

II

CHAPTER

Literature Study

CHAPTER 2 – LITERATURE STUDY: *This chapter discusses the various aspects around harmonic distortion.*

2.1 INTRODUCTION

Electrical power is one of the most important commodities of the modern world. As most things in life are driven by time, quality and cost, so is electrical energy. Electrical energy cannot be stored and a continuous flow is required. While the cost of generating electricity is important, so is the quality of supply. Electrical energy travels at approximately the speed of light and limited quality assurance checks can be done before it is supplied on to the grid. It is therefore vital that a utility implements a PQ management plan.

Electrical energy is normally generated hundreds of kilometres away and subjected to various impedances (transformers, transmission lines etc.) with different characteristics. These different types of loads, at different voltage levels, can have an effect on the rated system voltage waveform. Factors that have to be taken into account to ensure a good quality of supply include: design practices, co-operation between utilities and consumers, monitoring, maintenance and mitigation. In South Africa, NERSA [15] requires that every licensee has to implement a quality assurance program to ensure that the quality of energy acquired is at a sufficient level. A PQ benchmarking program refers to the concept of measuring the success of such a quality assurance program. The focus is on benchmarking waveform distortion.

Power system harmonics are not new phenomena and throughout the history of AC systems there have been concerns over distortion levels. The increased system harmonic distortion is mostly related to the use of more non-linear loads. Harmonics have a greater impact on the consumer sector than on the utilities, due to the large impedance of the distribution network. The utility would be more likely to experience other PQ phenomena such as surges, dips etc. There is a new tendency to better understand these phenomena and to create new performance tools, which can aid the overall PQ management of a network.

The first section of this chapter will focus on the natural phenomena of harmonics and by which mathematical laws it is governed. A discussion will follow on how specific equipment and circuit configurations generate harmonics. The effects of harmonics and common mitigation practices are also discussed. Compatibility between equipment is one of the major concepts that are highlighted by the NERSA [15]. A review on the concept of compatibility, benchmarking and applicable standards can be found in this chapter.

2.2 BASIC PRINCIPLES OF HARMONICS

FOURIER SERIES

Harmonic distortion is a synthetic concept in general, used to describe waveform distortion in power systems. It represents the time-domain quantities of a waveform in the frequency domain by means of phasors. Such phasors are frequency dependent and can be used to reconstruct the original distorted waveform in the time-domain. J.B.J. Fourier (1768-1830) stated in 1822 that any continuous, repetitive wave function of time interval T can be represented by the summation of a DC component, sinusoidal fundamental component and higher order sinusoidal components, which are integrals of the fundamental component [30]. By using this theory, harmonic analysis can be done by calculating magnitudes and phases of the fundamental and high order harmonics. He formulated this expression which is known as the Fourier series [30]:

$$x(t) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right) \right) \quad (2.1)$$

Equation (2.1) is the trigonometric Fourier series, where a_0 represents the average value of the function, while a_n and b_n represent the coefficients of the series. By letting $\omega_0 = \frac{2\pi}{T_0}$ the coefficients can be calculated by:

$$a_0 = \frac{2}{T_0} \int_{-T_0/2}^{T_0/2} f(t) dt \quad (2.2)$$

$$a_n = \frac{2}{T_0} \int_{-T_0/2}^{T_0/2} f(t) \cos(n\omega_0 t) dt \quad (2.3)$$

$$b_n = \frac{2}{T_0} \int_{-T_0/2}^{T_0/2} f(t) \sin(n\omega_0 t) dt \quad (2.4)$$

Equation (2.1) can also be represented as:

$$f(t) = A_0 + \sum_{n=1}^{\infty} A_n \cos(n\omega_0 t + \theta_n) \quad (2.5)$$

With the magnitude and phase angle as:

$$A_0 = \frac{1}{2} a_0 \quad (2.6)$$

$$A_n = \sqrt{a_n^2 + b_n^2} \quad (2.7)$$

$$\theta_n = \tan^{-1} \left(\frac{b_n}{a_n} \right) \quad (2.8)$$

Equation (2.6) represents the DC component, while the magnitude and angle of the n^{th} harmonic components are represented by equation (2.7) and (2.8), respectively. These formulas form the base for harmonic analysis. The South African national power grid operates at a frequency of 50 Hz. Harmonic components refer to the multiple integral for the fundamental frequency. This means that if the fundamental component is at 50 Hz, the 3rd and 5th harmonic components will be at 150 Hz and 250 Hz, respectively. According to Fourier's theory [30] and explained above through equation (2.1) and (2.5), these harmonic components add up to create a distorted waveform. Figure 2.1 is an example of such a distorted waveform.

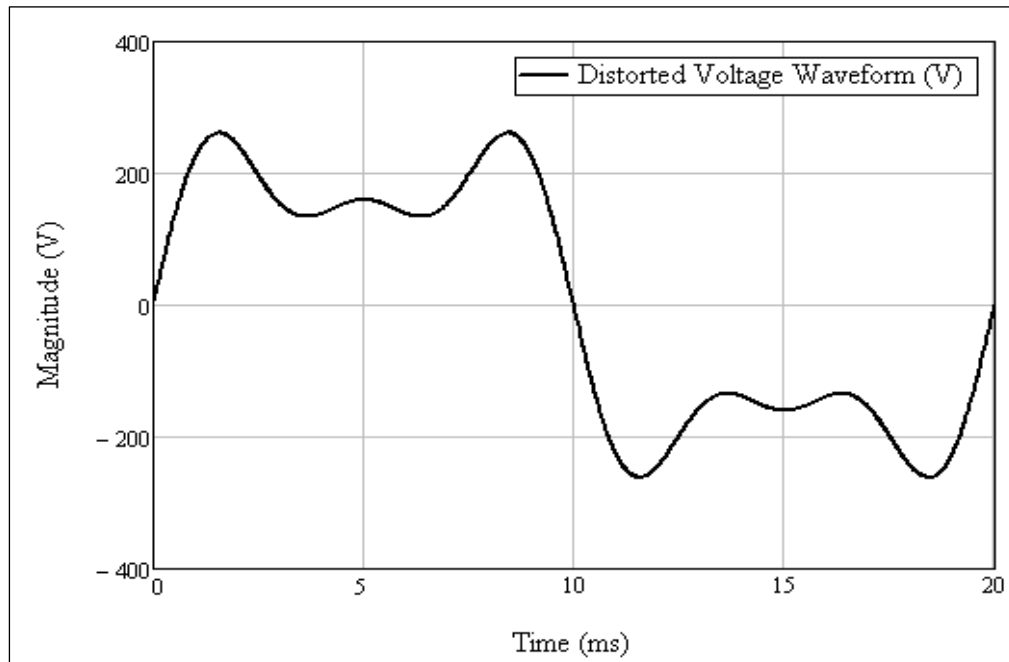


Figure 2.1: Distorted voltage waveform.

The distorted waveform can be broken up into its individual harmonic components by the use of equations (2.5) to (2.8). The harmonic component waveforms for the distorted waveform, as in Figure 2.1 are displayed in Figure 2.2. Negligible

To study power system harmonics beyond the 40th harmonic component is insignificant, due to the relatively small size of the component current [2]. Instrumentation requirements and constraints also justify the means to not include these higher harmonic components [2].

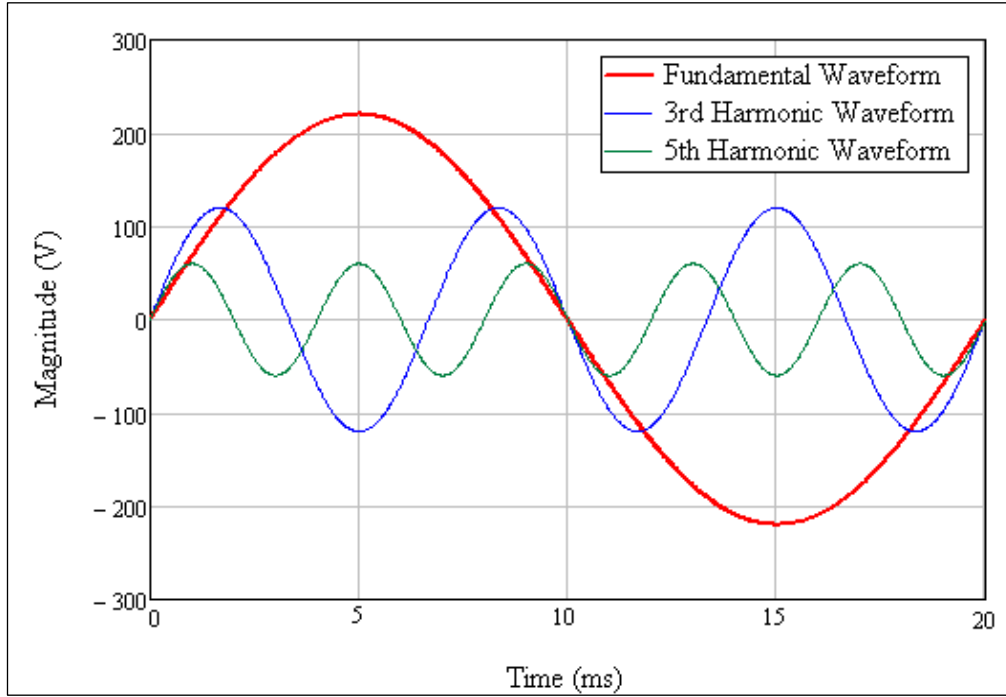


Figure 2.2: Harmonic component waveforms.

LINEAR AND NON-LINEAR LOADS

Over the past decade, increased power system harmonics were mostly caused by non-linear loads like solid-state electronics. The objective of a power utility is to produce electrical energy of a pure sinusoidal voltage waveform, at rated frequency. When a voltage of the mentioned characteristics is applied to a circuit that contains linear loads (resistors, inductors, capacitors etc.), the current flow will be a pure sinusoidal waveform, proportional to the applied voltage [8].

The load line is the relationship between the applied load voltage and current. Figure 2.3 illustrates the linear relationship. A phase shift can be expected for reactive elements in a circuit, but the relationship between the current and voltage applied to the load will still be linear [8].

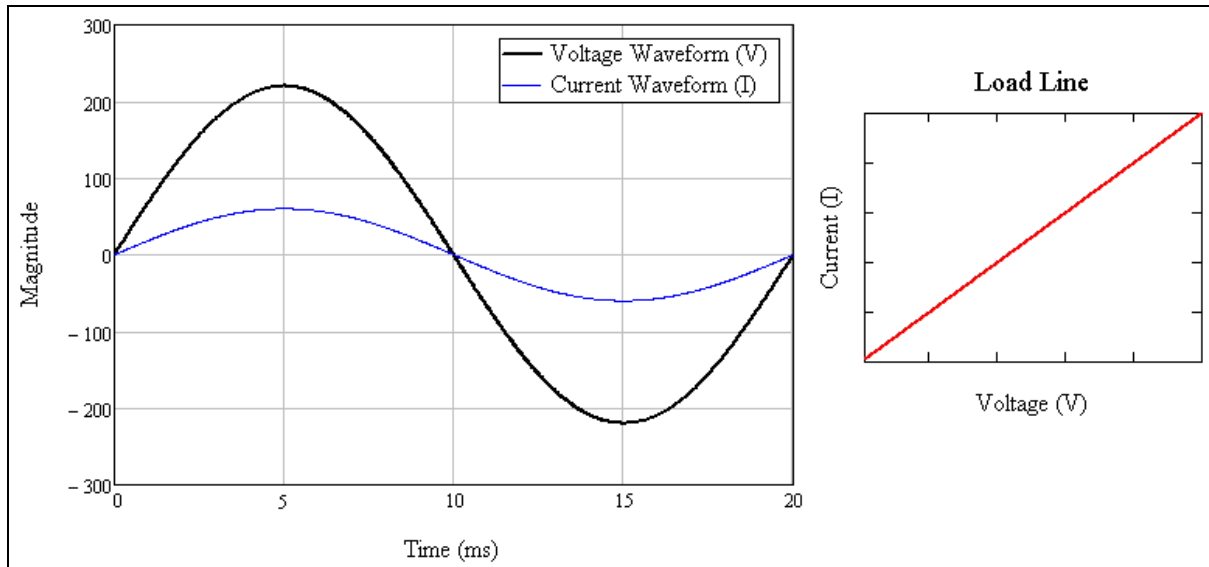


Figure 2.3: Voltage and current waveforms for linear loads.

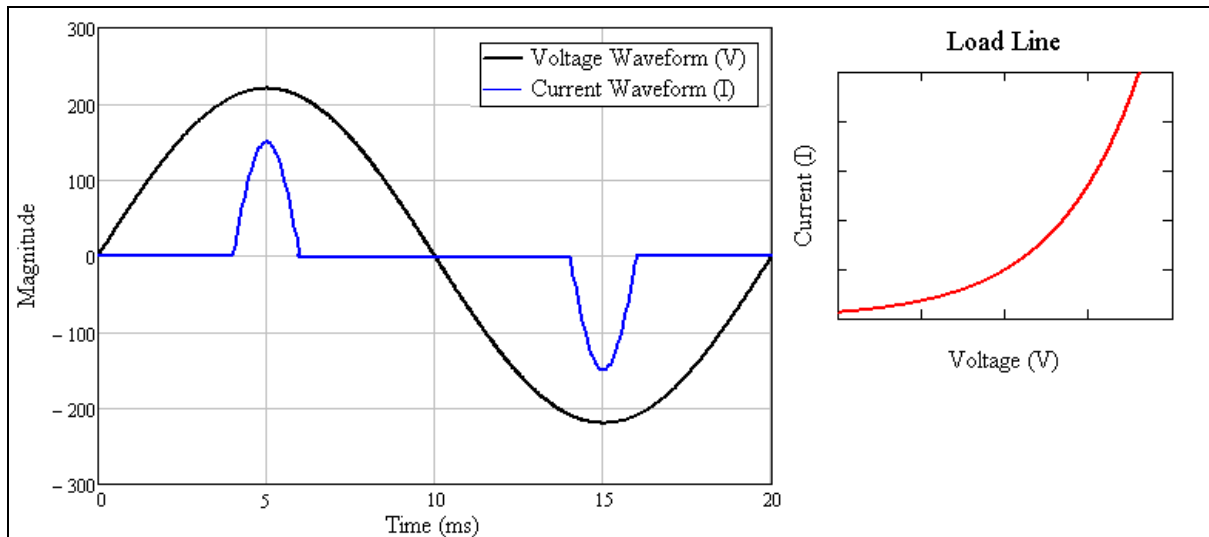


Figure 2.4: Voltage and current waveforms for non-linear loads.

Non-sinusoidal current is a result of the load having inherited non-linear characteristics. The current applied to such a load does not have a linear relationship to the applied voltage. With most non-linear loads, there is not always the need for continuous flow of current [8]. A typical example is a full wave rectifier and capacitor that are used in switch mode power supplies (SMPS). The current will only flow after the supply voltage exceeds the stored voltage level of the capacitor [8]. Figure 2.4 illustrates the non-linear flow of current and the non-linear characteristics of a load. In practice the load line is more complex than shown in Figure 2.4, which relates to more complex currents. These non-sinusoidal currents interact with the system impedances, which causes non-sinusoidal voltage drops. This leads to voltage distortion at the point of common coupling (PCC) [33].

HARMONIC PENETRATION INTO A POWER SYSTEM

As explained in the previous section, the non-linear loads cause non-sinusoidal currents at the connection point, between the utility's system and the consumer load. Various linear and non-linear loads are connected to a point of common coupling (PCC). Figure 2.5 illustrates this concept. Ideally, for a South African distribution network, there should be a 50 Hz sinusoidal voltage waveform at all point of common couplings. However, these non-sinusoidal currents propagate into the network and interact with the frequency dependent system impedances, causing frequency dependent volt drops. These volt drops superimpose themselves onto the pure 50 Hz sinusoidal voltage waveform, resulting in a non-sinusoidal voltage waveform at the PCC. Consumers connected to the PCC, irrespective of whether the loads are linear or non-linear, will be supplied by the non-sinusoidal voltage waveform [2], [33].

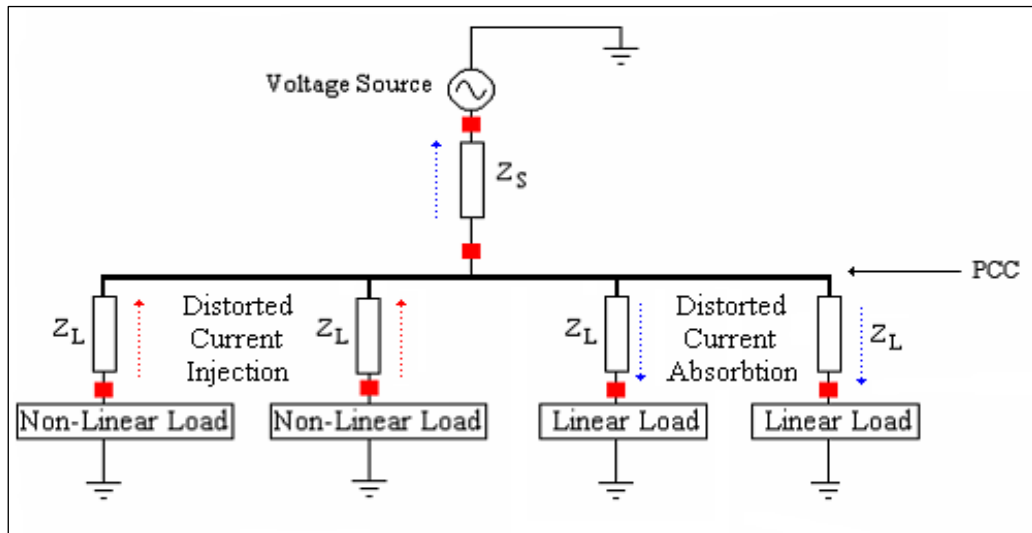


Figure 2.5: Network example of non-linear and linear loads connected to a point of common coupling.

Another example of harmonic penetration can be seen in Figure 2.6, which shows a simplified circuit of an electrical network for normal power flow (generated by various power stations) and harmonic power flow (generated by inherently non-linear loads). The generator supplies power (P_C) to the PCC through a system impedance of $(R_s + jX_s)$. At the PCC the resistive load (R_{L1}) absorbs a large portion of power (P_{L1}), while only a small amount of power (P_{L2}) is absorbed by the converter (R_{L2}). There is also a small amount of power absorbed by the transmission and distribution system (system losses $(P_S - P_C)$).

The circuit on the right hand side of Figure 2.6 shows the equivalent harmonic power flow circuit. The power (P_{L2}) being supplied to the load (R_{L2}) is converted to harmonic power as explained (linear and non-linear loads). The non-linear load (R_{L2}) then acts as a source of harmonic apparent power and supplies the power at the PCC. It is assumed that the terminal voltage of the generator has a pure

sinusoidal waveform and generates power at the fundamental frequency. The harmonic impedances of the system and generator are represented by $R_{HS} + jX_{HS}$ and $R_{HG} + jX_{HG}$ respectively. The harmonic power is supplied back into the system and absorbed by the load (P_{HL1}), transmission system (P_{HS}) and generator (P_{HG}). The largest portion of the harmonic power is absorbed by the load connected to the PCC (R_{L1}). The system impedance ($R_{HS} + jX_{HS}$) is very large, which causes harmonic power to be absorbed by smaller impedance loads. The generator is connected in series with the system impedance, which helps protect the generator from large amounts of harmonic power.

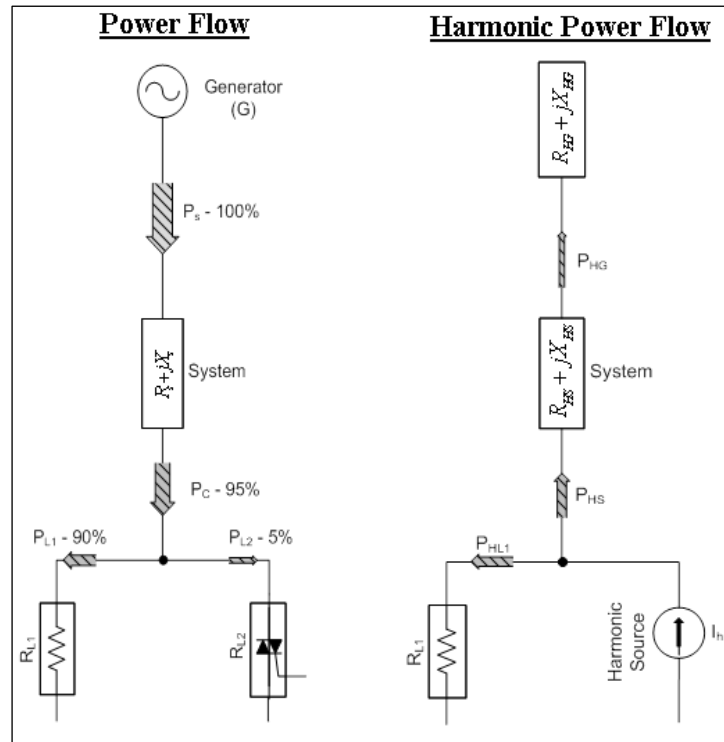


Figure 2.6: Power and harmonic power flow.

2.3 HARMONIC SOURCES

The earliest harmonic sources were arc furnaces, fluorescent lights and to a much lesser extent, transformers and rotating machines. Relative small distortion phenomena in a system are now being amplified by the introduction of more sophisticated power electronics.

Recently the study of harmonics in a power system has grown more intense due to increased implementation of harmonic sources. There are basically two types of harmonic sources. The one utilises solid state semiconductors, such as a single-phase rectifier and the others have a non-linear voltage and current relationship such as arc-furnaces [33].

CONVERTERS

Power converters have the ability to convert AC to DC, DC to AC and offers great advantages. They are also the biggest source of harmonic currents in a power system [30]. The commonly used power converters are rectifiers and inverters:

- Single-phase, half and full wave rectifiers.
- Six-pulse rectifiers and inverters.
- Twelve-pulse rectifiers and inverters.
- Higher order rectifiers.

SWITCH MODE POWER SUPPLIES

The majority of new technologies utilise the switch-mode power supply (SMPS). The SMPS (Figure 2.9) typically incorporates rectifier circuits as in Figure 2.7. There are various configurations that can be used for single-phase rectification. The most popular circuit is the single-phase full wave diode bridge rectifier (Figure 2.7). Non-sensitive to small voltage variations and relatively inexpensive to construct makes it popular for most home appliances. From the circuit diagram the capacitor is charged only when the supply voltage exceeds that of the capacitor voltage. This happens at the peak of the applied sinusoidal waveform and causes a very narrow current pulse (Figure 2.8). The current pulse has the following Fourier expression [33]:

$$I_n(t) = \frac{8\alpha I}{\pi} \sum_{n=1,3,5}^{\infty} \frac{\cos(n\alpha\pi)}{1 - n^2\alpha^2\pi^2} \cos(n\omega t) \quad (2.9)$$

The parameter I is the peak value and $\alpha = \frac{\theta}{T}$ the relative duration of the peak with regards to the fundamental frequency period [8], [33].

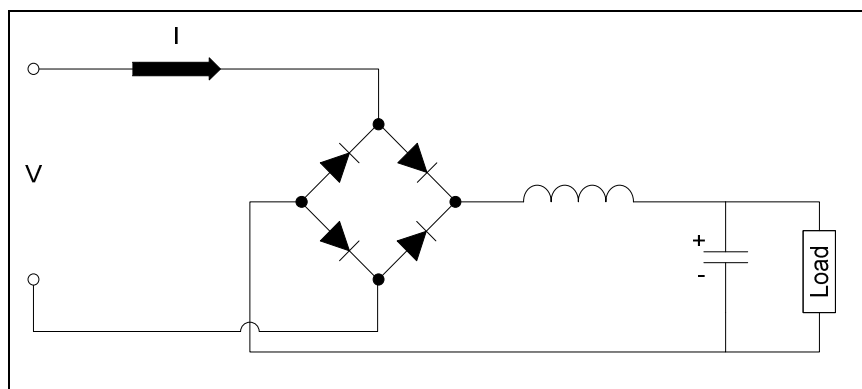


Figure 2.7: Single-phase diode bridge rectifier.

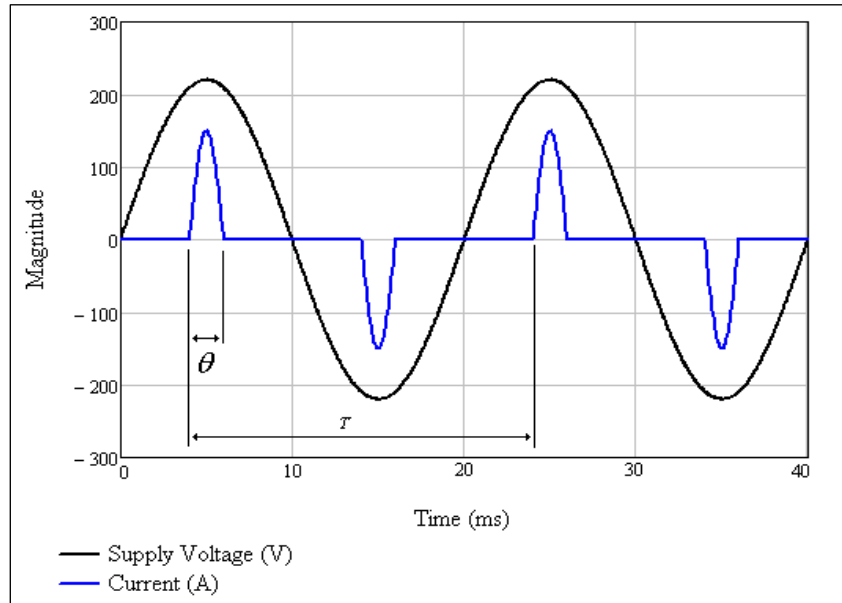


Figure 2.8: Voltage and current waveform distortion for a SPDR.

Older technologies would implement a transformer to reduce the AC voltage to the required level before it is rectified to obtain the correct DC voltage on the output terminals. The advantage is that the inductance of the transformer reduces the input current harmonic content [8]. The SMPS circuit takes supply directly from the AC source which eliminates the need for a 50 Hz transformer (Figure 2.9). This allows the circuit to tolerate even higher voltage variations and because there is no need for a supply transformer, the overall design has become more compact [2].

The AC voltage is rectified and a rugged DC supply is obtained on the capacitor. The switcher converts this DC voltage back to an AC voltage at a very high frequency, which is subsequently rectified again to obtain a smoother DC voltage [2]. For the manufacturer, this reduces the construction cost and physical size of the power supply. The SMPS circuit in Figure 2.9 utilises a high frequency transformer to convert the AC voltage to the correct level. Transformer losses are very high at such high frequencies, but the physical size of the component is smaller and less expensive.

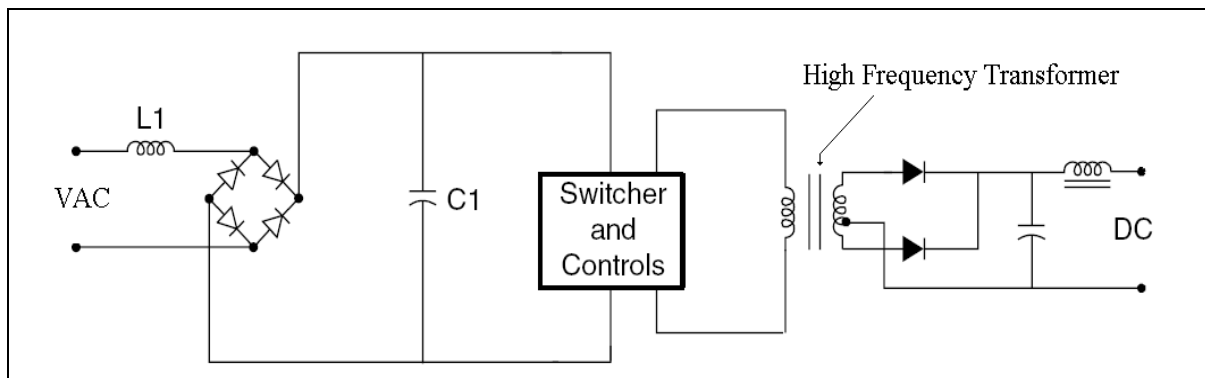


Figure 2.9: Switch mode power supply circuit [2].

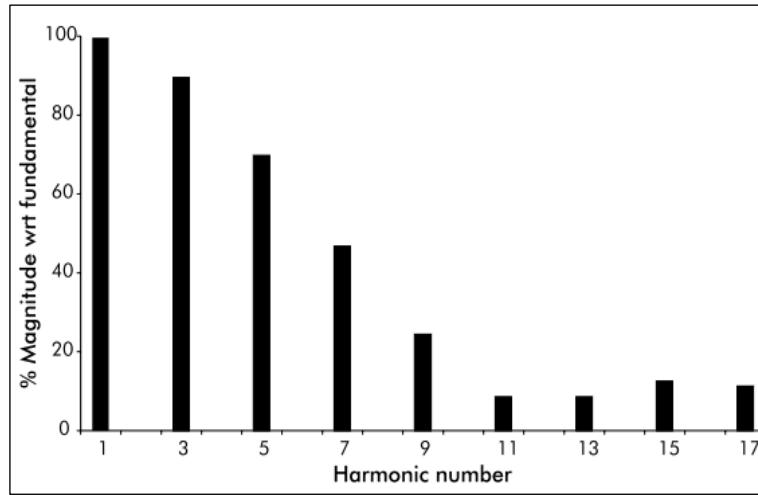


Figure 2.10: Harmonic spectrum for a computer power supply [8].

The SMPS is also used in computer power supplies. Figure 2.10 illustrates the harmonic spectrum that results from such a power supply. Harmonic components that stand out from the graph are the 3rd (90%), 5th (70%), 7th (48%) and the 9th (25%). To illustrate the impact of such a load, take a situation where an office block has 1000 personal computers. The transformer that supplies the office is rated at 1000 kVA, 11 kV/380 V. The rated fundamental current the transformer can supply would be 1443.3A. If it is assumed that every computer consumes 1A, the main harmonic currents would be:

$$I_{n=} = \frac{(N_Computers)(Current)(Harmonic\%)}{Phases}$$

$$I_3 = \frac{(1000)(1)(0.9)}{3} = 300 \text{ A}$$

$$I_5 = \frac{(1000)(1)(0.7)}{3} = 253.3 \text{ A}$$

$$I_7 = \frac{(1000)(1)(0.48)}{3} = 160 \text{ A}$$

$$I_9 = \frac{(1000)(1)(0.25)}{3} = 83.3 \text{ A}$$

Calculating the total distortion demand (TDD) yields:

$$TDD (\%) = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \times 100 \quad (2.10)$$

$$TDD (\%) = \frac{\sqrt{(300^2 + 253.3^2 + 160^2 + 83.3^2)}}{1443.3} \times 100 = 29.9 \%$$

The TDD is the ratio between the total harmonic current over the maximum fundamental supply current. In three-phase systems the voltages are displaced 120°, which theoretically means that the current in the neutral conductor will be equal to zero. This principle is applicable to the fundamental voltage which cancels each phase current to allow zero current flow in the neutral conductor, except for phase unbalances. This is however, not applicable to harmonic currents [2], [8], [30].

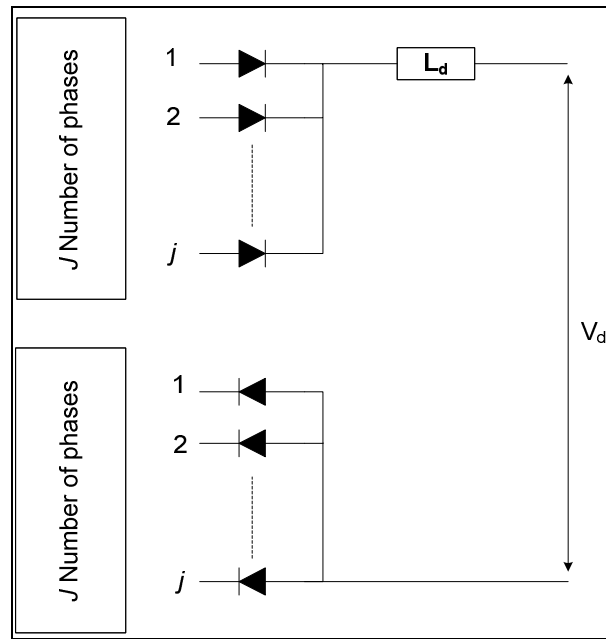
The odd “triple – N” harmonics (3rd, 9th etc.) of each phase adds in the neutral conductor [8], [30]. Thus, from the example, the 3rd and 9th harmonic current will be 900 A (300 A × 3) and 249.9 A (83.3 A × 3) respectively. Studies done on commercial buildings have shown that the neutral conductor carries harmonic current in the ranges of 150% to 210% of the phase harmonic currents [8], [30]. According to the results, the neutral conductor should be the same size as the phase conductor. Normally, the neutral conductor is smaller due to the phase balance [8]. This example clearly illustrates the impact SMPS can have on the supply voltage.

GENERAL EQUATIONS FOR TWO-WAY RECTIFIERS

To determine the Fourier series of a rectifier, consider the following situation to obtain the generic formulas. Figure 2.11 shows a two-way converter of j -number of phases. It is assumed that the system impedance is zero and there is an infinite smoothing inductance. This yields a positive and negative rectangular pulse of width $w = \frac{2\pi}{j}$, recurring at the supply frequency [30]. If the analysis of this pulse is done at the centre of it, an “even” function ($f(x) = f(-x)$) will result in the Fourier series only having cosine terms. The relevant Fourier coefficients are obtained with the following formulas [30]:

$$A_0 = \frac{1}{2\pi} \int_{-w/2}^{w/2} d(\omega t) = \frac{w}{2\pi} = \frac{1}{j} \quad (2.11)$$

$$A_n = \frac{1}{\pi} \int_{-w/2}^{w/2} \cos(n\omega t) d(\omega t) = \frac{2}{\pi n} \sin\left(\frac{nw}{2}\right) = \frac{2}{\pi n} \sin\left(\frac{\pi n}{j}\right) \quad (2.12)$$

Figure 2.11: j -Phase, two way rectifier.

When applying the Fourier coefficients (Equation 2.7 and 2.8) to an ideal j -phase, two-way rectifier (Figure 2.11), which produces positive and negative current pulses, the following Fourier series is obtained:

$$F_{Pos} = \frac{2}{\pi} \left(\frac{w}{4} + \sin \frac{w}{2} \cos \omega t + \frac{1}{2} \sin \frac{2w}{2} \cos 2\omega t + \frac{1}{3} \sin \frac{3w}{2} \cos 3\omega t + \dots \right) \quad (2.13)$$

$$F_{Neg} = \frac{2}{\pi} \left(-\frac{w}{4} + \sin \frac{w}{2} \cos \omega t - \frac{1}{2} \sin \frac{2w}{2} \cos 2\omega t + \frac{1}{3} \sin \frac{3w}{2} \cos 3\omega t + \dots \right) \quad (2.14)$$

The phase current for a two-way configuration is obtained by [30]:

$$F = F_{Pos} + F_{Neg} = \frac{4}{\pi} \left(\sin \frac{w}{2} \cos \omega t + \frac{1}{3} \sin \frac{3w}{2} \cos 3\omega t + \frac{1}{5} \sin \frac{5w}{2} \cos 5\omega t + \dots \right) \quad (2.15)$$

Formula (2.15) is important, because it justifies that these types of rectifiers basically eliminate the DC component and even harmonic components [30]. The two-way rectifier consists of positive and negative pulses, such that $F(\omega t + \pi) = -F(\omega t)$. If we substitute the $(\omega = \pi)$ into equation (2.15) it will yield the following equation, for a square wave:

$$F(t) = \frac{4}{\pi} \left(\cos(\omega t) - \frac{1}{3} \cos(3\omega t) + \frac{1}{5} \cos(5\omega t) - \frac{1}{7} \cos(7\omega t) + \dots \right) \quad (2.16)$$

Equation (2.16) is the frequency domain formula. The harmonic components (1, 5, 9) and (3, 7, 11) will be positive and negative sequence, respectively [30]. A typical example of the waveform from

equation (2.16) is seen in Figure 2.12. The waveform displayed contain harmonics only up to the 11th harmonic component.

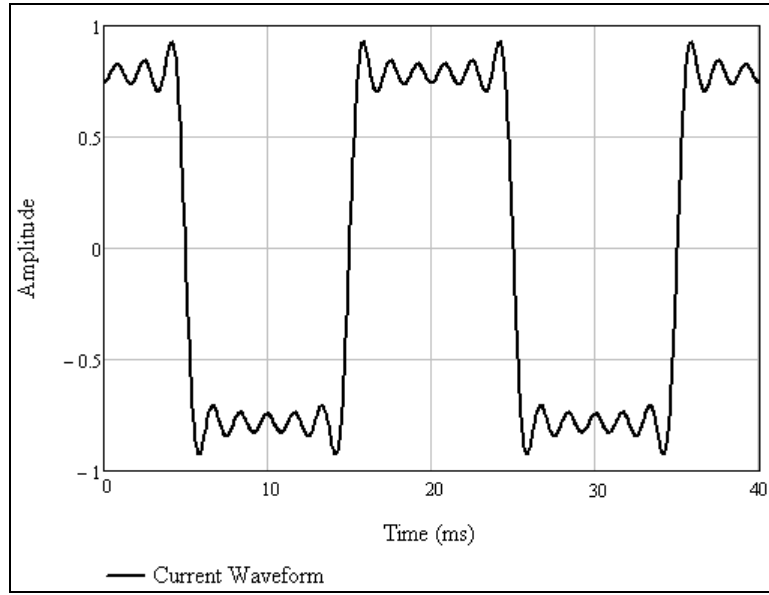


Figure 2.12: Square wave representation from equation (2.15).

SIX-PULSE RECTIFIERS

A six-pulse rectifier is basically a three-phase, two-way configuration. This means the width of the current waveform will be equal to ($w = \frac{2\pi}{3}$). Substituting this value into equation (2.15) with the DC component current will result in a frequency domain Fourier series. Figure 2.13 is a representation of such a phase current and for example purposes only inherit harmonic components up until the 19th. Frequency domain representation of phase current for a six-pulse rectifier is illustrated in Figure 2.14.

$$i_a = \frac{2\sqrt{3}}{\pi} i_d (\cos(\alpha) - \frac{1}{5} \cos(5\alpha) + \frac{1}{7} \cos(7\alpha) - \frac{1}{11} \cos(11\alpha) + \frac{1}{13} \cos(13\alpha) - \frac{1}{17} \cos(17\alpha) + \dots) \quad (2.17)$$

This type of rectifier does not produce the odd triple harmonic (3, 9, 15, etc.), but other harmonics of the order $6k \pm 1$ for integer values of k [30]. The most harmful harmonics produced from this type of rectifier is the 5th and the 7th harmonic [30].

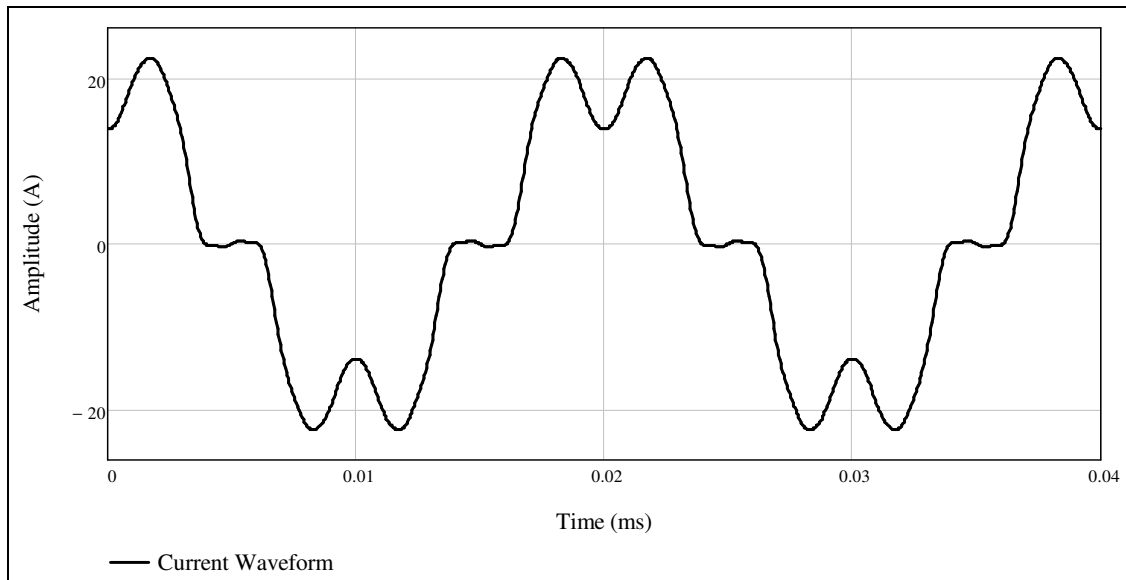


Figure 2.13: Current waveform distortion of a six-pulse rectifier.

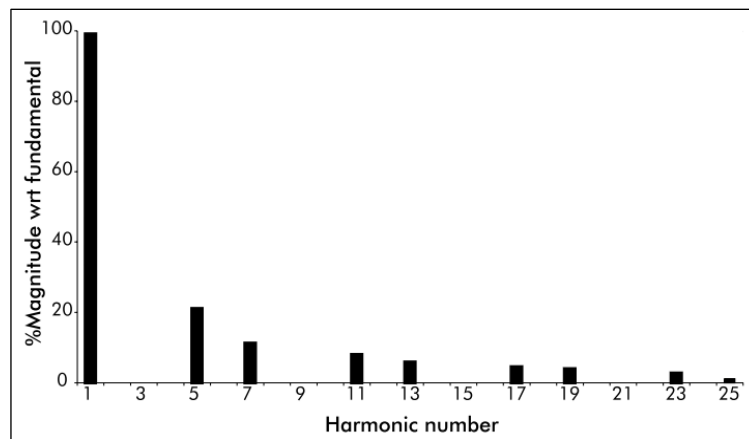


Figure 2.14: Harmonic spectrum for a six-pulse rectifier [8].

TWELVE-PULSE RECTIFIERS

A twelve-pulse rectifier is basically two, six-pulse rectifiers in parallel. It is supplied through a converter transformer. Figure 2.15 shows a common twelve-pulse rectifier setup. The advantage of this rectifier is the 30° phase shift between the delta and star connection on the secondary supply side of the transformer. The phase shift causes harmonic currents to be in the opposite phase on the supply side, which greatly reduces the overall harmonic generation of the rectifier. The $6k \pm 1$ harmonics are greatly reduced with this type of rectifier. The operation of a twelve-pulse rectifier requires the same control angle, thus the fundamental current on the AC side must be in phase with each other [30]. The rectifier however, still generates $12k \pm 1$ current harmonics, where the dominant components are the 11th and the 13th harmonic. The drawbacks of this type of rectifier are cost and the requirement for specialised equipment such as the supply transformer. Figure 2.17 illustrates the expected supply current, while Figure 2.16 shows the harmonic spectrum of a twelve-pulse rectifier.

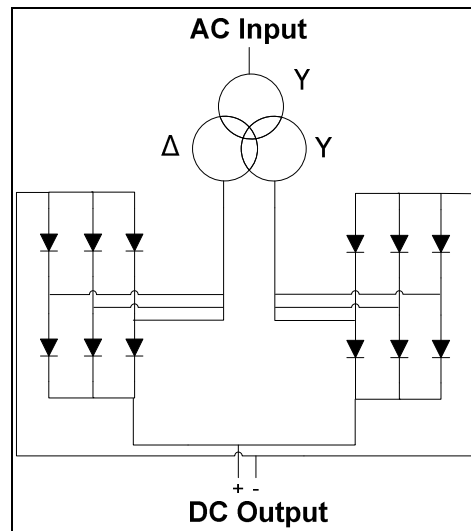


Figure 2.15: Twelve-pulse rectifier.

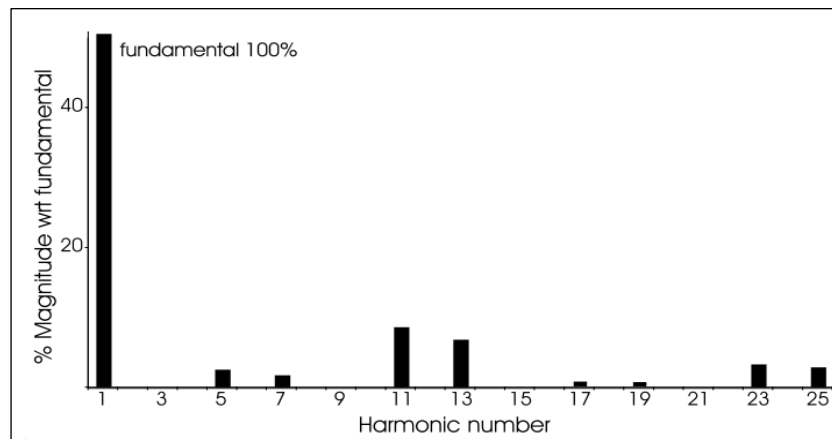


Figure 2.16: Harmonic spectrum for a twelve-pulse rectifier [8].

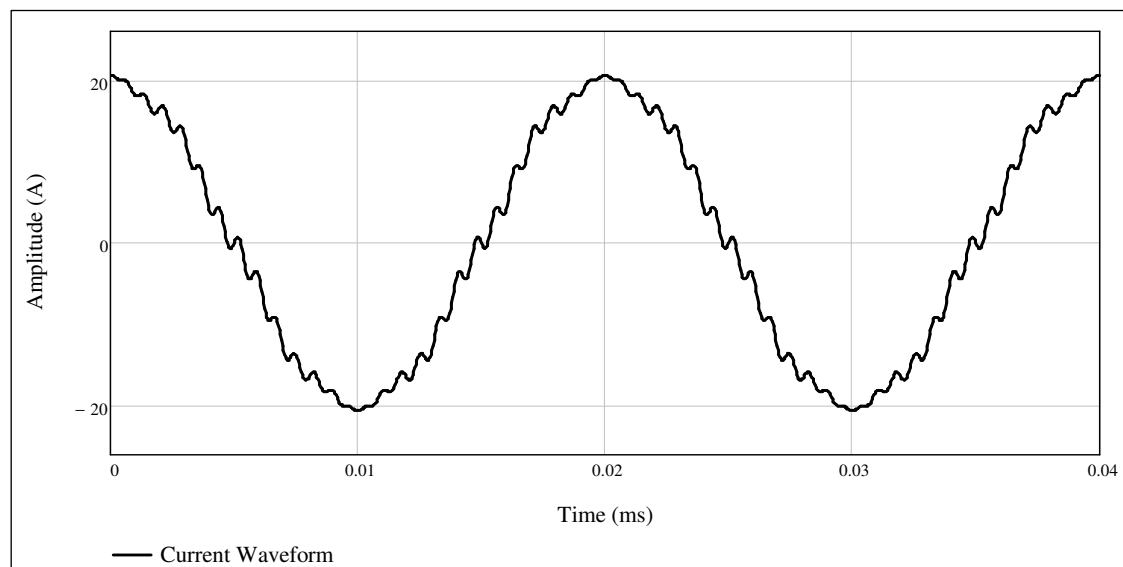


Figure 2.17: Current waveform distortion for a twelve-pulse rectifier.

ARC FURNACES

An arc furnace is a single piece of equipment that introduces the most PQ effects in an electrical system. Common PQ issues are: voltage and current harmonics, low power factors, voltage flicker and phase unbalances [40]. Electric arcs are a thermoelectric phenomenon, which is dependent on the applied electrode voltage and the medium in which the arc discharges [40]. The electric arc is unpredictable due to cycle-by-cycle variations related to the melting stages. Current and voltage characteristics of an electric arc is non-linear, which means that it produces harmonic current and voltages as explained in the previous section [6]. The initiation of the arc produces a wide spectrum of even and odd harmonic components [6]. As the metals start to melt, the arc becomes more stable, which produces less distorted currents, which causes less voltage distortion. Table 2.1 is an illustration by IEEE on the expected harmonic current distortion components before and after melting [6]. This table clearly shows how the harmonic components decrease as the arc becomes more stable.

Table 2.1: Harmonic content of arc furnaces for two stages [6].

	Harmonic Current % of Fundamental				
	Harmonic Order				
Furnace condition	2	3	4	5	7
Initial melting (active arc)	7.7	5.8	2.5	4.2	3.1
Refining (stable arc)	0.0	2.0	0.0	2.1	0.0

The complete arc furnace consists of various components, such as: reactive power compensation circuits (SVC), furnace transformers etc. These components contribute to harmonic voltage distortion along with the electric arc itself. When evaluating voltage distortion at PoD for an arc furnace, it should be taken into consideration, that the level of voltage distortion could be dependent on various other components and not just on the arc itself.

Figure 2.18 represents the three basic stages of arc furnace operation. Graph (a) represents the drilling period and is characterised by a short time duration (3 to 4 minutes) [40]. During this period, there is an irregular arc, which causes highly distorted voltages and currents [40]. This is caused by the heterogeneous mixture of the metals. Graph (b) is defined as the melting period. During this period the metal is melted – more homogeneously, which results in less voltage and current distortion. This period could last 21 to 23 minutes [40]. Graph (c) is known as the end of the melting period and reheating. It is characterised by lower voltage, higher current, shorter arcs and a time period of 5 minutes [40]. The voltage and current waveforms resemble an almost perfect sinusoidal waveform during this period [40].

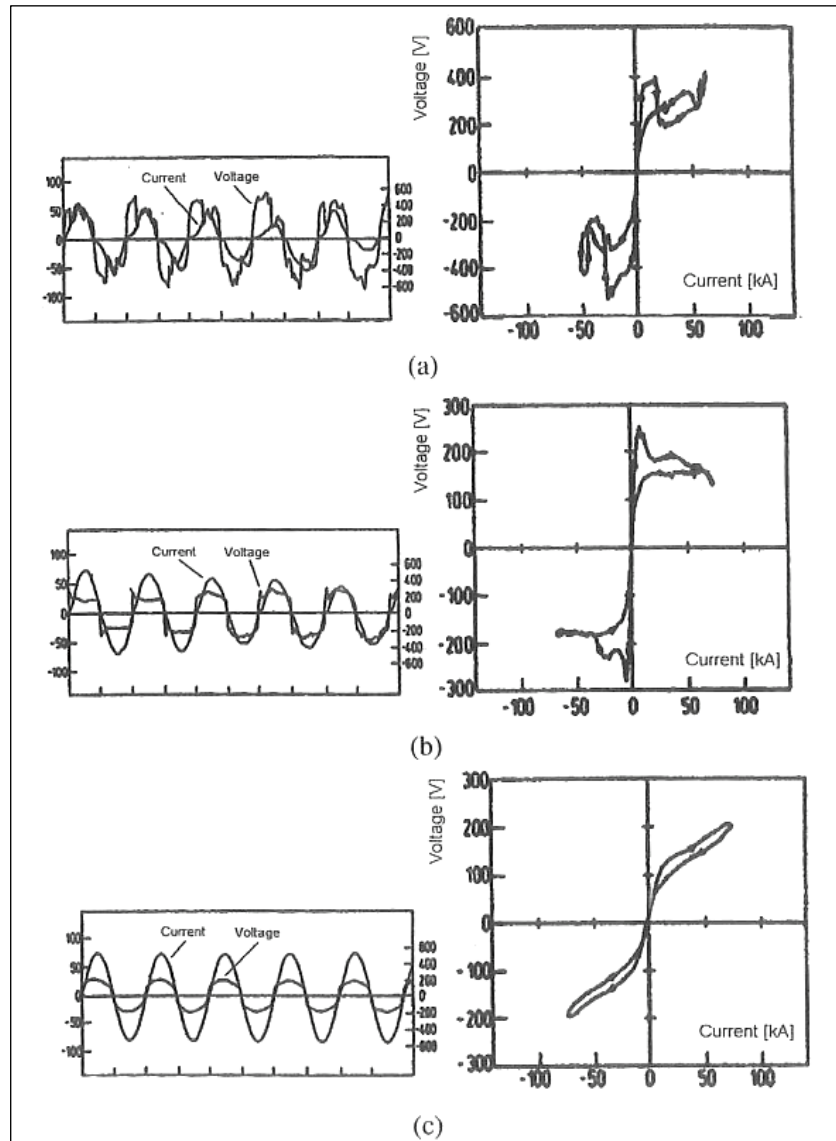


Figure 2.18: Characteristics of an arc furnace during various operating periods [40].

TRANSFORMERS

The transformer is an essential integrated part of electrical distribution networks all over the world. The equipment characteristics are slightly non-linear, due to the magnetic characteristics of the core. Under normal steady state conditions, transformers do not generate significant amounts of harmonic distortion. It is however under transient conditions that they contribute more to system distortion.

The non-linear properties of the magnetic core material (B-H Curve), causes the exciting current to be non-sinusoidal [40]. Graphical representation of the exciting current (I) can be obtained as a function of time from the hysteresis curve of the material (Figure 2.19). The hysteresis curve in Figure 2.19 is presented as a function of the flux (Φ) and exciting current (I), which is directly related to the magnetic flux density (B) and magnetic field intensity (H) by known geometric constants [40], [43].

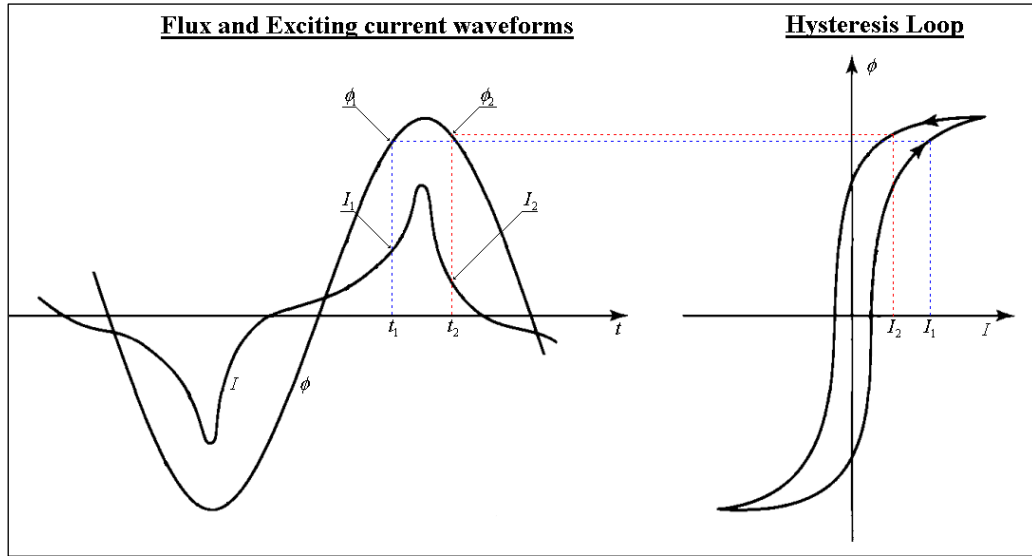


Figure 2.19: Exciting phenomena of a no load transformer [41].

The transformer flux expression is:

$$\phi = -\int \frac{e_1}{N_1} dt = \frac{E_m}{N_1 \omega} \cos \omega t = \phi_m \cos \omega t \quad (2.18)$$

The induced voltage as:

$$v_1 = -e_1 = -E_m \sin \omega t = N_1 \frac{d\phi}{dt} \quad (2.19)$$

And the exciting current (I) as a function of core loss current (I_C) and magnetising current (I_M) as:

$$I = \sqrt{I_C^2 + I_M^2} \quad (2.20)$$

Transformer exciting current is full of harmonics, but is less than 1% of rated full current [2]. Harmonic contribution to overall power system harmonics is low, however, it is still notable especially on utility networks, which have a lot of transformers. It is common to notice significant increases in triplen harmonics when the LV reticulation networks are lightly loaded [2].

Figure 2.20 illustrates simulated results of the exciting current on a no-load transformer. It clearly shows at various time intervals how the current waveform changes as the magnetic path in the core is created [40].

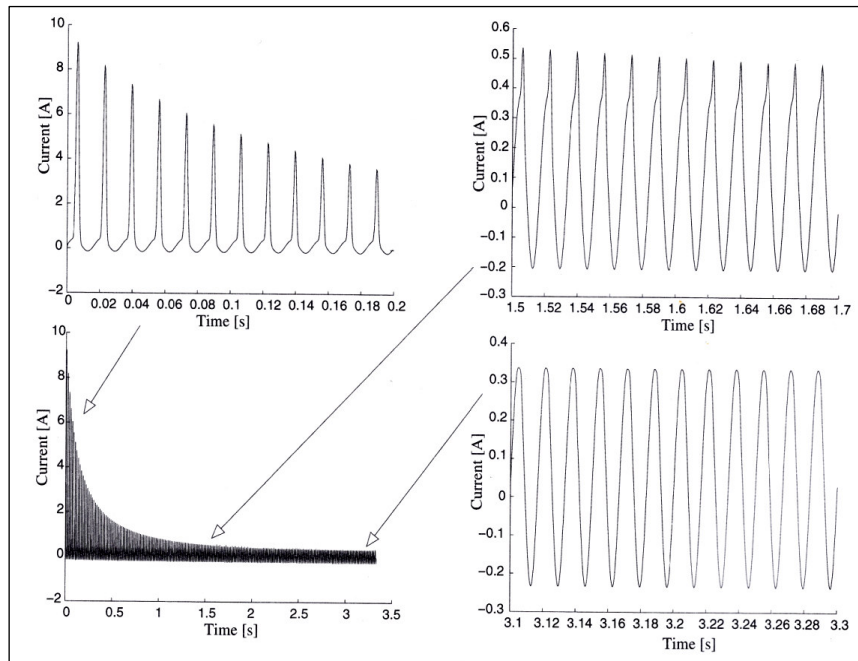


Figure 2.20: Exciting current of a no load transformer [40].

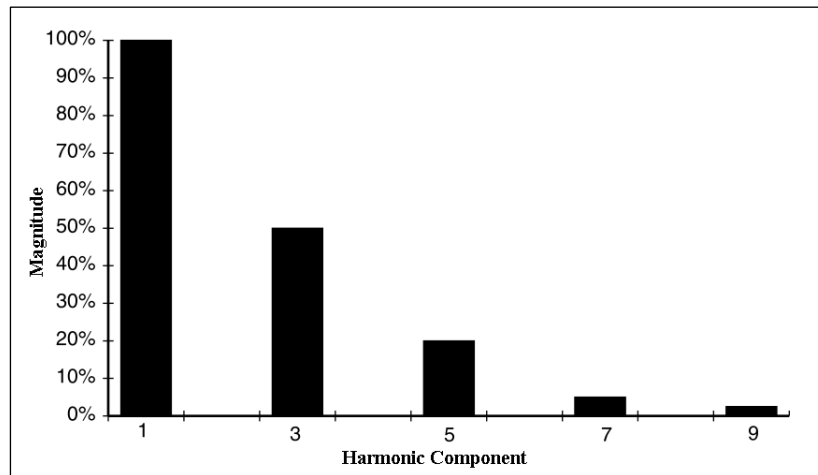


Figure 2.21: Harmonic spectrum of inrush current on a non-loaded transformer [2].

Figure 2.21 shows the harmonic spectrum of inrush currents. The third harmonic is typically 50% of the total RMS value of the exciting current [2]. A delta connection prevents the flow of zero sequence harmonic components. Triplen harmonics (3rd, 9th, 15th etc.) are known to be zero-sequenced and can be contained within winding connections. The line currents of the transformer will then in theory be void of such harmonics [2].

FLUORESCENT LIGHT

Discharge type lighting, such as fluorescent tubes have been in operation for more than 60 years [40]. These types of loads are non-linear and could cause current and voltage harmonic distortion. Unlike the arc furnace, the operating conditions of these loads are at a much lower current rating, while the

environment also differs, e.g. a sealed gas tube. In light of the non-linear V-I characteristics, one discharge type lamp will not cause high levels of voltage and current distortion due to their low power rating. However, the low power usage and advancement in ballast technology makes them a popular lighting choice. A typical example is the CFL campaign, initiated by Eskom, the electrical utility company of South Africa. The campaign organisers distributed 43 million CFL to buildings and households to achieve an estimated power saving of 1.8 MW [45]. A study in the U.S.A founded that lighting loads account for 40% - 60% of commercial buildings [2]. When compact fluorescent lights are used on such a large scale, it is a potential source of network waveform distortion.

A fluorescent light is basically an arc current that flows between two electrodes in a tube filled with gas. In order to establish the arc, the incoming voltage must be raised to a higher value. The voltage drops as the arc is formed, while the current increases [2], [30]. The ballast also acts as a current limiting device, preventing excessive current flow and maintaining the luminal output [2], [40]. The V-I characteristics of the fluorescent light is dependent on the state of ionisation initiated by the electrical discharge [40]. The de-ionising time is short, which means that a direct supply of 50 Hz would not be able to initiate the fluorescent lamp. When the applied power frequency is raised (25 kHz to 40 kHz), the discharge arc goes into a state of dynamic equilibrium, which means there is a constant state of ionisation [40].

The recommended ballast technology is electronic ballasts, which implements a typical SMPS circuit to raise the voltage and frequency to the required levels. These ballasts are small and economical, which makes them popular. However, their harmonic current producing potential can be double or triple the value of normal magnetic ballasts [2]. Harmonic current components, especially the 3rd and 5th harmonic generated from this equipment are the biggest contributor to voltage distortion. Figure 2.22 shows the expected harmonic current component spectrum generated by a CFL.

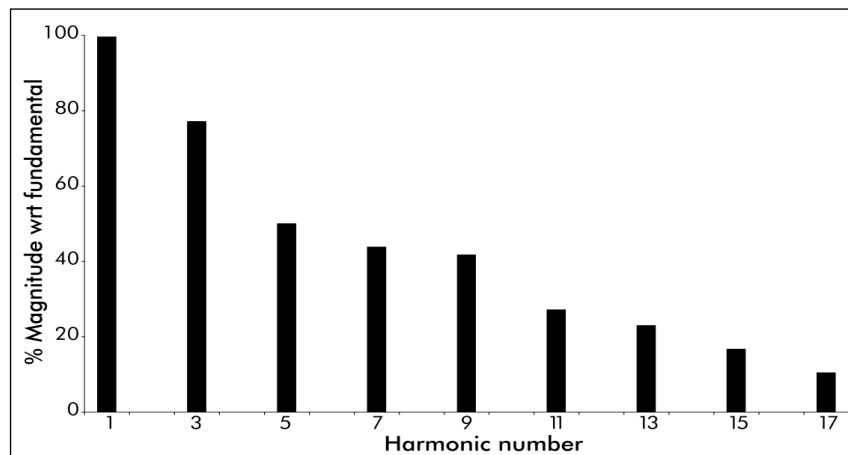


Figure 2.22: Harmonic current components generated by a CFL [8].

2.4 HARMONIC EFFECTS

Section 2.3 highlighted the equipment that produces harmonic distortion. It is important to know what effects harmonic distortion have on network loads. Harmonics have different effects on equipment, dependent on the vulnerability of the load. For example, communication loads require a pure sinusoidal waveform, which makes them more vulnerable to harmonics [6]. Even in least vulnerable equipment, harmonics can be harmful. Typical problems caused by current and voltage harmonics are [8]:

- Neutral conductor overloading;
- Transformer overheating;
- Nuisance tripping of breakers;
- Induction motor eddy current losses;
- Skin effect.

The following sections will discuss harmonic effects, expected on network equipment.

ROTATING MACHINES

Below is summarised effects that can be expected when rotating machines (induction and synchronous) are subjected to harmonics.

- Voltage and current harmonics in rotating machinery causes increased heating, due to copper and iron losses at harmonic frequencies [6]. Additional heating reduces the efficiency of the machines and affects the torque development [6].
- Machines that are subjected to harmonic currents can give higher audible noise than machines subjected to pure sinusoidal current [6].
- Harmonic current produces a resultant flux in the air gap of an induction machine, which could result in cogging (difficulty to start-up) or crawling (a very high slip) [6].

TRANSFORMERS

Power system harmonics can cause increased audible noise in transformers [6]. Current harmonics increase copper and stray flux losses, while voltage harmonics increase iron losses [6]. Copper losses are mainly caused by conductor heating and skin effect, while the increase in stray and eddy-current losses will be dependent on the square of the load current and frequency [6]. Higher harmonic components are more important to evaluate, because of increased losses at higher frequencies [6]. However, as seen in the previous section the amplitude of the higher harmonic components is smaller,

which greatly reduces the effects of higher order harmonics [6]. Higher temperatures cause insulation breakdown and a reduction in life expectancy as the transformer operates above rated values.

POWER CABLES

Non-sinusoidal currents result in higher conductor temperatures, compared to temperatures achieved during normal sinusoidal currents [6]. When high frequency harmonic currents flow in a conductor, the effective AC resistance (R_{AC}) of the conductor increase, which amplifies the I^2R_{AC} losses [6]. Additional heating is a direct result of the “skin” and “proximity” effects, which varies as the frequency, conductor size and conductor spacing changes [6]. The skin effect becomes the main concern from the 7th harmonic (350 Hz) component and higher [8]. Normally, conductor heating is of less concern due to a prudent design.

POWER FACTOR CORRECTION CAPACITORS

Power factor correction (PFC) in the form of shunt capacitors are used in a network to improve the supply power factor and voltage. The capacitors are installed in predominately highly inductive networks, mostly found in heavy industries. PFC capacitors draw current with a leading phase angle, to offset lagging current being drawn by the inductive load [8].

Figure 2.23 shows an equivalent PFC network, connected to a non-linear load. The load injects harmonic currents and is indicated in Figure 2.23 as harmonic current sources. When the frequency increases, the impedance of the PFC capacitor decreases due to the capacitive characteristics, while the supply impedance increases, relating to the inherent inductive characteristics of the network [8]. This means PFC capacitors are therefore more susceptible to carry high harmonic currents [8]. If the capacitor is not designed for this, serious damage can result.

Another potential problem is resonance between the PFC capacitor and stray inductance from the supply network [8]. Resonance occurs near, or close to a harmonic frequency, which could generate very large currents and voltages [8]. Overloading can causes capacitor damage due to heating or by dielectric stresses [8].

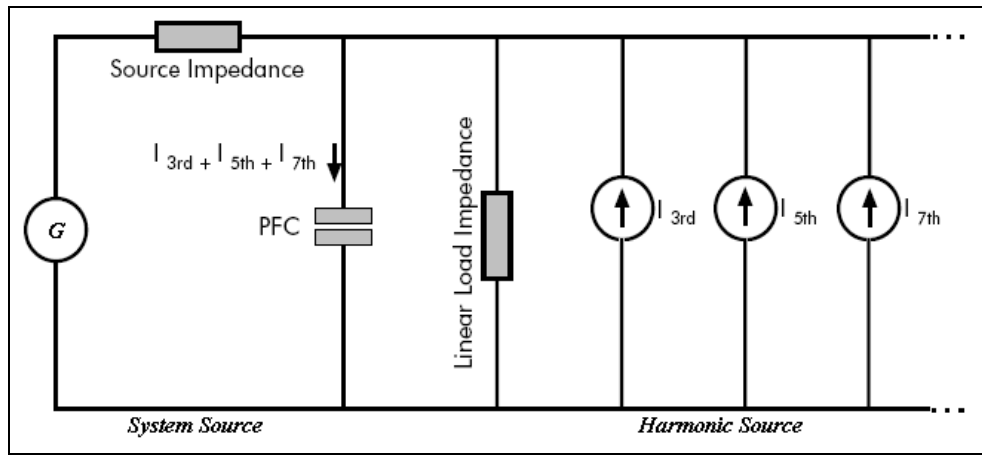


Figure 2.23: Network example with power factor correction [8].

ELECTRONIC EQUIPMENT

Most power electronic equipment is designed based on the assumption that the supply voltage has a pure sinusoidal waveform. Zero voltage crossings are where the fundamental frequency waveform crosses the zero line and is mostly used for timing purposes [33]. With harmonic voltages and currents present, the distorted waveform can cross the zero line more often and could cause the miss operation of equipment, giving erroneous data and performing unpredictably [6]. Equipment most commonly affected by these phenomena are sensitive devices such as: medical equipment, radio and television equipment [6].

SYSTEM PROTECTION RELAYS

Waveform distortion could affect the performance of system protection relays. Relay responses can vary a lot in a harmonic environment, depending on relay type, harmonic magnitudes, harmonic orders and harmonic phase angles [6]. Load current distortion has little effect on large fault currents. However, with smaller fault currents the distorted current could have a significant influence [33]. Harmonic distortion may cause nuisance tripping when there is no fault, or may cause the relay not to trip at all.

NEUTRAL LINE OVERHEATING

In a three-phase system the voltage for each phase is displaced by 120° . In theory, for a balanced load the net current flowing in the neutral conductor is supposed to be zero. In the past power system harmonics were not that common and therefore designers installed half-size neutral conductors [8]. The problem is that the fundamental currents balance each other, but the harmonic currents, especially the triplen harmonics, tend to add in the neutral conductor [8]. In Figure 2.24 the fundamental

waveform is displaced 120° , which results in a neutral current being zero. For this example, the 3rd harmonic is identically present in each phase. A 70% harmonic current per phase results in a 210% neutral current as seen in Figure 2.24 [8]. Case studies done at commercial buildings have shown neutral conductor current as high as 150% to 200% of the phase current [8].

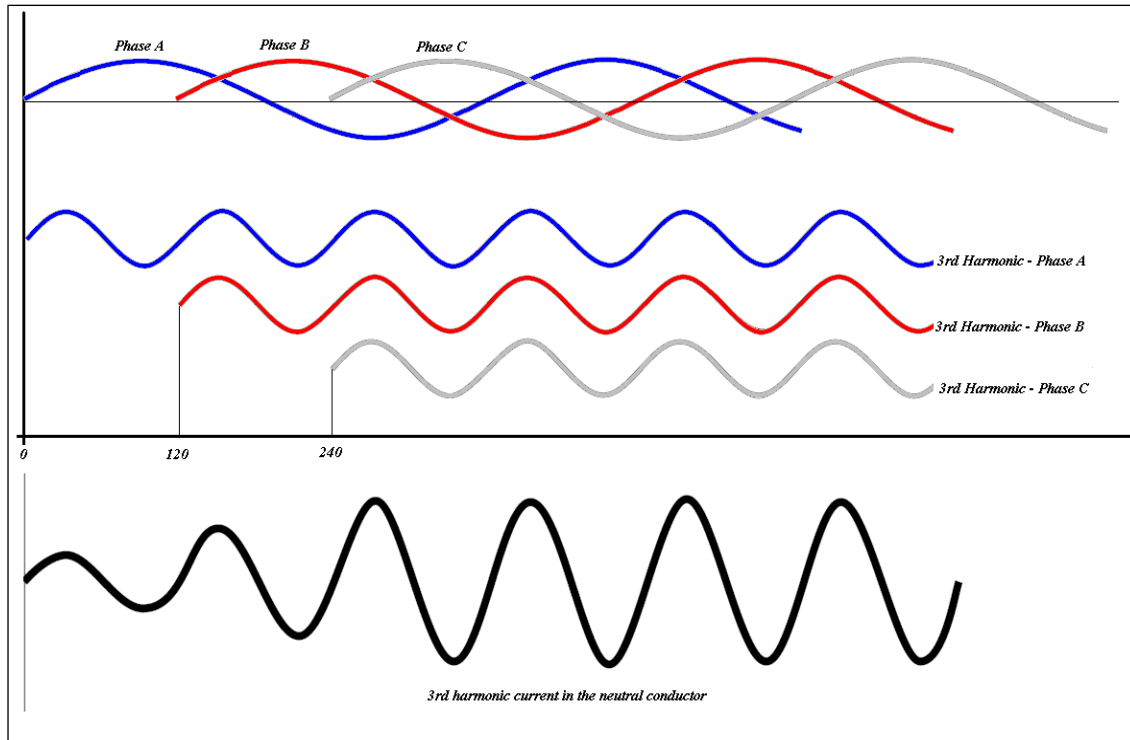


Figure 2.24: Neutral conductor harmonic current [8].

SWITCHGEAR

Harmonic currents present in switchgear can cause additional heating and losses, thereby reducing current carrying capability and shorting life expectancy [6]. Components such as fuses are thermally actuated. Additional heating, caused by harmonic currents during normal operation, can cause degrading of the fuse [6], [33].

RESIDUAL CURRENT CIRCUIT BREAKERS

Residual current circuit breaker (RCCB) is a combination of overload protection and earth leakage detection. RCCB operates on the principle of summing the phase and neutral currents. This measured value must then be within certain current ranges in order for it not to trip. The RCCB is an electromagnetic device and nuisance tripping can occur if the higher order harmonic components are not included in the summation [8].

Another issue is that components that generate harmonics usually generate switching noise. This could also lead to nuisance tripping and must be filtered out at the power connection. Typical filters consist of a capacitor that allows a small current (3.5 mA) flow to ground [8]. Nuisance tripping of a miniature circuit breaker (MCB) is due to higher current flow, caused by harmonic distortion. This effect usually happens when circuit designers didn't take harmonic distortion into consideration, when breaker sizes were selected [8].

2.5 MITIGATION OF HARMONIC DISTORTION

After evaluating harmonic sources and effects, it is important to understand mitigation techniques. Overall power system harmonics are normally at reduced levels. However, in local smaller networks, harmonics distortion can increase. This presents a problem for which mitigation systems must be put in place to reduce harmonic effects. Factors that justify the need for these mitigation systems are [2]:

- Power system harmonic currents overall are increasing due to sophisticated non-linear equipment;
- Distribution networks are expanding, which means additional impedance is added in series and parallel. Harmonic currents along with added series impedance could result into higher voltage distortion;
- The system response can amplify the magnitude of harmonics, greater than the initial design tolerances.

There are several options available to mitigate harmonic distortion in a system.

PASSIVE FILTERS

Passive filters refer to shunt filters put in place near the supply connection, allowing all the harmonic currents generated from the load to flow into the filter instead of entering the system. Likewise, harmonic currents from the system will flow into the filter and not to the load. The filter has low impedance, thereby absorbing the harmonic currents. Figure 2.25 shows a simple diagram, illustrating where the filter should be installed. The filter could be designed as a band pass filter, or individual frequencies could be filtered out.

A more complex passive filter uses a series band stop design which blocks the harmonic currents instead of rerouting them. Harmonic voltages drop over the filter and the supply side appears distorted [8]. Voltage distortion is now not within supply limits and could damage equipment. The series filter is only used in certain situations and is not recommended as a permanent solution. The drawback of this filter system is that the non-linear load profile could change, which could render the filter useless for certain harmonic frequencies [8].

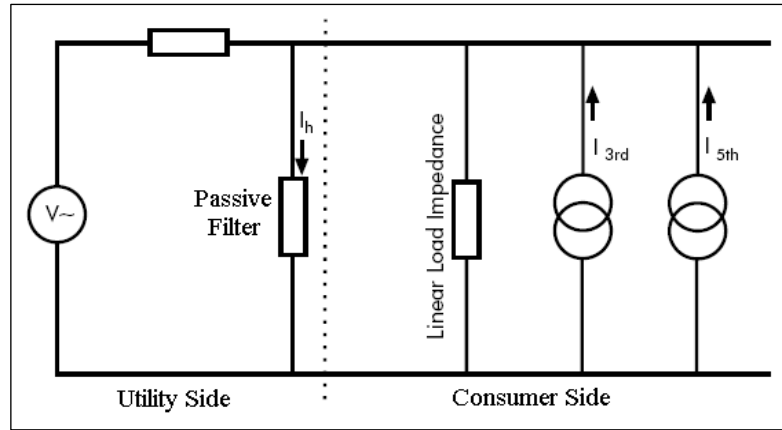


Figure 2.25: Passive harmonic filters [8].

ACTIVE FILTERS

Active filters are used in installations where the harmonic content is not constant and is not predictable. Active filters are also known as active harmonic conditioners (AHC). The theory behind the technology is relatively old and was not rapidly implemented in the past, due to the lack of market competitiveness [24]. With the advancement and general availability of insulated gate bipolar technology (IGBT) and digital signal processor (DSP), the AHC have become the practical solution for rendering harmonic distortion [24].

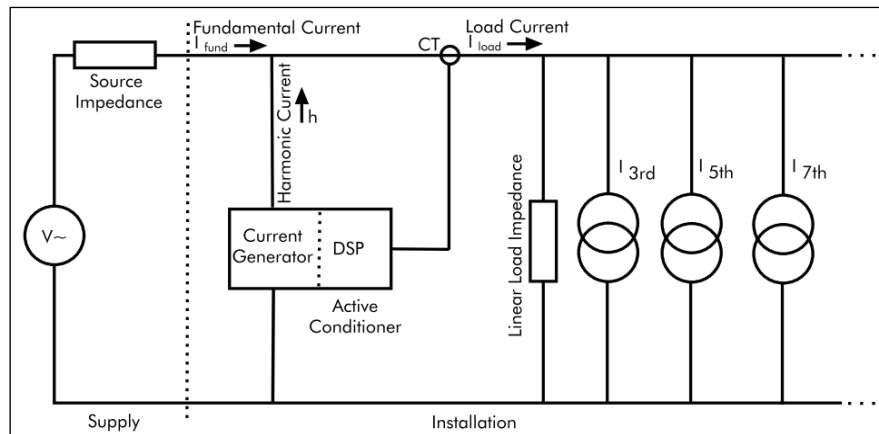


Figure 2.26: Parallel active harmonic conditioner [24].

As explained in section 2.2, the non-linear load draws non-sinusoidal currents, which interact with the system impedance causing voltage distortion at the PCC. Figure 2.26 is a circuit illustration of a parallel AHC. From Figure 2.26 the non-linear load current is measured by a current transformer (CT), which sends a replica of the waveform to a digital signal processor [24]. The DSP analyses the waveform and determines the non-linear load harmonic profile [24]. The AHC automates a harmonic current generator to produce exactly the harmonic current spectrum that is required by the non-linear load [24]. The harmonic generator is constructed out of power electronics and injects the harmonic

currents into the installation network to compensate for harmonic currents being drawn from the supply system [24]. In theory, only the fundamental current waveform is drawn by the non-linear load and reduces harmonic current from the system supply by 90% [24]. The AHC requires continuous input from the CT, which means if the harmonic load profile changes, then the AHC will auto-adjust to generate new harmonic currents for the new harmonic profile [24]. This technology greatly reduces voltage distortion at the PCC between the system and the load. Figure 2.27 and 2.28 illustrate practical results on how an AHC reduces harmonic components for a variable speed drive (VSD) [24].

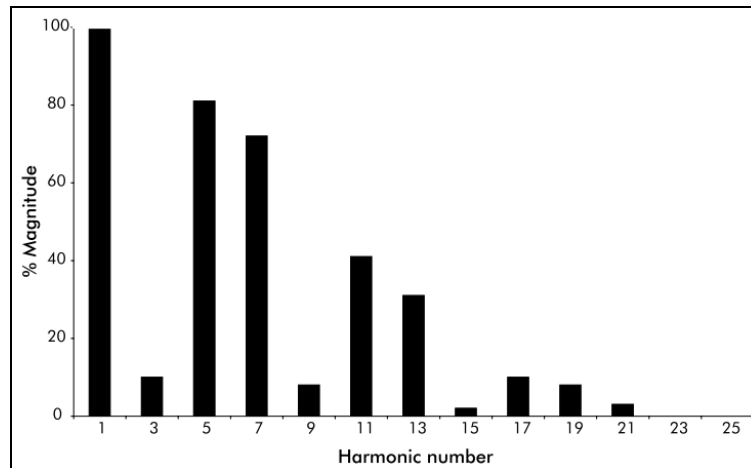


Figure 2.27: Typical harmonic spectrum for a VSD as measured from the supply side [24].

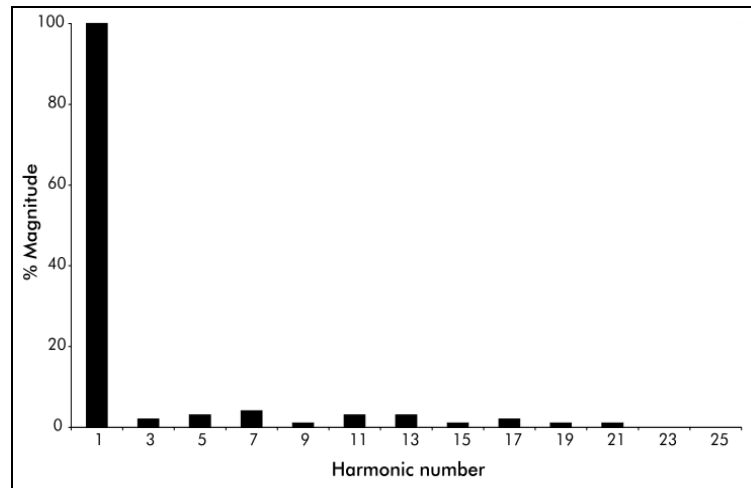


Figure 2.28: Harmonic spectrum of a VSD with AHC installed [24].

AMENDING THE FREQUENCY RESPONSE OF THE SYSTEM

Another way to deal with system harmonics is to modify the frequency response of the system. Here is a list of actions that can be used to do this:

- Connecting a shunt filter eliminates harmonic content, but also changes the frequency response;

- Changing the capacitor size will alter the frequency response. This method is less expensive for both the consumer and the utility;
- Moving of capacitor to an area of different impedance and higher losses. Most of the time the consumer is unable to move the capacitor far away;
- On the consumer side the capacitor can be removed, which will reduce harmonic content, but the user will be liable for power factor penalties, higher losses and lower voltage. It is recommended that a feasibility study be done, before executing this suggestion [8].

2.6 POWER QUALITY STANDARDS

This section provides a brief background on PQ standards developed by various institutions. PQ standards set qualitative and quantitative parameters so that both the utility and the consumer can be assured that the quality of electrical energy is not neglected over a large transmission network or small distribution network. The underlying philosophical principles used in formulating specific PQ standards, are the sufficient level of compatibility between consumers and utilities. A PQ standard defines the measurable limits and compliancy levels, which constitutes the acceptable deviation. PQ standards can thus be used in a mutual agreement between the utility and consumer with regards to acceptable and unacceptable PQ levels [1]. Harmonic standards are divided into two groups, namely system and equipment standards [33]. System standards provide limits for transmission and distribution networks, while equipment standards provide threshold limits for individual harmonic components produced by a variety of equipment [33]. Table 2.2 presents a historical overview of the development of PQ standards since 1890. Although harmonics have been present since the inception of the power system, applicable standards were only developed in the 1980's [1]. PQ standards must evolve with technology advancement to ensure adherence to CL.

Table 2.2: Historical overview of standard development [1].

Years	Standard
1890	Voltage & Current
1900	Frequency
1920	Flicker
1930	Preferred Voltages
1960	Interruptions
1980	Harmonics
1990	Sags & Transients

NER DIRECTIVE ON POWER QUALITY

The national electricity regulator (NER) has ranked PQ as 4th most important priority on their regulatory agenda. Their objectives include reliable QoS service, customer satisfaction, complaints

handling and conditions of service [15]. The main objective of this directive is to define a general framework for PQ management in South-Africa. It also defines the rights and responsibilities of the utilities and the consumers. The directive states that PQ management can only be effective when utilities, consumers and equipment manufacturers approach PQ issues together [15]. By using the input from all stakeholders, the NER aims to create a framework for PQ management in South-Africa [15]. The responsibilities and services of the NER are summarised in Figure 2.29.

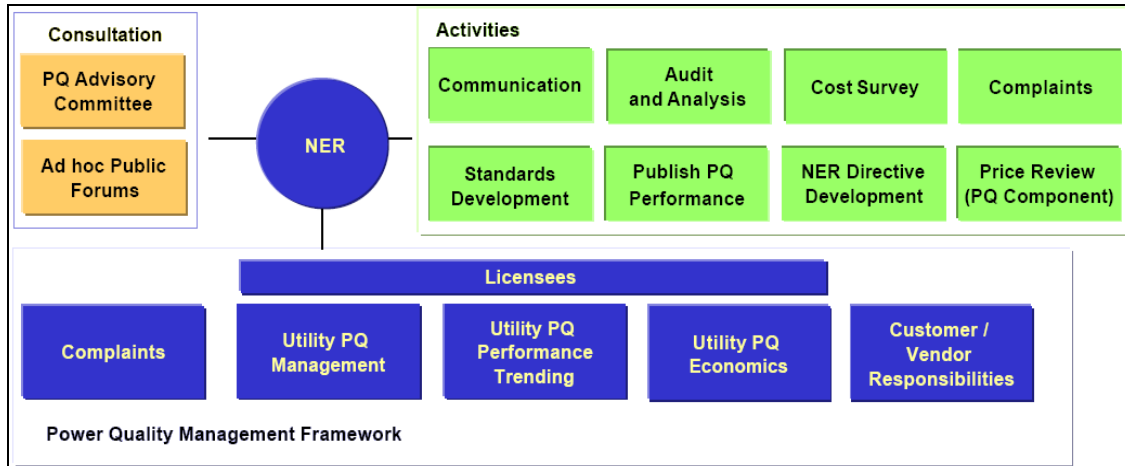


Figure 2.29: Roles of the NER [15].

Section 3 of the directive provides an overview on the proposed PQMS [15]. Section 3.2 explains the philosophy of the management plan while section 3.3 is more applicable to quality management [15].

ELECTROMAGNETIC COMPATIBILITY LEVEL

Quality of supply has become one of the most important subjects in recent times. Most utilities strive to operate their network at unity power factor, balanced phases, sinusoidal voltage and current waveforms. Consumer loads, network disruptions and natural phenomena like lightning, are some of the primary contributing factors, which cause degradation of system PQ. These factors relate to several types of events such as harmonic currents, phase unbalances, flicker created by fluctuating loads, dips and interruptions caused by system faults etc. The principal concept used to formulate specific aspects of PQ standards, are to be found in a sufficient level of compatibility between consumers and utilities. One such body that has developed standards based on this concept is the IEC, which has defined the interaction between consumers and utilities as [22]:

“The ability of an item of equipment or a system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances in that environment”

NERSA and the NRS 048 have adopted this principle in their PQ directive and standards, respectively [15], [17], [18]. This statement, as defined by the IEC, introduced the concept of “Compatibility”. This basically means that distribution networks must be able to withstand a certain amount of distortion injected into the network by the consumer, while still deeming the network operable. On the other hand, a distribution network has interconnections between various loads, which means the supplied power to a consumer can also inherit distortion. Equipment must be designed in such a way that it is able to handle a level of distortion. There are several sections that need to be addressed with regards to compatibility. Each section will be touched on briefly.

EMISSION LEVEL (EL)

This is defined as the level of disturbance, which is produced by a specific load at a specific location [22]. The magnitude of the distortion depends on the characteristics of the equipment and the supply point on the network. Most equipment is designed and manufactured to meet a pre-defined standard which specifies allowable EL, but ultimately on mass production scale some equipment tends to deviate from their original allowable disturbance level. This means that the same type of equipment can produce different distortion levels in the same network. Equipment disturbances manifest in the system current supply, which means the system impedance will contribute to the measured voltage distortion.

The measured value for the EL is a statistical distribution, which is dependent on various factors such as network impedance, load operating conditions, density of loads and equipment EL etc. Figure 2.30 displays this statistical distribution and is plotted over the probability of obtaining a certain EL value for the level of disturbance [22].

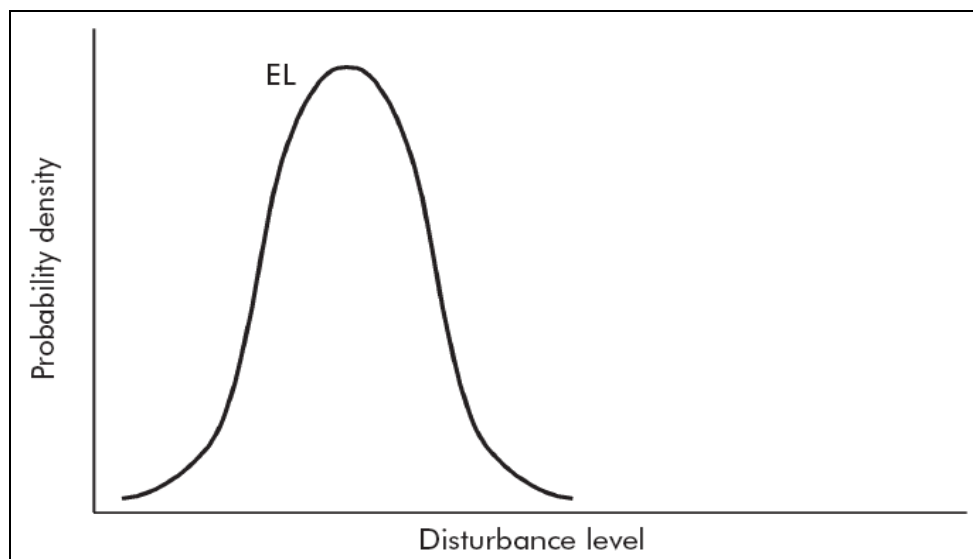


Figure 2.30: Graphical display of emissions levels [22].

IMMUNITY LEVEL (IL)

Immunity level is the maximum number of disturbances present in the network, that does not affect any operations or behaviour of equipment connected [22]. In reality the IL is dependent on other factors like installation conditions, cable lengths, earthing arrangements and component tolerances etc. [22], [17]. The statistical distribution for the IL is the same as for the EL, displayed in Figure 2.30 [22].

COMPATIBILITY LEVEL (CL)

Individual load distortion combines with local network distortion to create a level of distortion on all feeders in the network. This phenomenon has been discussed in previous sections. The combined distortion level will vary daily, weekly and monthly, which is also dependent on the network impedance and load density. The CL parameter, used in the statistical disturbance model, is defined as the amount of system distortion that does not exceed 95% of the total distortion measurements in the entire system [22]. Figure 2.31 shows the CL for the statistical distribution. CL is a statistical value for the whole network and not applicable to a single piece of equipment. It also depends on various parameters.

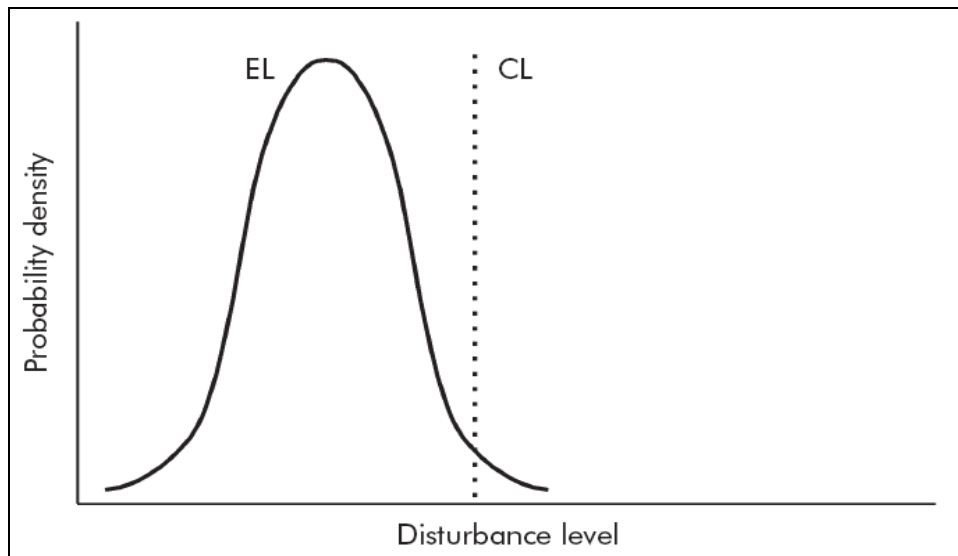


Figure 2.31: Statistical distribution of emissions level and compatibility threshold value [22].

EMISSION LIMIT (E)

The maximum allowable amount of distortion being generated by a single piece of equipment is called the emission limit (E). Equipment must be tested by manufactures to determine the value of the emission limit. Users must report equipment that is not adhering to the design emission limit [22]. The CL is set at a higher value than the emission limit due to the fact that emission limit looks at

individual emissions from equipment while the CL is for a number of loads. Multiple distortions from different loads in the system combine to give an overall system distortion. Certain harmonic current components can be added to produce an overall system distortion level, but there is also equipment that mitigates these effects. Equipment such as transformers, which have the HV or LV winding connected in a delta configuration, diminishes some of these harmonic components [22]. The emission limit is not a statistical value, but is defined as the absolute limit of the maximum allowable distortion produced.

IMMUNITY LIMIT (I)

Immunity limit (I) is defined as the amount of distortion a piece of equipment must handle without any loss of performance. This limit is determined through the design and assurance testing of the equipment. Immunity limits will differ for each piece of equipment based on the area of installation. Since these limits change, there will also be statistical distribution of IL for equipment on the network. To achieve electromagnetic compatibility (EMC), 95% of the immunity limits (I) from the statistical distribution must be higher than the CL [17], [22]. Figure 2.32 illustrates this concept. By setting proper standards for equipment and utilising good installation procedures, adequate CL can be achieved.

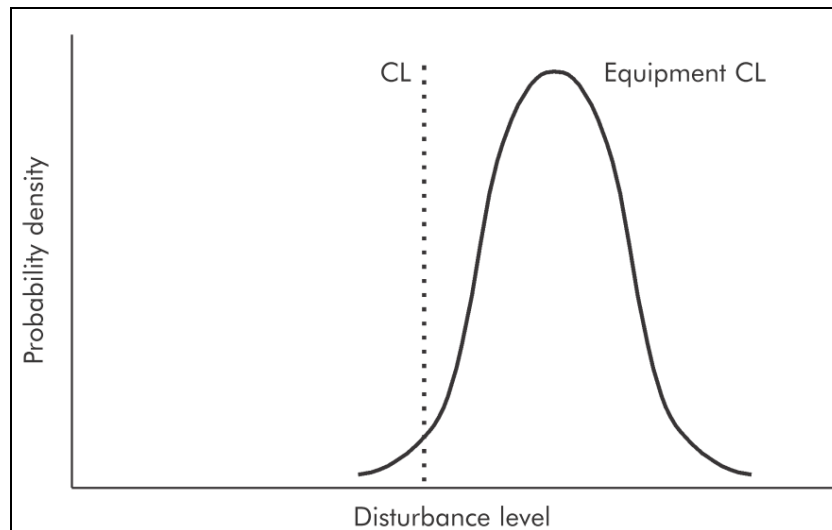


Figure 2.32: Statistical distribution of emissions level and compatibility threshold value [22].

PLANNING LEVEL (PL)

Planning levels are internal goals of the utilities to limit the amount of distortion being injected into the network by commercial and industrial consumers. CL is higher than the PL due to the nature of the problem being statistical.

RELATIONSHIP BETWEEN PARAMETERS

The concept of electromagnetic compatibility is a complex relationship between the supply network and user equipment. Figure 2.33 illustrates the Gaussian statistical distribution of all the parameters as discussed above. The ultimate goal is to move the system disturbance level graph and the equipment IL graph far away from each other; allowing a smaller overlapping section. The further away they are from each other, increase the EMC.

This can be done by sufficient design and network infrastructure investment. The overlapping section is dependent on the equipment immunity and the planning level of the network. The CL is set at 95% of the system disturbance level graph. This allows only a small probability (< 5%) of environmental disturbance levels to exceed the CL [22], [43], [17]. Figure 2.33 illustrates this.

After discussing the concept of electromagnetic compatibility, evaluation and discussions are needed on standards applicable to South Africa.

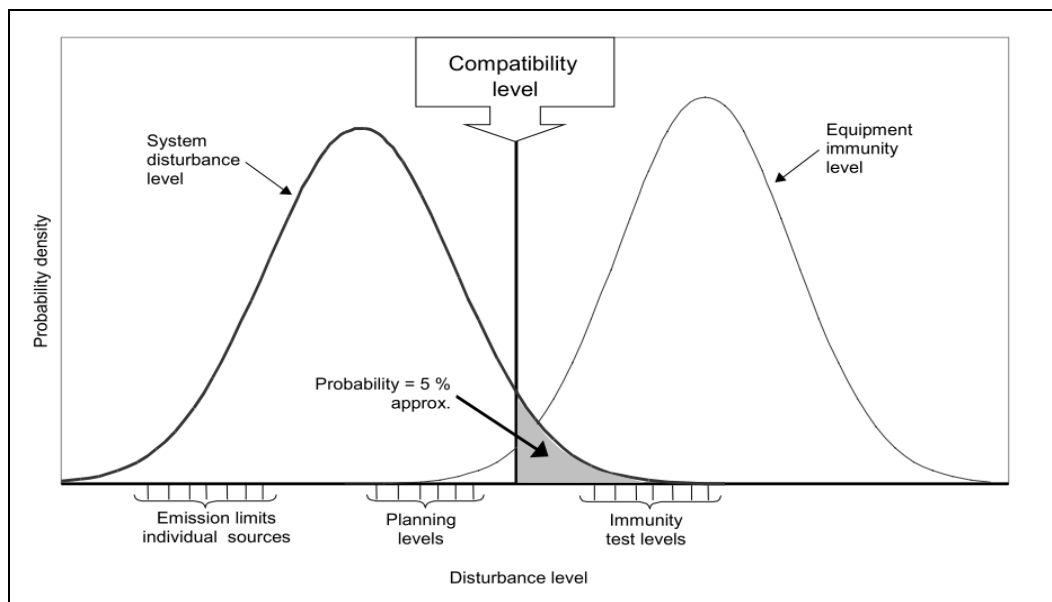


Figure 2.33: Relationship between various compatibility parameters [43].

NRS 048 STANDARDS

The NRS document is the South African PQ standard, which defines QoS standards. Limits for voltage and current distortion at the PCC are set forth here. There are four documents that are part of the NRS 048 that defines different standards for different PQ issues. The standards available are summarised in Table 2.3.

Table 2.3: Quality of supply standards

NRS-048 Part 2	QoS : Voltage characteristics, compatibility levels, limits and assessment methods
NRS-048 Part 4	QoS : Application practices for licensees
NRS-048 Part 6	QoS : Measurement and reporting of MV network interruption performances
NRS-048 Part 8	QoS : Measurement and reporting of HV and eHV network interruption performances.
SANS 1816	Power Quality Instruments

NRS 048 PART 2

This project focuses on harmonic limits. Section 4.2.5 of the NRS 048-Part 2 document, defines voltage harmonics and interharmonics [17]. Compatibility levels are defined according to steady state values and are specified for long and short-term effects [17]. Long-term effects are related to the thermal impacts on equipment, while short-term effects deal with disoperation of electronic equipment [17].

Table 2.4 describes the CL for the LV and MV networks. The supply voltage that contains harmonics up to the 40th component must not exceed a voltage total harmonic distortion (VTHD) value of 8% [17]. Table 2.5 displays compatibility limits for HV and EHV networks. The limit for VTHD is 4% and applies to the supply voltage that is polluted with harmonics up to the 40th component. CL for individual harmonic components can be obtained by applying the following formula:

$$k = 1.3 + \left(\frac{0.7}{45} \right) (h - 5) \quad (2.21)$$

Where h is the harmonic component. The factor k can then be multiplied by the values in Table 2.5 to obtain the CL.

Table 2.4: Compatibility levels for individual harmonics [17].

1	2	3	4	5	6
Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3 ^a			
Harmonic order <i>h</i>	Magnitude %	Harmonic order <i>h</i>	Magnitude %	Harmonic order <i>h</i>	Magnitude %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,5	6	0,5
13	3	21	0,3	8	0,5
17 ≤ <i>h</i> ≤ 49	{2,27 × (17/ <i>h</i>)} – 0,27	21 ≤ <i>h</i> ≤ 45	0,2	10 ≤ <i>h</i> ≤ 50	{0,25 × (10/ <i>h</i>)} + 0,25
^a The levels given for odd harmonics that are multiples of 3 apply to zero sequence harmonics. Also on a three-phase network without a neutral conductor or without load connected between phase and earth, the actual values of the third and ninth harmonics might be much lower than the compatibility levels, depending on the voltage unbalance of the system.					

Table 2.5: Compatibility levels for EHV and HV [17].

1	2
Harmonic order h	HV and EHV harmonic voltage %
3	2,5
5	3,0
7	2,5
11	1,7
13	1,7
17	1,2
19	1,2
23	0,8
25	0,8
NOTE The compatibility levels are those recommended by Cigré TB261, which contains recommendations derived from international data collected. Data for even harmonics and higher-order harmonics was not available, and has therefore not been included. Reference values for these harmonic orders may be based on the planning levels given in NRS 048-4.	

NRS 048 PART 4

Part 4 is a document that provides guidance to utilities and consumers on how to apply QoS standards. Possible procedures and techniques that can be used by old and new network consumers connected to the grid are discussed [18]. It prescribes PL that utilities can implement to provide a reasonable level of compatibility [18]. The standard specifies that the amount of harmonics that is injected into the grid

at the PCC by consumers is the utility's own responsibility. Table 2.6 can be used by utilities to recommend PL for harmonic voltages.

Table 2.6: NRS guidance for planning levels on harmonic voltages [18].

1	2	3	4	5	6	7	8	9
Odd harmonics (non-multiples of 3)			Odd harmonics (multiples of 3)			Even harmonics		
Order	Harmonic voltage %		Order	Harmonic voltage %		Order	Harmonic voltage %	
h	MV	HV/EHV	h	MV	HV/EHV	h	MV	HV/EHV
5	5,0	2,0	3	4,0	2,0	2	1,6	1,5
7	4,0	2,0	9	2,0	2,0	4	1,0	1,0
11	3,0	1,5	15	0,3	0,3	6	0,5	0,5
13	2,5	1,5	21	0,2	0,2	8	0,4	0,4
17	1,6	1,0	> 21	0,2	0,2	10	0,4	0,4
19	1,2	1,0				12	0,2	0,2
23	1,2	0,7				> 12	0,2	0,2
25	1,2	0,7						
> 25	0,2+	0,2+						
	$0,5 \frac{25}{h}$	$0,5 \frac{25}{h}$						
NOTE Total harmonic distortion (THD): $\leq 6,5$ % in MV networks and ≤ 3 % in HV networks.								

Annex E and F of Part 4 also provides standards that were developed by the USA (IEEE) and the European community (IEC) [18]. The NRS and IEC approaches are based on individual harmonics, whereas the IEEE standards do not distinguish between them and takes the load current into consideration. The NRS summarises these standards to give the user of this standard the option of a second and third opinion.

Table 2.7 shows CL for LV and MV networks. Table 2.8 and 2.9 prescribe PL for utilities on HV and EHV networks. Earlier IEC standards were adapted by Eskom and are more or less the same standards described by the NRS. The IEEE standard [6] is structured to a current based approach. Table 2.10 to 2.13 describes IEEE harmonic current limits. Voltage harmonic limits specified by IEEE can be seen in Table 2.10. The limits specified may be exceeded by 50% for a period less than 1 hour. The differences between the IEC and IEEE are part of annex E and summarised in Table 2.14.

Table 2.7: IEC Compatibility levels for LV and MV networks [18].

1	2	3	4	5	6
Odd harmonics (non-multiples of 3)		Odd harmonics (multiples of 3)		Even harmonics	
Order	%	Order	%	Order	%
5	2,0	3	2,0	2	1,5
7	2,0	9	1,0	4	1,0
11	1,5	15	0,3	6	0,5
13	1,5	21	0,2	8	0,4
17	1,0	> 21	0,2	10	0,4
19	1,0			12	0,2
23	0,7			> 12	0,2
25	0,7				
> 25	0,2 + 0,5 x 25/h				
Planning level for total harmonic distortion at HV and EHV = 3 %.					

Table 2.8: IEC planning levels for MV networks [18].

1	2	3	4	5	6
Odd harmonics (non-multiples of 3)		Odd harmonics (multiples of 3)		Even harmonics	
Order	%	Order	%	Order	%
5	6,0	3	5,0	2	2,0
7	5,0	9	1,5	4	1,0
11	3,5	15	0,3	6	0,5
13	3,0	21	0,2	8	0,5
17	2,0	> 21	0,2	10	0,5
19	1,5			12	0,2
23	1,5			> 12	0,2
25	1,5				
> 25	1,3 + 0,5 x 25/h				
Compatibility level for total harmonic distortion (THD) = 8 %.					

Table 2.9: IEC Planning levels for HV and EHV networks [18].

1	2	3	4	5	6
Odd harmonics (non-multiples of 3)		Odd harmonics (multiples of 3)		Even harmonics	
Order	%	Order	%	Order	%
5	5,0	3	4,0	2	1,6
7	4,0	9	1,2	4	1,0
11	3,0	15	0,3	6	0,5
13	2,5	21	0,2	8	0,4
17	1,6	> 21	0,2	10	0,4
19	1,2			12	0,2
23	1,2			> 12	0,2
25	0,2				
> 25	0,2 + 0,5 x 25/h				
Planning level for total harmonic distortion at MV = 6,5 %.					

Table 2.10: IEEE voltage distortion [18].

1	2	3
Bus voltage at PCC kV	Individual voltage distortion %	Total harmonic distortion (THD) %
≤ 69	3,0	5,0
$> 69 \leq 161$	1,5	2,5
> 161	1,0	1,5

Table 2.11: IEEE current distortion limits for low voltages (120 V – 69 kV) [18].

1	2	3	4	5	6	7
Maximum harmonic current distortion as a percentage of I_L Odd harmonics (even harmonics limited to 25 % of those below)						
I_{SC}/I_L	< 11	11 to < 17	17 to < 23	23 to < 35	> 35	TDD
< 20	4,0	2,0	1,5	0,6	0,3	5,0
20 < 50	7,0	3,5	2,5	1,0	0,5	8,0
50 < 100	10,0	4,5	4,0	1,5	0,7	12,0
100 < 1000	12,0	5,5	5,0	2,0	1,0	15,0
> 1000	15,0	7,0	6,0	2,5	1,4	20,0
where						
I_{SC} is the maximum short circuit current at PCC;						
I_L is the maximum demand (MD) load current at PCC (averaged MD over 12 months).						

Table 2.12: IEEE current distortion limits for medium voltages (> 69 kV – 161 kV) [18].

1	2	3	4	5	6	7
Maximum harmonic current distortion as a percentage of I_L Odd harmonics (even harmonics limited to 25 % of those below)						
I_{SC}/I_L	< 11	11 to < 17	17 to < 23	23 to < 35	> 35	TDD
< 20	2,0	1,0	0,75	0,3	0,15	2,5
20 < 50	3,5	1,75	1,25	0,5	0,25	4,0
50 < 100	5,0	2,25	2,0	0,75	0,35	6,0
100 < 1000	6,0	2,75	2,5	1,0	0,5	7,5
> 1000	7,5	3,5	3,0	1,25	0,7	10,0
where						
I_{SC} is the maximum short circuit current at PCC;						
I_L is the maximum demand (MD) load current at PCC (averaged MD over 12 months).						

Table 2.13: IEEE current distortion limits for high voltages (> 161 kV) [18].

1	2	3	4	5	6	7
Maximum harmonic current distortion as a percentage of I_L						
Odd harmonics (even harmonics limited to 25 % of those below)						
I_{sc}/I_L	< 11	11 to < 17	17 to < 23	23 to < 35	> 35	TDD
< 50	2,0	1,0	0,75	0,30	0,15	2,50
> 50	3,0	1,5	1,15	0,45	0,22	3,75
where						
I_{sc} is the maximum short circuit current at PCC;						
I_L is the maximum demand (MD) load current at PCC (averaged MD over 12 months).						

Table 2.14: Comparison between IEC and IEEE standards [18].

IEC & IEEE Comparison
COMMON
Readings at PCC
Current Emission Level
Worst case network impedance
No guarantee for compatibility
DIFFERENCE
Harmonic percentage levels
IEC Planning levels
IEC Staged approach
IEEE linear impedances vs. IEC actual impedances
IEC actual upstream distortion
IEC installed capacity vs. IEEE short circuit ration

In annex F, the NRS explains a method for assessing contractual EL based on the IEC procedures [18]. None of the loads connected to the network have a significant impact on voltage distortion levels. This methodology proposes a structured stage approach to calculate EL. A consumer load can be classified according to different stages. Table 2.15 illustrates the various stages. This approach is adapted by the NRS to quantify EL.

Table 2.15: Consumer categorising for emission level stages [18].

1	2	3	4	5
Stage	PCC voltage	Load maximum demand	Load maximum demand as a percentage of minimum designed operating three-phase PCC fault level	Method of acceptance
1	< 132 kV	< 25 MVA**	< 1 %	Accept
2	< 132 kV	< 25 MVA**	> 1 %	Apportion
3	≥ 132 kV	≥ 25 MVA	–	Special analysis
NOTE Care should be taken where capacitors or underground cables are involved.				

2.7 HARMONIC BENCHMARKING

PQ data is generated all over an electrical network and requires benchmarking methodology to translate the data as obtained from the PQ recorders into system performance information. A specific PQ recorder records data at a single PoD in a network. It is possible to use NRS 048 to assess compliancy to minimum standards of this specific PoD. It could, to some extent, be said that “benchmarking” of a single site can be done and general agreement will be possible as NRS 048 is widely used in South Africa.

The concept of PQ benchmarking on a system scale, however, has other goals such as to understand how the power system as a whole is performing against the NRS 048. The user requirements on PQ benchmarking will depend on the role that the user has in the electrical energy industry. The benchmarking methodology requires, amongst others, statistical analysis which can be used to generate information regardless of voltage and power level.

Various international examples on previous PQ benchmarking projects exist. EPRI is a prominent role-player in this field and has contributed much in this field. The purpose of the EPRI’s benchmarking indices (BI) was to [3]:

“Define an extensive set of service performance indices which assess all areas of power quality based on monitoring data and to provide the methodology and software tools necessary for calculating these indices”.

Most utilities have a huge amount of monitored data available and this has to be transformed into informative data. As mentioned, the South African electrical network infrastructure is relatively old, whilst loading is growing in level and sophistication. It is important to have knowledge on system performance, since maintenance and budget planning have to set priorities to specific areas or part of the network. PQ benchmarking in this dissertation deals with one parameter only, namely voltage waveform distortion. Non-linear loading of a network is expected to comply with the process of energy saving and increased efficiency. Development and implementation of a benchmarking methodology can be very beneficial.

SEGMENTATION

In order to conduct an accurate benchmarking study, the system that is being assessed must be divided into segments. BI are calculated by averaging across the segment of the total network being assessed. The smaller the circuit segments, the more accurate the indices will be. It is preferable that the circuit segment voltage is constant. For this project, there will be limited circuit data available due to the large system that must be assessed. To compensate for this, load estimations will be used. Each

segment must inherit a PQ monitor, thus the number of segments are determined by the amount of monitors present. Figure 2.27 shows an example of circuit segmentation used during EPRI's project [3]. Here it is notable that segment 3 has two PQ monitors, while segment 2 has none. The problem is that a power quality state estimator (PQSE) must be implemented to estimate the PQ status for that segment. Incorrect estimations may cause PQ indices to be less accurate [3]. The best practice is to establish network segments with at least one PQ monitor per segment. Segments are not of the same size and for this reason benchmarking indices have to be normalised by a factor representing the size of a specific segment. A weight factor is used to normalise the calculated indices for that segment. A typical weighing factor will use either the number of customers served or the connected apparent load (kVA).

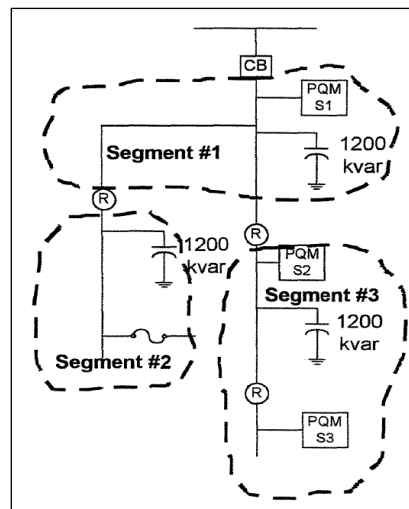


Figure 2.34: Example of network segmentation [3].

HARMONIC INDICES

Distribution systems are voltage regulated, thus voltage indices are of prime concern to assess the network circuits. Harmonic current indices are more applicable to single point measurements at the PoD. Voltage distortion indices are also affected by the size of the system that is being assessed. The greater the size of the system, the easier it is for a segment of high distortion to become de-emphasised [3] and the more inaccurate the indices become. However, accuracy can be increased by the number of segments [3]. The minimum requirement for a segment is to have a PQ recorder in the segment. The more recorders, the smaller each segment can be, which in turn increases the accuracy of the calculated BI.

TOTAL HARMONIC DISTORTION

Total harmonic distortion (THD) is the ratio of RMS harmonic voltage (V_h) to that of the fundamental RMS value (V_1) and is based on a single point measurement [2], [3].

$$THD_V = \frac{\sqrt{\sum_{h=2}^{50} V_h^2}}{V_1} \quad (2.22)$$

For this particular formula the harmonic voltage is only calculated up to the 50th harmonic component. This index is designated as the primary indicator of harmonic distortion according to the IEEE STD 519-1992 [6]. Network voltage is relatively constant and does not fluctuate as much as network current [3]. BI are related to the characteristics of a statistical distribution of the voltage THD [3].

SYSTEM AVERAGE TOTAL HARMONIC DISTORTION (SATHD)

Before the system average THD index can be calculated, network segments must be clearly defined. This index represents the average VTHD of multiple segments, taken over a certain period. The result is normalised by the total apparent power load (kVA) of all the segments connected to the portion of the network that is being assessed. The formulas (2.23) and (2.24) are defined by EPRI as [2], [3]:

$$MEANTHD = \frac{\sum_{j=1}^N THD_j}{N} \quad (2.23)$$

$$SATHD = \frac{\sum_{s=1}^k L_s \times MEANTHD_s}{L_T} \quad (2.24)$$

N	Number of THD measurements collected for a segment over a period
s	Segment number
k	Total number of segments
L_s	kVA rating of the specific segment
L_T	Total amount of kVA connected
THD	Total harmonic distortion calculated for the segment
MEANTHD	Average THD values for a specific segment taken over a period of time
i	measurement number

This calculation reflects two important indices. SATHD is a unique normalised system index, average across all circuit segments. The MEANTHD is a statistical value for a number of individual VTHD taken over a time period. These parameters give a good representation with regards to distortion patterns within a system.

SYSTEM AVERAGE TOTAL HARMONIC DISTORTION – CP95 %

The cumulative probability (CP) holds much information regarding network harmonic distortions. The definition of CP is described in the histogram overview section. The index, CP95% represents the CP value obtained from the segment histogram that is created by the recorded VTHD readings. The CP95% values per segment are used to calculate the system average value (SATHD_CP95%). Each CP95% value is normalised by the weighing factor. Formulas (2.25) and (2.26) as described by EPRI were used to calculate this index [3].

$$\frac{\sum_{-\infty}^{SATHD95} f_t(CP95_s) \times L_s}{\sum_{-\infty}^{\infty} f_t(CP95_s) \times L_s} = 0.95 \quad (2.25)$$

$$\frac{\sum_{-\infty}^{CP95_s} f_s(x_i)}{\sum_{-\infty}^{\infty} f_s(x_i)} = 0.95 \quad (2.26)$$

S	Segment Number
x_i	THD measurements for the number i
L_s	Total connected kVA for segment s
f_s(x_i)	Distribution function
CP95	Cumulative probability representing the 95% value of the THD distribution
f_t(CP95_s)	Distribution function of THD CP95 values for segments

This index is important, because equipment damage caused by harmonics is caused over a long time period. Peak VTHD levels will only be present for a short duration and will not have a significant effect on consumer equipment. The peak distortion values do not indicate the true QoS levels to

consumers. This index eliminates 5% of the maximum VTHD levels measured. The IEEE STD 519 states that VTHD must not exceed the 4% limit per hour per day [3].

SYSTEM AVERAGE TOTAL HARMONIC DISTORTION – CP99%

As with the previous index, the CP at 99% provides much information regarding network harmonics. This index represents the maximum VTHD recordings. Equation (2.27) and (2.28) are used to calculate this index [3]. The CP99% excludes the top 1% of all measurements which eliminates any possible error in the recordings.

$$\frac{\sum_{-\infty}^{SATHD99} f_t(CP99_s) \times L_s}{\sum_{-\infty}^{\infty} f_t(CP99_s) \times L_s} = 0.99 \quad (2.27)$$

$$\frac{\sum_{-\infty}^{CP99_i} f_s(x_i)}{\sum_{-\infty}^{\infty} f_s(x_i)} = 0.99 \quad (2.28)$$

S	Segment Number
x_i	THD measurements for the number i
L_s	Total connected kVA for segment s
f_s(x_i)	Distribution function
CP99	Cumulative probability representing the 99% value for the VTHD distribution
f_t(CP99_s)	Distribution function of VTHD CP99% values for segments

SYSTEM AVERAGE EXCESSIVE TOTAL HARMONIC DISTORTION RATIO INDEX

This index is known to be a frequency occurrence index and is difficult to calculate with regards to harmonics. If you have a distribution of VTHD measurements, it is difficult to determine the true amount of time a value exceeds a certain threshold. With that in mind, a good approximation can be achieved by creating a ratio between VTHD samples that exceeds a threshold and the total VTHD recordings. The SATHD₁ measures the number of VTHD measurements that exceeds a certain

threshold. It is normalised by the amount of connected apparent power load (kVA), which is the weighing factor. Equation (2.29) represents this index [3].

$$SATHD_I = \frac{\sum_{s=1}^k L_s \times \left(\frac{N_{THD_s}}{N_{MW_s}} \right)}{L_T} \quad (2.29)$$

s	Segment Number
k	Total number of network segments being assessed
L_s	Connected kVA from a segment S
L_T	Total connected kVA being assessed
I	Measurement number
THD	VTHD is the specified threshold
N_{THDs}	VTHD value for a segment s
N_{MWs}	The Total VTHD values for all segments

This index provides statistical information on the time an assessed circuit exceeds distortion thresholds. Discrete sampling techniques make it impossible to accurately calculate the time a distortion value exceeded the threshold. The only way is to use the index mentioned above to calculate a relative number that exceeds the threshold.

HISTOGRAMS AND CUMULATIVE PROBABILITY

According to Webster's online dictionary, the definition of a histogram is [35]:

“A representation of a frequency distribution by means of rectangles whose widths represent class intervals and whose areas are proportional to the corresponding frequencies”

Histograms are used to make sense of large volumes of data by creating a visual representation of statistical data. Figure 2.28 shows an example of a histogram with a cumulative percentage curve. The cumulative probability (CP) is a statistical factor obtained from a histogram distribution, which specifies the probability that arbitrary measurements will be less than a threshold value [3]. Figure 2.28 shows the CP as the red line. It is calculated by adding each frequency per interval up to the

100% margin. The CP curve can be used to acquire the CP95% and CP99% values for that set of measured frequencies [36].

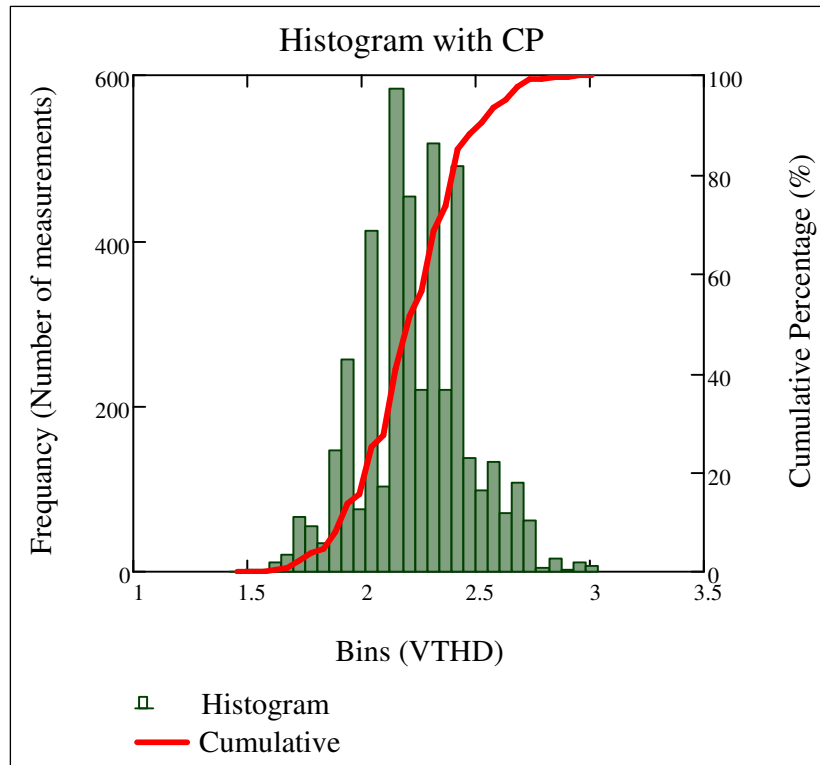


Figure 2.35: Example of cumulative probability curve with a histogram graph.

2.8 SUMMARY

This chapter explained all necessary technical aspects required to do a study on harmonic distortion. It identified harmonic sources, effects and mitigation techniques as it occurs in the industry today. The concept of compatibility and the applicable harmonic standards have also been discussed, to provide a better understanding, on how harmonic distortions are governed by different organisations. Benchmarking, Fourier and statistical theory were also explained and these will form the basis of the analysis done on a distribution network, as discussed in chapter 3.