Instantaneous Power Theory for Active Filtering of High Displacement Power Factor Non-linear Loads

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ABSTRACT

Modern industrial plants make use of large numbers of variable frequency drives, in combination with induction motors, for a variety process implementation and process controls. However, a drawback of this technology is that drives are a source of harmonic currents.

A common means for removing harmonic currents is the use of single-tuned shunt passive filters. Nevertheless, when the harmonic producing loads are mainly drives, the use of this technology may not provide for an adequate solution.

This work designs and models (in the PSCAD/EMTDC transient simulator) a test electrical distribution system typically encountered in modern industrial operations, where the load is composed of a large percentage of voltage-source converter type drives. The harmonic currents produced by such a system are compared against harmonic standards to assess the requirements of harmonic mitigation. After these requirements are defined, attempts are made to provide mitigation by solely employing passive shunt harmonic filters. Following the benchmarking of the passive filters, a shunt active filter, whose control algorithm is based on the Instantaneous Power Theory is designed, modeled and connected to the test electrical system, without the presence of passive filters. The results obtained for the active filter are then compared against results obtained for shunt active filters.

It will be shown that a shunt active filter is more suited solution for mitigation of harmonics generated by loads dominated by variable-frequency drives than ordinary passive filter as they provide the required level of harmonic suppression without over-compensating the reactive power.

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To Daniela, Matias and Micaela

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Power Electronics and Harmonics

Improvements in power electronics that have taken place in the last decades have made variable frequency drives (VFD) less expensive and more reliable. These improvements include fast power semiconductor devices with higher ratings, novel converter topologies and improved control methodologies. As a consequence, modern industrial plants make use of large numbers of variable-frequency drives, in combination with induction motors, for a variety process implementation and process controls. The use of VFDs has well-recognized advantages, most notably reduction of induction motor inrush current and precise speed control. However, a drawback of this technology is that VFDs are a source of harmonic currents [1].

Harmonic currents can adversely interact with power systems components causing mal-function of their operation; harmonics are also associated with losses, which imply reduced efficiency. Therefore, there is an incentive for utilities and end users to limit the amount of harmonics that are injected into a system by nonlinear and harmonic-generating loads such as VDFs. Thus, electrical utilities have adopted mandatory standards to limit harmonic flows in power systems [2-4].

1.2 Harmonics Filtering

A common means for removing harmonic currents is the use of single-tuned shunt passive filters [5]. Such a device is composed of a capacitor and an inductor, connected in series and properly tuned to provide a low impedance path for unwanted harmonics, effectively disallowing them to propagate throughout the system.

Since passive filters include capacitors, they also provide reactive power compensation and improved power factor. However, when the harmonic producing loads are mainly VFDs, the use of passive harmonic filters may not provide for an adequate solution [6, 7].

Voltage source converter type VFDs, which are the most common design for low voltage applications, have an inherently high displacement power factor and at the same time, high-distortion current waveforms [8, 9]. As a result, in order to provide adequate harmonic compensation (i.e. harmonic levels that will fall within industry standards), a passive harmonic filter will likely be oversized in terms of reactive power requirements, rendering the system "overcompensated", resulting in capacitive power factors. This is a condition that should be avoided, as it can create over-voltages that can damage power system components.

Passive harmonic filters can also interact with the power system, creating unwanted resonances, worsening an existing power quality problem by amplifying harmonic currents that the filter intended to eliminate in the first place [1]. Passive filters are also prone to overloading from remote harmonic sources [1]. These aspects of passive filter application will be discussed in later chapters.

1.3 Other Technologies for Harmonic Control

Passive filters are not the only available solution for harmonic removal; many other devices are available to provide harmonic control. This is particularly true when a new system is being designed, as more flexibility in selecting a proper solution can be expected at this stage. For example, if large VFDs are to be installed, they could be specified to include 12-pulse front end rectifiers. Distribution transformers could be used to artificially create 12-pulse front end rectifiers by properly selecting phase shifts [10]. The use of "broadband" filters may also be a good choice for application to single drives [11].

On an existing system, however, much less flexibility is normally available. Redesigning and rebuilding an existing electrical distribution system to comply with harmonic standards will be prohibitively expensive and impractical. As a consequence, a technology that can remove unwanted harmonics while not "overcompensating" power factor should be devised. This technology should be easy to install, require few or no changes to an existing system and be economically feasible.

1.4 Shunt Active Harmonic Filters

A shunt active filter is a power electronics based device that is connected in parallel to a harmonic producing load. The filter has the capability of injecting currents that are equal in magnitude and opposite in phase to the harmonic currents generated by the polluting load, thereby canceling the harmonics and preventing their flow into the power system. [12, 13, 14]

Due to their characteristics, active filters do not resonate with the power system as passive filters may do. They are also immune to overloading from remote harmonic sources. Much of the following chapters will be devoted to active filters; their theory of operation, installation, advantages, disadvantages and available commercial units.

1.5 Motivation

Industrial operations where VSC type VFDs represent a large percentage of the total installed load are commonplace. Since these facilities are required to limit the harmonic currents they inject into the power system to strict standards, some type of harmonic mitigation technology is often required. However, traditional harmonic mitigation techniques may not be suitable.

The author of this work has recently been involved in the design of a large industrial plant, where VFD-based loads accounted for more than 75% of the total installed load. Although it was possible to provide harmonic compensation with a combination of traditional methods (e.g. reactors and passive and broadband filters), it was evident at the time that, had the drive load been over 75%, it would have been challenging, both technically and economically, to provide harmonic compensation by solely employing these devices. Due to technical and economical constraints, the use of 12-pulse drives (or the combination of delta-delta and delta-wye transformers and 6-pulse drives) was not an option.

This experience suggests that the use of active filters could provide a feasible technical (and perhaps economical) solution when large VFD loads are installed.

1.6 Problem Definition

The goal of this work is to compare the performance of low voltage, single tuned, shunt passive filters readily available on the market and shunt active filters, when connected to electrical systems where the load is composed of a large percentage of VSC type of VFDs (approximately 90% of the total installed load). Such a system, typically encountered in modern industrial operations, has an inherently high displacement power factor and high harmonic distortion levels.

The harmonic currents produced for such a system will be compared against industry recognized harmonic standards to assess the requirements of harmonic mitigation. After these requirements have been defined, attempts will be made to provide mitigation by solely employing passive shunt harmonic filters.

Following the benchmarking of the passive filters, a shunt active filter, whose control algorithm will be based on the Instantaneous Power Theory [15, 16, 17], will be designed, modeled and connected to the test electrical system, without the presence of passive filters. The results obtained for the active filter will then be compared against results obtained for shunt active filters.

The modeling of the test electrical system and the passive and active filters will be carried out in the PSCAD/EMTDC electromagnetic transient simulation software [18]. This software is especially well suited when power electronics modeling is required. As well, it gives users the ability to build custom simulation modules that can be interfaced with the existing library models. This feature will be of particular importance when implementing the active filter control algorithm.

1.7 Outline of Thesis

Chapter 2 of the thesis provides a general background on harmonic indices, harmonic sources and the effect of harmonic currents on power systems. Recognized industry standards for harmonic control and available harmonic mitigation technologies will also be discussed.

Chapter 3 discusses shunt passive filters; presents their components and a methodology to size filters based on applicable IEEE standards. This chapter emphasizes the interactions between shunt passive filters and the power system.

Chapter 4 is devoted in its entirety to shunt active filters. It discusses filter components and presents the Instantaneous Power Theory, which is instrumental to develop filter control algorithms.

Chapter 5 details the development and validation of an active filter controller based on the previously presented Instantaneous Power Theory. A control algorithm will be modeled in PSCAD/EMTDC and cross checked against a mathematical model of the filter control algorithm, developed in Wolfram Mathematica [19].

Chapter 6 discusses the performance of the passive and active filters when connected to a test electrical system, which includes VSC-type VFDs aimed at representing modern industrial operations.

Chapter 7 concludes this thesis by presenting contributions of this work and recommendations for future work.

CHAPTER 2: HARMONICS IN POWER SYSTEMS – MEASURES AND IMPACTS

2.1 Harmonic Indices

The previous chapter briefly described, qualitatively, power quality problems directly related to the considerable use of power electronics-based devices in power systems. A more formal, quantitative discussion on power systems harmonics requires the introduction of harmonic indices that are commonly employed to characterize harmonics. The following sub-sections contain a description of a number of widely-used harmonic indices.

2.1.1 Total Voltage Harmonic Distortion

The total voltage harmonic distortion (THD_v) is defined as the root mean square of the summation of harmonic voltages expressed as a percentage of the nominal system voltage [20] as follows.

$$THD_v = \frac{\sqrt{\sum_{h=2}^{n} {V_h}^2}}{V_{nom}} \times 100\% \tag{2.1}$$

The THD_v is sometimes expressed as a percentage of the fundamental voltage component [21]. However, the advantage of normalizing to the nominal system voltage is that it allows the evaluation of the voltage distortion with respect to a fixed value (nominal system voltage) rather than the fundamental voltage component that can vary [22].

2.1.2 Total Demand Distortion (TDD)

The total demand distortion is defined as the root mean square of the harmonic currents expressed as a percentage of the average maximum demand load current, as follows.

$$TDD = \frac{\sqrt{\sum_{h=2}^{n} I_h^{\ 2}}}{I_L} \times 100\% \tag{2.2}$$

The reason for expressing this quantity as a percentage of a fixed value is that load levels tend to fluctuate. If the fundamental current were used instead, a fixed harmonic load would result in different distortion levels at different times. By normalizing to a fixed value, the *TDD* will only change as the harmonic load changes.

The term "total current harmonic distortion" (or *THD*), will still be used in this work to compare the performance of different non-linear loads. The term "distortion level" will also be used. For this particular analysis, the THD is defined as follows.

$$THD = \frac{\sqrt{\sum_{h=2}^{n} I_h^{\ 2}}}{I_1} \times 100\% \tag{2.3}$$

where I_1 represents the fundamental nominal current of the non-linear load under analysis. When harmonics are present in a system the rms value of the total current increases, according to:

$$I_{RMS} = \sqrt{I_1^{\ 2} + I_2^{\ 2} + ... + I_n^{\ 2}} \tag{2.4}$$

Combining this equation and equation 2.3 yields the following expression:

$$I_{RMS} = I_1 \sqrt{1 + THD^2} \tag{2.5}$$

This equation shows that the higher the distortion, the higher the total rms current. Since power losses are proportional to the square of the rms current, the presence of harmonics will increase the total system losses.

2.2 Harmonics and Power Factor

The power factor (PF) is defined as the active power *P* divided by the apparent power *S*. For the general case, where voltage and current harmonics may be present, the power factor will be expressed as follows:

$$PF = \frac{P}{S} \tag{2.6}$$

In the particular case where only the fundamental-frequency components are present, the following formula will be valid:

$$PF = \frac{P}{S} = \frac{V_1 I_1 \times \cos(\varphi_1)}{V_1 I_1} = \cos(\varphi_1) \tag{2.7}$$

where V_1 and I_1 are the rms values of the fundamental voltage and fundamental current respectively and φ is the phase angle between the voltage and current phasors. To differentiate the term power factor under non-sinusoidal and sinusoidal conditions, it is customary to refer the former as "true power factor" whereas the latter is referred as "displacement power factor"[10].

It this the displacement power factor the one that can be modified (i.e. improved) by the use of capacitors, as most often harmonic voltages will be very low, even if high harmonic currents are present. Since power factor correction capacitors are a source of reactive power, the net reactive power supplied by the power system decreases, decreasing the value of the apparent power S, which increases the displacement power factor.

This work will refer to the displacement power factor (or "cosφ") whenever a mention to power factor is made.

2.3 Harmonic Current Generation

Commonly encountered loads that are source of harmonic currents include computer power supplies, electronic ballasts for fluorescent lighting, transformer magnetizing currents, and particularly in industrial facilities, variable frequency drives. As mentioned in Chapter 1, this type of load can make up for a large percentage of the total installed load of an industrial plant. As a consequence, particular attention will be given to the mechanism of VFD harmonic generation.

2.3.1 Variable Frequency Drives

Modern low voltage VFDs are composed of four basic building blocks, namely a front end uncontrolled rectifier, a dc link, a power converter and a controller (Figure 2.1). Because of the presence of a dc link feeding the power converter, this type of drive design is known as voltage source converter (VSC), which is the standard drive design for low voltage applications (i.e. 600V in Canada and 480V in USA).

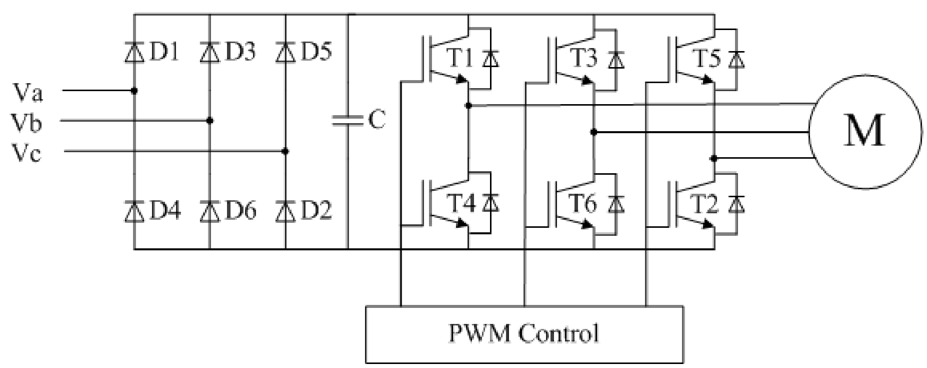


Figure 2.1 –VSC-type VFD

The front end three-phase uncontrolled rectifier feeds the dc link, composed of capacitors, creating a relatively robust voltage source for the power converter. By means of pulse-width modulation (PWM) techniques, the power converter synthesizes an ac three phase voltage whose magnitude and frequency can be continuously varied.

If no intentional inductance is connected between the power supply and the front end rectifier, the capacitors are charged rapidly, producing a distinctive high distortion current wave shape.

Since the drive is a three-phase, three-wire device, triple-*n* harmonics (assuming a balanced system) are not present [23]. As a consequence, the harmonic orders of a drive current can be represented by 6k±1, where k is an integer. Figure 2.2 shows a typical example of the source-side ac current of a VSC-type VFD, where the total harmonic distortion (*THD*), as defined by (2.3), is 50%. Such a high distortion figure is unacceptable and measures to lower it must be adopted.

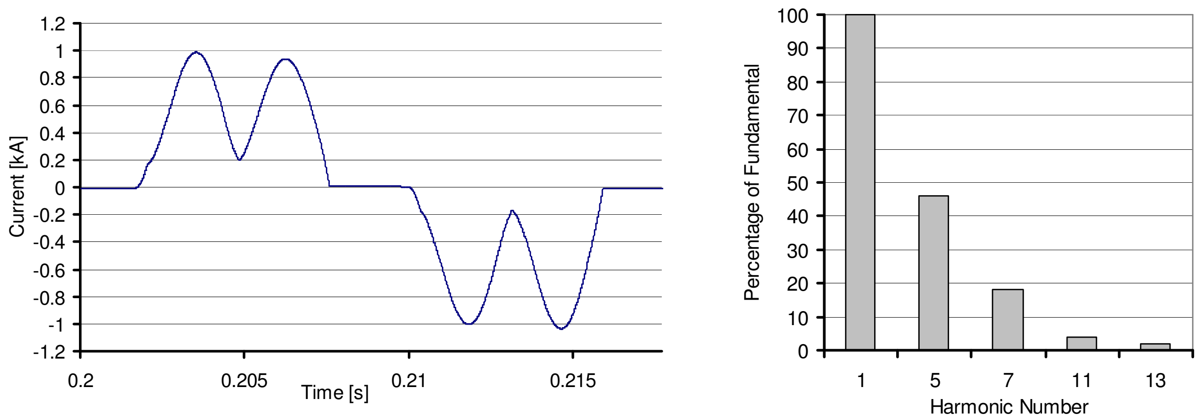


Figure 2.2 – Current from a typical VSC-type VFD

2.4 Effects of Harmonics on Power Systems

Harmonic currents can interact with electrical components in ways that can degrade the performance of a power system. The following sections describe harmonic behavior of common power systems components.

2.4.1 Effects on the System Voltage

When a purely sinusoidal voltage source is connected to a nonlinear load (Figure 2.3), the resulting current will not be sinusoidal; it will contain harmonics whose spectrum will be a function of the characteristics of the nonlinear load. This non-sinusoidal current will interact with the system impedance, producing harmonic voltage drops. As a result, the system voltage will also contain harmonics (i.e. the voltage will be distorted).

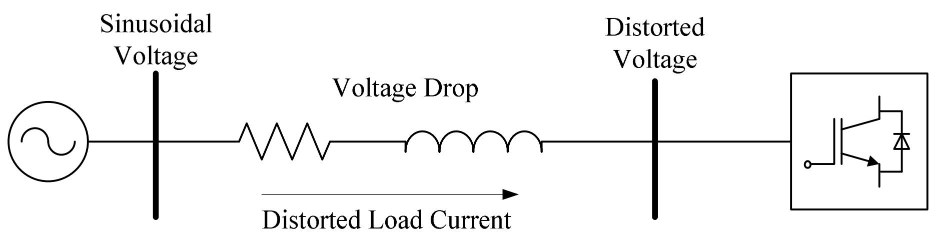


Figure 2.3 – Non-linear load connected to a power system [1]

Figure 2.4 shows the voltage at the source terminals and at the non-linear load terminals of a three-phase controlled rectifier. The harmonic current interacts with the system impedance producing harmonic voltage drops. As a consequence, the voltage at the load terminals has been distorted.

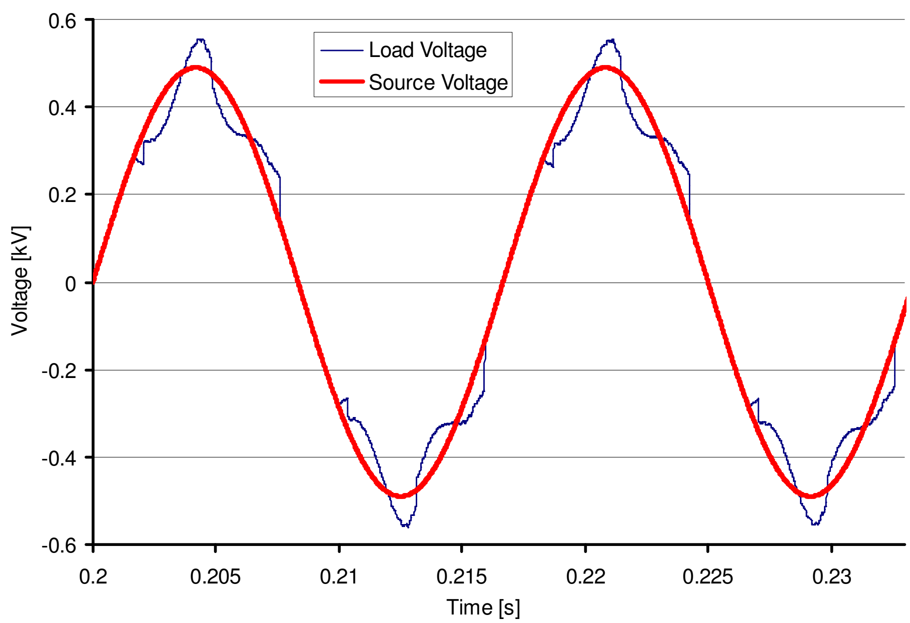


Figure 2.4 – System voltage at the source terminals and at the load terminals

A voltage source that contains harmonics, when applied to linear loads, will produce harmonic currents, further degrading the power system.

2.4.2 Effects on Transformers

Power and distribution transformers are designed for current distortion levels of 5% or lower [24]. When higher distortion levels are expected, the transformer has to be de-rated of the designed ratings to account for higher harmonic levels. [25]

Equation (2.5) shows that the total rms current increases when harmonics are present. As a consequence, for a given system load, the total current through a transformer will increase when distortion levels increase, increasing transformer heating. Core losses will also increase when harmonic currents are present.

2.4.3 Effects on Capacitors

Capacitors are employed by utilities and end users to improve power factor and provide voltage support. Harmonic currents can adversely interact with capacitors creating unwanted series and parallel resonances. Capacitor C_1 and the transformer reactance X_T shown in Figure 2.5 are, as viewed from the harmonic source, in parallel. Therefore, there will be a frequency at which this circuit resonates. If this resonance frequency is close to a frequency produced by a harmonic source, voltages and currents of that frequency may be amplified, potentially causing damage to equipment.

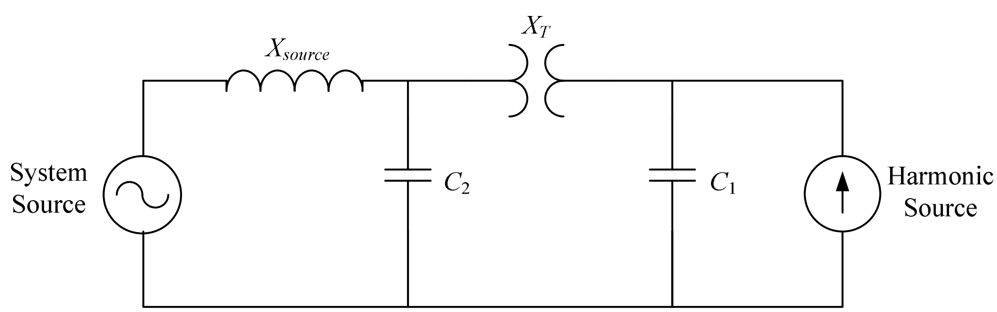


Figure 2.5 – System with potential for parallel and series resonances [1].

There are some instances in which a shunt capacitor and the system impedance can be seen by the harmonic source and a combination of series elements. In Figure 2.5, capacitor C_2 and the transformer reactance X_T appear as a series combination to the harmonic source. If a frequency is present which causes these two components to series resonate, the capacitor C_2 will attract the harmonic current at that frequency, likely overloading and damaging capacitor C_2. Figure 2.6 shows a frequency response of a system similar to that depicted in Figure 2.5, where the impedance Z is that seen by the harmonic source. This figure presents the parallel as well as the series resonance points.

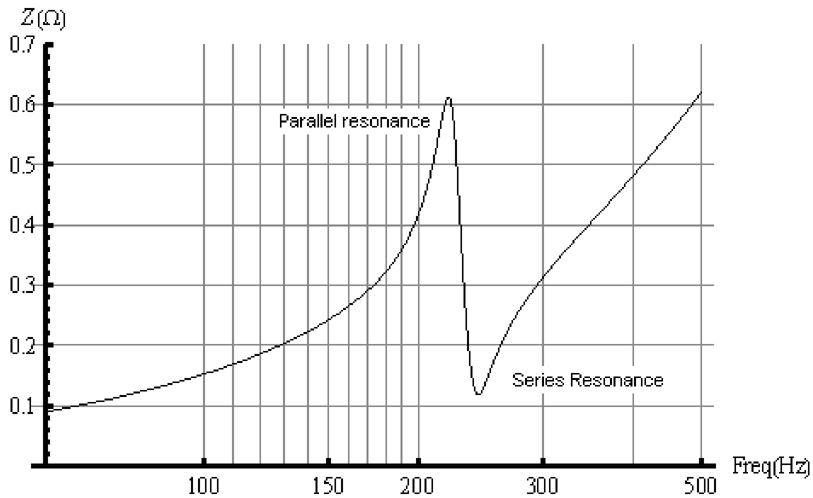


Figure 2.6 – Frequency response of a system with series and parallel resonances.

2.5 Harmonic Limits

Harmonics degrade the power system performance and create conditions for equipment damage. As a consequence, there is an incentive for utilities and end users to limit harmonics. IEEE Standard 519 proposes to limit the amount of harmonics an end user can inject into the power system so the resulting voltage distortion falls within specified limits. These limits, reproduced in Tables 2.1 and 2.2 below, have been adopted by many electrical utilities.

Since there is little control an end user can exercise over the utility supply voltage, the responsibility for harmonic control on the voltage falls in the utility, whereas the responsibility for harmonic control on injected currents falls on the end user.

These harmonic limits are applied at a point between the end user and the utility where another customer can be served. This point is known ad point of common coupling (PCC).

Table 2.1: Harmonic Voltage Distortion Limits [20]

Bus Voltage at PCC (V_n)	Individual Harmonic Voltage Distortion [%]	Total Voltage Distortion THDv [%]
$V_n \leq 69$kV	3.0	5.0
69kV < $V_n \leq 161$kV	1.5	2.5
$V_n > 161$kV	1.0	1.5

Table 2.2: Harmonic Current Distortion Limits [20]

$V_n \leq 69$kV						
I_{sc}/I_L	$h<11$	$11\leq h<17$	$17\leq h<23$	$23\leq h<35$	$35\leq h$	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	7.0	6.0	2.5	1.4	20.0
69kV<$Vn\leq$161kV						
<20	2.0	1.0	0.75	0.3	0.15	2.5
20-50	3.5	1.75	1.25	0.5	0.25	4.0
50-100	5.0	2.25	2.0	0.75	0.35	6.0
100-1000	6.0	2.75	2.5	1.0	0.5	7.0
>1000	7.5	3.5	3.0	1.25	0.7	10.0
Vn>161kV						
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.50	1.15	0.45	0.22	3.75

In Table 2, I_{sc} is the short circuit current at the point of common coupling and I_L is the maximum demand load current of the end user (fundamental component) at the PCC.

The system short circuit current I_{sc} is a measure of system strength; a low I_{sc}/I_L ratio means that the demand load current will have a high impact on the utility system voltage in terms of distortion. Therefore, when this ratio decreases, the TDD limit also decreases.

2.6 Harmonic Mitigation

This chapter has so far discussed harmonic indices, harmonic sources, effects of harmonics on power systems and standards for harmonic limitation. The next step is to introduce techniques for harmonics mitigation.

Based on the premise that it is not possible to modify the internal characteristics of a non-linear load to reduce the amount of harmonics injected into a system, harmonics mitigation techniques can be based on the following principles:

- Phase shifting of harmonic currents
- Modifying the system impedance
- Providing filtering devices.

Phase shifting methodologies are effective when dealing with large non-linear loads, such as medium voltage drives, where the diode front end is commonly designed as a twelve-pulse unit. This methodology is also effective when an equal number of smaller six-pulse units are expected to run at the same time.

Based on the fact that for a balanced system, harmonic currents have distinctive phase sequences (i.e. positive, negative or zero sequence), a twelve-pulse rectifier fed from two three-phase transformers whose connections are delta-delta and delta-wye, will only inject $12k\pm1$ harmonics, where k is an integer. Figure 2.7 shows a typical transformer connection for a twelve-pulse rectifier. This arrangement will by itself, in many cases, comply with harmonic limits presented in Table 2.1.

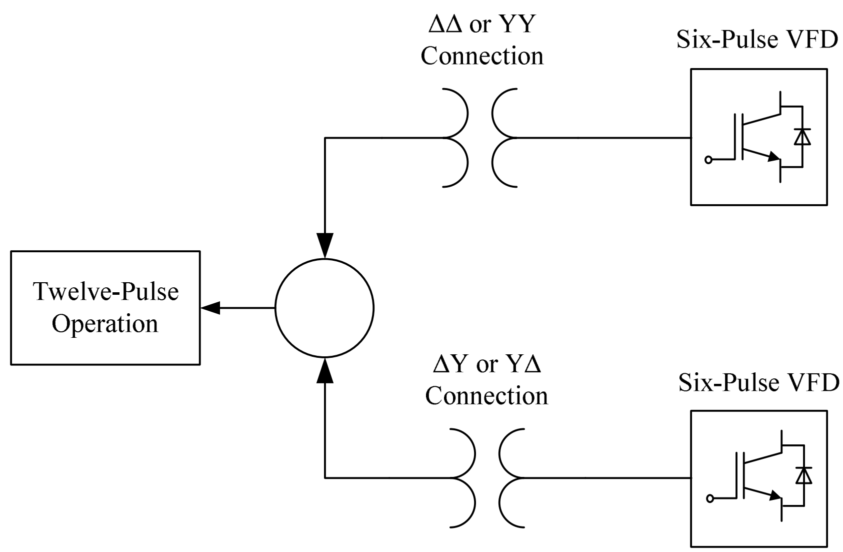
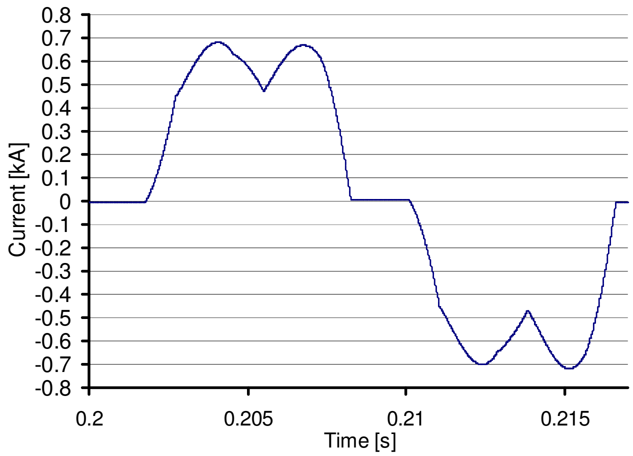


Figure 2.7 – Use of transformers for harmonic mitigation [15]

When several six-pulse units are expected to run at the same time, this arrangement can also recreate the behavior of a twelve-pulse rectifier if an equal number of loads are connected to each transformer. In this context, equal number refers to equal power and not to actual quantity of units.

Modifying the system impedance can be impractical in many instances. However, in the case of VSC-type VFDs, a common practice to reduce the harmonics is to add a 3% to 5% reactance (bases are nominal drive voltage and nominal drive power), between the power supply and the drive input. This line reactance has the effect of reducing the rate at which the DC link capacitors are charged, thereby decreasing the harmonic content of the drive current.

The addition of input reactors can result in reductions of the distortion level of up to 50%. Figure 2.8 shows the current of a VSC-type drive with a 3% reactor; the *THD* has been reduced from 50% (Figure 2.2) to 27%. This practice will usually not be enough to comply with harmonic limits presented in Table 2, however. Other strategies will also be required.



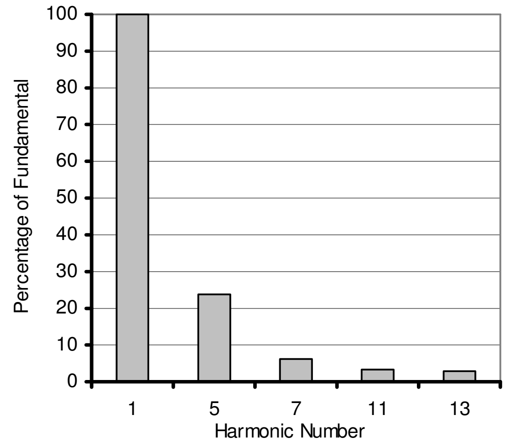


Figure 2.8 –VSC-type VFD Current With 3% Input Reactor

The use of filtering devices finds widespread use in utilities as well as in industrial plants. Since one of the goals of this work is to compare the performance of passive filter devices against active filter devices, an in-depth discussion of these distinctive types of filters is warranted. The following chapters are devoted to shunt passive filters and shunt active filters.

CHAPTER 3: SHUNT PASSIVE FILTERS

3.1 General

Shunt passive filters find widespread use in utility as well as industrial systems. In its basic design, it is composed of a combination of a capacitor in series with an inductor appropriately tuned to present a low impedance path to a specific harmonic, effectively removing them from the system. This type of arrangement, shown in Figure 3.1, is also known as “single-tuned passive filter”.

Since the filter includes capacitor elements, this device also provides reactive power compensation. Indeed, in many cases, the use of single tuned filters is driven by the need for providing reactive power control, but the use of capacitors alone would adversely interact with the power system.

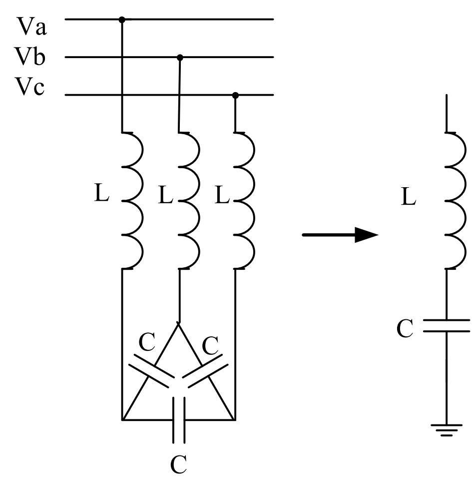


Figure 3.1 – Single tuned passive filter – Tree-phase and single-phase representations [1]

More complex designs of passive filters are composed of a combination of single tuned filters connected in parallel, each of which tuned to a different harmonic frequency. Such an arrangement is not as widely used as the single tuned filter previously discussed.

For systems where the harmonic level and power factor are expected to vary, single tuned filters can be designed to include multiple switchable steps, controlled by microprocessor power factor relays. However, fast, dynamic harmonic and power factor control cannot be easily realized with such a device, due to the discrete nature of each step and the need for allowing a switched-off capacitor to discharge before it can be switched on again. Switching delays can be eliminated by employing synchronous closing techniques [26, 27]. Although for typical industrial applications, this would not be economically viable.

3.2 Filter Interaction with the Power System

Although single-tuned passive filters are, in general, an effective solution to eliminate harmonics, they can adversely interact with a power system, creating unwanted resonances. Passive filters are also prone to overloading from remote harmonic sources.

Figure 3.2 shows the equivalent circuit of a simplified power system that includes a harmonic generating load, a shunt passive filter (L_f,C_f) tuned to a harmonic number that is to be removed, and the short circuit impedance (X_{sc},R_{sc})of the utility. An important characteristic of this circuit is that it also has a parallel resonance frequency, defined by the filter impedance and the utility short circuit impedance. This parallel resonance frequency will be lower than the series resonance frequency. Figure 2.6 in chapter 2 shows a typical frequency spectrum for a power system similar to the one shown in Figure 3.2

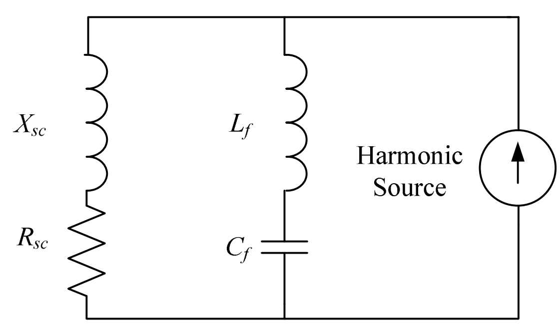


Figure 3.2 – Equivalent of a simplified power system

If there is a harmonic current component I_k whose frequency corresponds (or is close) to the parallel resonance frequency, this current can be amplified by a factor Q (i.e. Q x I_k), where Q, commonly known as the “quality factor”, is defined as:

$$Q = \frac{X_C}{R} = \frac{X_L}{R} \tag{3.1}$$

In this formula, X_C is the capacitive reactance at the resonant frequency, X_L is the equivalent inductive reactance (combination of power system and filter) at the resonant frequency and R is the equivalent resistance of the power system and filter inductor. Since the equivalent resistance will typically be much lower than the equivalent reactance, even a relatively small harmonic current can be greatly amplified, overloading components and producing large harmonic voltage drops.

To prevent a filter parallel resonance from adversely interacting with the system, filters are tuned to a harmonic number slightly lower than the harmonic number to be eliminated [28]. For example, a filter designed to eliminate the 5th harmonic (300Hz) will be tuned to the frequency that corresponds to 4.3 times the fundamental (258Hz) or to the frequency that corresponds to 4.7 times the fundamental (282Hz). This practice would place the parallel resonance frequency away of the 5th harmonic in case filter parameters change due to component ageing. Other means such as use of filters with lower quality factors (which gives the frequency response a more flat shape) is also possible.

Shunt passive filters are also prone to overloading as a result of absorbing harmonic currents from remote sources. This is a direct consequence of the power system and filter behaving as a current divider. A percentage of harmonic currents generated by a remote source may be absorbed by the filter if the impedance between the remote harmonic source and the filter is in the same order of magnitude as the impedance between the remote harmonic source and the power system short circuit impedance. There may be instances where a facility with multiple harmonic filters may be required to shut down many or all filters to prevent overloading, as a consequence of one unit being out of service.

3.3 Filter Sizing Methodologies

Since harmonic filters also provide reactive power compensation, the capacitive reactive power requirements and voltage control requirements are the basis for sizing a filter. The particular characteristics of the facility in which the filter will be installed (i.e. linear and non-linear load variations), will dictate the harmonic order to be compensated as well as the number and size of fixed and switchable steps. An appropriate filter design methodology should address the following requirements:

- Keep TDD at or below IEEE Std. 519 (or other applicable standard) limits
- Keep individual harmonics at or below IEEE Std.519 (or other applicable standard) limits
- Limit overvoltages caused by shunt capacitors (avoid capacitive power factors)
- Filter steps should be sized to keep voltage fluctuations under 3% when elements are switched on and off as recommended by IEEE Std. 1036 [29]
- Prevent filter capacitors from being overloaded by harmonics (IEEE Std. 18) [30]
- Limit current harmonics through transformers to 5% to avoid de-rating (Limits set by IEEE C57.12.00)

In this work, filter sizing and rating verification will be based on IEEE Standard 1531, which provides a methodology to size filters and verify ratings. The following paragraphs describe this methodology, while Chapter 5 provides numerical examples that are part of the test electrical distribution system.

The first step to size a shunt passive filter consists of determining the required capacitive reactive power to bring the power factor to a target value. As an example, a facility may have a displacement power factor of 0.86 and a target displacement power factor of 0.98. Knowing the active power of this plant, it is possible to determine the required capacitive reactive power as:

$$Q = P[\tan^{-1}(\varphi_0) - \tan^{-1}(\varphi_f)] \tag{3.2}$$

where Q is the required capacitive reactive power in kVAr, P is the active power in kW, φ_0 is the initial displacement angle between the fundamental components of the voltage and current and φ_f is the target displacement angle between the fundamental components of the voltage and current.

In general, the resulting reactive power will not correspond to a standard capacitor size. As a result, the designer will have to select the closest available unit.

Once the required reactive power is known, it is possible to determine the capacitor's reactance and the inductor's reactance, based on the filter tuning. As it was previously discussed, filters are not tuned to the exact harmonic to be eliminated, but rather to a lower value. In this work, the filter will be tuned to the 4.7 harmonic (282 Hz), for elimination of the 5th harmonic. The capacitor's reactance is:

$$X_C = \frac{V^2}{Q} \tag{3.3}$$

where X_C is the capacitive reactance in Ohms at the fundamental frequency, V is the line voltage and Q is the reactive power. The inductor's reactance is given by:

$$X_L = \frac{X_C}{h^2} \tag{3.4}$$

where X_L is the inductive reactance in Ohms at the fundamental frequency, X_C is the capacitive reactance and h is the harmonic number to which the filter is tuned. The effective reactance of the filter at the fundamental frequency is given by:

$$X_{EFF} = X_L - X_C \tag{3.5}$$

The fundamental current of this filter is:

$$I = \frac{V/\sqrt{3}}{X_{EFF}} \tag{3.6}$$

It should be recognized that because the effective reactance of the filter is lower than the reactance of the capacitor alone, the effective reactive power of the filter will be larger than that of the capacitor. This effective reactive power can be calculated as:

$$Q_{EFF} = \sqrt{3} \times V \times I \tag{3.7}$$

The reactive power value obtained above corresponds to a filter composed of an “equivalent” single capacitor and inductor. However, as previously mentioned, the application may require that the filter be composed of multiple switchable steps. A proper assessment will generally require computer simulations to analyze the effects of linear and non-linear load variations on the power system and filter performance.

In the final design step, the ratings of filter components should be verified against expected operating conditions to prevent overloading. In this respect, IEEE Std. 18 states that capacitors are to be capable of continuous operation under contingency system and bank conditions provided that none of the following limitations are exceeded:

- 110% of rated rms voltage
- 120% of rated peak voltage, including harmonics
- 135% of nominal rms current based on rated power and rated voltage
- 135% of rated reactive power

The rms voltage across the filter capacitor can be determined as:

$$V_{CAP-RMS} = \sqrt{\sum_{k=1}^{n} (I_k \times \frac{1}{k\omega C})^2} \qquad (3.8)$$

where k is the k-th harmonic, $1/\omega C$ is the capacitive reactance at the fundamental frequency and I_k is the harmonic current through the capacitor. In the general case, the harmonic current I_k can have two components; the harmonic current whose source is the non-linear load and the harmonic current whose source is the utility system (i.e. other end users).

The expected value of the harmonic current whose source is the non-linear load can be determined based on the known behavior of the harmonic source (VFD, power supply, etc) and, once the filter size has been defined, it can be validated with computer simulations.

Since the filter is in parallel with the power system, the harmonic current from the non-linear load that will flow into the filter will be dependent on the filter and power system impedances. This current can be calculated as a current divider (Figure 3.3):

$$I_k = I_{k-source} \times \frac{Z_{system}}{Z_{equivalent}} \tag{3.9}$$

where I_k is the harmonic current that will flow to the filter, $I_{k\text{-}source}$ is the total harmonic current, Z_{system} is the system Thevenin impedance and $Z_{equivalent}$ is the parallel combination of the filter and system impedances.

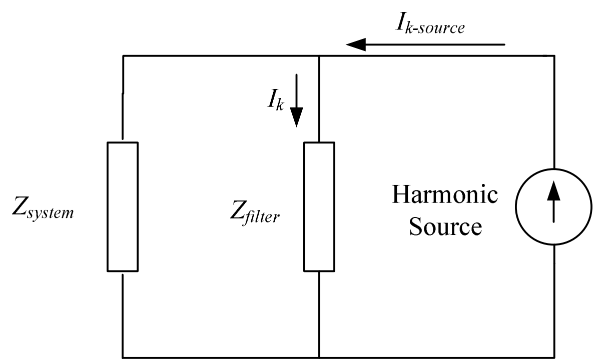


Figure 3.3 – Current divider

The peak voltage can be conservatively estimated by assuming that the peaks of all harmonic voltages are in phase, then:

$$V_{CAP-PEAK} = \sqrt{2}\left(\sum_{k=1}^{n} I_k \times \frac{1}{k\omega C}\right) \tag{3.10}$$

The total rms current that will flow to the filter should also consider any harmonic current contribution from the utility. In this respect, IEEE Standard 519 [20] states that the harmonic voltage distortion for voltages at and below 69kV should be limited to 3% for individual harmonics. Therefore, it is expected that a typical utility distribution system will have a voltage distortion level within this limits. As it was discussed in section 2.3.1, a voltage source that contains harmonics, when applied to a linear load, such as a harmonic filter, will produce harmonic currents.

The presence of non-linear loads (i.e. harmonic sources) upstream of the point of common coupling should also be cause of concern, since a percentage of this current may be absorbed by the harmonic filter.

A detailed analysis of the effect of harmonic current flow from the utility to a filter will require the use of computer models. However, its effects can also be approximated by assuming that a percentage of the nominal capacitor current will flow from the utility system to the capacitor in the form of harmonic currents, for example the 5^{th}. This current will then be added to the harmonic current whose source is the non-linear load being compensated, as shown in formula (3.11).

$$I_{CAP-RMS} = \sqrt{\sum_{k=1}^{n}(I_{k\,utility})^2 + \sum_{k=1}^{n}(I_{k\,source})^2} \tag{3.11}$$

where $I_{kutility}$ is the harmonic current whose source is the utility and $I_{ksource}$ is the harmonic current whose source is the non-linear load. This approach assumes that the *k-th* harmonic from the utility and from the non-linear load being compensated have the same phase shift. This assumption will render conservative results. The total reactive power of the capacitor will then be defined by:

$$Q_{CAP} = 3\sum_{k=1}^{n}(I_k \times V_k) \tag{3.12}$$

where I_k and V_k are the capacitor phase current and phase voltage respectively. If the ratings provided by IEEE Std. 18 are exceeded, consideration should be given to applying capacitors with higher voltage rating and / or increasing the kVAr rating of the filter.

CHAPTER 4: SHUNT ACTIVE FILTERS

4.1 General

A shunt active filter is a power-electronics based device that is connected in parallel to a harmonic producing load [31]. The filter has the capability of injecting currents that are equal in magnitude and opposite in phase to the harmonic currents generated by the polluting load, thereby eliminating the harmonic currents from the power system. Thus, it can be considered to be a controlled current source that injects currents into the power system to cancel out unwanted harmonic currents.

Figure 4.1 shows a simple power system where a non-linear load is connected. The shunt active filter, which is connected in parallel and close to the load, is equipped with a control system that allows it to eliminate the harmonic currents produced by the non-linear load. As a consequence, only the fundamental current component would be present upstream of the active filter.

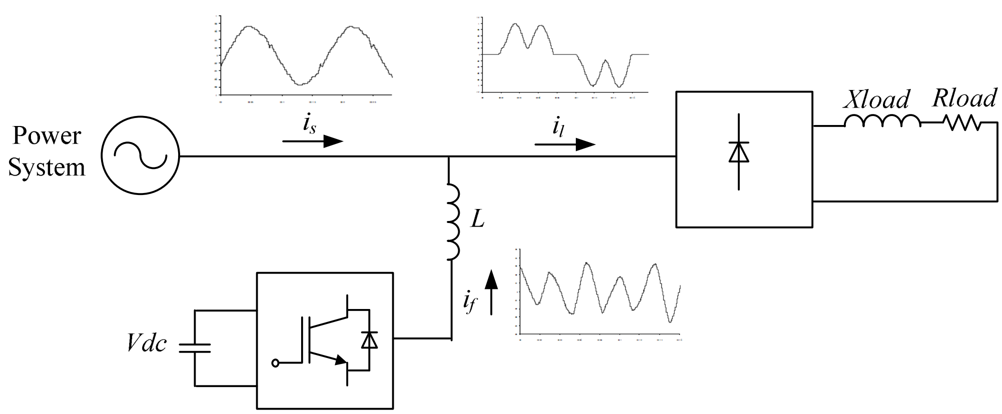


Figure 4.1: Shunt current compensation [15]

An important characteristic of an active filter is that its control system takes as inputs voltages and line currents of the harmonic producing load to be compensated. Therefore, the filter is immune to overloading from other harmonic sources. This is an advantage over passive filters, which may be subjected to overloads from remote harmonic sources. This important feature of active filters will be further discussed in later chapters.

4.2 Active Filter Components

Active filters include the following main components:

- Active filter controller
- Power converter
- PWM current controller
- DC link
- Commutation inductor

The active filter controller senses voltages and currents from the power system and processes these signals to calculate, in real time, a set of current references as inputs to the PWM current controller. This controller forces the power converter to behave as a controlled current source by appropriately switching on and off its controlled switches, e.g. Insulated Gate Bipolar Transistors (IGBT), which are the building block of the power converter. Figure 4.2 shows a block diagram of a typical shunt active filter [15]

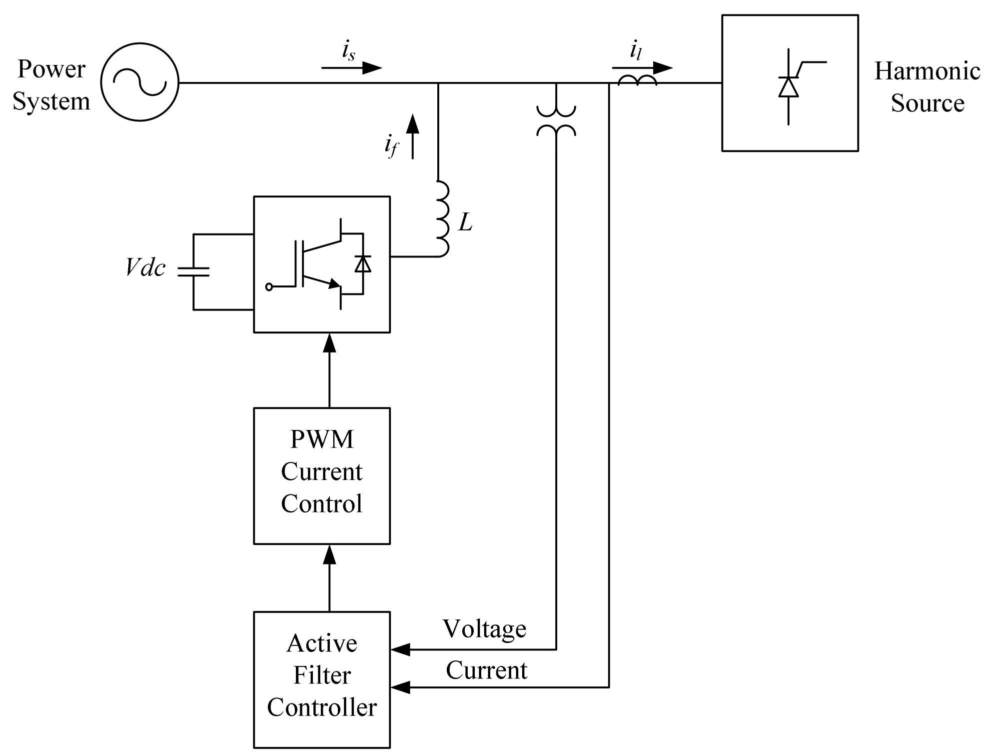


Figure 4.2: Block diagram of a shunt active filter

Two types of power converters can be applied to active filters: a voltage source converter (VSC) equipped with a dc capacitor for energy storage (Figure 4.3) or a current source converter (CSC) equipped with a dc inductor for energy storage (Figure 4.4). [31].

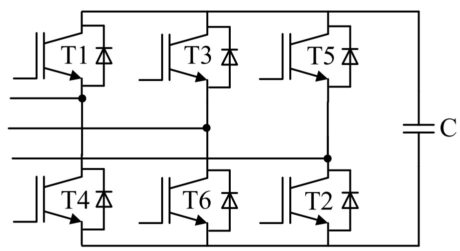


Figure 4.3: Voltage source converter based shunt active filter

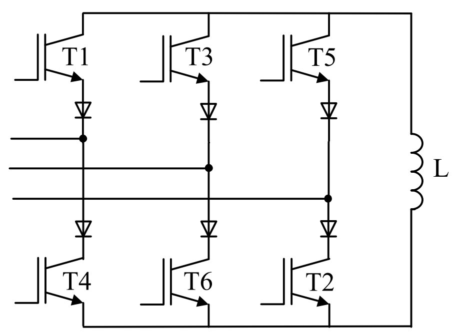


Figure 4.4: Current source converter based shunt active filter

The VSC design has several advantages over the CSC design [31, 32], the most notable of which are that the VSC is higher in efficiency, lower in cost, and smaller in physical size than the CSC. Insulated gate bipolar transistors are equipped with a free-wheeling diode in anti-parallel connection, which makes this device more suitable for a VSC converter rather than a CSC one. These advantages have resulted that practical applications (i.e. commercial units) are of the VSC type. This is also the justification for using a VSC shunt active filter in this study.

The PWM current control can be implemented as a hysteresis-band current controller, where the output current of the filter continually tracks the current command within a hysteresis band [33, 34]. The control circuit generates a current command of specified magnitude and frequency that is compared against the filter output current (Figure 4.5).

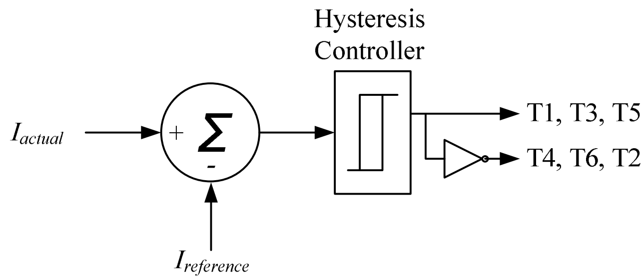


Figure 4.5: Control block of a hysteresis band current controller [33]

When the filter current is higher than the upper hysteresis band, the controller switches off the upper switches of the power converter and switches on the lower ones. As a result the filter current is reduced. When the filter current crosses the lower hysteresis band the upper switches are turned on and the lower ones are turned off.

Figure 4.6 shows the hysteresis bands, the output current and the PWM voltage of a shunt active filter modeled in PSCAD/EMTDC, which will be described in more details in a later chapter devoted to active filter modeling. When the voltage is positive the currents increases, while it decreases when the voltage is negative.

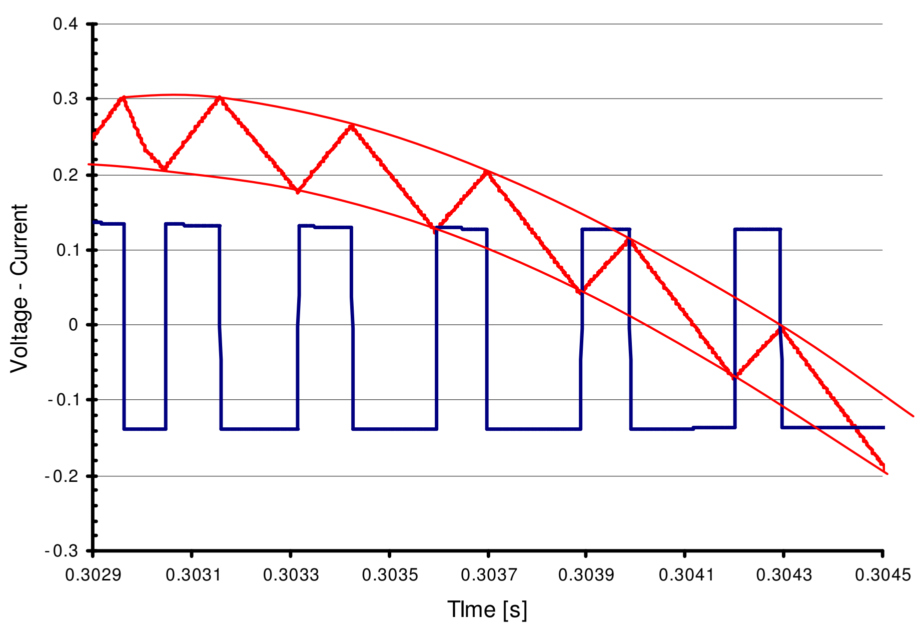


Figure 4.6: Hysteresis band current control

The PWM controller, by properly switching on and off the power converter, forces it to behave as a controlled current source, synthesizing a set of compensating currents that are ordered by the control system.

The commutation inductor, connected between the power system and the active filter, provides limitation against excessive rate of change of current. However, since high *di/dt* may be required to eliminate higher order harmonics, there is a tradeoff between IGBT protection and harmonic elimination capabilities. In this respect, it should be noted that the need to filter out high order harmonics may pose a challenge to the active filter.

Although there is a tendency for high order harmonics to be damped out by the power system, as a result of distribution lines being inductive, the active filter may also be required to filter some percentage of high order harmonics. Since power converter switching frequency will increase as a function of the harmonic order to be filtered, converter switching losses will also increase. (Reference [15] suggests that the switching frequency should be at least ten times higher than the highest harmonic requiring filtering).

A more in-depth description of control algorithms used in active filters requires the introduction of the Instantaneous Active and Reactive Power Theory, known as "*p-q* Theory". This theory, introduced by Hirofumi Akagi in 1983, is based on the Clarke transformation. A description of the mathematical basis of the theory is presented next.

4.3 The Clarke Transformation [15]

The Clarke transformation consists of a real matrix that transforms three-phase quantities (i.e. voltages, currents) into a stationary orthogonal reference frame ($0\alpha\beta$). The Clarke transformation is defined as:

$$\left(X_{0\alpha\beta}\right)=\sqrt{\frac{2}{3}}\begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix}\times\left(X_{abc}\right) \qquad (4.1)$$

In a three-wire system, the zero sequence (homopolar) components are eliminated, resulting in the following expressions for the voltage and current:

$$\left(X_{\alpha\beta}\right)=\sqrt{\frac{2}{3}}\begin{pmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 1 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2}\end{pmatrix}\times\left(X_{abc}\right) \tag{4.2}$$

The inverse Clarke transformation allows transforming *αβ0* quantities into *abc* quantities:

$$\left(X_{abc}\right)=\sqrt{\frac{2}{3}}\begin{pmatrix}\frac{1}{\sqrt{2}} & 1 & 0\\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2}\\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2}\end{pmatrix}\times\left(X_{0\alpha\beta}\right) \tag{4.3}$$

In a three-wire system, the following expressions are obtained:

$$\left(X_{abc}\right)=\sqrt{\frac{2}{3}}\begin{pmatrix}1 & 0\\ -\frac{1}{2} & \frac{\sqrt{3}}{2}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2}\end{pmatrix}\times\left(X_{\alpha\beta}\right) \tag{4.4}$$

4.4 Three-phase Instantaneous Power in Terms of Clarke Components

Three-phase instantaneous power is calculated from the *abc* instantaneous voltages and currents, as follows:

$$p_{3-phase}(t)=v_a(t)i_a(t)+v_b(t)i_b(t)+v_c(t)i_c(t) \tag{4.5}$$

This formula can also be expressed as a matrix product:

$$p_{3-phase} = \begin{pmatrix} v_a(t) & v_b(t) & v_c(t) \end{pmatrix} \times \begin{pmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{pmatrix} \tag{4.6}$$

The instantaneous three-phase power can be expressed in terms of *αβ* components by applying the inverse Clarke transformation and the linear algebra rule that states that the transpose of the product of two matrices is equal to the product of the transposes of the matrices in reverse order:

$$p_{3-phase} = \sqrt{\frac{2}{3}} \begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix}^T \times \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix}^T \times \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \times \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = v_\alpha i_\alpha + v_\beta i_\beta \tag{4.7}$$

This expression proves that the Clarke transformation is invariant in power. That is, the power in *abc* components is not altered by the transformation to *αβ* components [35].

4.5 Instantaneous Active and Reactive Powers for Three-wire Systems

Instantaneous active and reactive powers in three-wire systems, where the zero sequence components are not present, are defined by the following matrix:

$$\begin{pmatrix} p \\ q \end{pmatrix} = \begin{pmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{pmatrix} \times \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} \tag{4.8}$$

By multiplying the voltage and current matrices, the following expressions for the instantaneous powers are obtained:

$$\begin{aligned} p &= v_\alpha i_\alpha + v_\beta i_\beta \\ q &= v_\beta i_\alpha - v_\alpha i_\beta \end{aligned} \tag{4.9}$$

where p is the instantaneous active power and q is the instantaneous imaginary power. This instantaneous active power, defined by the *p-q* theory, has the same meaning as the instantaneous power traditionally defined; that is p is the total instantaneous energy flow per second between two subsystems. However, the *p-q* theory provides a new definition for q: the imaginary power q is proportional to the quantity of energy that is being exchanged between the phases of the system. It does not contribute to the energy transfer between the sources and the load at any time [11].

In general, p and q can have any mathematical expression, as they are functions of voltages and currents, which in the general case, can have any mathematical expression (as an example, voltages and currents may be unbalanced and have multiple harmonics). Therefore, Fourier analysis can be applied to these powers. This is further clarified by analyzing the following harmonic voltages and currents expressed as Fourier series in the *abc* reference frame:

$$
\begin{aligned}
v_a &= \sum_{j=1}^{\infty} \sqrt{2} \times V_j \times \sin(\omega_j t) \\
v_b &= \sum_{j=1}^{\infty} \sqrt{2} \times V_j \times \sin(\omega_j t - \frac{2\pi}{3}) \\
v_c &= \sum_{j=1}^{\infty} \sqrt{2} \times V_j \times \sin(\omega_j t + \frac{2\pi}{3}) \\
i_a &= \sum_{j=1}^{\infty} \sqrt{2} \times I_j \times \sin(\omega_j t + \varphi_j) \\
i_b &= \sum_{j=1}^{\infty} \sqrt{2} \times I_j \times \sin(\omega_j t - \frac{2\pi}{3} + \varphi_j) \\
i_c &= \sum_{j=1}^{\infty} \sqrt{2} \times I_j \times \sin(\omega_j t + \frac{2\pi}{3} + \varphi_j)
\end{aligned}
\tag{4.10}
$$

The subscript "j" corresponds to the *j-th* harmonic. It is possible to apply the Clarke transformation as defined in (4.2) to each *j-th* harmonic term to obtain voltages and currents in the $\alpha\beta$ reference frame:

$$
\begin{aligned}
v_\alpha &= \sum_{j=1}^{\infty} \sqrt{3} \times V_j \times \sin(\omega_j t) \\
v_\beta &= \sum_{j=1}^{\infty} -\sqrt{3} \times V_j \times \cos(\omega_j t) \\
i_\alpha &= \sum_{j=1}^{\infty} \sqrt{3} \times I_j \times \sin(\omega_j t + \varphi_j) \\
i_\beta &= \sum_{j=1}^{\infty} -\sqrt{3} \times I_j \times \cos(\omega_j t + \varphi_j)
\end{aligned}
\tag{4.11}
$$

Applying (4.9) to these harmonic voltages and currents, the following expressions for the instantaneous active and imaginary powers are obtained:

$$
\begin{aligned}
p &= \sum_{j=1}^{\infty} 3 \times V_j \times I_j \times \cos(\varphi_j) + \sum_{\substack{n=1 \\ n \neq j}}^{\infty} \sum_{j=1}^{\infty} 3 \times V_n \times I_j \times \cos[(\omega_n - \omega_j)t + \varphi_j] \\
q &= \sum_{j=1}^{\infty} 3 \times V_j \times I_j \times \sin(\varphi_j) + \sum_{\substack{n=1 \\ n \neq j}}^{\infty} \sum_{j=1}^{\infty} 3 \times V_n \times I_j \times \sin[(\omega_n - \omega_j)t + \varphi_j]
\end{aligned}
\tag{4.12}
$$

The first term of the expression that defines the instantaneous active power p is time independent, while the second term is time dependent. Therefore, the instantaneous active power can be defined as the sum of two components; an average component p_{av} and an oscillating component p_{osc}.

$$
p = p_{av} + p_{osc} \tag{4.13}
$$

The same analysis applies to q, where the total instantaneous imaginary power can be defined as:

$$
q = q_{av} + q_{osc} \tag{4.14}
$$

By analyzing the expressions for the instantaneous active and imaginary powers obtained above, the following conclusions can be reached:

- The average instantaneous active power results from the product of voltages and currents of the same frequency;
- The oscillating instantaneous active power results from the product of voltages and currents of different frequencies;
- The average instantaneous imaginary power results from the product of voltages and currents of the same frequency;
- The oscillating instantaneous imaginary power results from the product of voltages and currents of different frequencies.

Active filter control algorithms will take advantage of these conclusions to calculate compensating currents aiming at removing harmonic currents.

4.6 Active Filter Control Algorithms

Active filters can be applied to a power system to obtain several objectives, including:

- Eliminate harmonic currents
- Improve power factor
- Provide harmonic damping
- Load balancing

Depending on the active filter application, different control strategies can be devised [36]. In the case under study, the main objective is the removal of harmonic currents. A secondary, less important objective is the improvement of power factor. As it was discussed in previous sections, variable frequency drives whose front end is composed of diode rectifiers, have an inherent high displacement power factor. As a consequence, for a system with a large percentage of drive loads, power factor will be high, even without compensation.

The next paragraphs further develop concepts presented previously to introduce the control algorithm for the active filter implemented in this work.

The inverse of a given matrix P is given by:

$$P^{-1} = \frac{1}{|P|} \times P^{T} \tag{4.15}$$

This formula can be applied to the matrix that defines the instantaneous powers from the voltages and currents in the $\alpha\beta$ axes:

$$\begin{pmatrix} p \\ q \end{pmatrix} = \begin{pmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{pmatrix} \times \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} \tag{4.16}$$

Then, the following expression is obtained for the current in the $\alpha\beta$ axes as a function of the instantaneous powers:

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \frac{1}{{v_\alpha}^2 + {v_\beta}^2} \begin{pmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{pmatrix} \times \begin{pmatrix} p \\ q \end{pmatrix} \tag{4.17}$$

The currents in the $\alpha\beta$ reference frame are given by:

$$\begin{aligned} i_\alpha &= \frac{v_\alpha}{{v_\alpha}^2 + {v_\beta}^2} p + \frac{v_\beta}{{v_\alpha}^2 + {v_\beta}^2} q = i_{\alpha p} + i_{\alpha q} \\ i_\beta &= \frac{v_\beta}{{v_\alpha}^2 + {v_\beta}^2} p - \frac{v_\alpha}{{v_\alpha}^2 + {v_\beta}^2} q = i_{\beta p} + i_{\beta q} \end{aligned} \tag{4.18}$$

The importance of these two expressions is that they allow calculating the current component that is responsible for the appearance of an instantaneous power component on the electrical system. Since the instantaneous active and imaginary powers can be expressed as the sum of an average component plus an oscillatory component, the above expressions can be further expanded as follows.

$$\begin{aligned} i_\alpha &= \frac{v_\alpha}{{v_\alpha}^2 + {v_\beta}^2} p_{av} + \frac{v_\alpha}{{v_\alpha}^2 + {v_\beta}^2} p_{osc} + \frac{v_\beta}{{v_\alpha}^2 + {v_\beta}^2} q_{av} + \frac{v_\beta}{{v_\alpha}^2 + {v_\beta}^2} q_{osc} = i_{\alpha pav} + i_{\alpha posc} + i_{\alpha qav} + i_{\alpha qosc} \\ i_\beta &= \frac{v_\beta}{{v_\alpha}^2 + {v_\beta}^2} p_{av} + \frac{v_\beta}{{v_\alpha}^2 + {v_\beta}^2} p_{osc} - \frac{v_\alpha}{{v_\alpha}^2 + {v_\beta}^2} q_{av} - \frac{v_\alpha}{{v_\alpha}^2 + {v_\beta}^2} q_{osc} = i_{\beta pav} + i_{\beta posc} + i_{\beta qav} + i_{\beta qosc} \end{aligned} \tag{4.19}$$

These formulas are the basis for a control algorithm that allows the removal of harmonic currents. It was previously concluded that the oscillating components of the active and imaginary instantaneous powers are the result of the presence of harmonic voltages and currents. Assuming a system with purely sinusoidal voltages, oscillating powers will result from the presence of harmonic currents. The control algorithm should be able to identify and remove (compensate) the current components that produce oscillating powers.

The block diagram shown in Figure 4.7 describes the control algorithm implemented for the active filter. System voltages and load currents are transformed to $\alpha\beta$ components with the Clarke transformation. These components are then used to calculate the instantaneous active and imaginary powers.

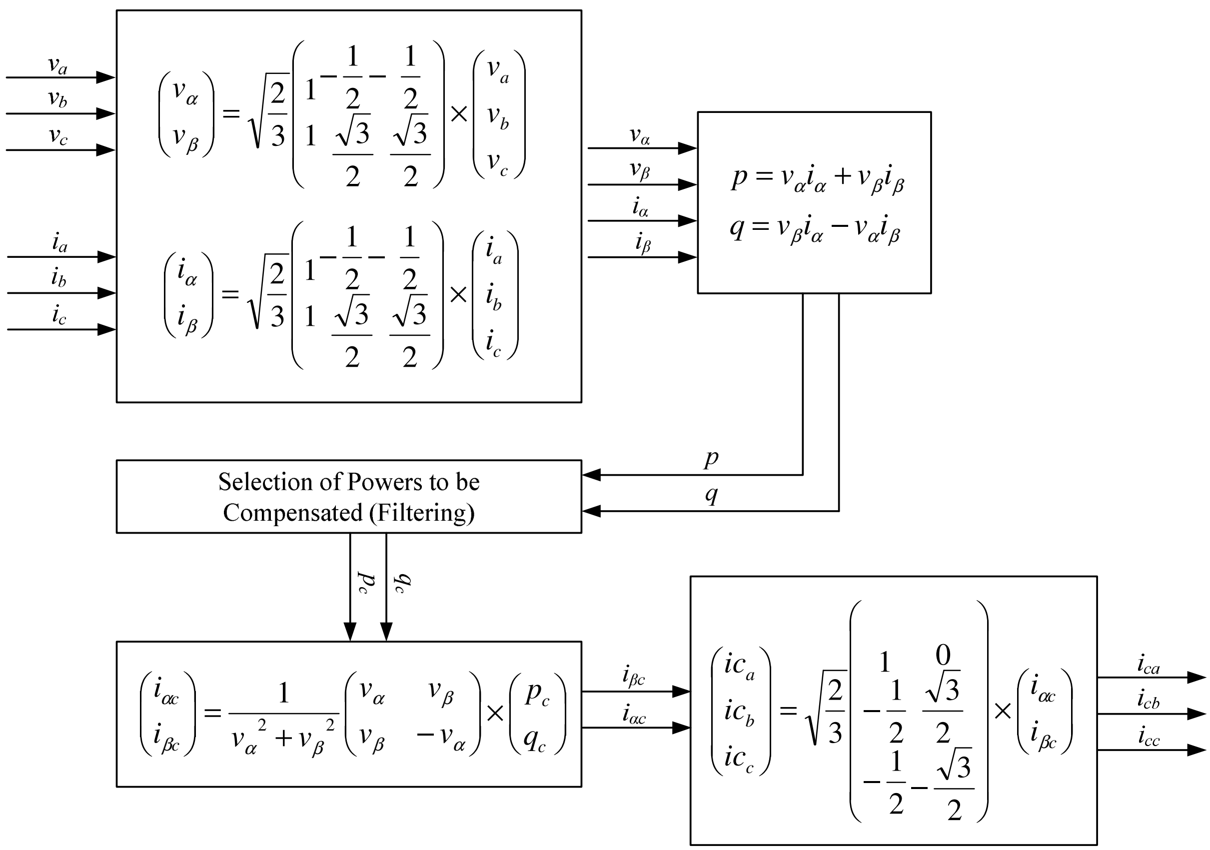


Figure 4.7: Block diagram of an active filter controller. (From H. Akagi, E. Watanabe and M. Aredes, Instantaneous Power Theory and Applications to Power Conditioning, John Wiley, 2007. With permission.)

These instantaneous powers will contain, in the general case, an average component and an oscillating component. The oscillating power components are extracted from the instantaneous powers by a high-pass filter; which are then used to calculate the *αβ* current components associated with these oscillating powers. These currents, transformed to *abc* components with the inverse Clarke transformation, are the reference currents used by the active filter's PWM current controller and power converter to synthesize compensating currents that will remove (compensate) harmonic currents from the power system.

The resulting instantaneous real and imaginary powers will contain no oscillating component. However, the average instantaneous imaginary power will still be flowing in the power system, lowering the power factor. An improvement to this control algorithm would entail the removal of this power, allowing the active filter to also improve the power factor. This added function, however, would increase the current rating of the power converter, as the filter would be required to inject an extra current into the power system to compensate for the average instantaneous imaginary power.

The next chapter describes how control algorithms are implemented for software simulations and how reference currents are used by the filter to compensate harmonics.

4.6 Hybrid Active Filters

Hybrid active filters are a combination of active filters, either in series or parallel configuration, with a shunt passive filter [37] with the purpose of reducing the capital cost of the harmonic filtering system. Several hybrid filter configurations have been proposed [38]:

- Combination of shunt active filter and shunt passive filter (Figure 4.8)
- Combination of series active filter and shunt passive filter (Figure 4.9)
- Series connection of active filter and passive filter (Figure 4.10)

Chapter 6 will assess the performance of a hybrid active filter configured as a shunt active filter and shunt passive filter.

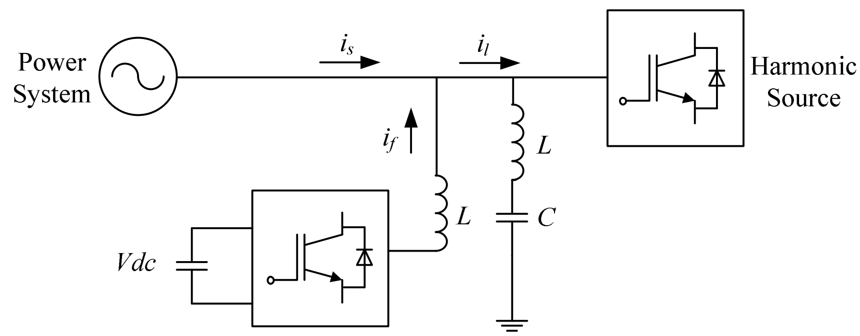


Figure 4.8: Combination of shunt active filter and shunt passive filter

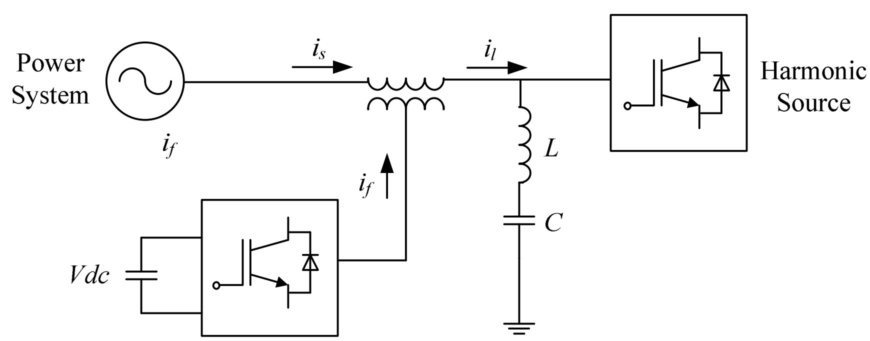


Figure 4.9: Combination of series active filter and shunt passive filter

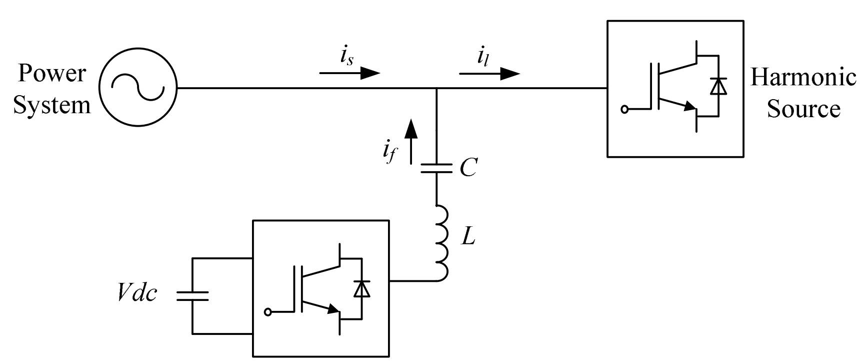


Figure 4.10: Series connection of active filter and passive filter

CHAPTER 5: ACTIVE FILTER MODELING AND VALIDATION

5.1 Introduction

The previous chapter provided a description of the main components of a shunt active filter and presented the mathematical basis for the development of the control algorithms. This chapter makes use of these concepts to develop a PSCAD/EMTDC transient model of a shunt active filter. The active filter controller is then compared against a mathematical model of an active filter controller developed in Wolfram Mathematica [19] to cross-check both models.

5.2 PSCAD/EMTDC Model of a Shunt Active Filter

5.2.1 Active Filter Controller

The block diagram shown in Figure 5.1, already presented in chapter four but included in this chapter for convenience, describes the control algorithm implemented for the active filter, which is based on the *p-q* theory. System voltages and load currents are transformed to *αβ* components with the Clarke transformation.

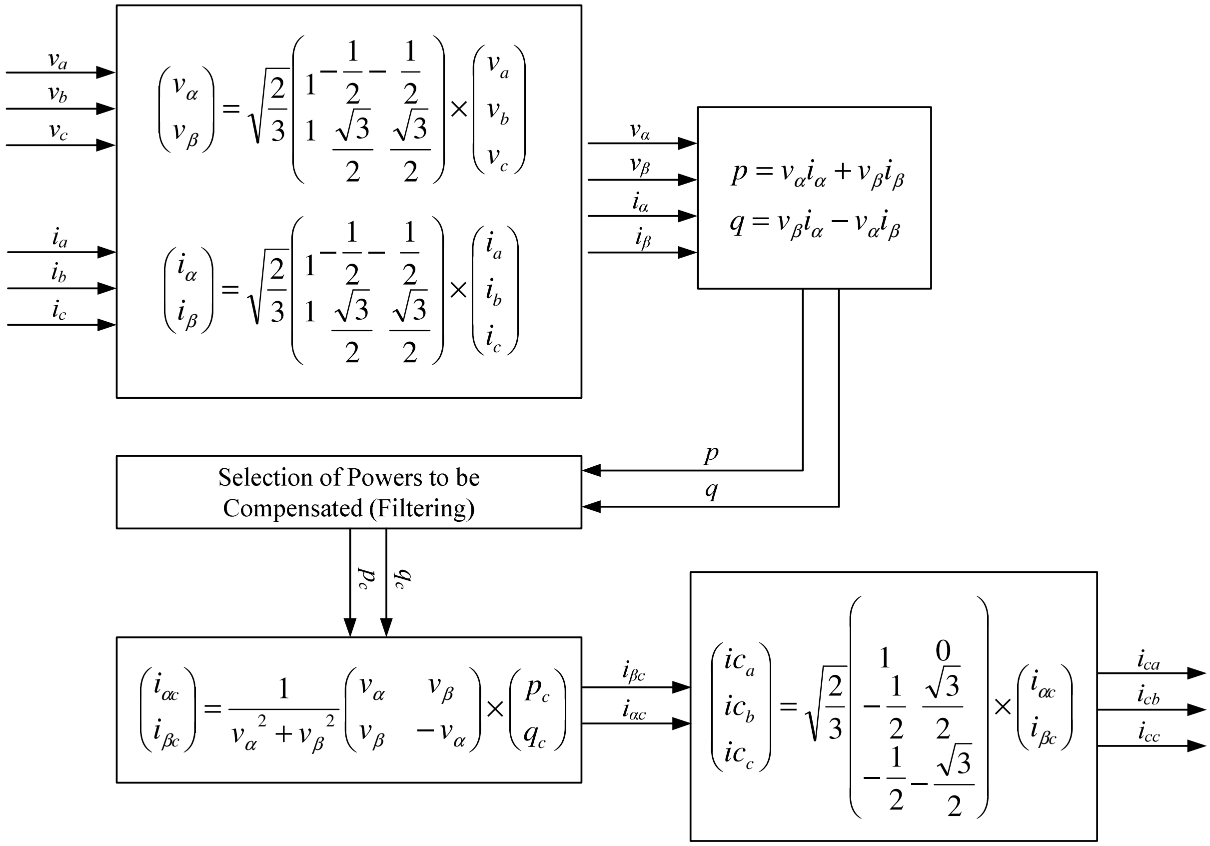


Figure 5.1: Block diagram of an active filter controller

Since PSCAD does not include the Clarke transformation in its standard library, a custom simulation module had to be developed. This module is shown in Figure 5.2, where the input variables are voltages and currents in the *abc* reference frame and output variables are voltages and currents in $\alpha\beta$ reference frame.

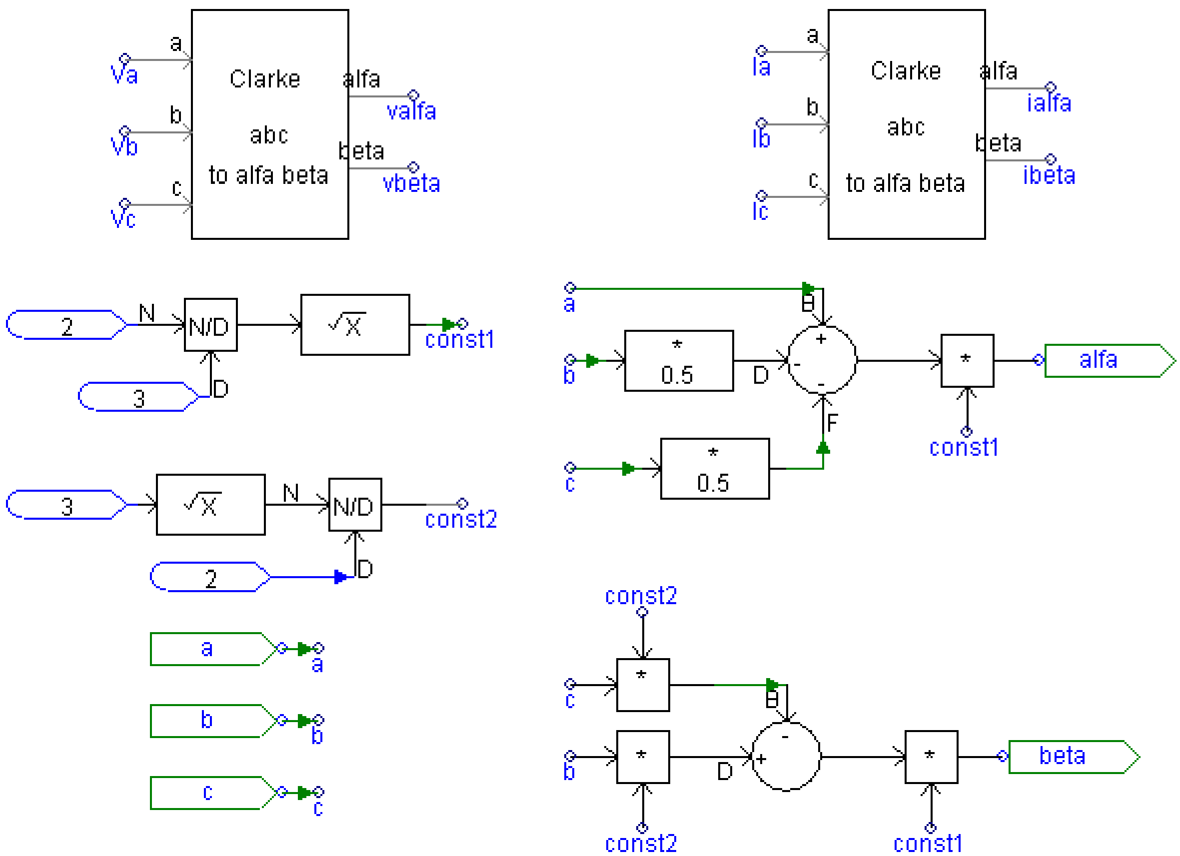
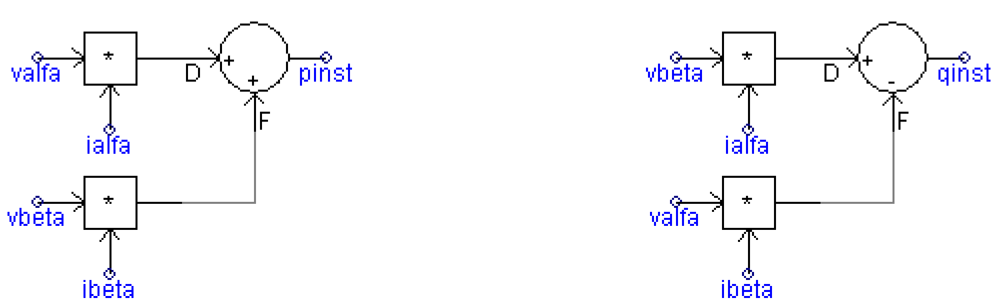


Figure 5.2: Clarke transformation implementation in PSCAD

Voltages and currents in the $\alpha\beta$ reference frame are then used to calculate the instantaneous active and imaginary powers. Figure 5.3 shows the implementation of the instantaneous powers calculator in PSCAD.



(a) Active power (b) Reactive power

Figure 5.3: Instantaneous powers calculator in PSCAD

As the purpose of this active filter is to compensate for harmonics, the oscillating power components are extracted from the instantaneous powers by a high-pass filter. This is justified by recalling these conclusions reached in chapter four:

- The oscillating instantaneous active power results from the product of voltages and currents of different frequencies;
- The oscillating instantaneous imaginary power results from the product of voltages and currents of different frequencies.

The high-pass filters were implemented in PSCAD as second order transfer functions [39], a standard component of the PSCAD library (Figure 5.4). These filters output the oscillating component of the instantaneous active and imaginary powers.

Figure 5.4: Second order high-pass filters in PSCAD

This second order transfer functions are represented by the following equation [18]:

$$\frac{Y(s)}{X(s)} = \frac{G \times (\frac{s}{\omega_c})^2}{1 + 2 \times \xi \times \frac{s}{\omega_c} + (\frac{s}{\omega_c})^2} \qquad (5.1)$$

where G is the gain, ω_c is the characteristic frequency and ξ is the damping ratio. After a series of simulations in Wolfram Mathematica and PSCAD, the following parameters were obtained:

- G=1
- ω_c=100 Hz
- ξ=0.2

Figure 5.5 shows the frequency response of the filter's transfer function defined by equation (5.1) for the parameters provided above. It represents the ratio of the filter's output to the filter's input as a function of the frequency of the input signal. Figure 5.6 shows the phase angle of equation (5.2) as a function of the input signal.

Figure 5.7 shows the behavior of this filter when the instantaneous active power corresponding to a three-phase diode rectifier is applied to the filter. The input instantaneous active power contains both constant and oscillatory components, while the output instantaneous active power contains only oscillatory components.

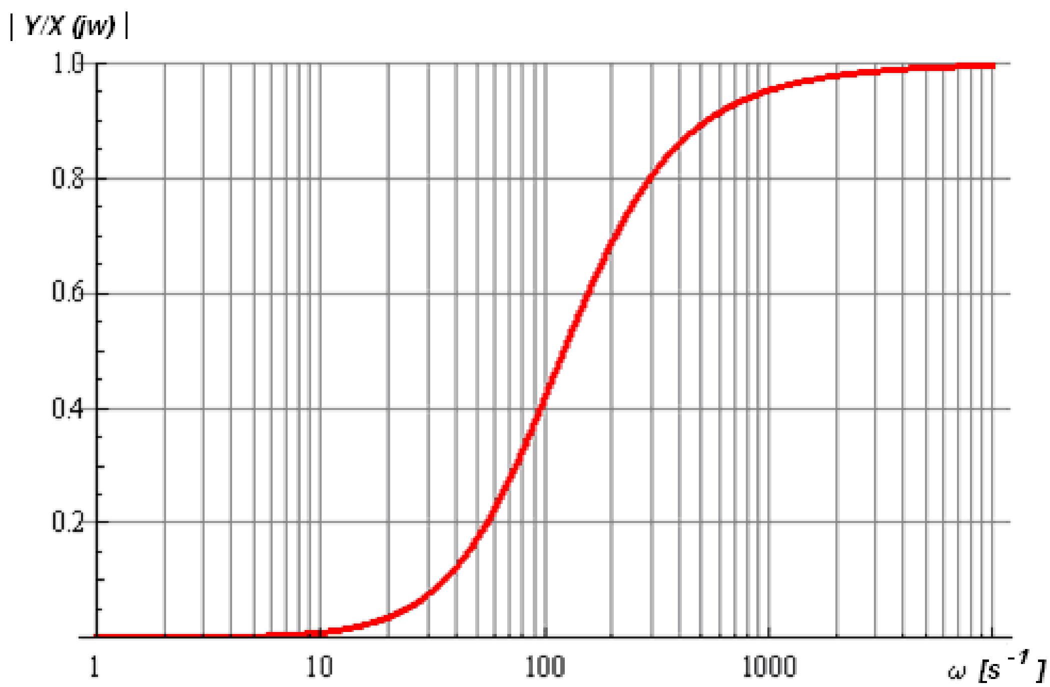


Figure 5.5: Frequency response of the second order filter

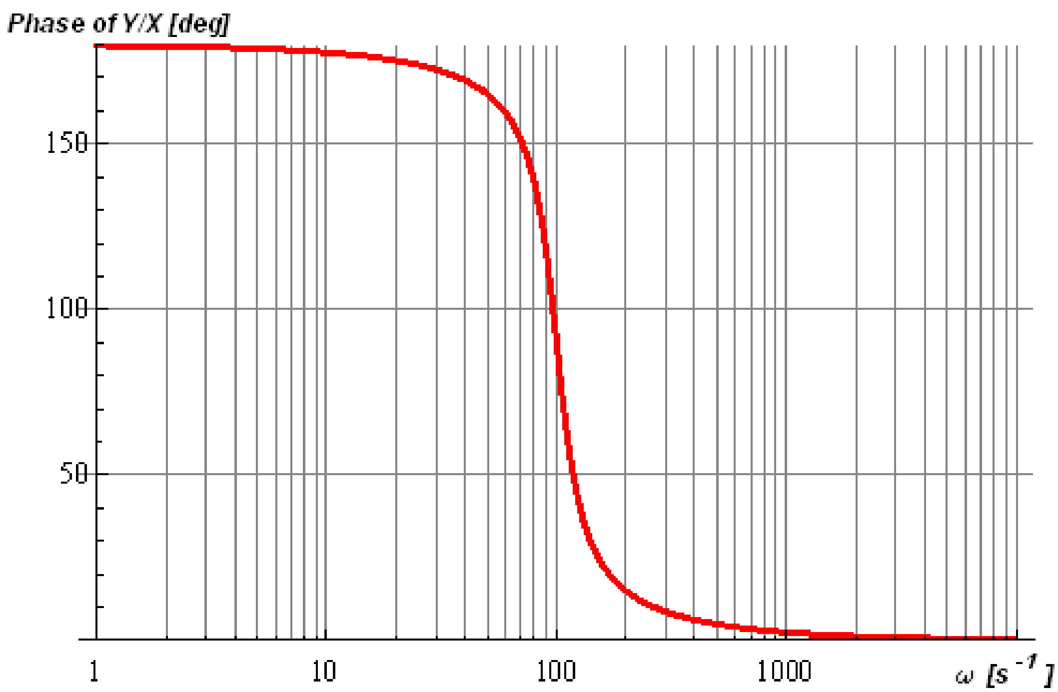


Figure 5.6: Phase angle of the second order filter

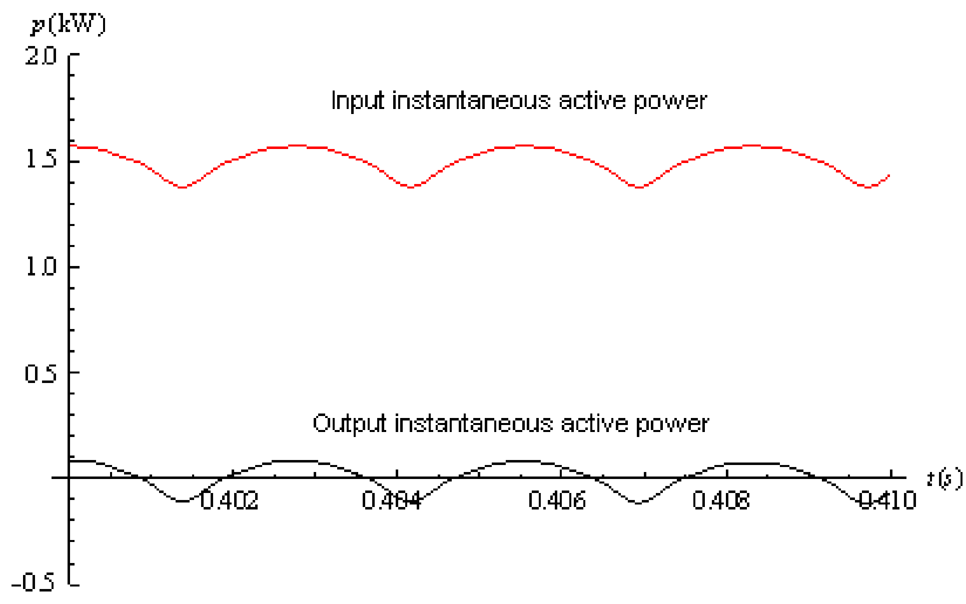


Figure 5.7: Filter output

The oscillating instantaneous active and imaginary powers are then used to calculate the $\alpha\beta$ current components associated with these oscillating powers by applying (4.23) for the oscillating powers:

$$
\begin{aligned}
i^{*}{}_{\alpha} &= \frac{v_{\alpha}}{v_{\alpha}{}^{2}+v_{\beta}{}^{2}}\,p_{osc} + \frac{v_{\beta}}{v_{\alpha}{}^{2}+v_{\beta}{}^{2}}\,q_{osc} = i_{\alpha posc} + i_{\alpha qosc} \\
i^{*}{}_{\beta} &= \frac{v_{\beta}}{v_{\alpha}{}^{2}+v_{\beta}{}^{2}}\,p_{osc} - \frac{v_{\alpha}}{v_{\alpha}{}^{2}+v_{\beta}{}^{2}}\,q_{osc} = i_{\beta posc} + i_{\beta qosc}
\end{aligned}
\tag{5.2}
$$

Figure 5.8 shows how the formulas presented above; used to calculate the reference currents in the *αβ* reference frame were implemented in PSCAD.

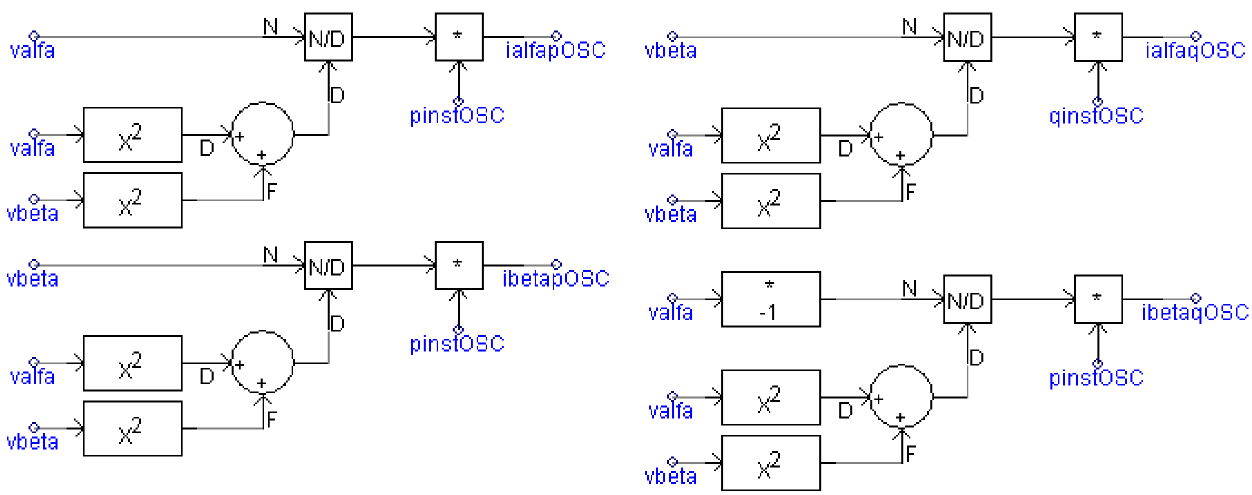


Figure 5.8: Determination of *αβ* reference currents in PSCAD

These currents are then transformed to *abc* components with the inverse Clarke transformation. Since PSCAD does not include the inverse Clarke transformation in its standard library, a custom simulation module was developed. This module is shown in Figure 5.9, where input variables are reference currents in the *αβ* reference frame and output variables are reference currents in *abc* reference frame.

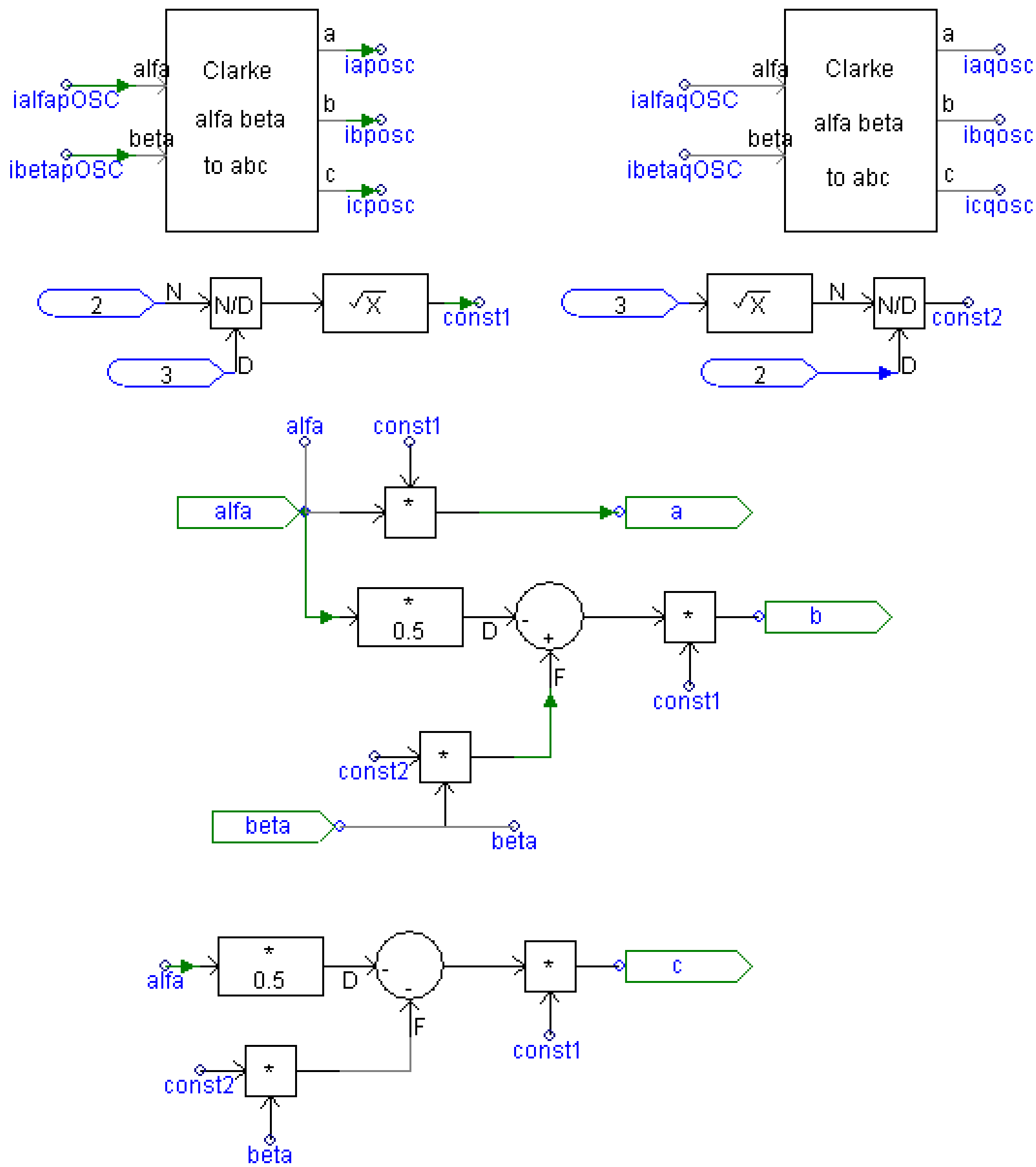


Figure 5.9: Inverse Clarke transformation implementation in PSCAD

5.2.2 PWM current controller

The reference currents in the *abc* reference frame input the filter's PWM hysteresis-band current controller. Figure 5.10 shows the implementation of this controller in PSCAD; the reference currents are compared against the active filter current output, and the resulting error signals form the inputs to six firing pulse generators (one per IGBT), another standard component of PSCAD's library. The hysteresis band is defined as a real constant.

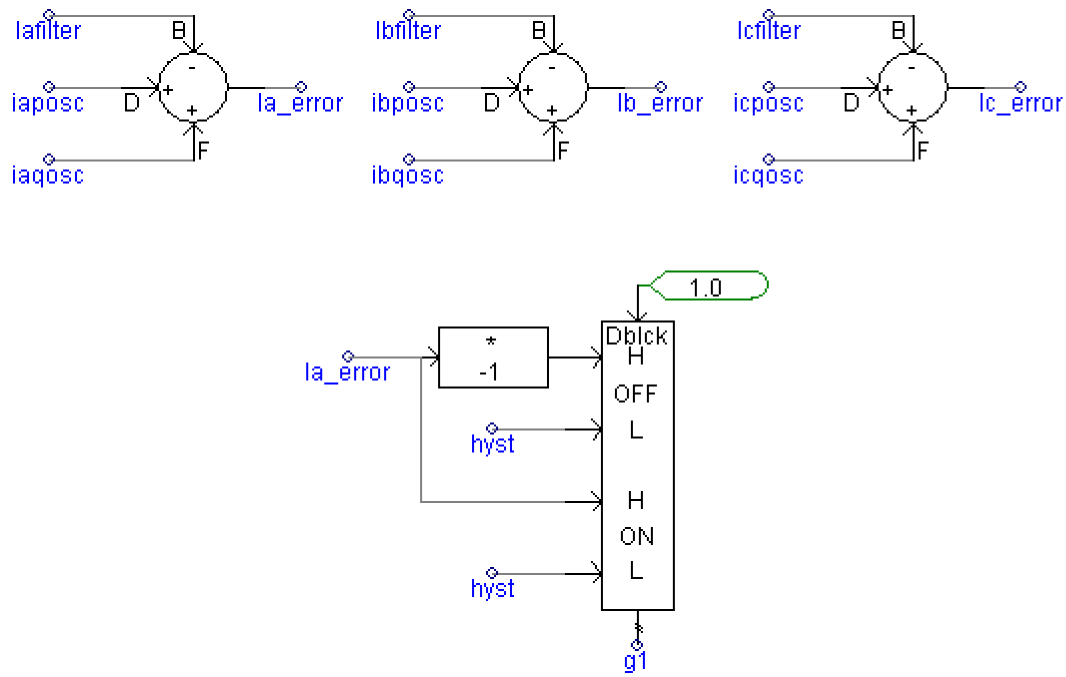


Figure 5.10: Hysteresis-band current controller (one pulse generator shown)

5.2.3 Power Converter, Commutation Inductance and DC Link

The power converter, as shown in Figure 5.11, was modeled in PSCAD as a voltage source converter (VSC) equipped with a DC capacitor for energy storage and IGBT switching devices.

The commutation reactor should be kept small to obtain fast response (*di/dt*); however, decreasing the reactor inductance increases the switching frequency of the hysteresis current controller, increasing losses [15]. A research of literature on active filters [13, 15, 31] showed values in the range of 250µH to 2.5mH. These values, when compared against active filter ratings corresponded to reactances in the range of 1.5% to 9% (on the active filter kVA base). For this work, after testing several values of inductance, a commutation reactor of 1.5mH was selected. Although this value is higher (as a percentage of the active filter kVA base), than those previously discussed, it provided a better active filter operation as compared to lower inductance values.

The DC capacitor for energy storage should be selected so that it maintains a constant DC link voltage. However, a large capacitor will increase the overall cost of the active filter and its footprint. The following chapter will show that a DC link capacitor of 100uF provides an adequate active filter performance.

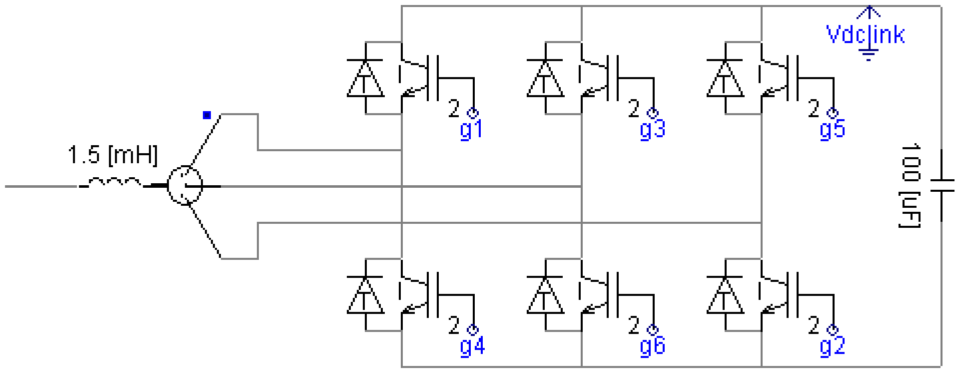


Figure 5.11: VSC based power converter

5.3 PSCAD/EMTDC Algorithm Model Cross-Check

In order to cross-check the operation of the active filter controller implemented in PSCAD, a mathematical model of the filter control algorithm shown in Figure 5.1 was developed in Wolfram Mathematica. Thus, both PSCAD and Mathematica models are based on the same control algorithm. If both models provide a similar filtering performance for a given harmonic current, it can be assumed that the PSCAD controller representation has been accurately modeled.

5.3.1 Mathematical Model of the Active Filter

The active filter controller shown in Figure 5.1 was modeled in Wolfram Mathematica [19], a computational software program used in scientific, engineering and mathematical fields.

The Clarke transformations, inverse Clarke transformations, high-pass filter and all other calculations were represented with its corresponding mathematical expressions. The harmonic generating load, a three-phase controlled rectifier feeding a *RL* load as shown in Figure 5.12, was modeled as a Fourier series up to the 25th harmonic component. For simplicity, the firing angle of the controller rectifier was set at zero degrees so it would effectively behave as an un-controlled rectifier.

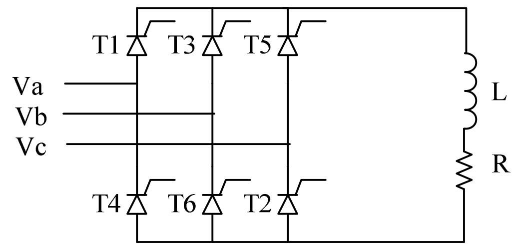


Figure 5.12: Three-phase controlled rectifier feeding a RL load

5.3.2 Mathematical and PSCAD Models Comparison

The shunt active filter developed in PSCAD was connected in parallel to a non-linear load modeled as a three-phase controlled rectifier (Figure 5.13).

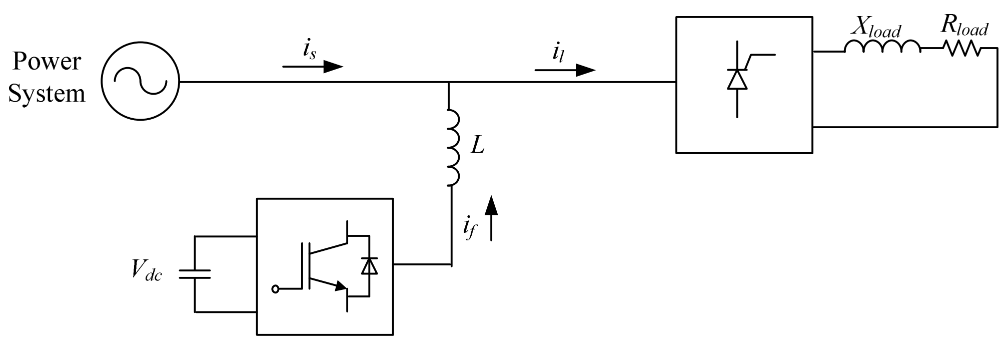


Figure 5.13: Test circuit for PSCAD model

The *RL* load connected to the three-phase rectifier was adjusted until the value of the harmonic current was similar in both models.

Figure 5.14 shows an overlay of the mathematical and PSCAD harmonic currents. Both harmonic currents have similar values, although there is a slight difference on the slopes of these two currents. This difference is caused by the commutating inductance included in the PSCAD model that are absent in the mathematical model. The mathematical model also shows the characteristics of overshoot or "ringing" occurring at the discontinuities, caused by the use of truncated Fourier series (Gibbs phenomenon) [40].

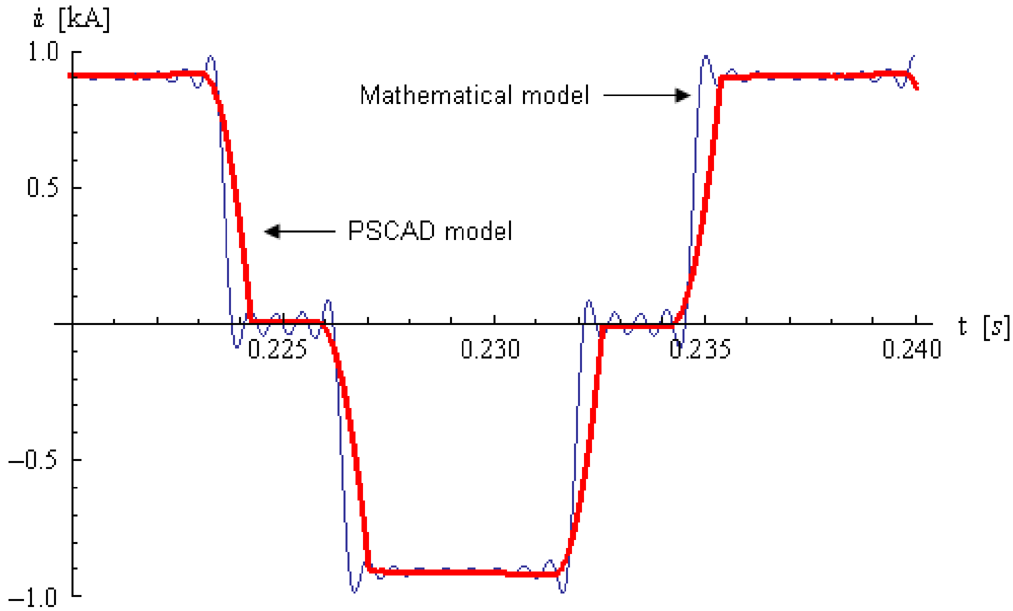


Figure 5.14: Mathematical and PSCAD harmonic currents

Figure 5.15 shows an overlay of the mathematical and PSCAD filter currents. While both filter currents have similar wave shapes and values, there are differences that should be addressed; the mathematical model is based on a load current that contains up to the 25th harmonic, while the PSCAD load current is the result of a complete converter model.

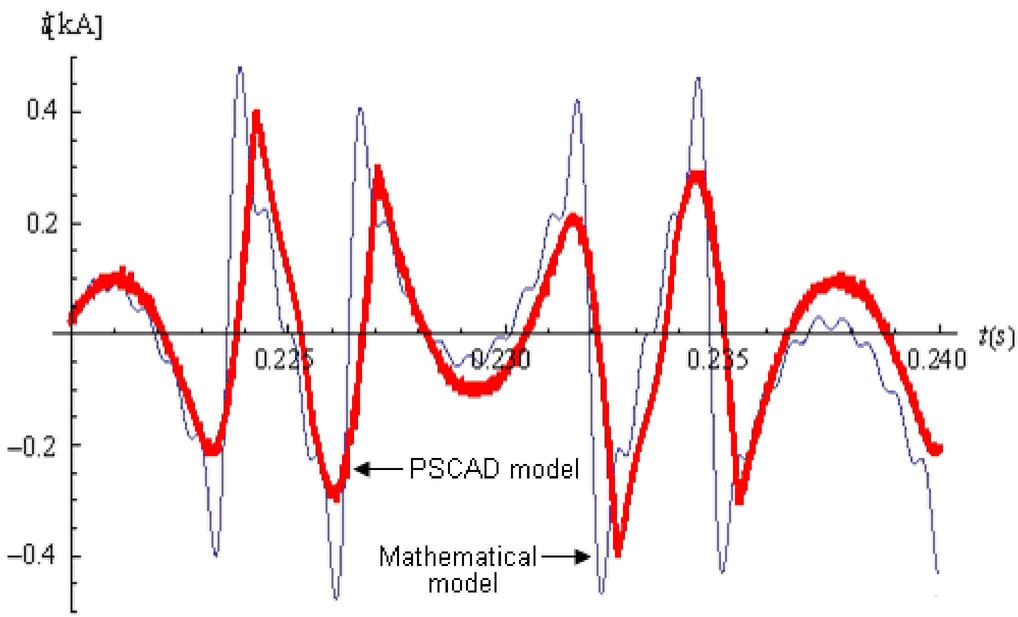


Figure 5.15: Mathematical and PSCAD filter currents

Figure 5.16 shows an overlay of the mathematical and PSCAD filtered currents. Since both the mathematical model and the PSCAD model provide similar filtering performance, it can be stated that the PSCAD control algorithm is an accurate representation of the control block of Figure 5.1

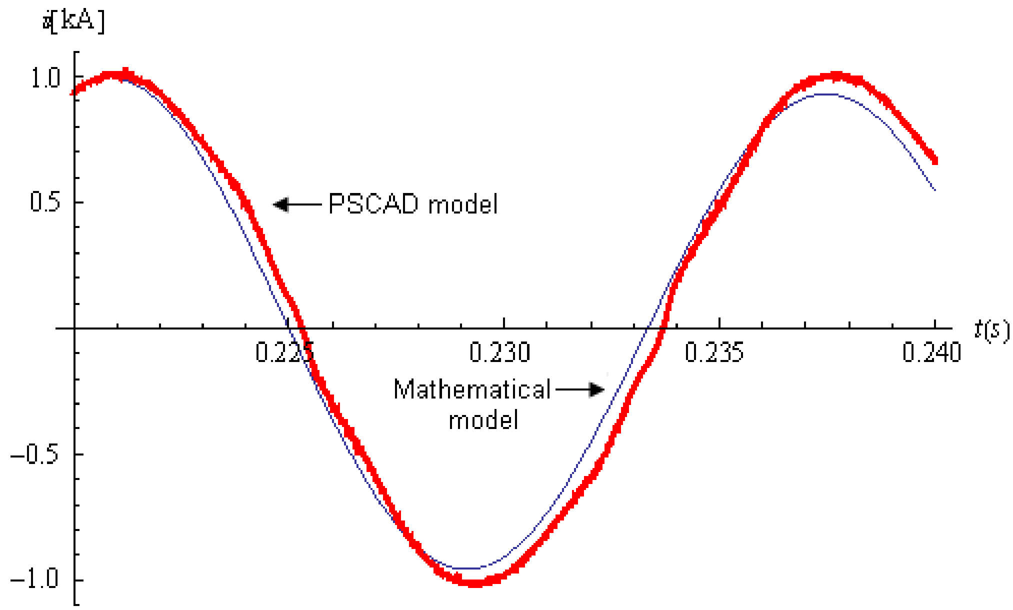


Figure 5.16: Mathematical and PSCAD filter currents

The next section compares the performance of the active filter developed in this chapter against a shunt passive filter.

CHAPTER 6: ACTIVE AND PASSIVE FILTERS PERFORMANCE

6.1 Introduction

This chapter develops a test electrical distribution system, in which the connected load is composed of VSC-type variable frequency loads (90% of total connected load) and heating loads (10% of total connected loads). This load arrangement, in which the drive load represents a large percentage of the total connected load, is becoming increasingly common in modern industrial facilities.

The harmonic currents produced by such a system are compared against industry recognized harmonic standards (i.e. IEEE Std. 519–1992) to assess the requirements of harmonic mitigation. After these requirements have been defined, attempts are made to provide mitigation by solely employing passive shunt harmonic filters.

Following the benchmarking of the passive filters, the shunt active filter described in the previous chapter is connected to the test electrical system, without the presence of passive filters. The results obtained for the active filter are then compared against results obtained for shunt active filters.

6.2 Description of the Test Electrical System

Since the test electrical system is to contain a 90% load connected to VFDs, it is expected that the harmonic level at the point of common coupling will be high. A proper harmonic mitigation strategy should comply with the following requirements:

- Maintain TDD below IEEE Std. 519 limits;
- Maintain individual harmonics under IEEE Std. 519 limits;
- Limit over-voltages caused by shunt capacitors (avoid capacitive power factors);
- Capacitor bank steps should be sized to limit voltage fluctuations under 5% when elements are switched on and off (IEEE Std. 1036);
- Prevent capacitors from being overloaded by harmonics. (Limits set by IEEE Std. 18).

Figure 6.1 shows a circuit diagram of the test electrical system and Table 6.1 shows the corresponding circuit parameters. The following sections explain how these parameters were selected.

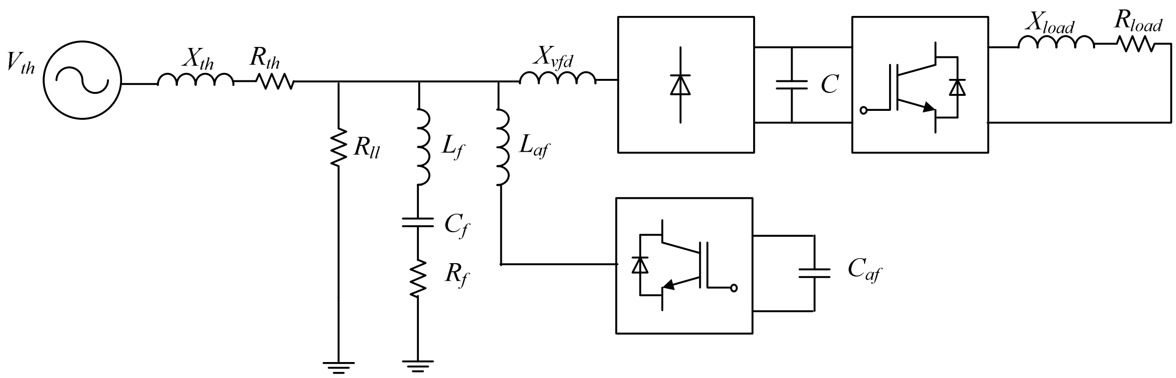


Figure 6.1: Circuit diagram of the test electrical system

Table 6.1: Parameters of the test electrical system

Component	Symbol	Value
Power System Voltage	V_{th}	600V
Power System Impedance	R_{th}, X_{th}	(0.42+j0.132) Ω
Active Filter Capacitance	C_{af}	100 µF
Active Filter Inductance	L_{af}	1.5 mH
VFD Input Reactance	X_{vfd}	0.024 Ω (*)
VFD Capacitor (DC Link)	C	1500 µF
VFD Load	R_{load}, X_{load}	(0.0193+J0.031) Ω
Linear Load	R_{ll}	6.9 Ω
Passive Filter Inductance	L_f	See section 6.2.4
Passive Filter Capacitance	C_f	See section 6.2.4
Passive Filter Resistance	R_l	See section 6.2.4

(*) This reactance corresponds to a 3% reactor. Bases are nominal drive voltage (600V) and nominal drive current (450A)

6.2.1 Non-Linear Load Model

The harmonic generating load is modeled as an RL load of (0.42+j0.132) Ω connected to a VSC-type variable frequency drive, resulting in a current of 450A (fundamental component) at the input drive terminals.

The PDCAD model of the VSC-type VFD included the diode front end, capacitor DC link and IGBT-based power converter. Figure 6.2 shows the sinusoidal PWM converter controller implemented in PSCAD [41].

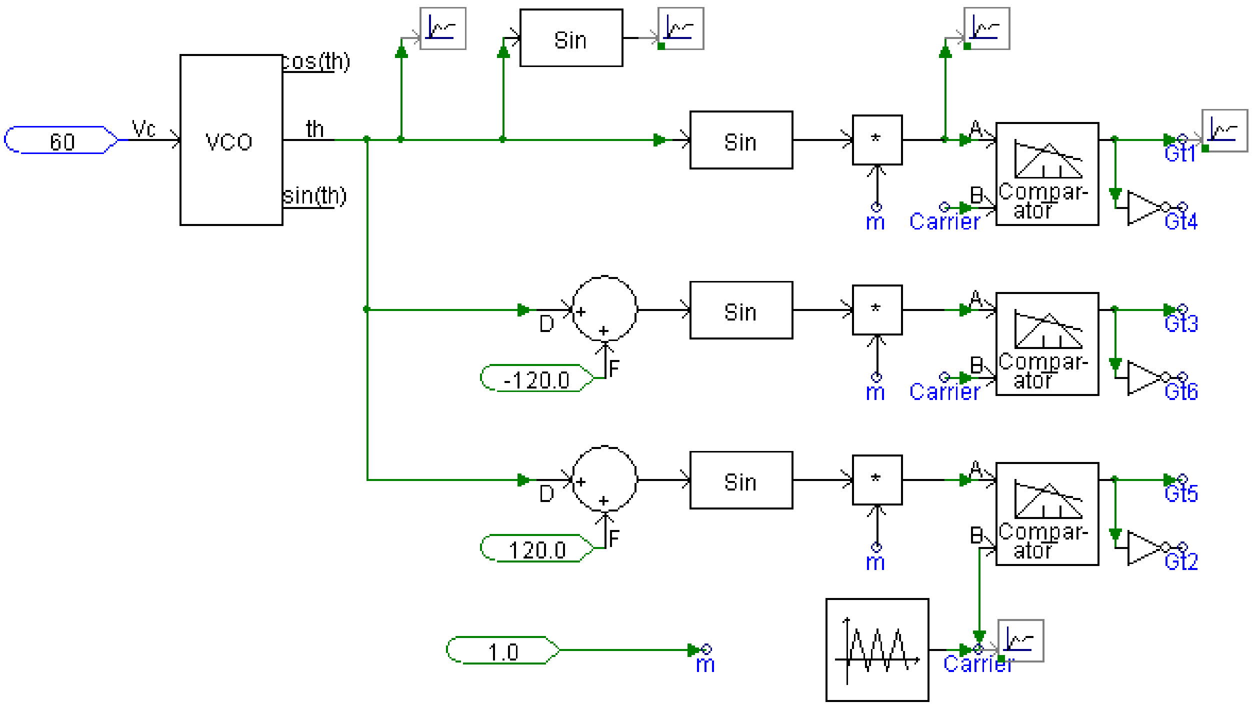


Figure 6.2: PWM converter controller

Figure 6.3 shows the VFD load voltage and current; the synthesized voltage produced by the PWM controlled power converter is applied to a RL load, resulting in a nearly sinusoidal load current.

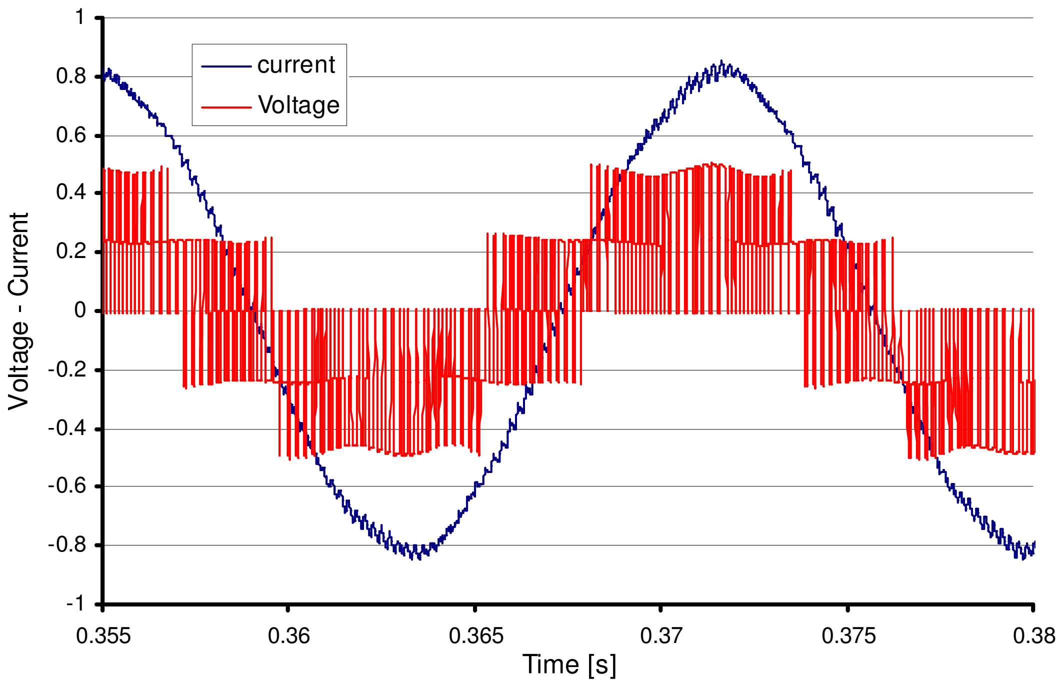


Figure 6.3: VFD load voltage and current

6.2.2 Linear Load Model

The linear load component is modeled as a resistive load of 6.9 Ω, resulting in a fundamental current component of 50A, which added to the drive current gives a total fundamental system current of 500A and a displacement power factor of 0.96 (inductive) at the point of common coupling.

6.2.3 Utility System

The utility system is modeled as a Thevenin equivalent whose parameters are selected to obtain a short circuit level of 9.5kA. These parameters are Z_{th}= (0.0193+J0.031) Ω and V_{th}=600V.

Based on IEEE Std. 519, Table 2.2, for a utility fault level of 9.5kA and a plant load (I_L) of 500A, I_{sc}/I_L=19. Then, the maximum allowed TDD for the facility would be 5% as per Table 2.2.

6.2.4 Harmonic Filter Parameters

The first step to size a shunt passive filter consists of determining the required capacitive reactive power to bring the system power factor to a target value. In this case, the target power factor was selected to be 0.99 inductive. Applying formula (3.2) for the selected target power factor, an initial power factor of 0.96 and a connected power of 500kW (assuming an average drive load of 450kW and an average heating load of 50kW), the required capacitive reactive power was determined to be 75kVAr. As a consequence, the standard commercial size of 100kVAr at 600V was selected [42].

The shunt passive filter was tuned to the 4.7 harmonic (282 Hz) and the quality factor (*Q)* was assumed to be 47, equivalent to an X/R of 10 at the fundamental frequency. The quality factor determines the sharpness of the filter tuning; the higher the *Q*, the lower the filter impedance at its resonant frequency, which would result in higher harmonic currents being absorbed by the passive filter.

Filter specifications for a range of *C, L* and *R* values are given in Table 6.2.

Table 6.2: Shunt passive filter specifications

Nominal Filter Size	Z	C	L	R	Nominal Capacitor Current
100 kVAr	3.60 Ω	737 μF	432.3 μH	16.3 mΩ	96 A
200 kVAr	1.80 Ω	1474 μF	216.1 μH	8.1 mΩ	192 A
300 kVAr	1.20 Ω	2210 μF	144.1 μH	5.4 mΩ	289 A
400 kVAr	0.90 Ω	2947 μF	108.1 μH	4.1 mΩ	384 A

Figure 6.4 shows the overall test electrical system as implemented in PSCAD. It includes the utility equivalent modeled as a Thevenin impedance and the non-linear load modeled as a VSC-type variable frequency drive (diode front end, DC link and IGBT power converter). The shunt passive filter and the VSC-type shunt active filter have been connected to the electrical system immediately downstream of the point of common coupling through circuit breakers to easily disconnect them form the system. The heating load is included as a resistor connected in parallel to the non-linear load.

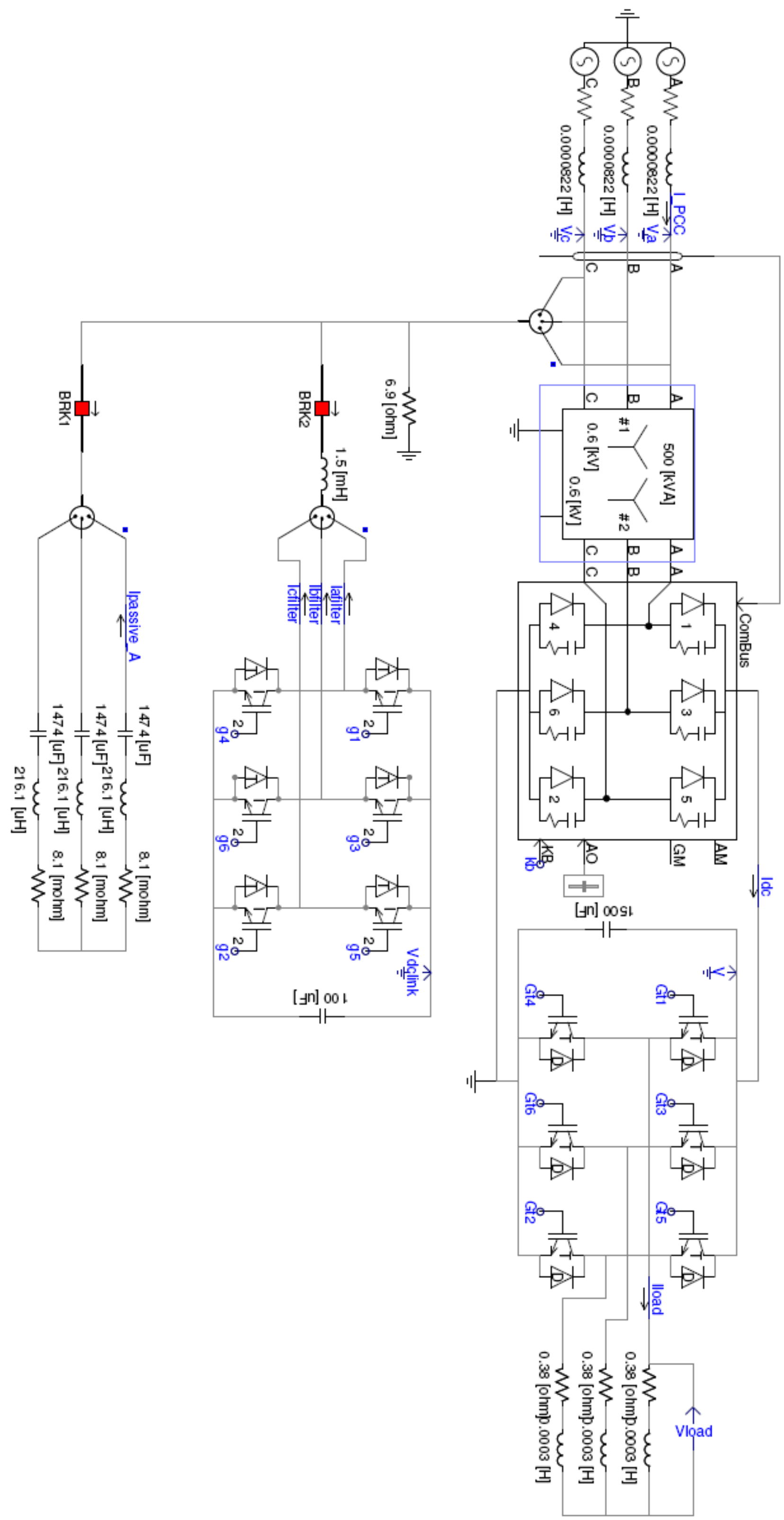


Figure 6.4: PSCAD implementation of the test electrical system

6.3 Performance of Test Electrical System

In order to benchmark the shunt passive and active harmonic filters, a base case simulation with both filters disconnected and linear and non-linear loads connected is run to determine harmonic levels a the PCC. Figures 6.5 and 6.6 show the resulting line current and its corresponding harmonic spectrum at the PCC.

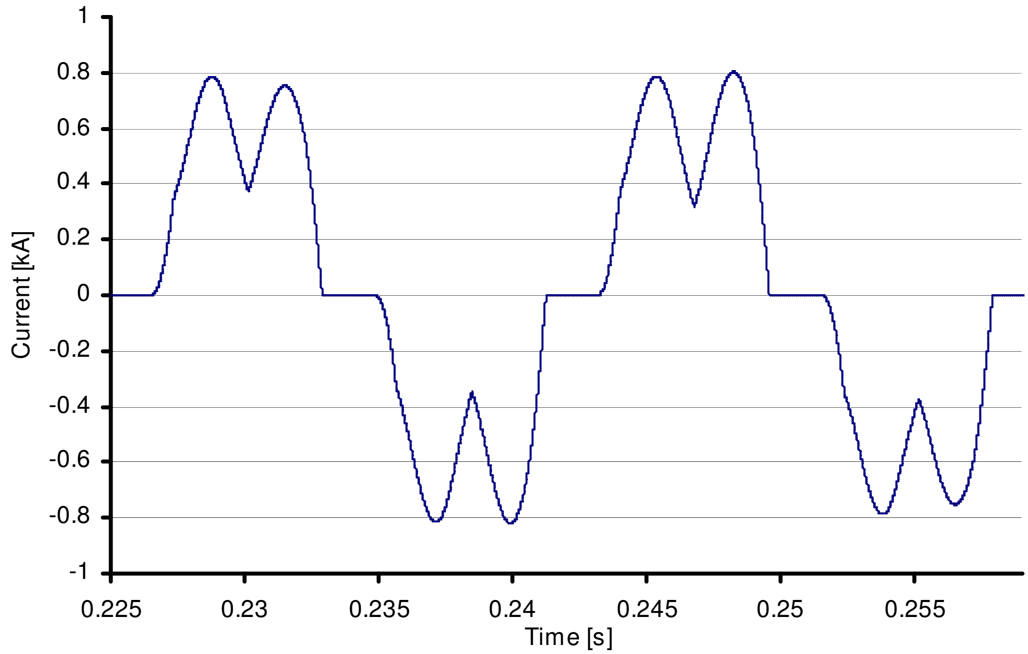


Figure 6.5: System current at the PCC – No filtering

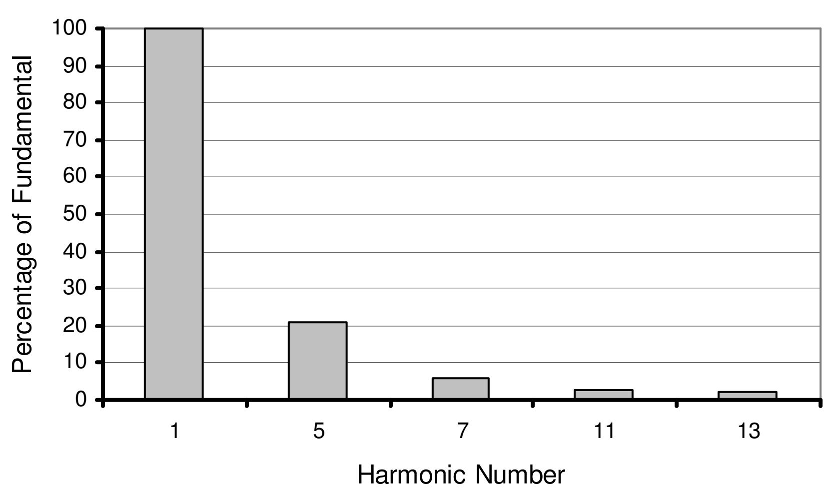


Figure 6.6: Harmonic spectrum at PCC – No filtering

The total harmonic distortion (TDD), calculated with formula (2.2) is 21.9%. This TDD is higher than the maximum 5% allowed by IEEE Std. 519. As a consequence, some form of harmonic filtering is required. The displacement power factor at the PCC is 0.96 inductive.

6.4 Test Electrical System with 100 kVAr Shunt Passive Filter

Following the benchmarking of the electrical system, a 100 kVAr shunt passive filter is connected at the PCC. Figure 6.7 shows the resulting line current, while Figure 6.8 shows its corresponding harmonic spectrum at the PCC. Figure 6.9 shows the harmonic filter output current.

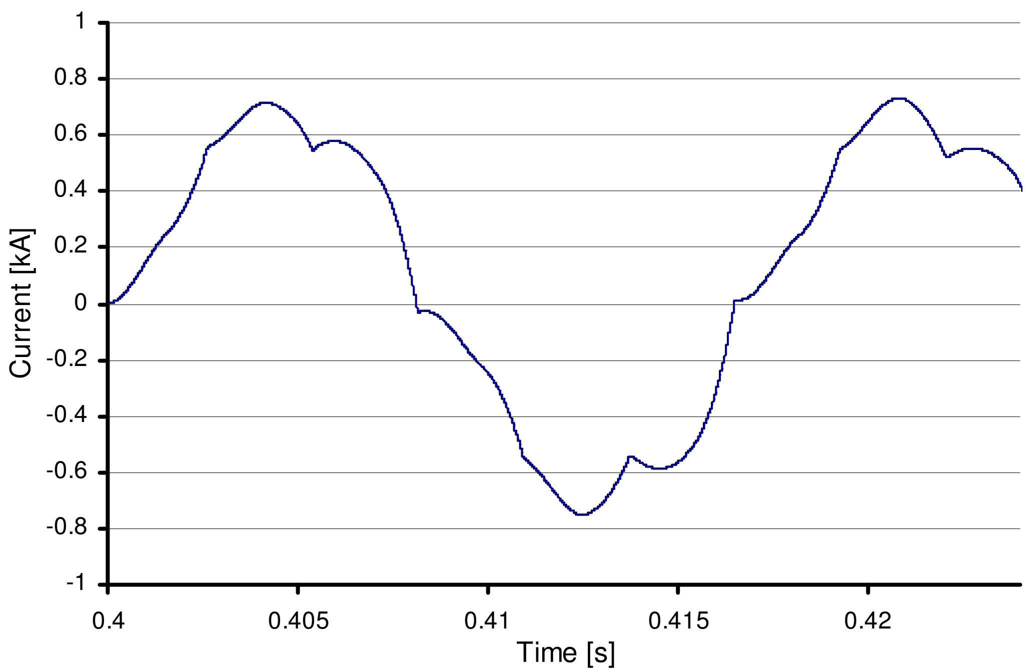


Figure 6.7: System current at the PCC – 100kVAr passive filter

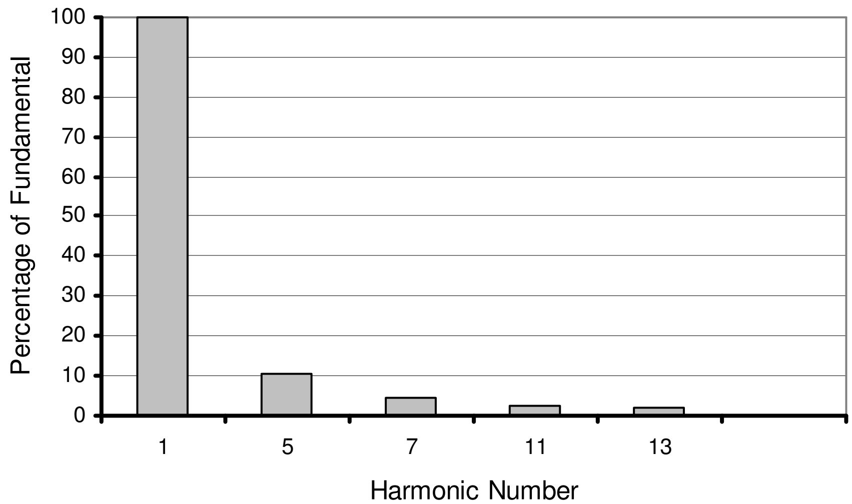


Figure 6.8: Harmonic spectrum – 100kVAr Filter

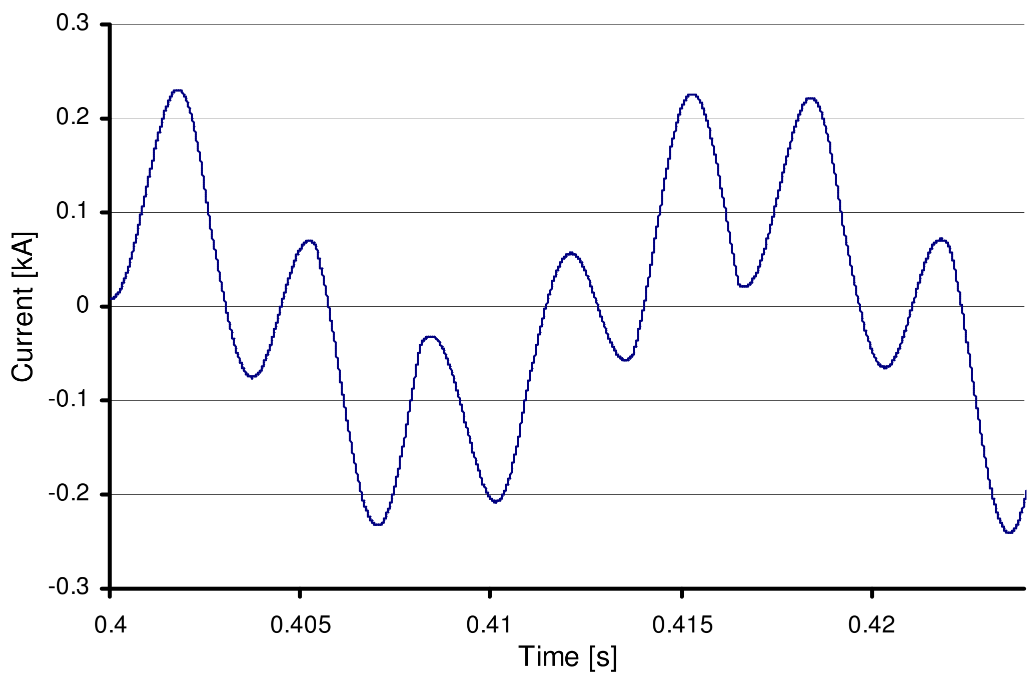


Figure 6.9: 100kVAr shunt passive filter current

The total harmonic distortion (TDD) is 11.9 %, while the displacement power factor at the PCC is 0.994 capacitive. These results indicate that although the displacement power factor is essentially unity, the harmonic distortion level at the PCC is still above the maximum 5 %

allowed by IEEE Std. 519. Any further reduction of the TDD by increasing the filter size will overcompensate the power factor.

Table 6.3 summarizes results and compares filter capacitor operating conditions against limits provided by IEEE Std. 18 (refer to Chapter 4) for a 600V rated capacitor.

Table 6.3: System performance - 100kVAr filter

Parameter	Simulation	Limit	Standard	Pass / Fail
TDD	11.9 %	5 %	IEEE Std. 519	Fail
RMS Capacitor Voltage	619V	660V	IEEE Std. 18	Pass
Peak capacitor Voltage	869V	1018 V	IEEE Std. 18	Pass
RMS Capacitor Current	124 A	130 A	IEEE Std. 18	Pass
Capacitor Reactive Power	117 kVAr	135 kVAr	IEEE Std. 18	Pass

Although simulation results places capacitor operating conditions below IEEE Std. 18 limits, the RMS capacitor current is 129% of its nominal current (96A). As a result, this filter is expected to fail prematurely. A series / parallel combination of 100kVAr capacitors will provide an equivalent capacitance (and equivalent 100kVAr reactive power) while eliminating capacitor overloads. However, this arrangement will not increase the amount of harmonic currents absorbed by the filter, as this is limited by the Q factor and filter resonant frequency.

Theoretically, a 100 kVAr filter (or any filter size) could fully compensate harmonics by combining capacitors in series and parallel (to prevent capacitor overload), minimizing the Q factor by oversizing the reactor and tuning the filter exactly to the harmonic to be eliminated (5^{th} harmonic in this case). However, as discussed in chapter 3, this practice is not recommended, as it could cause harmful parallel resonances [28].

6.5 Test Electrical System with 200 kVAr Shunt Passive Filter

Even though a 100 kVAr filter provided enough capacitive reactive power to compensate the power factor, it did not provide enough filtering to reduce harmonic levels at or below 5 % at the PCC. As a result a 200 kVAr shunt passive filter is connected at the PCC.

Figures 6.10 and 6.11 show the resulting line current and its corresponding harmonic spectrum at the PCC. Figure 6.12 shows the harmonic filter output current.

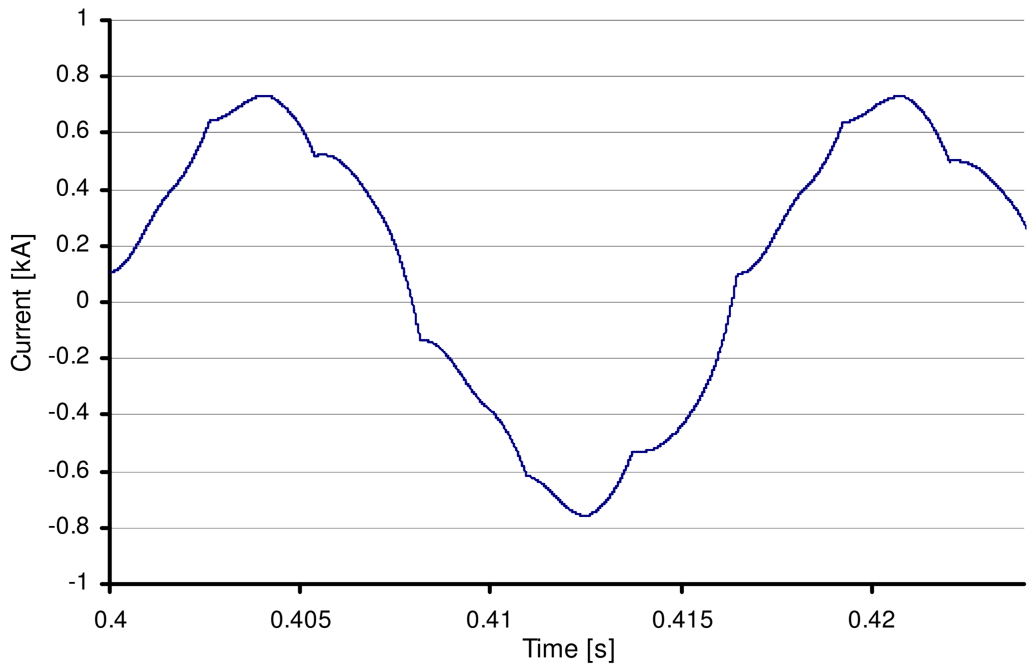


Figure 6.10: System current at the PCC – 200kVAr passive filter

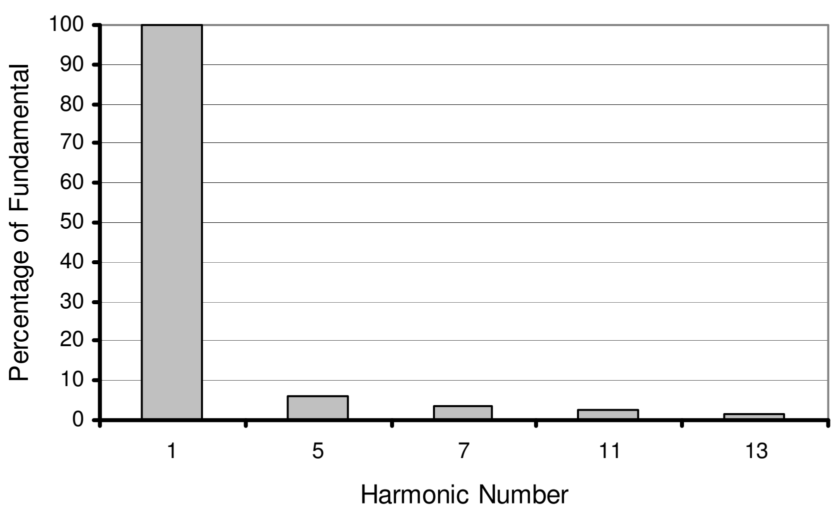


Figure 6.11: Harmonic spectrum – 200kVAr

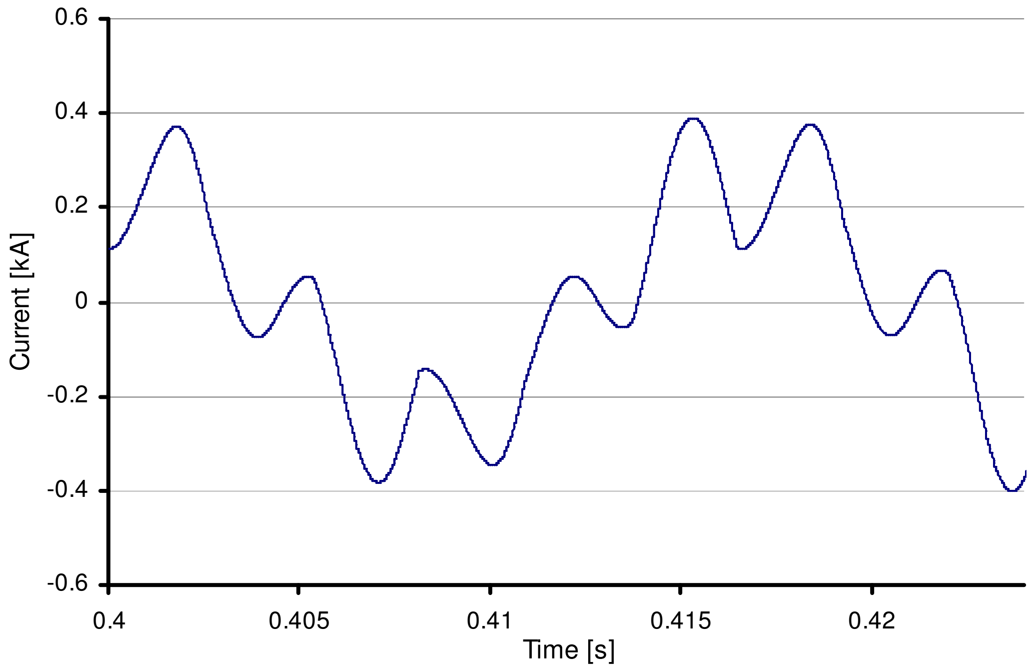


Figure 6.12: 200kVA passive filter current

With a 200 kVAr filter, the total harmonic distortion (TDD) is 7.7 % at the PCC, still higher than the target 5% maximum, while the displacement power factor is 0.98 capacitive.

Table 6.4 summarizes results and compares filter capacitor operating conditions against limits provided by IEEE Std. 18.

Table 6.4: System performance - 200kVAr filter

Parameter	Simulation	Limit	Standard	Pass / Fail
TDD	7.7 %	5 %	IEEE Std. 519	Fail
RMS Capacitor Voltage	618V	660V	IEEE Std. 18	Pass
Peak capacitor Voltage	835V	1018 V	IEEE Std. 18	Pass
RMS Capacitor Current	224 A	259 A	IEEE Std. 18	Pass
Capacitor Reactive Power	222 kVAr	270 kVAr	IEEE Std. 18	Pass

6.6 Test Electrical System with 300 kVAr Shunt Passive Filter

With the 200 kVAr passive filter failing to reduce the TDD at or below 5 % at the PCC, a 300 kVAr shunt passive filter is connected at the PCC. Figures 6.13 and 6.14 show the resulting line current and its corresponding harmonic spectrum at the PCC. Figure 6.15 shows the harmonic filter output current.

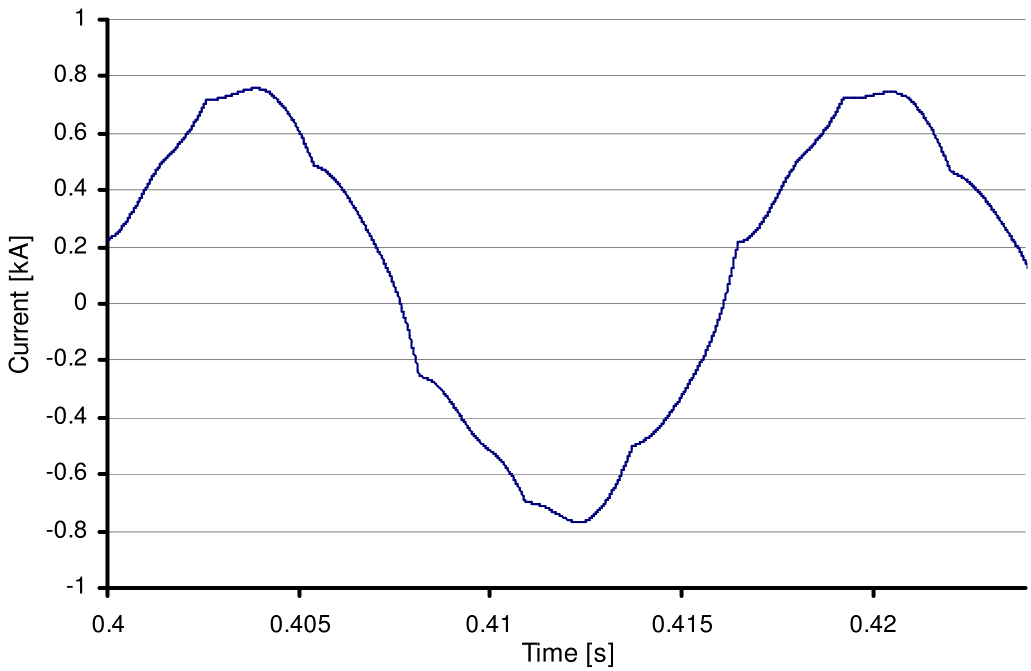


Figure 6.13: System current at the PCC – 300kVAr passive filter

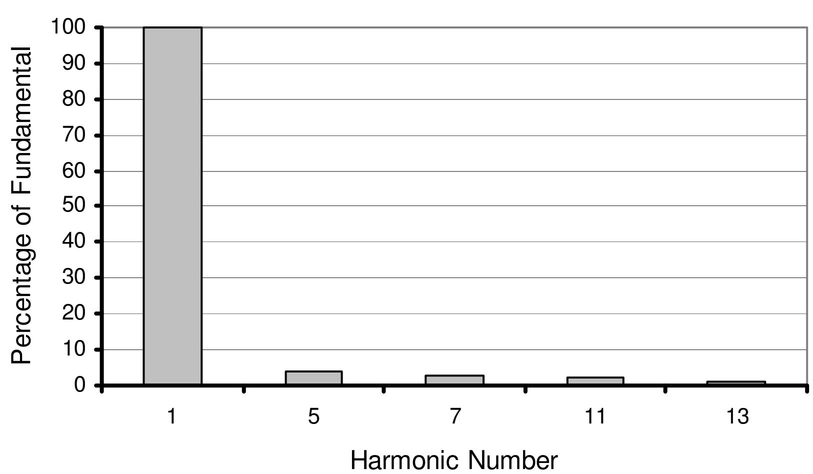


Figure 6.14: Harmonic spectrum – 300kVAr

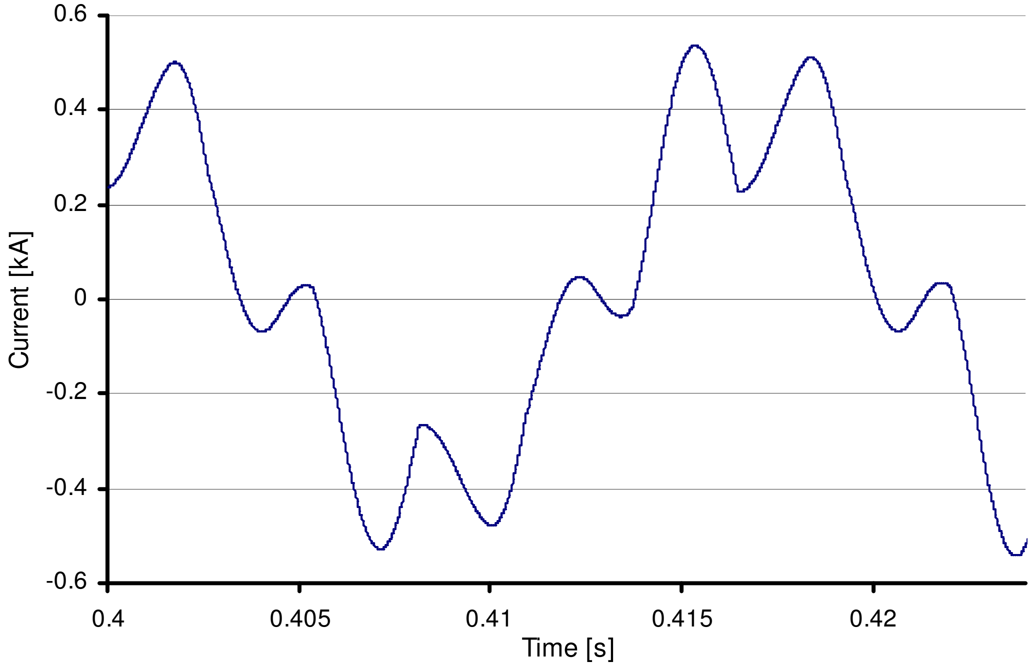


Figure 6.15: 300kVA passive filter current

The total harmonic distortion (TDD) is 5.7%, while the displacement power factor at the PCC is 0.96 capacitive. The PCC voltage fluctuation when the filter is connected is 2.7%, a value below the maximum 3% recommended by IEEE Std. 1036 in order to have a minimal effect upon customer loads.

Table 6.5 summarizes results and compares filter capacitor operating conditions against limits provided by IEEE Std. 18.

Table 6.5: System performance - 300kVAr filter

Parameter	Simulation	Limit	Standard	Pass / Fail
TDD	5.7 %	5 %	IEEE Std. 519	Fail
RMS Capacitor Voltage	623V	660V	IEEE Std. 18	Pass
Peak capacitor Voltage	838V	1018 V	IEEE Std. 18	Pass
RMS Capacitor Current	321 A	386 A	IEEE Std. 18	Pass
Capacitor Reactive Power	330 kVAr	405 kVAr	IEEE Std. 18	Pass

6.7 Test Electrical System with 400 kVAr Shunt Passive Filter

A further attempt is made to provide adequate harmonic filtering by increasing the filter's rating to 400 kVAr. With this filter, total harmonic distortion (TDD) is 5%, complying with IEEE Std. 519 requirements for this particular system. However, the displacement power factor at the PCC is 0.89 capacitive.

A direct result of this capacitive power factor is that the total rms current at the PCC when the 400 kVAr filter is connected will be 563 A, equivalent to a 113% of the nominal system current of 500 A. This overload is explained by the fact that the plant load is fully compensated in terms of reactive power. As a result, there is a net export of reactive power from the harmonic filter to the utility system. Such an overload is likely to produce equipment overheating and protective relaying tripping. The voltage fluctuation is 3.6%, a value slightly higher than the maximum 3% limit recommended by IEEE Std. 1036.

Figures 6.16 and 6.17 show the resulting line current and its corresponding harmonic spectrum at the PCC. Figure 6.18 shows the harmonic filter output current.

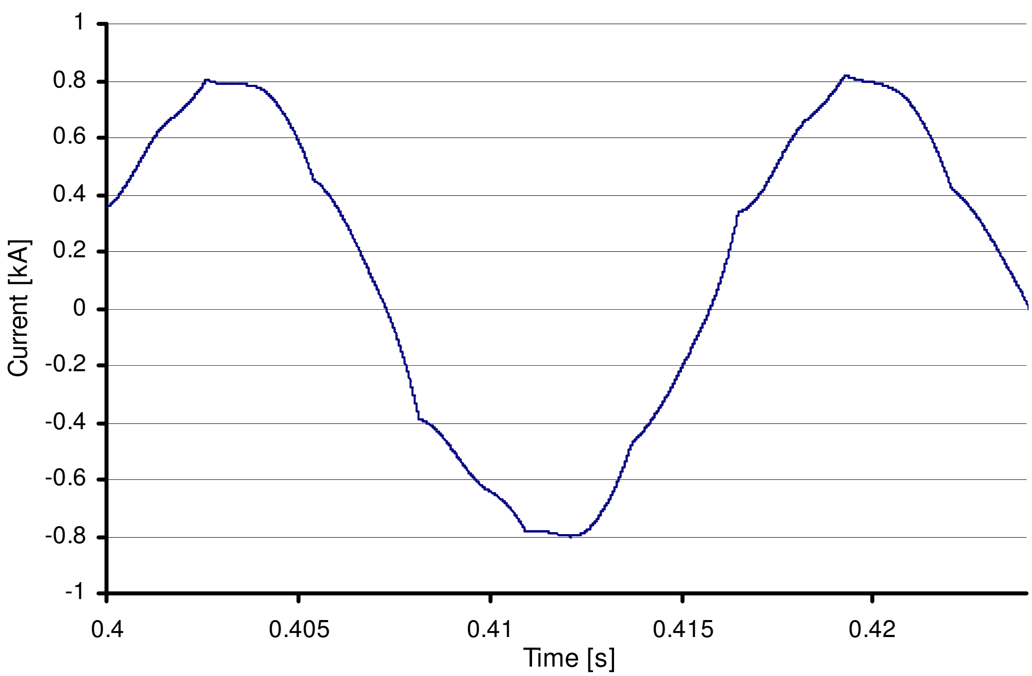


Figure 6.16: System current at the PCC – 400kVAr passive filter

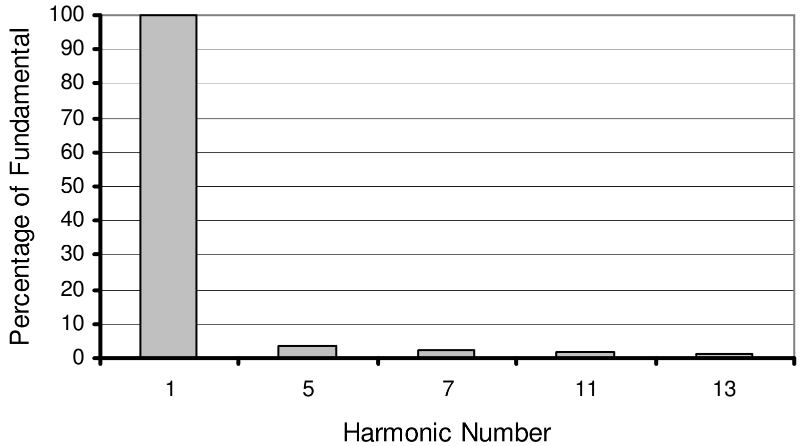


Figure 6.17: Harmonic spectrum – 400kVAr

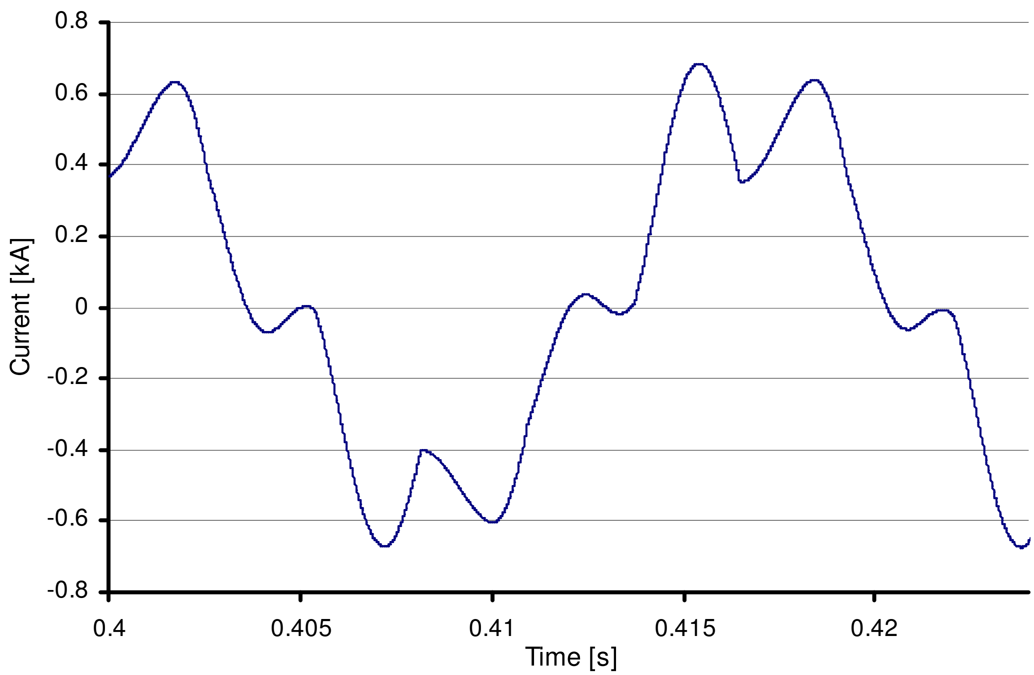


Figure 6.18: 400kVA passive filter current

Table 6.6 summarizes results and compares filter operating conditions against limits provided by IEEE Std. 18 (refer to Chapter 4) for a 600V rated capacitor.

Table 6.6: System performance - 400kVAr filter

Parameter	Simulation	Limit	Standard	Pass / Fail
TDD	5 %	5 %	IEEE Std. 519	Pass
RMS Capacitor Voltage	628 V	660V	IEEE Std. 18	Pass
Peak capacitor Voltage	843 V	1018 V	IEEE Std. 18	Pass
RMS Capacitor Current	420 A	518 A	IEEE Std. 18	Pass
Capacitor Reactive Power	445 kVAr	540 kVAr	IEEE Std. 18	Pass

While a 400 kVAr shunt passive filter provides adequate harmonic filtering performance in terms of IEEE Std. 519, it produces system overvoltages and overcurrents that are likely to produce nuisance trippings and equipment failure due to overloads. As a result, it can be concluded that for the proposed test electrical system, shunt passive filters cannot provide adequate harmonic filter performance without overloading the electrical system.

The following section analyzes the performance of the shunt active harmonic filter when connected to this test electrical system.

6.8 Test Electrical System with a Shunt Active Filter

The shunt active filter whose control algorithm was described in previous chapters is connected to the test electrical system. After connecting the shunt active filter, the total harmonic distortion (TDD) is 3.7%, complying with IEEE Std. 519 requirements for this particular system. Since the filter algorithm is designed for harmonic compensation only (i.e. the average component of the instantaneous imaginary power are not removed), the displacement power factor at the PCC remains unaffected at 0.96 inductive.

Figure 6.19 shows the resulting line current and its corresponding harmonic spectrum at the PCC, while figure 6.20 shows the current at the harmonic filter. Figure 6.21 shows the harmonic filter output current.

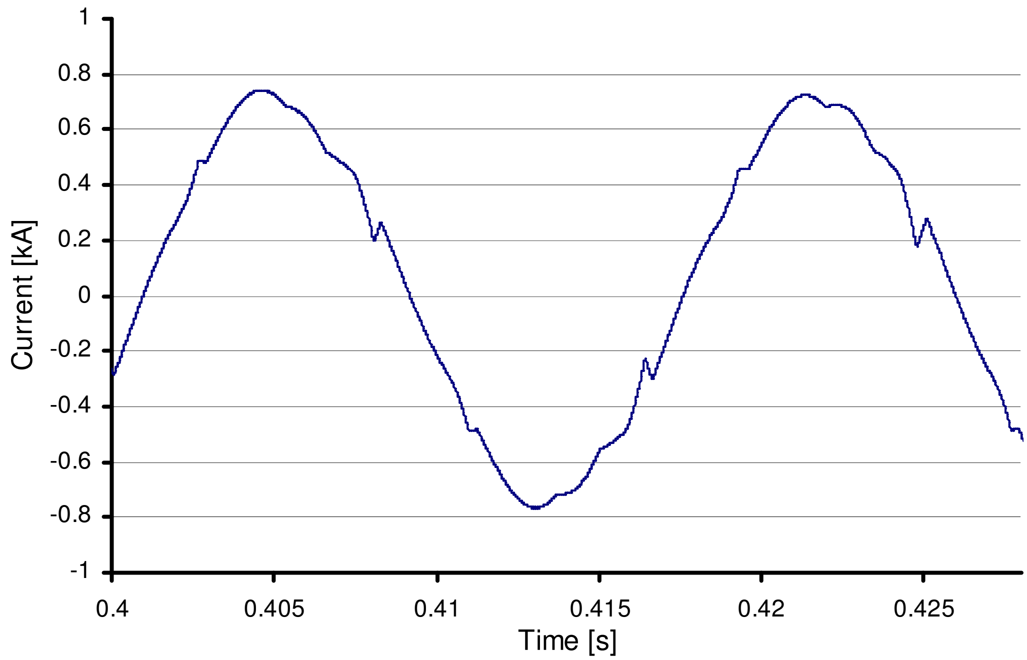


Figure 6.19: Phase A current at point of common coupling – Active filter

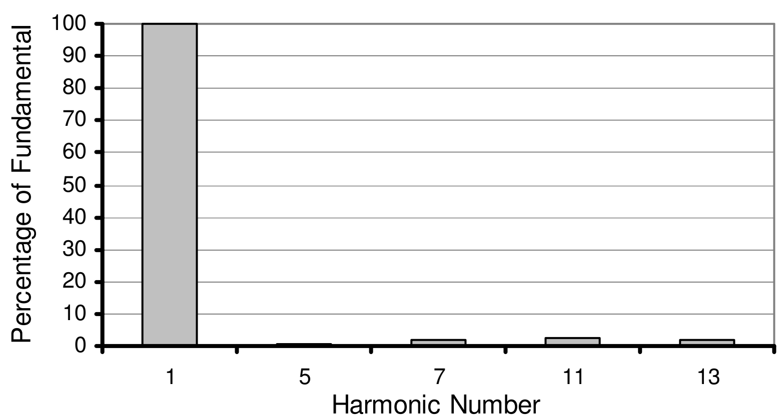


Figure 6.20: Harmonic spectrum – Active Filter

As opposed to the results obtained for the 400 kVAr shunt passive filter, no overloads are observed when the active filter is connected. The fundamental RMS current at the PCC is 505 A, while the total RMS current is 506 A. RMS voltage fluctuations at the PCC are less than 1%. As a result, it can be concluded that for electrical systems that are composed of a large percentage of

VSC-type of drives, the shunt active system technology provides a better performance than shunt passive filters.

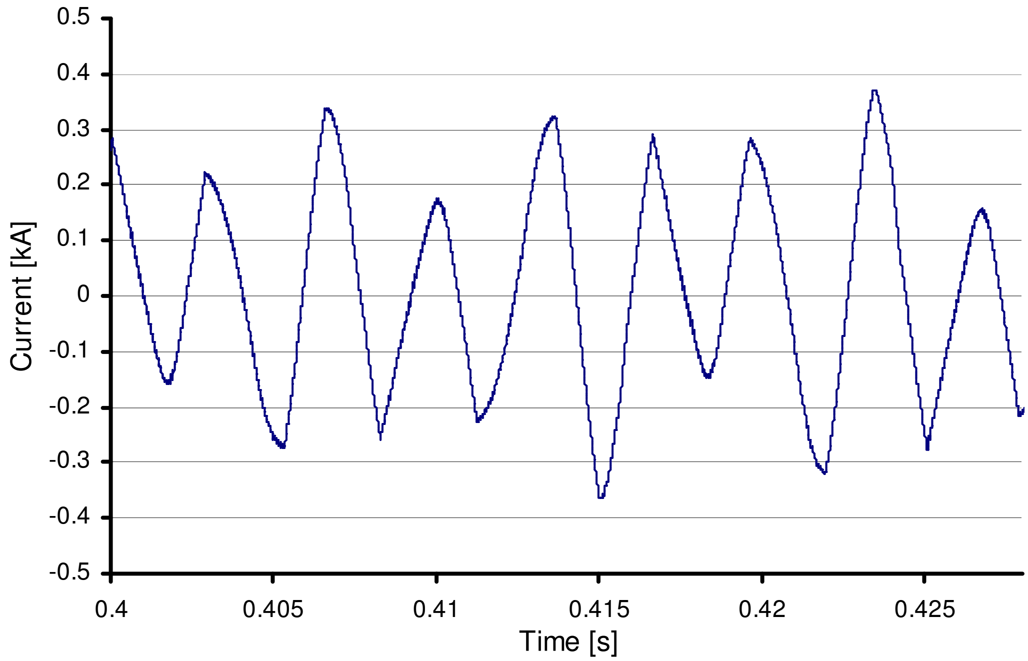


Figure 6.21: Active filter output current

So far there has not been an indication as to the current rating of the shunt active filter. By analyzing its harmonic current spectrum (Figure 6.22), this filter would need a minimum current rating of 180 A. After researching the available commercial units, it is concluded that for this application, a 200 A active filter would be required [435, 44].

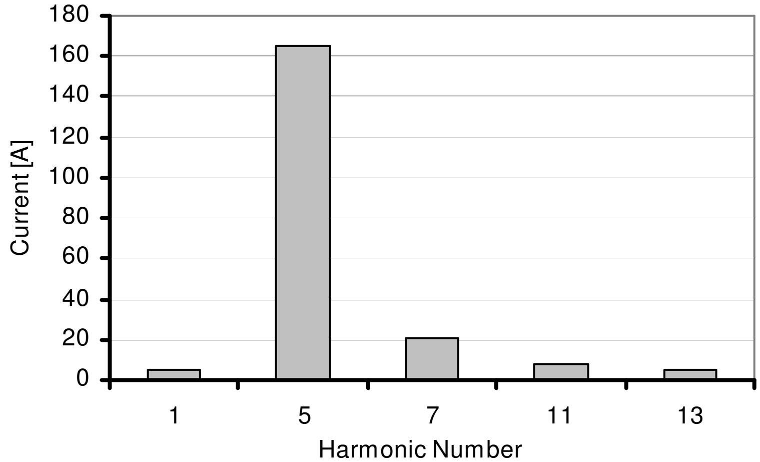


Figure 6.22: Shunt active filter harmonic spectrum

6.9 Effects of Remote Non-linear Loads on Filter Performance

It was discussed in chapter 4 that shunt passive filters are prone to overloading as a result of absorbing harmonic currents from remote sources. This section compares the performance of passive and active filters when a non-linear load is connected upstream of the PCC. Figure 6.23 shows a circuit diagram of the test electrical system with the addition of this non-linear load.

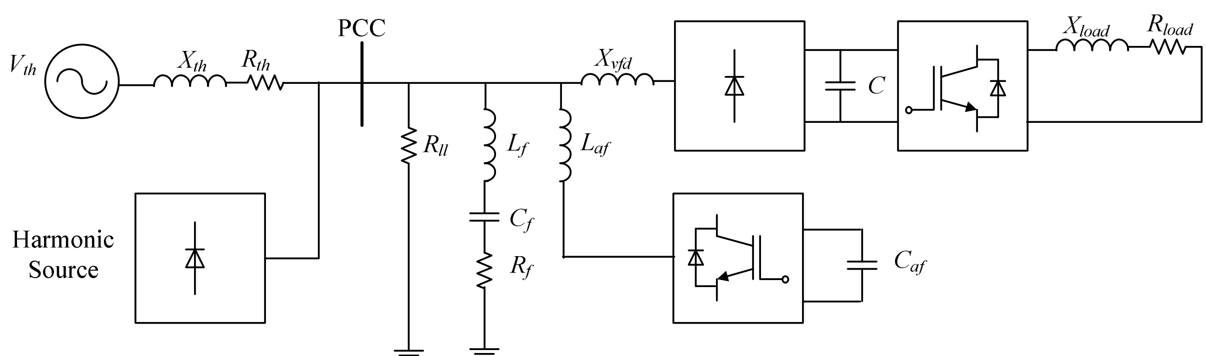


Figure 6.23: External non-linear load connected to the test system

The non-linear load connected upstream of the PPC is modeled as a VSC-type drive, whose current wave shape and harmonic spectrum are shown in Figures 6.24 and 6.25 respectively.

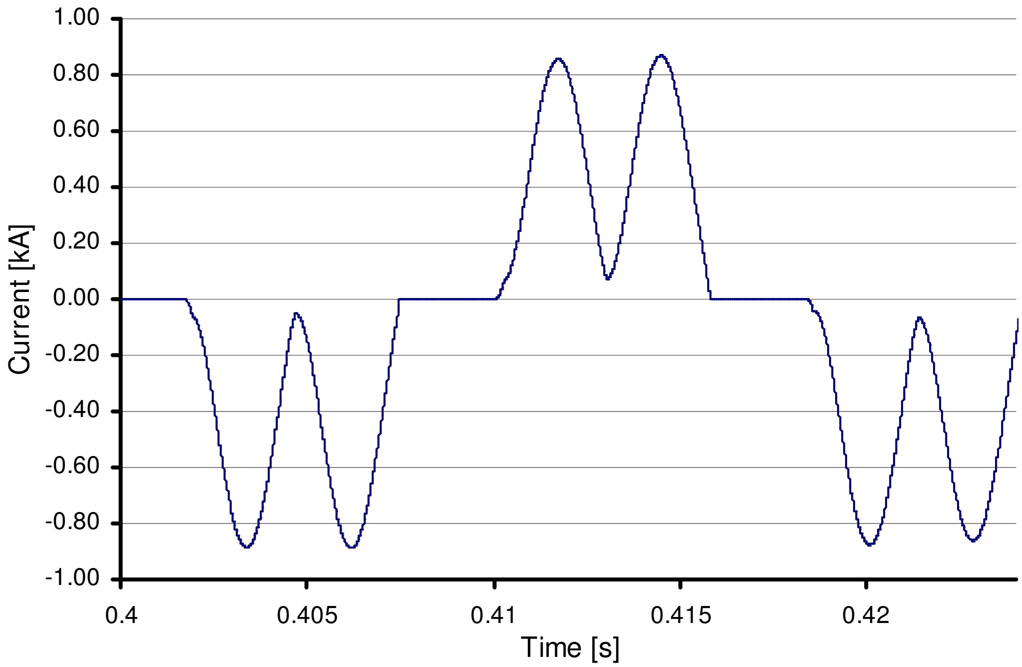


Figure 6.24: External load output current

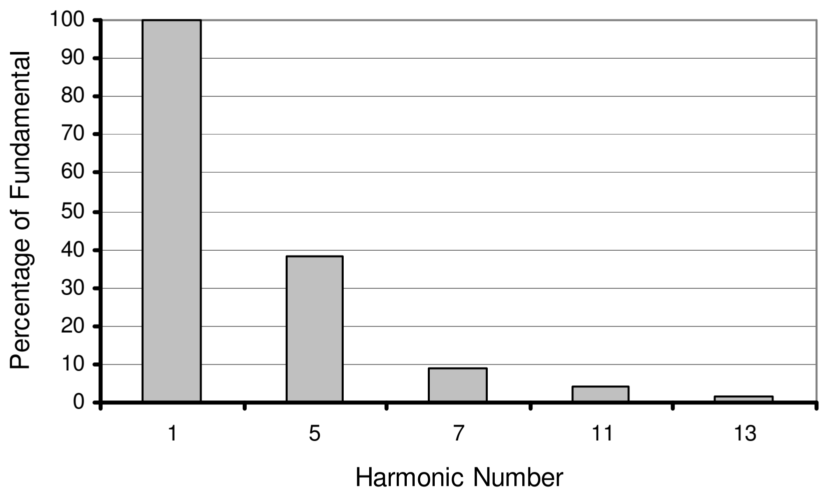


Figure 6.25: External load harmonic spectrum

6.9.1 Shunt Passive Filter Performance

A simulation case is started with a 200 kVAr shunt passive filter, after steady state is reached, the external load is connected in parallel upstream of the PCC. Table 6.7 summarizes results and compares filter capacitor operating conditions against limits provided by IEEE Std.

18 for a 600V rated capacitor. When the external non-linear load is connected, the 200 kVAr filter is overloaded as a result of absorbing a percentage of the harmonic current injected by the external load.

Table 6.7: System performance – 200kVAr filter and external load

Parameter	Simulation	Limit	Standard	Pass / Fail
RMS Capacitor Voltage	625 V	660V	IEEE Std. 18	Pass
Peak capacitor Voltage	943 V	1018 V	IEEE Std. 18	Pass
RMS Capacitor Current	283 A	259 A	IEEE Std. 18	Fail
Capacitor Reactive Power	252 kVAr	270 kVAr	IEEE Std. 18	Pass

Since harmonic limits provided by IEEE Std. 519 do not apply to harmonic currents being absorbed from the power system [22], the TDD is not determined for this case.

Figure 6.26 compares the harmonic filter currents before and after the non-linear external load was connected to the power system and Figure 6.27 shows the filter's harmonic spectrum for these conditions. The overloading condition is due to the increased absorption of the 5th and 7th harmonic by the passive filter.

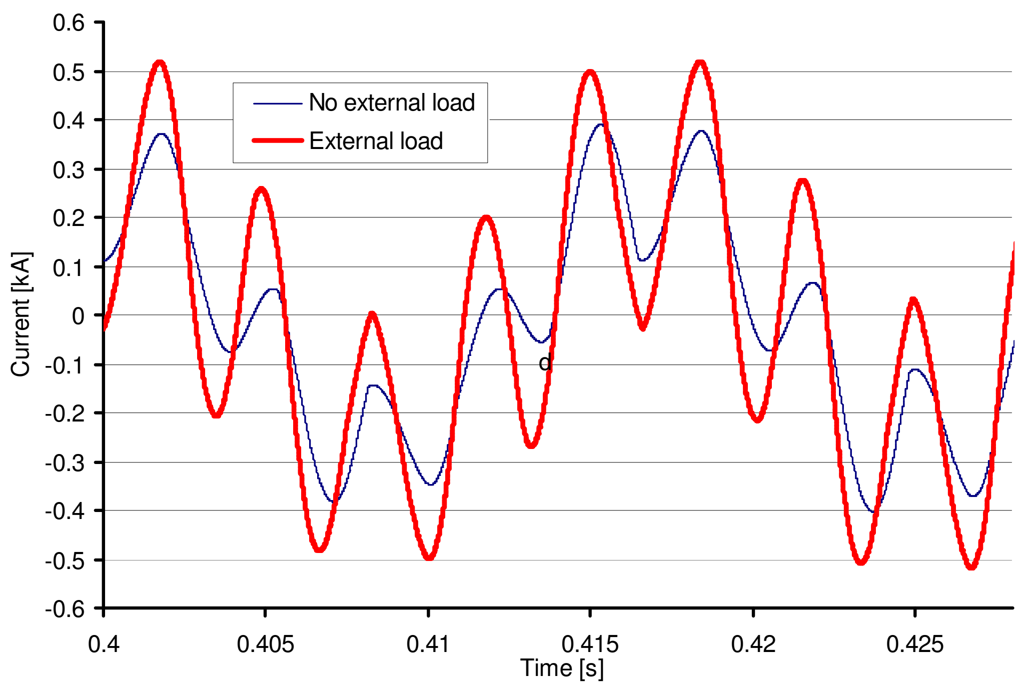


Figure 6.26: 200kVAr passive filter output current

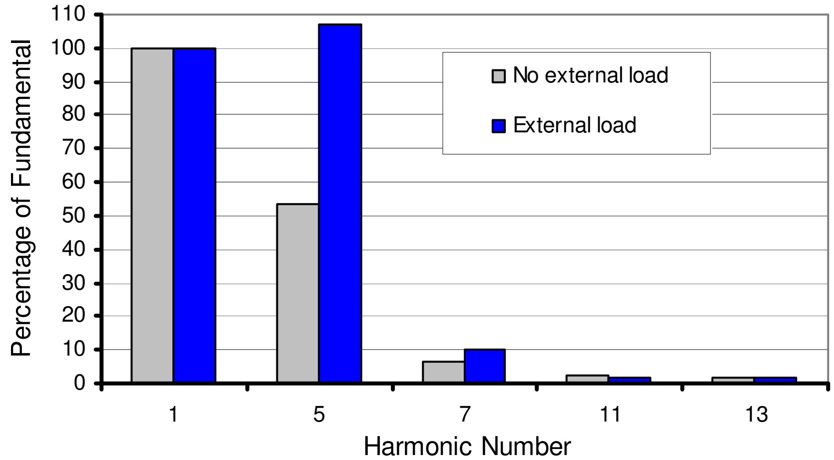


Figure 6.27: 200 kVAr filter harmonic spectrum

Filter overloading due to external non-linear loads can be further analyzed by plotting frequency response curves. Figure 6.28 shows an overlay of the shunt passive filter and the electrical system (upstream of the PCC) frequency responses.

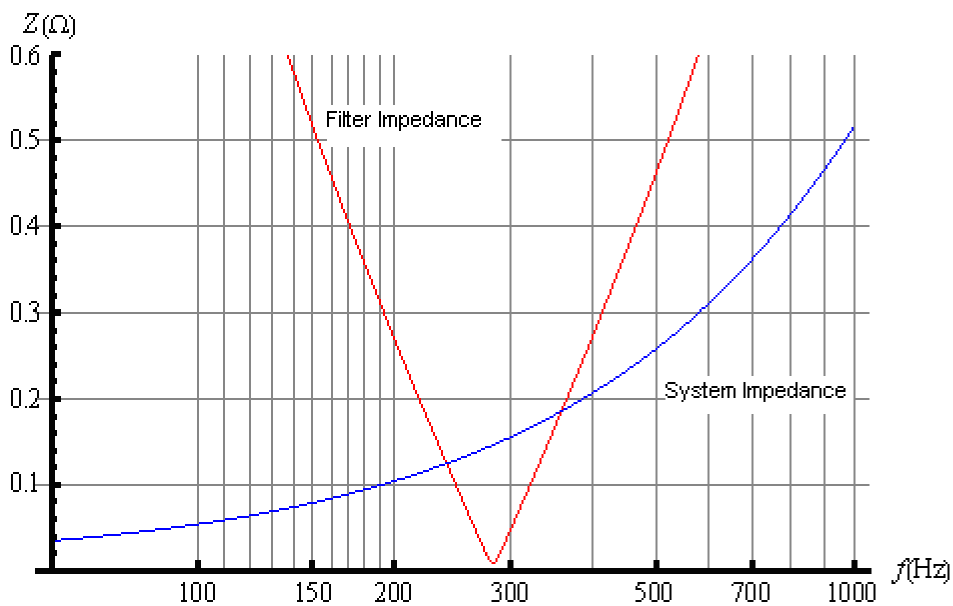


Figure 6.28: 200 kVAr filter and system frequency responses

At the frequency corresponding to the 5th harmonic (300 Hz) the filter's impedance is lower than the system's impedance. Since the filter and the system (as viewed from the external load) are in parallel, the current division will be dependent on the filter and power system impedances (the system behaves as a current divider as discussed in Chapter 4). As the filter's impedance is lower than the system's impedance, it is expected that a higher percentage of the 5th harmonic current will flow towards the filter rather than towards the system.

6.9.2 Shunt Active Filter Performance

The shunt active filter is connected at the PCC and the simulation is started; after steady state is reached, the external load is connected in parallel upstream of the PCC. The resulting active filter current is 178 A. By comparing this result to the 180 A obtained when no external load is connected (section 6.8), it can be concluded that the external non-linear load does not cause the active filter to overload. This result is explained by the fact that the active filter controller draws its reference voltage and current signals from the load it compensates (VFD in this case) and not from the external non-linear load.

Figure 6.29 shows an overlay of the shunt active filter currents with and without the external non-linear load. Although there is a phase shift between these currents and wave shapes are slightly different. The RMS values are nearly identical.

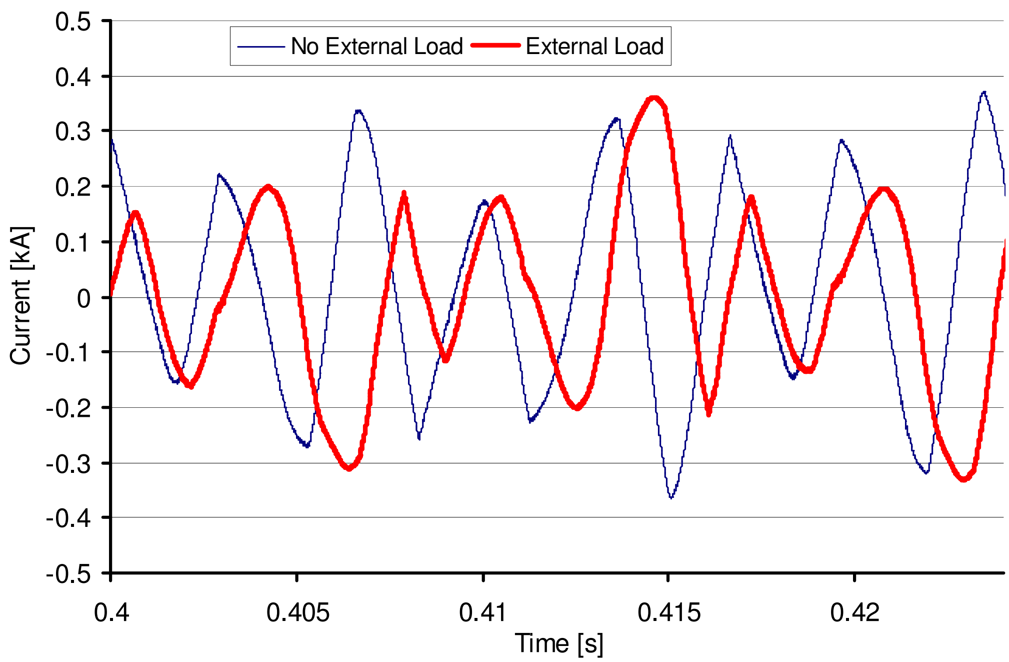


Figure 6.29: Active filter currents

6.10 Dynamic Performance of the Active Filter

When shunt passive filters are adequately sized for a given system load condition, the harmonic indices at the PCC will be within established limits. However, for fast load variations, the harmonic indices may be higher than those limits if the non-linear loads increase.

Although shunt passive filters may be composed of multiple steps that can be switched on and off depending on system requirements, the speed at which these steps can be added or removed is limited. On the contrary, since shunt active filters do not rely on mechanical switching devices, it is expected they will offer a better dynamic response than shunt passive filters. This section is dedicated to this analysis.

The fixed *RL* load connected to the VFD on the PSCAD model is replaced for a variable resistor with external controls. A simulation is then started with an initial load resistance of 2Ω and after 200 ms; it is reduced to 0.4Ω

Figure 6.30 shows an overlay of the PCC current and the VFD current. The PCC current reaches steady state in less than one cycle after the drive load is modified. This dynamic response cannot be obtained with contactor-based switched passive filters.

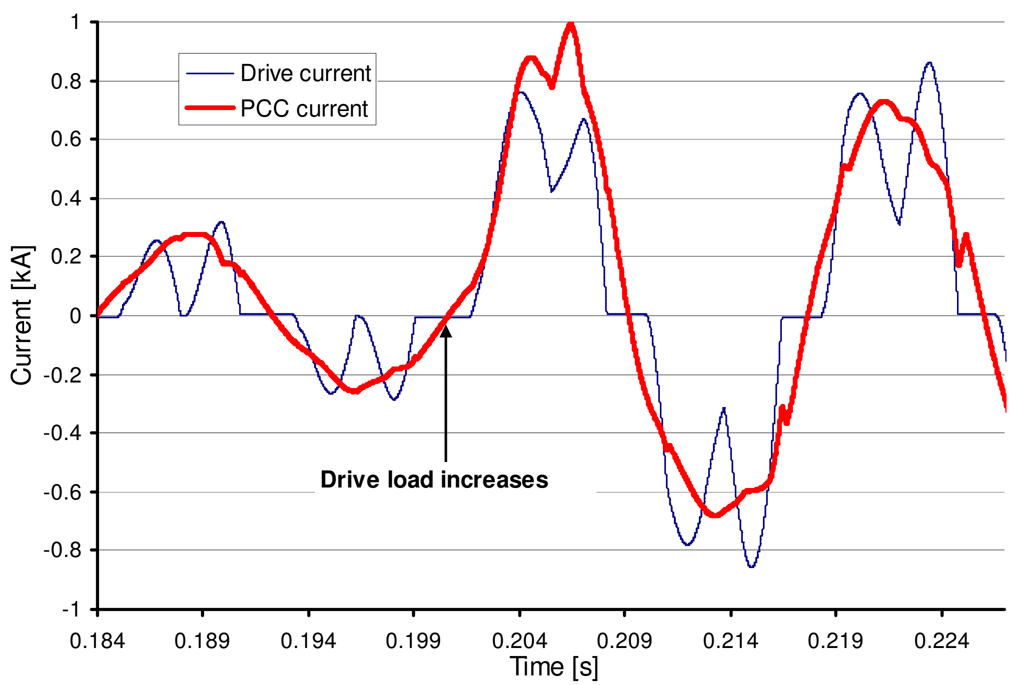


Figure 6.30: Dynamic response of active filter under non-linear load changes

6.11 Hybrid Filter Performance

As stated in chapter 4, hybrid active filters have been proposed as an alternative to pure active filters as a means of reducing the capital cost of the harmonic filtering system. This section investigates the performance of a combination of the shunt active filter that was analyzed in previous sections with a 100kVAr shunt passive filter.

Figure 6.31 shows the hybrid filter; the passive filter is connected between the non-linear load and the active filter, while the current reference for the active filter is connected upstream of the passive filter. As a result, the active filter's current reference sees a reduction on the harmonic current content due to the presence of the passive filter. Reactance X_{block} was added to prevent passive filter overloading as a result of large harmonic current being absorbed from the active filter.

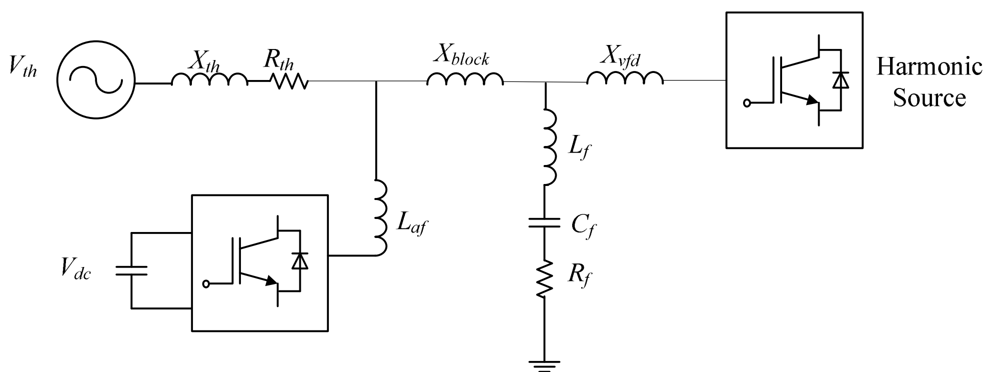


Figure 6.31: Hybrid active filter

After connecting the hybrid active filter, the total harmonic distortion (TDD) was 2.1%, slightly lower than the 3.7% obtained with the pure shunt active filter. Figure 6.32 shows the resulting line current, while figure 6.33 shows the harmonic spectrum for the pure active and hybrid active filter at the PCC.

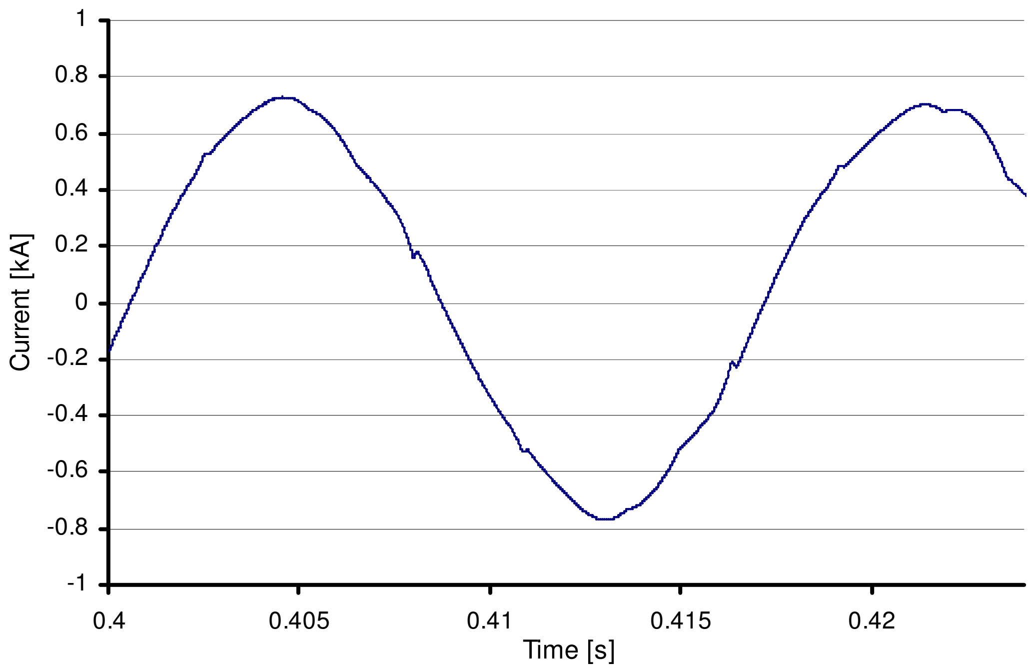


Figure 6.32: Current at PCC – Hybrid active filter

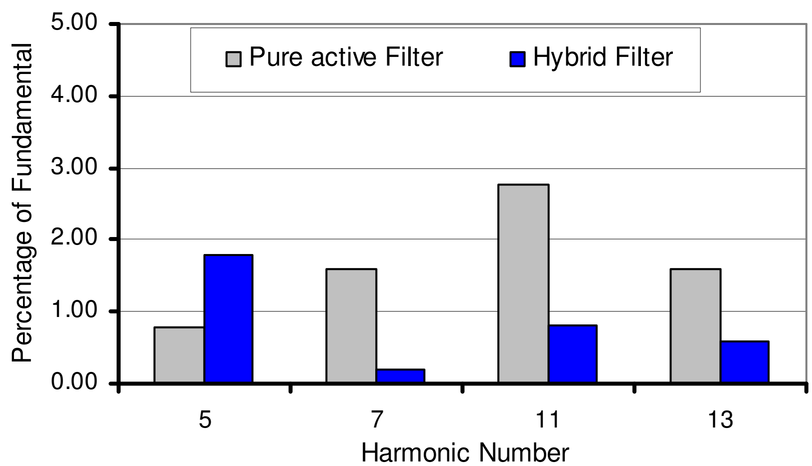


Figure 6.33: Harmonic spectrum at PCC – Active and hybrid filters

Figure 6.34 compares the harmonic current output of the pure active and hybrid filters. The addition of the 100kVAr passive filter has decreased the output current of the active filter to 58% of the pure active filter (105A for the hybrid filter against 180A of the pure active filter).

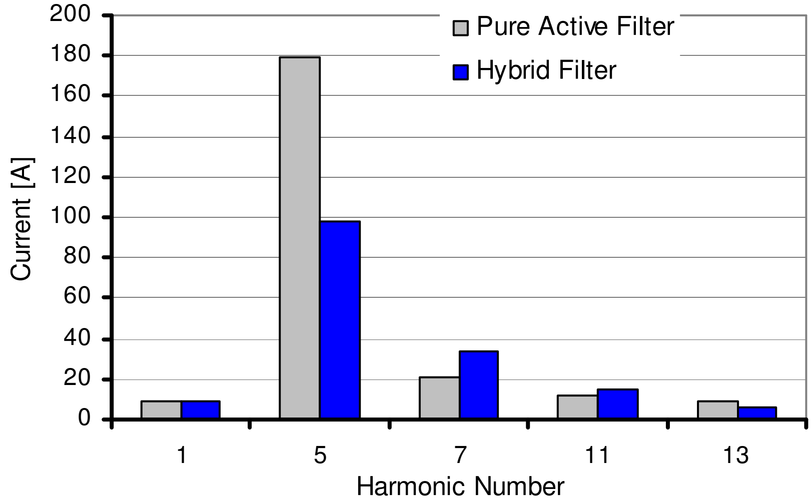


Figure 6.34: Harmonic components of active and hybrid filters

For a given size of harmonic filter, the active filter technology is expected to require a capital investment of approximately three times more than that required for a switched passive filter. As a result, any reduction in the size of the active filter, by adding a passive filter will result in an overall lower capital investment.

CHAPTER 7: CONCLUSIONS

7.1 Contributions

This thesis discussed the effects on power systems of harmonic currents generated by modern industrial facilities, where the load is composed of a large percentage of VSC type of VFDs. A test system composed of 90% of non-linear loads was modeled in PSCAD, and its resulting TDD at the point of common coupling was compared against industry recognized harmonic standards to assess the requirements of harmonic mitigation.

After harmonic mitigation requirements were established, several attempts were made to provide for harmonic compensation by the sole use of shunt passive filters.

Following the benchmarking of the passive filters, a shunt active filter whose control algorithm was based on the Instantaneous Power Theory, was modeled in PSCAD and cross-checked against a mathematical model built in Wolfram Mathematica. After checking the control algorithm, the shunt active filter was connected to the test electrical system. The simulation results obtained for the active filter were compared against results obtained for shunt active filters.

This work proved that when the harmonic producing load is largely composed of VSC-type drives, single tuned shunt passive filters readily available in the market may not be able to reduce the TDD to levels below the limits provided by harmonic standards without overloading the electrical system and overcompensating power factor.

Computer simulations for the active filter connected to the test electrical system proved that it was possible to comply with harmonic limits. Furthermore, it was shown that the active filter control algorithm was able to respond to non-linear load changes and reach steady state in less than one cycle.

The performance of passive and active filters was also assessed under the presence of external (i.e. upstream of the PCC) non-linear loads. Computer simulations confirmed the immunity of active filters to overloading due to the presence of such loads; while it was proved that the presence of non-linear loads upstream of the PCC should not be overlooked when a passive filter is designed.

A hybrid active harmonic filter composed of a shunt active filter and a shunt passive filter was modeled and connected to the test electrical systems. Simulation results showed that this arrangement can provide for adequate harmonic compensation while reducing the initial capital cost of the overall harmonic mitigation system. Computer simulations proved that it is possible to combine a shunt passive filter and a shunt active filter without harmonic interactions between the active and passive component that results in passive filter overloading.

7.2 Future Work

Although the shunt active filter successfully filtered harmonic currents to levels below the limits of industry standards, it did not provide power factor correction. The active filter's control algorithm could be improved to add this capability. Furthermore, the control algorithm could include capabilities to compensate for unbalanced loads.

Hybrid harmonic filter topologies could be optimized to obtain active and passive filters ratings that minimize the initial capital cost for the harmonic mitigation system. This would also require assessing the effects of external non-linear loads on the passive filter component of the hybrid filter (i.e. overloading).

The footprints of a given VSC-type VFD and the commercially available shunt active filter that would provide adequate harmonic compensation are similar [29, 30]. Research in drive and filter topologies could lead to improved designs where these devices share common components, such as the DC link capacitor, aiming at reducing the overall footprint. A successful result of these investigations could lead to a commercial design of a VSC-type VFD that has built in a shunt active filter. As a result, a 6 –pulse drive with a built in active filter could be connected to given power system without the potential of exceeding harmonic limits.

In summary, this work discussed the effects of harmonic currents generated by a model test electrical distribution system typically encountered in modern industrial operations, where the load is composed of a large percentage of VSC type of VFD's. Attempts were made to filter harmonics by the sole use of shunt passive filters. These work proved the difficulties presented for harmonic elimination with passive filters when the non-linear loads involved have an inherent high power factor.

An active shunt active filter was subsequently modeled in PSCAD and validated against a mathematical model. This filter was connected to the model electrical system, successfully reducing harmonic levels below limits set by industry standards.

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