ENERGY LOSS MINIMISING FUNCTION OF VARIABLE SPEED DRIVE FILTERS

A thesis submitted in fulfilment of the requirements
for the degree of Master of Engineering

Hong Cheng
B. Eng.

School of Electrical and Computer Engineering
Science, Engineering and Technology Portfolio
RMIT University

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and, any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Hong Cheng

22/8/2008

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List of symbols and abbreviations

Symbols

F_{dist}	Distortion power factor
ϕ_1	Displacement angle
$I_{1\ (rms)}$	RMS value of fundamental input current
I_1	Peak value of fundamental input current
I_{R1}	RMS value of input current without filters
L_s	Source inductance
I_{L11}	RMS value of input current with filters

Abbreviations

VSD	Variable speed drive
TPF	True power factor
RMS	Root mean square
THD	Total harmonic distortion
PCC	Point of common coupling
PF	Power factor
DPF	Displacement power factor

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Abstract

With their many benefits, Variable Speed Drives (VSDs) have grown rapidly in their usage in recent years. However, a unfortunate side effect of their usage is the introduction of harmonic distortion in the power system and reduction of true power factor (TPF). Low true power factor means poor electrical efficiency. The lower the true power factor, the higher the apparent power drawn from the distribution network.

A filter connected at the input side of a VSD converter reduces energy losses in the power supply system by reducing harmonics and improving the true power factor. In this thesis, a typical three-phase rectifier is used as an example to present a methodology of designing such filters in technical and economic terms. The relationship between the cost of input filters and the energy cost reduction they provide on the power supply side of VSDs is discussed. By extending the same method to different loads, filters are designed and power savings are calculated. The pricing of relevant harmonic filters is also discussed.

The basics of harmonics and the power factor are presented in the introduction. The summary of the results and suggestions for further research are contained in the last sections of the thesis.

Chapter 1

Introduction

1.1 Research Objective

1) To develop a methodology of designing filters that meet technical and economic requirements.
2) To determine the relationship between the cost of an input filter and the energy cost reduction it provides on the power supply side.

1.2 Introduction to Variable Speed Drives (VSDs)

Variable speed drives with induction motors are widely utilized in industry. They can improve product quality, increase equipment life and decrease maintenance costs. Variable speed drives are an essential part of process control systems. Variable speed drives can reduce noise levels, save annual electricity costs, and increase efficiency. The main components of a variable speed drive are a rectifier, an inverter, a control circuit and an induction motor as shown in figure 1.1[1].

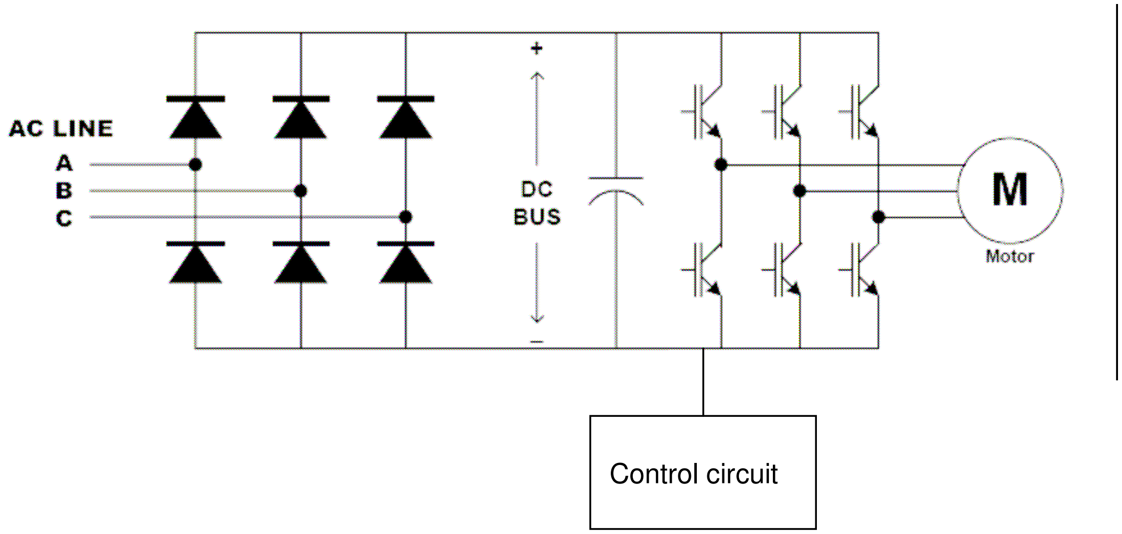


Figure 1.1 Typical configuration of a VSD with an induction motor

Adding a variable speed drive to a motor-driven system can offer potential energy savings in a system in which the loads vary with time. The operating speed of the motor in a variable speed drive is varied by changing the frequency and voltage of the motor power supply. This allows continuous speed control. The ability to adjust motor speed enables closer matching of the motor output to the load, and often results in energy savings.

Induction motors, the workhorses of industry, rotate at a speed that is determined by the frequency of the supply voltage. Alternating current applied to the stator windings produces a magnetic field that rotates at synchronous speed. This speed may be calculated by dividing line frequency by the number of magnetic pole pairs in the motor winding. A four-pole motor, for example, has two pole pairs, and therefore the magnetic field will rotate 50 Hz / 2 = 25 revolutions per second, or 1500 rpm. The rotor of an induction motor will attempt to follow this rotating magnetic field, and, under load, the rotor speed "slips" slightly behind the rotating field. This small slip results in currents being induced in the rotor. The rotor currents interact with the magnetic field in the air gap to produce the torque.

Since an induction motor rotates near synchronous speed, the most effective and energy-efficient way to change the motor speed is to change the frequency of the applied voltage. Variable speed drives convert the fixed-frequency supply voltage to a continuously variable frequency, thereby allowing adjustable motor speed. A variable speed drive converts 50 Hz power to a new frequency in two stages: the rectifier stage and the inverter stage.

Rectifier stage:

A full-wave rectifier converts the three-phase voltage from utility supply to either fixed or adjustable DC voltage. The system may include transformers if higher supply voltages are used.

Inverter stage:

The electronic switches (power transistors in the inverter) switch the rectified DC voltage in a Pulse Width Modulation pattern to produce a current and voltage waveforms at the desired new frequency.

Control system:

An electronic circuit receives main speed and current from the driven motor and adjusts the output voltage and frequency to the selected values. Usually the output voltage is regulated to produce a constant ratio of voltage to frequency (V/Hz). Controllers may incorporate many complex control functions.

In addition, variable speed drives can provide other benefits:

- A variable speed drive may be used for control of process temperature, pressure or flow without the use of a separate controller. Suitable sensors and electronics are used to interface the driven equipment with the variable speed drive.
- Eliminating the throttling valves and dampers also does away with maintaining these devices and all associated controls.
- A soft starter for the motor is no longer required.
- Controlled ramp-up speed in a liquid system can eliminate water hammer problems.
- The ability of a variable speed drive to limit torque to a user-selected level can protect driven equipment that cannot tolerate excessive torque [2], [24].

However, an unfortunate side effect of variable speed drives' usage is the production of harmonic distortion in the power system. As a non-linear load, a variable speed drive draws a non-sinusoidal current, rich in harmonic components. These harmonics flow through the power system where they can distort the supply voltage, overload electrical distribution equipment (such as transformers) and resonate with power factor correction capacitors and cause other problems [3].

The efficiency of variable speed drives can be improved by a) appropriate motor selection and design; b) utilization of a suitable control method; c) improvement of the input and output waveforms of the converter [1]. In the last case above, the reduction of energy losses is achieved through the use of filters. This thesis will focus on the input filters of variable speed drives, as a means of minimising the total energy losses due to the operation of variable speed drive systems. Different types of harmonic filters are presented in the following section.

1.3 Types of Harmonic Filters

1.3.1 Introduction

Filters are designed to selectively filter one frequency or range of frequencies out of a mix of different frequencies in a circuit. Harmonic Filters are broadly classified into two types namely

- Active harmonic filters
- Passive harmonic filters

A. Active harmonic filter

The harmonic current produced due to the load is monitored by the filter. It generates a waveform that is of opposite phase to the harmonic current of the nonlinear load. When connected, the filter injects the current into the load and thus reduces the harmonic in the power system [4].

B. Passive harmonic filter

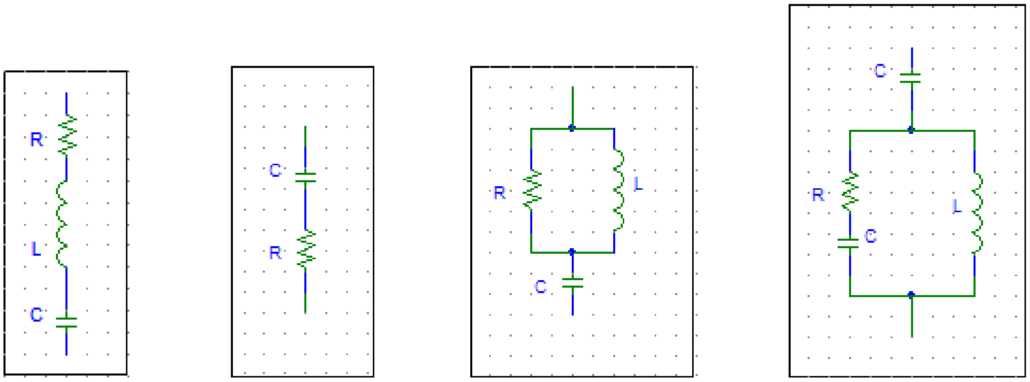
The shunt filter works by short-circuiting harmonic currents as close to the source of distortion as practical. This keeps the currents out of the supply system. This is the most common type of filtering applied because of economics and because it also tends to correct the load power factor as well as remove the harmonic current. Another approach is to apply a series filter that blocks the harmonic currents. This is a parallel-tuned circuit that offers high impedance to the harmonic frequency current [5].

1.3.2 Types of Passive Harmonic Filters

Passive filters consist of inductance, capacitance, and resistance elements connected in configurations that help to control harmonics. They are commonly used and are relatively inexpensive compared with other means of eliminating harmonic distortion. However, they have the disadvantage of potentially interacting adversely with the power system if selected improperly. Figure 1.2 shows several types of shunt filters.

A. Shunt passive filters

The most common type of passive filter is the single-tuned filter. The filter is series-tuned to present low impedance to a particular harmonic current, and is connected in shunt with the power system. Thus, harmonic currents are diverted from their normal flow path on through the filter. Shunt filters can provide power factor correction in addition to harmonic suppression. In fact, power factor correction capacitors may be used to make shunt filters.



Single-tuned 1ST-order high-pass 2nd-order high pass 3rd-order high-pass

Figure 1.2 Common shunt passive filter configurations

One important side effect of this type of filter is that it creates a sharp parallel resonance point at a frequency below the notch frequency. This resonant frequency must be safely away from any significant harmonic or other frequency component that may be produced by the load. Ideally, the filter must be tuned exactly to the characteristic harmonic it is supposed to suppress. For example, for a three-phase, six-pulse variable speed drive, the 5th and 7th harmonic filters are most effective when tuned exactly to 250 Hz and 350Hz. Practically, however, the filters are tuned to a frequency slightly lower than the nominal resonant frequency in order to avoid the possibility of parallel resonance in case the filter component parameters change due to temperature and aging. Most low and medium voltage harmonic filters are usually tuned to about 0.94 times the nominal resonant frequency.

Also, to avoid problems with this resonance, filters are added to the system starting with the lowest significant harmonic found in the system. For example, installing a seventh-harmonic filter usually requires that a fifth-harmonic filter also be installed. The new parallel resonance with a seventh-harmonic filter alone is often very near the fifth, which is generally disastrous [5], [6], [14], [21].

B. Series passive filters

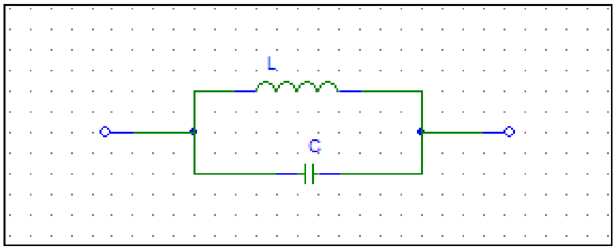


Figure 1.3 A series passive filter

Unlike a shunt filter which is connected in shunt with the power system, a series passive filter is connected in series with the load. The inductance and capacitance are connected in parallel and are tuned to provide high impedance at a selected harmonic frequency. The high impedance then blocks the flow of harmonic current at the tuned frequency only. At fundamental frequency, the filter would be designed to yield low impedance, thereby allowing the fundamental current to flow with only minor additional impedance and losses. Figure 1.3 shows a typical series filter arrangement.

Series filters are used to block a single harmonic current (such as the third harmonic) and are especially useful in a single-phase circuit where it is not possible to take advantage of zero-sequence characteristics. The use of the series filter is limited in blocking multiple harmonic currents. Each harmonic current require a series filter tuned to that harmonic. This arrangement can create significant losses at the fundamental frequency.

Further more, like other series components in power systems, a series filter must be designed to carry a full rated load current and must have an over current protection scheme.

C. low-pass filters

Multiple stages of both series and shunt filters are often required in practical applications. For example, in shunt filter applications, a filter for blocking a seventh-harmonic frequency would typically require two stages of shunt filters, the seventh-harmonic filter itself and the lower fifth-harmonic filter. Similarly, in series filter applications, each frequency requires a series filter of its own; thus, multiple stages of filters are needed to block multiple frequencies.

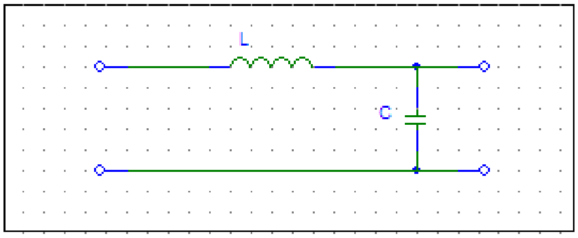


Figure 1.4 A low-pass filter configuration

In most power system loads, harmonics have a wide range of frequencies. A six-pulse converter generates characteristic harmonics of 5th, 7th, 11th, 13th, etc.

Power electronic converters can essentially generate time-varying inter harmonics covering a wide range of frequencies. Designing a shunt or series filter to eliminate or reduce these widespread and time-varying harmonics would be very difficult. Therefore, an alternative harmonic filter must be devised.

For general usage in electric circuits, low-pass filters are composed of series inductors and parallel capacitors. This LC combination provides a low-impedance path to ground for selected range of frequencies. A low-pass filter is an ideal application to block multiple or widespread harmonic frequencies. The current frequency components below the filter cut-off frequency can pass; however, the frequency components above the cut-off frequency are filtered out. A typical configuration of a low-pass filter is shown in figure 1.4 [5], [6].

In industrial system applications, commercial low-pass filters have been used to prevent harmonics produced by nonlinear loads from entering the ac system. The cut-off frequency for a low-pass filter for variable speed drive applications is typically designed at a low harmonic frequency, such as at 100 to 200 Hz on a 50-Hz system and that means the tuned frequency is between 2 to 4 times of the fundamental frequency of the design system. With this low tuning frequency, the filter is unlikely to excite any undesired resonance with the rest of the system and can filter out much of the harmonic currents. In variable speed drive applications, the filter can generally reduce the overall current harmonic distortion from the 90 to 100 percent range down to the 5 to 12 percent range under rated load conditions. This performance is certainly much better than a simple ac line choke, which only reduces the overall current distortion down to the 30 to 40 percent range.

1.4 Outline of the Thesis

This thesis contains seven chapters. They present theoretical considerations and simulation and computation results.

The aim of variable speed drive harmonic filters is to reduce harmonics of input current and improve the power factor of power supply. Therefore, in chapter 2 and chapter 3, the basic of harmonics and the power factor are presented. Chapter 4 contains simulation results of a typical three-phase rectifier with a focus on total harmonic distortion and true power factor. Chapter 5 introduces detailed procedure for designing a low-pass passive harmonic filter. Chapter 6 presents analysis of savings that may result from the installation of filters. Chapter 7 concludes the thesis with suggestions for further research.

Chapter 2

Introduction to Harmonics

2.1 Introduction

Harmonics are often viewed as a relatively new phenomenon. However, harmonics have been around since waves were first used in the 1930s. Aside from grounding, many deem harmonics as one of the greatest concerns about the power quality today [25]. In this chapter, the fundamentals of harmonics and the problems they can cause within the power system will be discussed.

2.2 Definition of Harmonics

A sinusoidal voltage or current function that is dependent on time *t* may be represented by the following expressions:

$$\text{Voltage function, } v(t) = V \sin(\omega t) \tag{2.1}$$

$$\text{Current function, } i(t) = I \sin(\omega t + \phi) \tag{2.2}$$

Where $\omega = 2 \times \pi \times f$ is known as the angular velocity of the periodic waveform and ϕ is the difference in phase angle between the voltage and the current waveforms. The sign of phase angle ϕ is positive if the current leads the voltage and negative if the current lags the voltage.

A periodic nonsinusoidal waveform, such as that shown in figure 2.1 can be represented in general by following Fourier expression:

$$v(t) = V_1 \sin(\omega t) + V_2 \sin(2\omega t) + V_3 \sin(3\omega t) + \ldots + V_n \sin(n\omega t) + V_{n+1} \sin((n+1)\,\omega t) + \ldots \tag{2.3}$$

In the above infinite series, $V_1, V_2, V_3, \ldots, V_n$ are the peak values of the successive terms of the expression. The terms are known as the harmonics of the periodic waveform. The fundamental (or first harmonic) has a frequency of *f*, the second harmonic has a frequency of 2×*f*, and the *n*th harmonic has a frequency of *n*×*f*.

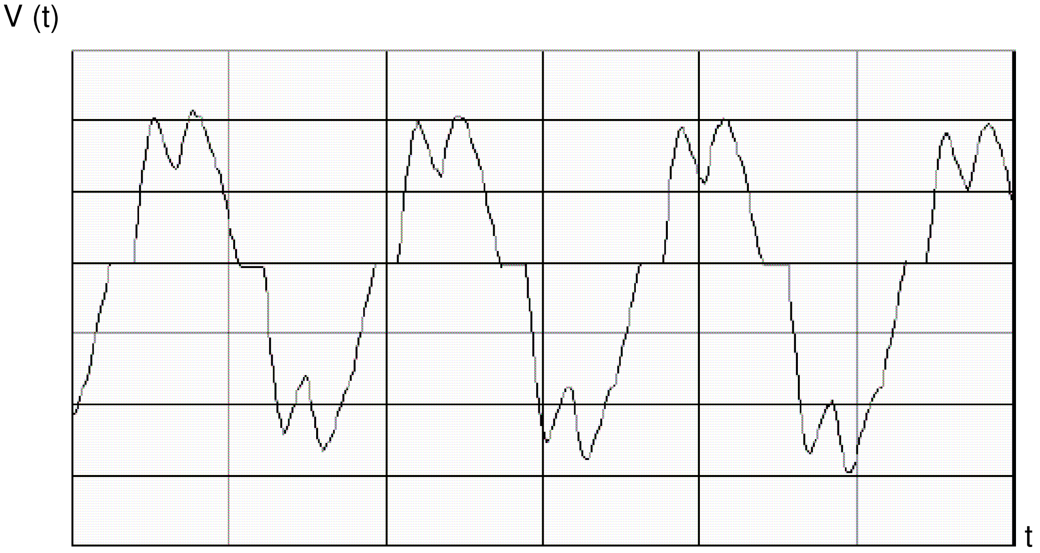


Figure 2.1 Nonsinusoidal voltage waveform [7]

In order to find the effect of a nonsinusoidal voltage or current on a piece of equipment, we only need to determine the effect of the individual harmonics, and then sum the results to find the net effect. Figure 2.2 illustrates how individual harmonics that are sinusoidal can be added to form a nonsinusoidal waveform [7].

2.3 Harmonic Number (*h*)

Harmonic number (h) refers to the individual frequency elements that comprise a composite waveform. For example, h= 5 refers to the fifth harmonic component with a frequency equal to five times of the fundamental frequency. Dealing with harmonic numbers and not with harmonic frequencies is done for following reason.

The fundamental frequency varies among individual countries and applications. The fundamental frequency in the U.S. is 60 Hz, whereas in Europe, Australia and many Asian countries it is 50 Hz. Also, some applications use frequencies other than 50 or 60 Hz; for example, 400 Hz is a common frequency in the aerospace industry, while some AC systems for electric traction use 25 Hz . The inverter part of an AC variable speed drive can operate at any frequency between zero and its full rated maximum frequency, and the fundamental frequency then becomes the frequency at which the motor is operating. The use of harmonic numbers allows us to simplify how we express harmonics.

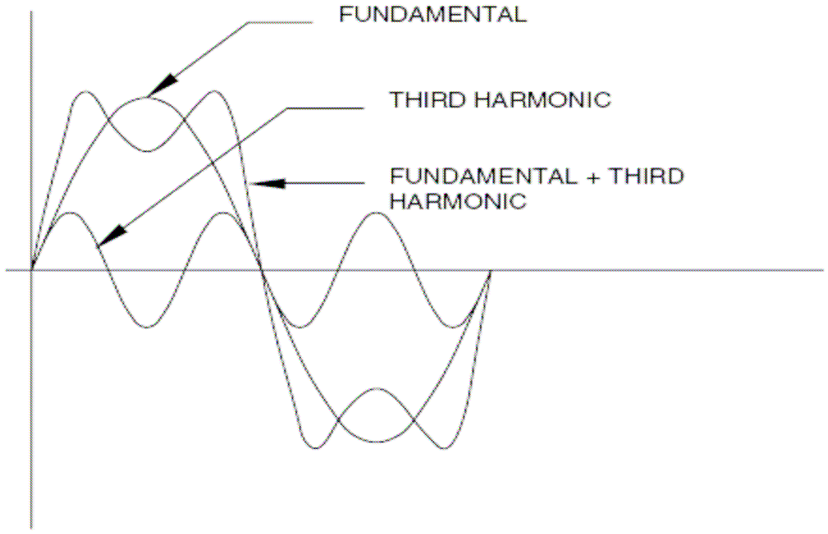


Figure 2.2 A nonlinear waveform formed by adding the fundamental and third harmonic [7]

Furthermore, harmonics can be divided into odd and even order harmonics. As their names imply, odd harmonics have odd numbers (e.g., 3, 5, 7, 9, 11), and even harmonics have even numbers (e.g., 2, 4, 6, 8, 10). Harmonic number 1 is the fundamental frequency component of a periodic wave. Harmonic number 0 represents the constant or DC component of the waveform. The DC component is the net difference between the positive and negative halves of one complete waveform cycle. The DC component of a waveform has undesirable effects, particularly on transformers, due to the phenomenon of core saturation. Saturation of the core is caused by operating the core at magnetic field levels above the knee of the magnetization curve. Transformers are designed to operate below the knee portion of the curve. When DC voltages or currents are applied to the transformer winding, large DC magnetic fields are set up in the transformer core. The sum of the AC and the DC magnetic fields can shift the transformer operation into regions past the knee of the saturation curve. Operation in the saturation region places large excitation power requirements on the power system. The transformer losses are substantially increased, causing excessive temperature rise. Core vibration becomes more pronounced as a result of operation in the saturation region.

Harmonics are usually thought as integers, however some applications produce harmonic voltages and currents that are not integers. Electric arc furnaces are examples of loads that generate non-integer harmonics. Arc welders can also generate non-integer harmonics. In both cases, once the arc stabilizes, the non-integer harmonics mostly disappear, leaving only the integer harmonics.

The majority of nonlinear loads produce harmonics that are odd multiples of the fundamental frequency. Certain conditions need to exist for production of even harmonics. Uneven current draw between the positive and negative halves of one cycle of operation can generate even harmonics. The uneven operation may be due to the nature of the application or could indicate problems with the load circuitry. Transformer magnetizing currents contain appreciable levels of even harmonic components and so do arc furnaces during start-up.

Subharmonics have frequencies below the fundamental frequency and are rare in power systems. When subharmonics are present, the underlying cause is resonance between the harmonic currents or voltages with the power system capacitance and inductance. Subharmonics may be generated when a system is highly inductive (such as an arc furnace during startup) or if the power system also contains large capacitor banks for power factor correction or filtering. Such conditions produce slow oscillations that are relatively undamped, resulting in voltage sags and light flicker [7].

2.4 Harmonic Phase Sequences

The method of symmetrical components can be employed for analysis of the system's response to harmonic currents provided care is taken not to violate the fundamental assumptions of the method. The method allows any unbalanced set of phase currents (or voltages) to be transformed into three balanced sets. The positive-sequence set contains three sinusoids displaced 120° from each other, with the normal A-B-C phase rotation (e.g., 0°, -120°, 120°). The sinusoids of the negative-sequence set are also displaced 120°, but have opposite phase rotation (A-C-B, e.g., 0°, 120°, -120°). The sinusoids of the zero sequence are in phase with each other (e.g., 0°, 0°, 0°).

In a perfect balanced three-phase system, the harmonic phase sequence can be determined by multiplying the harmonic number h with the normal positive-sequence phase rotation. For example, for the second harmonic, h=2, we get 2 *(0,-120°, +120°) or (0°, 120°, -120°), which is the negative sequence. For the third harmonic, h= 3, we get 3 *(0°,-120°, +120°) or (0°, 0°, 0°), which is the zero sequence. Phase sequences for all other harmonic orders can be determined in the same fashion. Because a distorted waveform in power systems contains only odd-harmonic components, only odd-harmonic phase sequence rotations are summarized here:

- Harmonics of order h =1, 7, 13,… are generally positive sequence.
- Harmonics of order h =5, 11, 17,… are generally negative sequence.
- Triplens (h=3, 9, 15,…) are generally zero sequence.

2.5 Triplen Harmonics

Triplen harmonics are the odd multiples of the third harmonic (h= 3, 9, 15, 21…). They deserve special consideration because the system response is often considerably different for triplens than for the rest of the harmonics. Triplens become an important issue for grounded-wye systems with current flowing in the neutral. Two typical problems are overloading the neutral and telephone interference. One also hears occasionally of devices that misoperate because the line-to-neutral voltage is badly distorted by the triplen harmonic voltage drop in the neutral conductor.

2.6 Causes of Voltage and Current Harmonics

A pure sinusoidal waveform with zero harmonic distortion is a hypothetical quantity and not a practical one. The voltage waveform, even at the point of generation, contains a small amount of distortion and the distortion at the point of generation is usually very low, typically less than 1.0%.The generated voltage is transmitted many hundreds of miles, transformed to several levels, and ultimately distributed to the power user. The user equipment generates currents that are rich in harmonic frequency components, especially in large commercial or industrial installations. As harmonic currents travel to the power source, the current distortion results in additional voltage distortion due to impedance associated with various power distribution equipment, such as transmission and distribution lines, cables, transformers, buses, and so on. However, not all voltage distortion is due to the flow of distorted current through the power system impedance. For example, static uninterruptible power source (UPS) systems can generate appreciable voltage distortion due to the nature of their operation. Normal AC voltage is converted to DC and then reconverted to AC in the inverter section of the UPS. Unless waveform shaping circuitry is provided, the voltage waveforms generated in UPS units tend to be distorted.

As nonlinear loads are propagated into the power system, voltage distortions are introduced because of the circuit impedances. Current distortions for the most part are caused by loads. Even loads that are linear will generate nonlinear currents if the supply voltage waveform is significantly distorted. When several power users share a common power line, the voltage distortion produced by harmonic current injection of one user can affect the other users. This is why standards are being issued. They limit the amount of harmonic currents that individual power users can feed into the source. The major causes of current distortion are nonlinear loads, such as variable speed drives, fluorescent lighting, rectifiers, arc furnaces, and so on. One can easily visualize an environment where a wide spectrum of harmonic frequencies are generated and transmitted to other loads or other power users, thereby producing undesirable results throughout the system [5].

2.7 Individual and Total Harmonic Distortion

Individual harmonic distortion (IHD) is the ratio between the root mean square (RMS) value of the individual harmonic and the RMS value of the fundamental.

$$\text{IHD}_n = I_n / I_1 \tag{2.4}$$

For example, in a nonlinear load, if the RMS value of the third harmonic current is 20 A, the RMS value of the fifth harmonic current is 15 A, and the RMS value of the fundamental is 60 A, then, the individual third harmonic distortion is:

$$\text{IHD}_3 = 20/60 = 0.333, (33.3\%)$$

and the individual fifth harmonic distortion is:

$$\text{IHD}_5 = 15/60 = 0.25, (25.0\%)$$

According to the above definition, the value of IHD_1 is always 100%.

Total harmonic distortion (THD) is a term used to describe the net deviation of a nonlinear waveform from ideal sine waveform characteristics. Total harmonic distortion is the ratio between the RMS value of the harmonics and the RMS value of the fundamental. For instance, if a nonlinear current has a fundamental component of I_1 and harmonic components of I_2, I_3, I_4, I_5, I_6, I_7, …, then the RMS value of the harmonics is:

$$I_h = \sqrt{(I_2^{\,2} + I_3^{\,2} + I_4^{\,2} + I_5^{\,2} + I_6^{\,2} + I_7.^2..)} \tag{2.5}$$

$$\text{THD} = (I_h / I_1) \times 100\% \tag{2.6}$$

The individual harmonic distortion indicates the contribution of each harmonic frequency to the distorted waveform, and the total harmonic distortion describes the net deviation due to all harmonics. In order to solve harmonic problems, we require information on the composition of the individual distortions. The total harmonic distortion is used to describe the degree of pollution of the power system as far as harmonics are concerned. The individual and total harmonic distortions used to characterise some typical nonlinear loads.

2.8 Harmonic Sources

Many of the loads installed in present-day power systems are harmonic current generators. Combined with the impedance of the electrical system, the loads also produce harmonic voltages. The nonlinear loads may therefore be viewed as both harmonic current generators and harmonic voltage generators. Variable speed drives perform speed control functions very effectively, but they are generators of large harmonic currents. Fluorescent lights use less electrical energy for the same light output as incandescent lighting, but also produce a lot of harmonic currents. The explosion of personal computer use has resulted in harmonic currents increasing in commercial buildings.

These harmonic sources can be grouped into three main areas:

- Power electronic equipment: Variable speed drives (AC VSDs, DC drives, PWM drives, etc.); UPS systems, rectifiers, switch mode power supplies, static converters, thyristor systems, diode bridges, SCR controlled induction furnaces and SCR controlled systems.
- Arcing equipment: Arc furnaces, welders, lighting (mercury vapour , fluorescent)
- Saturable devices: Transformers, motors, generators, etc. The harmonic amplitudes on these devices are usually insignificant compared to power electronic and arcing equipment, unless saturation occurs [8].

Typical harmonic loads fluorescent lighting, arcing devices and saturable devices are detailed discussed in section 2.8.1 to 2.8.3. Three phase power converters will be the topic of chapter 4.

2.8.1 Fluorescent Lighting

Lighting typically accounts for 40 to 60 percent of a commercial building load, and fluorescent lights are a popular choice for energy savings. Fluorescent lights are discharge lamps; thus they require a ballast to provide a high initial voltage to initiate the discharge for the electric current to flow between two electrodes in the fluorescent tube. Once the discharge is established, the voltage decreases as the arc current increases. It is essentially a short circuit between the two electrodes, and the ballast has to quickly reduce the current to a level to maintain the specified lumen output. Thus, a ballast is also a current-limiting device in lighting applications.

There are two types of ballasts, magnetic and electronic. A standard magnetic ballast is simply made up of an iron-core transformer with a capacitor encased in an insulating material. A single magnetic ballast can drive one or two fluorescent lamps, and it operates at the line fundamental frequency. The iron-core magnetic ballast contributes additional heat losses, which makes it inefficient compared to an electronic ballast.

An electronic ballast employs a switch-mode–type power supply to convert the incoming fundamental frequency voltage to a much higher frequency voltage typically in the range of 25 to 40 kHz. This high frequency has two advantages. First, a small inductor is sufficient to limit the arc current. Second, the high frequency eliminates or greatly reduces the 100 Hz flicker associated with an iron-core magnetic ballast.

Standard magnetic ballasts are usually rather benign sources of additional harmonics themselves, because the main harmonic distortion comes from the behaviour of the arc. As a comparison, electronic ballasts, which employ switch-mode power supplies, can produce double or triple the standard magnetic ballast harmonic output. Other electronic ballasts have been specifically designed to minimize harmonics and may actually produce less harmonic distortion than the normal magnetic ballast-lamp combination. Most electronic ballasts are equipped with passive filtering to reduce the input current harmonic distortion to less than 20 percent [5].

2.8.2 Other Arcing Devices

These devices include arc furnaces, arc welders. The arc is basically a voltage clamp in series with a reactance that limits current to a reasonable value.

The voltage-current characteristics of electric arcs are nonlinear. Following arc ignition, the voltage decreases as the arc current increases, limited only by the impedance of the power system. This gives the arc the appearance of having a negative resistance for a portion of its operating cycle. In electric arc furnace applications, the limiting impedance is primarily the furnace cable and leads with some contribution from the power system and furnace transformer. Currents in excess of 60,000 A are common.

The electric arc itself is actually best represented as a source of voltage harmonics. If probes were to be placed directly across the arc, one would observe a somewhat trapezoidal waveform. Its magnitude is largely a function of the length of the arc. However, the impedance of furnace leads acts as a buffer so that the supply voltage is only moderately distorted. The arcing load thus appears to be a relatively stable harmonic current source, which is adequate for most analyses. The exception occurs when the system is near resonance.

The harmonic content of an arc furnace load and other arcing devices is similar to that of a magnetic ballast. Three phase arcing devices can be arranged to cancel the triplen harmonics through the transformer connection.

2.8.3 Saturable Devices

Equipment in this category includes transformers and other electromagnetic devices with a steel core, including motors. Harmonics are generated due to the nonlinear magnetizing characteristics of the steel (refer to figure 2.3).

Power transformers are normally designed to operate just below the “knee” point of the magnetizing saturation characteristic. The operating flux density of a transformer is selected based on a complicated optimization of steel cost, no-load losses, noise, and numerous other factors. Many electric utilities will penalize transformer manufacturers by various amounts for no-load and load losses, and the manufacturers will try to meet the specification with a transformer that has the lowest evaluated cost. A high-cost penalty on the no-load losses or noise will generally result in more steel in the core and a higher saturation curve that yields lower harmonic currents.

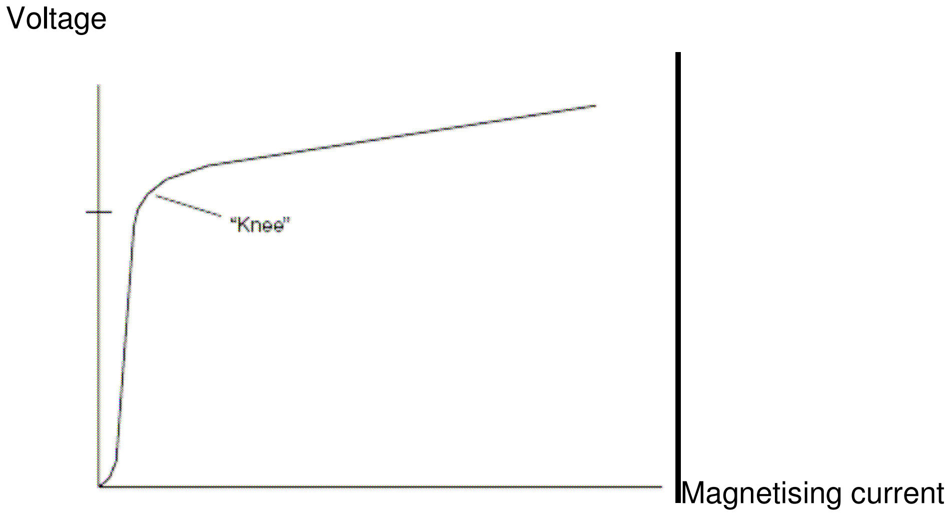


Figure 2.3 Transformer magnetizing characteristic [7]

Although transformer exciting current is rich in harmonics at normal operating voltage, it is typically less than 1 percent of rated full load current. Transformers are not as much of a concern as power electronic converters and arcing devices, which can produce harmonic currents of 20 percent of their rating, or much higher. However, their effect will be noticeable, particularly on utility distribution systems, which have hundreds of transformers. It is common to notice a significant increase in triplen harmonic currents during the early morning hours when the load is low and the voltage rises. Transformer exciting current is more visible then because there is insufficient load to obscure it and the increased voltage causes more current to be produced. Harmonic voltage distortion from transformer overexcitation is generally only apparent under these light load conditions. Some transformers are purposefully operated in the saturated region. One example is a triplen transformer used to generate 150 Hz for induction furnaces.

Motors also exhibit some distortion in the current when overexcited, although it is generally of little consequence. However, there are some fractional horsepower, single-phase motors that have a nearly triangular waveform with significant third-harmonic currents [5].

2.9 Effect of Harmonics on Power System Devices

Harmonics have harmful effects on power system devices and most time the effects of harmonics are not known until failure occurs. Insight into how harmonics can interact within a power system and how they can affect power system components is important for preventing failures.

2.9.1 Transformers

Harmonics can affect transformers primarily in two ways. Voltage harmonics produce additional losses in the transformer core as the higher frequency harmonic voltages set up hysteretic loops, which superimpose on the fundamental loop. Each loop represents higher magnetization power requirements and higher core losses. A second and a more serious effect of harmonics are due to harmonic frequency currents in the transformer windings. The harmonic currents increase the net RMS current flowing in the transformer windings which results in additional I^2R losses. Winding eddy current losses are also increased. Winding eddy currents are circulating currents induced in the conductors by the leakage magnetic flux. Eddy current concentrations are higher at the ends of the windings due to the crowding effect of the leakage magnetic field at the coil extremities. The winding eddy current losses increase as the square of the harmonic current and the square of the frequency of the current. Thus, the eddy loss is proportional to

$I_h^2 \times h^2$, where I_h is the RMS value of the harmonic current of order h, and h is the harmonic frequency order or number. Eddy currents due to harmonics can significantly increase the transformer winding temperature. Transformers that are required to supply large nonlinear loads must be derated to handle harmonics.

2.9.2 Capacitor Banks

Capacitor banks are commonly found in industrial power systems to correct for low power factor conditions. Capacitor banks are designed to operate at a maximum voltage of 110% of their rated voltages and at 135% of their rated kVARS. When large levels of voltage and current harmonics are present, the ratings are quite often exceeded, resulting in failures. Because the reactance of a capacitor bank is inversely proportional to frequency, harmonic currents can find their way into a capacitor bank. The capacitor bank acts as a sink, absorbing stray harmonic currents and causing overloads and subsequent failure of the bank.

A more serious condition with potential for substantial damage occurs due to a phenomenon called harmonic resonance. Resonance conditions are created when the inductive and capacitive reactances become equal at one of the harmonic frequencies. The two types of resonances are series and parallel. In general, series resonance produces voltage amplification and parallel resonance results in current multiplication. In a harmonic-rich environment, both series and parallel resonance may be present. If a high level of harmonic voltage or current corresponding to the resonance frequency exists in a power system, considerable damage to the capacitor bank as well as other power system devices can result.

2.9.3 AC Motors

Applying distorted voltage to a motor result in additional losses in the magnetic core of the motor. Hysteresis and eddy current losses in the core increase as higher frequency harmonic voltages are impressed on the motor windings. Hysteresis losses increase with frequency and eddy current losses increase as the square of the frequency. Also, harmonic currents produce additional I^2R losses in the motor windings which must be accounted for.

Another effect is torsional oscillations due to harmonics. Two of the more prominent harmonics found in a typical power system are the fifth and seventh harmonics. The fifth harmonic is a negative sequence harmonic, which results magnetic field revolves in a direction opposite to the fundamental field at a speed five times of the fundamental. The seventh harmonic is a positive sequence harmonic with a resulting magnetic field revolving in the same direction as the fundamental field at a speed seven times of the fundamental. The net effect is a magnetic field that revolves at a relative speed of six times the speed of the rotor. This induces currents in the rotor bars at a frequency of six times the fundamental frequency. The resulting interaction between the magnetic fields and the rotor-induced currents produces torsional oscillations of the motor shaft. If the frequency of the oscillation coincides with the natural frequency of the motor rotating members, severe damage to the motor can result. Excessive vibration and noise in a motor operating in a harmonic environment should be investigated to prevent failures.

Motors intended for operation in a severe harmonic environment must be specially designed for the application. Motor manufacturers provide motors for operation with variable speed drive units. If the harmonic levels become excessive, filters may be applied at the motor terminals to keep the harmonic currents from the motor windings. Large motors supplied from variable speed drives are usually provided with harmonic filters to prevent motor damage due to harmonics.

2.9.4 Cables

A current flowing in a cable produces I^2R losses. When the load current has harmonic content, additional losses are introduced. The effective resistance of the cable increases with frequency because of the phenomenon of skin effect. Skin effect is due to unequal flux linkage across the cross section of the conductor which causes AC currents to flow only on the outer periphery of the conductor.

This has the effect of increasing the resistance of the conductor for AC currents. The higher the frequency of the current, the greater the tendency of the current to crowd at the outer periphery of the conductor and the greater the effective resistance for that frequency [7].

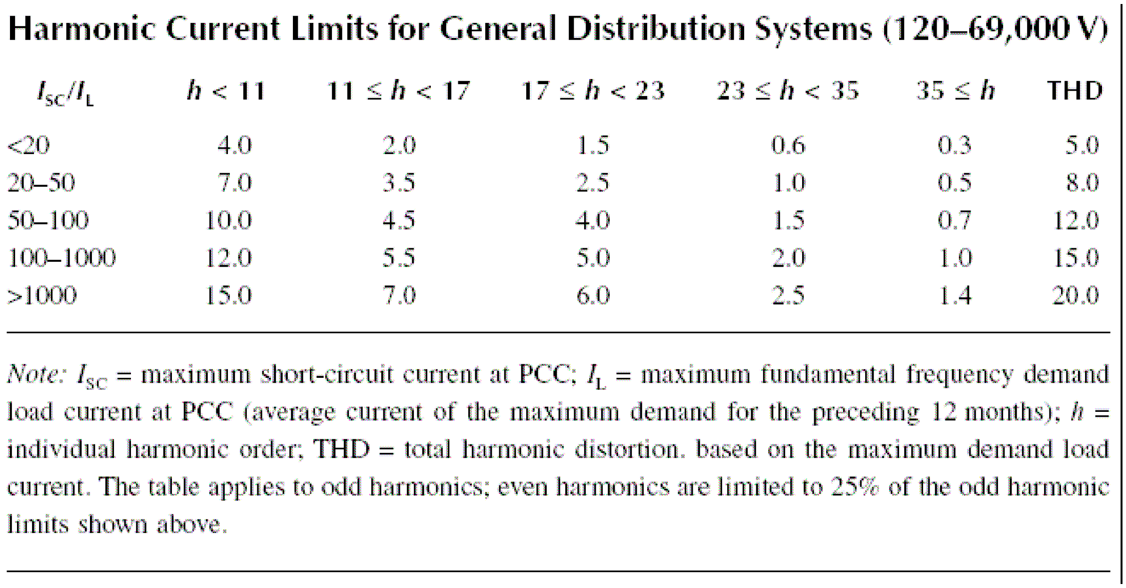
2.9.5 Protective Devices

Harmonic currents influence the operation of protective devices. Fuses and motor thermal overload devices are prone to nuisance operation when subjected to nonlinear currents. This factor should be given due consideration when sizing protective devices for use in a harmonic environment. Electromechanical relays are also affected by harmonics. Depending on the design, an electromechanical relay may operate faster or slower than the expected times for operation at the fundamental frequency alone. Such factors should be carefully considered prior to placing the relays in service.

2.10 Guidelines for Harmonic Voltage and Current Limitation

As discussed above, there are many adverse effects of harmonics on power system operation. So it is important to limit the harmonic distortion that a facility might produce. There are two benefits for this. First, the lower the harmonic currents produce in an electrical system, the better the equipment within the confinement of the system will perform. Also, lower harmonic currents produce less of an impact on other power users sharing the same power lines. The IEEE 519-1992 standard provides guidelines for harmonic current limits at the point of common coupling (PCC) between the facility and the utility. It is a given fact that within a particular power use environment, harmonic currents will be generated and propagated. Harmonic current injection at the PCC determines how one facility might affect other power users and the utility that supplies the power.

Table 2.1 lists harmonic current limits based on the size of the power user. As the ratio between the maximum available short circuit current at the PCC and the maximum demand load current increases, the percentage of the harmonic currents that are allowed also increases. This means that larger power users are allowed to inject into the system a relatively less amount of harmonic current (as a percentage of the fundamental current). Such a scheme tends to equalize the amounts of harmonic currents that large and small users of power are allowed to inject into the power system at the PCC.



Harmonic Current Limits for General Distribution Systems (120–69,000 V)

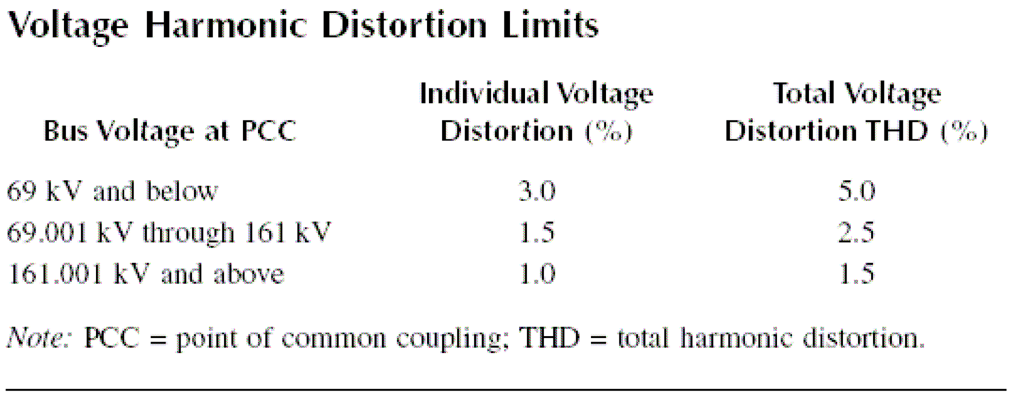
I_{SC}/I_L	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	THD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20–50	7.0	3.5	2.5	1.0	0.5	8.0
50–100	10.0	4.5	4.0	1.5	0.7	12.0
100–1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Note: I_{SC} = maximum short-circuit current at PCC; I_L = maximum fundamental frequency demand load current at PCC (average current of the maximum demand for the preceding 12 months); h = individual harmonic order; THD = total harmonic distortion, based on the maximum demand load current. The table applies to odd harmonics; even harmonics are limited to 25% of the odd harmonic limits shown above.

Table 2.1 Harmonic current limits [7]

IEEE 519 also provides guidelines for maximum voltage distortion at the PCC (refer to Table 2.2). Limiting the voltage distortion at the PCC is the concern of the utility. It can be expected that as long as a facility’s harmonic current contribution is within the IEEE 519 limits the voltage distortion at the PCC will also be within the specified limits.

When the IEEE 519 harmonic limits are used as guidelines within a facility, the PCC is the common junction between the harmonic generating loads and other electrical equipment in the power system. It is expected that applying IEEE guidelines renders power system operation more reliable. In the future, more and more utilities might require facilities to limit their harmonic current injection to levels stipulated by IEEE 519 [7].



Voltage Harmonic Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

Note: PCC = point of common coupling; THD = total harmonic distortion.

Table 2.2 Voltage harmonic distortion limits [7]

2.11 Methods for Reducing Harmonics

There are many ways to reduce harmonics, ranging from variable frequency drive designs to the addition of auxiliary equipment. Following are some of the more common methods used today for controlling power system harmonics.

A. Power system design

A practical approach to keeping harmonic in check is to limit the nonlinear load to 30% of the supply transformer rating.

B. Multi-pulse converter design

In a 12-pulse configuration, the front-end rectifier circuit uses twelve diodes instead of six. When properly designed, this configuration practically eliminates the 5th and 7th harmonics. The disadvantages are cost and construction due to the requirement for either a delta-delta / delta-wye transformer pair, or three-winding transformer to accomplish the 30° phase shifting necessary for proper operation. This configuration also affects the overall drive system efficiency rating because of the voltage drop associated with the transformer requirement. Figure 2.4 illustrates the typical elementary diagram for a 12-pulse converter front end. Higher pulse orders are also possible, thereby reducing more of the lower order harmonics.

C. Source impedance at the load

The harmonic current injected by a non-linear load is determined to some extent by the source impedance. With a relatively stiff source, the current total harmonic distortion for a typical variable speed drive may be as high as 50% to 100% at full load. With source impedance of 2% to 5% of the load impedance, the current total harmonic distortion can drop to less than 40%.

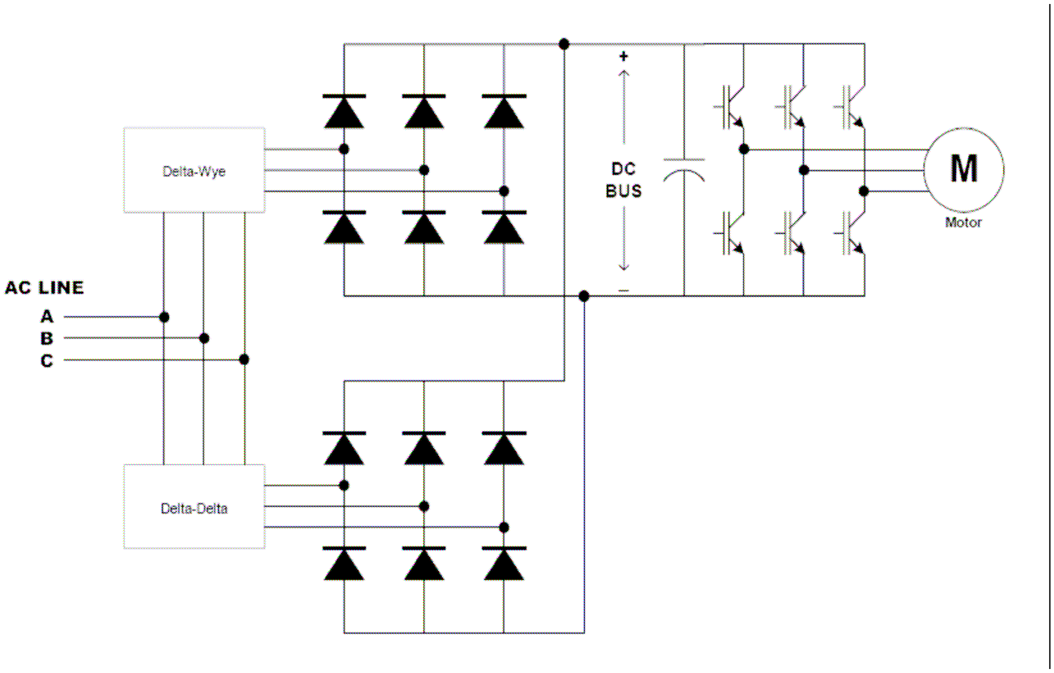


Figure 2.4 Typical twelve-pulse AC drive components [31]

D. Pseudo 12-pulse systems

This configuration uses phase-shifting transformers to cancel 5th and 7th harmonics at the common bus. For cancellation to occur, the non-linear loads must be operated simultaneously and have similar characteristics. One cost-effective implementation of this concept uses delta-wye isolation transformers on a few large variable speed drives, while using smaller and less costly line reactors on smaller variable speed drives.

E. Isolation transformers

An isolation transformer provides several advantages. First and foremost, it provides impedance to the drive, which reduces current distortion. It obviously resolves voltage mismatch between the supply and the load. If the secondary is grounded, it isolates ground faults and reduces common mode noise.

F. Line reactors

A line reactor provides the impedance to reduce harmonic current, similar to an isolation transformer, but with a smaller size and cost. Line reactors (or inductors) are available in standard impedance ranges from 1.5%, 3%, 5% and 7.5% of the load impedance. Where system voltage is on the lower end of nominal, the greater impedance values should be avoided. This method is particularly effective for PWM-type drives. This solution, used for variable speed drives and three phase rectifiers, consists in connecting a reactor in series upstream of a non-linear load. One must be installed for each non-linear load. Current total harmonic distortion is divided by a factor of approximately two and most time harmonic current is still greater than IEEE 519-1992.

G. passive filters

This kind of filters has been introduced in section 1.2.2.

H. active filters

The active harmonic filter can be an economical solution for applications where the harmonic load is either 30% of the total transformer capacity or several hundred kVA. They provide a cost-effective alternative to 18-pulse technology when several drives are installed in one location. Unlike passive filters, active filters cannot be overloaded if the level of harmonics increases. Often times, active filter units can be paralleled to accommodate increases in non-linear load [31].

2.12 Conclusions

The issue of harmonics is becoming more important in power systems, small, medium, or large. As the use of power electronic devices grows, so will the need to understand the effects of harmonics and the application of mitigation methods. Fortunately, harmonics in a strict sense are not transient phenomena. Their presence can be easily measured and identified. In some cases, harmonics can be lived with indefinitely, but in other cases they should be minimized or eliminated. Either of these approaches requires a clear understanding of the theory behind harmonics.

Chapter 3
Power Factor

3.1 Introduction

Power factor is a power quality issue in that low power factor can sometimes cause equipment to fail. In many instances, the cost of low power factor can be high; Utilities penalize facilities that have low power factor because they find it difficult to meet the resulting demands for electrical energy. The study of power quality is about optimizing the performance of the power system at the lowest possible operating cost.

3.2 Active and Reactive Power

Apparent power (*S*) in an electrical system which is a pure linear load can be defined as being equal to voltage times current:

$$S = 3 \times V \times I \quad \text{(3 phase)} \qquad (3.1)$$

In three-phase systems, V is line to neural voltage (RMS) and I is line current (RMS).Active power (*P*) can be defined by:

$$P = 3 \times V \times I \times \mathrm{PF} \quad \text{(3 phase)} \qquad (3.2)$$

Apparent power is what a power supply serves all electrical equipment that connects with it in order for those facilities to function. Active power is the portion of the apparent power that performs useful work and supplies losses in the electrical equipment that are associated with doing the work. Higher power factor leads to more optimum use of electrical current in a facility. The reactive power is that portion of the apparent power that prevents it from obtaining a power factor of 100% and is the power that an AC electrical system requires in order to perform useful work in the system. Reactive power sets up a magnetic field in the motor so that a torque is produced. It is also the power that sets up a magnetic field in a transformer core allowing transfer power from the primary to the secondary windings.

All reactive power requirements are not necessary in every situation. Any electrical circuit or device when subjected to an electrical potential develops a magnetic field that represents the inductance of the circuit or the device. As current flows in the circuit, the inductance produces a voltage that tends to oppose the current. This effect produces a voltage drop in the circuit that represents a loss in the circuit. At any rate, inductance in AC circuits is present whether it is needed or not. In a linear electrical circuit, the apparent and reactive powers are represented by the power triangle shown in Figure 3.1 [7].

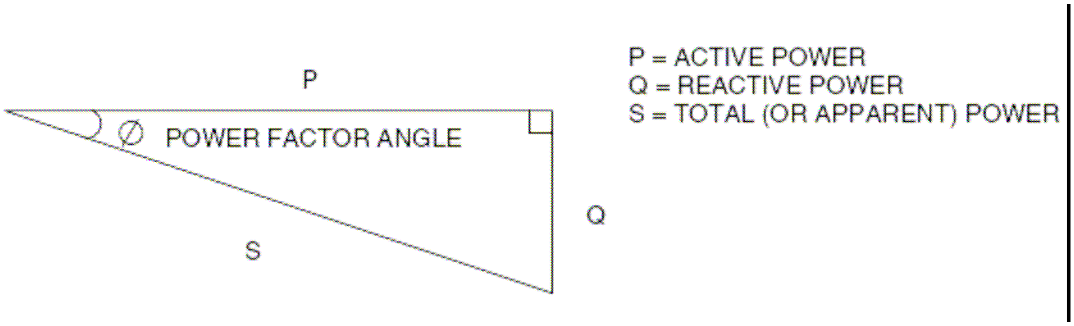


Figure 3.1 Power triangle and relationships between active, reactive and apparent power [7]

The following relationships apply:

$$S=\sqrt{P^2+Q^2} \tag{3.3}$$

$$DPF= \cos\phi \tag{3.4}$$

Where S is apparent power, P is active power, Q is reactive power, and ϕ is the power factor angle.

3.3 Displacement and True Power Factor

Normally, there is a misunderstanding of definitions of the true power factor (TPF) and the displacement power factor (DPF). The power factor is known as the cosine of the phase angle between a current and a voltage waveform as described in above section. However, this is only valid for systems with voltage and current purely sinusoidal, that is, the load must be linear, presenting total harmonic distortion equals to zero. In nonlinear load, the true power factor is defined as the ratio of total active power in a system to total apparent power (including harmonics) supplied from the source in a same period. This expression of power factor is shown in equation 3.5.

$$\text{TPF} = \frac{P}{S} = \frac{\frac{1}{T}\int_0^T v(t)i(t)dt}{\sqrt{\frac{1}{T}\int_0^T v(t)^2\,dt}\sqrt{\frac{1}{T}\int_0^T i(t)^2\,dt}} \qquad (3.5)$$

The displacement power factor is determined by the cosine of the angle between the fundamental voltage and current waveforms, which they are by definition pure sinusoidal waveforms. When the load is nonlinear (total harmonic distortion different of zero), the total RMS value is higher than the RMS value of the fundamental component. Thus, the power factor is lower than the value calculated by the cosine of phase angle between the current and the voltage waveforms. Thus, the true power factor can he calculated as a function of the displacement factor and the total harmonic distortion, as shown below [26]:

$$\text{TPF} = \text{DPF} * \text{F}_{dist} \qquad (3.6)$$

Where F_{dist} (distortion factor) = fundamental current/RMS current .This new term, "distortion factor", is defined as being the fundamental current divided by the RMS current. Also, F_{dist} can be defined as:

$$F_{dist} = \sqrt{\frac{1}{1+THD_i^2}} \qquad (3.7)$$

And that means:

$$TPF = DPF * \sqrt{\frac{1}{1+THD_i^2}} \qquad (3.8)$$

For a linear load on a non-distorted supply, the displacement power factor and true power factor have the same value. The greater the proportion of harmonic content in the current waveform of a given load, the greater the difference between the true and displacement power factors, and the worse the true power factor will be.

3.4 True Power Factor Improvement

It can be found from section 3.3 that there are two elements which combine to reduce the true power factor - the inductive or capacitive loads which affect the displacement factor - and the harmonic currents of the non-linear loads which affect the distortion factor. As utilities measure the total power factor (true power factor), we have to check the value of both displacement factor and distortion factor if true power factor is to be corrected. This will help us understand the cause of the reduction in power factor and choose the best way to improve it [27].

Thus, three ways to improve the true power factor and minimize the apparent power drawn from the power source are:

- Reduce the lagging reactive current demand of the loads
- Compensate for the lagging reactive current by supplying leading reactive current to the power system
- Reducing the level of harmonic currents in a system

Lagging reactive current represents the inductance of the power system and power system components. Lagging reactive current demand may not be totally eliminated but may be reduced by using power system devices or components designed to operate with low reactive current requirements. Practically no devices in a typical power system require leading reactive current to function; therefore, in order to produce leading currents certain devices must be inserted in a power system. These devices are referred to as power factor correction equipment [7].

3.5 Displacement Power Factor Correction

In theory the true power factor of inductive loads can reach 100%, but in practice it cannot without some form of power factor correction device. Improper techniques can result in over-correction, under-correction, and harmonic resonance.

As discussed above, improving displacement power factor and reducing total harmonic distortion of the nonlinear load can increase the true power factor. The displacement power factor can be improved with capacitors. A solution to mitigate the harmonics produced by the nonlinear loads is to add passive or active filters or ac reactors. How to reduce harmonics and design passive filters to improve the true power factor will be discussed in chapter 5.

The most common method for improving displacement power factor is to add capacitor banks to the system. Capacitors are attractive because they are economical and easy to maintain. Furthermore, they have no moving parts. When a capacitor bank is added to the system, the capacitor supplies the reactive power needed by the load. If a customer sizes and selects a capacitor bank to compensate the displacement power factor to unity, the capacitor bank will supply all the reactive power needed by the load, and no reactive power will be required from the utility. If a customer designs the capacitor bank to improve the power factor to a value less than 1.0, the reactive power supplied by the bank will be its rated kVARs (or MVARs), while the rest of the reactive power needed by the load will be supplied by the utility.

In power factor calculations for a typical power system, the equivalent resistance, and inductance are not readily available. Instead, the values of active and reactive

power are used for calculation. Figure 3.2 shows power triangles before and after correction. To solve the triangles, three pieces of information are needed:
The existing power factor ($\cos\phi_1$), the corrected power factor ($\cos\phi_2$), and any one of the following: active power (P), reactive power (Q), or apparent power (S).
for example, given P, $\cos\phi_1$, and $\cos\phi_2$:

For rectangular triangles, $Q_1 = P\tan\phi_1$ and $Q_2 = P\tan\phi_2$. The reactive power required to correct the power factor from $\cos\phi_1$ to $\cos\phi_2$ is:

$$\Delta Q = P(\tan\phi_1 - \tan\phi_2) \tag{3.15}$$

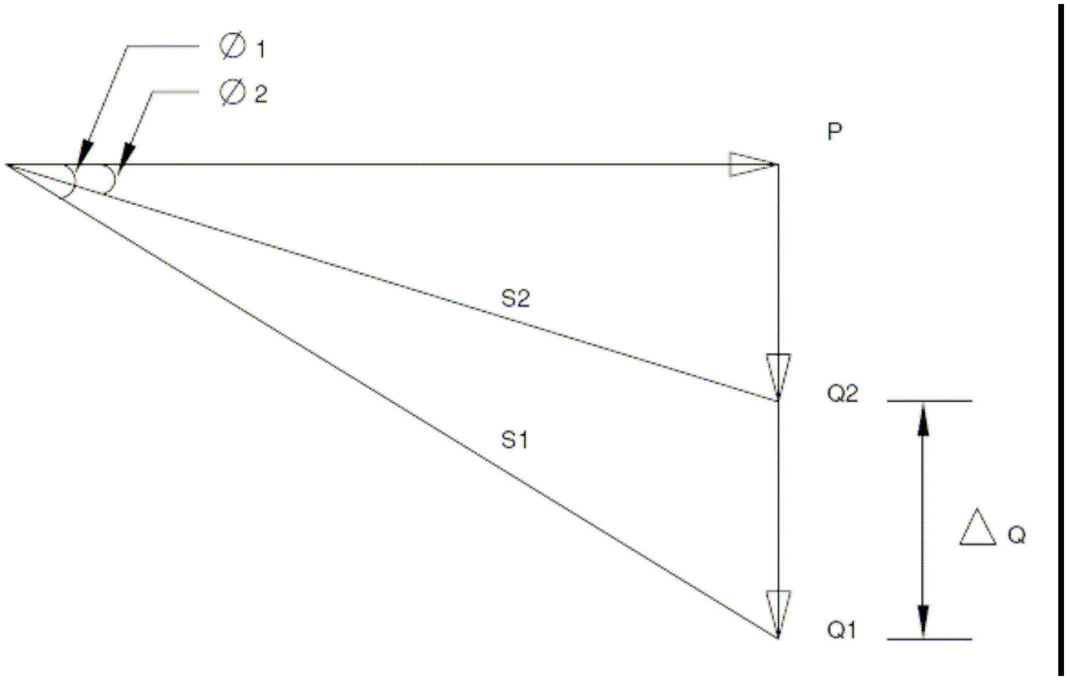


Figure 3.2 General power factor correction triangles [7]

Inductive reactive power is needed by all magnetic devices found in a power system. This is the cause of a low power factor. A low power factor means a higher apparent power, which translates into a high current and inefficient transfer of electrical power. A higher current causes elevated losses in transmission lines, an increased voltage drop, and poor voltage regulation. Many utilities apply a penalty to users with a low power factor as a way to get reimbursed for supplying higher apparent power.

Beware of power system resonance

The operation of nonlinear loads in a power system creates harmonic currents that flow throughout the power system. The inductive reactance of that power system increases and the capacitive reactance decreases as the frequency increases, or as the harmonic order increases. At a given harmonic frequency in any power system where a capacitor exists, there will be a crossover point where the inductive and capacitive reactances are equal. This crossover point, called the parallel resonant point. Every power system with a capacitor has a parallel resonant point.

If parallel resonant occurs on, or close to, one of the harmonics generated by nonlinear loads, then large harmonic currents can circulate between the power supply system and the capacitor equipment. Such currents will add to the harmonic voltage disturbance in the power system causing an increased voltage distortion. This results in a higher voltage across the capacitor and excessive current through all capacitor components. Resonance can occur on any frequency, but in general, the resonance we are concerned with is on, or close to, the 5th, 7th, 11th and 13th harmonics for 6 pulse systems. To avoid resonance, we should perform an electrical survey prior to installation of the capacitor bank [8], [29].

3.6 Advantages of True Power Factor Correction

3.6.1 Physical Benefits of True Power Factor Correction

The reduction in demand on the supply from the installation of true power factor correction equipment results in:

- ‘Spare’ supply capacity which may be used to connect additional load without the necessity of network reinforcement

- Reduced losses and hence reduced heating in transformers, cables and switchgear, increasing reliability, useful service life, and reducing servicing costs
- Improved voltage regulation. (The voltage drop in a supply network is approximately proportional to the reactive power supplied by that network $\Delta V \cong QX$, where ΔV is the voltage drop, Q the reactive power demand, and X the system reactance)
- An increase in power quality, as the presence of a large capacitor bank gives significant attenuation of mains borne voltage spikes, and can also reduce the effects of short duration dips or notches in the supply voltage
- Lower carbon dioxide emissions as a reduction in distribution system losses means that fewer kWhs are required from the electricity generators

3.6.2 Financial Benefits of True Power Factor Correction

- Reduction in kVA required to supply a given kW load means the capital expenditure can be reduced, as the primary distribution network components (transformers, switchgear etc.) can be reduced in rating and hence cost.
- The tariff under which charges are made for electricity may include items which relate directly or indirectly to poor true power factor. These are usually specific to the consumer, and hence generalizations are difficult. Items falling into this category which may be affected include authorized supply capacity, metered monthly maximum demand, and reactive unit charges [29].

3.7 Power Factor Penalty

Typically, electrical utilities charge a penalty for power factors below 0.95. The method of calculating the penalty depends on the utility. In some cases, the formula is simple, but in other cases the formula for the power factor penalty can be much more complex. Normally, one utility charges a rate of 0.20¢/KVAR-h for all the reactive energy used if the power factor falls below 0.95. No KVAR–h charges are levied if the power factor is above 0.95.

In the future, as the demand for electrical power continues to grow, the penalty for poor power factors is expected to increase [7].

3.8 Conclusions

Good power factor is not necessarily critical for most equipment to function in a normal manner. Having low power factor does not cause a piece of machinery to shut down, but high power factor is important for the overall health of the power system. Operating in a high power factor environment ensures that the power system is functioning efficiently. It also makes economic sense. Electrical power generation, transmission, and distribution equipment have maximum rated currents. If these levels are exceeded, the equipment operates inefficiently and suffers a loss of life expectancy. This is why it is important not to exceed the rated currents for power system equipment. It is also equally important that the available energy production capacity be put to optimum use. Such an approach helps to provide an uninterrupted supply of electrical energy to industries, hospitals, commercial institutions, and our homes. As the demand for electrical energy continues to grow and the resources for producing the energy become less and less available, the idea of not using more than what we need takes on more relevance.

Chapter 4

Input Side Harmonics Analysis of Variable Speed Drives

This chapter focuses on the mechanism of harmonic generation by variable speed drives. It also presents a PSPICE analysis of a diode rectifier typical for most variable speed drives.

4.1 Harmonic-Producing Loads

Nonlinear loads drawing nonsinusoidal currents from three-phase sinusoidal voltages are classified into identified and unidentified loads. High-power diode or thyristor rectifiers, cycloconverters, and arc furnaces are typically characterized as identified harmonic-producing loads, because electric power utilities identify the individual nonlinear loads installed by high-power consumers on power distribution systems in many cases. Each of these loads produces a large amount of harmonic current. The utilities can determine the point of common coupling of high-power consumers who install their own harmonic-producing loads on power distribution systems. Moreover, they can determine the amount of harmonic current drawn by an individual consumer.

A “single” low-power diode rectifier produces a negligible amount of harmonic current if it is compared with the system total current. However, multiple low-power diode rectifiers can produce a significant amount of harmonics into the power distribution system. A low-power diode rectifier used as a utility interface in an electric appliance is typically considered as an unidentified harmonic-producing load. So far, less attention has been paid to unidentified loads than identified loads [10].

4.2 Harmonics Produced by Converters

Variable speed drives technology is evolving steadily, with greater emphasis being placed on reduction in harmonic currents. The order of significant harmonic currents generated in power conversion equipment can be stated as:

$$n = kq \pm 1 \qquad (4.1)$$

where *n* is the significant harmonic order, *k* is any positive integer (1, 2, 3, etc.), and *q* is the pulse number of the power conversion equipment which is the number of power pulses that are in one complete sequence of power conversion. For example, a three-phase full wave bridge rectifier has six power pulses and therefore has a pulse number of 6. With six-pulse-power conversion equipment, the following significant harmonics may be generated:

For $k = 1$, $n = (1 \times 6) \pm 1$ = 5th and 7th harmonics.
For $k = 2$, $n = (2 \times 6) \pm 1$ = 11th and 13th harmonics.

With six-pulse-power conversion equipment, harmonics below the 5th harmonic are insignificant. Also, as the harmonic number increases, the individual harmonic distortions become lower due to increasing impedance presented to higher frequency components by the power system inductive reactance. So, typically, for six-pulse power conversion equipment, the 5th harmonic current would be the highest, the 7th would be lower than the 5th, the 11th would be lower than the 7th, and so on, as shown below:

$$I_{13} < I_{11} < I_7 < I_5$$

We can deduce that, when using 12-pulse-power conversion equipment, harmonics below the 11th harmonic can be made insignificant. The total harmonic distortion is also considerably reduced [7].

4.3 Variable Speed Drives as a Cause of Harmonics

All variable speed drives cause harmonics because of the nature of the front end rectifier design. Figure 4.1 illustrates a 6-pulse rectifier, which is the standard input in most AC variable speed drives today.

The current waveform at the inputs of the circuit shown in figure 4.1 is not continuous. It may have multiple zero crossings in one electrical cycle. The current harmonics content is the result of the pulsed current pattern at the input of the diode with a DC bus capacitor rectifier. The capacitor draws charging current only when it gets discharged due to the motor load. The charging current flows into the capacitor when the relevant diodes are forward biased, which occurs when the instantaneous input voltage is higher than the steady-state DC voltage across the DC bus capacitor. The pulsed current drawn by the dc bus capacitor is rich in harmonics due to the fact that it is not sinusoidal as shown in Figure 4.5 in section 4.5. The voltage harmonics generated by variable speed drives are due to the "flat-topping" effect caused by an AC source charging the DC bus capacitor without any "intervening" impedance [30].

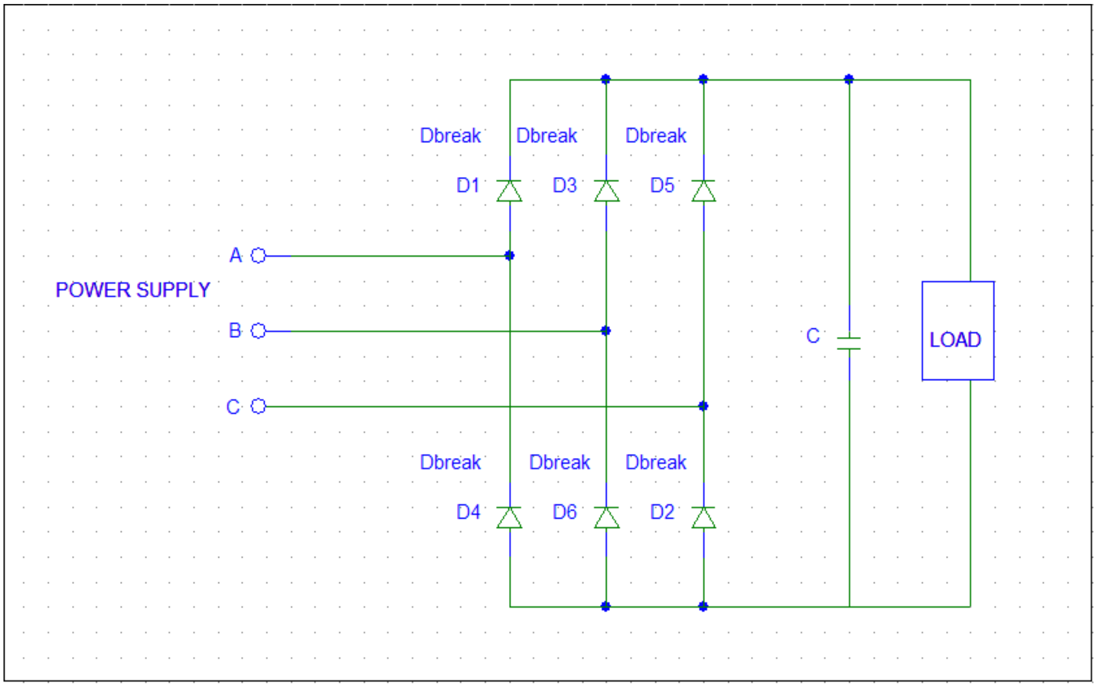


Figure 4.1 Typical six-pulse front end rectifier of an AC drive

The degree and magnitude of the harmonics created by a variable frequency drive is a function of the drive design and the distribution system impedance. The power source line impedance ahead of the rectifier will determine the amplitude of harmonic currents in the distribution system. The distorted current across the system impedance causes a voltage drop or harmonic voltage distortion. This relationship is proportional to the distribution system available fault current [11].

4.4 Introduction to PSPICE Simulation

PSPICE is a software package used to analyse electric circuits for the behaviour of currents and voltages as functions of time. In PSPICE, circuits can contain the basic elements of R, L, and C, as well as devices such as diodes. The design of a power harmonic filter is based on a three-phase system, for example, a three-phase rectifier. A simplified approach can be used to find the inductance and capacitance values for each filter. These values defy then the simulated circuit. PSPICE can assist in verifying the filter design and analysis. The simulation may also be used to determine the increase in capacitor voltage and the actual capacitor operating kilovars, and may also be used to generate the waveform of the current and voltage. The simulation can also be used to perform a parametric calculation of the impact of the capacitor kilovars for no-load and full-load conditions. Computer simulation may also be used to simulate large banks power-factor-correction capacitors [12].

PSPICE student version supports a few low-power diodes such as DIN4002, DIN4148 and DIN914. However, the user can change the diode model parameters (Dbreak). A rectifier converts an AC voltage to a DC voltage and uses diodes as switching devices. The output voltage of an ideal rectifier should be pure DC and contain no ripple, and the input current should be pure sine wave and contain no harmonics. That is, total harmonic distortion of the input current should be zero, and the input true power factor should be unity. The input true power factor in PSPICE simulation can be determined from the total harmonic distortion computed by the program (equations 3.6 to 3.8 in chapter 3).

Some exemplary PSPICE results obtained for a single-phase rectifier shown in figure 4.2 are presented below. Supply voltage is 240 V, 50Hz, the load is assumed R=20 Ω, the utility inductance L_s=1mH, the power line resistance R_s=1mΩ, L_1 is input side inductor filter which is 10mH and DC side capacitor filter is C=300μF.

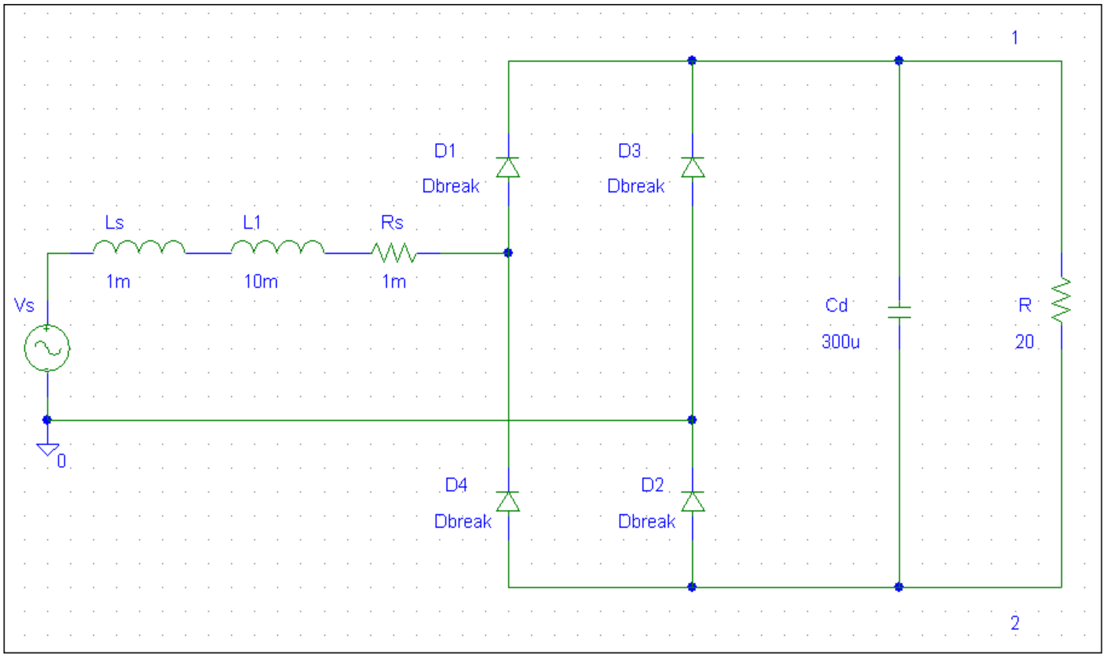


Figure 4.2 PSPICE diagram of a single phase rectifier with a capacitor filter

The harmonic components in the line current are listed in the PSPICE output file:

```
FOURIER COMPONENTS OF TRANSIENT RESPONSE I(L_Ls)
DC COMPONENT =   5.846163E-05
HARMONIC     FREQUENCY     FOURIER       NORMALIZED      PHASE      NORMALIZED
   NO           (HZ)       COMPONENT     COMPONENT       (DEG)      PHASE (DEG)

   1         5.000E+01     2.465E+01     1.000E+00     -2.053E+01    0.000E+00
   2         1.000E+02     1.025E-04      4.157E-06    -1.248E+02   -8.374E+01
   3         1.500E+02     1.063E+01     4.312E-01      1.133E+02    1.749E+02
   4         2.000E+02      3.349E-05    1.359E-06      2.111E+01    1.032E+02
   5         2.500E+02      1.436E+00     5.826E-02     1.635E+02    2.662E+02
   6         3.000E+02      2.739E-05     1.111E-06    -1.087E+01   1.123E+02
```

7	3.500E+02	1.087E+00	4.410E-02	-1.460E+02	-2.291E+00
8	4.000E+02	1.032E-05	4.186E-07	4.980E+01	2.140E+02
9	4.500E+02	6.747E-01	2.737E-02	-1.279E+02	5.681E+01
10	5.000E+02	1.983E-05	8.044E-07	1.164E+02	3 .216E+02

TOTAL HARMONIC DISTORTION = 4.381890E+01 PERCENT

The input current and true power factor can be calculated as follows:

RMS fundamental Input current $I_{1\ (rms)}$ $=24.65/\sqrt{2}=17.43$ A

THD of input current THD=43.82%=0.4382

RMS harmonic current $I_{h(rms)} = I_{1\ (rms)} \times \text{THD} = 17.43 \times 0.4382 = 7.64\text{A}$

RMS input current

$$I_s = (I_{1\ (rms)}^2 + I_{h(rms)}^2)^{1/2} = (17.43^2 + 7.64^2)^{1/2} = 19.03\text{A}$$

Displacement angle $\phi_1 = -20.53^0$

Displacement factor DPF= cos ϕ_1 =cos(-20.53)= 0.936(lagging)

Thus, the input power factor is:

$$\text{TPF} = \text{DPF} * \sqrt{\frac{1}{1+THD^2}} = \frac{1}{\sqrt{1+(0.4382)^2}} \times 0.93 = 0.8518(\text{lagging})$$

The simulation result of single bridge input current is in figure 4.3

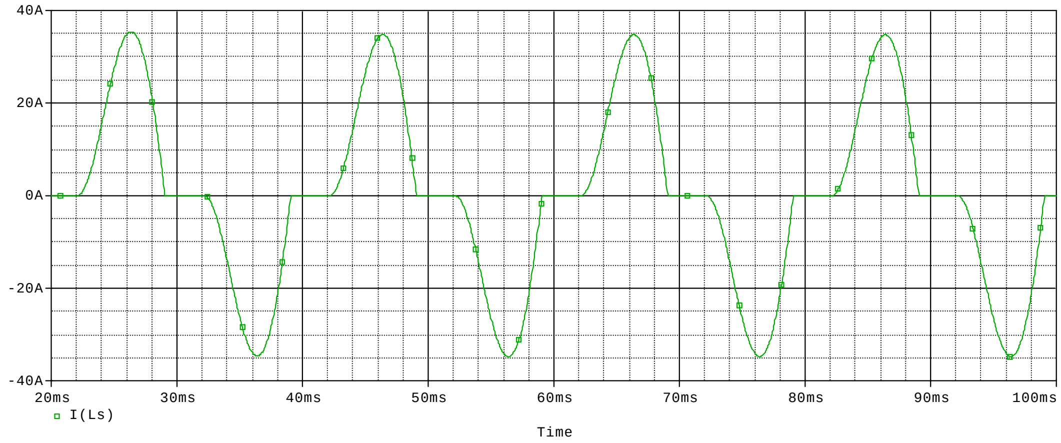


Figure 4.3 Single bridge input current waveform

4.5 Harmonics and Power Factor of a Typical Three-Phase Rectifier

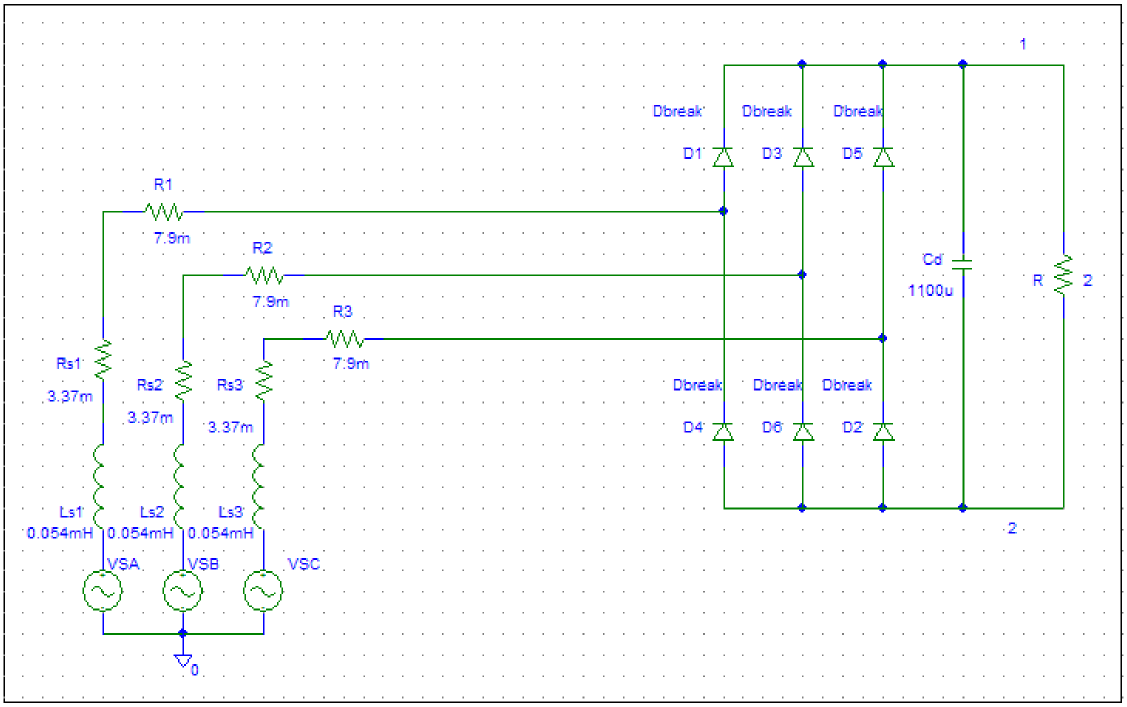


Figure 4.4 A three-phase bridge rectifier

A three-phase rectifier is shown in figure 4.4. The rectifier is supplied from a balanced three-phase supply 240V, 50 Hz. The load resistance is 2 Ω and DC side filter capacitance is 1100 μF. L_{s1}, L_{s2}, L_{s3} are power supply reactance, which are 0.054mH, R_{s1},R_{s2},R_{s3} are power supply resistance that is 3.37m Ω and R_1, R_2, R_3 represent power cable resistance that is 7.9 m Ω. This rectifier will be used for simulation and harmonic filter design as an exemplary case. The method of determining the impedance of a power source, including the resistance of power cables will be described in detail in chapter 5.

The main PSPICE simulation results for the input line current in the circuit of figure 4.4 are in table 4.1.Referring to the method introduced in section 4.4, the displacement and true power factor can be calculated as follows:

DPF=cos ϕ_1 =cos(-2.1)=0.999(lagging)

$$\text{TPF}=\frac{1}{\sqrt{1+(0.4747)^2}}\times 0.999=0.902(\text{lagging})$$

ϕ_1	THD	I_1 (Peak value)
-2.1^0	47.47%	303.8A

Table 4.1 Simulation result of the input current I_{R1}

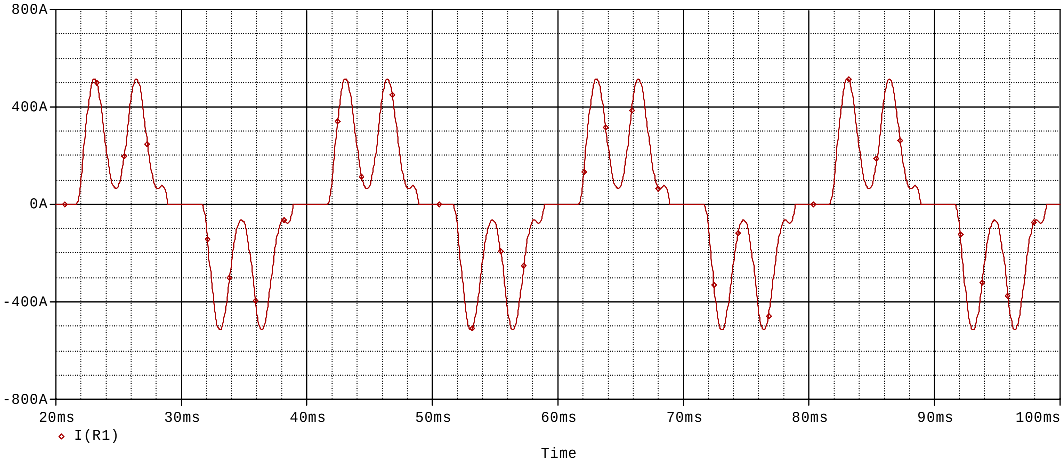


Figure 4.5 Input current waveform of the rectifier

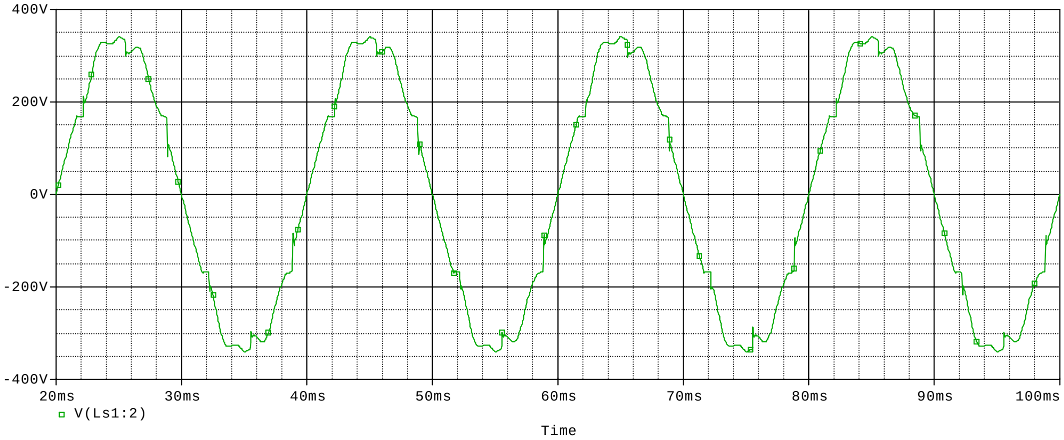


Figure 4.6 Input voltage waveform of the rectifier

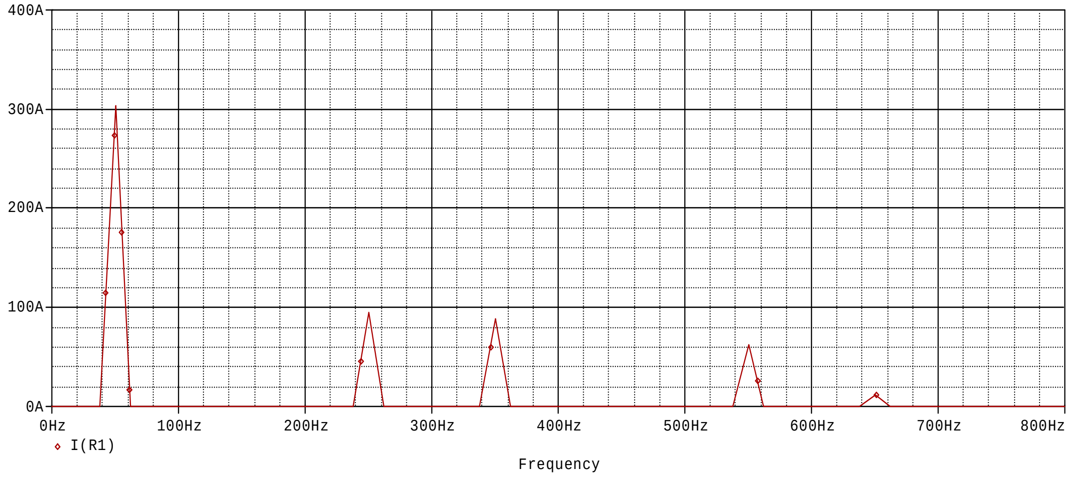


Figure 4.7 Harmonic spectrum of the rectifier input current

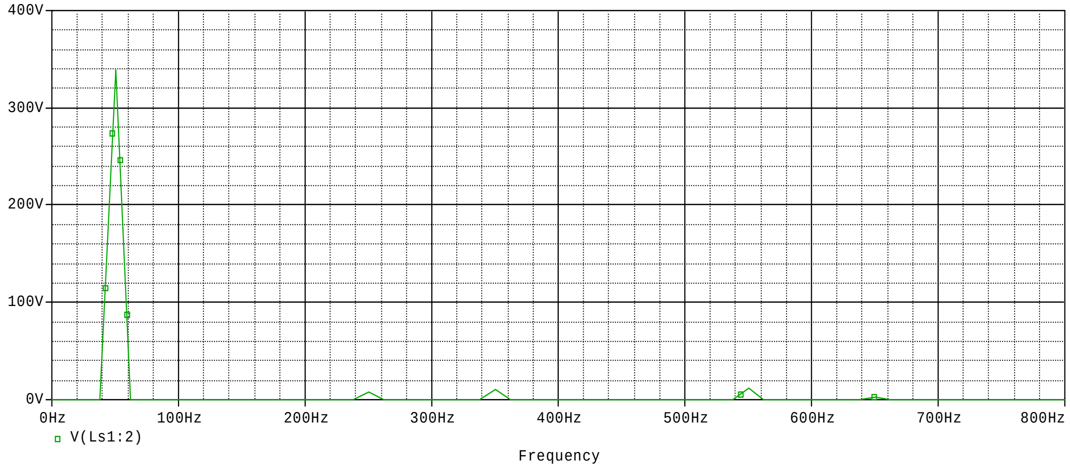


Figure 4.8 Harmonic spectrum of the rectifier input voltage

The waveforms of input current of the rectifier I $_{R1}$ are shown in figure 4.5 and the corresponding harmonic spectrum is given in figure 4.7.Figure 4.6 is the waveform of the voltage at the rectifier input terminals. It was stated earlier that large current distortions can produce significant voltage distortions. In this particular case, the voltage THD is 7.5%, which is higher than levels typically found in most industrial installations (5%). High levels of voltage THD also produce unwanted results. Figure 4.8 provides the spectrum of the voltage harmonic.

4.6 Conclusions

Three-phase converters differ from single-phase converters by the fact that they do not generate currents whose order is a multiple of three (tripplen harmonics). However, they can still be a significant source of other harmonics as can be seen from the simulation result of figure 4.7.This distorted current may result in a poor true power factor. It may be necessary to install some devices on the power supply side to reduce harmonics and increase the true power factor.

Chapter 5

Input Side Harmonic Filters Design

In this chapter, the principles of designing passive filter for the supply side of variable speed drives are presented.

5.1 Harmonic Distortion Evaluations

Harmonic currents injected from individual end users on the system must be limited. These currents propagate toward the supply source through the system impedance, creating voltage distortion. Thus by limiting the amount of injected harmonic currents, the voltage distortion can be limited as well. This is indeed the basic method of controlling the overall distortion levels proposed by IEEE Standard 519-1992.

5.1.1 Current Distortion Limit Evaluation Procedure

The steps of this procedure are as follows:

1. System modelling. The system response to the harmonic currents injected at end-user locations is determined by developing a model of the system.
2. Determination of the PCC. The concept is illustrated in section 5.2.1.
3. Calculating the ratio of $I_{shortcircuit}$ and $I_{fundamental}$ at the PCC, and finding the corresponding limits on the total harmonic distortion.
4. Evaluation of harmonic current levels with respect to the limits in table 2.1. If these values exceed the limits, the facility does not meet the IEEE Standard 519-1992, and filters may be required [5].

5.2 Power Supply Model of VSDs

5.2.1 Concept of Point of Common Coupling

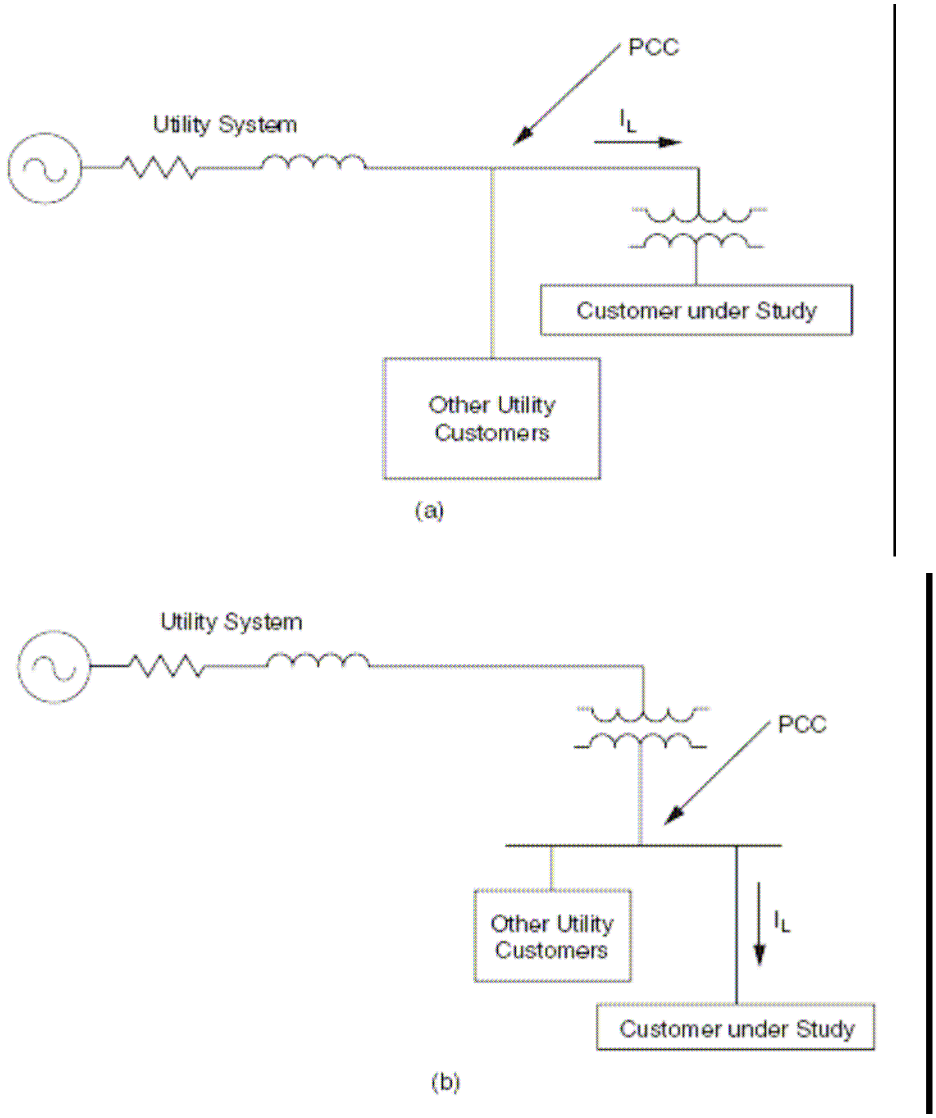


Figure 5.1 PCC selections depends on where multiple customers are served (*a*) PCC at the transformer primary where multiple customers are served (*b*) PCC at the transformer secondary where multiple customers are served[5]

Evaluations of harmonic distortion are usually performed at a point between the end user or customer and the utility system where another customer can be served. This point is known as the point of common coupling (PCC). The PCC can be located at either the primary side or the secondary side of the service transformer depending on whether or not multiple customers are supplied from the transformer. In other words, if multiple customers are connected at the primary side of the transformer, the PCC is then located at the primary. On the other hand, if multiple customers are served from the secondary of the transformer, the PCC is located at the secondary [5]. Figure 5.1 illustrates these two possibilities.

For industrial and commercial end users, the PCC (also metering point) is usually at the primary side of a service transformer supplying the facility. The power savings that are discussed in the thesis concern the section of the power systems part between the PCC and the load terminals. The equivalent circuit of variable speed drive systems to be considered is shown in figure 5.2. Where L_S presents the source inductance and R is the resistance of the source and power cables.

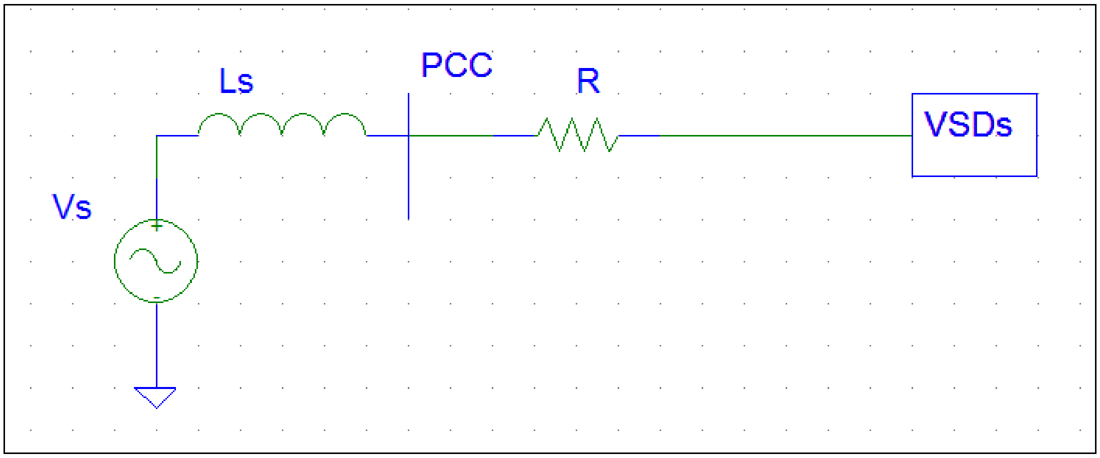


Figure 5.2 Equivalent circuits of a VSD power supply circuit

5.2.2 Calculation of Transformer Impedance

In industrial power systems, the equivalent source impedance is often dominated by the service transformer impedance. Transformer impedance in ohms can be determined from the percent impedance Z_{tx} found on the nameplate by

$$Z=R_s+jX_{tx} = (\frac{V^2}{VA_{3\phi}})*Z_{tx}(\%) \tag{5.1}$$

where $VA_{3\phi}$ =the VA rating of the transformer

Z= transformer impedance

R_s =transformer resistance

X_{tx} =transformer reactance

V = phase-to-phase voltage, V

In this thesis, the source in figure 5.2 is assumed to be a 1000 KVA, 415VAC secondary, 10% impedance, *X*/*R* ratio of 5 at for a typical transformer. The equivalent impedance on the 415V side is:

$$Z=\left(\frac{415^2}{1000*10^3}\right)*0.1=17.2\ m\Omega$$

With $|Z|=\sqrt{X_{tx}^2+R_s^2}$ and $X_{tx}/R_s=5$, we have:

$$R_s=3.37m\Omega,\ X_{tx}=16.86m\Omega$$

so
$$L_s=\frac{X_{tx}}{\omega_1}=\frac{16.86}{2*3.14*50}=0.054mH$$

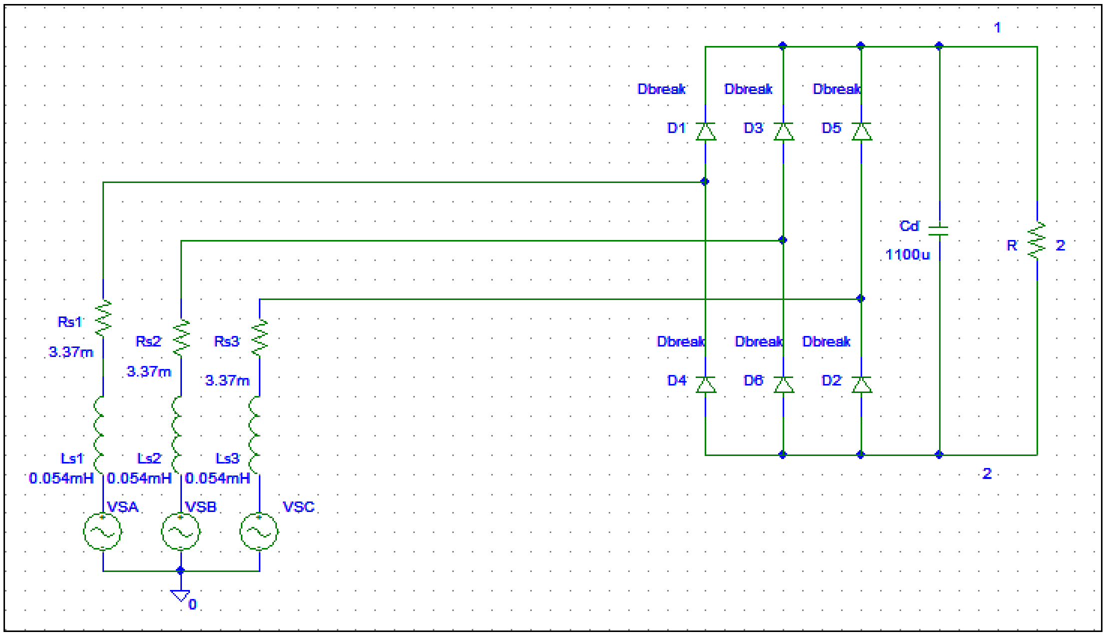


Figure 5.3 A full circuit of VSD power system

The full circuit of variable speed drive power system with the assumed transformer is shown in figure 5.3. In this figure, the load is 2Ω and the DC side voltage is 560V. According to equation 5.2 below:

$$P=\frac{V^2}{R} \tag{5.2}$$

the corresponding load power is:

$P=\frac{560^2}{2}$=157kW, and the load current I = 240 A.

The values of the load power current corresponding to a range of load resistances are shown in table 5.1.

Load R(Ω)	0.6	0.75	1	1.5	2
Power(kW)	504	410	313	209	157
Load current(A)	726	590	450	309	240

Table 5.1 Different loads with corresponding power and current

5.2.3 Resistance Calculation of Power Cables

Power cables should be selected to different size. Appendix A lists current carrying capacity of low smoke fume SWA power cable (from UK data). According to the full load current in table 5.1, the cable size is chosen as shown in table 5.2.For an exemplary load of 2 Ω (refer to figure 5.3), the power cable cross sectional area is 70mm^2.

The equation for calculating resistance of cable is:

$$R=\rho\frac{l}{S} \tag{5.3}$$

Where ρ is the resistivity of the material, for copper $\rho = 0.01851$ $\Omega\,\text{mm}^2$/m, l is length of the conductor in meters and S presents the cross sectional area of conductor in mm^2. Assuming that the length of the cable connecting the supply terminals with the rectifier terminals is 30m, and the cable is made of copper, the cable resistance is:

$$R_c = 0.01851 * \frac{30}{70} = 7.9\ \text{m}\Omega$$

Load P(kW)	504	410	313	209	157
Power cable cross sectional area(mm^2)	400	300	182	120	70

Table 5.2 Power cable size under different loads

Figure 4.4 shows a rectifier with a 2Ω load and the corresponding parameters of the supply circuit for the above case. The cable resistances calculated for different loads and three different cable lengths are listed in table 5.3.

Load P(kW)	15m cable resistance(mΩ)	30m cable resistance(mΩ)	50m cable resistance(mΩ)
504	0.7	1.4	2.3
410	0.95	1.9	3.1
313	1.6	3.1	5.1
209	2.3	4.6	7.7
157	3.95	7.9	13.2

Table 5.3 Supply cable resistance for different nominal loads and various lengths

5.3 Harmonic Filters Design

One of the most common methods for control of harmonic distortion in industry is the use of passive filtering techniques that make use of single-tuned or low-pass filters. Because passive filters always provide reactive compensation to a degree dictated by the voltampere size and voltage of the capacitor bank used, they can in fact be designed for the double purpose of providing the filtering action and compensating power factor to the desired level.

5.3.1The Basic Concept of Three Type Passive Filters

In figure 5.4, the impedance seen by the source in this circuit is given by

$$Z_s = R+j(2\pi fL-\frac{1}{2\pi fC}) \tag{5.4}$$

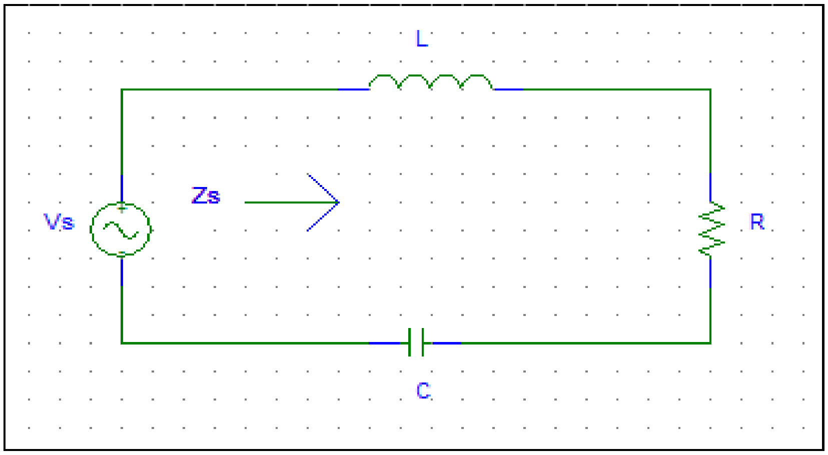


Figure 5.4 The series resonant circuit

The resonant frequency f_0 is defined to be the frequency at which the impedance is purely resistive. For the reactance to equal zero, the impedance of the inductance must equal the impedance of the capacitance in magnitude. Thus, we have

$$2\pi f_0 L=\frac{1}{2\pi f_0 C} \tag{5.5}$$

And the resonant frequency is given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad (5.6)$$

Another type of resonant circuit known as a parallel resonant circuit is shown in figure 5.5. The impedance of this circuit if given by:

$$Z_P = \frac{1}{1/R + j2\pi fC - j(1/2\pi fL)} \qquad (5.7)$$

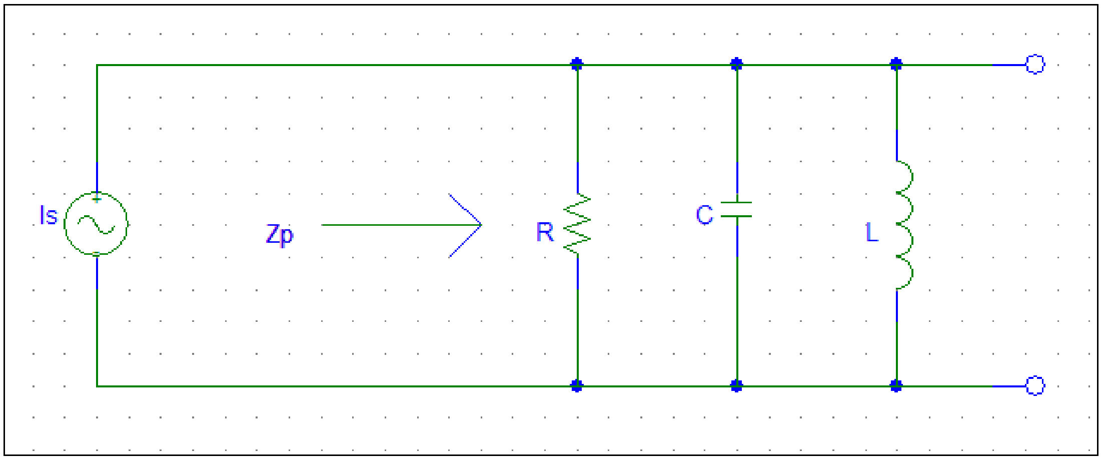


Figure 5.5 The parallel resonant circuit

As in the series resonant circuit, the resonant frequency f_0 is the frequency for which the impedance is purely resistive. This occurs when the imaginary parts of the denominator of equation 5.7 cancel. Thus, we have

$$2\pi f_0 C = \frac{1}{2\pi f_0 L} \qquad (5.8)$$

And the resonant frequency is given as: $f_0 = \frac{1}{2\pi\sqrt{LC}}$, this is exactly the same as the expression for the resonant frequency of the series circuit [33].

Therefore, according to chapter 1,it is easily to be found the single-tuned passive filter and low-pass passive filters work base on the theory of series resonant and series filters follow parallel resonant.

5.3.2 Methodology for Design of Single-Tuned Harmonic Filters

In this chapter, basic steps of designing a single-tuned filter are introduced, and a detailed design procedure of low-pass filters is presented.

A. Selecting the tuned frequency of the filter

The tuned frequency is selected based on the harmonic characteristics of the loads involved. For example, for a three-phase variable speed drive, the 5th and 7th harmonic filters are most effective when tuned exactly to 250 Hz and 350 Hz. Practically, however, the filters are tuned to a frequency slightly lower than the nominal resonant frequency as introduced in section 1.2.2.

B. Calculating the capacitor bank size and the resonant frequency

As a general rule, the filter size is based on the load reactive power requirement for power factor correction. When an existing power factor correction capacitor is converted to a harmonic filter, the capacitor size is given. The reactor size is then selected to tune the capacitor to the desired frequency. As introduced in section 3.5, the capacitive reactance needed to supply the needed VARs to improve the power factor from TPF_1 (associated with ϕ_1) to TPF_2 (associated with ϕ_2) is given by:

$$Q = P(\tan\phi_1 - \tan\phi_2) \tag{5.9}$$

With

$$P = VI\cos\phi_2 \quad \text{or} \tag{5.10}$$

$$P = \frac{V^2}{R}$$

The capacitive reactance required is obtained with the following relation:

$$X_{c1} = \frac{3V^2}{VARs} \tag{5.11}$$

where V is capacitor-rated line to neutral voltage and the filter capacitance is then calculated using,

$$C = \frac{1}{2\pi f X_{C1}} \tag{5.12}$$

where f is the fundamental frequency.

C. Calculating the filter reactor size

The filer reactor size can now be selected to tune the capacitor to the desired frequency as follows:

$$L = \frac{1}{(2\pi f)^2 (rh)^2 C} \tag{5.13}$$

Where, h is the harmonic to which the filter is tuned, and r is an empirical factor smaller than one. The typical value of r is 0.94 [15].

5.3.3 Methodology for the Design of Low- Pass Filters

Compared to a single-tuned filter, a low-pass filter that has a series L and a shunt C is not a tuned filter. The reactance of the L and C at the cutoff frequency is equal to the characteristic impedance, and that means the L and C happen to resonate at the cutoff frequency. The L starts to stop higher frequency signals getting from the load to the source, and the C starts to shunt higher frequency signals away from the load [34].

The same circuit of figure 4.4 in section 4.5 will be used here again with the same parameters. The main PSPICE simulation and calculation results for the input line current (I_{R1}) are given in table 5.4:

ϕ_1	DPF	THD	$I_{1(RMS)}$	PF	DC link voltage (V_{DC})
-2.09^0	0.999(lagging)	47.47%	214.85 A	0.902(lagging)	560 V

Table 5.4 Simulation and calculation results for the input current

Also, utilizing the same equations as in section 4.4, the total harmonic current I_h and the RMS value of input current I_{R1} are:

$$I_h = 214.85 \times 47.47\% = 102.87 \text{ A}$$

$$I_{R1} = \sqrt{I_h^{\ 2} + I_1^2} = \sqrt{102.87^2 + 214.85^2} = 238.2\text{A}$$

Series low-pass filters are the best choice for a voltage source rectifier. This filter is applied to individual loads or groups of loads in a system. They also can be applied on SCR rectifiers, including phase control and pre-charge front ends, as well as six-pulse rectifiers using AC line reactors or DC chokes.

Harmonic passive filters are designed as needed based on the minimum reactive power and maximum harmonic current requirements. As discussed in chapter 3, the true power factor becomes a combination of the displacement power factor and the distortion power factor. For most typical non-linear loads, the displacement power factor will be near unity. True power factor however, is lower because of the distortion component (harmonics). It can be found from table 5.4 that the displacement power factor of the rectifier of figure 4.4 without a filter will be near unity (0.999). But its true power factor is lower (0.902) because of high total harmonic distortion of 47.47%. Thus, the best way to improve the poor true power factor caused by this rectifier system is to remove the harmonic currents by adding reactors first.

5.3.3.1 Selections of Line Reactors

There are several methods available for treatment of variable speed drive harmonics as introduced in section 2.11. Ac input reactors (either1.5%, 3% or 5%, 7.5%impedance) are the most commonly used treatment.

A. Benefits of using AC reactors

AC Reactors help keep equipment running longer by absorbing many of the power line disturbances which otherwise damage or shut down variable speed controllers, or other sensitive equipment. They are the modern technology solution to converter and drive application problems. AC Reactors are harmonic compensated to assure optimum performance in the presence of harmonics. The benefits of them are:

- Extend semiconductor life
- Reduce harmonic distortion
- Reduce surge currents
- Improve true power factor
- Helps meet IEEE 519 [36]

B. Calculation of impedance

Reactors reduce harmonic currents. The definition of the percentage impedance of a reactor is:

$$\%\ \text{impedance} = \frac{I_{fundamental} * 2\pi f L * \sqrt{3}}{V_{LL}} * 100 \qquad (5.14)$$

Hence the inductance of a reactor can be calculated:

$$L = \frac{\% impedance * V_{LL}}{\sqrt{3} I_{fundamental} * 2\pi f * 100} \qquad (5.15)\ [37]$$

$I_{fundamental}$ (or $I_{1\ (RMS)}$) is the RMS value of the fundamental line current component before adding the reactors, (found from PSPICE simulation refer section 4.4 PSPICE output file). In this section, 5% impedance is chosen to be added to the system of figure 4.4. The new configuration is shown in figure 5.6. With $I_{fundamental}$ =214.85A (refer I_1 in table 5.4), L is:

$$L=\frac{5\% * 415}{\sqrt{3} * 214.85 * 2\pi * 50 * 100} = 0.18\text{mH}$$

The values of L calculated for other load levels are shown in figure 5.7.

C. Selection of low pass filters inductance

In figure 5.6, after installing 5% line reactors, the total harmonic distortion is 42.17%, compared with the total harmonic distortion of 47.47% before, the harmonic distortion is reduced. However, the total harmonic distortion of the input

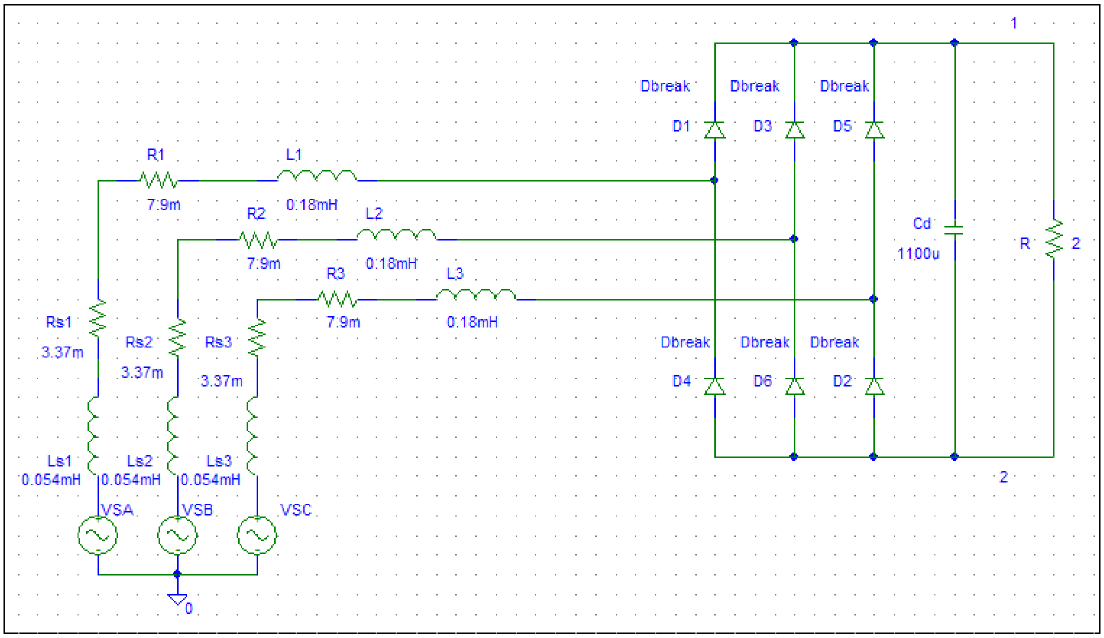


Figure 5.6 A three-phase rectifier with 5% impedance reactors

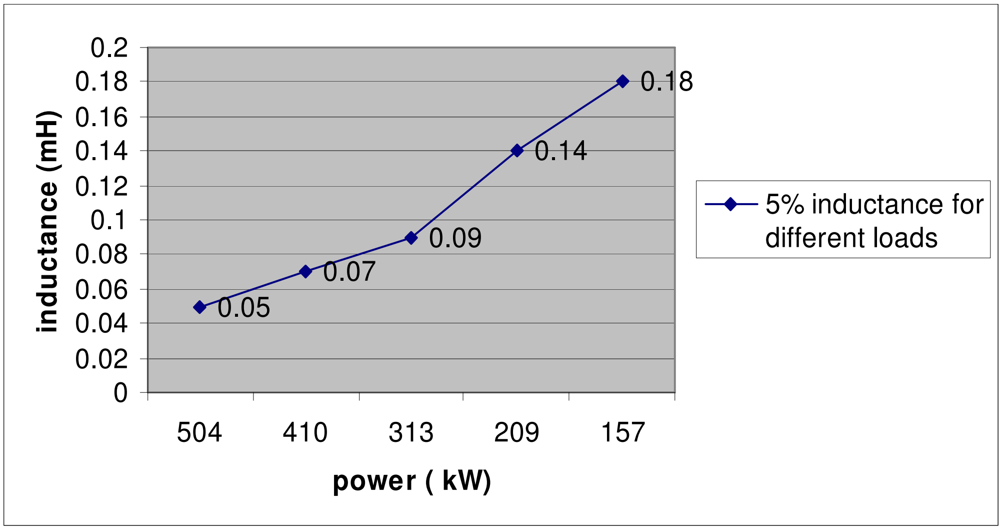
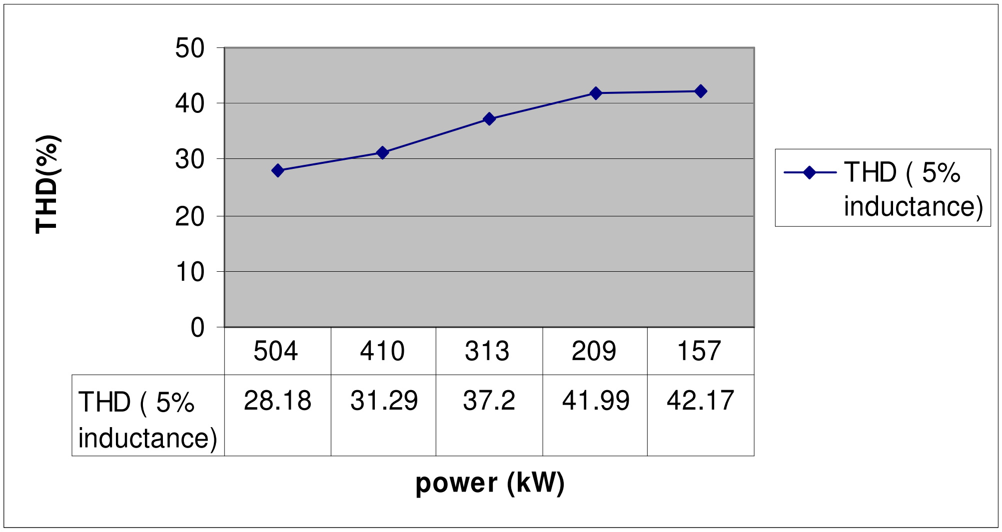


Figure 5.7 Inductance under different load

current in a power system should reach the limits set in IEEE519-1992 standard, which are listed in table 2.1. Thus, according to current distortion limit evaluation procedure introduced in section 5.1.1, the short-circuit ratio at the PCC should be calculated to find the corresponding limits for the total harmonic distortion. The total harmonic distortion after the addition of 5% line reactors changes with load level as shown in figure 5.8.



	504	410	313	209	157
THD (5% inductance)	28.18	31.29	37.2	41.99	42.17

Figure 5.8 THD under various loads with 5% line reactors

In the three-phase diode circuit of figure 4.4, per-phase short-circuits current can be calculated as:

$$I_{shortcircuit} = \frac{V_{LL}/\sqrt{3}}{\omega_1 L_s} \qquad (5.16)$$

Here L_s represents the inductance of the power supply and ω_1 is fundamental angular frequency [9]. So

$$I_{shortcircuit} = \frac{415/\sqrt{3}}{2*3.14*50*0.054*10^{-3}} = 14131\text{A}$$

as known above, fundamental input current $I_{fundamental}$ =214.85A, in this case, assuming $I_{fundamental}$ just equals I_L , according to the guidelines in table 2.1, so the ratio between $I_{shortcircuit}$ and I_L is:

$$I_{shortcircuit}/I_L = 14131/214.85 = 65$$

Thus, the harmonic current limitation of the circuit in figure 4.4 should be less than 12 percent. Similarly, the total harmonic distortion limitation of input current under other loads can be determined as shown in table 5.5.

Load P(kW)	504	410	313	209	157
THD limitation level (%)	8	8	8	8	12

Table 5.5 THD limitation level under different loads

For easy calculating and analysing, we limit the total harmonic distortion of load 157kW to 8% too. It can be found from figure 5.8 that 5% line reactors in figure 5.6 are only moderately effective in reducing harmonic current distortion. For reducing total harmonic distortion lower than 8 percent (IEEE-1992 standard), the reactance should be increased and some typical reactance and corresponding other parameters are listed in table5.6 and graphs are in figure 5.9 and 5.10.

Inductance (mH)	0.18	0.4	0.8	1.2	1.4	1.8	2.0	2.2
THD (%)	42.17	21.22	17.4	13.33	11.85	9.5	8.63	7.82
ϕ_1 (degree)	16.26	25.48	26.24	30.03	31.63	33.83	35.46	36.6
DPF (lagging)	0.96	0.9027	0.8969	0.8658	0.8515	0.8307	0.8145	0.8028

Table 5.6 simulation and calculation result with different reactance for 157kW load

Figure 5.9 shows that the total harmonic distortion reduces when the reactance of the line reactors increases. According to table B.1 of appendix B, the higher reactance, the bigger cost of the reactors. Also, the aim of designing passive filters

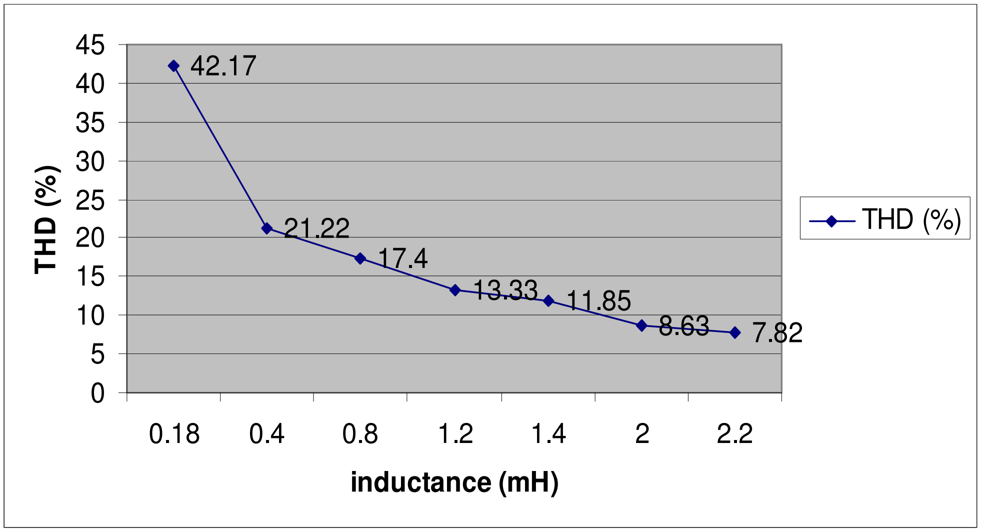


Figure 5.9 Different inductance vs THD of input current for 157kW load

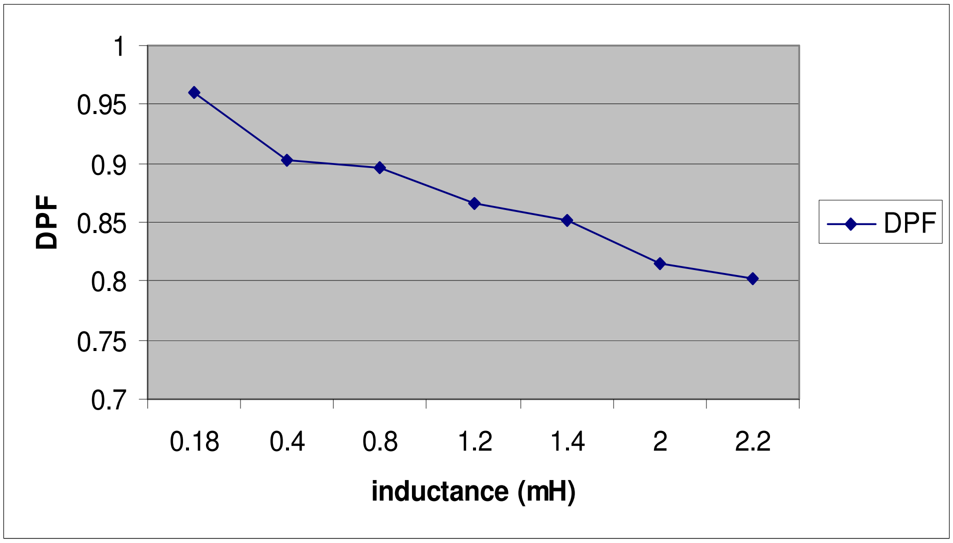


Figure 5.10 Different inductance vs DPF for 157kW load

in this thesis is to find the minimum filters requirement to meet energy saving objectives. For example L=2.2mH is the minimum value that is required to reduce the THD to 8%. The high inductance of ac input reactors can often introduce troublesome voltage drops at the rectifier input. Furthermore, 2.2 mH is 12.2 times 0.18mH (5% reactance of the reactors). The solution is to converter reactors into low-pass filters. The reactances of low-pass filters for different loads at THD ≤ 8% are listed in figure 5.11 and the corresponding THD and DPF are shown in table 5.7.

DC load R(Ω)	0.6	0.75	1	1.5	2
Load P(KW)	504	410	313	209	157
THD (%)	7.87	7.96	7.92	7.96	7.82
DPF	0.804	0.8062	0.8117	0.8059	0.8028

Table 5.7 THD and DPF after the addition of reactors

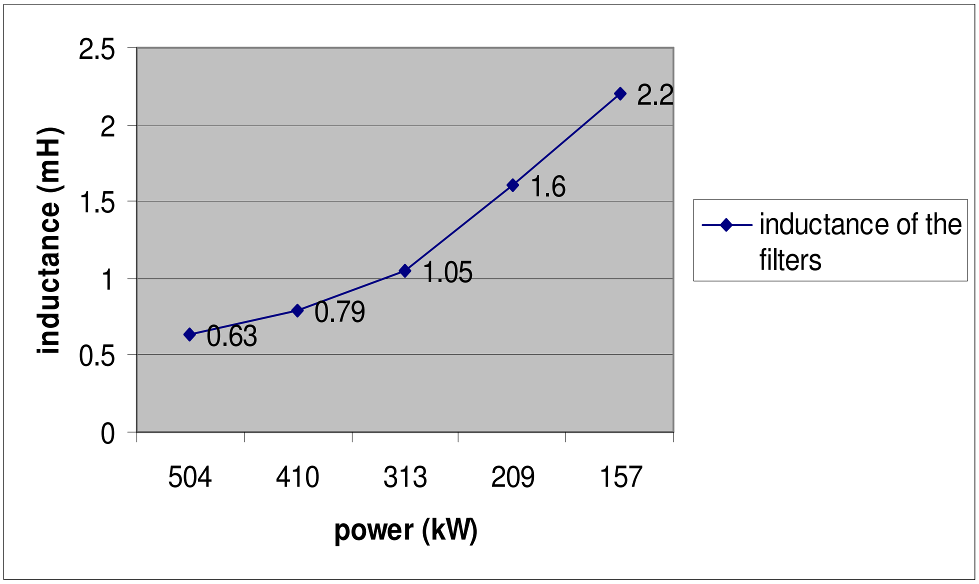


Figure 5.11 Inductance of low-pass filter for different loads

5.3.3.2 Calculation of Capacitance of the Filters

It can be seen from figure 5.10, that the displacement power factor of the system in figure 5.6 trends to lower with the increase of the reactor inductance. For example, after the 2.2mH inductance is chosen, the displacement power factor of the rectifier system becomes 0.8028.

If displacement power factor correction capacitors are now added in front of the rectifier in figure 5.6, a low-pass passive filter is created. This procedure has introduced in section 3.5, and it is similar to that in section 5.3.2.B for designing the single-tuned filters. The main simulation and calculation results for $L_1 = L_2 = L_3 = 2.2$mH in the circuit of figure 5.6 are given in table 5.8.

ϕ_1	THD	DPF	TPF	V_{DC}
36.6^0	7.82	0.8028(lagging)	0.8004(lagging)	428 V

Table 5.8 Simulation and calculation results for the circuit of figure 5.6 (with $L_1 = L_2 = L_3 = 2.2$mH)

In this example, it is assumed that the desired true power factor is 96 percent. For the circuit in figure 5.6, ϕ_1= 36.6, from equation3.6, 3.7and table 5.8,

$$F_{dist} = 0.997,\ DPF_2 = \frac{TPF}{F_{dist}} = \frac{0.96}{0.997} = 0.9629,$$

So ϕ_2=arcos(0.9629)=15.65^0;

From table 5.8,

$$P = \frac{V^2}{R} = \frac{428^2}{2} = 91{,}592\ W,$$ where V is the DC side voltage of load R.

$$Q = P(\tan\phi_1 - \tan\phi_2) = 91{,}592*(\tan 36.6 - \tan 15.65) = 42{,}370.5VAR$$

The capacitive reactance required is:

$$X_{c1} = \frac{3V^2}{VARs} = \frac{3*240^2}{42370.5} = 4.08\ \Omega$$

and the filter capacitance is:

$$C = \frac{1}{2\pi f X_{C1}} = \frac{1}{2*3.14*50*4.08} = 780.6\,\mu F$$

Therefore, according to the theoretical calculation, the capacitance of this three-phase low-pass filter should be:

C11=C12=C13=780.6μF

and the configuration of the rectifier system with a input side low-pass filter is shown in figure 5.12.

Main simulation and calculation result of figure 5.12 is listed in table 5.9.It shows that after adding the capacitors, the true power factor of the system becomes

0.9744. It exceeds the desired value of 0.96. Thus, the parameters of the filter need to be recalculated for the purpose of cost saving.

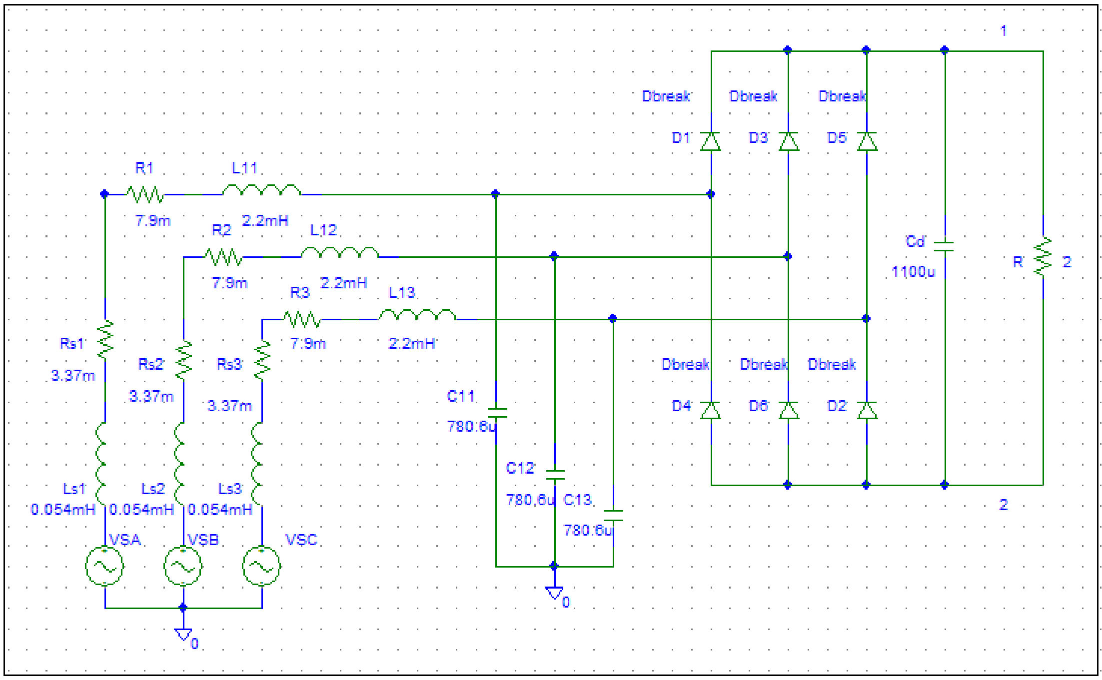


Figure 5.12 A three-phase rectifier with a low-pass filter

ϕ_1	THD	DPF	TPF
-12.7	5.84%	0.9755(lagging)	0.9744(lagging)

Table 5.9 Simulation and calculation result for the circuit of figure 5.12

In figure 5.12, if the capacitance is decreased and the inductance of the filter kept constant, the DPF and TPF will reduce with nearly no effect on total harmonic distortion. According to table 5.9,

$$F_{dist} = \frac{1}{\sqrt{1+0.0584^2}} = 0.9983$$

that is almost unity, since DPF and TPF are nearly of the same value. If the capacitance is selected from the typical range of 420 μ F to 781 μ F, the corresponding values of DPF and THD will be as shown in figure 5.13 and 5.14. For true power factor reaching near 0.96, the minimum capacitance can be found from figure 5.13, which is C=480μF.

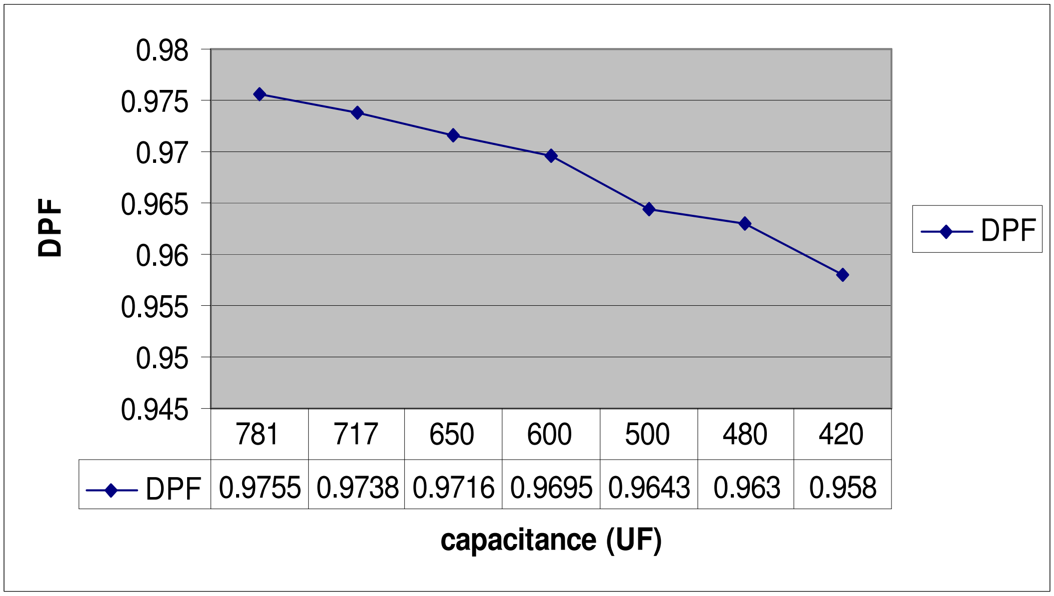


Figure 5.13 DPF vs capacitance

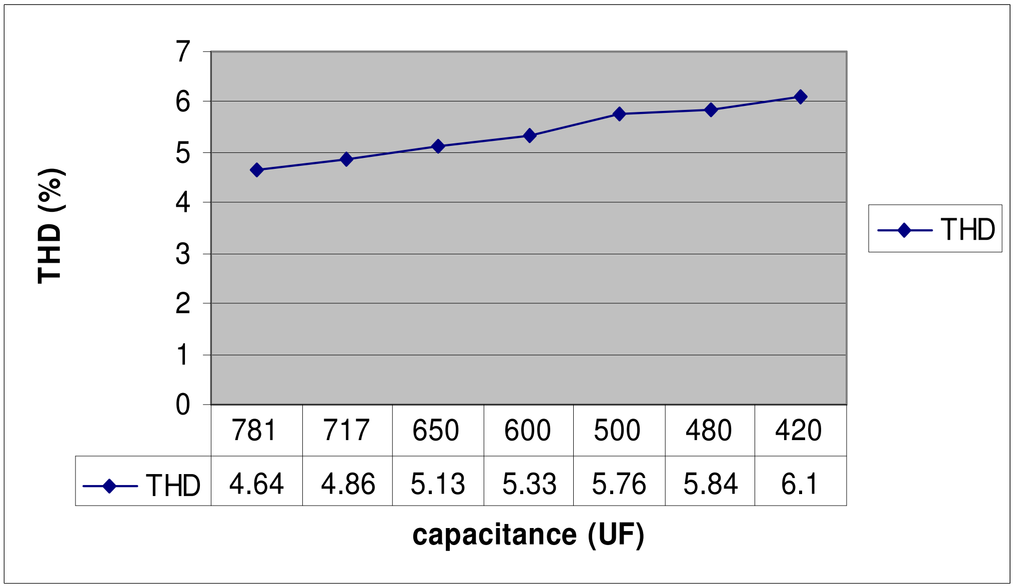


Figure 5.14 THD vs various capacitance

With L=2.2mH, the cutoff frequency of this low-pass filter is:

$$f_0 = \frac{1}{2\pi\sqrt{2.2 * 10^{-3} * 480 * 10^{-6}}} = 155 \text{ Hz},$$

which is 3.1 times the fundamental frequency (50Hz).The resonant frequency is well below the 5th harmonic current, which is the lowest significant harmonic on this power system. The parameters of the low-pass filter calculated for other loads can be found in table 5.10.the variation of the filter capacitance vs the load is shown in the graph of figure 5.15.

Load P(kW)	504	410	313	209	157
Filter inductance (mH)	0.63	0.79	1.05	1.6	2.2
Filter capacitance (μF)	1650	1250	855	580	480

Table 5.10 The final parameters of different Low-pass filters

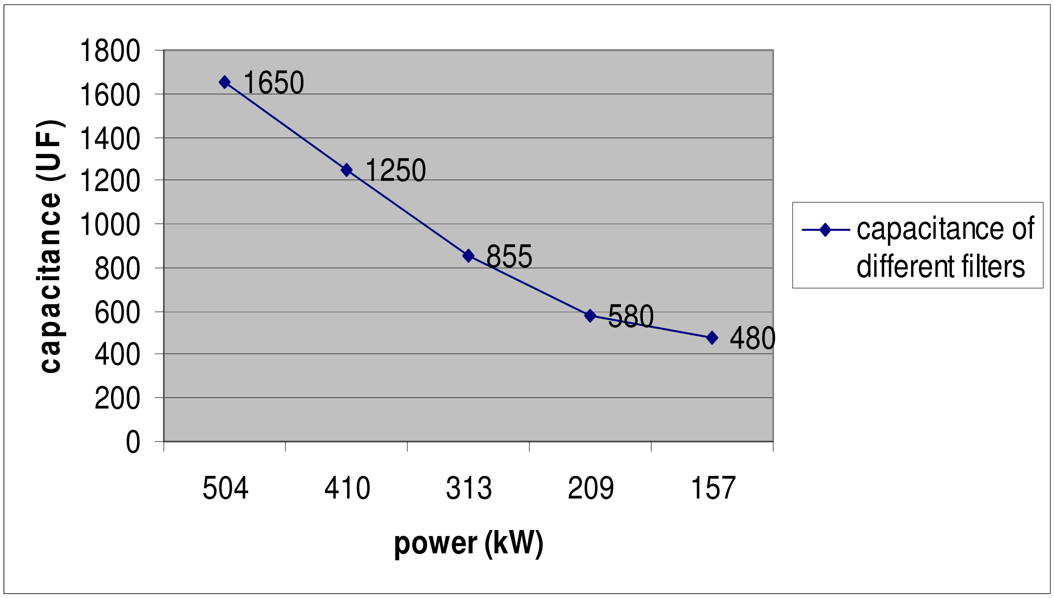


Figure 5.15 Capacitance of the filters under different loads

In general, the procedure of designing low-pass filters for rectifier systems as presented above is as follows:

A. Connect line reactors on the input side of the rectifier. If the current total harmonic distortion does not meet the limitation of IEEE Standard 519-1992, increase the reactor inductance until the current distortion reaches the standard. Normally, the minimum inductance that meets the requirement is chosen.

B. Keeping the inductance selected above, connect capacitors to improve the displacement power factor to the desired value.

5.4 Analysis of the Performance of a Rectifier after with a Low-pass Filter

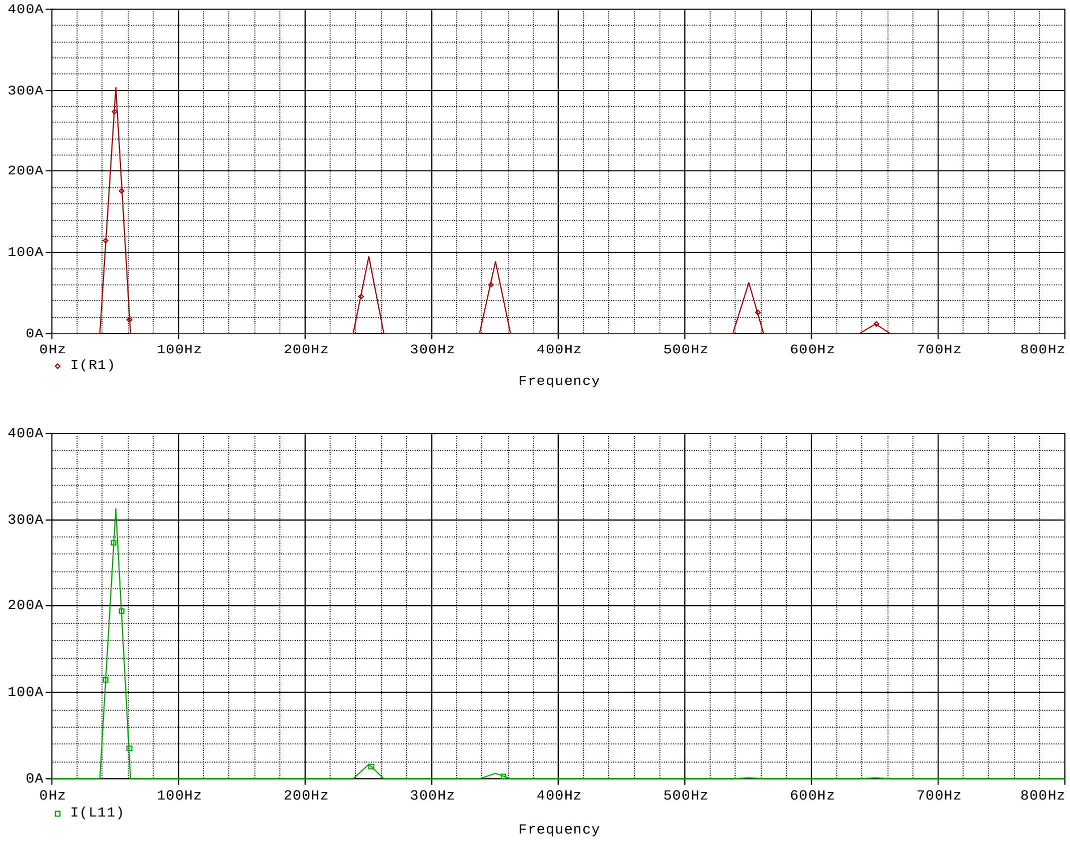


Figure 5.16 Harmonic spectrum of the rectifier input current
(upper: no filters , lower: with a filter)

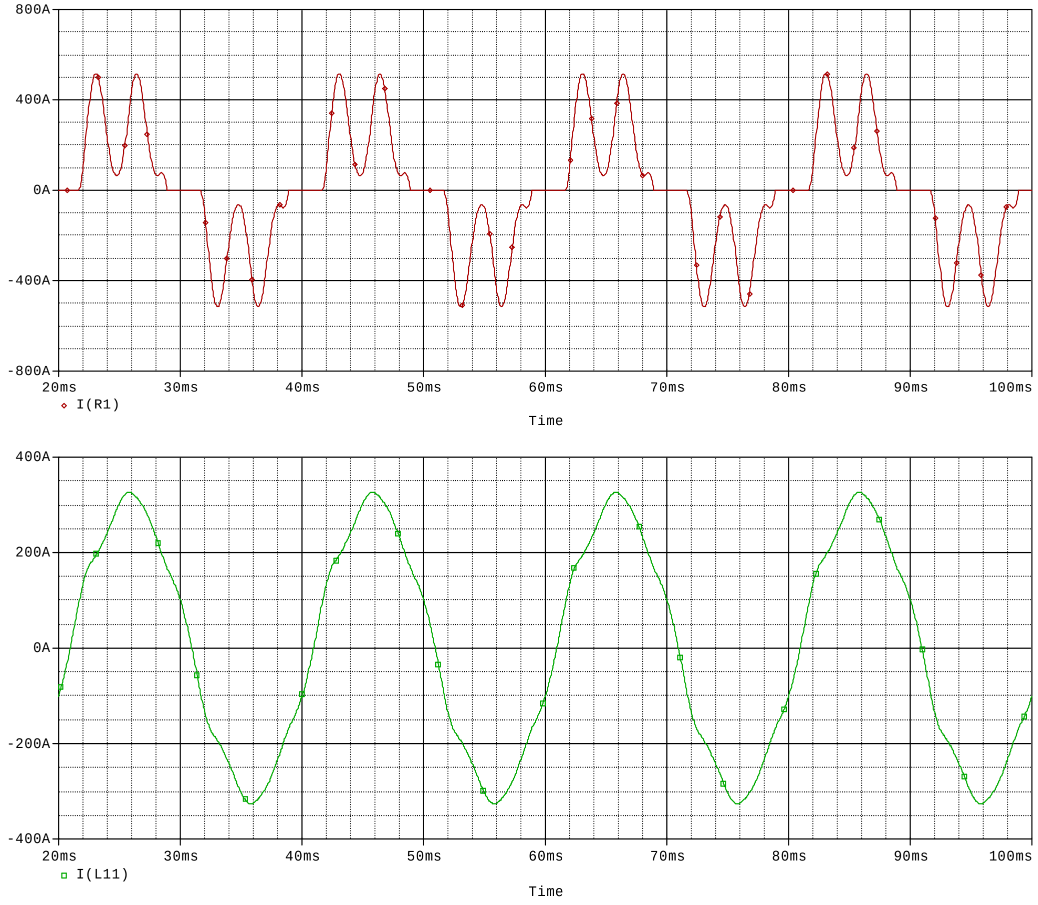


Figure 5.17 Input current waveforms of the rectifier

(upper: no filters , lower: with a filter)

The main simulation and calculation result for the circuit of figure 5.12 with L=2.2 mH, C=480 μ F are given in table 5.11. I $_{L11}$ is the input line current of the rectifier after installing a filter.

ϕ_1	THD	DPF	TPF	I $_{L11}$ (RMS)
-15.63 ^{0}	5.84%	0.963	0.9613(lagging)	226.8 A

Table 5.11 Simulation and calculated results for the circuit of figure 5.12 with C=480 μ F

In table 5.11, the line current I_{L11} with a filter connected is calculated according to equation 5.10 as follows:

$$I_{L11} = \frac{P}{3U * TPF} = \frac{157 * 10^3}{3 * 240 * 0.9613} = 226.8 \text{ A}$$

According to the simulation and calculation results, after connecting a low-pass filter on the power supply side of the rectifier, the power factor increases from 0.902 to 0.9613, and the harmonics of the rectifier input current reduce from 47.47% to 5.84%. (The change in the amplitude of individual harmonics can be viewed in figure 5.16) Furthermore, comparing the waveforms of the input current before and after adding a filter, shown in figure 5.17, it can clearly be found that the input current waveform has significantly improved, and it is nearly sinusoidal.

5.5 Conclusions

In this chapter, the design procedure of low-pass passive harmonic filters for diode rectifiers is presented. It is illustrated with exemplary numerical results for rectifiers supplied at 415V, 50Hz and loaded up to 500kW.

Chapter 6

Economic Aspects of Low-pass Filters

In this chapter, the savings resulting from the installation of filters in variable speed drive systems and the cost of different low-pass filters are considered.

6.1 Energy Savings after Filter Installation

As discussed in chapter two, the current flowing in a cable and a transformer produces I^2R losses. When the current contains harmonics, additional losses are introduced. The main aim of designing a filter for the power supply side of a rectifier is to reduce harmonics and improve the power factor. With reference to the circuit of figure 5.12, the load draws the same active power after the addition of a filter. The line current I_{L11} should be smaller than the current I_{R1} (before installing a filter) in order to reduce I^2R losses.

In most power systems, one can generally assume that the resistance does not change significantly when studying the effects of harmonics less than the nine. For lines and cables, the resistance varies approximately by the square root of the frequency, once the skin effect becomes significant in the conductor at a higher frequency [5]. According to section 2.7,

$$I_{R1} = \sqrt{(I_1^2 + I_5^{\ 2} + I_7^{\ 2} + I_{11}^2 + I_{13}^2 \ldots)} \tag{6.1}$$

In this thesis, we only consider the harmonics lower than 13th. The RMS values of fundamental and harmonic components of the input line current for different loads are listed in table 6.1. The energy loss in cables in the circuit of figure 4.4 is:

$$P_1 = 3\,I_{R1}^2 R_{cables} = 3(I_1^2 + I_5^2 + I_7^2 + I_{11}^2 + I_{13}^2)\,R_{cables}$$

Load P(kW)	I_1(A)	I_5(A)	I_7(A)	I_{11}(A)	I_{13}(A)
504	701.1	172.8	79.6	56.1	16.3
410	561.8	141.6	78	54.5	11.6
313	425.8	110.3	74.4	52.1	7.1
209	285.8	80.6	68.1	48.1	7
157	214.9	67.6	62.4	44.1	8.7

Table 6.1 RMS values of fundamental and harmonic components of the line current

If the skin effect is to be taken into account, the power loss in cables should be calculated as follows:

$$P \cong 3(I_1^2+\sqrt{5}\,I_5^2+\sqrt{7}\,I_7^2+\sqrt{11}\,I_{11}^2+\sqrt{13}\,I_{13}^2)\,R_{cables}$$

Including the resistance of the transformer (R_{TX}), and neglecting the harmonic components of the line current after the installation of a filter, the power saving in the system of figure 5.12 (C=480μF) is:

$$\Delta P = 3[(I_1^2+\sqrt{5}\,I_5^2+\sqrt{7}\,I_7^2+\sqrt{11}\,I_{11}^2+\sqrt{13}\,I_{13}^2)\,R_{cables}+I_{R1}^2 R_{TX}] - 3I_{L11}^2\,(R_{cables}+R_{TX})$$

$$=3*[73426.9*7.9*10^{-3}+238.2^2*3.37*10^{-3}]-3*226.8^2*(3.37+7.9)*10^{-3}$$

$$=575.1\text{ W}$$

The energy saving per hour is:

$$E=\Delta P\,t=575.1*10^{-3}\text{ kWh}$$

Assuming the load is supplied 24 hours a day and 365 days a year, the energy saving of per year is:

$$575.1*10^{-3}\text{ kWh}*24*365=5037.9\text{kWh}$$

The above example shows a possible electrical energy saving of 5032.9 kWh per year after low-pass filter installation. At energy rates of $0.20/kWh, the annual savings are 5037.9*0.2=$1007.6.

6.2 Saving Calculations for Different Loads and Different Cables

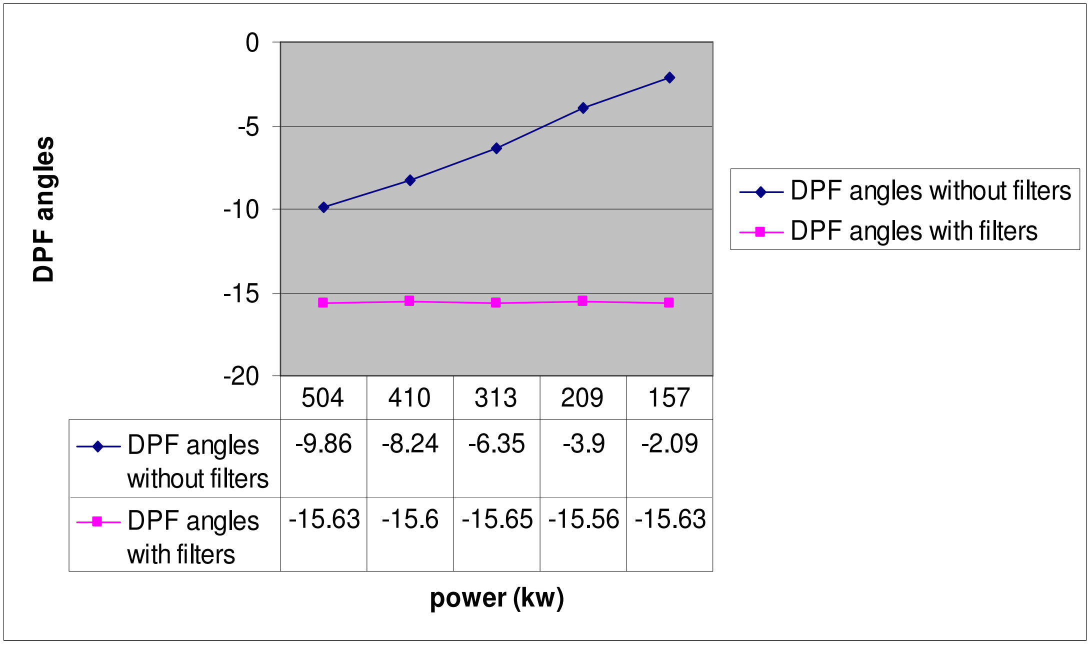
For the load levels specified in table 5.1, the simulation and calculation results for a system without low-pass filters are shown in table 6.2, and the corresponding results for a system with low-pass filters are listed in table 6.3. The graphs of figure 6.1 to 6.4 present comparison of the results.

Load P(kW)	THD (%)	ϕ_1 (degree)	I $_{R1}$ (RMS) (A)	TPF(lagging)
504	28.3	-9.86	728.5	0.948
410	30.21	-8.24	590	0.9474
313	33.53	-6.35	449.2	0.9423
209	40.56	-3.9	310.6	0.9246
157	47.47	-2.09	238.2	0.902

Table 6.2 Simulation and calculation result for different loads without filters

Load P(kW)	THD (%)	ϕ_1 (degree)	I $_{L11}$ (RMS) (A)	TPF(lagging)
504	6.06	-15.63	722.6	0.961
410	6.19	-15.6	586	0.9613
313	6.41	-15.65	445.1	0.961
209	6.25	-15.56	302	0.9612
157	5.84	-15.63	226.8	0.9613

Table 6.3 Simulation and calculation result for different loads with filters



	504	410	313	209	157
DPF angles without filters	-9.86	-8.24	-6.35	-3.9	-2.09
DPF angles with filters	-15.63	-15.6	-15.65	-15.56	-15.63

Figure 6.1 Displacement power factor angle comparison

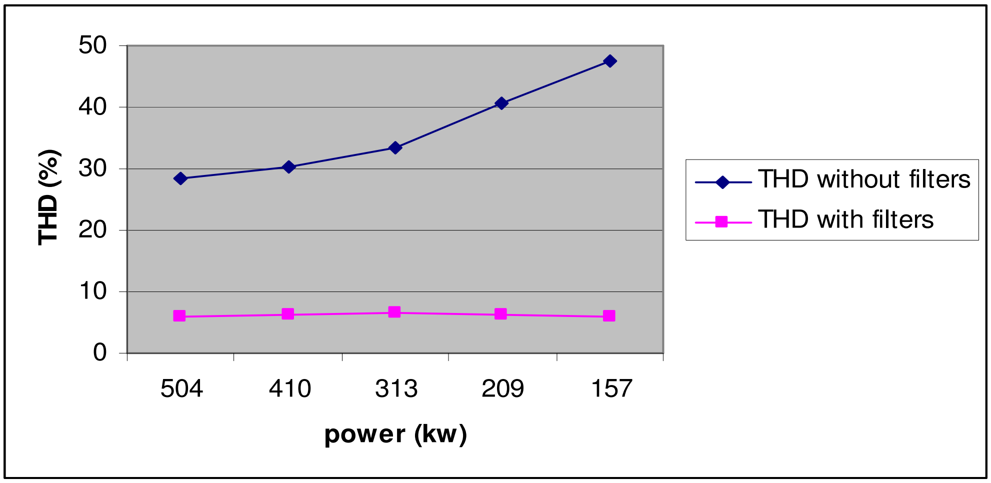


Figure 6.2 Total harmonic distortion comparison

According to the result of table 6.1, 6.2 and 6.3, and utilizing the same method as discussed in section 6.1, the energy saving per year and the corresponding cost saving for various loads are calculated for the power cable length is 30 meters. The results are shown in table 6.4. If the length of power cables is changed to 15 meters or 50 meters (refer cable resistance list in table 5.4), THD, ϕ_1 and the power factor of the system stay nearly the same compared with the case of 30 meters. The filter parameters are not affected. The savings for different power levels and different cable lengths are given in table 6.4 and the corresponding graphs are shown in figure 6.5 and 6.6.

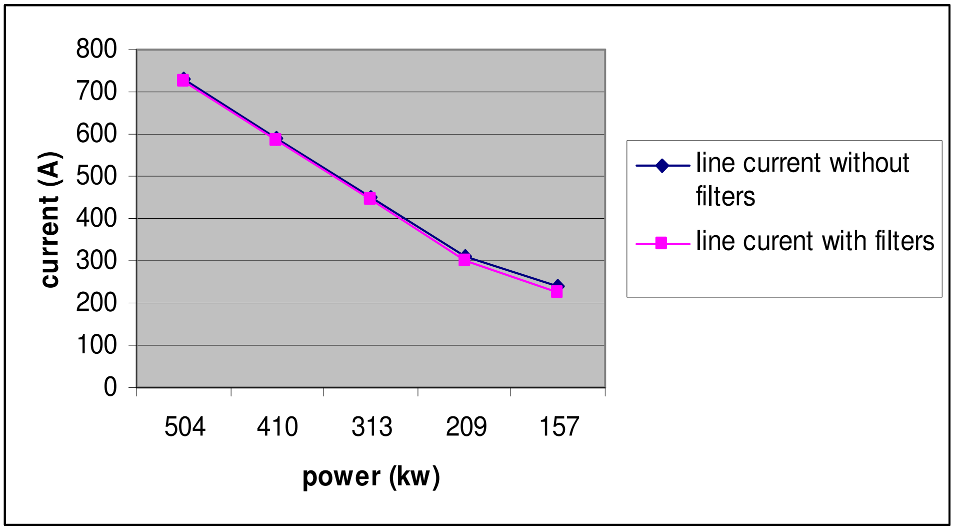


Figure 6.3 Line current comparisons

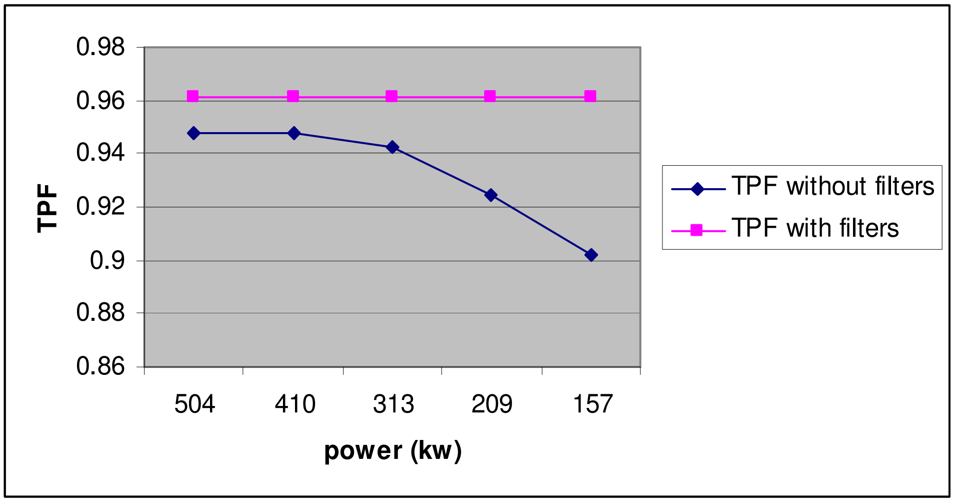


Figure 6.4 True power factor comparisons

Load P(kW)	Energy savings/year (kWh)			Cost savings/year (dollars)		
	15m	30m	50m	15m	30m	50m
504	1318.9	2290.5	3500.2	263.8	458.1	700.1
410	1503.3	2591.3	3960.4	300.7	518.3	792.1
313	1764.3	3116.9	4912.7	352.9	623.4	982.6
209	1985.9	3511.1	5552.1	397.2	702.3	1110.5
157	2752.4	5037.9	8096	550.5	1007.6	1619.3

Table 6.4 Savings with filters under different load

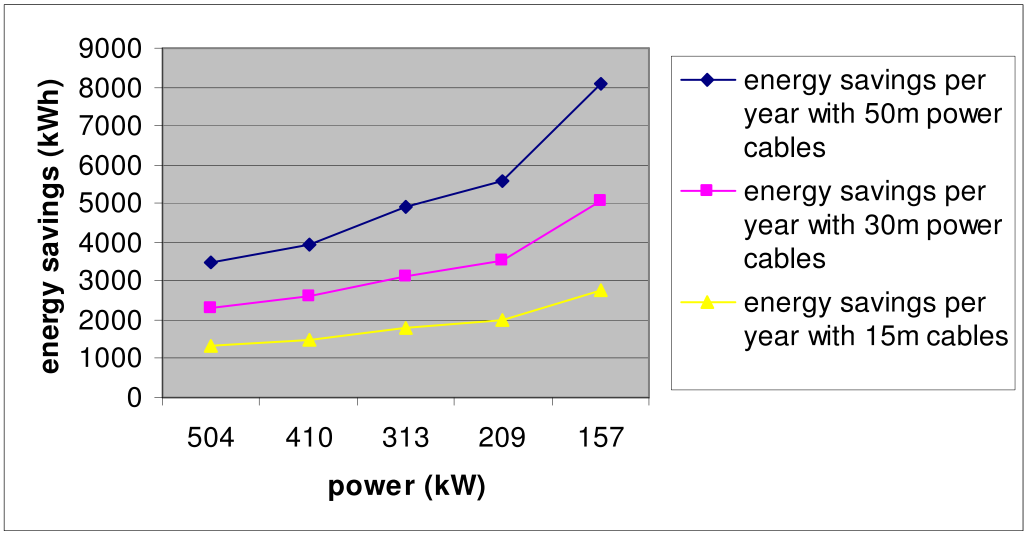


Figure 6.5 Energy savings per year of various power cables

The above energy and cost savings are calculated only for the power cables and transformer resistance in a variable speed drive system. As mentioned in section 3.7, a penalty for power factors below 0.95 can be charged. For the circuit of figure 4.4 and the data in table 6.2,

$$Q= P\tan (\arccos 0.902) =157\text{kW}*0.4786=75.2 \text{ KVAR}$$

The total reactive energy used per year = 75.2*24*365=658,752 KVARh. The total power factor penalty incurred each year = 658752*0.2*10^{-2} = $1314. Thus, with a low-pass filter in the circuit of figure 4.4, the annually savings are 1314 dollars. Similarly, the cost savings are calculated for other loads and listed in table 6.5.The total cost savings from table 6.4 and 6.5 are listed in table 6.6.

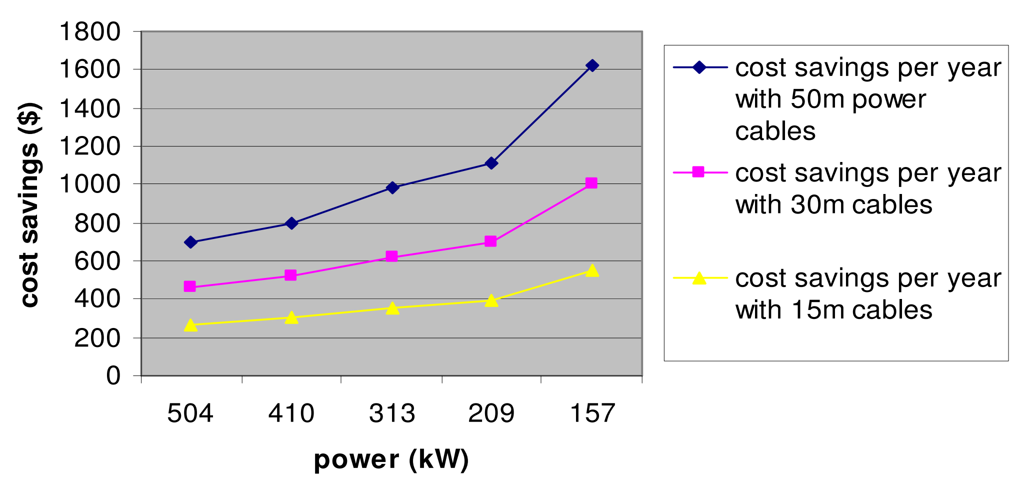


Figure 6.6 Cost savings per year of various power cables

Load P(kW)	504	410	313	209	157
Reactive power savings/year ($)	2964.5	2426.7	1948.3	1508.7	1314

Table 6.5 Reactive power penalties savings under various loads

Load P(kW)		504	410	313	209	157
Total cost savings/year ($)	15m	3228.3	2727.4	2300.7	1905.9	1864.5
	30m	3422.6	2945	2571.7	2560.6	2321.6
	50m	3664.6	3218.8	2930.9	3058.8	2933.3

Table 6.6 Total savings with filters under different loads

6.3 Selection of Filters

A. Assembled filters

Using the calculated values of filter parameters, we can purchase capacitors separately and connect them into a filter. The other option is to acquire a complete filter from a filter manufacturer. In appendix B, table B.1 and B.2 list inductors and capacitors from MTE Corporation and GE Company. For a load of 157 KW, as a example, the inductance of the filter is 2.2 mH , the rated current is 226.8 A, the capacitance is 480 μF and the rated voltage is 240 V. Item RL-25003, which costs \$1263.8 each, is rated at 0.15mH and 250A. For RL-25002, the price is \$947.17, and the rated values are 0.09 mH and 250 A. Fourteen RL-25003 and one RL-25002 connected in series make the total inductance of 2.2 mH, and total price is \$18640.37. Item 97F6866 (280V, 40 μF) costs \$21.07. Twelve are connected in parallel, the total capacitance will be 480 μF. Three phases need 36 capacitors, costing in total \$758.52. Overall, the cost of the filter for a 157KW load is \$19398.9.Utilizing the same method, the cost of assembled filters for various loads are calculated and listed in table 6.7.

Load P(kW)	504	410	313	209	157
Designed filter prices(\$)	51,046.5	42,089.1	30,942.7	22,440.3	19,398.9

Table 6.7 Cost of assembled filters

B. Selecting from manufactures

Customers can purchase complete filters from manufactures. The budget price algorithm for the SOCOMEC ATRYS series passive harmonic filters which come from Power Parameters P/L of Melbourne is as follows:

Budget Price = 70 x Amps + \$ 6,000

The price of a 226.8 A current per phase, 415 V, 3 phase, 50 Hz passive harmonic filter (for a157 kW load) can be calculated as follow:

Price = 70 x 226.8 + 6,000 = $ 21,876

The prices of different harmonic filters calculated according to the above algorithm for the load levels in table 6.3 are listed in table 6.8.

Load P(kW)	504	410	313	209	157
Filter prices ($)	56,582	47,020	37,157	27,140	21,876

Table 6.8 Prices of different SOCOMEC ATRYS series harmonic filters

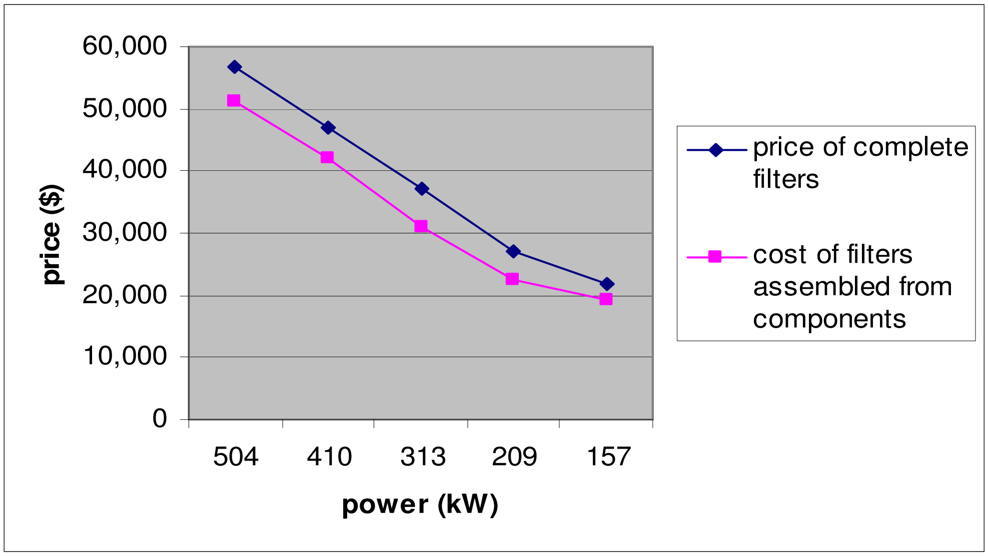


Figure 6.7 Comparison of filter prices

Figure 6.7 is based on the data of table 6.7 and 6.8. It shows that the prices of passive harmonic filters purchased on the market as a set maybe higher than the cost of the same size filters assembled from components. In other words, purchasing capacitors and inductors, and connecting them into harmonic filters by the user maybe a more economical choice.

	Load P(kW)		504	410	313	209	157
15m	Payback period(year)	Assembled	15.9	15.4	13.4	11.7	10.4
		Purchased	17.5	17.2	16.1	14.2	11.7
30m	Payback period(year)	Assembled	14.9	14.2	12	8.7	8.3
		Purchased	16.5	15.9	14.4	10.6	9.4
50m	Payback period(year)	Assembled	13.9	13	10.5	7.3	6.6
		Purchased	15.4	14.6	12.6	8.8	7.4

Table 6.9 Paying back time of different filters

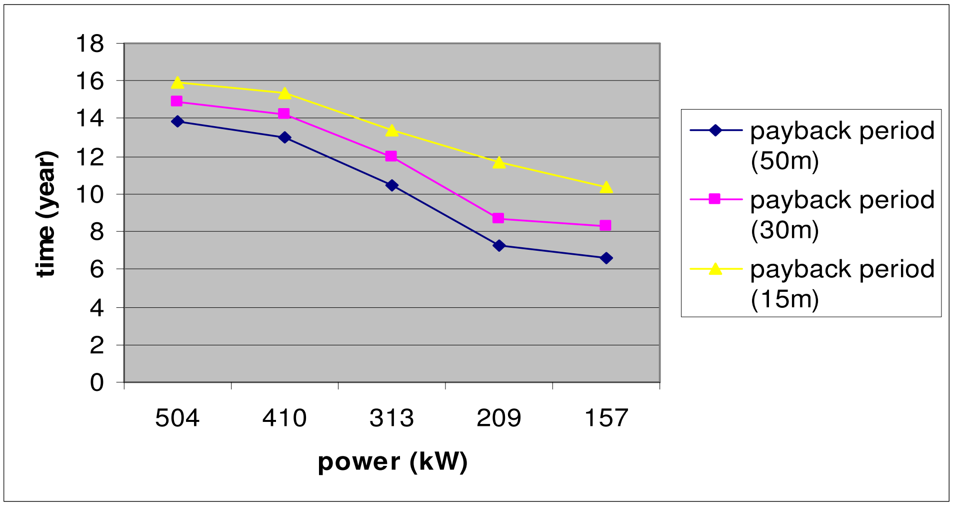


Figure 6.8 Payback period of assembled filters for different power cables

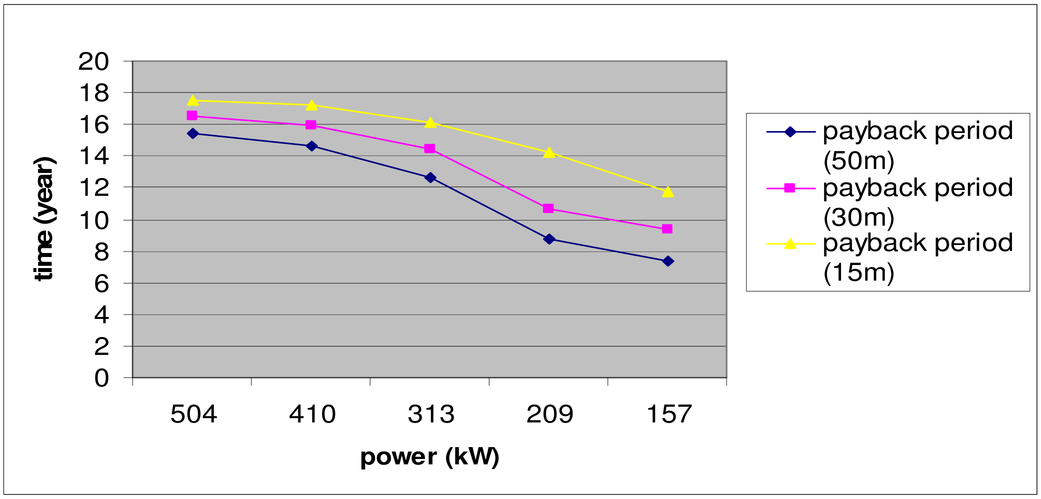


Figure 6.9 Payback period of purchased complete filters for different power cables

Using the data of tables 6.6, 6.7 and 6.8, the payback periods for different filters have been calculated and listed in table 6.9. Figure 6.8 and 6.9 show the payback period of assembled filters and purchased filters for different power cables.

6.4 Conclusions

In this chapter, energy and cost savings resulting from the installation of a filter on the power supply side of a rectifier are calculated. The results are presented for arrange of rectifier loads up to 507 kW. Furthermore, the options of assembling filters from individual components or purchasing complete filters are discussed. It can be observed that, in addition to other benefit of improving the true power factor as described in section 3.6, there is a large cost saving potential in practical cases, and the payback periods for the filters can be even shorter.

Chapter 7

Conclusions and Further Research

7.1 Summary and Contribution of the Thesis

In chapter one of this thesis, the basics of harmonic filters and variable speed drives are presented including the principles of three types of passive harmonic filters and their application. Harmonics are discussed in chapter two, which includes the cause of harmonics, harmonic sources, the effects of harmonics on the power system and the IEEE-1992 standard for harmonic limitation. The concept of the displacement power factor and the true power factor, and the methods of their improvement are presented in chapter three. The line current harmonics produced by typical variable speed drives are discussed in chapter four. The chapter contains results of circuit simulation and relevant details of PSPICE software used.

In chapter five, a model of a variable speed drive system is developed. This model is then utilised to determine and discuss the system harmonics and the power factor. With reference to system model, a method of designing low-pass filters is also presented in this chapter. The method is applied to different loads, various power cables and filters. In chapter six, the energy savings resulting from the installation of filters are calculated. The prices of relevant harmonic filters available on the market are also considered.

The research contribution of this thesis can be summarised as follows:

- Formulas for designing an input low-pass filter according to the parameters of the variable speed drives are given.
- Practical recommendation for the minimum filter requirement to meet energy saving objectives is given.
- The economic aspects of the input filter design for industrial variable speed drives are given consideration.

- The relationship between the cost of input filters and the energy cost reduction they provide on the power supply side of variable speed drives is discussed.

7.2 Comparative Characteristics of Passive Harmonic Filters

In chapter 5, only the design procedure of low-pass filter is presented in detail. In practice, shunt passive filters and series passive filters are also often utilized. Their characteristics can be summarised as follows.

Besides harmonics reduction, shunt passive filters can also provide limited reactive power compensation and voltage regulation. These filter, though quite useful, cause various practical problems. The capacitance of the filter enlarges the DC voltage ripple and the AC peak current of the rectifier. Besides these, L-C component tolerances and the supply impedance strongly influence the compensation characteristics of the passive filters. Moreover, at light load conditions the shunt filters also cause problems of voltage regulation [35].

Since these filters are connected in shunt with the power system, they cause a shift in the power system natural resonant frequency. If the new frequency is near any harmonic frequencies, then it is possible to experience an adverse resonant condition which can result in amplification of harmonics, and capacitor or inductor failures. Whenever using shunt passive filters, a complete system analysis must always be performed. We must determine the total harmonics which will be absorbed by the filter, the present power system resonant frequency, and the expected system resonant frequency after the shunt filter is installed [39].

A series passive filter effectively blocks the flow of harmonic currents towards source side by providing a high impedance path at specific harmonic frequencies, as presented in chapter 1. Also, series passive filters have been found suitable for voltage fed type of harmonics producing loads and the application of these filters can reduce the current ripple on the DC side. However, they suffer heavily on account of poor voltage regulation at PCC, and poor power factor throughout its range of operation.

Low- pass harmonic filters, also referred to as broad band harmonic suppressors, offer a non-invasive approach to harmonic mitigation. Rather than being tuned for a specific harmonic, they filter all harmonic frequencies, including the third harmonic. They are connected in series with the non-linear load with a large series connected impedance. Therefore they do not create system resonance problems and no field tuning is required with the low pass filter. It is very easy to predict the distortion levels which will be achieved and to guarantee the results. It can be found from the design procedure, that a low-pass harmonic filter can easily offer harmonic current levels as low as 8% to 12% total harmonic distortion. In most cases, this results in less than 5% total harmonic distortion and meets most international standards. Also, the low-pass filter not only offers guaranteed results, it is also more economical than tuned harmonic filters. For the sake of economy, a single low-pass filter may be used to supply several variable speed drives.

However, although low-pass filter address some of the issues associated with tuned filters, they are not problem-free. Specifically, their large series reactor necessitates the use of a large capacitor bank to compensate for voltage drops. They also will reduce the DC bus voltage within the drive at full-speed, full-load conditions and this prevents the drive from providing full power to the motor [35].

7.3 Recommendations for Further Research

In this thesis, a model of a typical voltage source rectifier is a basis for the design of low-pass passive harmonic filters and calculations of energy and cost savings resulting from the installation of a filter on the power supply side of a variable speed drive. Further research can focus on shunt passive filters applied to current source converters and series passive filters applied to loads producing voltage harmonics. The design of some combined system of series-passive and shunt-passive filters for nonlinear loads also needs further research. The same can be said about combinations of series reactors and shunt passive filters.

Appendix A

Conductor cross-sectional area	Clipped direct		On a perforated horizontal or vertical cable tray or free air	
	One two core cable, single phase a.c. or d.c.	One three-or-four core cable, three-phase a.c.	One two core cable, single phase a.c. or d.c.	One three or four core cable, three phase a.c.
mm^2	(A)	(A)	(A)	(A)
1.5	27	23	29	25
2.5	36	31	39	33
4	49	42	52	44
6	62	53	66	56
10	85	73	90	78
16	110	94	115	99
25	146	124	152	131
35	180	154	188	162
50	219	187	228	197
70	279	238	291	251
95	338	289	354	304
120	392	335	410	353
150	451	386	472	406
182	515	441	539	463
240	607	520	636	546
300	698	599	732	628
400	787	673	847	728

Table A.1 Current carrying capacity (amperes) [38]

Appendix B

Part Number	Amps (A)	Inductance (mH)	Price(dollars)
RL-00201	2	12	89.17
RL-00202	2	20	93.91
RL-00203	2	32	109.68
RL-00204	2	6	79.59
RL-00401	4	3	90.12
RL-00402	4	6.5	92.96
RL-00403	4	9	96.76
RL-00404	4	12	110.99
RL-00801	8	1.5	94.86
RL-00802	8	3	106.24
RL-00803	8	5	145.14
RL-00804	8	7.5	148.93
RL-01201	12	1.25	111.93
RL-01202	12	2.5	118.58
RL-01203	12	4.2	170.75
RL-01801	18	0.8	146.08
RL-01802	18	1.5	149.88
RL-01803	18	2.5	198.26
RL-02501	25	0.5	152.72
RL-02502	25	1.2	172.65
RL-02503	25	1.8	203.95
RL-03501	35	0.4	172.65
RL-03502	35	0.8	181.18
RL-03503	35	1.2	270.35
RL-04501	45	0.3	227.66
RL-04502	45	0.7	239.05
RL-04503	45	1.2	316.83
RL-05501	55	0.25	252.33
RL-05502	55	0.5	258.18

RL-05503	55	0.85	328.06
RL-08001	80	0.2	279.84
RL-08002	80	0.4	295.96
RL-08003	80	0.7	520.78
RL-10001	100	0.15	376.59
RL-10002	100	0.3	413.59
RL-10003RL03	100	0.45	608.05
RL-13001	130	0.1	470.51
RL-13002	130	0.2	621.33
RL-13003	130	0.3	279.84
RL-16001	160	0.075	532.86
RL-16002	160	0.15	581.49
RL-16003	160	0.23	699.12
RL-20001	200	0.055	756.10
RL-20001B14	200	0.055	571.68
RL-20002	200	0.11	540.33
RL-20002B14	200	0.11	696.89
RL-20003	200	0.185	853.74
RL-20003B14	200	0.185	873.54
RL-25001	250	0.045	831.80
RL-25001B14	250	0.045	647.39
RL-25002	250	0.09	945.17
RL-25002B14	250	0.09	1,009.42
RL-25003	250	0.15	1,263.80
RL-25003B14	250	0.15	1,548.11
RL-32001	320	0.04	1,204.51
RL-32001B14	320	0.04	1,020.10
RL-32002	320	0.075	1,364.66
RL-32002B14	320	0.075	1,180.25
RL-32003	320	0.125	1,839.29
RL-32003B14	320	0.125	1,654.87
RL-40001	400	0.03	1,297.69
RL-40002	400	0.06	1,842.20
RL-40003	400	0.105	2,213.94

RL-40001B14	400	0.03	1,113.28
RL-40002B14	400	0.06	1,657.78
RL-40003B14	400	0.105	2,029.52
RL-50001	500	0.025	1,189.96
RL-50002	500	0.05	1,753.87
RL-50003	500	0.085	2,355.65
RL-60001	600	0.02	1,453.02
RL-60002	600	0.04	2,052.82
RL-60003	600	0.065	3,258.30
RL-75001	750	0.015	2,297.41
RL-75002	750	0.029	2,969.07
RL-75003	750	0.048	4,192.99

Table B.1 Three-phase inductors list of MTE Corporation USA [16]

part	μF	Voltage	Case Style	Price(dollars)
97F6504	15	330VAC	P	13.49
97F6505	17.5	330VAC	P	13.56
97F6506	14	330VAC	P	12.40
97F6509	38	280VAC	P	18.91
97F6515	10	330VAC	P	11.00
97F6516	22.5	280VAC	P	14.35
97F6518	8	330VAC	P	10.30
97F6519	16	330VAC	P	13.00
97F6521	28	330VAC	P	17.19
97F6522	24	280VAC	P	20.88
97F6530	40	280VAC	P	19.47
97F6531	7	330VAC	P	9.98
97F6533	30	280VAC	P	16.56
97F6535	24	400VAC	P	16.63
97F6537	24	330VAC	P	16.63
97F6538	35	280VAC	P	18.02
97F6540	45	280VAC	S	26.63
97F6541	48	280VAC	S	22.54
97F6622	24	400VAC	C	23.21
97F6623	24	400VAC	D	20.88
97F6673	14	480VAC	B	16.26
97F6674	12	480VAC	B	14.28
97F6675	16	480VAC	C	16.98
97F6676	3	480VAC	A	8.49
97F6677	4	480VAC	A	8.98
97F6678	4.5	480VAC	A	9.19
97F6679	24	480VAC	D	29.50
97F6680	24	480VAC	C	27.26
97F6681	5	480VAC	A	9.49
97F6683	21	480VAC	C	19.14
97F6685	15	480VAC	B	16.81

97F6692	8.5	480VAC	B	16.74
97F6694	20	480VAC	C	23.65
97F6695	6.5	480VAC	A	10.65
97F6703	8	330VAC	A	12.41
97F6708	13	330VAC	B	12.44
97F6715	19	330VAC	B	15.05
97F6716	20	330VAC	B	19.47
97F6726	30	330VAC	C	19.47
97F6727	32	330VAC	C	20.12
97F6745	21	330VAC	B	15.65
97F6746	12	330VAC	A	11.58
97F6749	13.5	330VAC	B	15.97
97F6755	26	330VAC	B	18.54
97F6757	34	330VAC	C	21.93
97F6758	15	330VAC	B	17.44
97F6759	24	330VAC	B	17.86
97F6760	12	330VAC	B	15.32
97F6761	17.5	330VAC	B	14.54
97F6762	11	330VAC	B	11.84
97F6763	10	330VAC	A	10.86
97F6764	5	330VAC	A	11.09
97F6765	6	330VAC	A	9.05
97F6766	7	330VAC	A	9.49
97F6767	10	330VAC	B	14.41
97F6768	14	330VAC	B	12.63
97F6769	16	330VAC	B	14.05
97F6770	17.5	330VAC	C	14.60
97F6771	18	330VAC	B	14.67
97F6773	22.5	330VAC	C	17.05
97F6774	24	330VAC	C	17.54
97F6776	28	330VAC	C	18.86
97F6778	45	330VAC	D	27.63
97F6779	18	330VAC	C	14.88

97F6780	29	330VAC	C	19.21
97F6784	36	330VAC	C	22.49
97F6801	6	280VAC	A	8.70
97F6812	17.5	280VAC	B	13.23
97F6823	28	280VAC	C	17.05
97F6824	28	280VAC	B	16.81
97F6836	48	280VAC	C	24.49
97F6846	29	280VAC	B	21.68
97F6850	45	280VAC	C	28.50
97F6854	34	280VAC	B	19.74
97F6855	22.5	280VAC	B	15.21
97F6857	8	280VAC	A	9.49
97F6858	10	480VAC	A	10.02
97F6860	15	280VAC	B	15.82
97F6861	20	280VAC	B	14.05
97F6862	20	280VAC	C	14.67
97F6864	24	280VAC	C	15.88
97F6865	35	280VAC	C	19.70
97F6866	40	280VAC	C	21.07
97F6867	52	280VAC	D	37.85
97F6868	26	280VAC	B	16.98
97F6869	42	280VAC	B	22.00
97F6871	12	280VAC	A	11.07
97F6872	48	280VAC	D	26.19
97F6873	24	280VAC	B	15.65
97F6907	10	480VAC	B	13.77

Table B.2 GE company capacitors list [17]

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