortion due to the load is less effective on overall system and the limitations on such load is less strict. Table 1.1 shows IEEE 519 limits on IHD and TDD at distribution level for various values of SCR. From the table it can observed that even harmonics which cause asymmetry in current wave form have more strict limitations to avoid magnetic saturation of cores due to DC component. IEEE 519 standards also imposes limitations on voltage notching and voltage flicker which are out of scope of the present work.

Table 1.1: IEEE maximum current distortion limits for odd harmonics at 120 V- 69 kV

| $\frac{I_{sc}}{I_L}$ | < 11 | 11$\leq h$ < 17 | 17$\leq h$ < 23 | 23$\leq h$ < 35 | 35 $\leq h$ | TDD |
|---|---|---|---|---|---|---|
| <20 | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20<50 | 7.0 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50<100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| 100<1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| >1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |
| limit values for even harmonics are 25% of the values for odd harmonics | | | | | | |

### Guidelines for utilities

IEEE 519 standards provide limits on voltage distortion in supply voltage and utilities are made responsible for that. For distribution level voltages the expected IHD limit for odd harmonics in voltage is 3% and THD limit for voltage is 5%. IHD limits for even harmonics are 25% of the value for odd harmonics.

## 1.2 Harmonic Compensation with Filters

Filtering is elimination of unwanted harmonics from currents and voltages. Early solutions involved harmonic filtering using passive filters which are combinations of R-L-C elements. Even though these filters provided compensations for harmonics, the risks of resonance and dependence on source parameters [3] made these filters incompetent. With the introduction of power electronic devices such as custom power devices, the harmonic compensation became more efficient. Examples of custom power devices used for harmonic compensation and reactive power compensation are distribution static compensator (DSTATCOM), dynamic voltage regulator (DVR) and unfied power quality conditioner (UPQC). The operating and installation costs of these devices is very high compared to passive filters. The operating costs depend on VA rating of the device. Hence the focus shifted to decreasing the VA rating of the custom power devices.

Hybrid filters are combination of passive filters and active filters or custom power devices. Various combinations of hybrid filters are discussed in [2]. The hybrid filters are designed to either decrease overall VA rating of the custom power devices or to improve the performance of passive filters. The active filters are capable of producing voltages and currents in required shape with very good accuracy. Control methods were developed based on "instantaneous symmetric component theory" [4] and "p-q theory" [3],[5] to generate references for these active filters in such a way that the harmonic distortion decreases with minimum VA rating of filter.

The filters connections can be either in series or in shunt with the system. Passive filters are in general connected in shunt to the power system, to provide path for harmonics from load to ground. In the case of active filters, DSTATCOM is connected in shunt to the system and DVR is connected in series with source and load.

## 1.3 Motivation and Objectives

As explained in section 1.1 harmonics cause severe problems for consumers and utility and the IEEE 519 limitations should be achieved for currents and voltages. Literature provides various designs based on active filters which can suppress harmonics satisfactorily. One such designs is provided in [6], which uses DSTATCOM to supress harmonics and unbalances. This design was found to be successful in providing harmonic compensation and power factor correction. But simulations showed that the VA rating of the DSTATCOM and switching frequency of the voltage source inverter is very high. These factors limit the maximum load that this filter design can compensate. Hence a new hybrid filter design based on DSTATCOM is proposed in this work. The concept for the filter is inspired from a similar design proposed in [7]. The design proposed in [7] is found to be useful only for loads that produce 6n$\pm$1 harmonics.

Another set of hybrid filters were proposed in [3] and [5] to improve passive filter performance. These filters designed such that improve the performance of passive filter by adding an active filter as a feedback device. Control for these filters is implemented using “p-q theory”. P-Q method has certain disadvantages that arise due to digital filter systems used for reference generation which are explained in chapter 3. The filter designs provide good harmonic compensation, but the cost of the generation can be decreased if the reference is generated using “instantaneous symmetric component theory”. One other setback of these filter designs is that the load is assumed to be purely harmonic generating load. But in practical scenarios the load will have linear loads that do not generate harmonics. The filter designs do not take linear loads into account and if the source voltage contains harmonics then they appear at the load. This situation is undesired. Thus other control has to be used for such situations.This analysis provided motivation for designing hybrid filters that can over come such difficulties. The following objectives are expected outcomes of this work.

1. Minimizing VA rating of DSTATCOM without compromising on the performance with the aid of passive filters.
2. Minimize switching losses in DSTATCOM by decreasing switching frequency without affecting performance.
3. Design a control method for DVR based hybrid filters for better harmonic compensation for source voltage harmonics and minimize cost.

## 1.4 Thesis Organization

Chapter 1 gives introduction to power quality problems caused by harmonics. IEEE 519 standards on harmonics are discussed briefly. An overview of various types of filters is provided. Hybrid filter solutions provided in literature are discussed briefly along with their setbacks. Motivation and objectives for the work and organization of thesis is presented.

Chapter 2 discusses about conventional filtering methods based on standalone active and standalone passive filters. Design and performance related issues pertinent to both filtering techniques are discussed in detail. Simulation of a distribution system for typical loads is carried out to analyze performance of the filter techniques. Advantages and disadvantages of the conventional filters is discussed.

In chapter 3, three types of hybrid filter topologies are presented. Two of these filters are existent in literature and in this work they are presented with different control algorithm and a new hybrid filter topology is proposed. Analysis of the compensation, control methods and system configurations are discussed for each filter topology separately. Simulations with these topologies are carried out and the performance of hybrid filters is compared with performance of conventional filters. Advantages and disadvantages of each hybrid topology are discussed.

Chapter 4 draws important conclusions from the work and scope for future work is discussed.

# CHAPTER 2

# CONVENTIONAL ACTIVE AND PASSIVE FILTERS

In this chapter conventional filtering methods for filtering harmonics produced by rectifier loads are presented. Shunt passive filters constitute set of tuned LC filters and RLC filters which are designed so that the filter offers minimal impedance paths for harmonics [8]. DSTATCOM is one of the active filters used for harmonic compensation and balancing three-phase loads [9]. These filters have been discussed in this chapter in detail. Before going in to the details it is good to layout expected outcomes of using the filters to gauge the performance of the filters. The following outcomes suggest a good performance of a filter

1. Total Harmonic distortion (THD) of source current and load voltage should be within IEEE 519 allowed limits (5% for source current and 3% for load voltage).
2. Total Demand distortion (TDD) and individual harmonic distortion compared to maximum demand current fundamental component should be within IEEE 519 limits.
3. Power factor of the power supplied by the source should be more than 0.95 and the source currents in all the three-phases should be balanced.
4. Settling time of the filter is also one of the parameters to gauge the performance of a filter. It is expected that the filter should be able to attenuate THD to allowed levels within 2-3 cycles.

## 2.1 Shunt Passive Filters

In this section design and analysis of harmonic current compensation using shunt passive filters is discussed. This section will help in understanding limitations of passive filters and the need for active filter topologies. This study is limited to compensation for rectifier loads and the study of other active and passive filters is conducted on the same load.

### 2.1.1 Basic working principle

A tuned L-C filter gives zero impedance path at the tuned frequency. As the source will have non-zero source impedance in series, the harmonic current drawn by the load will be shared between the filter and source based on ratio of their impedances. The filter which offers almost zero impedance will extract most of the harmonic component of current at tuned frequency and source current will be free of harmonics. In practical scenario L-C filters will not offer zero impedance as Inductance will have non-zero resistance and this resistance limits impedance to non-zero values.

However the harmonics in rectifier load currents are at 6n$\pm$1 multiples and it is not practically feasible to use tuned L-C filters for all the harmonics. Hence to overcome this, L-C filters are used only for $5^{\mathrm{th}}$ and $7^{\mathrm{th}}$ harmonic and a second order R-L-C High pass filter is used to eliminate higher order harmonics. The performance of such combination is inferior to that of using multiple tuned filters, but it is economical and can reduce harmonics up to a good extent.

### 2.1.2 Designing the passive filters

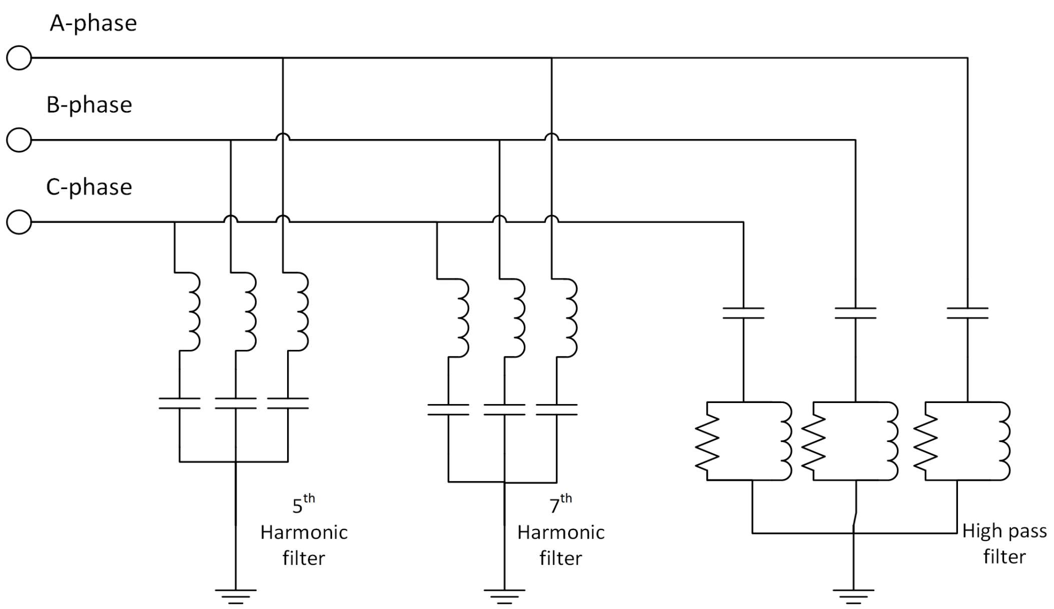


Figure 2.1: Three-phase circuit for $5^{th}$, $7^{th}$ and high pass shunt passive filter

While designing L-C filter following factors should be taken in to consideration.

1. The frequency at which the filter is tuned gives the value of LC , but values of L and C cannot be found separately.

$$LC = \frac{1}{(2\pi f)^2} \tag{2.1}$$

2. Impedance of the L-C element at fundamental frequency should be high because lower value means more reactive power drawn from the source.

$$Impedance = sL + \frac{1}{sC} = \frac{s^2LC + 1}{sC} \tag{2.2}$$

   In (2.2) numerator value is constant at any given harmonic frequency as value of LC is fixed and hence the value of the capacitor should be decreased to increase the impedance. This will make the capacitor value an independent variable that decides the reactive power drawn by the filter.

3. Settling time of the system is also a deciding factor in determining the value of the Capacitor. As the capacitance value is decreased, the inductance should be increased to match the tuned frequency and this leads to slowing down the system response. The value of C should chosen such that the settling time will be at most three cycles.

Second order R-L-C filter shown in Fig. 2.1 is used as High-pass filter with cut-off frequency at$10^{\text{th}}$ harmonic. Parameters of this filter are decided by the following factors.

1. At high frequencies, the capacitor will offer very low impedance and inductor in parallel with resistance should mostly act like a resistance. For high pass behavior

$$R > \frac{1}{2\pi fC} \; for \; f > f_c \tag{2.3}$$

   Here $f_c$ is cut-off frequency. Hence value of RC is decided by the cut-off frequency of the filter.

2. At high frequencies, impedance offered by the filter is almost resistive with value R. This impedance should be very small compared to source impedance at those frequencies.

$$R < |Z_s| \;\; for \; f > f_c \tag{2.4}$$

3. At fundamental frequency, impedance offered by the filter should be decided by the capacitance and inductance as filter should draw only reactive power. Also this impedance should be large at fundamental frequency and hence C should be as small as possible. At fundamental frequency R-L combination should offer reactance dominantly.

$$L < \frac{R}{2\pi f} \; for \; f = 50\,\text{Hz} \tag{2.5}$$

Taking these factors in to consideration filter parameters have been designed for a system with fundamental frequency of 50 Hz as given in Table 2.1.

Table 2.1: Values of filter parameters for $5^{\text{th}}$, $7^{\text{th}}$ and high-pass filters

| $5^{th}$ harmonic filter | $7^{th}$ harmonic filter | High pass filter |
|---|---|---|
| L=1.2 mH | L=1.2 mH | L=0.25 mH |
| Q=10 | Q=10 | R=2 $\Omega$ |
| C=340 $\mu$F | C=170 $\mu$F | C=300 $\mu$F |

### 2.1.3 Impedance of filter vs frequency

Figure 2.2 shows the variations of the combined impedance of the all the filters with respect to the frequency. It can be observed that the impedance at $5^{\text{th}}$ and $7^{\text{th}}$ harmonics is quite low and also at higher frequencies the high pass filter dominates. There is a sudden drop in impedance at frequency of 550 Hz which will make the filter like a tuned filter at $11^{\text{th}}$ and at much higher frequency it has constant impedance. It is important to place this drop at appropriate frequency to get better THD attenuation.

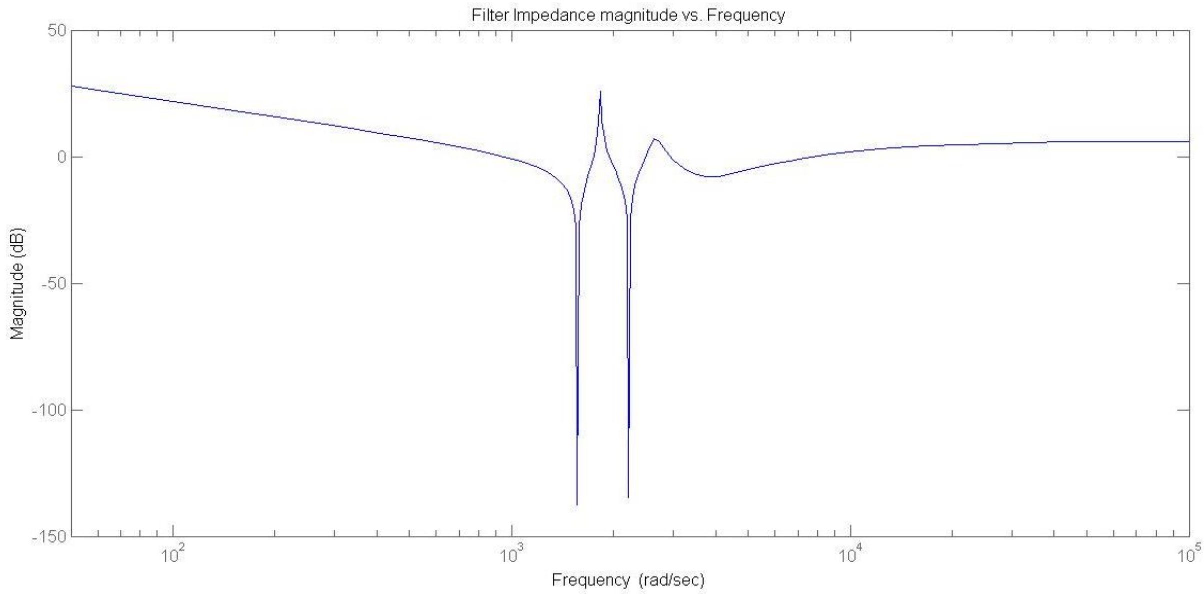


Figure 2.2: Variation of filter impedance with frequency

### 2.1.4 Simulation results

Simulation for the described harmonic compensation is performed in SimuLink for a rectifier load. In this section performance, limitations and disadvantages of shunt passive filters are discussed based on these simulations. Table 2.2 explains the source and load details used in the simulation and power transfer details without compensation. It should be noted that individual load details are taken when applied separately and total load details are when both the loads are applied together. Values of $THD_I$ and $THD_V$ are THDs for source current and load voltage respectively for the case when both the loads are applied together.

Table 2.2: Source and load details without filters .

| 3-$\phi$ source | 6 pulse rectifier | 3-$\phi$ balanced linear load | Total load |
|---|---|---|---|
| $V_{3-ph,rms}$=402 V | $V_{load}$ = 399.4 V | $V_{load}$ = 400 V | $V_{load}$ = 397.7 V |
| Zs = 0.01+0.04j Ω | $P_{l1}$= 28.85 kW, | $P_{l2}$ = 21.17 kW | $P_l$ = 49.65 kW |
| $THD_I$=15.7% | pf = 0.96 | pf = 0.89 | pf = 0.95 |
| $THD_V$= 2.4% | $THD_I$= 28.6% | | |

Now the filter is applied at the PCC as shown in Fig. 2.3 and the following results given in Table 2.3 are observed.

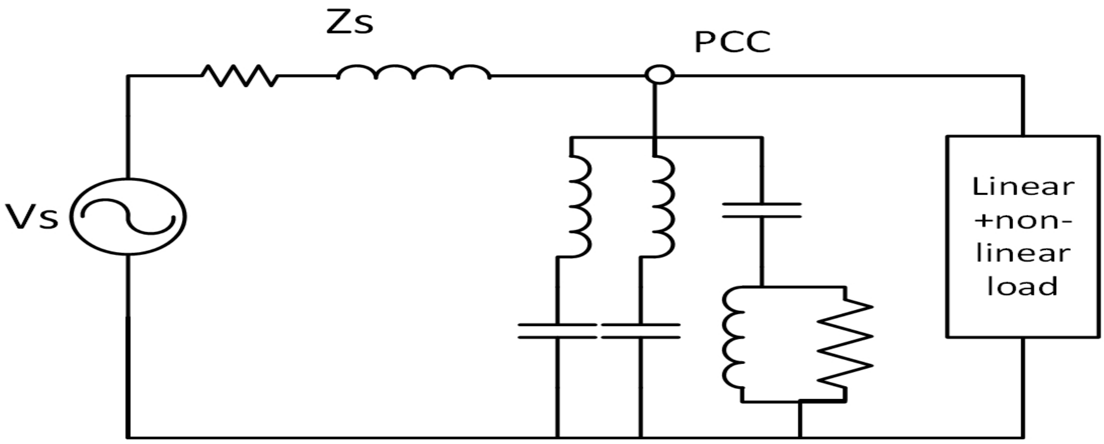


Figure 2.3: Single line schematic diagram of the compensated system

Table 2.3: Results after using passive filter

| | | | | |
|---|---|---|---|---|
| $V_{load}$=401.8 V | $P_s$= 50.78 kW | pf = 0.85 | $THD_V$ = 1.28% | $THD_I$= 7.3% (at 0.1 s) |

As observed in the Table 2.3, the current THD is not up to IEEE 519 standards but it is improved compared to the case without compensation. As shown in Fig. 2.4 there is improvement in shape of the current waveform. The voltage at load is increased compared to the case without compensation due to reactive power injection from the filter and hence active power consumption has also increased slightly. In the voltage waveform there is notching due to commutation of current between phases.

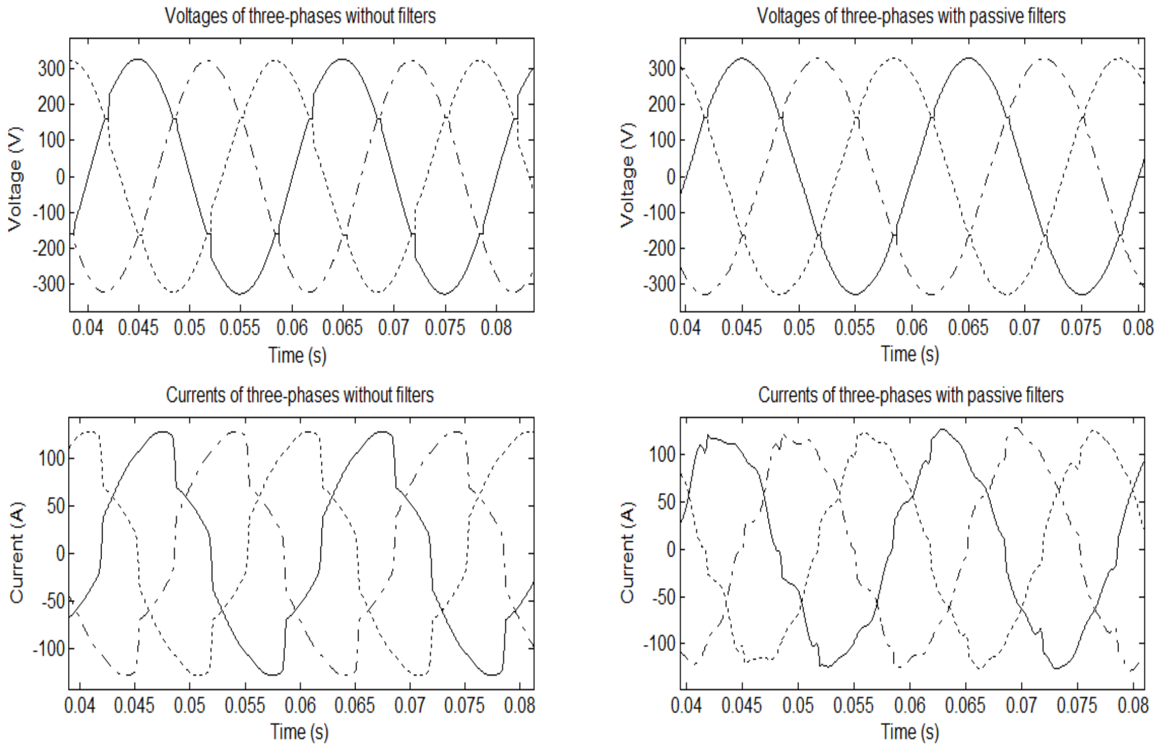


Figure 2.4: Current and voltage waveforms with and without compensation

Table 2.4 shows individual harmonic peak values up to $29^{th}$ harmonic with and without compensation. In this table only significant harmonics are compared. for the calculations maximum demand current fundamental is assumed to be 250 A. Without filters source currents violate individual harmonic distortion, THD and TDD limits of IEEE 519 standards. In the case of compensated system the individual and total demand distortion (TDD) limits are also satisfied.

Table 2.4: Individual harmonic distortion ($\frac{I_h}{I_l}$) percentages compared to maximum demand current fundamental

| | $4^{th}$ | $5^{th}$ | $6^{th}$ | $7^{th}$ | $11^{th}$ | $13^{th}$ | $17^{th}$ | $19^{th}$ | $23^{th}$ | $25^{th}$ | $29^{th}$ | TDD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| with filter | 0.64 | 2.08 | 0.96 | 1.92 | 1.28 | 1.28 | 0.64 | 0.56 | 0.4 | 0.45 | 0.35 | 3.36 |
| without filter | 0 | 6.2 | 0 | 3.0 | 2.08 | 1.6 | 1.12 | 0.96 | 0.8 | 0.64 | 0.5 | 7.7 |
| IEEE 519 | 2.0 | 4.0 | 2.0 | 4.0 | 2.0 | 2.0 | 1.5 | 1.5 | 0.6 | 0.6 | 0.6 | 5 |

Figure 2.5 shows FFT of higher order harmonics for the same load. It can be observed that the performance of high pass filter is the limiting factor for maximum ap-

plicable load as it does not provide exactly zero impedance path and some higher order harmonics in source current can still be seen. FFT plot for compensated case shows significant $4^{th}$and $6^{th}$ harmonics which were not present in the uncompensated system. These are observed due to transients along with resonance between passive filter and source impedance and they are reduced to very small values in steady state.

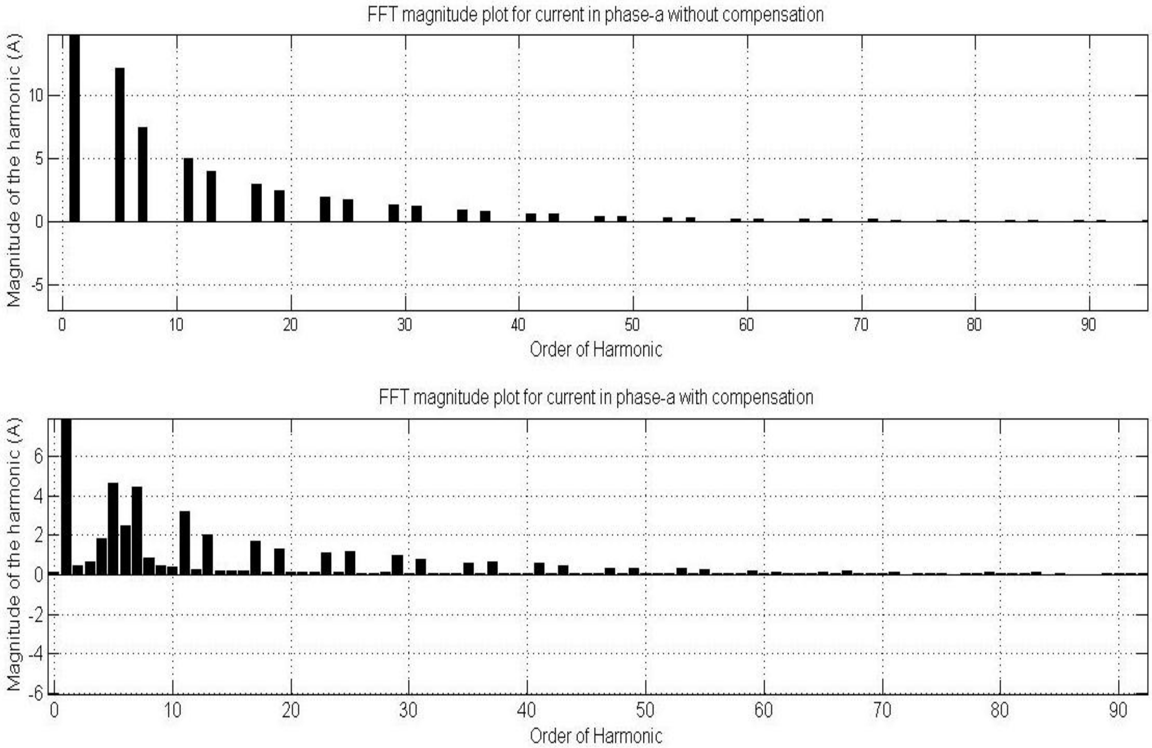


Figure 2.5: FFT of higher order harmonics for both cases

### 2.1.5 Limitations of passive filters

From the simulations in the previous section it is observed that passive filters can provide good compensation for harmonics. But their usage is limited by many factors that can even have negative impact on the load voltage and source currents. Those limitation are discussed in this section.

1. Passive filters have finite impedance at fundamental frequency and they draw reactive power from the source. This can be diminished by using lower magnitudes of capacitance. But this will slow down the system due to larger inductance required for same tuned frequency. In the simulation it is observed that the capacitor is providing reactive power to the load and thus it results in lower source current magnitude. But in the absence of such reactive load the passive filter draws fundamental current from source which will result in increasing of source current magnitude as indicated in Table 2.5. The increase observed in source power is

due to increase in the source voltage magnitude.

Table 2.5: Source current details for rectifier load alone

| 6-pulse rectifier load | Without compensation | with compensation |
|---|---|---|
| Source current RMS | 43.55 A | 72.33 A |
| $V_{load}$ | 400 V | 403.74 V |
| Source Power | 28.8 kW at 0.96 pf | 29.63 kW at 0.58 pf |
| Source current THD | 28.8% | 6.1% |

2. The filters can form parallel resonant structure which will result in amplification of undesired harmonics in load voltage. Hence before installing the filters they should be tested for various possible source impedance to avoid any resonances. In many cases the source impedance keeps varying which makes filter design very difficult.

3. As the THD goes up, the filtering capability of the designed system goes down as high pass filter is not a perfect filter and hence the current still gets divided between source and filter. Settling time of the filter also increases as THD increases. For the designed filter maximum THD that the filter can compensate up to 5% within 4-5 cycles is 14%. But the settling time for this load is more than 15 cycles which is undesired. Hence a better filtering system is required to compensate for higher THDs in lesser time.

4. Generally balancing of loads is achieved by using reactive power compensation, but because of the parallel resonance problem, it is difficult to use them along with shunt passive filters.

## 2.2 Shunt Active Filters

In the previous section passive filters that work like current sinks at specific tuned frequencies were presented. The shunt active filters are designed to overcome the difficulties involved in design and performance of passive filters. In this section control methods, design issues involved with DSTATCOM which is used as shunt active filter in distribution system are discussed. Simulation studies are performed to understand the performances of the DSTATCOM for rectifier load system.

The basic working principle of shunt active filter is explained in Fig. 2.6 which shows compensation for one of the phases. The current injected by filter ($i_f$) should be such that the source current ($i_s$) is of sinusoidal shape. The load is assumed to be a constant current source which draws load current ($i_l$) which is unbalanced and contains harmonics. The filter current should be generated using high bandwidth current source to compensate for larger harmonic contents. In the case of DSTATCOM the filter current is such that the source currents in three phases will be balanced with maximum PF and minimum THD. A control method based on instantaneous symmetric component theory is implemented to generate reference filter current ($i_f^*$) [4].

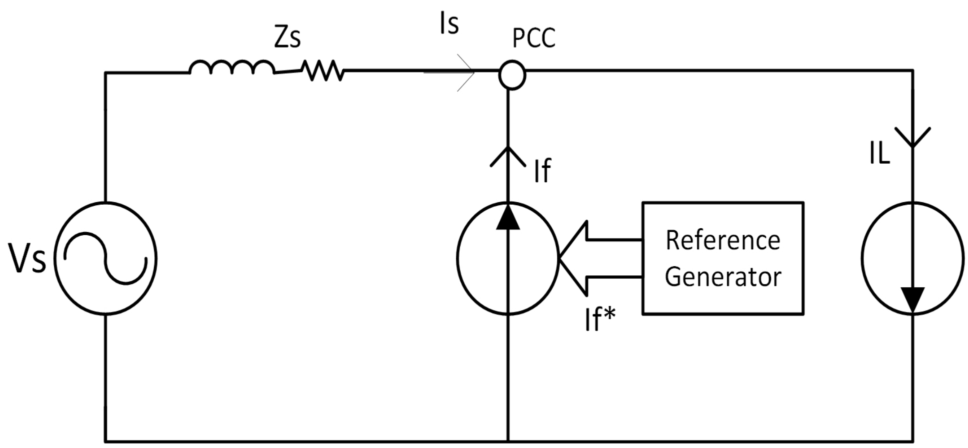


Figure 2.6: Basic schematic of shunt active filter

### 2.2.1 Reference current generation

Compensation current reference ($i_f^*$) can be generated by using either p-q theory or instantaneous symmetric component theory. In this section $i_f^*$ generation using instantaneous symmetric component theory is explained. The idea is to translate "abc" phase currents into "012", that is positive, negative and zero sequence currents and imposing conditions on those components. To compensate for unbalances and harmonics in the load current, the filter currents need to achieve the following objectives.

1. The zero sequence current should be zero to get zero neutral current which is the case with 3- $\phi$ balanced currents.
2. Instantaneous three-phase power supplied by the source should be equal to average power required by the load. In 3-$\phi$ balanced circuits without harmonic distortion the source power is constant and the source should supply only real power to the load.
3. For positive sequence currents, voltages should lead the current by required power factor angle.

These three independent conditions provide three different equations to find filter currents in three-phases. Instantaneous voltages and currents of abc phases can be translated to symmetric components using the following transformation matrix.

$$V_{012} = AV_{abc} \tag{2.6}$$

$$I_{012} = AI_{abc} \tag{2.7}$$

where,

$$A = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \; and \; a = e^{j2\pi/3} \tag{2.8}$$

**Objective 1:** In order to make the zero sequence current zero, the following condition should be satisfied

$$i_0 = \frac{i_{sa} + i_{sb} + i_{sc}}{3} = 0 \tag{2.9}$$

**Objective 2:** Instantaneous power supplied by the source is the sum of $v{*}i$ of each phase. Second objective is to make instantaneous 3-$\phi$ source power to average load power. Averaging of instantaneous load power over fundamental period eliminates variable power due to unbalances and reactive power supplied.

$$v_{sa}i_{sa} + v_{sb}i_{sb} + v_{sc}i_{sc} = P_{lavg} \tag{2.10}$$

**Objective 3:** The power factor for source voltage and currents without any distortion is equal to cosine of angle between voltage and current of the positive sequence voltage and current components. If $\cos\phi$ is the expected power factor then

$$\angle V_{a1} = \angle I_{a1} + \phi \tag{2.11}$$

$V_{a1}$ and $I_{a1}$ are positive sequence voltage and current respectively and they can be expanded from (2.6), (2.7). Taking their angles gives the following expression

$$\angle V_{a1} = \arctan \frac{\frac{\sqrt{3}}{2} v_{sb} - \frac{\sqrt{3}}{2} v_{sc}}{v_{sa} - \frac{v_{sb}}{2} - \frac{v_{sc}}{2}} = \arctan \frac{k_1}{k_2} \tag{2.12}$$

$$\angle I_{a1} = \arctan \frac{\frac{\sqrt{3}}{2} i_{sb} - \frac{\sqrt{3}}{2} i_{sc}}{i_{sa} - \frac{i_{sb}}{2} - \frac{i_{sc}}{2}} = \arctan \frac{k_3}{k_4} \tag{2.13}$$

substituting (2.12) and (2.13) in (2.11) and taking tangent on both sides

$$k_1 k_4 - k_3 k_2 = \tan \phi (k_1 k_3 + k_2 k_4) \tag{2.14}$$

substituting values of $k_1$- $k_4$ in (2.14) and simplifying gives

$$[(v_{sb} - v_{sc}) + 3\beta(v_{s0} - v_{sa})] i_{sa} + [(v_{sc} - v_{sa}) + 3\beta(v_{s0} - v_{sb})] i_{sb+} [(v_{sa} - v_{sb}) + 3\beta(v_{s0} - v_{sc})] i_{sc} = 0 \tag{2.15}$$

Here $\beta = \tan \phi$ and $v_{s0} = (v_{sa} + v_{sb} + v_{sc})/3$. Power factor angle $\phi$ can be assumed to be zero as power factor needs to be as close as to 1. Combining (2.9), (2.10) and (2.15) in to matrix form gives

$$\begin{bmatrix} 1 & 1 & 1 \\ v_{sb} - v_{sc} & v_{sb} - v_{sc} & v_{sb} - v_{sc} \\ v_{sa} & v_{sb} & v_{sc} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ P_{lavg} \end{bmatrix} \tag{2.16}$$

$$A I_{sabc} = B \tag{2.17}$$

$$I_{sabc} = A^{-1} B \tag{2.18}$$

As B vector has two zeros, determinant of matrix A and co-factors $a_{31}$, $a_{32}$ and $a_{32}$ are sufficient to find $i_{sa}$, $i_{sb}$ and $i_{sc}$. The simplified values of $\det A$, $a_{31}$, $a_{32}$ and $a_{33}$ are given by

$$a_{31} = 3(v_{sa} - v_{s0}), \quad a_{32} = 3(v_{sb} - v_{s0}), \quad a_{33} = 3(v_{sc} - v_{s0}) \tag{2.19}$$

$$detA = 3[(\sum_{i=a,b,c} v_{si}^2) - 3v_{s0}^2] \tag{2.20}$$

the values of $i_{sa}$, $i_{sb}$ and $i_{sc}$ are calculated from equations (2.18), (2.19) and (2.20).

$$i_{sa} = \frac{3(v_{sa} - v_{s0})}{detA} P_{lavg} \tag{2.21}$$

$$i_{sb} = \frac{3(v_{sb} - v_{s0})}{detA} P_{lavg} \tag{2.22}$$

$$i_{sc} = \frac{3(v_{sc} - v_{s0})}{detA} P_{lavg} \tag{2.23}$$

As shown in Fig. 2.6 the shunt active filter injects currents at PCC. Hence following reference current expressions can be derived from KCL equation as.

$$i_{fa}^* = i_{la} - i_{sa} = i_{la} - \frac{3(v_{sa} - v_{s0})}{detA} P_{lavg} \tag{2.24}$$

$$i_{fb}^* = i_{lb} - i_{sb} = i_{lb} - \frac{3(v_{sb} - v_{s0})}{detA} P_{lavg} \tag{2.25}$$

$$i_{fc}^* = i_{lc} - i_{sc} = i_{lc} - \frac{3(v_{sc} - v_{s0})}{detA} P_{lavg} \tag{2.26}$$

If the filter can provide these reference current then all the three objectives are accomplished. It should be noted that in deriving these expressions nothing is assumed about load configuration (Y or $\triangle$). Hence it can be assumed that these reference currents can be used for both load configurations.

## 2.2.2 DSTATCOM control and operation

In the previous section expressions for reference filter currents using symmetrical components were developed. In this section current compensation using voltage source inverter (VSI) topology and control methods for generation of the filter currents are discussed. Figure 2.7 gives overviews of the blocks involved in control and operation of DSTATCOM. The blocks shown in Fig. 2.7 are discussed in detail below.

1. In Fig. 2.7 load currents can be unbalanced or distorted or both. In general such cases arise in practical scenarios because of single phase power supplies and nonlinear load systems like rectifiers, arc-furnaces etc. These currents will cause THD more than permissible IEEE 519 limits and poor power factor.

2. The measurement unit needs to measure source voltages, load currents and filter output currents. For proper compensation the measurement has to detect very high frequency variations too and hence it is important to have high bandwidth measurement and amplification units. This work doesn't take measurement issues in to consideration and it is assumed that measurement unit works ideally.

3. Reference generation unit uses equations (2.24), (2.25) and (2.26) to generate instantaneous values of reference filter currents ($i_f{}^*$). $P_{lavg}$ is found by performing moving average with period of 0.02 s on total instantaneous power to eliminate variation in time which comes due to harmonics and reactive current components.

$$P_{lavg} = \frac{1}{T}\int_{t}^{t+T} (v_{sa}i_{la} + v_{sb}i_{lb} + v_{sc}i_{lc})dt \quad for \quad T = 0.02\ s \tag{2.27}$$

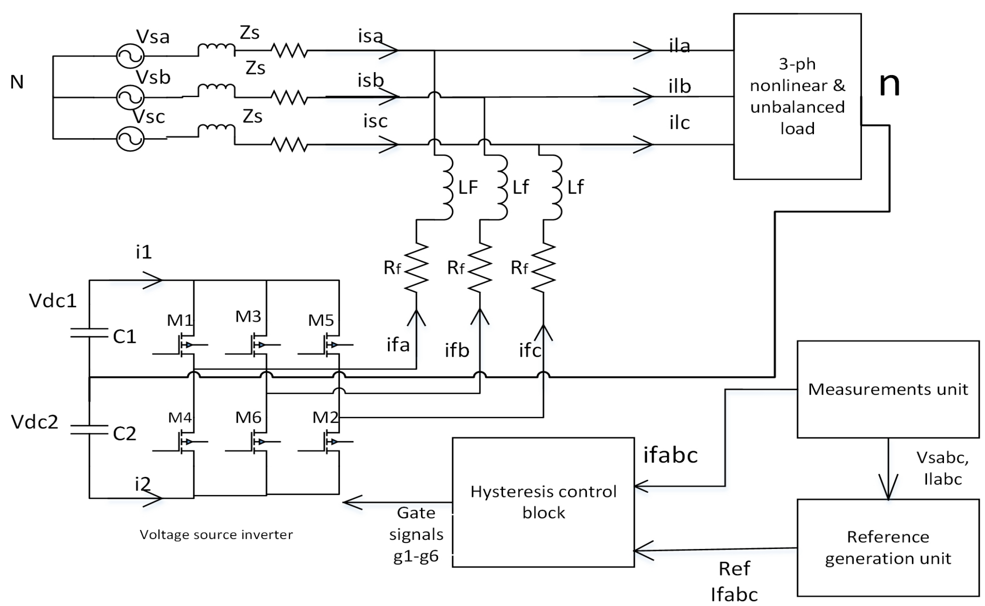


Figure 2.7: Schematic diagram of DSTATCOM

4. VSI is used to generate required filter currents. There are two voltage levels available to any phase. The filter inductance ($L_f$) is used to integrate the voltage difference between the line voltage and VSI voltage output. For the present analysis filter resistance $R_f$ is neglected to make switching analysis easier. For example for $a-$phase if M1 is on and M4 is off then $i_{fa}$ is given by the expression,

$$i_{fa}^{k} = i_{fa}^{k-1} + \frac{1}{L_f} \int (V_{dc1} - V_{la}) dt \tag{2.28}$$

and if M4 is on and M1 is off then,

$$i_{fa}^{k} = i_{fa}^{k-1} - \frac{1}{L_f} \int (V_{dc2} + V_{la}) dt \tag{2.29}$$

From both the expressions it can be observed that the value of $i_{fa}$ at any instant can be increased or decreased by controlling the switches M1 and M4. The value of $L_f$ should be chosen such that the filter can follow highest rate of change in $i_{fa}^{*}$.

$$\frac{V_d}{L_f} > \frac{di_{fa}^{*}}{dt} \; and \; V_d = (V_{dc1} - V_{pcc}) \; or \; (V_{dc2} + V_{pcc}) \tag{2.30}$$

where, $V_{pcc}$ is the voltage at PCC when rate of change in $i_{fa}^{*}$ is maximum.

5. The increase in $i_{fa}$ is almost linear if integration time in (2.28) and (2.29) is very small compared to time period of the maximum harmonic frequency intended to be followed. For example IGBT can handle switching frequencies up to 20 kHz and if the filter has to follow harmonics upto 10 kHz, the sampling rate should be as high as 50 kHz if the filter needs to follow all the harmonics accurately.

6. The hysteresis control block generates gate signals for VSI by using hysteresis band current control on $i_f$. This block will generate gate signals such that $i_f$ varies between $i_f^{*} + h$ and $i_f^{*} - h$, where h is the hysteresis parameter which decides how much switching ripple can be present in the filter output currents.

$$i_f^{*} - h < i_f < i_f^{*} + h \tag{2.31}$$

If the sampling frequency is very high then the integration expressed in (2.28) and (2.29) might happen in more than 1 sampling period. Hence it is beneficial to use memory elements to store previous states. There are three possible states and corresponding gate signals for phase-a are generated as explained below

$$\begin{aligned} i_{fa} &< i_{fa}^{*} - h \Rightarrow M1 = 1, M4 = 0 \\ i_{fa} &> i_{fa}^{*} + h \Rightarrow M1 = 0, M4 = 1 \\ i_{fa}^{*} - h < i_{fa} &< i_{fa}^{*} + h \Rightarrow retain\, previous\, gate\, signals \end{aligned} \tag{2.32}$$

7. The IGBT are used as switches for controlling VSI output voltage. Maximum switching frequency allowed for IGBT is 20 kHz. As seen from (2.31) and (2.32) switching frequency depends upon $V_{dc}$, $L_f$ and h. Value of $V_{dc}$ is chosen to be around 1.4 - 1.8 times peak value of the source voltage. Value of h decides switching ripple in output current and very small value leads to very high switching frequency. Based on the values of $V_{dc}$ and h , $L_f$is chosen to limit switching

frequency.

$$\frac{V_{dc} + V_{pcc-peak}}{L_f * 2h} < 2 * 20kHz \tag{2.33}$$

equations (2.28) and (2.33) can be used for designing of $L_f$ .

8. The dc-link capacitors lose charge because of switching losses in IGBTs and hence the dc-link voltage decreases. To maintain the voltage at the required level a thyristor based rectifier circuit connected to main supply is used to charge the capacitors. A PI controller based control to generate switching losses can be used to control the thyristor gates.

9. High pass filter is used to eliminate high frequency switching ripples from the filter current output. A simple first order RC tuned for minimum frequency around switching frequency ($F_s$) will suffice.

$$\frac{1}{RC} \leq F_s \tag{2.34}$$

### 2.2.3 State space modeling of DSTATCOM

This section presents state space modeling of compensator. The compensator topology used is a 3-$\phi$, 4-wire system. Hence one of the phases can be considered separately and the result can be extended for other two phases. In Fig. 2.8 the two switching states are shown, i.e. in 2.8 (a) $M_1$ is closed and $M_4$ is open and in 2.8 (b) $M_1$ is open and $M_4$ is closed.

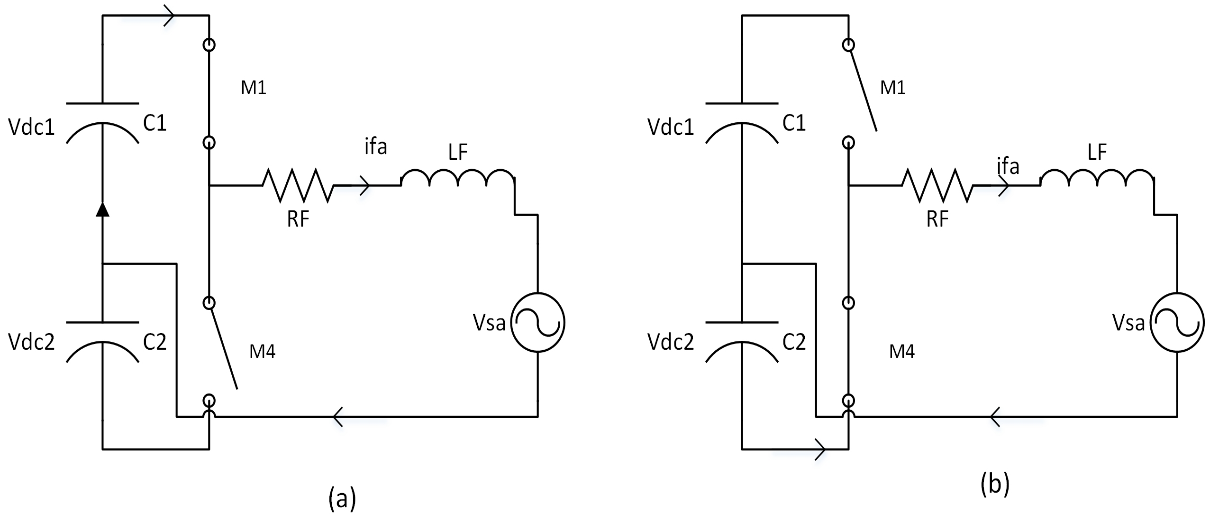


Figure 2.8: Current flow in two different switching states

for Fig. 8 (a)

$$\frac{di_{fa}}{dt} = -\frac{R_f}{L_f} i_{fa} - \frac{v_{sa}}{L_f} + \frac{V_{dc1}}{L_f} \tag{2.35}$$

for Fig. 8 (b)

$$\frac{di_{fa}}{dt} = -\frac{R_f}{L_f} i_{fa} - \frac{v_{sa}}{L_f} - \frac{V_{dc2}}{L_f} \tag{2.36}$$

Now combining both (2.35) and (2.36) using binary switching variable $S_a$ which is one if M1 is closed and its compliment $\bar{S_a}$

$$\frac{di_{fa}}{dt} = -\frac{R_f}{L_f} i_{fa} - \frac{v_{sa}}{L_f} + S_a \frac{V_{dc1}}{L_f} - \bar{S_a} \frac{V_{dc2}}{L_f} \tag{2.37}$$

similarly for b and c phases

$$\frac{di_{fb}}{dt} = -\frac{R_f}{L_f} i_{fb} - \frac{v_{sb}}{L_f} + S_b \frac{V_{dc1}}{L_f} - \bar{S_b} \frac{V_{dc2}}{L_f} \tag{2.38}$$

$$\frac{di_{fc}}{dt} = -\frac{R_f}{L_f} i_{fc} - \frac{v_{sc}}{L_f} + S_c \frac{V_{dc1}}{L_f} - \bar{S_c} \frac{V_{dc2}}{L_f} \tag{2.39}$$

DC-link capacitor voltages and currents can be written in terms of filter output currents as

$$C_1 \frac{dV_{dc1}}{dt} = -i_1 \tag{2.40}$$

$$C_2 \frac{dV_{dc2}}{dt} = -i_2 \tag{2.41}$$

$$i_1 = S_a i_{fa} + S_b i_{fb} + S_c i_{fc} \tag{2.42}$$

$$i_2 = \bar{S}_a i_{fa} + \bar{S}_b i_{fb} + \bar{S}_c i_{fc} \tag{2.43}$$

Now combining (2.37)-(2.43) in to a matrix form gives

$$\frac{d}{dt}\begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \\ V_{dc1} \\ V_{dc2} \end{bmatrix} = \begin{bmatrix} \frac{R_f}{L_f} & 0 & 0 & \frac{S_a}{L_f} & -\frac{\bar{S_a}}{Lf} \\ 0 & -\frac{R_f}{L_f} & 0 & \frac{S_b}{L_f} & -\frac{\bar{S_b}}{Lf} \\ 0 & 0 & -\frac{R_f}{L_f} & \frac{S_c}{L_f} & -\frac{\bar{S_c}}{Lf} \\ -\frac{S_a}{C_1} & -\frac{S_b}{C_1} & -\frac{S_c}{C_1} & 0 & 0 \\ \frac{\bar{S_a}}{C_2} & \frac{\bar{S_b}}{C_2} & \frac{\bar{S_c}}{C_2} & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \\ V_{dc1} \\ V_{dc2} \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_f} & 0 & 0 \\ 0 & -\frac{1}{L_f} & 0 \\ 0 & 0 & -\frac{1}{L_f} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{2.44}$$

(2.44) describes the compensator in standard state space equation form

$$\dot{x} = Ax + bu \tag{2.45}$$

### 2.2.4 Simulation of DSTATCOM

DSTATCOM implementation explained in section 2.2.2 is simulated in SimuLink. In this section various performance parameters and issues that were observed in simulation studies are presented. The source considered is the same that was used for passive filters but the load used is different. Table 2.6 shows source and load power transfers for the case without compensation.

Table 2.6: Distribution system parameters without compensation

| Source | | Load1 | linear | Load2 | nonlinear |
|---|---|---|---|---|---|
| Vs(L-L) | 400V | Za | 7.5+3j Ω | $P_l$ | 28.87kW |
| Zs | 0.01+0.0628j Ω | Zb | 5+3.5 Ω | THD% | 28.35 |
| Power(total) | 55.41kW, pf=0.97 | Zc | 3.5+2 Ω | pf | 0.96 |
| $THD_I$% | 16.6 | $P_l$ | 24.51kW, pf=0.86 | $V_{load}$ | 399.4 |

Figure 2.9 shows source current and voltages in the three-phases. It can observed that the current waveforms have distortions and unbalances in the three-phases.

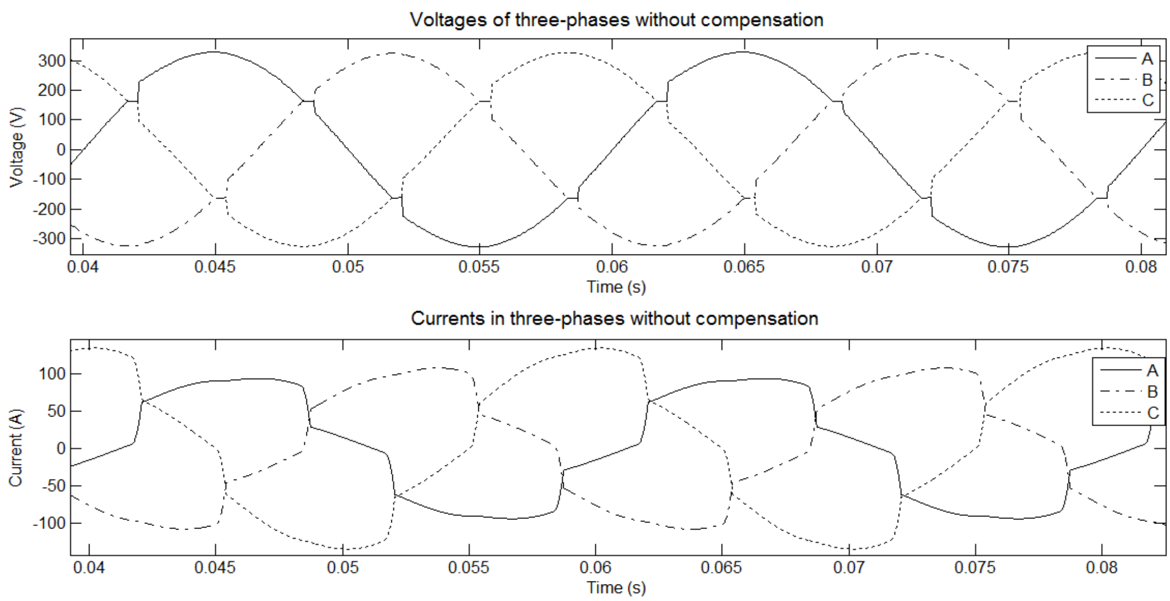


Figure 2.9: Voltages and currents of the three-phases without compensation

Now the DSTATCOM is used to compensate for load described above. Table 2.7 gives details of the DSTATCOM parameters and results with DSTATCOM in place.

Table 2.7: Source, load and DSTATCOM parameters

| Source | Load | DSTATCOM |
|---|---|---|
| $V_s$= 400 V | $P_{load}$ = 56.8 kW, pf = 0.977 | kVA rating= 16.4 kVA |
| $Z_s$= 0.01+0.0628j Ω | % $THD_{Iload}$= [17.01, 18.02, 11.55] | average $F_s$= 15.9 kHz |
| $I_{sabc}$=[83.21, 83.18, 83.24] A | % $THD_{Vload}$ = [1.5, 1.4, 1.7] | $V_{dc}$= 1.8*$V_{s,peak}$, h = 0.05 |
| $P_s$= 57.6 kW, pf = 0.99 | $I_{labc}$=[69.5, 73, 109.5] A | $L_f$=3 mH, $R_f$= 0.01 Ω |
| average $THD_I$= 3.3% | | |

**Blocks used for simulation:**

1. Hysteresis control block uses S-R flip-flops to realize the control method explained in (2.27) as explained in equations below

$$\begin{aligned} i_{fa} &< i^*_{fa} - h \Rightarrow S = 0, R = 1 \\ i_{fa} &> i^*_{fa} + h \Rightarrow S = 1, R = 0 \\ i^*_{fa} &- h < i_{fa} < i^*_{fa} + h \Rightarrow S = 0, R = 0 \end{aligned} \tag{2.46}$$

2. Switching frequency is calculated using block shown in Fig. 2.10. This block gives the number of transitions happened in the simulation time at the point at which voltage is being measured. From this value average switching frequency can be found by dividing the output by 2*(simulation time).

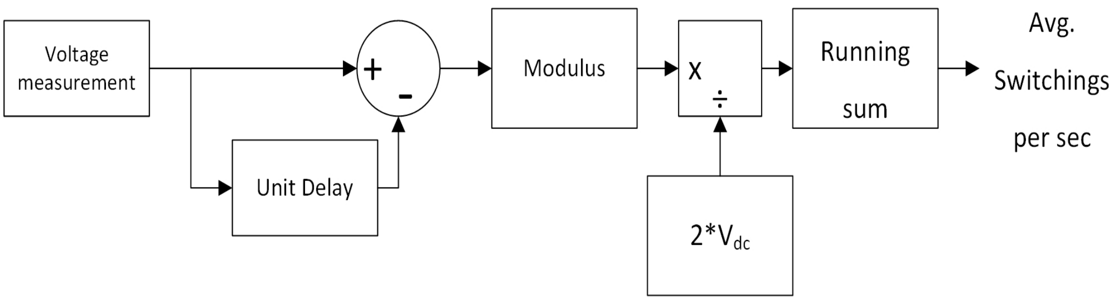


Figure 2.10: Switching transistions measurement block.

**Observations:**

1. Source currents are balanced with RMS values of 83.2 A and with average THD of 3.3%. The source current values have increased for a and b phases and decreased for phase c.

2. Load voltage THD has also decreased to an average of 1.4%. Figure 2.11 shows source current and load voltages in all the three-phases. It can be observed that both voltages and currents are sinusoidal in shape and currents are almost in-phase with their corresponding phase voltages

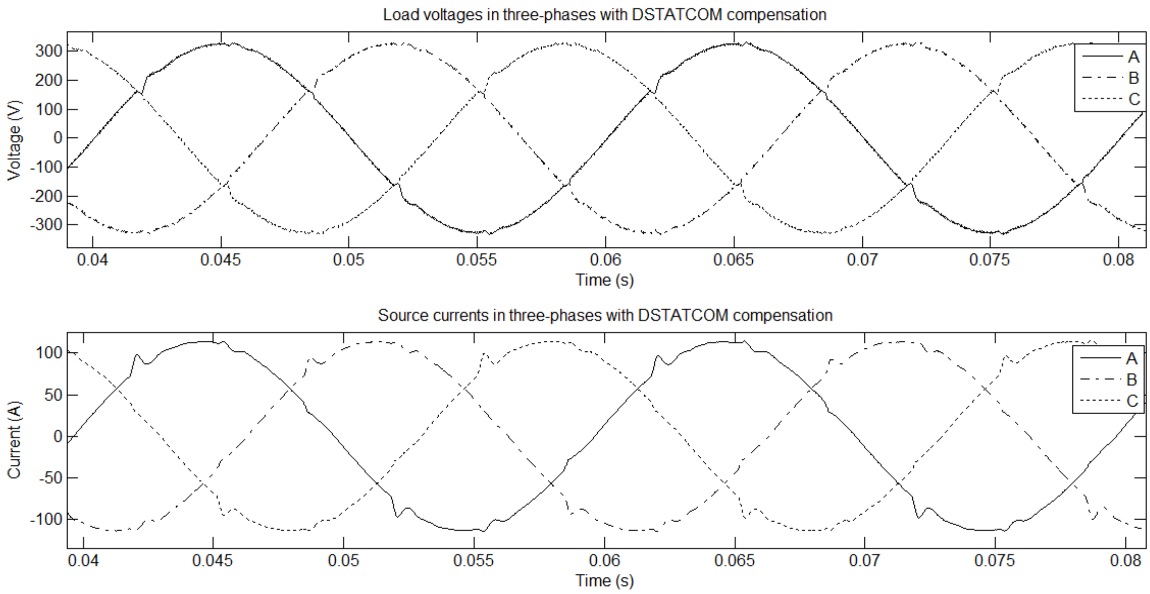


Figure 2.11: Load voltages and source currents for compensated system

3. The source power is 2% higher than load power, the remaining power is drawn by the DSTATCOM due to sharp changes in reference current which DSTATCOM cannot provide. Lowering $L_f$ value will not solve this problem as switching frequency increases beyond IGBT limits. Figure 2.12 shows instantaneous three-phase power of the source. In each cycle there are 6 small peaks which results from sharp changes in reference currents in each phase. Because of these peaks, the source power increases by 1 kW.

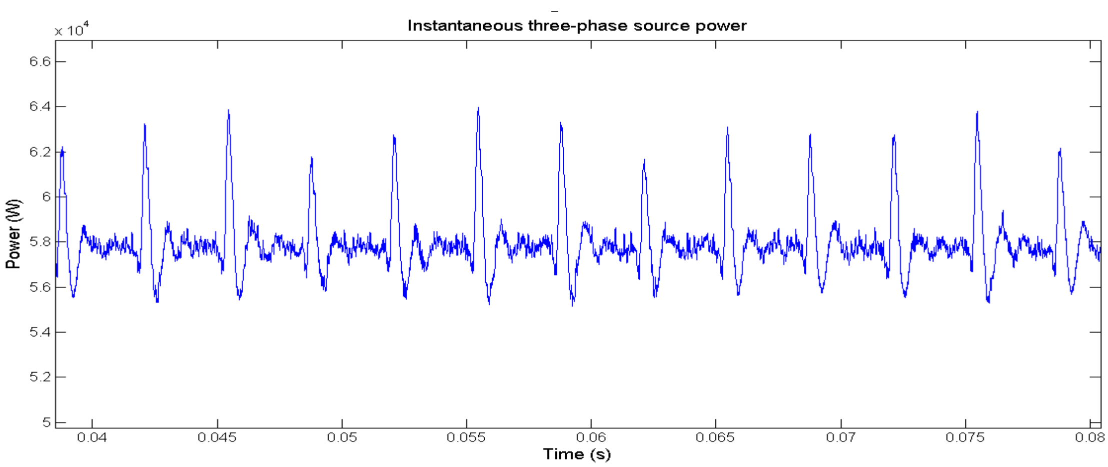


Figure 2.12: Instantaneous three-phase source power

4. kVA rating of filter is 16.4 kVA. This value is very high for the given load conditions. But the real power supplied by the compensator is a fraction of the total

kVA. Compensator currents in the three-phases are shown in Fig. 2.13.

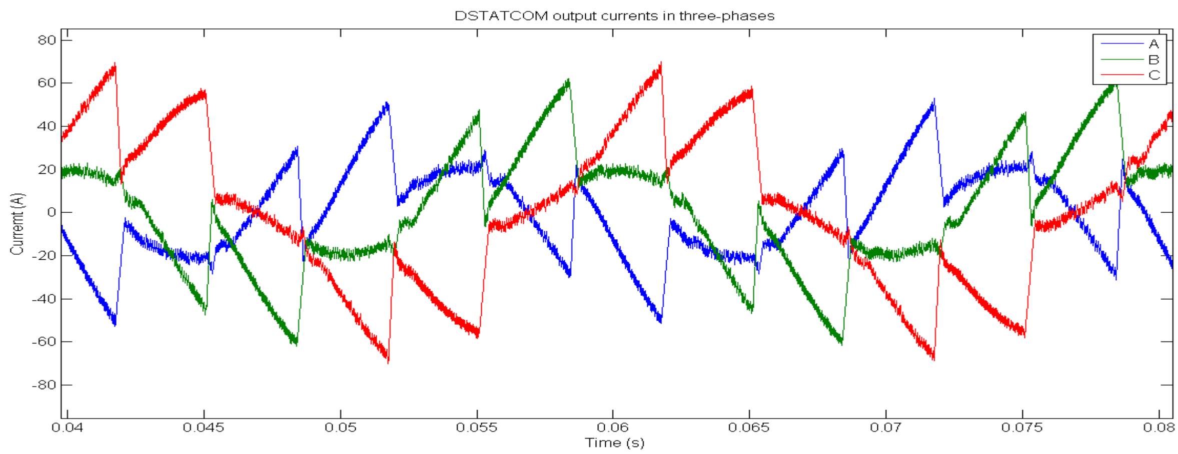


Figure 2.13: Compensator currents in three-phases

5. Switching frequency is found using taking running sum of number of transitions in output voltage. This number will be approximately double to the switching frequency. The average value of the switching frequency is approximately 16 kHz.

6. Comparison of FFT plots for uncompensated and compensated system as given in Fig. 2.14, shows that shunt active filter compensates for THD very effectively.

7. Table 2.8 shows individual harmonic distortion and total demand distortion(TDD) for $\frac{I_{sc}}{I_L} = 20$. As $I_{sc}$ is around 5 kA, maximum demand fundamental is considered as 250 A. In this table only significant harmonics are shown.

Table 2.8: Individual harmonic distortion for case with compensator

| $I_{sc}/I_l = 20$ | 5 | 7 | 11 | 13 | 17 | 19 | 23 | 25 | 29 | 31 | TDD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| with filter $I_h/I_l\%$ | 0.4 | 0.6 | 0.4 | 0.7 | 0.4 | 0.7 | 0.4 | 0.3 | 0.4 | 0.3 | 2.9 |
| IEEE 519 limits | 4 | 4 | 2 | 2 | 1.5 | 1.5 | 0.6 | 0.6 | 0.6 | 0.6 | 5 |

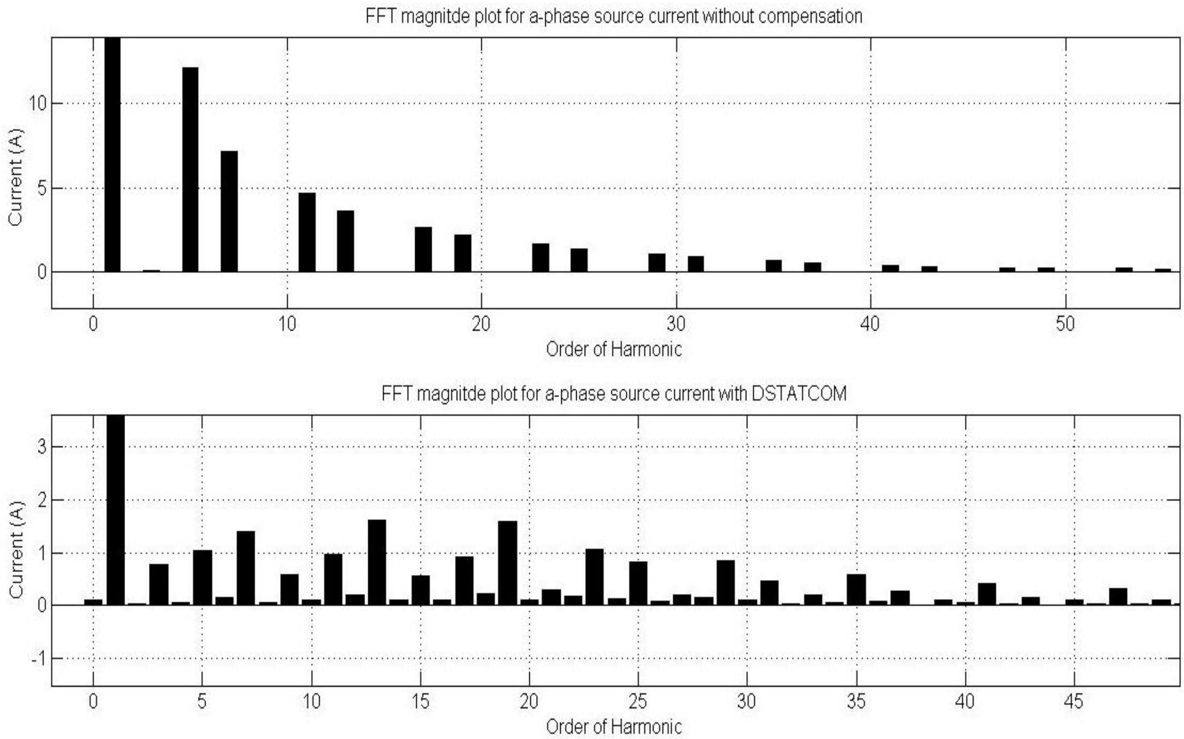


Figure 2.14: FFT for current in phase a for compensated and uncompensated systems

### 2.2.5 Advantages and limitations of DSTATCOM

**Advantages:**

1. DSTATCOM can compensate for harmonic distortions and unbalances in load and provide power factor closer to 1.
2. Passive filter were observed consuming reactive power from source, leading to very poor power factor which is not the case with DSTATCOM as it provides reactive power required for the load and doesn't draw any reactive power from source.
3. THD for currents and voltages is brought down within IEEE 519 limits within 2-3 cycles which was not the case with passive filters.
4. Maximum THD that DSTATCOM can compensate is 40 kW with THD of 23%.
5. DSTATCOM doesn't have the problems like parallel resonance and its performance is mostly unaffected by source impedance.

**Limitations:**

1. Dc-link voltage required is very high as it compensates for all the harmonics which have very high rate of change of current.

2. Switching frequency of Inverter switches is very high which leads to more switching losses. Also IGBT has switching frequency limits of 20 kHz which limits the smallest value of $L_f$ that can be used and maximum THD that the filter can compensate.

3. Additional high pass filter is required to eliminate switching harmonics.

4. kVA rating of filter is very high.

## 2.3 Summary

In this chapter performance of conventional filtering methods, shunt passive filters and DSTATCOM for harmonic producing loads was discussed. The DSTATCOM has better performance compared to passive filters. The design of the DSTATCOM also doesn't have difficulties that passive filters can have. But the kVA rating of Active filter and switching frequency limits the applicability of DSTATCOM. Passive filters have the advantage with respect to cost factor. Overall both types of filters present two contrasting advantages that are cost and performance which hints the idea to combine both of them to get better performances at lower cost.

# CHAPTER 3

# HYBRID ACTIVE AND PASSIVE FILTERS

In Chapter 2, analysis of performance of conventional active and passive filters suggested that hybrid filters designed to minimize cost and kVA rating are better alternatives in practical applications. Hybrid filter combinations of active and passive filters, which perform as well as active filters, have lower cost and kVA rating. Three hybrid filter topologies discussed in this chapter. These three hybrid filter topologies overcome the limitations of conventional filters. Two of these hybrid filter topologies, series active filter plus shunt passive filter (hybrid filter-1) and active filter connected in series with shunt passive filter (hybrid filter-2) are proposed in [2]. The third topology shunt-passive-shunt-active-shunt (hybrid filter-3) is proposed in this work to decrease VA rating of the DSTATCOM without compromising on performance.

## 3.1 Improving Passive Filter Performance

In section 2.1.5 the limitations of passive filters were discussed. In this section, hybrid filters that integrate active filter to existing passive filter combinations to improve the overall performance are presented. These filter topologies were presented by H. Akagi et al. [3] and Peng et al. [5] with control implementation using "P-Q theory". In this section both filter topologies are presented with control implementation based on "instantaneous symmetric component theory". Limitations of passive filters that can be addressed by the hybrid filters are reproduced here for quick reference.

1. Harmonic compensation performance of the passive filters depends on source impedance. Higher order harmonics are not compensated properly due to comparable impedances of source and filter.
2. Passive filter can form parallel resonance structure with source impedance leading to undesired amplification of harmonics around the resonance frequency of such combination.
3. Passive filters designed to draw low reactive power from source have very high settling time. It is desirable to have filters that can reduce high THDs in source current to IEEE 519 limits within 2-3 cycles.

### 3.1.1 Combination of series active filter plus shunt passive filter

Figure 3.1 explains series active filter plus shunt passive filter topology(mentioned as hybrid filter-1 from here onwards). The active filter is a voltage source inverter (VSI) with voltage as output. VSI output is connected in series to the feeder using a transformer. The passive filter is a combination of L-C filters tuned at $5^{\mathrm{th}}$ and $7^{\mathrm{th}}$ harmonic frequency and a high-pass filter with cut-off frequency at $10^{\mathrm{th}}$ harmonic.

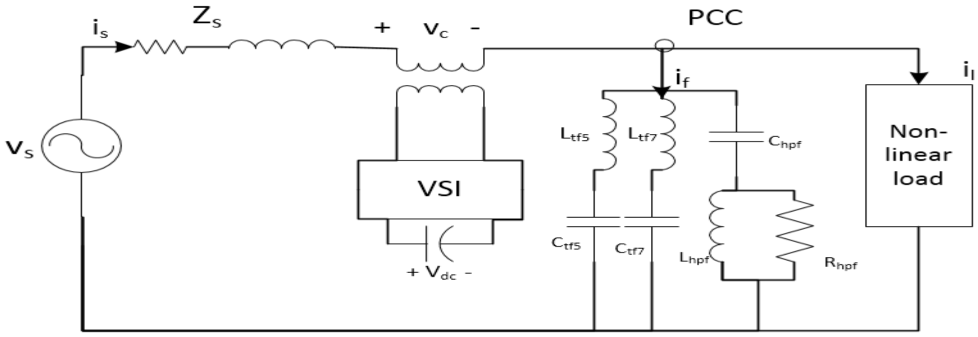


Figure 3.1: Single-line diagram of a compensated distribution system with hybrid filter-1

#### Compensating principle

Active filter works like a "harmonic isolator" in this filter topology. The basic idea of compensation with active filter is to make impedance of source side very high and resistive for harmonic frequencies. The filter has two objectives, first is to decrease source current harmonics and second is to make load voltage free of harmonics present in source voltage. If K is the value of resistance that the filter needs to offer at harmonic frequencies then its output voltage is given by

$$v_c = Ki_{sh} \tag{3.1}$$

The circuit can be analyzed at fundamental frequency and harmonic frequencies separately and the results can be superimposed. Figure 3.2 shows two circuits with active filter represented as a controlled voltage source ($v_c$) , passive filter represented as Impedance $Z_f$ and load represented as constant current.

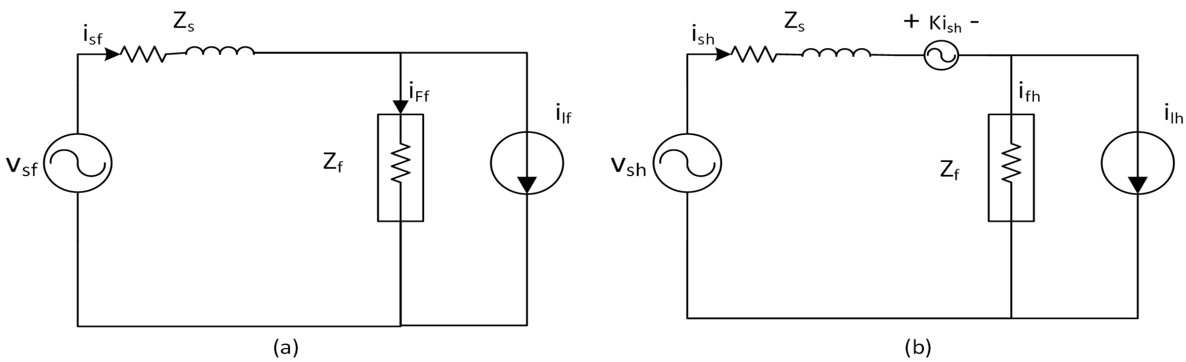


Figure 3.2: Equivalent circuit at (a) fundamental frequency and (b) harmonic frequencies

In Fig. 3.2 (a), the source fundamental voltage is represented as $V_{sf}$ and fundamental current is represented as $I_{sf}$ and the filter acts like a short circuit as there is no voltage at fundamental frequency. For this analysis the transformer is considered to be ideal. The load gets voltage from source with a drop across feeder impedance at fundamental frequency.

In Fig. 3.2 (b), $V_{sh}$ is harmonic component of source voltage and the filter can be considered as a resistor with resistance K because voltage drop across it is directly proportional to current flowing in it. Harmonic current from the load ($I_{lh}$) gets divided between $Z_f$ and source path. Source current harmonic component ($I_{sh}$) is given by

$$I_{sh} = \frac{Z_f}{Z_f + Z_s + K} I_{lh} + \frac{V_{sh}}{Z_f + Z_s + K} \tag{3.2}$$

$$I_{sh} \approx 0 \; if \; K \gg |Z_s| \, , \, |Z_f| \tag{3.3}$$

From (3.3) , if the value of K is much larger than magnitude of $Z_s$ and $Z_f$ then all the harmonic components of load current flow in to the filter and any harmonics in source voltage are blocked by the filter which acts like a damping resistance. In qualitative terms the impedance that $I_{lh}$ encounters in source path is much higher compared to $Z_f$ and hence most of $I_{lh}$ should flow in to $Z_f$.

Load voltage harmonic component is given by

$$
\begin{aligned}
V_{lh} &= -\frac{Z_s + K}{Z_f + Z_s + K}.Z_f I_{lh} + \frac{Z_f V_{sh}}{Z_f + Z_s + K} \qquad (3.4)\\
V_{lh} &\approx -Z_f I_{lh} \quad if\ K \gg |Z_s|\,,\ |Z_f| \qquad (3.5)
\end{aligned}
$$

From (3.5) it can observed that source harmonic voltage doesn't appear on load side thus the active filter acts like an open circuit to harmonic voltages in source.

**Overall filter characteristics**

In this section the filtering characteristics of the hybrid filter-1 is compared with stand alone passive filter. This analysis is carried out separately for the case without any source voltage harmonic and the case without load current harmonics. Fraction of $I_l$ that flows to source is called distribution factor [3] and for harmonic components it is given by

$$
\frac{I_{sh}}{I_{lh}} = \frac{Z_f}{Z_f + Z_s + K}\ for\ V_{sh} = 0 \qquad (3.6)
$$

Transfer function for source harmonic voltage $V_{sh}$ to load harmonic voltage is given by

$$
\frac{V_{lh}}{V_{sh}} = \frac{Z_f}{Z_f + Z_s + K}\ for\ I_{lh} = 0 \qquad (3.7)
$$

From (3.6) and (3.7), both distribution factor and source to load transfer function have same expression. Distribution factor value should be unity at fundamental frequency and should be very low at harmonic frequencies. Figure 3.3 shows distribution factor over frequency range 20 Hz - 1000 Hz for three different values of $K$, with passive filter and source impedance parameters taken as discussed in previous chapter. For $K$ = 0, the distribution factor shows peaks around $4^{\text{th}}$ harmonic frequency and 330 Hz due to resonance between source impedance and passive filter. Thus if a load draws current of $4^{\text{th}}$ harmonic frequency then the source current harmonic at that frequency is amplified. If the source has any harmonic voltage around $4^{\text{th}}$ harmonic frequency then it gets amplified at load due to the peak at $4^{\text{th}}$ harmonic frequency.

For $K$ = 1 and $K$= 2, no such peaks were observed and depth of the troughs at $5^{\text{th}}$, $7^{\text{th}}$ and higher order harmonic frequencies is more than that of $K$ = 0. There is a peak between $5^{\text{th}}$ and $7^{\text{th}}$ harmonic troughs around 295 Hz, which makes the filter ineffective against $6^{\text{th}}$ harmonic. Thus hybrid filter-1 explained in this section cannot be used for compensation of harmonic loads such as cyclo-converters which draw harmonic components other than 6n±1.

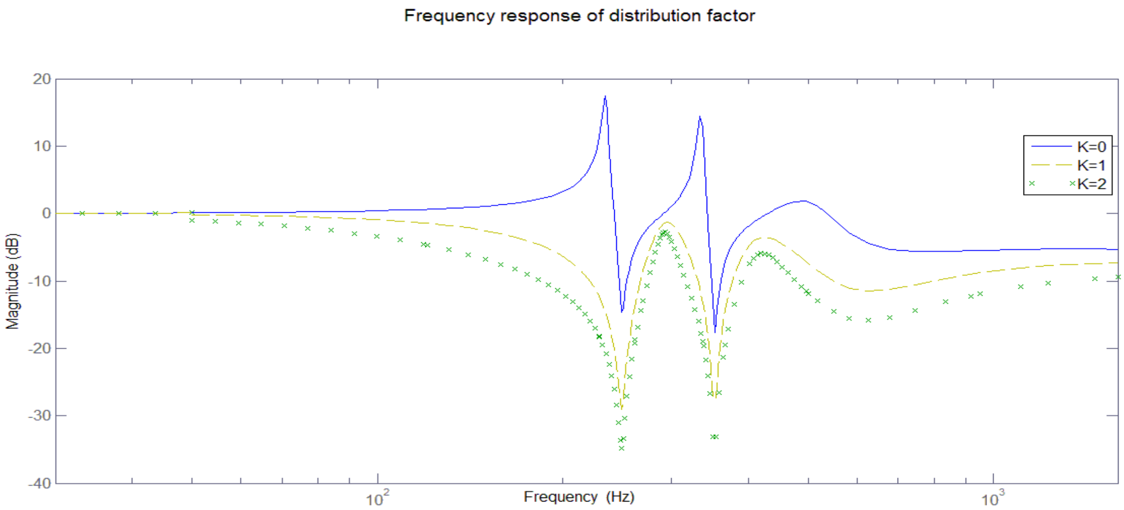


Figure 3.3: Distribution factor variations with frequency of hybrid filter-1

**Reference voltage generation**

The filter reference voltage is given by

$$v_c^* = K i_{sh} \tag{3.8}$$

Generating $i_{sh}$ from $i_s$ by using a high-pass filter is ideal if the source impedance is zero. For non-zero source impedance load voltage will have harmonics due to harmonic current drawn and hence the source current should also have harmonics to make source power factor unity. Thus to find reference voltage either "P-Q theory" or "instantaneous symmetric component theory" should be used. The original work [3] used "P-Q theory" to find $i_{sh}$. The P-Q method uses a high-pass filter with cut-off frequency of 35 Hz which requires very high order FIR (finite impulse response) filter even for sampling frequencies as low as 20 kHz. In the present work instantaneous symmetric component theory is used to overcome this difficulty.

Figure 3.4 explains the difference in reference generation between P-Q method and symmetric component method. Reference generation using instantaneous symmetric component theory has $i^*_{fabc}$ discussed in section 2.2.1. It should be recalled that this reference is such that the source current is free of harmonics and without unbalances which means $i^*_{fabc}$ contains both $i_{sh}$ and fundamental component to remove unbalances. $i_{sh}$ can be separated from $i^*_{fabc}$ by using a high pass filter with cut-off frequency 200 Hz as the lowest harmonic that is present in $i_{sh}$ is the $5^{\text{th}}$ harmonic. Because of this high cut-off frequency FIR filter order is smaller compared to the filter used in p-q method. In symmetric component method passive filter is considered as a part of the load to get residue harmonics in source current after filtering with passive filter.

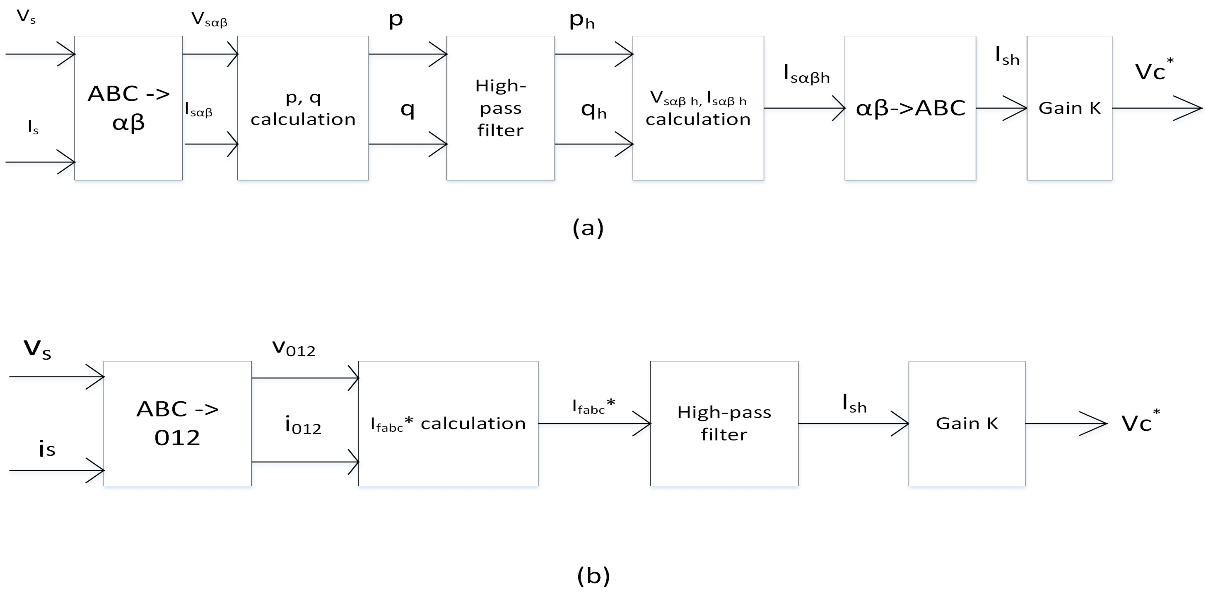


Figure 3.4: Reference generation using (a) p-q theory (b) symmetric component theory

### Filter voltage generation

The filter reference voltage is initially high and as $i_{sh}$ reduces with the feedback action, $v^*_c$ also settles down at smaller magnitude. The output can be generated using a voltage source inverter using PWM or hysteresis method. PWM method has certain disadvantages due to the injection transformer [10], most important factors are saturation of transformer and fundamental frequency voltage drop appearing across secondary of the transformer. The analysis of these issues is out of scope for this work. Hysteresis method is suitable for small magnitude harmonic voltage generation. The hysteresis limit is applied on transformer secondary voltage rather than for VSI output voltage to account for transformer parameters. Suitable integrator (filter) should be designed to follow all the harmonic components. Because of transformer reactance and magnetizing branch effects, using analytical method to find filter parameters becomes very difficult. In this work trial and error method is used to find appropriate filter.

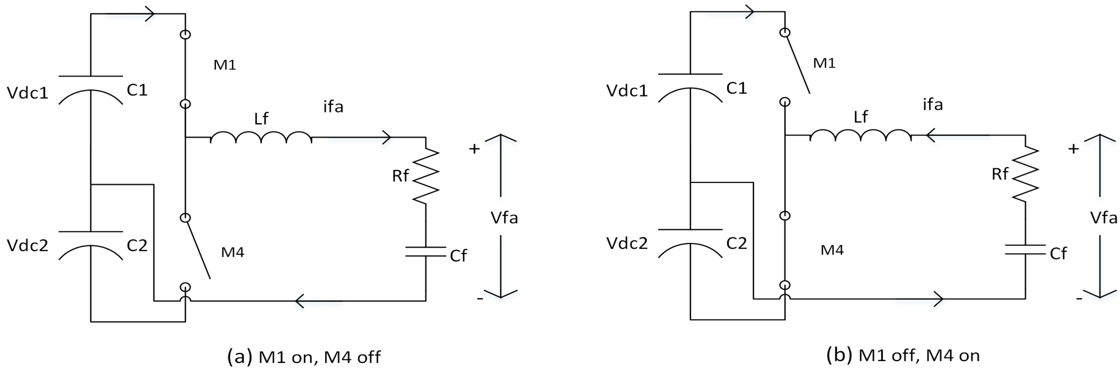


Figure 3.5: Voltage generation in two different switching states

Figure 3.5 shows two switching states of VSI in one phase. The output of VSI is connected to transformer primary side. The secondary side of the transformer is connected in series with mains. Hysteresis band is applied at the secondary of transformer. In the present analysis the transformer is considered to be ideal to analyze the switching states.

In Fig. 3.5(a) $M_1$ is on and $M_2$ is off, $L_f$ integrates the voltage difference $V_{dc1} - v_{fa}$ and the current $i_{fa}$ increases and capacitor $C_f$ gets charged and voltage $v_{fa}$ increases. $R_f$ is used to avoid any resonance between $L_f$ and $C_f$. Similarly in the case of Fig. 3.5(b), $L_f$ integrates the voltage difference $v_{fa} - V_{dc2}$ and $C_f$ gets discharged and $v_{fa}$ decreases. Thus by controlling the two switching states, the voltage output of VSI can be controlled. Equations (3.9) explains switching control of $M_1$ and $M_4$.

$$\begin{aligned} v_{fa} &< v^*_{fa} - h \Rightarrow M1 = 1,\ M4 = 0 \\ v_{fa} &> v^*_{fa} + h \Rightarrow M1 = 0,\ M4 = 1 \\ v^*_{fa} - h &< v_{fa} < v^*_{fa} + h \Rightarrow retain\, previous\, gate\, signals \end{aligned} \tag{3.9}$$

**System Configuration**

Overall system configuration is explained in Fig. 3.6. It should be noted that VSI in Fig. 3.6 are single-phase half bridge inverters. This filter configuration cannot compensate for unbalances in load and reactive power compensation using capacitor banks should be used. Since this filter is used to improve passive filter performance, the load is considered to be balanced. The passive filter capacitance can be decreased as the hybrid filter doesn't suffer from the slow settling as in the case of passive filter, because the feedback from active filter makes overall compensation faster.

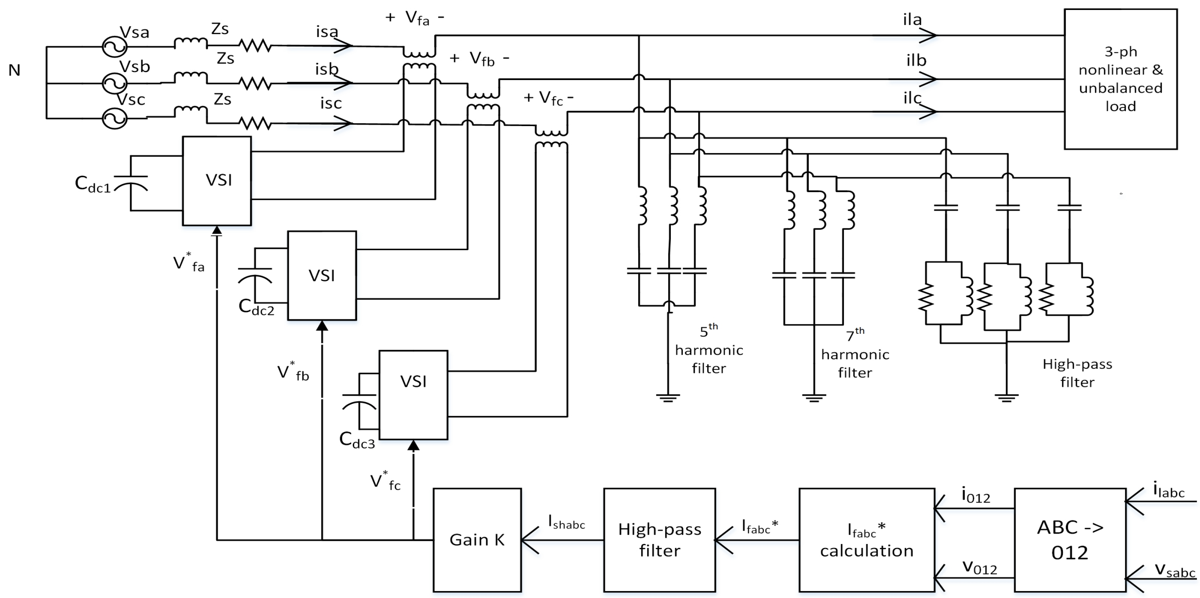


Figure 3.6: Hybrid filter-1 three-phase system configuration

### 3.1.2 Active filter connected in series with shunt passive filter

Active filter connected in series with shunt passive filter (mentioned as hybrid filter-2) is a hybrid filter topology to improve performance of passive filters. Similar feedback principle that was used for hybrid filter-1 discussed in previous section is used with different system configuration as indicated by the name of the filter. Figure 3.7 explains the filter configuration. The active filter which is a voltage source inverter (VSI) with voltage as its output is connected in series with the passive filter with an injection transformer.

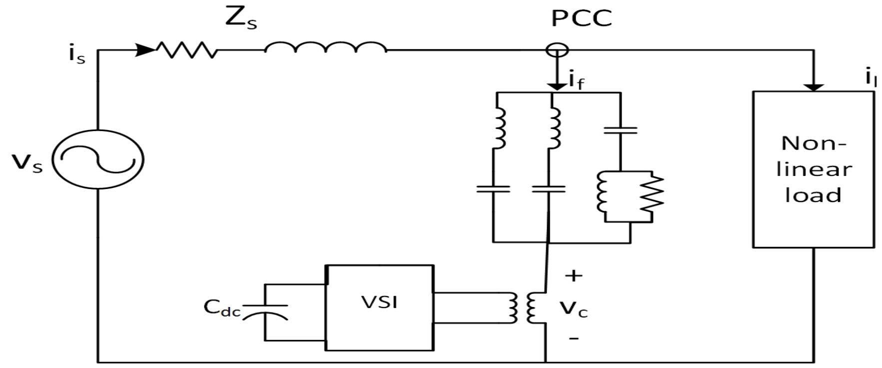


Figure 3.7: Single-line diagram of distribution system with hybrid filter-2

### Compensation principle

The basic idea of the filter is to force current in to passive filter by providing sufficient voltage drop across the passive filter. Active filter output voltage is given by

$$v_f = Ki_{sh} \tag{3.10}$$

If the load current is constant then having such feedback will reduce source harmonic components as most of the harmonic are forced to flow through the passive filter. Analysis of the circuit is carried out in a similar fashion that was used in section 3.1.1.1.

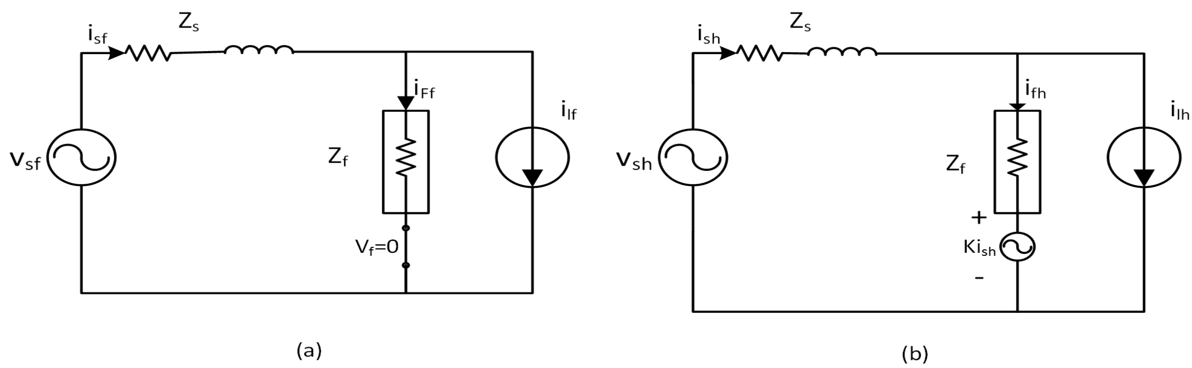


Figure 3.8: Equivalent circuits at (a) fundamental frequency and (b) harmonic frequencies

Figure 3.8 shows circuit at fundamental frequency and harmonic frequencies separately. In Fig. 3.8 (a), at the fundamental frequency the circuit is not effected due to the filter, as the filter acts like a short circuit at fundamental frequency. In Fig. 3.8 (b), the filter gives voltage output according to (3.10). This circuit is analyzed to derive expression for $I_{sh}$ in terms of $I_{lh}$ and $V_{sh}$.

$$
\begin{aligned}
I_{sh} &= I_{fh} + I_{lh} \\
I_{fh} &= \frac{V_{sh} - Z_s I_{sh} - K I_{sh}}{Z_f} \\
I_{sh} &= \frac{I_{sh}}{Z_f + Z_s + K} + \frac{Z_f}{Zs + K + Z_f} I_{lh} \qquad (3.11) \\
I_{sh} &\approx 0 \; if \; K \gg |Z_s|, \; |Z_f| \qquad (3.12)
\end{aligned}
$$

Thus for large real values of K, the filter can improve passive filter performance and provide harmonic compensation.

### Overall filter characteristics

From (11), the distribution factor for harmonic frequencies can be given by

$$
I_{sh} = \frac{Z_f}{Zs + K + Z_f} I_{lh} \quad for \; V_{sh} = 0 \qquad (3.13)
$$

this distribution factor is the same as of hybrid filter-1 and observations in section 3.1.1.2 can be extended here. The filter provides blocking resistance to prevent resonance between source impedance and filter impedance. From Fig. 3.3, the filter can not provide sufficient compensation against $6^{th}$ harmonic and is inefficient against load currents with $6^{th}$ harmonic.

Harmonic component of load voltage is given by

$$
\begin{aligned}
V_{lh} &= V_{sh} - Z_s I_{sh} \\
V_{lh} &= \frac{Z_f + K}{Z_f + Z_s + K} V_{sh} - \frac{Z_f}{Zs + K + Z_f} Z_s V_{lh} \qquad (3.14) \\
V_{lh} &\approx V_{sh} \; if \; K \gg |Z_s|, \; |Z_f| \qquad (3.15)
\end{aligned}
$$

From (3.15), the filter cannot provide harmonic isolation and any harmonics in source voltage will be present at the load terminal. But unlike in the case of stand alone passive filters, there is no chance of resonance between source impedance and filter impedance that might amplify any unwanted harmonics. For example in Fig. 3.3, the passive filter has resonance at $4^{th}$ harmonic. Hence the transfer function from source to load voltage of the filter is improved compared to passive filter alone.

**System configuration**

Figure 3.9 explains the overall system configuration of the hybrid filter-2. The filter reference is generated as explained in section 3.1.1.3 and section 3.1.1.4. Only harmonic currents flow in the secondary of injection transformer, thus the overall rating of the filter is expected to smaller compared to hybrid filter-2. This filter can compensate for harmonics and cannot compensate for unbalances in the load currents.

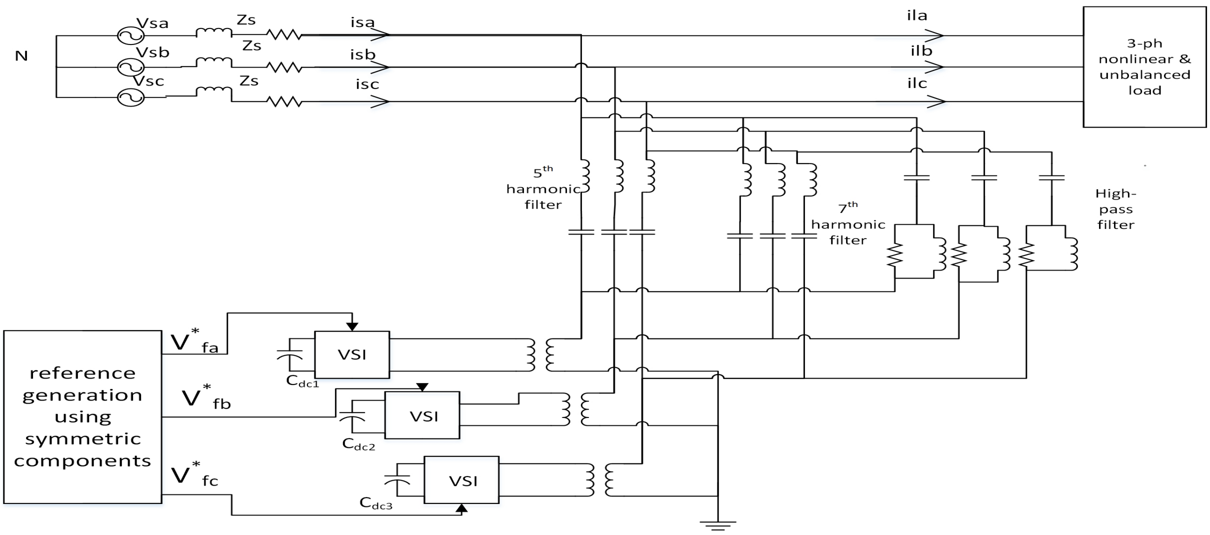


Figure 3.9: Hybrid filter-2 three-phase system configuration

## 3.2 Improving Performance of DSTATCOM

A new hybrid filter topology is proposed and is discussed in this section. The proposed hybrid filter topology, hybrid filter-3, is a combination of shunt passive filter with shunt active filter. . This filter includes passive filter in parallel to the DSTATCOM. There are many variations of this hybrid filter with designs varying with the type of load and purpose of adding the passive filter. A hybrid filter combination of capacitor bank and shunt active filter is proposed [7] to reduce the kVA rating of the active filter by providing half of the reactive power compensation by capacitor bank. This present work focuses on overcoming the limitations that were found in simulations as explained in chapter 2 , which are listed below.

1. DC-link voltage required is very high as it compensates for all the harmonics which have very high rate of change of current.
2. Switching frequency of inverter switches is very high which leads to more switching losses. Also IGBT has switching frequency limits of 20 kHz which limits the smallest value of $L_f$ that can be used and maximum THD that the filter can compensate.
3. Additional high pass filter is required to eliminate switching harmonics.
4. kVA rating of filter is very high.

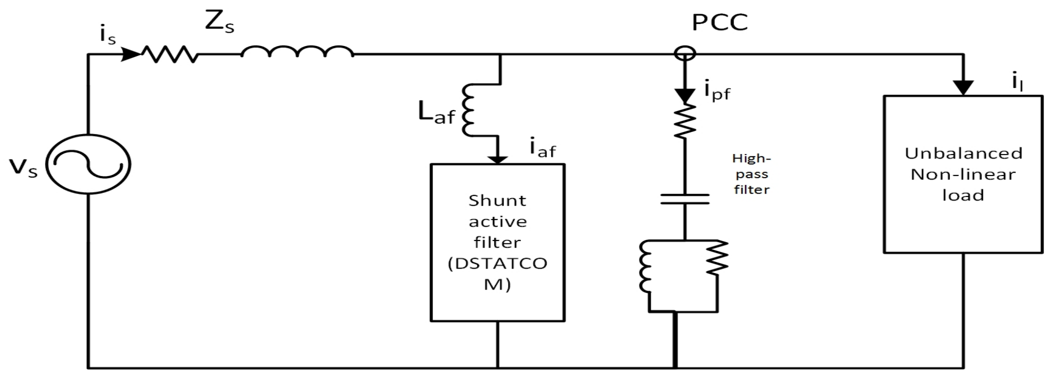


Figure 3.10: Single-line diagram of compensated distribution system with hybrid filter-3

### 3.2.1 Compensation principle

Figure 3.10 explains the filter configuration is one of the phases. The active filter will compensate for unbalances and harmonics up to $13^{\text{th}}$ harmonic and the passive filter will compensate harmonics of higher order and switching harmonics. The basic idea is to have maximum rate of change in filter current ($\frac{di}{dt}_{max}$) to be as small as possible. The higher order harmonics are filtered by using a R-L-C high pass filter tuned at $15^{\text{th}}$ harmonic frequency, due to which the maximum rate of change in filter current is decreased as the sharpness in the waveform occurs due to higher order harmonics. If PWM control of VSI is implemented then the minimum carrier frequency required decreases as maximum harmonic that needs to be compensated is $13^{th}$ harmonic. The kVA rating of the filter reduces compared to DSTATCOM as the passive filter is capacitive at fundamental frequency and part of the harmonics are compensated by the passive filter.

### 3.2.2 Filter characteristics and reference generation

Filtering characteristics of active filter were discussed in section 2.2. The passive filter is a high-pass filter with cut-off frequency around $15^{\text{th}}$ harmonic. Figure 3.11 shows the bode magnitude plot of the passive filter. The filter has high impedance at fundamental frequency and it eventually decreases. The filter impedance drops significantly around $15^{th}$ harmonic and stays constant at higher frequencies.

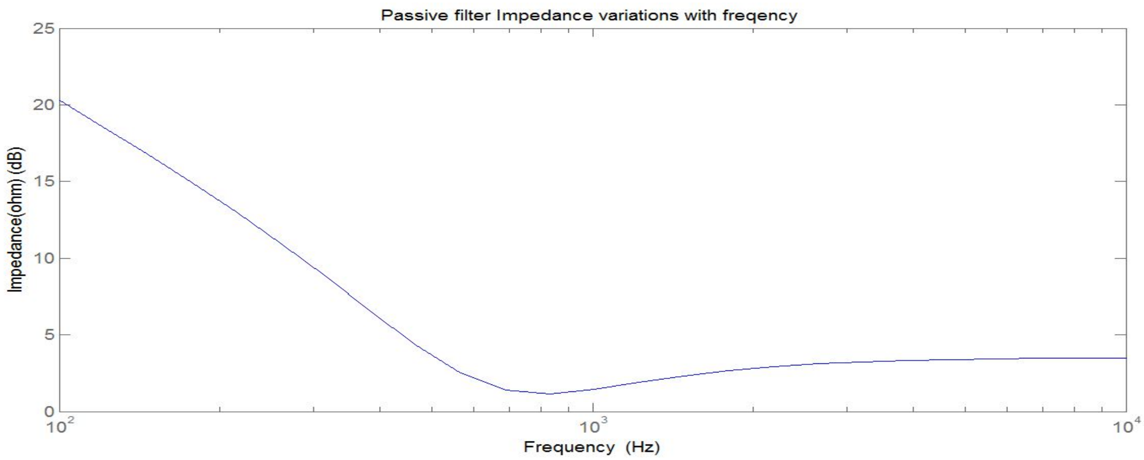


Figure 3.11: Passive filter impedance variations with frequency

Reference for the filter is generated using instantaneous symmetric component theory. The method explained in section 2.2.1 generates filter reference currents which make source currents free of harmonics and unbalances. The current references are then passed through a low-pass filter with cut-off frequency of 750 Hz ($15^{th}$ harmonic) and then fed as reference to the active filter.

### 3.2.3 System configuration

Figure 3.12 shows system configuration of the proposed hybrid filter-3 topology. The active filter has similar structure as that of DSTATCOM and its parameters such as $L_f$, hysteresis constant $h$ and DC-link voltage $V_{dc}$ are decided by the similar rules that were used for DSTATCOM. The passive filter design depends upon filter specifications and various other parameters such as source impedance. Linear unbalances and harmonics in the source currents can be compensated by this filter system. Design issues of filter are discussed along with simulation studies in next section.

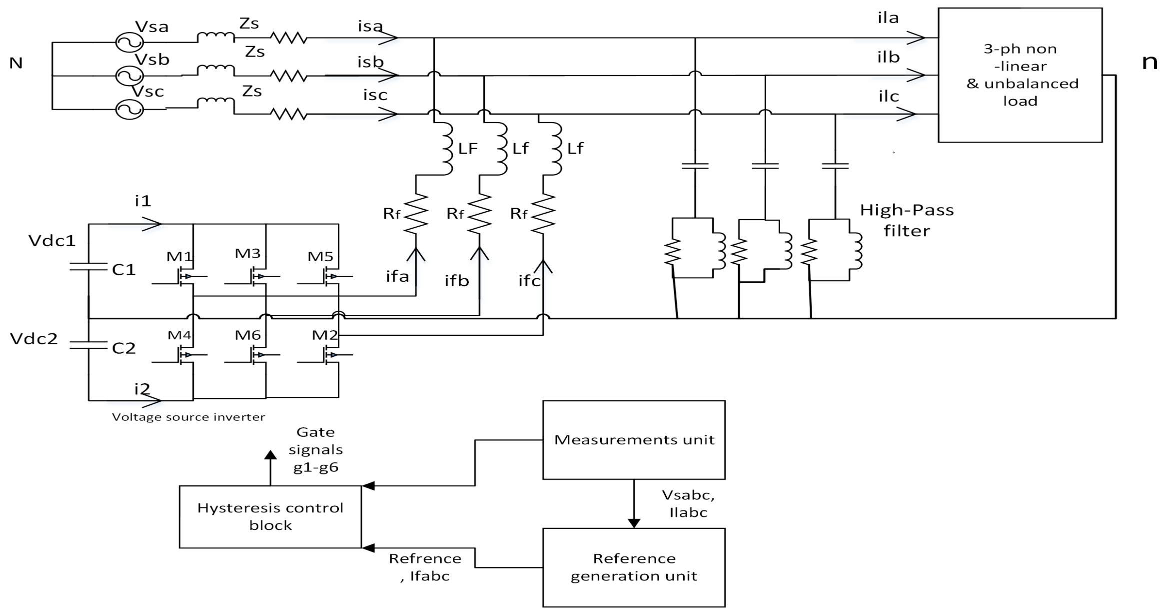


Figure 3.12: Three-phase compensated distribution system with hybrid filter-3 topology

## 3.3 Simulation Results

Performance of the various filters discussed in the sections 3.1 and 3.2 is discussed in this section. Filters that are discussed in section 3.1 are compared with performance of passive filter as these filters are proposed to improve passive filter performance. Similarly filter discussed in section 3.2 is compared with performance of DSTATCOM. The loads considered for hybrid filter-3 and passive filter are different and hence the simulations are discussed separately.

### 3.3.1 Simulation of hybrid filters that improve passive filters

In this section performance of hybrid filter-1 and hybrid filter-2 is compared with stand-alone passive filter. The load used for the simulation is a rectifier load combined with balanced linear load. Table 3.1 describes source and load parameters.

Table 3.1: Source and load parameters

| Source | rectifier load | 3-$\phi$ balanced R-L load | total load |
|---|---|---|---|
| $V_{1\phi,rms}$=230.9 V | $V_{load}$= 230.4 V | $V_{load}$ = 229.6 V | $V_{load}$= 229.1 V |
| $Z_s$= 0.01+ 0.04j $\Omega$ | $P_{rect}$= 41.02 kW | $P_l$=17.26 kW, | $P_l$= 57.69 kW |
| | pf= 0.96 lag | pf= 0.68 lag | pf= 0.92 lag |
| | $THD_i$=27.8% | $THD_i$=0.5% | $THD_i$= 18.22% |
| | $THD_v$=1.9% | $THD_v$= 0.6% | $THD_v$=2.1% |

Now the filters are applied to this system. It should be noted that, the hybrid filters have same passive filter parameters as the stand-alone passive filter to show the comparison for same parameters.

Table 3.2 gives filter parameters for each filter configuration. It should be noted that passive filter parameters are same as that were used in section 2.1.3. The DC-link voltages should be small to decrease the switching ripples and increasing these values will result in poor performance of the filters.

Table 3.2: Filter parameters for hybrid filters

| | $V_{dc}$ | K | h | filter |
|---|---|---|---|---|
| Hybrid filter-1 | 50 V | 1 $\Omega$ | 0.01 | $R_f$ = 4$\Omega$, $L_f$ = 0.1 mH, $C_f$= 500 $\mu$F |
| Hybrid filter-2 | 50 V | 1 $\Omega$ | 0.01 | $R_f$ = 4$\Omega$, $L_f$ = 0.1 mH, $C_f$= 500 $\mu$F |

Table 3.3 shows various performance parameters for each load. It is apparent from Table 3.3 that, the hybrid filters improve passive filter performance and IEEE 519 limits on THD are also met.

Table 3.3: Performance comparison on passive filter and hybrid filters.

| parameter | without filters | Passive filter | hybrid filter-1 | hybrid filter-2 |
|---|---|---|---|---|
| $THD_i$ | 18.22% | 9% | 2.7% | 4.3% |
| $THD_v$ | 2.1% | 1.7% | 2.4% | 1.9% |
| $V_{load}$ | 229.1 | 231 V | 231.4 | 231.3 |
| $P_{load}$ | 57.7 kW | 59.11 kW | 59.3 kW | 59.2 kW |
| $P_s$ | 57.7 kW | 59.28 kW | 59.82 kW | 59.71 kW |
| pf | 0.92 lag | 0.936 lead | 0.94 lead | 0.94 lead |

**Observations**

1. The voltage and current waveforms of the two hybrid filters are compared with passive filter and without filters in Fig. 3.13. As indicated in Table 3.3, THDs in the voltages and currents for the hybrid filters are within IEEE 519 limits. Some switching ripples can be observed in the voltage in case of hybrid filter-2. An RC high-pass filter is used to suppress these ripples.

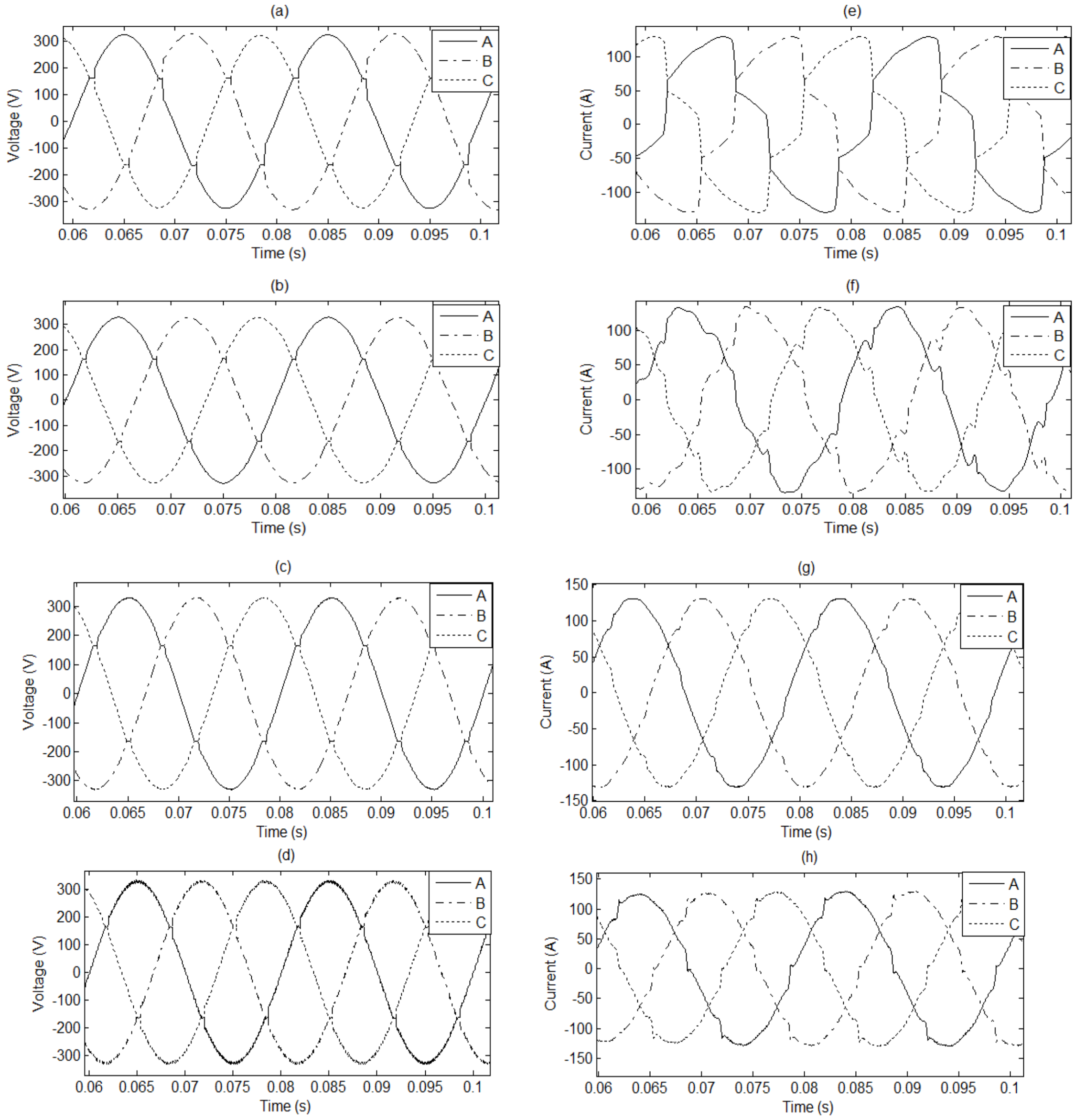


Figure 3.13: Three-phase source currents for (a) without filter, (b) passive filter, (c) hybrid filter-1, (d) hybrid filter-2 and load voltages for (e) without filter, (f) passive filter, (g) hybrid filter-1, (h) hybrid filter-2

2. Individual harmonic distortion(IHD) and total demand destortion (TDD) for passive filter and hybrid filters are compared in Table 3.4 for $I_{l,max}$ = 250 A. The passive filter fails to meet IHD limits for $23^{rd}$ harmonic but satisfies overall TDD limits. Both the hybrid filters have IHD and TDD values well under the limits.

Table 3.4: IHD% and TDD% values for filter topologies

| $I_{sc}/I_l = 20$ | 5 | 7 | 11 | 13 | 17 | 19 | 23 | 25 | 29 | 31 | TDD% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Without filters | 6.8 | 4.4 | 3 | 2.3 | 1.6 | 1.5 | 0.9 | 0.8 | 0.7 | 0.6 | 8.76 |
| Passive filter | 2.5 | 1.8 | 1.8 | 1 | 0.85 | 0.8 | 0.7 | 0.5 | 0.4 | 0.4 | 4.1 |
| Hybrid filter-1 | 0.88 | 0.2 | 0.7 | 0.2 | 0.2 | 0.2 | 0.2 | 0.18 | 0.15 | 0.15 | 1.24 |
| Hybrid filter-2 | 0.92 | 0.5 | 1 | 0.7 | 0.7 | 0.6 | 0.55 | 0.5 | 0.45 | 0.4 | 2.09 |
| IEEE 519 limits | 4 | 4 | 2 | 2 | 1.5 | 1.5 | 0.6 | 0.6 | 0.6 | 0.6 | 5 |

3. FFT plots of the source currents in phase-a are compared in Fig. 3.14. The effect of adding active filter to the passive filter can be clearly seen, as all the higher order harmonics are suppressed effectively.

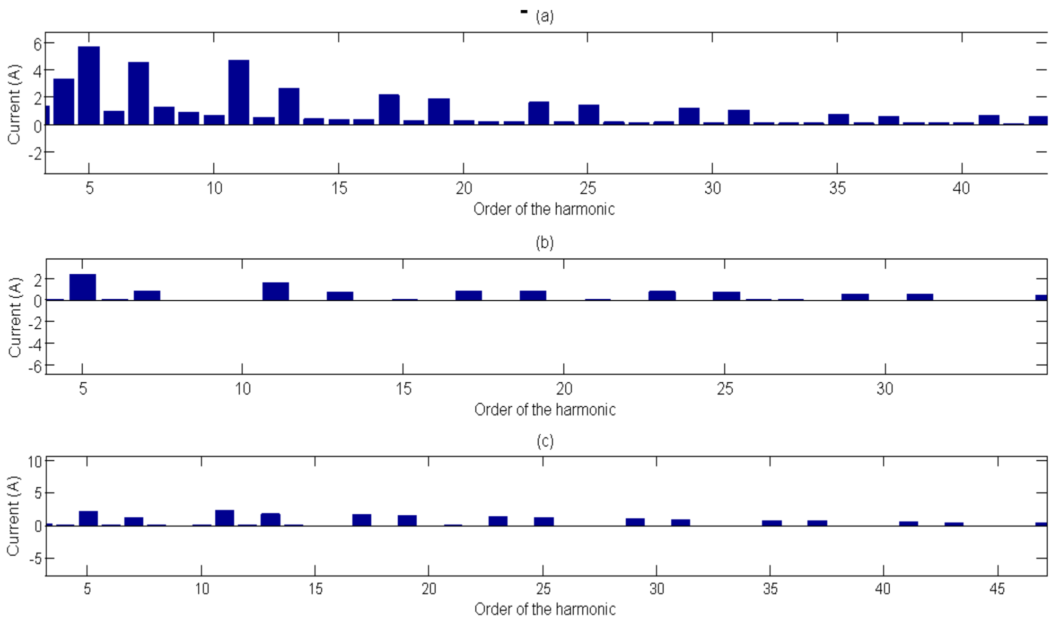


Figure 3.14: FFT magnitude plots of currents in phase-a for (a) passive filter, (b) hybrid filter-1, and (c) hybrid filter-2

4. Compensator output voltages for a-phase are shown in Fig. 3.15. Compensator output voltages decrease because source current harmonics reduce due to filtering. The filter output voltages in other phases will also be similar as all the phases are compensated independently.

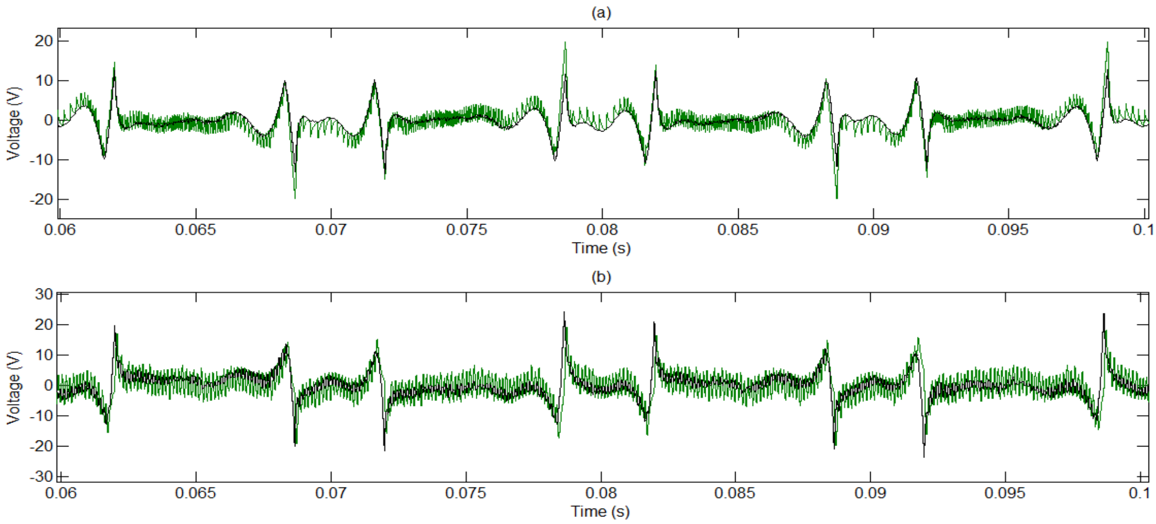


Figure 3.15: Active filter output voltages of phase-a for (a) hybrid filter-1 and (b) hybrid filter-2

5. Average switching frequency of the active filters is found using the block explained in section 2.2.4. The average switching frequency of hybrid filter-1 is 7 kHz, where as average switching frequency of hybrid filter-2 is 10 kHz. The difference comes from DC-link voltage which has direct effect on integration rate and in turn average switching frequency.

6. The kVA rating of the active filters used for the hybrid filter-1 is 1.5 kVA and for the hybrid filter-2 kVA rating is 0.96 kVA. These values are quite low when compared with DSTATCOM. This is due to the fact that the active filters in the case of hybrid filters are used as feedback devices where as for DSTATCOM, it is a compensating device. kVA rating of hybrid filter-2 is low compared to hybrid filter-1 because dominantly harmonic currents flow in hybrid filter-2 and fundamental load current which is high compared to harmonics flows in hybrid filter-1.

7. Maximum current THD that hybrid filter-1 can compensate for is 100 kW load with 24% THD in current. Maximum current THD that hybrid filter-2 can compensate is 75 kW with 20% THD. These limits are much higher when compared to passive filter compensated systems.

**Advantages and limitations**
**Advantages:**

1. Both hybrid filter-1 and hybrid filter-2 can enhance passive filter compensation for very high THD values in load currents.

2. kVA rating of the filters is very small compared to stand alone active filters and hence overall cost of the filter will be much smaller compared to DSTATCOM

3. Switching frequency is well within allowed IGBT switching frequency and switching losses are much smaller compared to DSTATCOM.

4. Reactive power compensation using capacitor banks can be used without any risk of resonances.

**Limitations:**

1. Hybrid filter-2 requires additional high pass filter to eliminate switching harmonics from filter output voltages.
2. Hybrid filter-1 and hybrid filter-2 require very low DC-link voltages when compared to DSTATCOM and hence additional dc-dc converter is required to maintain these voltages.
3. The hybrid filters discussed in this section can not provide reactive power compensation for balancing the source currents, however it is feasible to implement reactive power compensation using capacitor banks.

### 3.3.2 Simulation with proposed hybrid filter-3 topology

Simulation studies on DSTATCOM and hybrid filter-3 topologies are carried out to compare the performance of the hybrid filter with DSTATCOM performance for similar loads. The load considered for the simulation is 3-$\phi$ unbalanced load combined with rectifier load. The primary objectives of hybrid filter are reducing the kVA rating and average switching frequency. Table 3.5 gives DSTATCOM parameters and hybrid filter parameters that are used for simulation. Lower DC-link voltage is used for hybrid filter-3 compared to DSTATCOM, to minimize switching losses.

Table 3.5: Filter parameters for DSTATCOM and hybrid filter-3

| | Active filter | Passive filter |
|---|---|---|
| DSTATCOM | $V_{dc}$= 1.8* $V_s$, h= 0.01, $L_f$ = 3 mH | NA |
| Hybrid filter-3 | $V_{dc}$= 1.4* $V_s$, h= 0.01, $L_f$ = 5 mH | C=200 $\mu$F, R = 1 $\Omega$, L = 0.4 mH |

Table 3.6 shows load details used in simulations and source used is same as shown in Table 3.1. From the table it can be observed that the load is unbalanced with THD more than IEEE 519 limits.

Table 3.6: Load details used in simulations

| Rectifier load | 3-$\phi$ unbalanced R-L load | Total load |
|---|---|---|
| $V_{load}$= 230.4 V | $V_{load}$ = 229.1 V | $V_{load}$= 229.1 V |
| $P_{rect}$= 28.74 kW | $P_l$=20.52 kW, | $P_l$= 48.7 kW |
| pf= 0.96 lag | pf= 0.78 lag | pf= 0.92 lag |
| $THD_i$=27.8% | $THD_i$=0.5% | $THD_i$= [17, 14, 14]% |
| $THD_v$=1.9% | $THD_v$= 0.6% | $THD_v$=2.1% |
| $I_{sabc}$=[43, 43, 43] A | $I_{sabc}$=[28, 40 , 46] A | $I_{sabc}$= [69, 79, 83] A |

DSTATCOM and hybrid filter-3 are used to compensate for harmonics and unbalances in the system. Table 3.7 compares various performance parameters for the filters. Both filters perform similarly, but the kVA rating of the hybrid filter-3 is much less when compared with the DSTATCOM. The mismatch between source power and load power arises due to losses in high-pass passive filters and inability of active filter to follow the references accurately which leads to active power being drawn by the active filter.

Table 3.7: Performance of DSTATCOM and hybrid filter-3

| parameter | without filters | DSTATCOM | hybrid filter-3 |
|---|---|---|---|
| $THD_i$ | [17, 14, 15]% | [4.2, 4.1, 4.2]% | [4.3, 4.4, 4.4]% |
| $THD_v$ | 2.1% | [1.6, 1.6, 1.7]% | [2.5. 2.5, 2.4]% |
| $V_{load}$ | 229.1 | 230.9 | 230.3 |
| $P_{load}$ | 48.7 kW | 50 kW | 49.53 kW |
| $P_s$ | 48.7 kW | 51.27 kW | 50.3 kW |
| pf | 0.92 lag | 0.985 lead | 0.999 lead |
| $I_{sabc}$ | [69, 79, 83] A | [75, 75.1, 75.1] A | [72.3, 72.4, 72.4] |
| filter kVA | — | 19.92 kVA | 12.77 |

**Observations**

1. Figure 3.16 shows load voltages and source currents of three-phases without filter, with DSTATCOM and with hybrid filter-3. Both DSTATCOM and hybrid filter-3 achieve the objective of having balanced and undistorted currents in three-phases. Some residue harmonics can be seen in the case of hybrid filter-3, but the overall THD% and IHD% values are within IEEE 519 allowed limits.

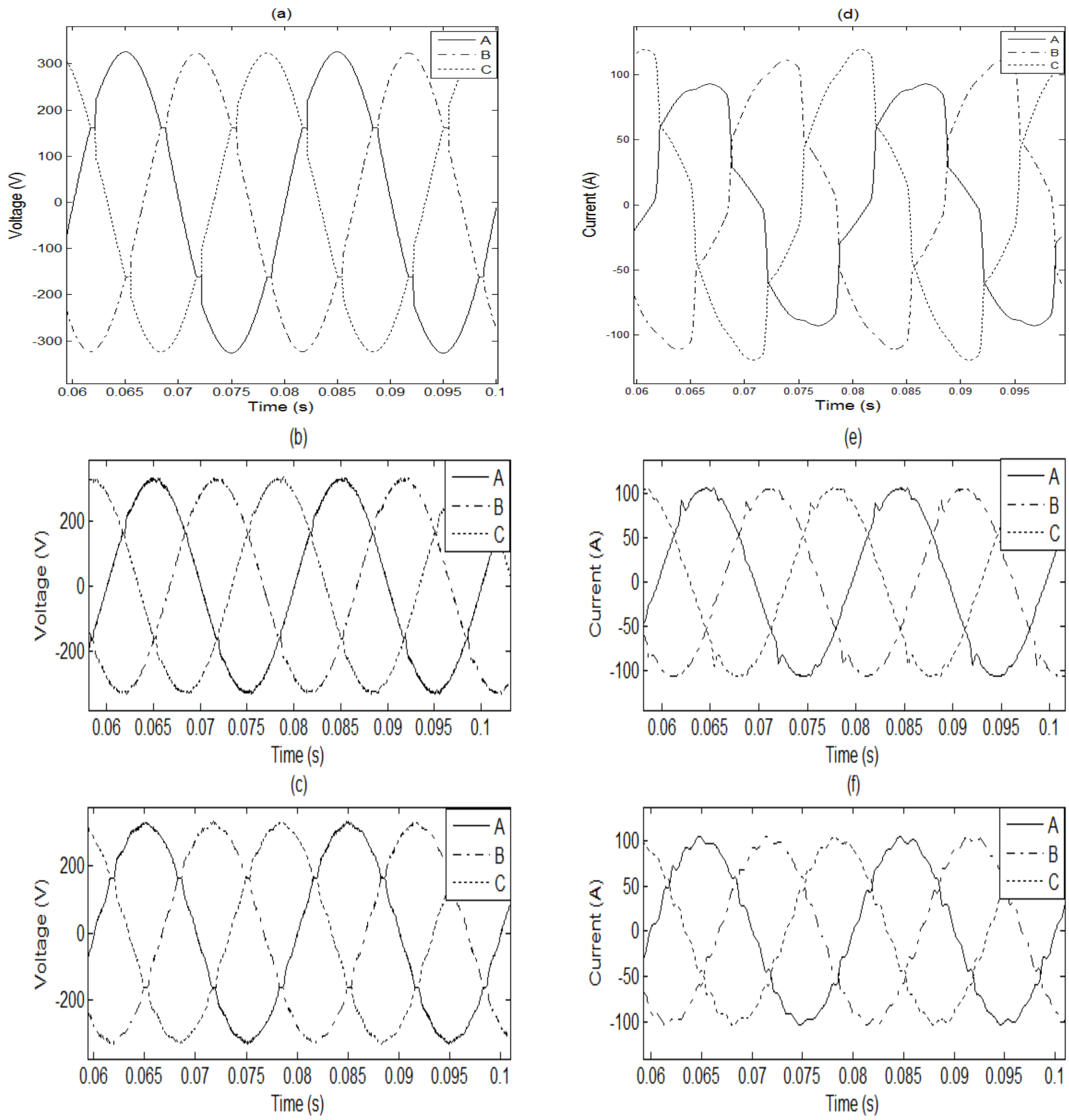


Figure 3.16: Three-phase load voltages for (a) without filters, (b) DSTATCOM, (c) hybrid filter-3 and three-phase source currents for (d) without filters, (e) DSTATCOM, (f) hybrid filter-3

2. Figure 3.17 shows FFT plots of source currents in phase-a without filter and with filters. In the FFT plot of hybrid filter-3, the values of $17^{th}$ and $19^{th}$ harmonic are slightly more compared to DSTATCOM, but these values were observed to decrease with time because of slow nature of passive filters.

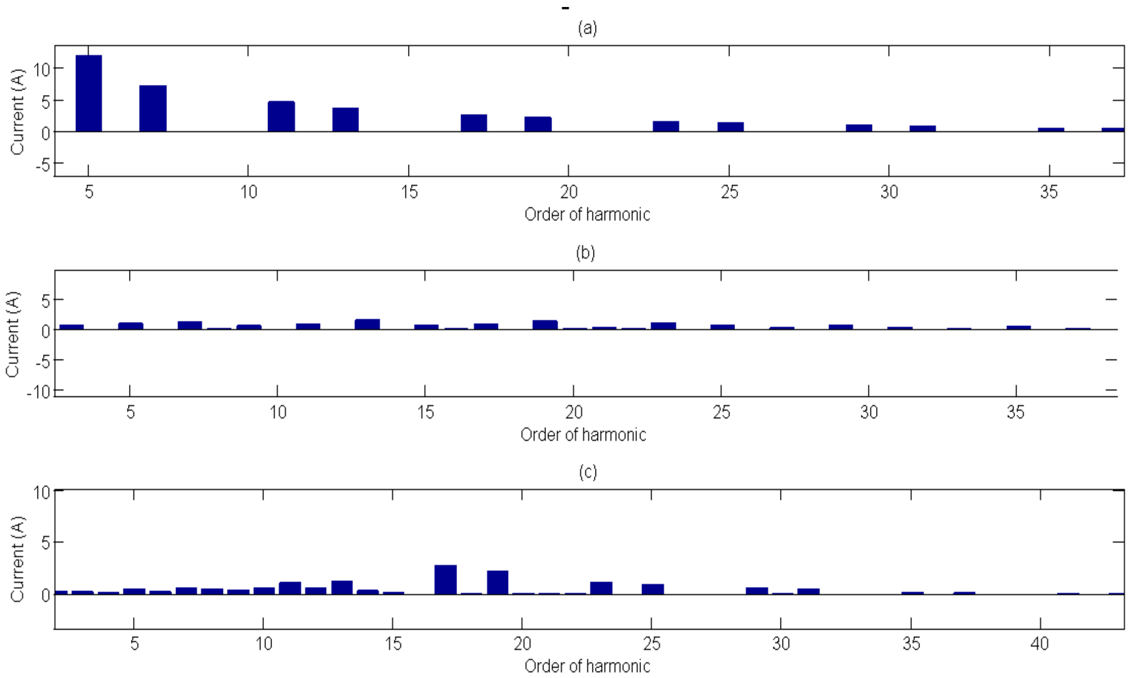


Figure 3.17: FFT magnitude plot of a-phase source current for (a) without filters, (b) DSTATCOM, (c)hybrid filter-3

3. Table 3.8 gives IHD% and TDD% for maximum demand fundamental current of 250A. Hybrid filter-3 satisfies all IHD% and TDD% requirements and its performance is comparable to DSTATCOM performance.

Table 3.8: IHD% and TDD% of the source currents in a-phase

| $I_{sc}/I_l$ = 20 | 5 | 7 | 11 | 13 | 17 | 19 | 23 | 25 | 29 | 31 | TDD% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Without filters | 4.8 | 3 | 2 | 1.5 | 1.1 | 0.9 | 0.7 | 0.6 | 0.4 | 0.4 | 6.44 |
| DSTATCOM | 0.4 | 0.55 | 0.5 | 0.6 | 0.4 | 0.5 | 0.5 | 0.3 | 0.3 | 0.2 | 1.38 |
| Hybrid filter-3 | 0.3 | 0.35 | 0.4 | 0.5 | 1.1 | 0.9 | 0.5 | 0.4 | 0.3 | 0.2 | 1.8 |
| IEEE 519 limits | 4 | 4 | 2 | 2 | 1.5 | 1.5 | 0.6 | 0.6 | 0.6 | 0.6 | 5 |

4. Compensator output currents are shown in Fig. 3.18. DSTATCOM filter currents have sharp rises and flat regions which leads to high switching frequency and increase in minimum DC-link voltage required. Hybrid filter-3 filter currents do not have such sharp rises or flat regions which gives advantage over DSTATCOM with respect to switching losses and DC-link voltage.

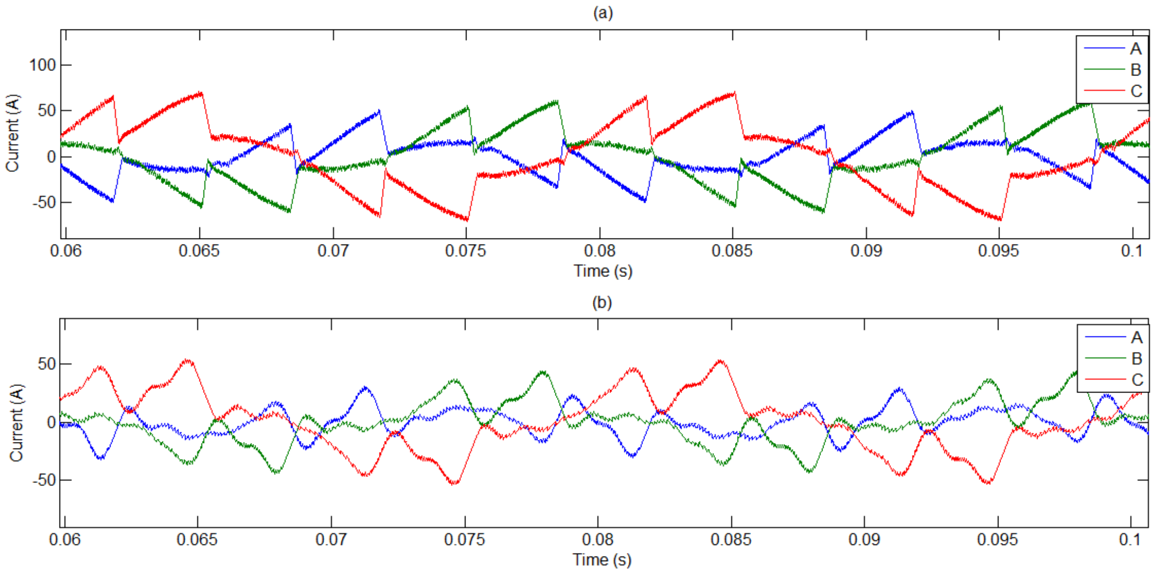


Figure 3.18: Filter output currents in three-phases for (a) DSTATCOM and (b)hybrid filter-3

5. Average switching frequency of DSTATCOM is 14 kHz, where as average switching frequency of hybrid filter-3 is 8.5 kHz and hence switching losses in hybrid filter-3 is much less compared to DSTATCOM. This behavior is expected as reference for hybrid filter doesn't contain high frequency harmonics.

6. kVA of DSTATCOM 19 kVA and kVA rating of hybrid filter-3 is 13 kVA which implies hybrid filter can be used to compensate for larger loads with the same kVA when compared to DSTATCOM.

**Advantages and limitations**
**Advantages:**

1. Hybrid filter-3 has less kVA rating compared to DSTATCOM which means larger loads can be compensated using hybrid filter compared to DSTATCOM

2. Average switching frequency is less for hybrid filter-3 and hence lesser switching losses.

3. DC-link voltage used for hybrid filter-3 is less compared to DSTATCOM, this will reduce the switching losses further.

4. Hybrid filter-3 doesn't required additional high pass filter to suppress switching harmonics.

**Limitations:**

1. Maximum THD that the filter can compensate for any given kW load is lesser for hybrid filter-3 when compared to DSTATCOM due to slow response of passive filter.

2. Settling time for the hybrid filter-3 is more than 5 cycles.

3. Hybrid filter-3 is less effective for loads lesser than 30 kW in terms of kVA rating of the filter, because the filter compensates for passive filter reactive power, it requires larger loads that make filter currents less than DSTATCOM filter currents.

## 3.4 Summary

Various hybrid filters are discussed in this chapter that can improve performance or lower the cost of conventional active and passive filters. The hybrid filters discussed improves the performance of passive filters and have very low kVA rating and can compensate for large THD. The hybrid filter-3 is designed to decrease the cost of DSTATCOM and losses due to switching without affecting performance. These filter designs are much more effective when compared to standalone passive and active filters and economically more viable. Limitations of the hybrid filters are minor when compared to advantages.

# CHAPTER 4

# CONCLUSIONS

## 4.1 Summary

Hybrid filters provide alternative solutions to conventional active and passive filters. The standalone passive filters are inadequate due to low performance and standalone active filters have high VA rating and switching losses. The hybrid filters are found to offer advantages when compared to stand alone active and passive filters. Hybrid filter-1 shows improvement in performance when compared to passive filters. Hybrid filter-1 provides harmonic isolation from source to load for harmonic frequencies greater than $7^{th}$ harmonic and provides less distribution factor for load current harmonics to source current harmonics, but hybrid filter-1 is ineffective against loads that produce harmonics other than 6n$\pm$1. Hybrid filter-2 improves performance of passive filters and VA rating of hybrid filter-2 is smaller than VA rating of hybrid filter-1. Hybrid filter-2 can not provide harmonic isolation from source to load. Both hybrid filter-1 and hybrid filter-2 require very low VA rating and can compensate for harmonics in currents and voltages within IEEE 519 limits. Computational costs for reference generation is less for hybrid filter-1 and hybrid filter-2 if references are generated using instantaneous symmetric component theory.

Hybrid filter-3 requires less VA rating when compared to DSTATCOM and switching losses are also less. The performance of hybrid filter-3 is as good as DSTATCOM for larger loads. Both DSTATCOM and hybrid filter-3 can provide reactive power compensation at fundamental frequency to balance unbalanced loads.

| | Hybrid filter-1 | Hybrid filter-2 | Hybrid filter-3 |
|---|---|---|---|
| Unbalances | cannot balance | cannot balance | can balance |
| Voltage isolation | possible | not possible | not possible |
| voltage regulation | possible | not possible | not possible |
| VA rating | 4% of the load | 2% of the load | 20% of the load |

Table 4.1: Comparison of three hybrid filter topologies

## 4.2 Scope for Future Work

Both hybrid filter-1 and hybrid filter-2 suffer from design issues of transformer. The proposed hysteresis control solves the problem up to some extent. But the transformer design for PWM techniques should be studied to improve overall performance. Reactive power compensation using capacitor banks can be used along with these two hybrid filters for balancing unbalanced loads without resonances. Hybrid filter-1 can be improved to provide isolation for all the harmonics instead of harmonics greater than seven.

Harmonic compensation using hybrid filter-3 is slow when compared to DSTATCOM. Hybrid filter-1 and hybrid filter-3 can be integrated for faster performance at somewhat higher VA rating.

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