TENAGA NASIONAL BERHAD

A GUIDEBOOK ON

MANAGING POWER SYSTEM HARMONICS

A GUIDEBOOK BY TENAGA NASIONAL BERHAD

ASSET MANAGEMENT DEPARTMENT
DISTRIBUTION DIVISION TNB

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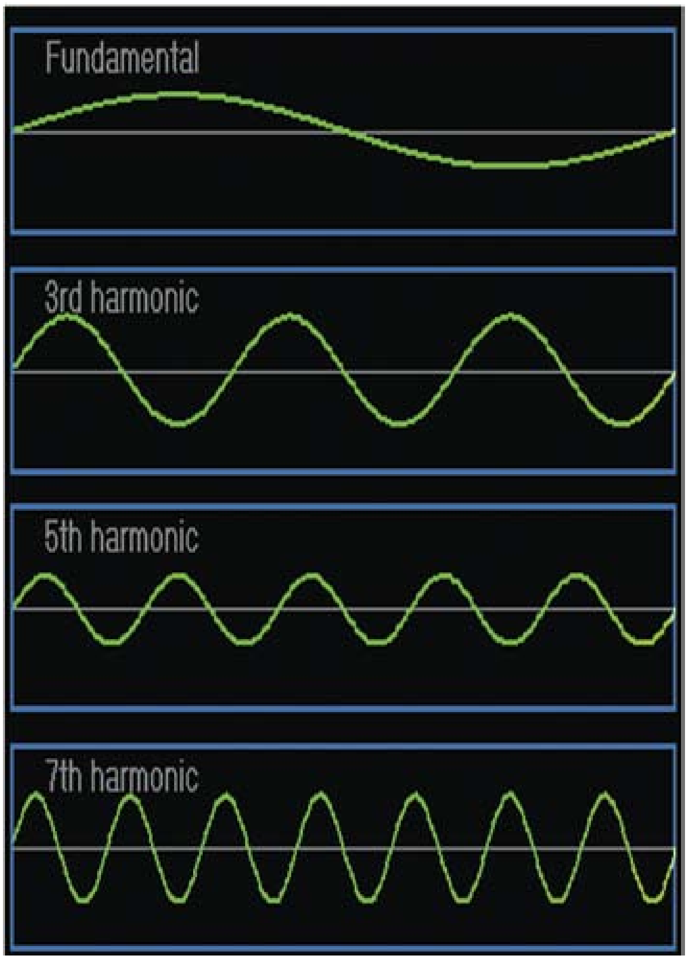

A guidebook by Tenaga Nasional Berhad

A GUIDEBOOK ON MANAGING POWER SYSTEM HARMONICS

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Date: 1st March 2012

FOREWORD BY CHAIRMAN OF ENERGY COMMISSION

I would like to congratulate TNB on its effort to produce this guidebook on power quality titled "A Guidebook on Managing Power System Harmonics".

This book comes at an opportune time as the impetus of growth for the nation is being focused on capital intensive industries and as such the demand for quality of supply is of importance. As such the focus has now shifted from addressing issues related to reliability in the late nineties to that of power quality.

The new economy with an array of other global pressures has increased the need for industries to remain competitive and as such the drive for automation. Technology brings with itself other manifested issues and among them is power quality.

The Government through the Ministry of International Trade and Industry (MITI) has set up a National Committee on Business Competitiveness to look at measures to be adopted and implemented for maintaining our competitive edge. As such, the effort taken by SIRIM and Department of Standards Malaysia (DSM) in coming up with the Malaysian Standards (MS) standards is definitely a step forward in achieving a more compatible power supply and equipment relationship, in line with similar efforts all over the world. We are proud to know that the committee had adopted several international standards to be the standards for power quality in Malaysia.

While power quality seems to be a concern for both the customer and the utility it requires an equal understanding of the issue from all industry players including consultants, equipment manufacturers, the government and the regulator. As such, TNB and the affected consumer need to co-operate and work hand in hand to find the most effective and economical solution to mitigate the problems. Whilst TNB is spending billions on system improvement, customers need to ensure all their equipment meet or exceed the MS IEC standards on Electromagnetic Compatibility (EMC).

Finally, I would like to congratulate TNB again for this effort and hope that this education process would be continuous.

Tan Sri Datuk Dr.Ahmad Tajuddin Ali
Chairman
Energy Commission

FOREWORD BY PRESIDENT/CEO OF TNB

First of all, congratulation, to the Asset Management Department (Distribution Division TNB) for taking the initiative in producing this guidebook called "A Guidebook on Managing Power System Harmonics".

At TNB, we care about the reliability, consistency, and quality of power supply more than ever. The reason is straightforward. People are using more and more sophisticated electronic controls in their business equipment, most of which are energy efficient but inject harmonic currents in the power system. These harmonic currents cause voltage distortions in the supply systems, which later lead to equipment maloperation.

Harmonics can cause serious damage to an electrical distribution because they increase the operating current and voltage on the system. Not only can motors and other components on the system be overloaded, the increase to the current and voltage also results in the generation of huge amounts of heat. Therefore, operating with a harmonic contaminated network quickly shortens the life expectancy of your electrical equipment and costs money.

It is well known that programmable logic controllers (PLCs), adjustable-speed drives (ASDs), energy efficient motors, Computer Numerical Control (CNC) machines, and other power electronic devices increase productivity, increase the quality of products, and are categorized as energy efficient devices. However, these devices cause harmonic distortion in the power systems. As a result of these harmonic emissions, the owners of industrial processes also experienced unexplained process interruptions and unplanned equipment shutdowns.

In this guidebook, overview of the harmonic induced problems together with recommended mitigating solutions are presened. This guidbook is recommended to be used by electrical engineers as a reference for understanding harmonics, related technical standards and in selecting suitable harmonics mitigating solutions.

We at TNB are always willing to provide information and support our customers in their efforts to improve the electromagnetic compatibility (EMC) of their installations.

Dato' Sri Che Khalib Mohd Noh
President/CEO
Tenaga Nasional Berhad

FOREWORD BY CHIEF OPERATING OFFICER OF TNB

Service reliability and quality of power have become growing concerns for many facility managers, especially with the increasing sensitivity of electronic equipment and their automated controls. There are several types of voltage fluctuations that can cause problems, including surges, spikes, voltage sags, voltage swells, harmonic distortion and momentary disruptions.

Harmonics can cause sensitive equipment to malfunction and other related problems, including overheating of transformers and wiring, nuisance breaker trips, and reduced power factor.

Only ten years ago, harmonics were not yet considered a real problem because their effects on distribution networks were generally minor. However, the massive introduction of power electronics in equipment has made the phenomenon far more serious in all sectors of economic activity.

In general, the best way to deal with harmonics problems is through prevention: choosing equipment and installation practices that minimize the level of harmonics in any one circuit or portion of a facility. Common solutions include fixing grounding on individual equipment or the facility as a whole, moving a few loads between branch circuits, or adding additional circuits to help isolate the sensitive equipment from what is causing the harmonic distortion. If the harmonic problems cannot be solved by these simple measures, there are two basic choices: to reinforce the distribution system to withstand the harmonics or to install mitigation devices (reactors, passive harmonic filters and active harmonic filters) to attenuate or remove the harmonics.

And it is good to know that in view of the rapidly attenuating effects of harmonics, a triple system of standards and regulations is currently being reviewed by SIRIM for standardization. The subcommittee on power quality in SIRIM has been aggressively reviewing many related standards on harmonics for standardization in the Malaysian Electricity Supply Industries (MESI).

Lastly, I am glad to say that TNB has successfully document all the necessary technical information on harmonics, the relevant technical standards and practical solutions in this power quality guidebook. This guidebook is a must have guidebook for all electrical engineers – TNB and customers.

Dato' Azman Mohd
Chief Operating Officer
Tenaga Nasional Berhad

FOREWORD BY VICE PRESIDENT (DISTRIBUTION DIVISION OF TNB)

Harmonics have been made out to be mystical problems leaving most people convinced they will never understand what they are, what they can do to electrical systems, why they occur, and how to conquer them. We in TNB want to change that.

Harmonic distortion causes system resonance that can damage sensitive equipment and disturb sensitive processes. Such a power quality variation invariably has major impact in terms of production losses on many modern manufacturing industries and businesses that are equipped with sophisticated microprocessor-based technologies.

Harmonic is normally associated with the customers' operations. Harmonic injections due to non-linear loads are becoming more and more rampant due to the proliferation of energy efficient controller and equipment. Currently, there are many complaints on nuisance tripping due to unknown events. After power quality measurement was performed, some of the causes of these disturbances were verified to be due to harmonics. Harmonics are steady state power quality disturbances that cause high voltage problems which can damage equipment insulation. If the non-linear load on an electrical system exceeds 20% of the total load, customers are likely to suffer from a harmonic contaminated network.

In Malaysia, TNB has started to implement new electricity supply application guidelines that stresses on power quality requirement. These guidelines highlight the requirement to manage power quality during the supply application processes. All the standards on power quality including harmonics are explained in the Electricity Supply Application Handbook (ESAH).

This power quality guidebook is intended to provide useful illustrations to customers and electrical engineers on many possible solutions towards managing harmonic emissions. Minimizing the emission of harmonics will go a long way in ensuring electromagnetic compatibility of customer's equipment. Such investments on mitigating solutions can indeed minimize costly equipment mal-operations and disruptions to manufacturing and business processes.

Datuk Ir. Baharin Din
Vice President (Distribution)
Tenaga Nasional Berhad

CHAPTER 1

OVERVIEW ON POWER QUALITY

1.0 INTRODUCTION

As factory automation continues to evolve with the movement of data centers from computer rooms to the factory floor, the importance of power quality (PQ) has escalated. The inclusion of more sensitive electronic equipment in industrial processes demands the delivery of clean and stable power. Even the smallest service or process interruption can have a devastating effect on the efficiency and productivity of a company. The most obvious signs of a PQ problem include flickering lights, damaged equipment or a complete loss of power. Shorter than expected life span of equipment or unexplained shutdowns can also be a result of PQ problems. In some cases, such problems are caused by improper wiring and grounding practices. PQ problems may also be caused by natural disruptions such as lightning strikes, operations of large nonlinear loads such as arc furnaces and large rotating motor loads. The types of PQ problems frequently experienced by customers are voltage sags and harmonics while the less frequent ones include transient, flicker and noise.

1.1 POWER QUALITY DEFINITIONS

As any other product, electric power can also be characterized by the term quality. Customers generally grade the quality for the electrical power based on the effects of problems associated with the electric power supply. The more equipment outages, erratic behaviour or damage, the worse is the level of power quality (PQ). While PQ is a convenient term for many, it is the quality of the voltage rather than power or electric current that is actually described by the term. Power is simply the flow of energy and the current demanded by a load is largely uncontrollable. The Institution of Electrical, Electronic Engineers (IEEE) defines PQ as "the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment" [1] & Dugan et al. [2] defines PQ as "any electrical power problem manifested in voltage and current to frequency deviations that result in failure or misoperation of customer equipment".

The main concern on PQ is due to today's electronic loads susceptibility to short duration voltage disturbances such as voltage sags and other PQ disturbances that historically were not a cause for concern. In other words, today's equipment is no longer compatible with the existing electrical power supply environment or better known as the electromagnetic environment [3].

1.2 CLASSIFICATION OF POWER QUALITY DISTURBANCES

Power quality or electromagnetic disturbance is defined as any electromagnetic phenomenon which, by being present in the electromagnetic environment can cause electrical equipment to depart from its intended performance. Electromagnetic phenomena are low-frequency conducted disturbances in the frequency range from 0 kHz to 9 kHz voltage deviations. An electromagnetic disturbance may be an electromagnetic noise, an unwanted signal or an immediate change in the propagation medium. Table 1.1 describes the IEEE categorization of electromagnetic disturbances used by the power quality community [4].

Table 1.1 Classification of Power Quality Disturbances (IEEE Std.1159 2009)

Category of disturbance	Typical spectral content	Typical duration	Typical voltage magnitude in per unit (pu)
Impulsive transients			
Nanosecond	5 nsec rise	< 50 nsec	
Microsecond	5 nsec rise	50 nsec – 1msec	
Millisecond	1µsec rise	> 1 msec	
Oscillatory transients			
Low frequency	< 5 kHz	0.3 – 50 msec	0 – 4pu
Medium frequency	5 – 500 kHz	20 µsec	0 – 4pu
High frequency	0.5 – 5 MHz	5 µsec	0 – 4pu

continue …

… continued

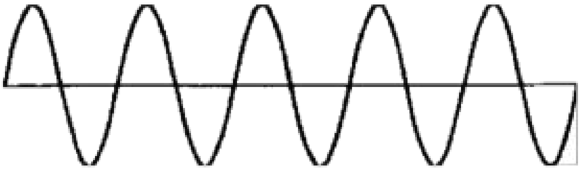
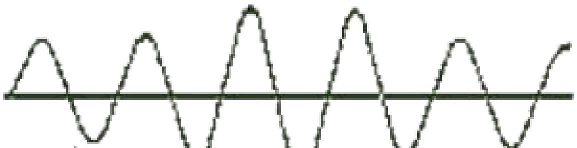
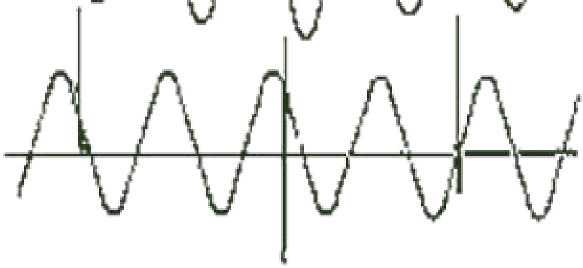
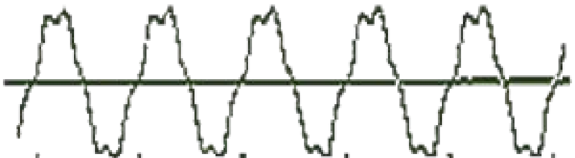
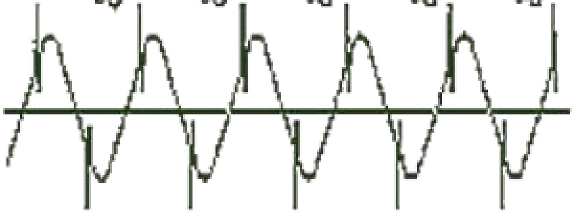
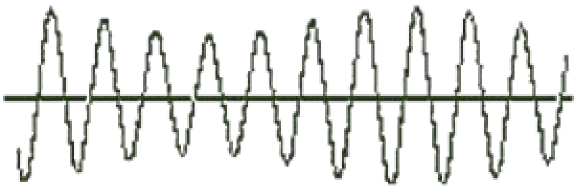
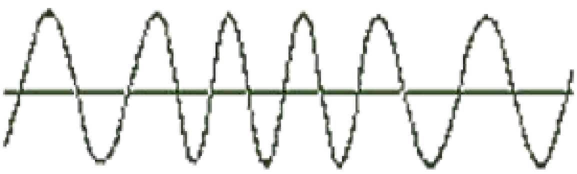
Short duration variations			
Instantaneous			
Interruption		0.5 – 30 cycles	< 0.1pu
Sag		0.5 – 30 cycles	0.1 – 0.9pu
Swell		0.5 – 30 cycles	1.1 – 1.8pu
Momentary			
Interruption		30 cycles – 3 sec	< 0.1pu
Sag		30 cycles – 3 sec	0.1 – 0.9pu
Swell		30 cycles – 3 sec	1.1 – 1.4pu
Temporary			
Interruption		3 sec – 1 min	< 0.1pu
Sag		3 sec – 1 min	0.1 – 0.9pu
Swell		3 sec – 1 min	1.1 – 1.2pu
Long duration variations			
Interruption sustained		> 1 min	< 0.1pu
Undervoltage		> 1 min	0.9 – 0.1pu
Overvoltage		> 1 min	>1.1pu
Voltage unbalance		Steady state	0.5 – 2 %
Waveform distortion			
DC offset		Steady state	0 – 0.1%
Harmonics	0 – 100th	Steady state	0 – 20 %
Inter-harmonics	harmonic	Steady state	0 – 2 %
Notching	0 – 6 kHz	Steady state	
Noise	Broadband	Steady state	0.1 %
Voltage fluctuation	< 25 Hz	Intermittent	0.1 – 7 %
Power frequency variation		< 10 sec	

Brief descriptions on the characteristics of the PQ disturbances listed in Table 1.1 are presented as follows:-

i. Transients also known as surges or spikes are caused by lightning, operation of appliances such as printers and copiers, as well as utility circuit breaker switching. Transients of sufficient energy can upset computers, corrupt data, or even cause damage to power supplies and components. Transients are further categorized as impulsive and oscillatory transients.
ii. Voltage sag is a brief drop in voltage and is caused by motor starting, heaters in printers and copiers cycling, as well as short circuits in power systems. Sags often cause lights to dim or flicker and computer equipment to lock up or lose memory.
iii. Voltage swell is a brief increase in the normal voltage level. Most swells are caused by stopping of a motor. Although not generally a problem, swells have been known to cause failure of marginal components in electronic equipment.
iv. Overvoltage and undervoltage are longer term increases or decreases in the normal voltage, respectively. These disturbances often indicate an overloaded transformer or circuit, or the misoperation of a voltage regulating device.
v. Momentary outage is a type of power outage generally caused by utility protective equipment operation when trees, animals, vehicles, lightning or others contact the utility wires or striking the utility pole.
vi. Harmonics are a regular distortion of the voltage waveform often caused by the power supplies of electronic equipment. Harmonics can cause overheating in transformers, building wiring, and motors.
vii. Noise due to electromagnetic interference (EMI) is electrical interference caused by electric and magnetic fields emanating from electrical equipment, typically transformers or wiring. One impact often seen is a wavy computer screen.
viii. Noise due to radio frequency interference is electrical interference from equipment that radiates high frequency electrical energy such as TV/radio transmitters and cell phones. Interference can also be caused by arcing sources or switching power supplies such as those found in electronic ballasts and adjustable speed drives. This kind of noise often causes interference to control circuits.

Table 1.2 shows the common voltage waveforms for the respective power quality disturbances.

Table 1.2 Common power quality disturbance waveforms

Waveforms	Types of PQ disturbances
	Normal voltage waveform
	Momentary Interruptions
	Voltage Dips / Sags
	Voltage Swells
	Voltage Transients
	Harmonic Distortion
	Notches
	Voltage fluctuations
	Frequency Deviations

CHAPTER 2

POWER SYSTEM HARMONICS

2.0 UNDERSTANDING HARMONICS

All power electric utilities in the world generate, transmit and distribute perfect sinusoidal voltages at fairly constant magnitudes and frequencies (50 or 60 Hz) throughout their systems. These tasks however get more complicated by the fact that there are connected loads on the systems that produce harmonic currents. These harmonic currents result in distorted voltages and currents that can adversely impact the system performance in different ways. Figure 2.1 shows the difference between perfect sinusoidal fundamental (50 or 60 Hz) & distorted waveforms. In Malaysia, the fundamental system frequency is 50 Hz. The distorted waveform is the resultant waveform when the sinusoidal waveform adds with the harmonic waveform. As the number of harmonic producing loads increased over the years, it has become increasingly necessary to address their impacts when making any additions or changes to the power systems.

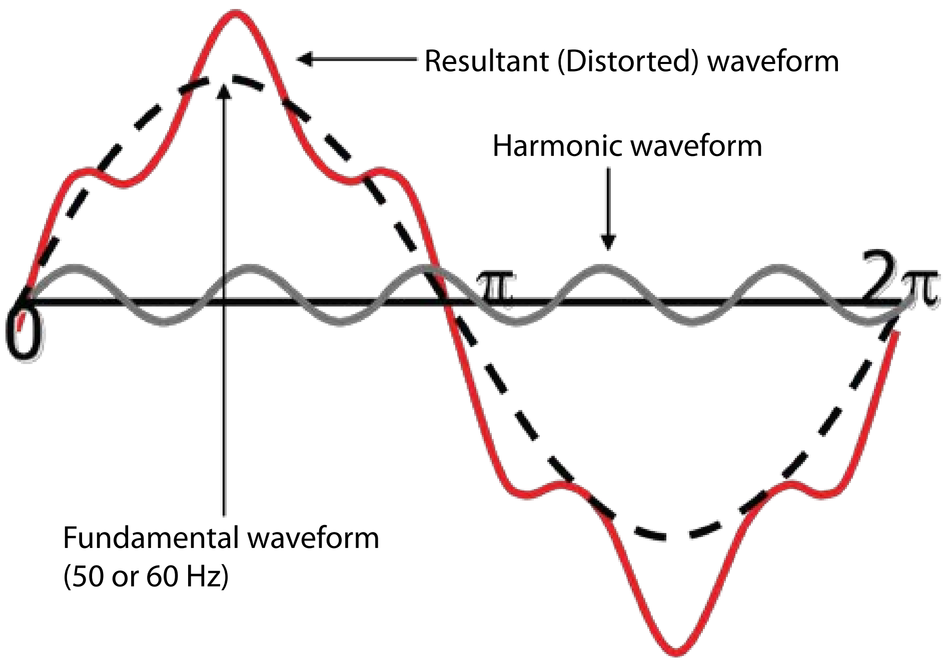


Fig.2.1 Comparison between sinusoidal & distorted waveforms

Power systems are able to absorb a considerable amount of current distortion without problems and the distortions produced by a facility may be below levels recommended in IEEE 519[5]. However, the collective effect of many industrial customers, taken together, may impact a power delivery system. When problems arise, they are usually associated with resonant conditions and other problems.

In general harmonic currents can produce a number of problems, namely:

- Equipment heating
- Equipment malfunction
- Equipment failure
- Communications interference
- Fuse and miniature circuit breaker maloperate
- Damage to power factor correction capacitor banks
- Conductor heating
- Etc.

2.1 DEFINITION OF HARMONICS

Harmonics are defined as voltages or currents at frequencies that are multiples of the fundamental frequency. In most power systems, the fundamental frequency is either 50 Hz or 60 Hz. In Malaysia, the system frequency is 50 Hz. Examples of harmonic frequencies in a 50 Hz system are the 3rd harmonic (150 Hz), 5th harmonic (250 Hz) and 7th harmonic (350 Hz). Figure 2.2 illustrates the comparison between the fundamental waveform (50 Hz), a 70% 3rd harmonic (150 Hz) and 50 % 5th harmonic (250 Hz) voltage waveforms. In one full cycle for the fundamental waveform, the 3rd harmonic waveform completed 3 full cycles with respect to the fundamental waveform. The 5th harmonic waveform completed 5 full cycles with respect to the fundamental waveform.

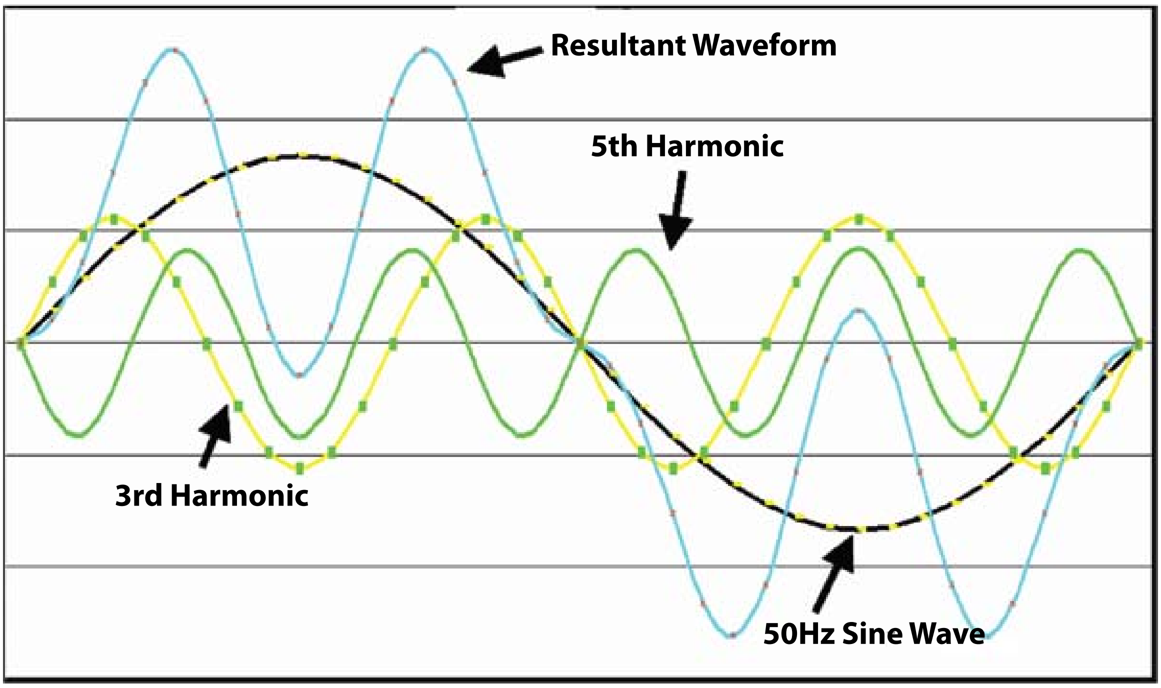


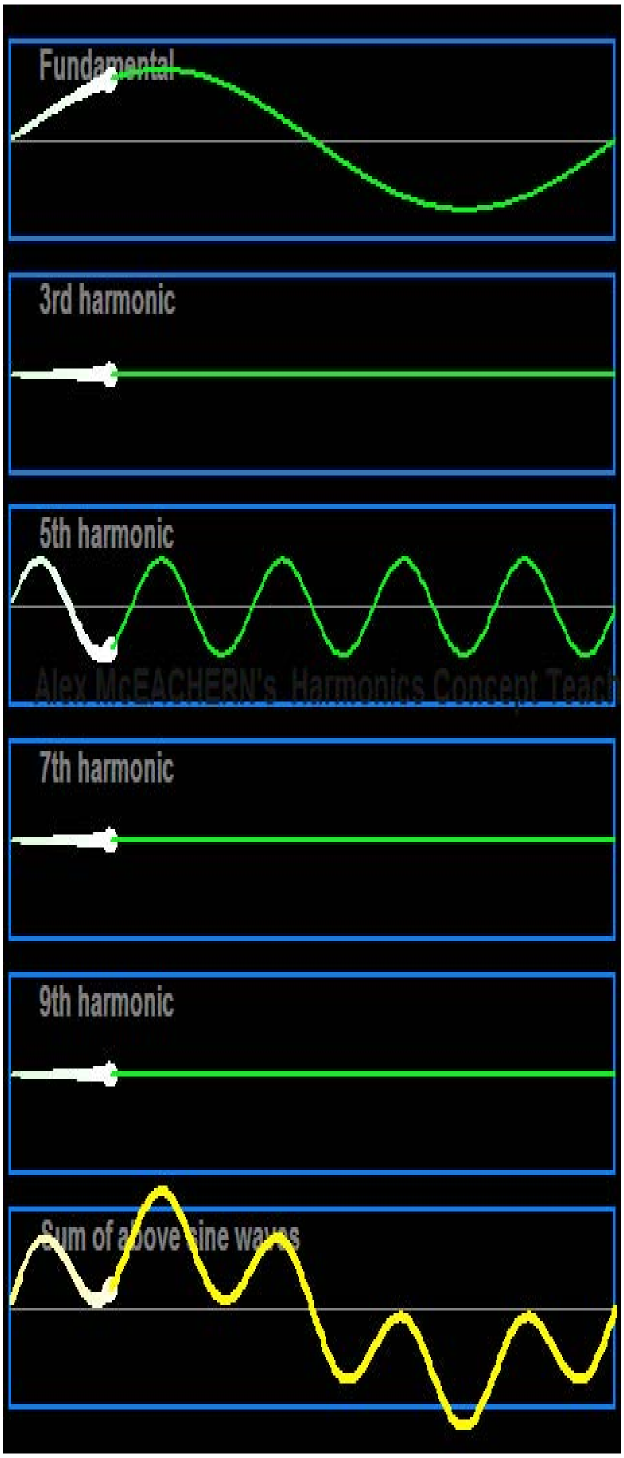
Fig 2.2 Fundamental (50 Hz), 3rd harmonic, 5th harmonic & resultant waveforms

Fundamental waveform: 50 Hz (1 complete cycle)

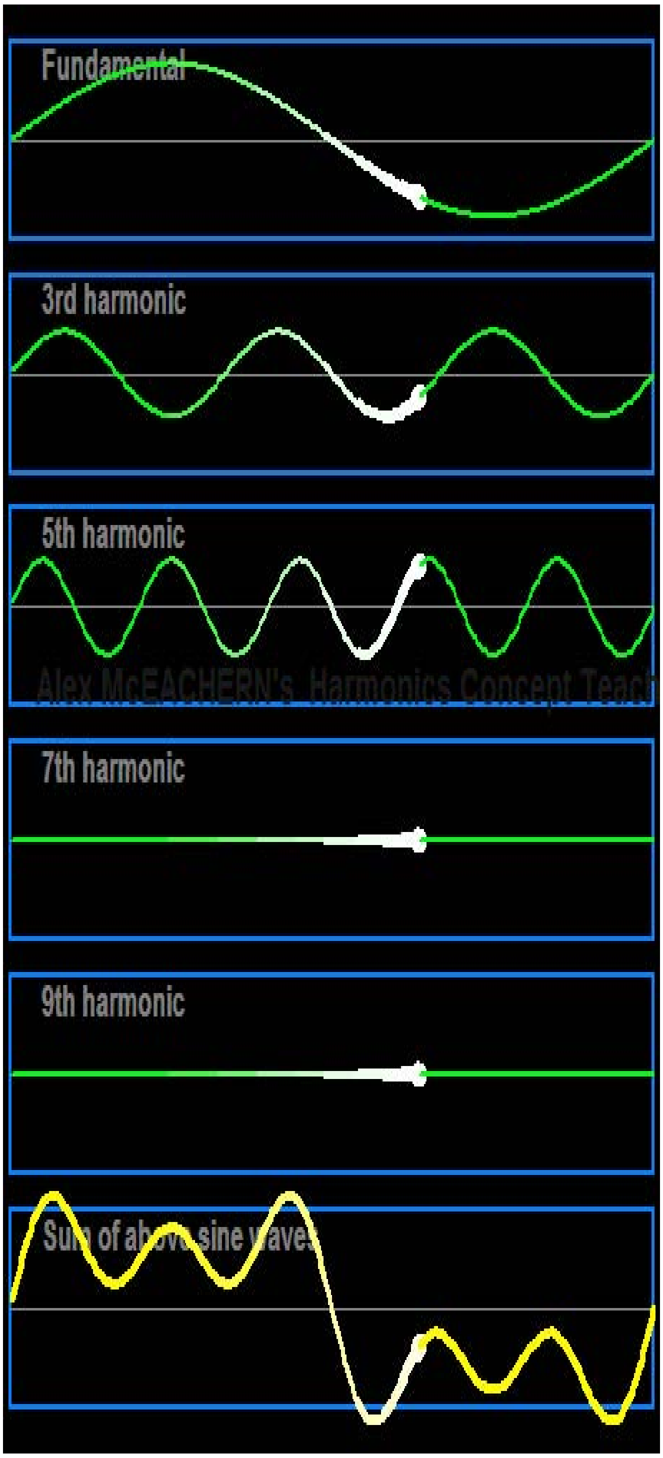
3rd harmonic waveform : 3 x 50 Hz (3 full cycles with respect to the fundamental)

5th harmonic waveform : 5 x 50 Hz (5 full cycles with respect to the fundamental)

All these harmonic waveforms will mathematically add up with the fundamental waveform and produce a resultant distorted waveform. Another example of a distorted waveform is shown in Figure 2.3. In Figure 2.3 (a), the 5th harmonic waveform is added to the fundamental waveform and resulted in the distorted waveform. In Figure 2.3 (b), the 3rd and 5th harmonic waveforms are added to the fundamental waveform and resulted in the distorted waveform. Readers can also easily visualize the resultant waveforms by downloading the Power Quality Teaching Toy from the Power Standards Lab web page [6]. The software was developed by Mr.Alex McEachern from Power Standard Labs USA.



a) Distorted waveform is the resultant of the fundamental and 5th harmonic waveforms.



b) Distorted waveform is the resultant of the fundamental, 3rd and 5th harmonic waveforms

Fig 2.3 Examples of simulated distorted waveforms from the PQ Teaching Toy

It is also important to note that the summated harmonics in Figure 2.3 gave a waveform with many zero crossings. The resultant distorted waveform is segregated from the other waveforms and shown in Figure 2.4.

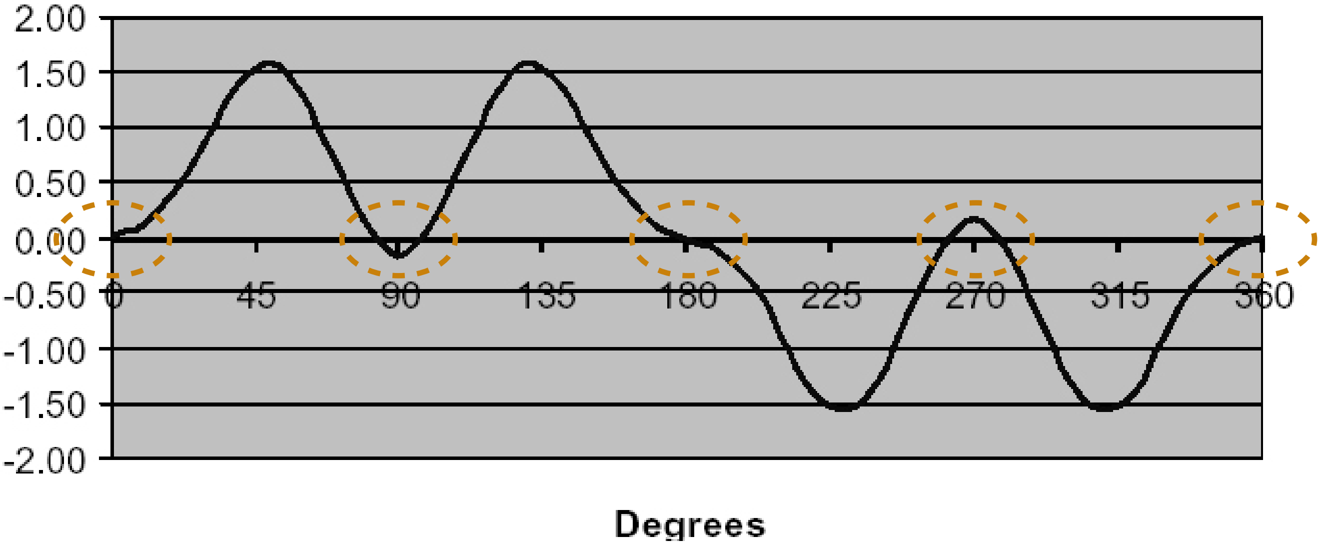


Fig 2.4 Distorted waveform with many zero crossings

These multiple zero crossings might cause problem for equipment that operationally is dependent on the zero crossing of the fundamental voltage waveform. These zero crossings can cause equipment, such as sensitive computer controls or digital clocks, to malfunction.

2.2 HARMONICS SEQUENCES

A harmonic's phase relationship to the fundamental is known as its harmonic sequence. Harmonic sequence can be positive, negative, or zero. Positive sequence harmonics have the same phase rotation as the fundamental voltage (50 or 60 Hz). Negative sequence harmonics have phase rotation opposite to that of the fundamental voltage. Zero sequence harmonics do not rotate relative to the fundamental voltage. Zero sequence harmonics are also termed as triplen harmonics.

2.2.1 EVEN NUMBERED HARMONICS

For 50 Hz power systems with nonlinear loads, even harmonics (2^{nd}, 4^{th}, 6^{th}, etc) have been found to be considerably less likely to be occur at levels detrimental to the electrical systems. This is because most nonlinear loads generate odd-numbered harmonics, which are associated with a current wave shape that is a distortion of the normal 50 Hz positive and negative half cycles.

2.2.2 ODD NUMBERED HARMONICS

Table 2.1 shows the odd multiples of the fundamental 50 Hz current and their associated sequence (positive, negative and zero).

Table 2.1 Harmonic sequence

Harmonic	Frequency	Sequence
1	50	Positive
3	150	Zero
5	250	Negative
7	350	Positive
9	450	Zero
11	550	Negative
13	650	Positive
15	750	Negative
17	850	Zero
19	950	Positive

2.2.2.1 POSITIVE SEQUENCE HARMONICS

The 1st, 7th, 13th, 19th etc. positive sequence harmonics consist of three phasors, each equal in magnitude, separated from each other by 120° phase displacement and having the same phase sequences as phasor representing the normal 50 Hz current.

2.2.2.2 NEGATIVE SEQUENCE HARMONICS

The 5th, 11th, 17th etc. negative sequence harmonics also consist of three phasors, each equal in magnitude, separated from each other by a 120° phase displacement, however, they have a phase sequence opposite to phasors representing the normal 50 Hz current.

2.2.2.3 ZERO SEQUENCE HARMONICS

Zero sequence harmonics consist of three phasors equal in magnitude and having a zero phase displacement from each other. Therefore, these phasors are concurrent in direction, producing amplitudes that are triples of any other phasor when they combine on the neutral of an electrical system. These harmonics (3^{th}, 9^{th}, 15^{th} etc.) are called triplen harmonics and are typical ones generated by phase-neutral nonlinear loads such as computers, electronic ballast, etc.).

2.2.3 EFFECTS OF HARMONICS ON ELECTRICAL LOADS

The phase sequences of these harmonics are very important because they determine the effect of the harmonics on the operation of the electrical equipment. In general the effects of the respective harmonic sequences are shown in Table 2.2. Positive sequence harmonics from phase-to-phase nonlinear loads will cause a three-phase motors (either induction or synchronous) to turn in the forward direction while the negative sequence harmonics will try to force motors to turn in the reverse direction. The details on effects of harmonics will be presented in Chapter 3.

Table 2.2 Effect of harmonic sequences

Sequence	Direction of rotation	Effects
+	Forward	Heating
-	Backward	Heating & Problem for motor
0	Insignificant	Heating of neutral conductor, accumulation in neutral conductor

We can easily visualize the harmonic sequences and the resultant vector sum by downloading the Power Quality Teaching Toy from the Power Standards Lab web page [6]. The graphical representations of the harmonic sequences are shown in Figure 2.5.

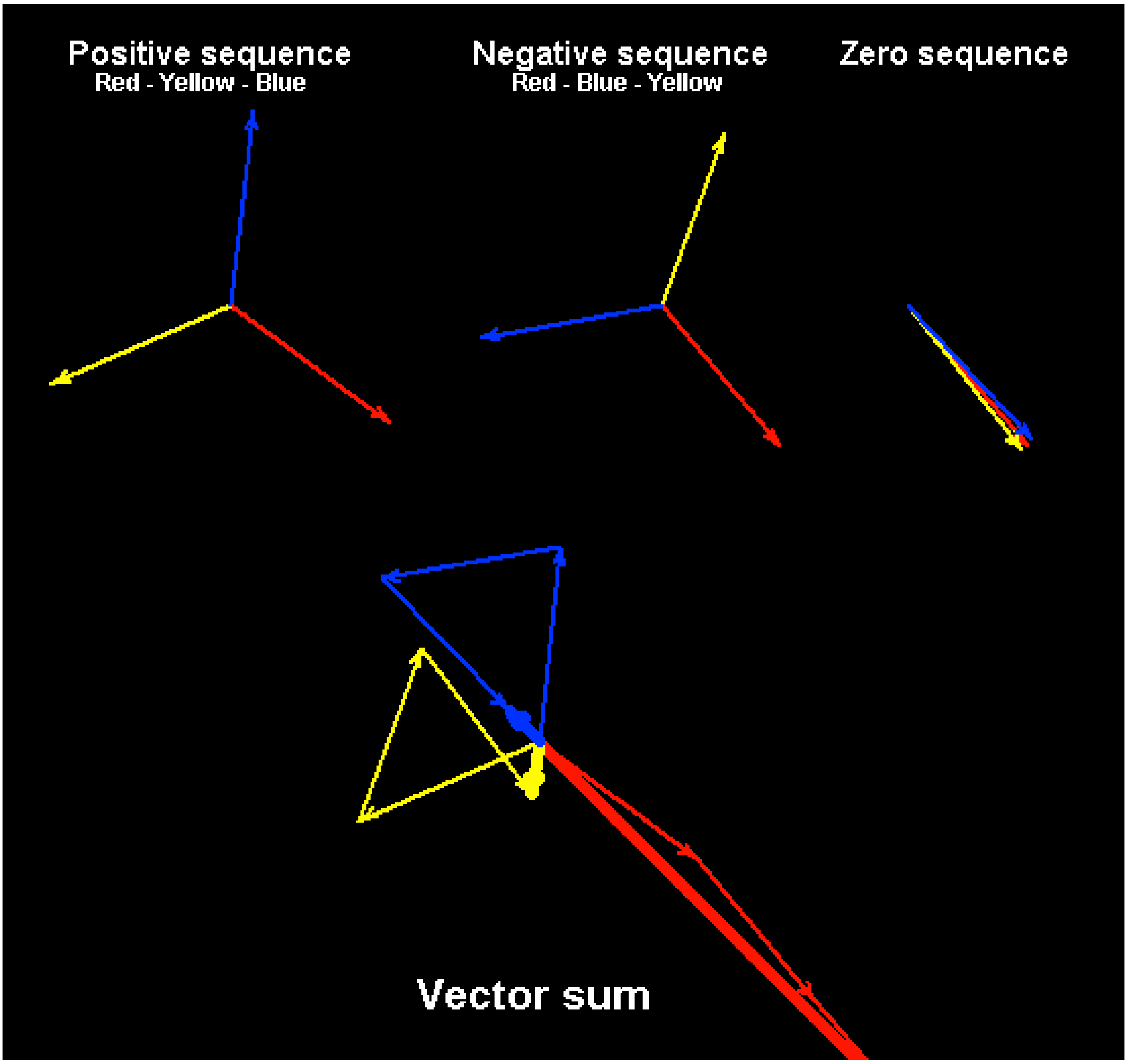


Fig.2.5 Harmonic sequences from PQ Teaching Toy

2.3 ORIGINS OF HARMONIC DISTORTION

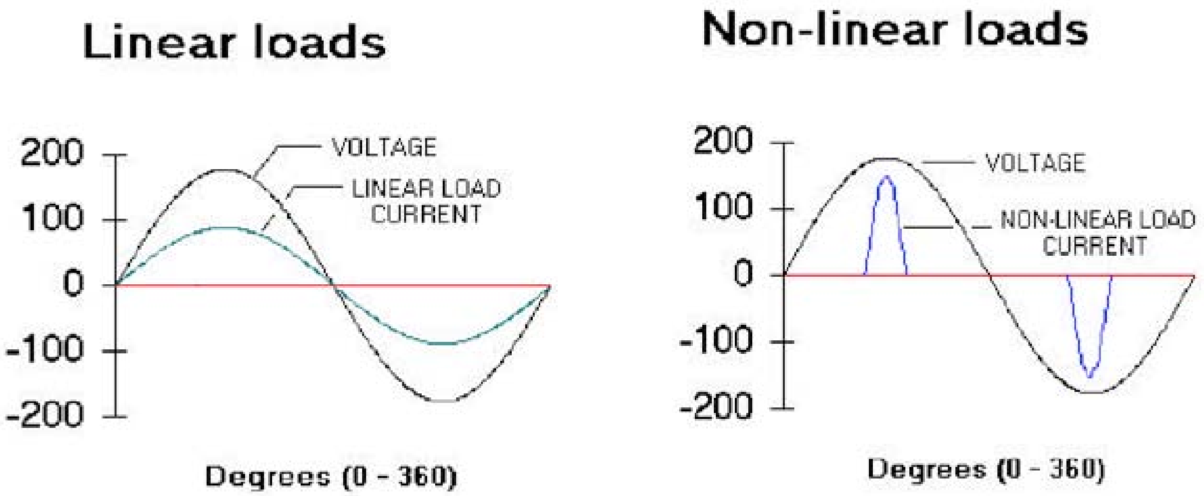
To fully appreciate the impact of harmonics, there are two important concepts to bear in mind with regards to power system harmonics. The first is the nature of harmonic-current producing loads (non-linear loads) and the second is the way in which harmonic currents penetrate the power systems and caused distorted voltages in the systems. The current harmonics are of most concern because the harmonics originate as currents and most of the ill effects are due to these currents. When harmonic propagate around a distribution system, that is, to other branch circuits not concerned with carrying the harmonic currents, they do so as harmonic voltages.

In general, harmonics currents are created by the use of non-linear devices such as UPS (Uninterruptible Power System), solid state variable speed motor drives, rectifiers, welders, arc furnaces, fluorescent ballasts, and personal computers. Individual harmonic frequencies will vary in amplitudes and phase angles, depending on the harmonic sources. Variable speed drives are usually referred to by the number of rectifiers in the system. The most common are six (rectifiers) and twelve (rectifiers) pulse drives. Today, the most common sources of harmonics are power electronic loads such as adjustable-speed drives (ASDs) and switch-mode power supplies. These loads use diodes, silicon-controlled rectifiers (SCRs), power transistors, and other electronic switches that chop voltage waveforms to control the power consumption or to convert the AC voltage to DC voltage. In the case of ASDs, the DC is then converted to variable frequency AC to control the speed of the motor. Examples on application of ASDs include installations at chillers and compressor pumps. Due to the tremendous advantages in efficiency and controllability, power electronic loads are proliferating and can be found at all power levels – from low voltage appliances to high voltage converters. It is important to note that, although solid state devices, such as the thyristors have brought significant improvements in control designs and efficiency, they have the disadvantage of producing harmonic currents.

In summary, the harmonic sources can be grouped into three main areas:

- Power electronic equipment: Variable speed drives (ASD, 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 vapor, fluorescent) etc.
- 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.

2.3.1 COMPARISON BETWEEN LINEAR & NON LINEAR LOADS



a) Voltage and current waveforms for linear load

b) Voltage and current waveforms for non-linear load

Fig 2.6 Comparison between currents drawn by linear & non linear loads

A linear element in a power system is a component in which the current is proportional to the voltage. In general, this means that the current wave shape will be the same as the voltage (See Figure 2.6a). Typical examples of linear loads include motors, heaters and incandescent lamps. On the other hand, the current wave shape on a non-linear load is not the same as the voltage (See Figure 2.6b). Typical examples of non-linear loads are explained earlier in this section. The equivalent circuit of a non-linear load is shown in Figure 2.7. It can be modeled as a linear load in parallel with a number of current sources, one source for each harmonic frequency. In Figure 2.7, the models for harmonic current sources are shown for the 3rd, 5th and 7th harmonics.

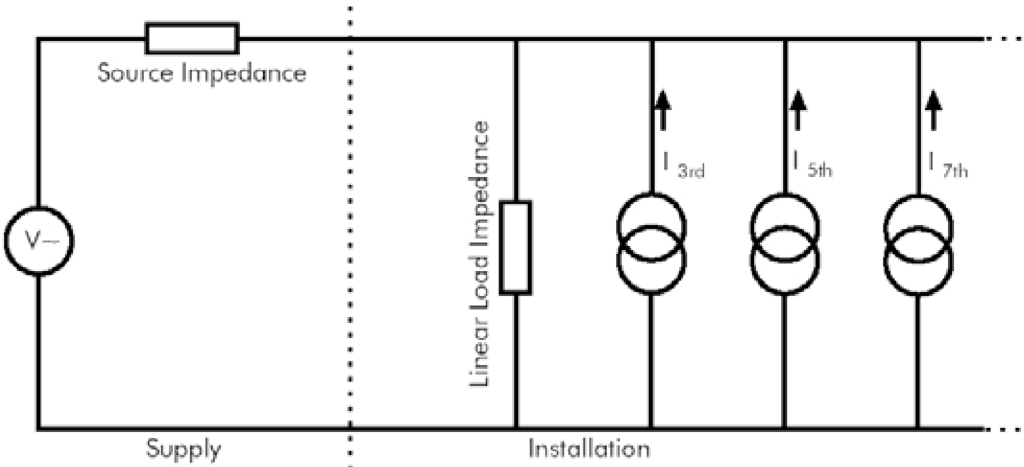
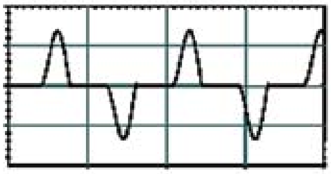
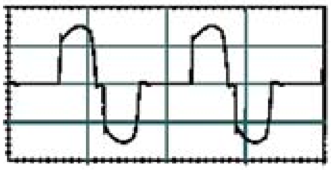
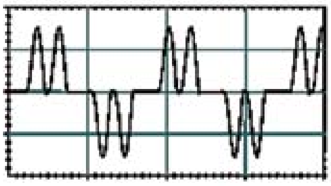
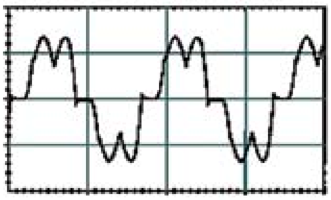
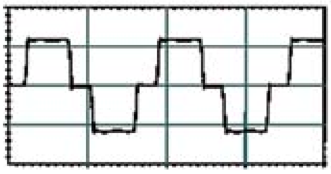
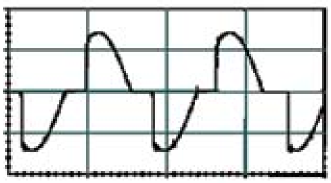
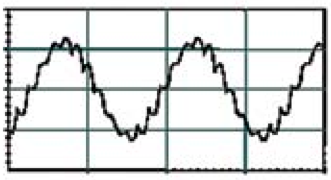


Fig.2.7 Equivalent circuit of a non-linear load

The current drawn by non-linear loads is not sinusoidal but it is periodic, meaning that the current wave looks the same from cycle to cycle. Periodic waveforms can be described mathematically as a series of sinusoidal waveforms that have been summed. These non-linear currents flow around the circuit via the source impedance and all other parallel paths. Examples of common non-linear current waveforms are shown in Table 2.3.

Table 2.3: Examples of harmonic sources and non-linear current waveforms

Typical equipment connected to LV, MV or HV	Typical current waveform
Single phase power supply (rectifier and smoothing capacitor)	
Semi-converter	
6-pulse converter, capacitive smoothing, no series inductance	
6-pulse converter, capacitive smoothing with series inductance > 3%, or d.c. drive	
6-pulse converter with large inductor for current smoothing	
AC voltage regulator	
12-pulse converter	

2.4 HARMONIC CURRENT FLOW

When a non-linear load draws current, the current passes through all of the impedance that is between the load and the system source (See Figure 2.8). When harmonic currents (I_h) flow through the impedances (Z) of the power supply system, they generate harmonic voltage drops which will distort the voltage supply as seen by other loads. As a result, harmonic voltages (V_h) appear across the supply impedance and are present throughout the installation.

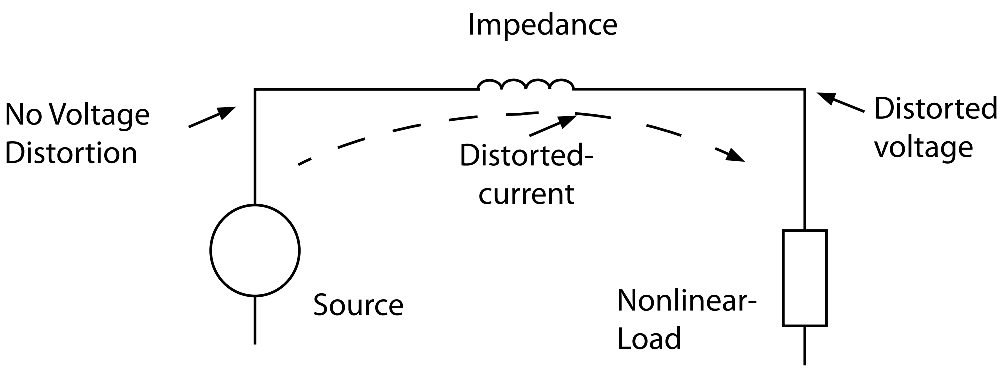


Fig.2.8 Distorted current induces voltage distortion

If the supply voltage, which now has a harmonic voltage component, is placed across a linear load, the linear load will draw a distorted current with the same level of harmonic distortion as the distorted voltage. Whenever harmonic voltages (V_h) are suspected, or when trying to verify their presence, the harmonic currents (I_h) must be measured using a power quality recorder (PQR). The use of a PQR will be presented later in this guidebook.

The harmonic voltages (V_h) when added to the nominal/fundamental (50/60Hz) voltage will produce the resultant voltage or true rms voltage. The magnitude of the true rms voltage depends on the source impedance (Z_s) and the harmonic voltages (V_h). If the source impedance (Z_s) is low then the voltage distortion will be low. If a significant portion of the load becomes non-linear (harmonic currents increase) and/or when a resonant condition prevails (system impedance increases), the distorted voltage can increase dramatically. These harmonic currents (I_h) can cause a voltage disturbance on the supply network and adversely affect the operation of other electrical equipment including power factor correction capacitors.

CHAPTER 3

GENERAL PROBLEMS CAUSED BY HARMONICS

3.0 OVERVIEW

Besides distorting the shape of the voltage and current sinusoids, what other effects do harmonics cause? Since harmonic voltages (V_h) produce harmonic currents (I_h) with frequencies considerably higher than the power system fundamental frequency (50/60 Hz), these currents encounter much higher impedances as they propagate through the power system than does the fundamental frequency current. This is due to "skin effect," which is the tendency for higher frequency currents to flow near the surface of the conductor. Since little of the high-frequency current penetrates far beneath the surface of the conductor, less cross-sectional area is used by the current. As the effective cross section of the conductor is reduced, the effective resistance of the conductor is increased.

This is expressed in the following equation:

$$R - p\frac{L}{A} \quad (3.1)$$

where R is the resistance of the conductor, ρ is the resistivity of the conductor material, L is the length of the conductor, and A is the cross-sectional area of the conductor. The higher resistance encountered by the harmonic currents will produce a significant heating of the conductor, since heat produced or power lost in a conductor is I^2R, where I is the current flowing through the conductor.

This increased heating effect is often noticed in two particular parts of the power system: neutral conductors and transformer windings. Harmonics with orders that are odd multiples of the number three (3rd, 9th, 15th, and so on) are particularly troublesome, since they behave like zero sequence currents. These harmonics, called triplen harmonics, are additive due to their zero sequence like behavior. They flow in the system neutral and circulate in delta-connected transformer windings, generating excessive conductor heating in their wake. The distorted load current drawn by the non-linear load causes a distorted voltage drop in the cable impedance. The resultant distorted voltage waveform is applied to all other loads connected to the same circuit, causing harmonic currents to flow in them - even if they are linear loads.

The immediate solution is to separate the circuits supplying harmonic generating loads from those supplying loads which are sensitive to harmonics. The separated circuits will feed the linear and non-linear loads differently from the point of common coupling, so that the voltage distortion caused by the non-linear load does not affect the linear load. When considering the magnitude of harmonic voltage distortion it should be remembered that, when the load is transferred to a UPS or standby generator during a power failure, the source impedance (Z_s) and the resulting voltage distortion will be much higher.

Where local transformers are installed, they should be selected to have sufficiently low output impedance and to have sufficient capacity to withstand the additional heating, in other words, by selecting an appropriately oversized transformer. Note that it is not appropriate to select a transformer design in which the increase in capacity is achieved simply by forced cooling such a unit will run at higher internal temperatures and have a reduced service life. Forced cooling should be reserved for emergency use only and never relied upon for normal running.

3.1 OVERALL IMPACT OF HARMONICS

Increasing use of electronic equipment has changed the way we work but the power electronics has also changed the load characteristic of our homes offices and factories. Electronic loads are “non-linear” in the way they draw electrical power. A common type, the “switch mode” power supply, produces the low voltage required for electronic equipment by drawing current from the supply for only a short part of each mains cycle. When they draw current there is a voltage drop in the supply and any other equipment connected to this supply will also experience the voltage drop for part of every cycle.

The overall adverse effects of concentrated non-linear loads are:

- Voltage distortion
- Excessive neutral currents
- High levels of neutral-to-earth voltage

- Overheated transformers
- Large magnetic fields emanating from transformers
- Decreased distribution system capacity
- Excessive heating and failure of capacitors, capacitor fuses, transformers, motors, fluorescent lighting ballasts, etc.
- Nuisance tripping of circuit breaker or blown fuses
- Presence of the 3rd harmonic & multiples of the 3rd harmonic in neutral grounding systems may require the derating of neutral conductors
- Noise from harmonics that lead to erroneous operation of control system components
- Damage to sensitive electronic equipment
- Electronic communications interference

Computers, laser printers, medical instrumentation, microwave ovens, stereos and televisions, are among the devices using switch mode power supplies. Other types of non-linear loads include light dimmers, and fluorescent lighting. Variable speed drives (VSD) commonly use six-pulse rectified and phase-angle controlled power supplies, which also generate harmonics.

Process industries, hospitals, airports, banking, data processing, communication centers and many other industries rely on quality power supplies to efficiently run their sensitive electronic equipment. Many facility and IT managers are becoming aware of the problem of harmonics. As more and more computers and electronic equipment are added in the supply system, the effective power factor may also drop. In some cases, the drop in effective power factor has been sufficient to trigger extra charges. Even worse, transformer and wiring failures seemed to coincide with low power factor.

3.2 EXCESSIVE NEUTRAL CURRENTS

In 3-phase distribution systems, load currents for balanced loads share the return current between phases, a neutral conductor is therefore not needed for return currents. In unbalanced 3 phase systems, a neutral conductor is required for the return current which is the vector sum of the imbalance. With switch mode supplies, the short bursts of current for each phase do not coincide and thus introduced return current in the neutral. When the return currents of three similar loads meet at the distribution board, the neutral current can be 1.73 or 2 times the phase currents. Any imbalance in the loads can lead to even higher neutral currents.

Wiring sized for neutral currents may not be adequate to carry the combined neutral current. The pulse current from a switch mode supply may repeat at 50 Hz but when they are combined they are at 150 Hz or the 3rd harmonic. The frequency components in the neutral wave form usually include this 3rd harmonic and other higher order odd harmonics. Odd multiples of the 3rd harmonic are additive in the neutral and are known as triplen harmonics. Example of the addition of triplen harmonics from the phase conductors adding in the neutral conductor is shown in Figure 3.1.

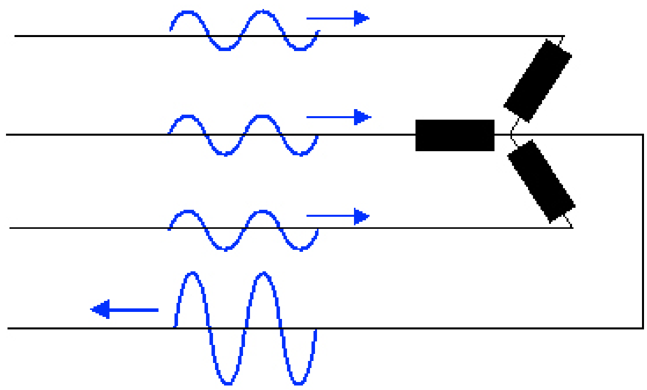


Fig.3.1 Excessive neutral current in 4-wire applications

3.3 EFFECT TO MOTORS

All harmonics cause heat in conductors and other system components. This is in addition to the normal heat generated by normal operating currents. Negative sequence harmonics, in addition to this heating effect, also causes another problem in induction motors. The reverse phase rotation of these harmonics generates a reversely rotating magnetic field, which not only reduces forward motor torque, but also increases the motors' current demand.

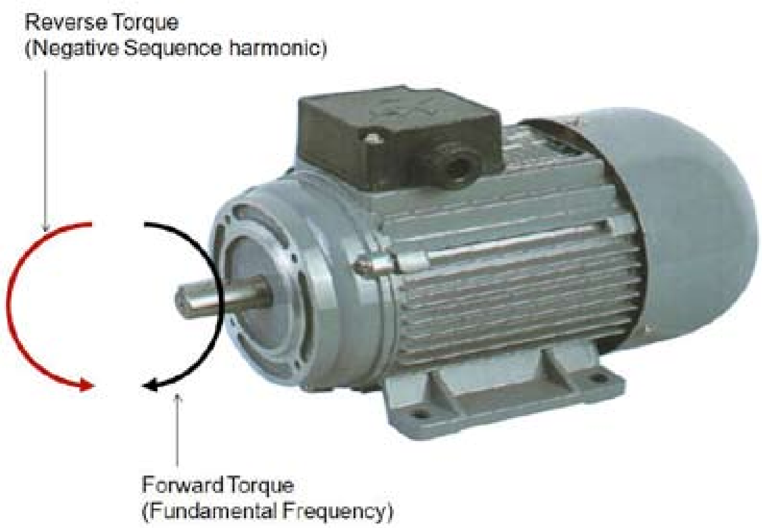


Figure 3.2 Effect of harmonics to motor

3.4 EFFECTS TO POWER TRANSFORMERS

Distribution transformers supplying non-linear loads are adversely affected by the harmonics. The increased RMS value due to distorted current waveform causes additional copper losses in the phase windings. The higher frequency harmonic currents also resulted in higher core losses, copper losses as well as eddy current losses in the metal tank and windings. These higher losses reduce transformer rated capacity.

In a delta-star distribution transformers, the triplen harmonic currents which algebraically sum up in the neutral of the secondary star windings, are reflected as circulating current in the delta winding of the primary and cause overheating and may result in transformer failures.

3.4.1 OVERSIZED TRANSFORMERS

Specifying transformers for non-linear loads is the topic of much controversy. Recent studies suggest oversizing transformers to account for greater heating and load losses as one solution to harmonic heating. Unfortunately, the larger conductors in oversized transformers may accentuate the high frequency heating effects created by harmonic loads. Additionally, oversized transformers allow larger amounts of harmonic currents to flow in the distribution system during steady-state non-linear load conditions.

Some transformers, when located close to the non-linear load, can also play a part in absorbing the triplen harmonic currents and preventing them from affecting the rest of the installation. These transformers are specially wound with a ‘K’ factor derating to reduce the circulating triplen harmonic heating effect.

Transformers represent the majority of source impedance within a distribution circuit. The skin effect, whereby high frequency currents only flow in the outer layer of a conductor, dictates that the inductive component of the transformer can present significant impedance to the flow of higher frequency harmonic currents. The higher the frequency of the harmonics, the more the transformer will act to suppress the harmonic components of the load current. Higher levels of phase and neutral conductor currents may increase neutral-to-earth voltage drop to potentially damaging levels for sensitive electronic loads.

3.4.2 K FACTOR TRANSFORMER

K factor is a value used to determine how much harmonic current a transformer can handle without exceeding its' maximum temperature rise level. K factor values range from 1 to 50. K factor of 1 is used for linear loads only, and a K factor of 50 is used for the harshest harmonic environment possible. A transformer with a K factor of 5 rating would be able to handle 5 times the harmonic heating effects of a standard transformer. When transformers use a K factor value, they are said to be K rated.

3.5 NUISANCE TRIPPING OF CIRCUIT BREAKERS

Residual current circuit breakers (RCCB) operate by summing the current in the phase and neutral conductors and, if the result is not within the rated limit it will disconnect the power from the load. Nuisance tripping can occur in the presence of harmonics for two reasons. Firstly, the RCCB, being an electromechanical device, may not sum the higher frequency components correctly and therefore trips erroneously. Secondly, the kind of equipment that generates harmonics also generates switching noise that must be filtered at the equipment power connection.

The filters normally used for this purpose have a capacitor from line and neutral to ground, and so leak a small current to earth. This current is limited by standards to less than 3.5 mA, and is usually much lower, but when equipment is connected to the same circuit the leakage current can be sufficient to trip the RCCB. This situation is easily overcome by providing more circuits, each supplying fewer loads. Nuisance tripping of miniature circuit breakers (MCB) is usually due to the leakage current flowing in the circuit is higher than that expected from calculation or simple measurement due to the presence of harmonic currents.

3.5.1 NUISANCE TRIPPING OF MCCB

Moulded case circuit-breakers (MCCB) are operated based on the thermal tripping circuit. The scheme consists of a bimetallic strip which is deflected by the heat generated in the strip by the fault current or higher line current and eventually trips the circuit breaker. Examples of MCCBs are shown in Figure 3.3.

Fig.3.3: Common MCCBs found in Malaysia

Thermal circuit protectors utilize a bimetallic strip electrically in series with the circuit. The heat generated by the current during an overload deforms the bimetallic strip and trips the breaker. Thermal protectors have a significant advantage over fuses in that they can be reset after tripping. They can also be used as the main ON/OFF switch for the equipment being protected. However, thermal breakers have some disadvantages. They are, in effect, "heat sensing" devices, and can be adversely affected by changes in ambient temperature. When operating in a cold environment, they will trip at a higher current level. When operating in a hot environment, they will "nuisance trip" at a lower current level resulting in unwanted equipment shut downs.

The current sensing ability of the thermal magnetic circuit breakers can also be affected by harmonic current distortion. The instantaneous mechanism of some breakers is a solenoid that dissipates additional heat due to losses for harmonic frequencies. The heat then raises the temperature of the thermal device and reduces the trip point. The trip point of a 600 A MCCB can be reduced by 10-20% at 300 Hz etc.

3.6 EFFECTS OF HARMONICS ON CAPACITORS

Capacitors are devices which experience to the largest extent the effects of electromagnetic environment distortion. They are exposed to voltage, current and power overloads. For this reason the permissible overload factors i.e. IEEE Standard 18-2002 [7] provided by manufacturers and expressed in terms of the rated value ratio, are related to these quantities. They determine the non-destructive conditions for a capacitor bank, though operation under a long-duration overload significantly shortens the capacitors' life.

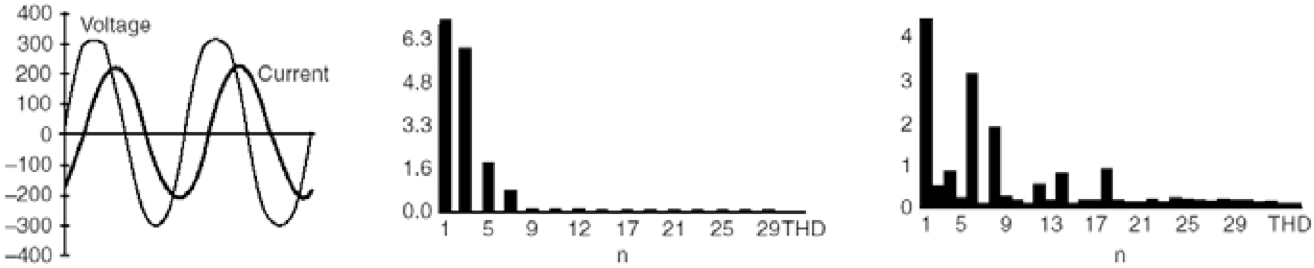
The increase in peak voltage value due to harmonics is an additional dielectric stress. It may cause a partial discharge (PD) in the insulation, a foil short circuit and result in permanent damage to the capacitor. The permissible overvoltage factor of a capacitor normally does not exceed 110% of the rated voltage value. Most of the problems with capacitors, caused by harmonics, are current related. Voltage harmonics produce additional currents flowing through the capacitor which increase with the harmonic order (as a result of the reduction in capacitor equivalent impedance $Z_C = \frac{1}{2\pi f C}$), and can be of significant value.

An excessive current through the capacitor bank results in additional losses and, consequently, adverse effects such as fuses blowing, physicochemical processes in the dielectric resulting in accelerated ageing of the insulation and reduced service life, permanent damage, etc. All these effects can be dramatically magnified by the incidences of series or parallel resonance in the supply system.

Table 3.1 shows examples voltage and current waveforms and their respective spectrums, both prior to and after the connection of a capacitor bank. The increase in magnitudes of certain harmonics, due to the increased equivalent impedance of the supply network and capacitor bank circuit for these frequencies, is evident. And examples on impact of harmonics on a capacitor bank installation and the related testing procedure to evaluate the health of the capacitors are shown in figures 3.4 and 3.5

Table 3.1 Examples of voltage and current waveforms and their spectrums, before and after connection of capacitor bank

Without capacitor



With capacitor

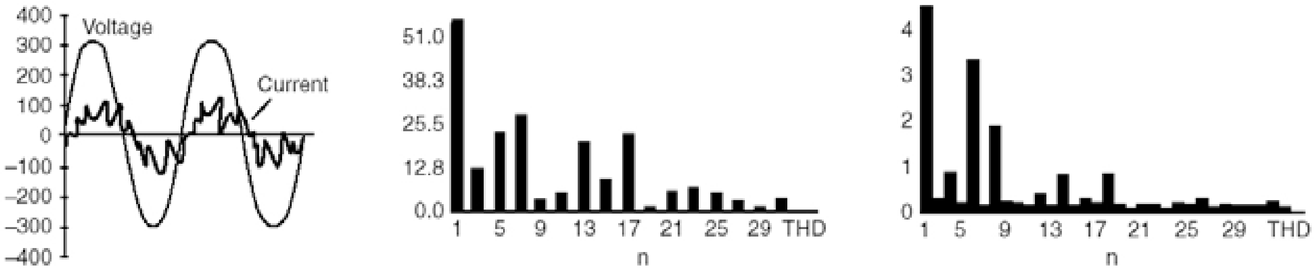


Fig.3.4 Damaged capacitor units due to parallel resonances

Fig.3.5 Capacitance measurement to evaluate faulty capacitor units.

CHAPTER 4

HARMONIC SPECTRUMS AND HARMONIC INDICES

4.0 UNDERSTANDING HARMONIC SPECTRUMS

Most of the voltage and current waveforms are time-domain waveforms/signals in their raw formats. That is, whatever that signal is measuring, is a function of time. A root mean square (RMS) plot is a representation for a time-domain signal. This representation is not always the best representation of the signal for detection of the existence of harmonics. Example of time-domain voltage waveforms and the respective RMS plots are shown in Figure 4.1. In the first row are the time-domain voltage waveforms and the second row are the RMS plots.

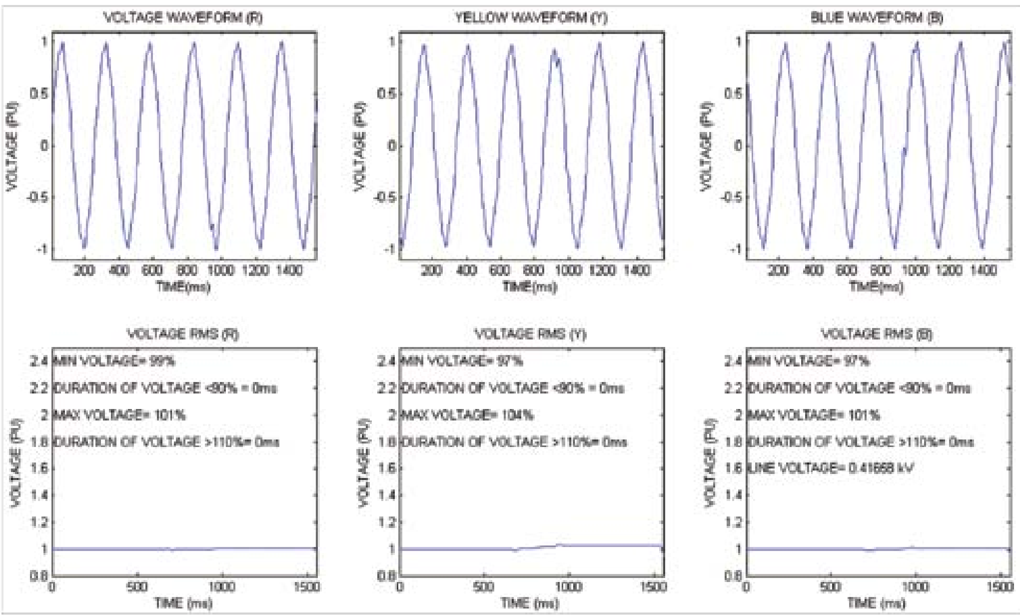


Fig.4.1 Time-domain voltage waveforms & RMS plots

Often times, the information that cannot be readily seen in the time-domain can be seen in the frequency domain [7]-[8]. In the frequency domain, the frequency spectrum of a signal is basically the frequency components (spectral components) of that signal. The frequency spectrum of a signal what frequencies exist in the signal.

The most common technique to identify the frequency content is the Fourier Transform (FT) [9]. Fourier theory says that any complex periodic waveform can be decomposed into a set of sinusoids with different amplitudes, frequencies and phases. The process of doing this is called Fourier Analysis and the result is a set of amplitudes, phases, and frequencies for each of the sinusoids that makes up the complex waveform. Adding these sinusoids together again will reproduce exactly the original waveform. A plot of the frequency or phase of a sinusoid against amplitude is called a harmonic spectrum. Using physical terminology, the Fourier transform of a signal *x(t)* can be thought of as a representation of a signal in the frequency domain i.e. how much each frequency contributes to the signal. This is similar to the basic idea of the various other FTs including the Fourier series of a periodic function. Signals are converted from time or space domain to the frequency domain usually through the FT. The most common purpose for analysis of signals in the frequency domain is analysis of signal properties and the common equation to define the Fourier transform *X(t)*of a function *x(t)* is based on Equation (4.1).

$$X(F) = \int_{-\infty}^{\infty} x(t)e^{-,2\pi ft} dt \text{, for every real number } f \qquad (4.1)$$

In Equation (4.1), t stands for time, *f* stands for frequency, and *x* denotes the signal at hand. Note that *x(t)* denotes the signal in time domain and *x(f)* denotes the signal in frequency domain. FT is a reversible transform that is allowed to go back and forward between the raw and processed (transformed) signals. However, only either of them is available at any given time. That is, no frequency information is available in the time-domain signal, and no time information is available in the Fourier transformed signal. The effective way to utilize FT is to calculate the Discrete Fourier Transform (DFT). In mathematics, the discrete Fourier transform (DFT) is one of the specific forms of Fourier analysis. As such, it transforms one function into another, which is called the frequency domain representation, or simply the DFT of the original function (which is often a function in the time domain). In particular, the DFT is widely employed in signal processing and related fields to analyze the frequencies contained in a sampled signal, to solve partial differential equations, and to perform other operations such as convolutions. There are several ways to calculate the Discrete Fourier Transform (DFT). The Fast Fourier Transform (FFT) is another method for calculating the DFT. While it produces the same result as the other approaches, it is incredibly more efficient, often reducing the computation time by hundreds [10]-[12]. Example of time-domain voltage waveforms and the respective FFT spectrums are shown in Figure 4.2. In the first row are the time-domain voltage waveforms and the second row are the frequency spectrums. From the frequency spectrums, the harmonics that distorted the voltage waveforms are the 5th harmonics (250 Hz) and 7th harmonics (350 Hz). The FFT is best method to verify the existence of harmonic frequencies and the level of distortion.

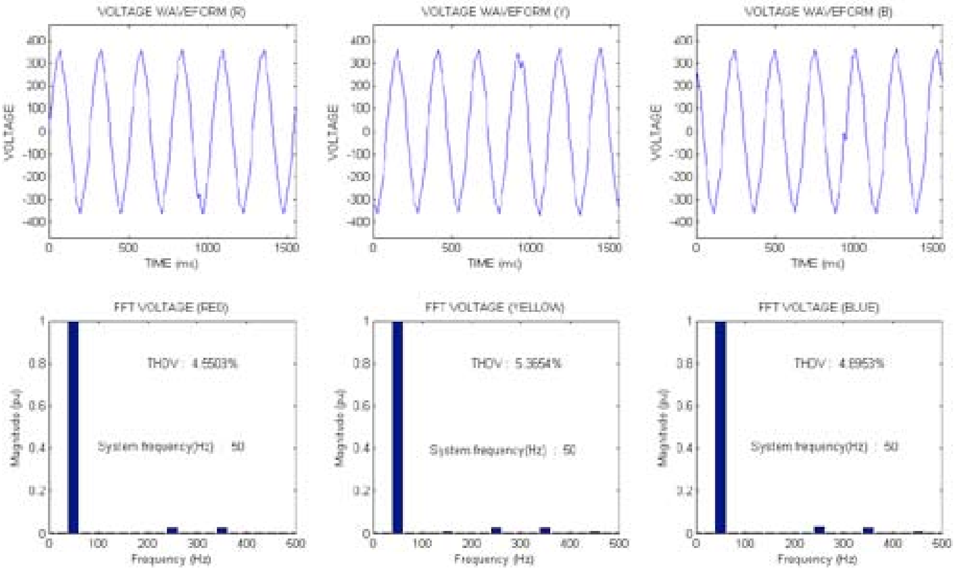


Fig.4.2 Time-domain voltage waveforms & frequency spectrums

Another example for the current drawn by a rectifier system (non-linear load) and the respective frequency spectrum is shown in Figure 4.3.

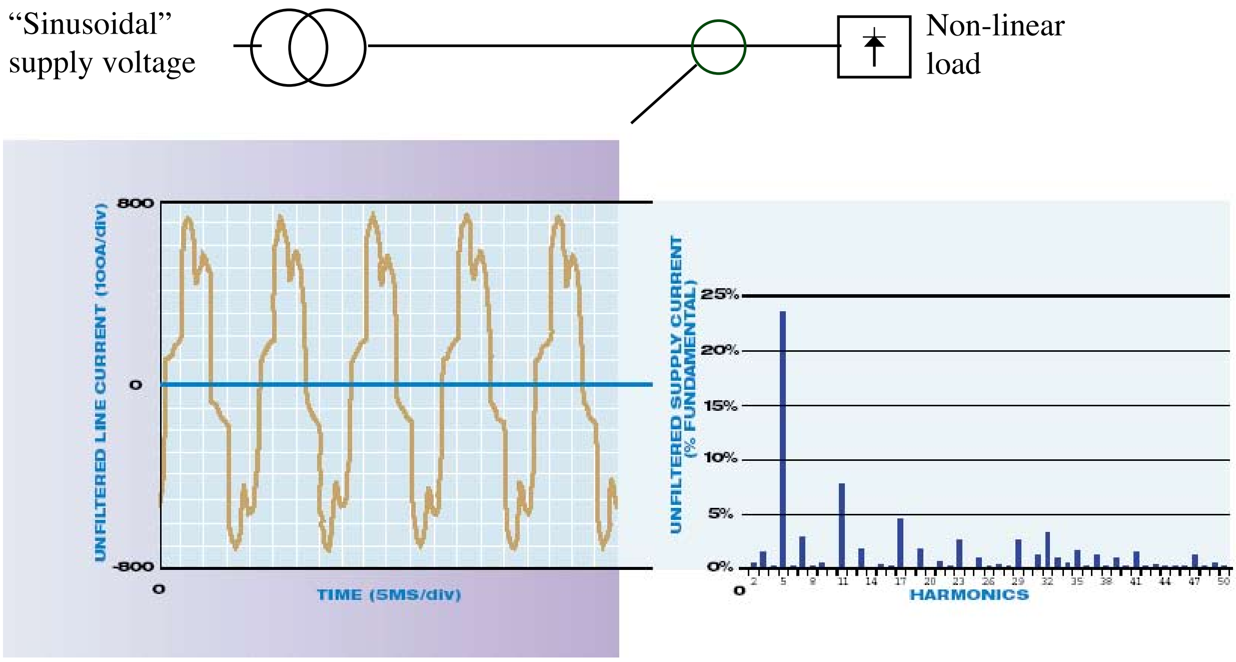


Fig.4.3 Time-domain voltage waveform & frequency spectrum for a rectifier

From the frequency spectrums, the harmonics that distort the voltage waveforms are the 5th, 11th, 13th, 17th, 23rd and etc. harmonics. The FFT is the best method to verify the existence of harmonic frequencies and the level of distortion. This example also shows the importance of the FFT in identifying the harmonic frequencies in the recorded waveform.

4.1 Total Harmonic Distortion (THD)

An every important index used to indicate the existence of harmonic is the total harmonic distortion or THD [13]. The equation to calculate total harmonic distortion voltage (THD_V) is explained in Equation (4.2). To calculate the values of total harmonic distortion current (THD_I), change the values of voltage to current.

$$THD_V = \frac{\sqrt{\sum_{h=2}^{N} V^2}}{V_{fundamental}} \quad (4.2)$$

THD_V	Total harmonic distortion for voltage
V_h	Harmonic voltage
$V_{fundamental}$	Fundamental voltage at 50 Hz
N	Harmonic number

THD, or Total Harmonic Distortion, is one measure of the total distortion. It is the RMS sum of the individual voltage or current harmonics, divided by either the fundamental value, or the RMS value of the total waveform distortion. Both are legitimate definitions of THD. For small values of distortion, they both produce roughly the same number. Examples on the calculations of THD for voltages and currents are shown below.

Example 1 Calculation of Total Harmonic Distortion Current (THD_I)

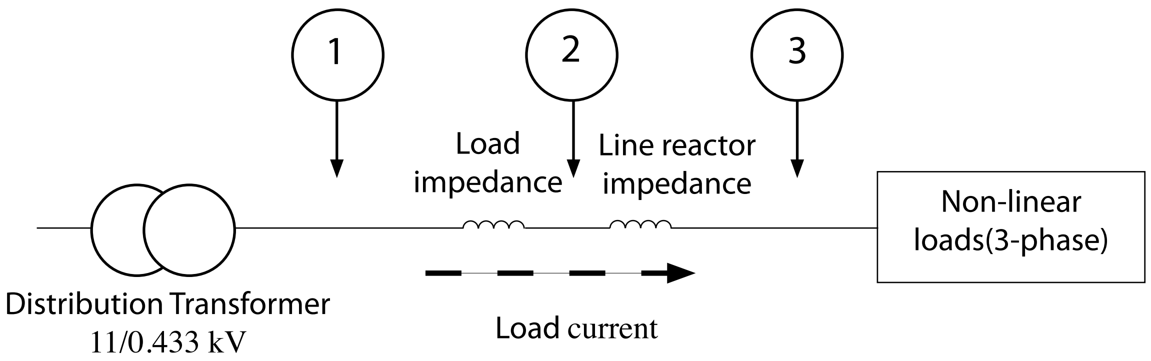


Fig.4.4 Single line diagram for a supply scheme to non-linear loads

In Figure 3.4, three recordings were performed at points 1, 2 and 3. The data recorded in this example were recorded using a power quality recorder (PQR). The PQR records the harmonic waveforms with respect to the 10 minutes interval requirement stipulated in IEC 61000-4-7[13]. Details on power quality recorder requirement are presented in Chapter 5. The values of the fundamental and harmonic currents in ampere (A) are shown in Table 4.1.

Table 4.1 Harmonic currents recorded at points 1, 2 and 3.

Measuring point.	1	2	3
1st harmonics	70	70	70
5th harmonic	18	18	18
7th harmonic	14	14	14
11th harmonic	11	11	11
Distortion rms	25.32	25.32	25.32
RMS current	74.44	74.44	74.44
THD_I % (fund)	36.2%	36.2%	36.2%

From Table 4.1, the supply system carries 70A of fundamental (1st harmonic) current, 18A of 5th harmonic current, 14A of 7th harmonic current, and 11A of 11th harmonic current. The effective current would be 74.4A rms. The effective (RMS) current is calculated based on Equation (4.3) and the distortion RMS current is calculated based on Equation (4.4).

$$I_{RMS} = \sqrt{\left[I_1^2 + I_3^2 + I_5^2 + I_5^2 + \dots\dots\dots\dots\dots + I_n^2 \right]} = 7.44A \qquad (4.3)$$

$$I_{Distortion\ RMS} = \sqrt{\left[I_3^2 + I_5^2 + I_5^2 + \dots\dots\dots\dots\dots + I_n^2 \right]} = 25.32A \qquad (4.4)$$

n is the harmonic number.

And the THD_I (fundamental) values are calculated using Equation (4.2).

THD_I (fund) at point 1 = Distortion RMS current/ Fundamental current x 100

= (25.32 / 70) x 100 = 36.2 %

And the THD_I (rms) values are calculated using Equation (4.2).

THD_I (rms) at point 1 = Distortion RMS current/ RMS current x 100

= (25.32 / 74.44) x 100 = 34.0 %

Using the fundamental as the reference produces a THD_I value of 36.2 %, and using the RMS as the reference produces a THD_I value of 34.0 %.

For this and other reasons, most experts in power system harmonics frown on using THD as a measure of current harmonics. Other measures such as Total Demand Distortion (TDD) [13] make more sense in verifying the severity of the harmonic currents.

Example 2 Calculation of Total Harmonic Distortion Voltage (THD_V)

The fundamental and harmonic voltages recorded for the system in Figure 4.4 are shown in Table 4.2.

Table 4.2 Harmonic voltages recorded at points 1, 2 and 3.

Measuring point.	1	2	3
1st harmonics	415.00	415.00	415.00
5th harmonic	25.20	25.20	25.20
7th harmonic	12.50	12.50	12.50
11th harmonic	7.80	7.80	7.80
Distortion rms	29.19	29.19	29.19
Rms voltage	415.07	415.07	415.07
THD_V % (fund)	7.0%	7.0%	7.0%

From Table 4.2, the fundamental (1st harmonic) voltage is 415V, 25.2V of 5th harmonic voltage, 12.5V of 7th harmonic voltages, and 7.8V of 11th harmonic voltages. The effective voltage would be 415.07V rms. The effective and distorted RMS voltages are calculated based on Equation (4.5) and Equation (4.6).

$$V_{RMS} = \sqrt{\left[V_1^2 + V_3^2 + V_5^2 + V_5^2 + \ldots\ldots\ldots\ldots + V_n^2\right]} = 415.07V \quad (4.5)$$

$$V_{Distortion\ RMS} = \sqrt{\left[V_3^2 + V_3^2 + V_5^2 + \ldots\ldots\ldots\ldots + V_n^2\right]} = 29.19V \quad (4.6)$$

n is the harmonic number

And the THD_V (rms) values are calculated using Equation (4.2).

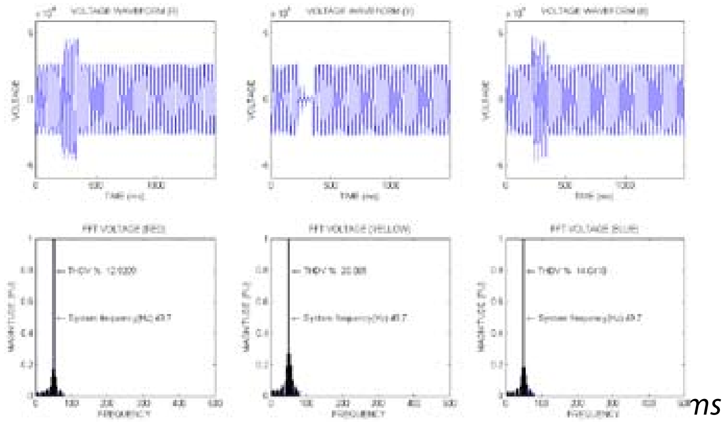
THD_V (rms)at point 1 = Distortion rms voltage/ Fundamental voltage x 100

= (29.19 / 415) x 100 = 7.0 %

Using the fundamental as the reference produces a THD_V value of 7.0 %, and using the RMS as the reference produces a THD_V value of 7.0 %. Both values are correct. This makes sense because the fundamental voltage varies only by a few percent, so any reference of voltage THD, relative to the fundamental, is nearly always a meaningful number.

Example 3 Harmonic spectrums and THD values for voltage sag/swells.

Examples of both harmonic spectrums and THD values for voltage sag/swells are shown in Figure 4.5.



Example 4 Harmonic spectrums and THD values for harmonics waveforms

Examples of both harmonic spectrums and THD values for harmonics waveforms are shown in Figure 4.6.

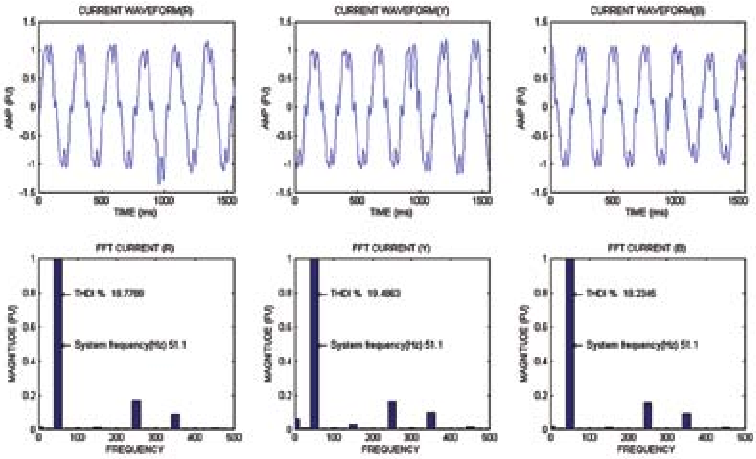


Fig. 4.6 FFT conversion for distorted current waveforms

Other examples of harmonic spectrums for harmonic loads are shown below.

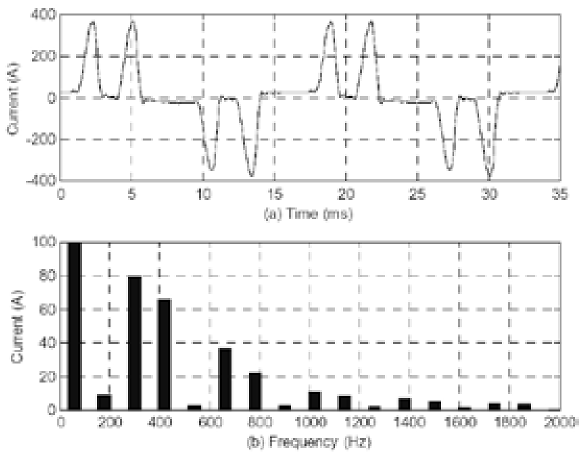


Fig.4.7 Current waveform and harmonic spectrum of a Pulse Width Modulator (PWM) converter for Adjustable Speed Drive (ASD).

4.2 Total Demand Distortion (TDD)

As mentioned in Example 1, we can characterize harmonic current distortion levels with a THD value, but this value can be misleading. According to the book "Electrical Power Systems Quality," a small current can have a high THD but not be a significant threat [2]. For example, many adjustable-speed drives (ASD) will exhibit high THD values for the input current while operating at very light loads. This shouldn't be a concern, because the magnitude of harmonic current would be low in this instance, even though its relative current distortion is quite high. Responding to such scenarios, some analysts have referred to THD as the fundamental of the peak demand load current rather than the fundamental of the present sample. This is named as the total demand distortion, or TDD. Contrary to popular belief, TDD and not THD serve as the basis for the guidelines in IEEE 519, "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems." [13]. In fact, IEEE 519 defines TDD as "the total root-sum-square harmonic current distortion, in percent of the maximum demand load current".

The following equation defines TDD:

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \times 100 \qquad (4.7)$$

where:

I_h = magnitude of individual harmonic current (Amp)

h = harmonic order

and I_L is the peak or maximum demand load current at the fundamental frequency component measured at the point of common coupling (PCC), which is usually at the customer's metering point. TDD is meaningful when monitored at the PCC over a period of time that reflects maximum customer demand i.e. typically 15 minutes to 30 minutes. There are two ways in which to measure I_L. With the load already in the system, one can calculate IL as the average of the maximum demand current for the preceding 12 months.

CHAPTER 5

HARMONIC RESONANCES & SYSTEM RESPONSES

5.0 OVERVIEW

Power system problems related to harmonics are rare but it is possible for a number of undesirable effects to occur. High levels of harmonic distortion can cause such effects as increased transformer, capacitor, motor or generator heating, misoperation of electronic equipment (which relies on voltage zero crossing detection or is sensitive to wave shape), incorrect readings on meters, misoperation of protective relays, interference with telephone circuits, etc. The likelihood of such ill effects occurring is greatly increased if a resonant condition occurs. Resonance occurs when a harmonic frequency produced by a non-linear load closely coincides with a power system natural frequency. There are 2 forms of resonance which can occur in the power system i.e. parallel resonance and series resonance.

5.1 PARALLEL RESONANCE

Parallel resonance (see Figure 5.1) occurs when the natural frequency of the parallel combination of capacitor banks (X_C) and the system inductance (X_{Leq}) falls at or near a harmonic frequency. The value of the system inductance (X_{Leq}) comprises of the transformer inductance (X_T) and the source inductance (X_{SOURCE})This can cause substantial amplification of the harmonic current that flows between the capacitors and the system inductance and lead to capacitor fuse blowing or failure or transformer overheating. The operation of nonlinear loads in a power distribution system creates harmonic currents that flow throughout the power system. The inductive reactance of that power system increases ($X_{Leq} = 2\pi fL$) and the capacitive reactance ($X_C = \frac{1}{2\pi fC}$) decreases as the frequency increases, or as the harmonic order increases. At a given harmonic frequency in any 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, is where the power system has coincidental similarity of system impedances. At the resonant frequency, the apparent impedance of the parallel combination of the equivalent inductance and capacitance as seen from the harmonic current source becomes very large and it is clear that during parallel resonance, a small harmonic current can cause a large voltage drop across the apparent impedance. The voltage near the capacitor bank will then be magnified and heavily distorted. It is important to note that every system with a capacitor has a parallel resonance point.

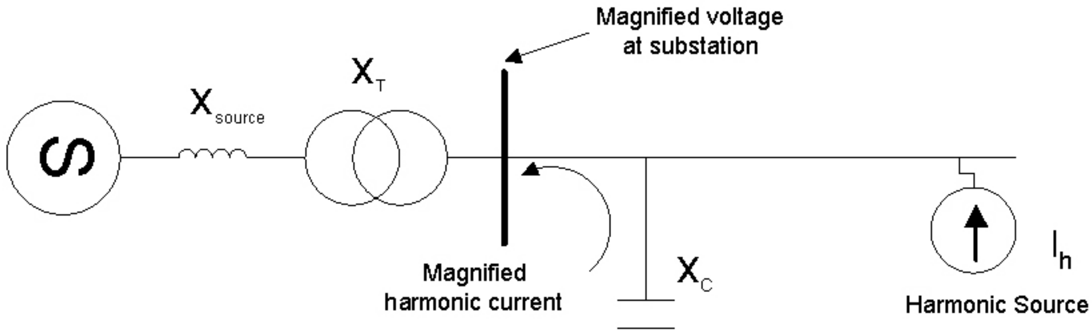


Fig.5.1 At harmonic frequencies, the shunt capacitor bank appears in parallel with the system inductance and cause parallel resonant circuit as seen from the harmonic source.

Parallel resonance occurs when the reactance of X_C and the distribution system cancel each other out. The frequency at which this phenomenon occurs is called the parallel resonant frequency (f_p). It can be expressed as follows:

$$f_p = \frac{1}{2\pi}\sqrt{\left[\frac{1}{L_{eq}C} - \frac{R^2}{4L^2_{eq}}\right]} \approx \frac{1}{2\pi}\sqrt{\frac{1}{L_{eq}C}} \qquad (5.1)$$

where R is the resistance of combined equivalent source and transformer

L_{eq} is the inductance of combined equivalent source and transformer

C is the capacitance of capacitor bank

Harmonic resonance can result in very high harmonic currents and voltages at the resonant frequency. Practically, it's extremely unlikely that these two inductances (X_{Leq} and X_C) are exactly identical, but near resonance can be very damaging as well. If, for example, the parallel resonant point is at the 5.3rd harmonic and a source of 5th harmonic current exists on the system, problems are likely to occur. In short, harmonic resonance can result if both of the following are true:

- Harmonic loads, such as AC/DC drive systems, induction heaters, arcing devices, switch mode power supplies, and rectifiers, are operating on the system.
- A capacitor or group of capacitors and the source impedance have the same reactance

(impedance) at a frequency equal to one of the characteristic frequencies created by the loads. In other words, the system will be at parallel resonant at a frequency equal to one of the harmonics flowing on the power system.

Generally, harmonic resonance is a steady-state phenomenon triggered by an event in which the harmonic source changes or the source impedance or capacitor size changes, such as if capacitors are switched on or off in steps. When installing power factor correction capacitors, one can estimate the resulting parallel resonant frequency (h_p), or harmonic order, by using the following equation:

$$h_P = \sqrt{\frac{X_C}{X_{SC}}} = \sqrt{\frac{MVA_{sc}}{MVAR_{cap}}} \approx \sqrt{\frac{kVA_{tx}\,x100}{kVar_{cap}\,x\,Z_{tx}(\%)}} \qquad (5.2)$$

Where X_{SC} is the system short-circuit reactance

MVA_{SC} is the system short-circuit MVA

MVA_{cap} is the Mvar rating of capacitor bank

kVA_{tx} is the kVA rating of step-down transformer

Z_{tx} is the step-down transformer impedance in %

$kVar_{cap}$ is the kvar rating of capacitor bank

The extent of voltage and current magnification is determined by the size of the shunt capacitor bank. Figure 5.2 shows the effect of varying capacitor size in relation to the transformer on the impedance seen from the harmonic source and compared with the case in which there is no capacitor.

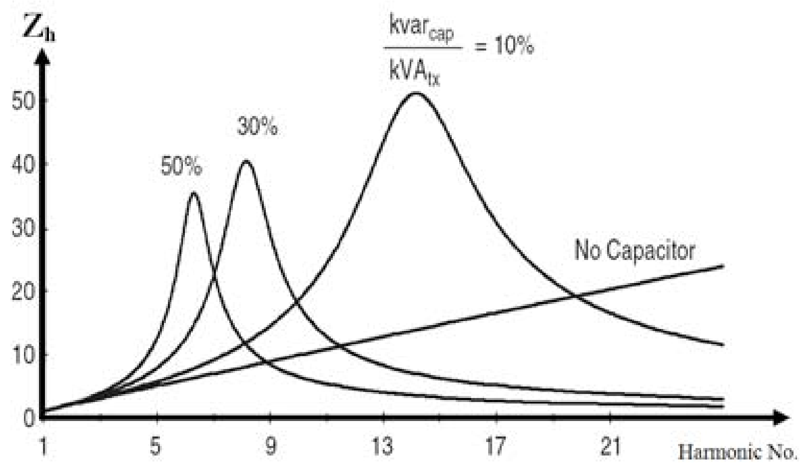


Fig.5.2 System frequency response as capacitor size is varied in relation to the transformer showing potential parallel resonances

Parallel resonance may occur at any frequency but the 5th, 7th, 11th and 13th are the common frequencies that we are most concerned. Examples on the impact of resonance on power factor correction capacitor are shown in figures 3.4 and 5.3.

Example

For example, consider a substation with a 1000kVA 11/0.433 kV transformer with 5.0 % impedance and a capacitor rating of 400 kVar.

Plugging these numbers into Equation 5.2 yields the following:-

$$h_P = \sqrt{\frac{X_C}{X_{SC}}} = \sqrt{\frac{MVA_{sc}}{MVAR_{cap}}} \approx \sqrt{\frac{kVA_{tx}\,x100}{kVar_{cap}\,x\,Z_{tx}(\%)}} = \sqrt{\frac{(1000\,x100)}{400x5.1}} = 7.07$$

So the 400 kVar capacitor bank will resonate with that source impedance at the 7th harmonic. If a 7th harmonic current flows on the same power system with the capacitor, the effect could be catastrophic. Practically, for most power systems we can estimate the MVA_{SC} based on the impedance of the nearest transformer upstream of the capacitor, often the main service transformer. For example, a 2,000kVA transformer with a 5% impedance (Z%) yields about 40 MVA_{SC} (2.0 MVA ÷ 0.05). Applying a 750 kVAR capacitor will result in a resonance condition near the 7th harmonic.

Fig.5.3 Capacitor damaged due to resonance

If the total bus load exceeds 15 to 20% of harmonic generation load, the potential for a resonance condition is high. Some indicators of resonance are overheating, frequent circuit breaker tripping, unexplained fuse operation, capacitor failure, electronic equipment malfunction, flicking lights and telephone interference.

5.2 SERIES RESONANCE

Series resonance (see Figure 5.4) is a result of a series combination of inductance and capacitance and presents a low impedance path for harmonic currents at the natural frequency. This condition occurs only in a series LC circuit at the frequency where inductive reactance (X_L) equals capacitive reactance (X_C). The overall impedance (Z) is minimum, current is maximum and limited only by the resistance (R) in the circuit.

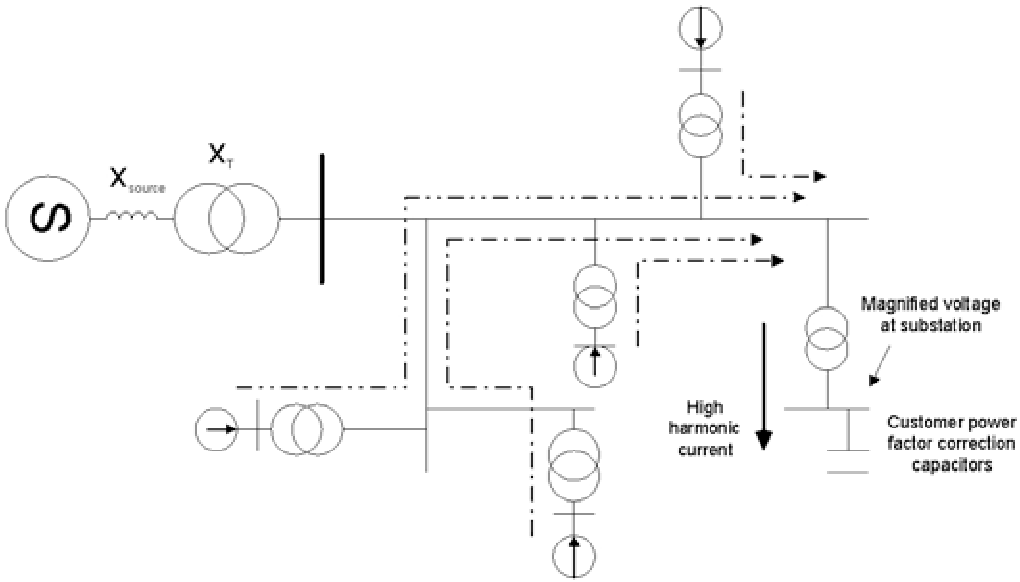


Fig.5.4 Series resonance

If the resonant frequency corresponds to a characteristic harmonic frequency of the nonlinear load, the LC circuit will attract a large portion of the harmonic current (I_h) that is generated in the distribution system. A customer having no nonlinear load, but utilizing power factor correction capacitors, may in this way experience high harmonic voltage distortion due to neighbouring harmonic sources. The effect of a series resonance can be a high voltage distortion level between the inductance (L) and capacitance (C). In many systems with potential series resonance problems, parallel resonance also arises due to the circuit topology. One of these is shown in Fig. 5.5 where the parallel resonance is formed by the parallel combination between X_{source} and a series between X_T and X_C. The resulting parallel resonant frequency is always smaller than its series resonant frequency due to the source inductance contribution.

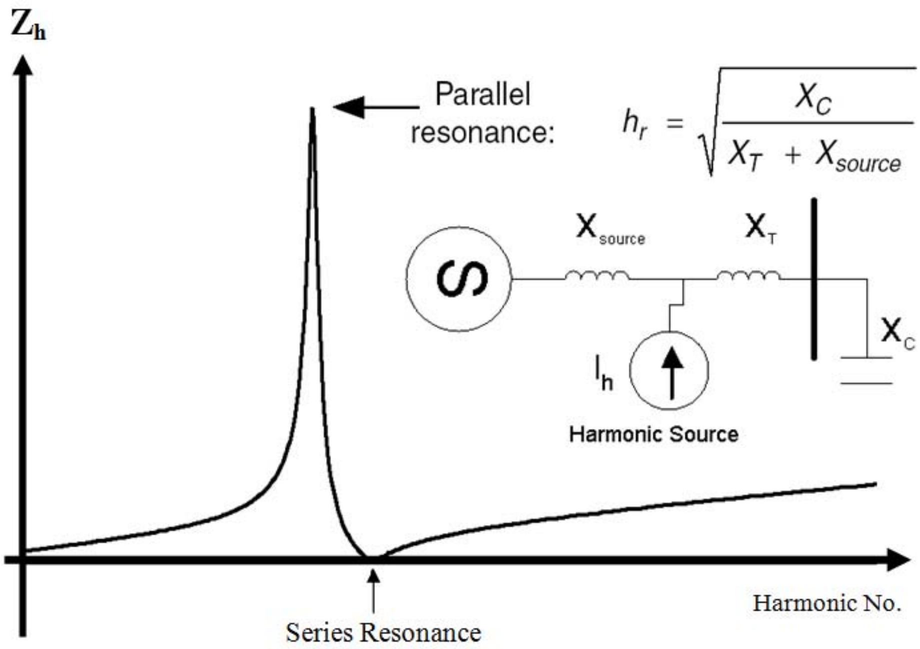


Fig.5.5 Comparison of system frequency responses between parallel & series resonances

The equations to determine the values of the series and parallel resonances are shown below:

Series resonance $$h_s = \sqrt{\frac{X_C}{X_T}} \quad (5.3)$$

Parallel resonance $$h_P = \sqrt{\frac{X_C}{X_T \times X_{source}}} \quad (5.4)$$

5.3 CAPACITOR DESIGN LIMITS TO MINIMIZE IMPACT OF RESONANCES

It is important to note that the impedance (Z) of a circuit dictates the current flow in that circuit. As the supply impedance (Z) is generally considered to be inductive (X_L), the network impedance increases with frequency while the impedance of a capacitor (X_C) decreases. This causes a greater proportion of the currents circulating at frequencies above the fundamental supply frequency to be absorbed by the capacitor, and all equipment associated with the capacitor. In certain circumstances, the harmonic currents can exceed the value of the fundamental (50 Hz) capacitor current. These harmonic problems can also cause an increased voltage across the dielectric of the capacitor, which could exceed the maximum voltage rating of the capacitor, resulting in premature capacitor failure.

To ensure longer lifetime, IEEE Standard 18-2002, Standard for Shunt

Power Capacitors, states that power capacitors must withstand a maximum continuous RMS overvoltage of 110% and an overcurrent of 180%, based on the nameplate rating [7]. This overvoltage and overcurrent conditions include both the fundamental frequency and any harmonic frequency contributions. This standard also states that the total VA rating of the capacitor cannot exceed 135%. Therefore, it is recommended to protect a capacitor at 135% of its full load current. Protection at a higher percentage will prevent overcurrent protection from operating during capacitor energizing.

The overall limits define in IEEE Standard for Shunt Power Capacitors (IEEE Standard 18-2002) specifies the following continuous capacitor ratings:

- 135 % of nameplate kVar
- 110 % of rated RMS voltage (including harmonics but excluding transients)
- 180 % of rated RMS current (including fundamental and harmonic current)
- 120 % of peak voltage (V_p) (including harmonics)

5.4 MANAGING HARMONIC RESONANCES

The general methods to manage harmonic resonances are as follows:

Methods	Description
Method 1	Adding or subtracting capacitance from the system to move the parallel resonance frequency to one that is not deleterious.
Method 2	Adding tuned/detuned harmonic suppression reactors in series with the capacitor i.e. tuned or detuned capacitors in order to prevent resonance
Method 3	Altering the size of non-linear devices.

The common method is Method 2. The problem is resolve by the application of a detuned harmonic filter or an appropriately sized capacitor to avoid harmonic resonance. Harmonic filters provide the same 50 Hz reactive compensation as regular capacitors, but they're typically designed with a parallel resonance point below any expected harmonics on the system. Make sure the existences of harmonic sources on the power system are considered and perform a harmonic frequency scan to identify potential resonance to guarantee the financial benefits of applying capacitive compensation. Details will be presented in Chapter 9.

CHAPTER 6

HARMONIC MEASUREMENT

6.0 OVERVIEW ON POWER QUALITY MONITORING

Many commercial and industrial installations suffer from persistent so-called nuisance tripping of circuit breakers. Often these trips seem random and inexplicable but, of course, there is always a reason and there are two common causes. The first possible cause is inrush currents that occur when some loads, particularly motors and other electronic devices, are switched on. The second likely cause is that the true RMS current flowing in the circuit has been under measured, in other words, the actual current really is too high. The higher current is due to harmonic currents (I_h) drawn by non-linear loads especially electronic equipment such as personal computers, electronically ballasted fluorescent lamps and variable speed drives. This means that, when troubleshooting or analyzing the performance of a power system, it is essential to use the correct monitoring tools for the job, monitoring tools that can record the non-sinusoidal currents and voltages called true RMS meters or power quality recorders.

Measurements using these monitoring equipments must be carried out at the selected industrial or commercial site to:-

- Determine the type, origin and cause of a disturbance and determine the solutions required to eliminate it.
- Check the validity of a solution (followed by modifications in the distribution network to check the reduction in harmonics).

The locations to perform the power quality monitoring are as follows:-

- At the supply source i.e. point of common coupling (PCC).
- At the main distribution board
- At the sub distribution board in the plants

These measurement devices will also serve to show both the instantaneous and long-term effects of harmonics. Analysis requires values spanning durations ranging from a few seconds to several minutes over observation periods of a number of days. The required values include:-

- The fundamental currents and voltages profiles
- The individual harmonic content of each harmonic current and voltage harmonics
- The THD for the current and voltage harmonics
- Where applicable, the phase displacement between the harmonic voltage and current of the same harmonic order and the phase of the harmonics with respect to a common reference (e.g. the fundamental voltage)
- Declared monitoring period.
- Condition with and without capacitor bank energized (if applicable)

When performing these measurements, it is necessary to know the precise operating conditions of the installation and particularly the status of the capacitor banks (operating, not operating, the number of disconnected steps).

6.1 UNDERSTANDING ROOT MEAN SQUARE (RMS) METERS/RECORDERS

The most common technique used in the analysis of voltage waveform and short duration PQ disturbances such as voltage sags, voltage swells and momentary interruption is based on the root mean square (RMS) technique ([15]-[20]. As the name implies, the RMS voltage, V_{RMS} is calculated by taking the square root of the mean average of the square of the voltage in an appropriately chosen interval and is given by,

$$V_{RMS} = \sqrt{\left(\frac{1}{T}\int_{0}^{T} v(t)^2\, dt\right)} \qquad (6.1)$$

where,

T: period of a voltage signal

v(t) : continuous function of a voltage signal in time domain

Example of a RMS conversion for a sinusoidal waveform is shown in Figure 6.1. The first row in Figure 6.1 shows perfect three phase voltage sinusoidal waveforms and the second row shows the RMS plots.

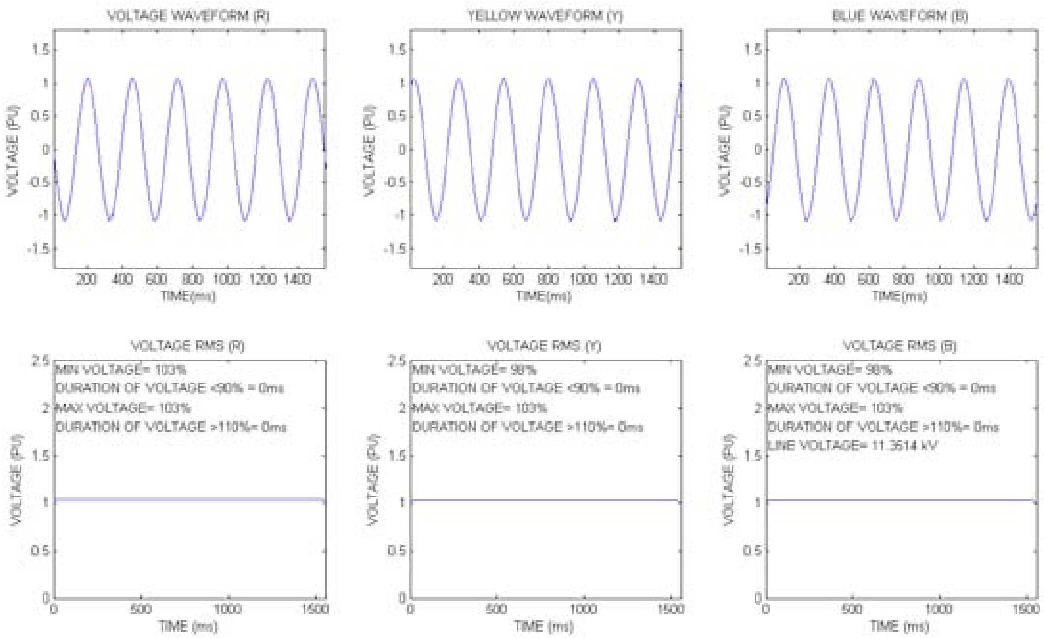


Fig.6.1 Sinusoidal waveform and RMS plots

Example of RMS plot for a voltage sag/swell event is shown in Figure 6.2. Voltage sag (7%, 91 ms) was detected in the yellow phase and is shown as a sudden reduction in the RMS plot. Voltage swells (Red Phase: 166%, 93 ms, and Blue Phase: 159%, 91ms) are depicted as sudden increases in the RMS values.

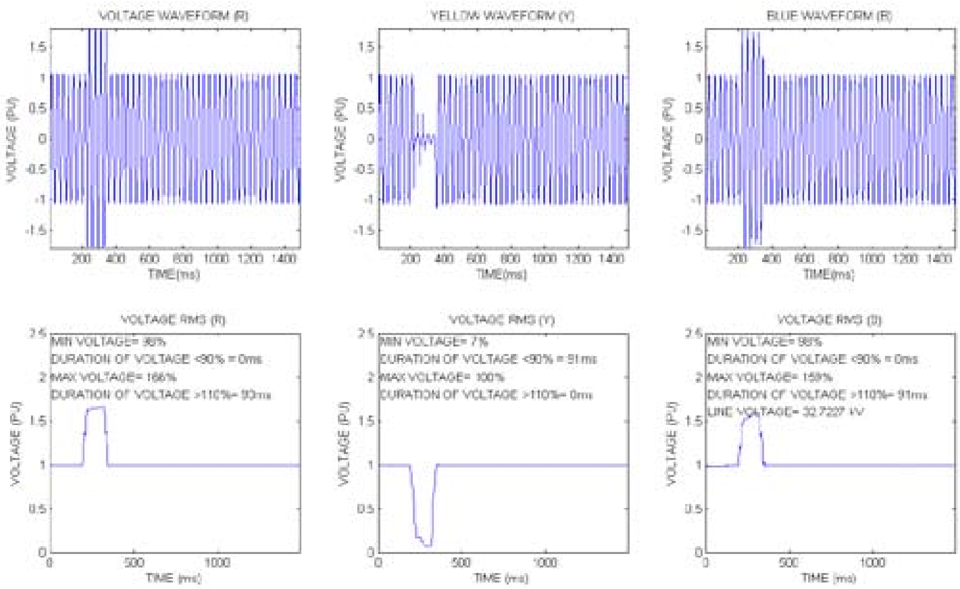


Fig.6.2 Voltage sag/swell and RMS plots

However, most RMS meters i.e. voltage meter or multi-meter apply the same concept but use a simpler equation shown as Equation 6.2.

$$V_{RMS} = \frac{V_P}{\sqrt{2}} \qquad (6.2)$$

where V_p is the voltage peak of the sinusoidal fundamental voltage waveform and $\sqrt{2}$ is equal to 1.414.

A multimeter or voltage meter is basically designed based on IEC 60044 [21], the instrument transformer either current transformer or voltage transformer, has accuracy limits based on rated i.e. 50 Hz frequency. The frequency response of the equipment is limited only to the fundamental frequency.

To justify the importance of the frequency response, Equation 6.2 is applied to the voltage waveform in Figure 6.3. The multi-meter or voltage meter will only show the RMS voltage value based only on the fundamental voltage waveform and not the resultant voltage waveform. And thus a lower RMS value will be recorded.

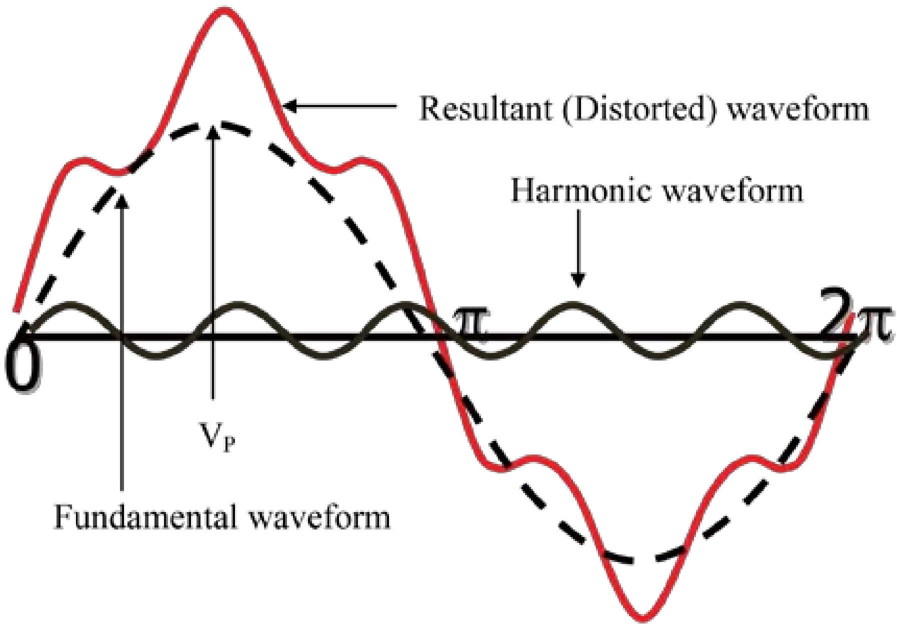


Fig.6.3 Comparison between sinusoidal & distorted waveforms

Therefore to overcome this problem, the use of equipment that has the capability to record various values for various frequency ranges is recommended. The recorder and the respective instrument transformers must be able to record frequencies more than 50 Hz. Example of a simple multi-meter is shown in Figure 6.4.

Fig.6.4 A multi-meter for measuring RMS values

6.2 HARMONIC RECORDERS/TRUE RMS METERS

True RMS values are also termed as the effective RMS values. In examples 1 and 2, the values of the effective RMS currents and voltages are presented. The effective (RMS) current is calculated based on Equation (4.3) and the distortion RMS current is calculated based on Equation (4.4). And the effective and distorted RMS voltages are calculated based on Equation (4.5) and Equation (4.6). Both the fundamental and effective RMS values for voltages and currents are shown below. The values of the effective RMS current (74.44 A) are higher than the fundamental load current (70 A). The values of the effective RMS voltages (415.07V) are slightly higher than the fundamental voltage (415V)

From Table 4.1 Harmonic currents recorded at points 1, 2 and 3.

Measuring point.	1	2	3
1st harmonics	70	70	70
5th harmonic	18	18	18
7th harmonic	14	14	14
11th harmonic	11	11	11
Distortion RMS	25.32	25.32	25.32
Effective RMS	74.44	74.44	74.44
THD_I % (fund)	36.2%	36.2%	36.2%

From Table 4.2 Harmonic voltages recorded at points 1, 2 and 3.

Measuring point.	1	2	3
1st harmonics	415.00	415.00	415.00
5th harmonic	25.20	25.20	25.20
7th harmonic	12.50	12.50	12.50
11th harmonic	7.80	7.80	7.80
Distortion RMS	29.19	29.19	29.19
Effective RMS	415.07	415.07	415.07
THD_V % (fund)	7.0%	7.0%	7.0%
THD_V % (rms)	7.0%	7.0%	7.0%

True RMS meters have been available for at least the past 20 years, but they used to be specialized and expensive instruments. Advances in electronics have now resulted in true RMS measurement capability being built into many handheld multimeters and power quality recorders. Nowadays, the cost of such equipment has been drastically reduced and this made such equipment easily available for engineers or technicians to perform diagnosis on their power delivery systems.

6.3 THE CONSEQUENCES OF UNDER MEASUREMENT

The limiting rating for most electrical circuit elements is determined by the amount of heat that can be dissipated so that the element or component does not overheat. Cable ratings, for example, are given for particular installation conditions (which determine how fast heat can escape) and a maximum working temperature. Since harmonic polluted currents have a higher true RMS value than that measured by an averaging meter, cables may have been under-rated and will run hotter than expected; the result is degradation of the insulation, premature failure and the risk of fire.

Busbars are sized by calculating the rate of heat loss from the bars by convection and radiation and the rate of heat gain due to resistive losses. The temperature at which these rates are equal is the working temperature of the busbar, and it is designed so that the working temperature is low enough so that premature ageing of insulation and support materials does not result. As with cables, errors measuring the true RMS value will lead to higher running temperatures. Since busbars are usually physically large, skin effect is more apparent than for smaller conductors, leading to a further increase in temperature. Other electrical power system components such as fuses and the thermal elements of circuit breakers are rated in RMS current because their characteristics are related to heat dissipation. This is the root cause of nuisance tripping i.e. the current is higher than expected so the circuit breaker is operating in an area where prolonged use will lead to tripping. The response of a breaker in this region is temperature sensitive and may appear to be unpredictable. As with any supply interruption, the cost of failure due to nuisance tripping can be high, causing loss of data in computer systems, disruption of process control systems, etc.

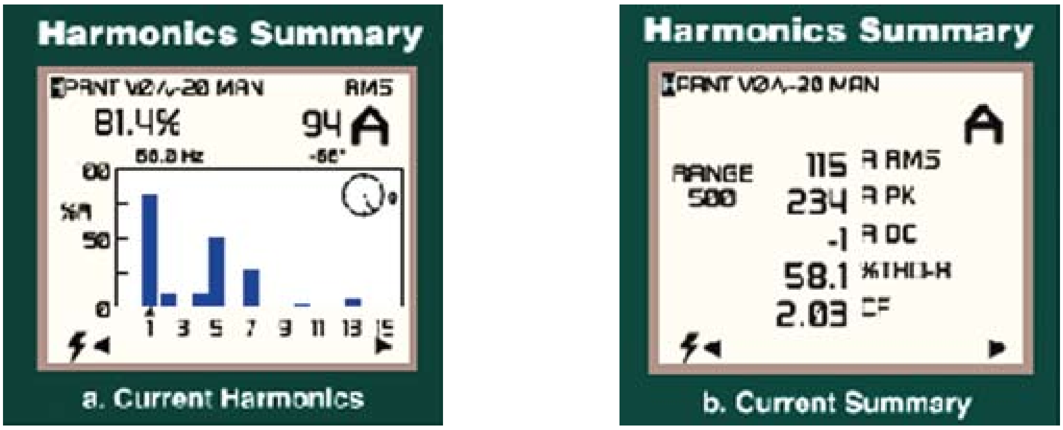
Obviously, only true RMS instruments will give the correct measurements so that the ratings of cables, busbars and breakers can be determined properly. A simple exercise can be performed by comparing measurements done using a known RMS averaging meter (i.e. Clamp Amp meter) and a known true RMS meter (Power Quality Recorder), measuring the current in a non-linear load such as a personal computer and the current drawn by a filament lamp. Both meters should read the same current for the filament lamp load. If one instrument reads significantly (say more than 20 %) higher for the PC load than the other then it is probably a true RMS instrument, if the readings are similar, the meters are of the same type.

6.4 MINIMUM REQUIREMENT FOR HARMONIC MEASURING EQUIPMENT

The harmonic measuring equipment (including the current and voltage transformers) must be able to measure these parameters.

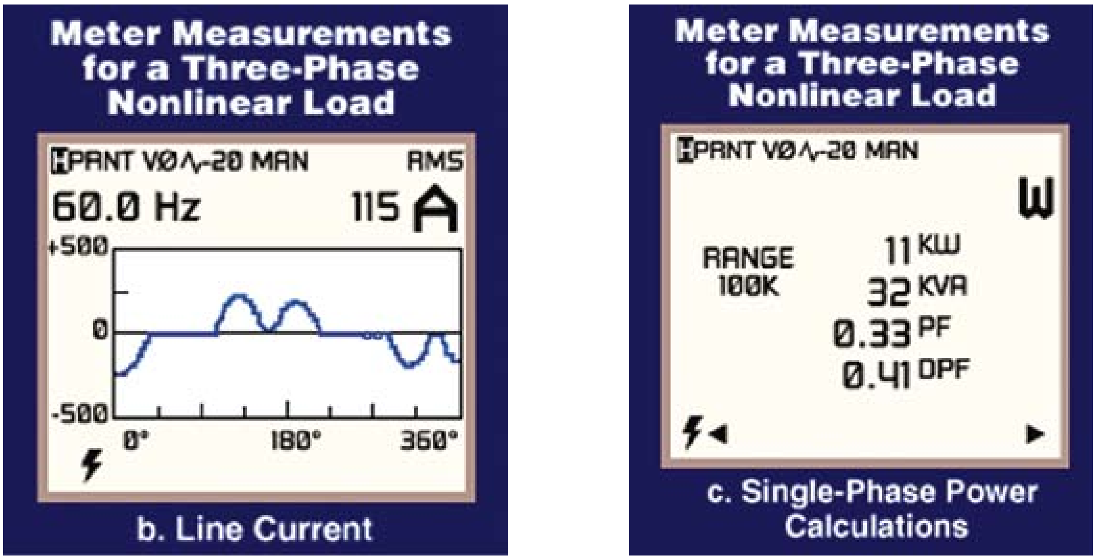
- Effective Voltage (True RMS Voltage)
- Effective Current (True RMS Current)
- Active Power (kW), Reactive Power (kVar)
- Apparent Power (kVA)
- Displacement Power Factor
- True Power Factor
- Total harmonic distortion (THD)
- Crest Factor (CF)

The harmonic meters/recorders must also show the results of the measurement in tabular or spectrum display. Examples of common displays for the harmonic meters/recorders are shown in figures 6.5 and 6.6. These photos were obtained from www.fluke.com.



Harmonic Spectrum *Summary of current values*

Fig.6.6 Screen display for a harmonic meter/recorder (1)



Current waveforms *Summary of power values*

Fig.6.6 Screen display for a harmonic meter/recorder (2)

The general technical standards for power quality monitoring equipment handheld and portable recorder are:-

Technical Standards	Description
IEC 61000-4-30	Testing and measurement techniques: Power quality measurement methods
IEC 61000-4-7	Guide for harmonics/interharmonics measurement and instrumentation.
IEEE Std.1159:2009	IEEE Recommended Practice for Monitoring Electric Power Quality

6.5 EXAMPLE ON APPLICATION OF HARMONIC HAND HELD METER FOR PERFORMING HARMONIC MEASUREMENT

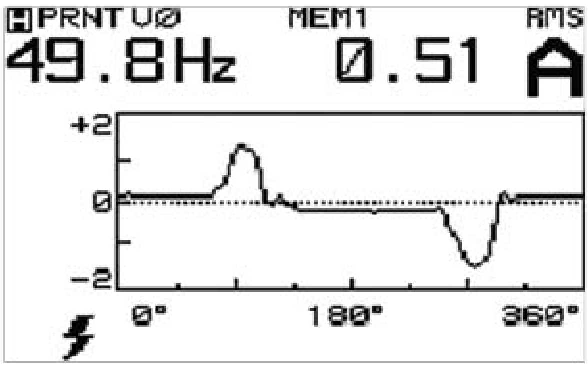
6.5.1 HARMONIC MEASUREMENT AT A SINGLE PHASE LOAD I.E. TELEVISION

Television

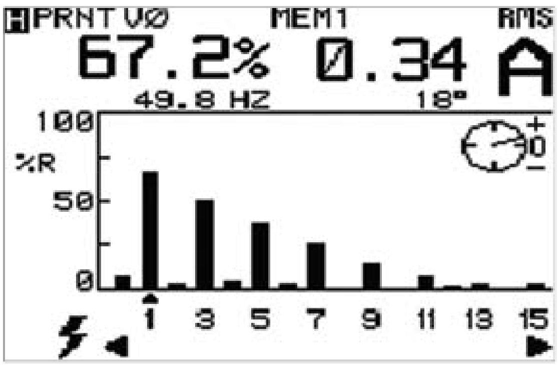
A hand held harmonic meter

Fig.6.7 Measurement of harmonic currents using a handheld harmonic meter

The results of the measurement are as follows:-



Current waveform



Harmonic spectrum

Fig.6.8 Results of harmonic measurement

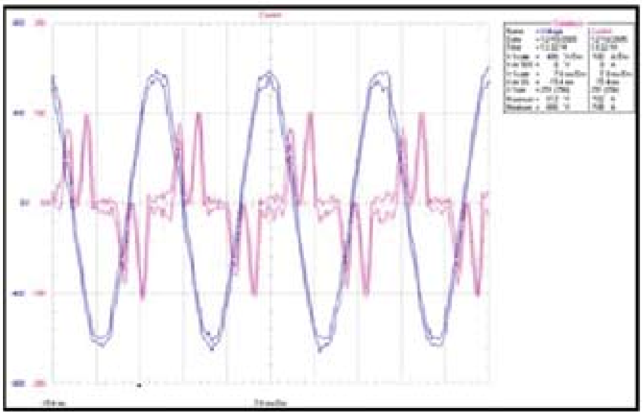
6.5.2 HARMONIC MEASUREMENT AT A THREE PHASE LOAD I.E. VARIABLE SPEED DRIVE

Variable Speed Drive

Measurement at VSD

Fig.6.9 Measurement of harmonic generated by a VSD

The results of the measurement are as follows:-



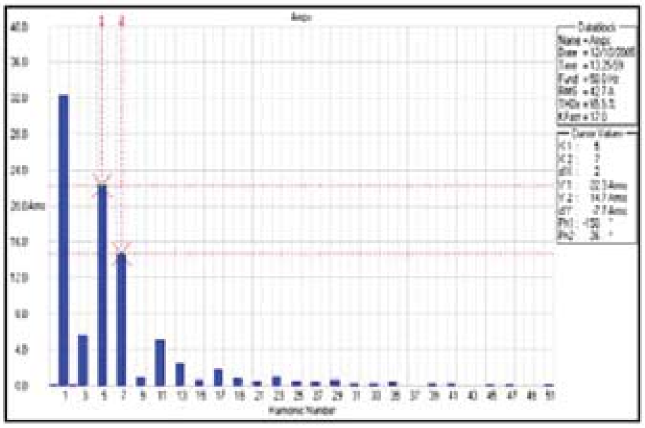


Fig.6.10 Results of harmonic measurement (Waveform & Spectrum)

Examples of harmonic current measurement taken at a hospital in Malaysia using a harmonic meter are shown in Figures 6.11 to 6.16.

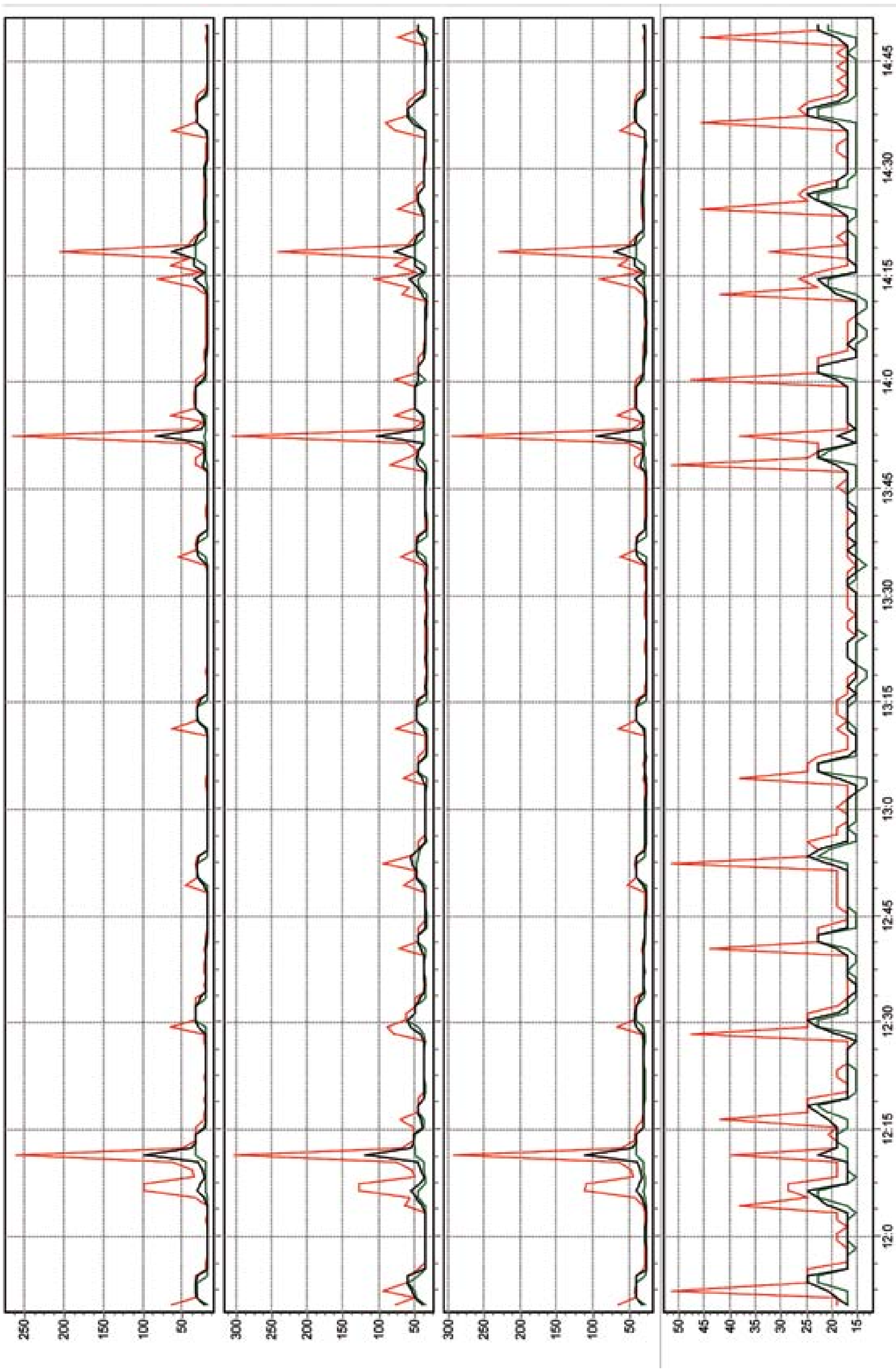


Fig.6.11 True RMS current profiles at a hospital in Malaysia

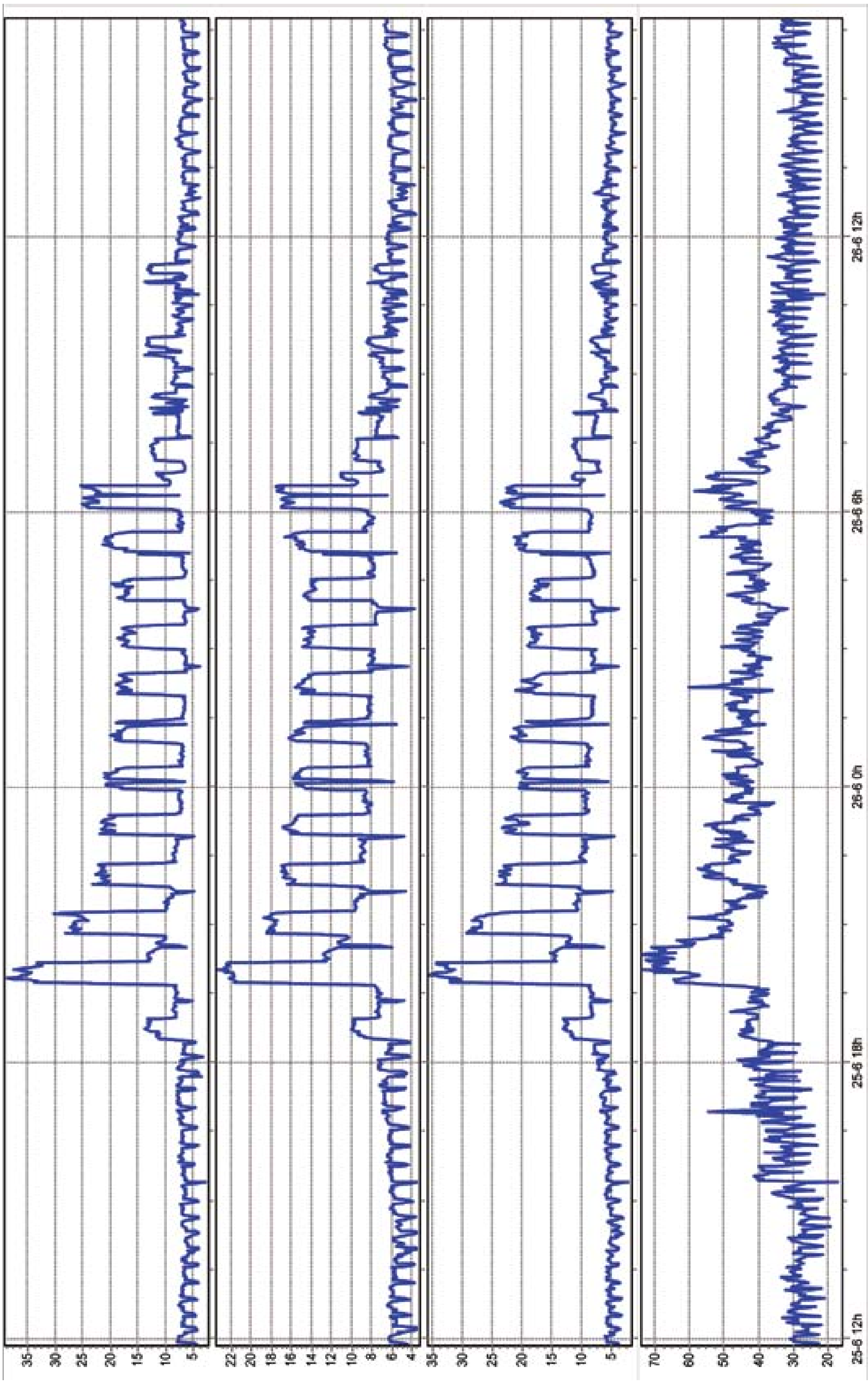


Fig.6.12 3rd Harmonic current profiles at a hospital in Malaysia

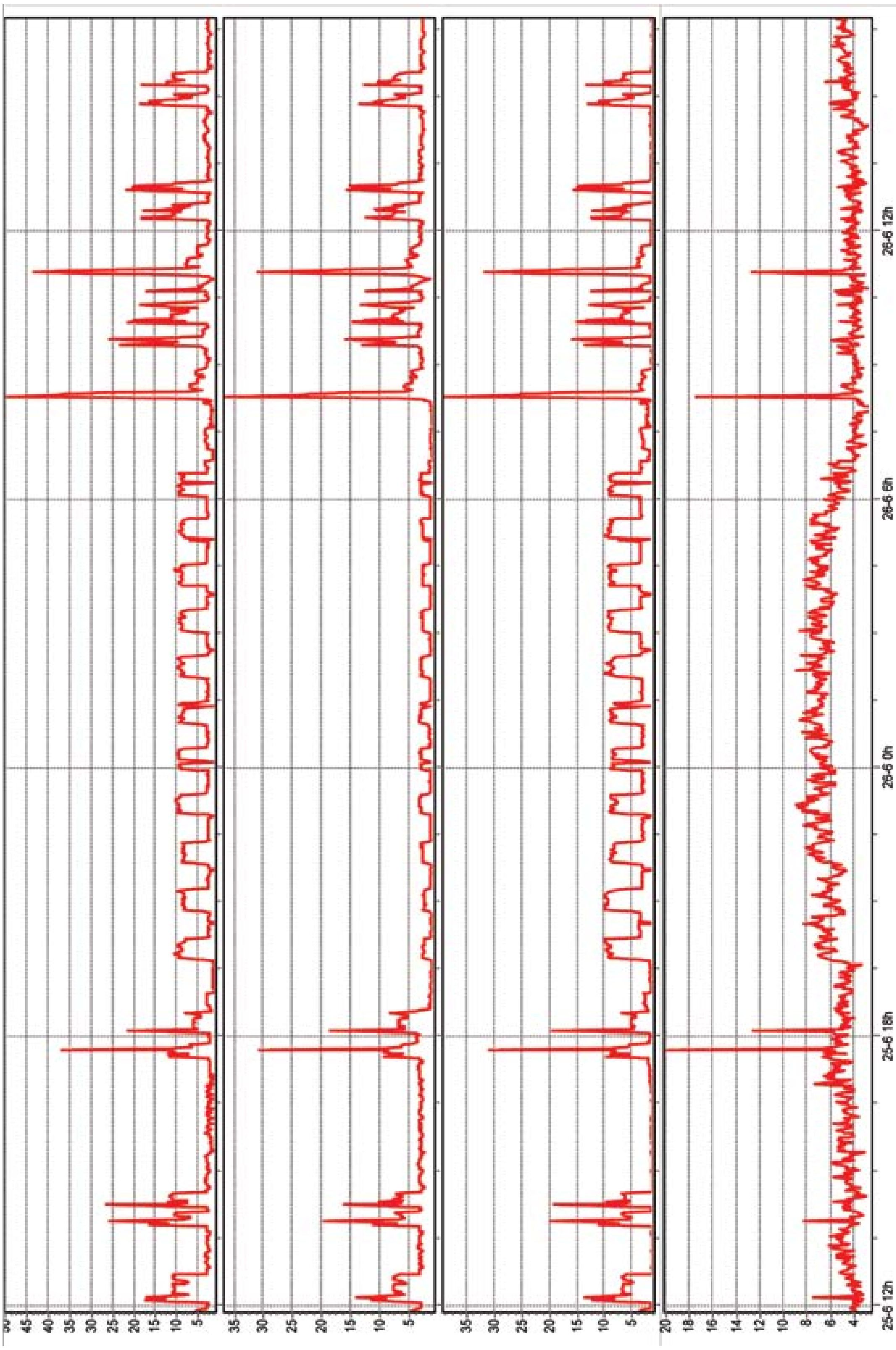


Fig.6.13 5th Harmonic current profiles at a hospital in Malaysia

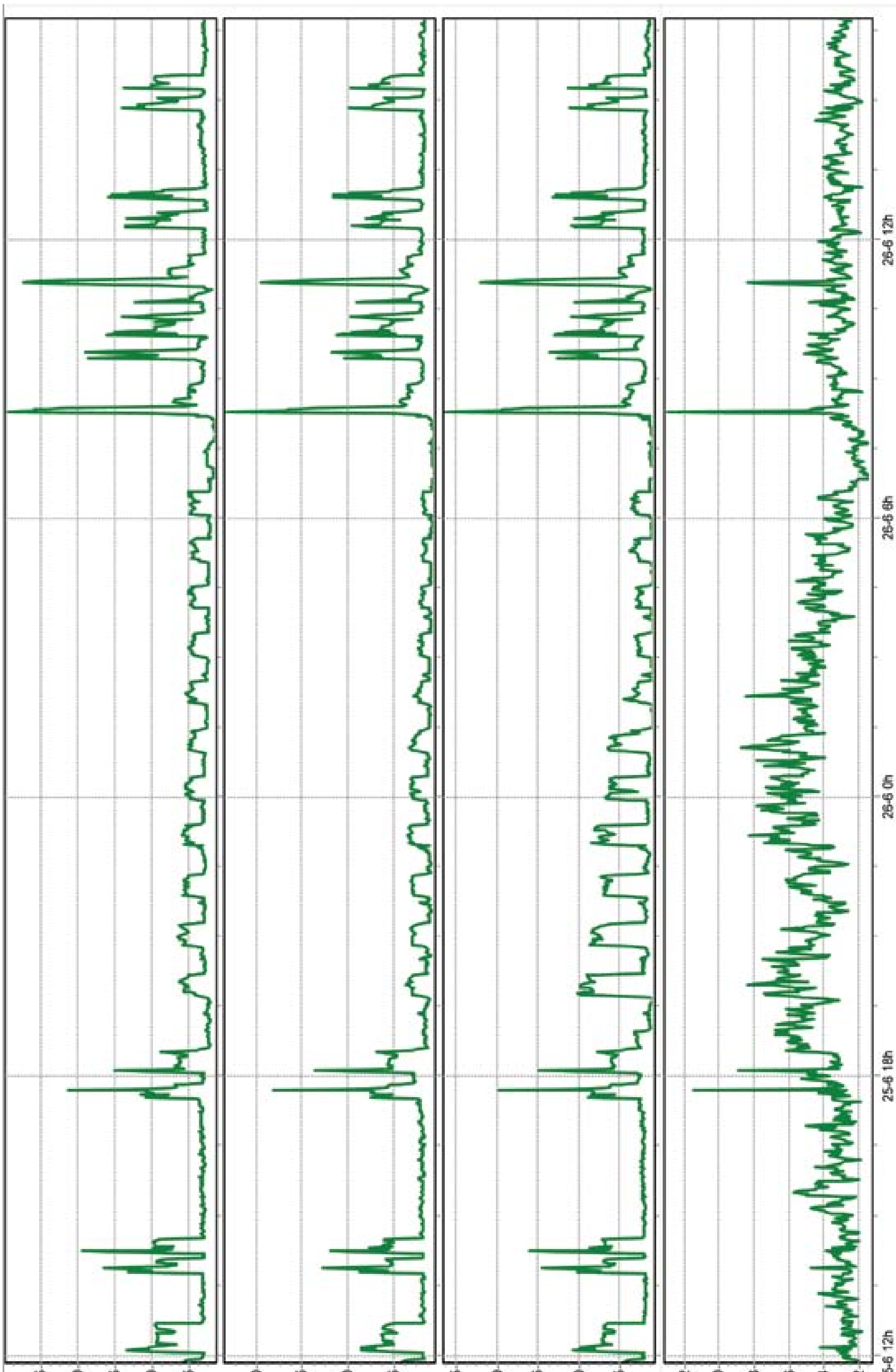


Fig.6.14 7th Harmonic current profiles at a hospital in Malaysia

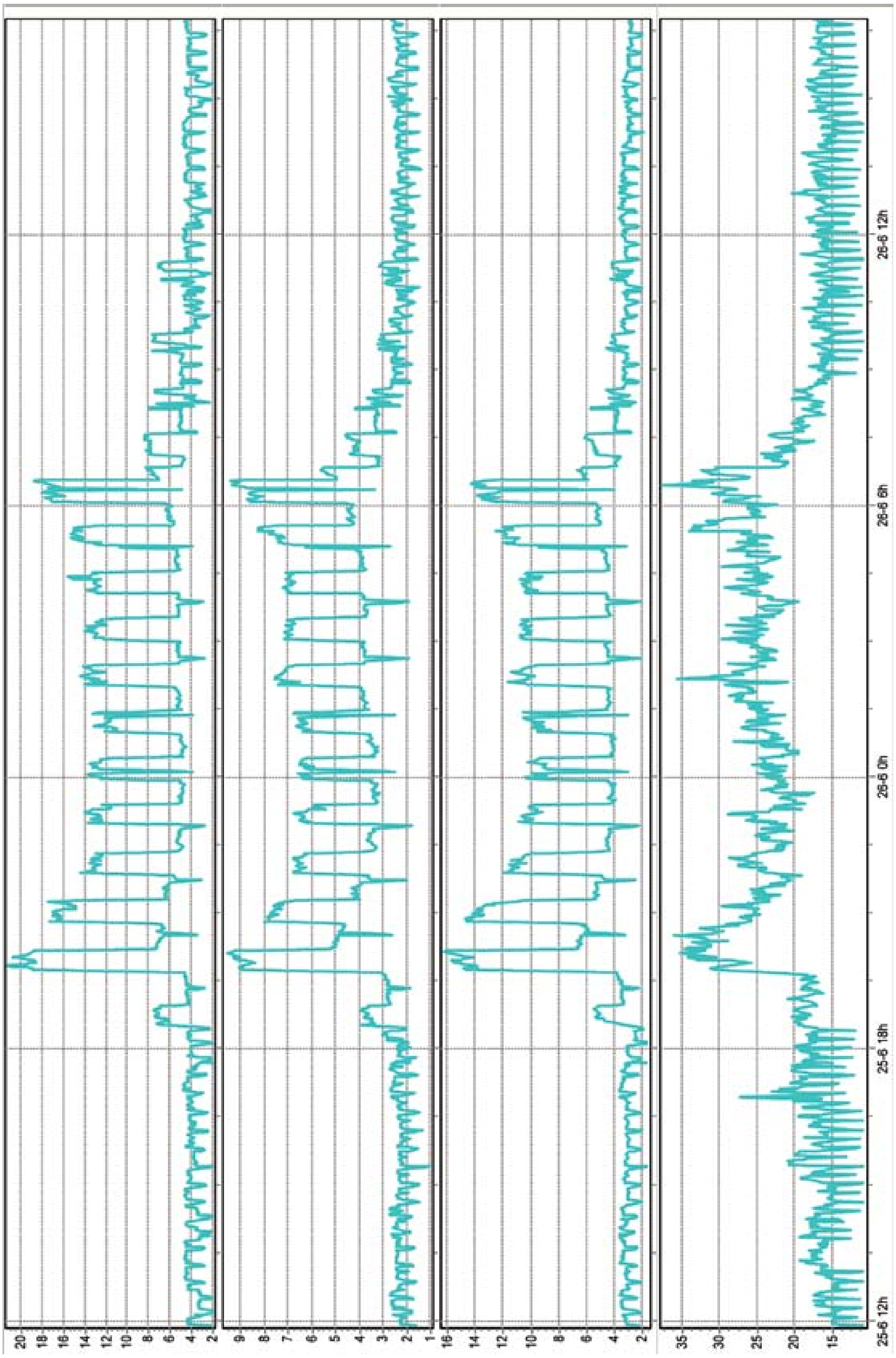


Fig.6.15 9th Harmonic current profiles at a hospital in Malaysia

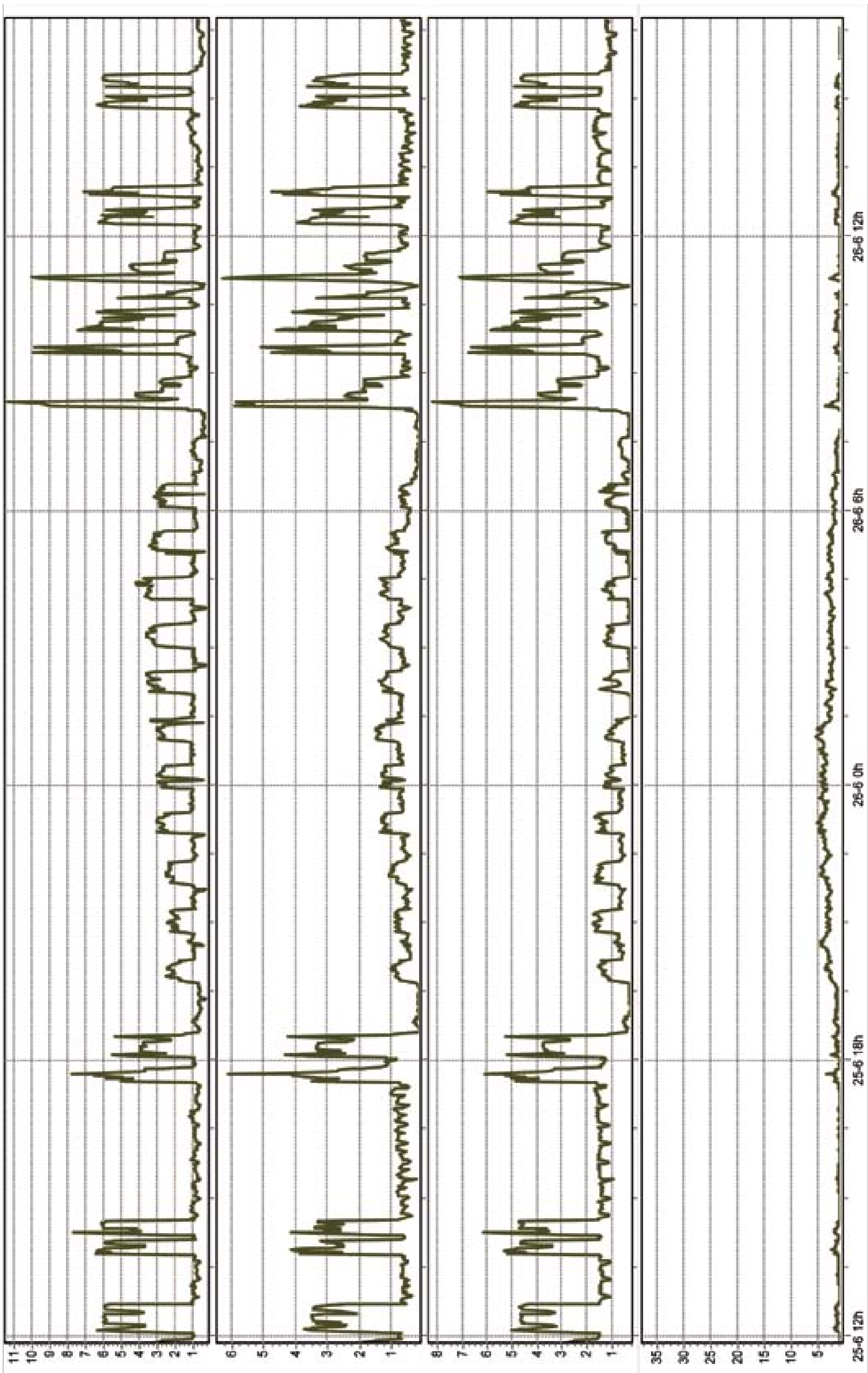


Fig.6.16 11th Harmonic current profiles at a hospital in Malaysia

CHAPTER 7

ELECTROMAGNETIC COMPATIBILITY (EMC) STANDARDS

7.0 UNDERSTANDING COMPATIBILITY LEVELS

In theory, the currents and voltages in a three-phase electricity distribution system have a perfect sinusoidal waveform, have unity power factor, are balanced (i.e. the voltages and currents in each phase have identical magnitudes) and the phases are displaced by exactly 120 degrees. In practice, the nature of the consumers' loads (primarily) causes distortion of current and voltages and poor balance between the phases. Over the last two decades the situation has become worse and today's networks have distorted voltages and currents and, even in their steady states, cannot be considered as a 'balanced and sinusoidal regime'.

Among the causes of this situation are:

- harmonic currents introduced by non-linear loads such as single- and three-phase rectifiers,
- arc furnaces, static-var compensators, etc.
- interharmonic currents produced by ac and dc arc furnaces, ac motor drives, etc.
- unbalance created by single-phase loads connected to the three-phase system
- flicker produced by fluctuating loads
- voltage variations (dips, interruptions) caused by faults on the grid, lightning strikes, etc.

In order to preserve good quality of power on the network, it is essential to have a set of standards that clearly specifies the limits that must be imposed on loads and networks. The objective is to provide an environment in which electromagnetic compatibility (EMC) is achieved. And to achieve this environment, the electromagnetic compatibility problem must first be addressed. There are two sides to the compatibility problem. Consumers' equipment operating on the network causes disturbances on the network and the resulting disturbances on the network affect the proper operation of other equipment on the network. To ensure compatibility it is necessary to control the maximum level of disturbance that may be present at any point on the network and establish a level of disturbance to which every item of equipment will be immune.

The network is very large and is far from homogeneous; for example, the impedance (Z) at the point of common coupling (PCC) depends on the structure and 'strength' of the local network and the density of equipment vary enormously. Each item of equipment produces some disturbance that aggregates in some way with that from other equipment. Equipment standards are designed to ensure that:

- the emission levels from each class of equipment are such that the connection of the equipment to the network will not unduly raise the overall level of disturbance
- the equipment will not be susceptible to the levels of disturbance that can be expected on the network.

7.1 TASK GROUP TO DEVELOP/REVISE EMC STANDARDS

The main task of IEC Technical Committee (TC) 77 working group and its' three subcommittees (SC) is to prepare Basic and Generic EMC publications specifying electromagnetic environments, emissions, immunity, test procedures, measurement techniques, etc. A most important part of this is the description and classification of the EM environment so that product committees can in turn specify the characteristics of the particular products they are standardizing. In general terms this means covering immunity and related questions over the whole frequency range, with these subcommittees:

- SC 77A dealing with low-frequency phenomena (up to and including 9 kHz),
- SC 77B handling high-frequency (> 9 kHz) continuous and transient phenomena, including electrostatic discharges, and
- SC 77C covering high-power transients such as the EM fields produced by high-altitude nuclear detonations (HEMP).

TC 77 covers the safety aspects of electromagnetic compatibility, having what in the IEC is called a horizontal safety function. The committee has also produced a Technical Specification (IEC 61000-1-2) on the methodology for achieving functional safety in an EMC context. The need and demand for TC 77's Basic and Generic EMC standards is strongly influenced by new technologies and industry trends that create a more and more 'hostile' EM environment. In particular, the density of electrical, electronic and radio communication equipment operating close to each other is increasing, as is miniaturization, and microelectronics have increasing operating frequencies. The need and demand for TC 77's Basic and Generic EMC standards is strongly influenced by new technologies and industry trends that create a more and more 'hostile' EM environment. In particular, the density of electrical, electronic and radio communication equipment operating close to each other is increasing, as is miniaturization, and microelectronics have increasing operating frequencies.

Although the most important standards have been completed in recent years, new trends in technology, as well as the globalization of trade, indicate that the standardization area covered by TC 77 will continue to develop. These trends include:

- the drive to save costs by harmonizing test methods world wide
- efforts to eliminate barriers to trade by harmonizing EMC requirements
- the need to ensure that equipment operates reliably despite the increasing likelihood of EM disturbances being present

The direct customers of TC 77 standards are EMC experts and product committees of the IEC - in effect the entire industry manufacturing or using electrical and electronic products. They are therefore not only amongst the most widely used standards within the IEC but are also becoming so in other international, regional and national standardizing organizations. This in turn means they are the basis for regional or national EMC regulations.

By ensuring EMC, the sensitive equipment can be protected from most power quality disturbances. In Malaysia, SIRIM coordinates the working group for the local IEC subcommittee. The members of these subcommittees comprise of professional institutions (IEM, FMM etc), customer associations (FMM, TEEAM etc), Energy Commission (EC), power utilities (TNB, SECSO etc), local universities and Government institutions (JKR etc).

7.2 EXAMPLES OF THE STANDARDS DEVELOPED BY SC 77A

Table 7.1 Examples of standards developed by SC 77A

Standards	Description
IEC 61000-2-2	Compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage power supply systems
IEC 61000-2-4	Compatibility levels in industrial plants for low-frequency conducted disturbances
IEC 61000-2-12	Compatibility levels for low-frequency conducted disturbances and signaling in public medium-voltage power supply systems
IEC 61000-4-7	General guide on harmonics and interharmonics measurements and instrumentation for power supply systems and equipment connected thereto.
IEC 61000-4-11	Testing requirement for Voltage dips, interruptions, variation Immunity for equipment rated less than 16A.
IEC 61000-4-13	Testing and measurement techniques – Harmonics and interharmonics including mains signaling at a.c. power port, low frequency immunity tests.
IEC 61000-4-14	Testing and measurement techniques – Voltage fluctuation immunity test.
IEC 61000-4-15	Testing and measurement techniques – Flicker meter – Functional and design specifications.

7.3 OBJECTIVE OF EMC STANDARDS

The objective of the EMC standard is to provide an environment in which electromagnetic compatibility (EMC) is achieved between the network and equipment.

The definition of EMC is:-

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

There are several parameters that need to be specified and controlled:

- emission level (EL)
- immunity level (IL)
- compatibility level (CL)
- emission limit (E)
- immunity limit (I)
- planning level (PL).

7.4 DESCRIPTION OF EMC STANDARDS

7.4.1 EMISSION LEVEL (EL)

The emission level is the disturbance level (DL) produced by a particular load at a particular location. Its value depends mainly on two factors:

- the characteristics of the equipment, including variations inherent in mass-produced equipment
- the characteristics of the supply network at the point of connection.

Although equipment is designed and manufactured to meet a standard (which will include the level of emissions permitted), individual items of mass produced equipment will inevitably have small differences in their emission of disturbances. Equipment is 'type tested' to ensure that it meets the requirements of standards but variations in components and exact assembly details will result in small variations in emission level.

This implies that the disturbance level produced by different examples of the same equipment in the same network would be different. Because many disturbances are manifested as variations or distortions in the current drawn by equipment the resulting disturbance, measured as a voltage disturbance, will depend on the supply network impedance, sometimes expressed in terms of short circuit power.

7.4.2 EMISSION LIMIT (E)

The emission limit is the maximum permitted value of emission level generated by a particular item of equipment. Note that the emission limit applies to a single piece of equipment, while compatibility level applies to the whole network. Emission limits can be confirmed by testing and non-compliant equipment design would then be eliminated. In practice, control of this process is left to the market, relying on manufacturers to test their designs properly and on users to report offending equipment.

The emission limit is a disturbance level set somewhat lower than the compatibility level. The reason for this is that the disturbances produced by all the loads in the system aggregate in a complex fashion to become the 'global' disturbance level. Some disturbances, such as 3rd harmonic currents, simply add arithmetically locally but are then mitigated by, for example, passing through the delta windings of transformers.

Other harmonic currents tend to aggregate as RMS sums, but are also mitigated by mixing with those from other sources, assisted by the phase changes that occur as the harmonics pass through transformers and the effects of inductance and capacitance on the network. However, locally, there may be unexpected increases due to resonance effects.

Emission levels are defined in absolute terms, e.g. an absolute limit on the current at a particular harmonic frequency, unlike the network disturbance levels, which are described in statistical terms. The correspondence between the two depends on the characteristics of networks and has been derived from many years of operating experience. Regulators and standards bodies have specified equipment emission limits that may be expected to lead to disturbance levels that will not exceed the required compatibility levels.

7.4.2.1 CLASSIFICATION OF EQUIPMENT

For the purpose of harmonic current limitation, equipment is classified as follows:-

Class A:

- balanced three-phase equipment;
- household appliances, excluding equipment identified as class D;
- tools, excluding portable tools;
- dimmers for incandescent lamps;
- audio equipment.

Class B:

- portable tools;
- arc welding equipment which is not professional equipment.

Class C:

- lighting equipment.

Class D:

Equipment having a specified power according to than or equal to 600 W, of the following types:

- personal computers and personal computer monitors;
- television receivers.

7.4.2.2 EMISSION LIMITS FOR HARMONIC

The standards specifying the emission limits are:

Table 7.2 Description of harmonic emission limits

Standards	Description
IEC 61000-3-2	Limits for harmonic current emissions (equipment input current < 16 A phase)
IEC 61000-3-4	Limits for harmonic currents produced by equipment connected to public low voltage systems with input current >16A per phase
IEC 61000-3-12	Limits for harmonic currents produced by equipment connected to public low voltage systems with input current >16A and ≤75A per phase

7.4.3 EMISSION LIMITS DEFINED IN IEC 61000-3-2 [22]

7.4.3.1 LIMITS FOR CLASS A EQUIPMENT

Table 7.3 Limits for Class A equipment

Harmonic order n	Maximum permissible harmonic current A
Odd harmonics	
3	2,30
5	1,14
7	0,77
9	0,40
11	0,33
13	0,21
$15 \leq n \leq 39$	$0,15 \frac{15}{n}$
Even harmonics	
2	1,08
4	0,43
6	0,30
$8 \leq n \leq 40$	$0,23 \frac{8}{n}$

7.4.3.2 LIMITS FOR CLASS B EQUIPMENT

For Class B equipment, the harmonics of the input current shall not exceed the values given in Table 7.3 multiplied by a factor of 1.5.

7.4.3.3 LIMITS FOR CLASS C EQUIPMENT

a) Active input power >25 W

For lighting equipment having an active input power greater than 25 W, the harmonic currents shall not exceed the relative limits given in Table 7.4. However, the limits given in Table 7.4 apply to incandescent lighting equipment that has built in dimmers or consists of dimmers built in an enclosure. For discharge lighting equipment that has built-in dimmers or consists of independent dimmers or dimmers built in an enclosure, the following conditions apply:

- harmonic current values for the maximum load condition derived from the percentage limits given in Table 7.4 shall not be exceeded;
- in any dimming position, the harmonic current shall not exceed the value of current allowed in the maximum load condition;

b) Active input power ≤ 25 W

Discharge lighting equipment having an active input power smaller than or equal to 25 W shall comply with one of the following two sets of requirements:

- the harmonic currents shall not exceed the power-related limits of Table 7.4.
- the third harmonic current, expressed as a percentage of the fundamental current, shall not exceed 86 % and the fifth shall not exceed 61 %; moreover, the waveform of the input current shall be such that it begins to flow before or at 60°, has its last peak (if there are several peaks per half period) before or at 65° and does not stop flowing before 90°, where the zero crossing of the fundamental supply voltage is assumed to be at 0°.
- If the discharge lighting equipment has a built-in dimming device, measurement is made only in the full load condition.

Table 7.4 Limits for Class C equipment

Harmonic order n	Maximum permissible harmonic currrent expressed as a percentage of the input current at the fundamental frequency %
2	2
3	$30 \cdot \lambda$ *
5	10
7	7
9	5
$11 \leq n \leq 39$ (odd harmonics only)	3
* λ is the circuit power factor	

7.4.3.4 LIMITS FOR CLASS D EQUIPMENT

For Class D equipment, the harmonic currents and the power shall be measured as defined in IEC 61000-4-7 [14]. The input currents at harmonic frequencies shall not exceed the values that can be derived from Table 7.5.

Table 7.5 Limits for Class D equipment

Harmonic order n	Maximum permissible harmonic current per watt mA/W	Maximum permissible harmonic current A
3	3,4	2,30
5	1,9	1,14
7	1,0	0,77
9	0,5	0,40
11	0,35	0,33
$13 \le n \le 39$ (odd harmonics only)	$\frac{3,85}{n}$	See Table 1

7.4.4 EMISSION LIMITS DEFINED IN IEC 61000-3-12 [23]

The IEC 61000-3-12 standard defines the harmonic limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ≤75 A per phase.

Table 7.6 Current emission limits for equipment other than balanced three-phase equipment

Minimal R_{sce}	Admissible individual harmonic current I_n/I_1 [a] %						Admissible harmonic current distortion factors %	
	I_3	I_5	I_7	I_9	I_{11}	I_{13}	*THD*	*PWHD*
33	21,6	10,7	7,2	3,8	3,1	2	23	23
66	24	13	8	5	4	3	26	26
120	27	15	10	6	5	4	30	30
250	35	20	13	9	8	6	40	40
≥ 350	41	24	15	12	10	8	47	47

NOTE 1 The relative values of even harmonics up to order 12 must not exceed $16/n$ %. Even harmonics above order 12 are taken into account in *THD* and *PWHD* in the same way as odd order harmonics.

NOTE 2 Linear interpolation between successive R_{sce} values is permitted. See also Annex B.

[a] I_1 = reference fundamental current; I_n = harmonic current component.

Note: PWHD (partial weighted harmonic distortion)

ratio of the RMS value of a selected group of higher order harmonics (in this International Standard beginning from the fourteenth harmonic), weighted with the harmonic order n, to the RMS value of the fundamental:

$$PWHD = \sqrt{\sum_{n=14}^{40} n \left[\frac{I_n}{I_1} \right]^2} \qquad (7.1)$$

The partial weighted harmonic distortion is employed in order to ensure that the effects of the higher order harmonic currents on the results are reduced sufficiently and individual limits need not be specified.

Table 7.7 Current emission limits for balanced three-phase equipment

Minimal R_{sce}	Admissible individual harmonic current I_n/I_1 [a] %				Admissible harmonic current distortion factors %	
	I_5	I_7	I_{11}	I_{13}	*THD*	*PWHD*
33	10,7	7,2	3,1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
≥350	40	25	15	10	48	46

NOTE 1 The relative values of even harmonics up to order 12 must not exceed 16/n %. Even harmonics above order 12 are taken into account in *THD* and *PWHD* in the same way as odd order harmonics.

NOTE 2 Linear interpolation between successive R_{sce} values is permitted. See also Annex B.

[a] I_1 = reference fundamental current; I_n = harmonic current component.

Table 7.8 Current emission limits for balanced three-phase equipment under specified conditions

Minimal R_{sce}	Admissible individual harmonic current I_n/I_1 [a] %				Admissible harmonic current distortion factors %	
	I_5	I_7	I_{11}	I_{13}	*THD*	*PWHD*
33	10,7	7,2	3,1	2	13	22
≥120	40	25	15	10	48	46

NOTE 1 The relative values of even harmonics up to order 12 must not exceed 16/n %. Even harmonics above order 12 are taken into account in *THD* and *PWHD* in the same way as odd order harmonics.

NOTE 2 Linear interpolation between successive R_{sce} values is permitted. See also Annex B

[a] I_1 = reference fundamental current; I_n = harmonic current component.

7.4.5 IMMUNITY LIMIT (I) FOR HARMONICS

The immunity limit (I) is the disturbance level that equipment must withstand without loss of performance. The immunity limit is determined by design and is assured by type testing, so there will be small variations between individual items of the same nominal design. Since installation conditions vary, there will be a much wider spread of performance among similar items in different installations. There will therefore be a distribution of immunity levels of equipment on the network.

For harmonics, the related standard for harmonic immunity is the IEC 61000-4-13, Electromagnetic compatibility (EMC) – Part 4-13: Testing and measurement techniques – Harmonics and interharmonics including mains signaling at a.c. power port, low frequency immunity tests [24]. Sensitive equipment is recommended to be tested to evaluate their sensitivities against harmonics.

7.4.6 COMPATIBILITY LEVELS FOR HARMONICS

There are two sets of standards that define the compatibility levels for most PQ disturbances i.e. European Union EN 50160 and IEC61000 series standards. EN 50160 gives the main voltage parameters and their permissible deviation ranges at the customer's point of common coupling (PCC) in public low voltage (LV) and medium voltage (MV) electricity distribution systems, under normal operating conditions. In this context, LV means RMS voltage does not exceed 1000 V and MV means RMS voltage value between 1 kV and 35 kV. The comparison of the EN 50160 requirements with those of the IEC 61000 standard are listed in Tables 7.9 (EN 50160 2000: Voltage characteristics for public power systems) [25] and 7.10 (IEC 61000-2-2/12: Voltage characteristics for public power system) [26].

Table 7.9 EN 50160 2000: Voltage characteristics for public power systems

Supply voltage phenomenon	Acceptable limits/ Frequency	Measurement Interval
Grid frequency	49.5Hz to 50.5Hz 47Hz to 52Hz	10 s
Slow voltage changes	230Volt ± 10%	10 min
Voltage Sags or Dips (≤1min)	10 to 1000 times (under 85% of nominal)	10 ms
Short Interruptions (≤ 3min)	10 to 100 times per year (under 1% of nominal)	10 ms
Accidental, long interruptions (> 3min)	10 to 50 times per year (under 1% of nominal)	10 ms
Temporary over-voltages (line-to-ground)	Mostly < 1.5 kV	10 ms
Transient over-voltages (line-to-ground)	Mostly < 6kV	N/A
Voltage unbalance Harmonic Voltages	Mostly 2% but occasionally 3% 8% (THD_V)	10 min 10 min

Table 7.10 IEC 61000-2-2/12: Voltage characteristics for public power system

Supply Voltage Phenomenon	Acceptable limits	Measurement Interval
Grid frequency	49.5Hz to 50.5Hz	10 s
Slow voltage changes	230Volt ± 8%	10 min
Voltage Sags or Dips (≤1min)	100 times (Rural / Overhead system) 10-100 times (Urban/Underground system)	10 ms
Short Interruptions (≤ 3min)	10 to 100 times per year (under 1% of nominal)	10 ms
Transient over-voltages (line-to-ground)	Mostly < 6kV	N/A
Voltage unbalance	2%	10 min
Harmonic Voltages	8% (THD_V)	10 min

For harmonics, both standards define the compatibility THD_V must be less than 8%. Details on the harmonic compatibility limits are shown in Table 7.11.

Table 7.11 Compatibility levels for individual harmonic voltages in low and medium voltage networks (% of fundamental component) reproduced from IEC 61000-2-2/12 [26].

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.4	6	0.5
13	3	21	0.3	8	0.5
$17 \le h \le 49$	$2.27 \cdot \frac{17}{h} - 0.27$	$21 < h \le 45$	0.2	$10 \le h \le 50$	$0.25 \cdot \frac{10}{h} + 0.25$

CHAPTER 8

ASSESSMENT PROCEDURE FOR EVALUATION AGAINST HARMONIC PLANNING LEVELS

8.0 UNDERSTANDING HARMONIC PLANNING LIMITS & EMC REQUIREMENT

At present, there are three technical standards that propose the work processes for assessing new harmonic loads before connection can be done to the power supply systems. These standards introduce harmonic limits termed as Harmonic Planning level. This level of a particular disturbance in a particular environment, adopted as a reference value for the limits to be set for the emissions from the loads and installations in a particular system, in order to co-ordinate those limits with all the limits adopted for equipment intended to be connected to the power supply system.

These are harmonic voltage levels that can be used for the purpose of determining emission limits, taking into consideration all distorting installations. Planning levels are specified by the power utility for all system voltage levels and can be considered as internal quality objectives of the power utility, and may be made available to individual customers on request. Planning levels for harmonics are equal to or lower than compatibility levels and they should allow co-ordination of harmonic voltages between different voltage levels. Only indicative values may be given because planning levels will differ from case to case, depending on system structure and circumstances.

The Electromagnetic Compatibility (EMC) level as explained in Chapter 6 is the specified electromagnetic disturbance level used as a reference level in a specified environment for co-ordination in the setting of emission and immunity limits. The basic concepts of planning and compatibility levels are illustrated in Figure 8.1 and Figure 8.2. They are intended to emphasize the most important relationships between the basic variables. Within an entire power system it is inevitable that some level of interference will occur on some occasions, hence there is a risk of overlapping between the distributions of disturbance levels and immunity levels. Planning levels for harmonics are generally equal to or lower than the compatibility level; they are specified by the system operator or owner. Immunity test levels are specified by relevant standards or agreed upon between manufacturers and customers.

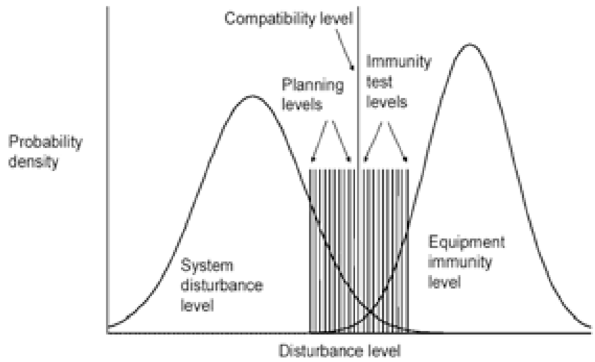


Fig.8.1: Illustration of basic voltage quality concepts with time/location statistics covering the whole system

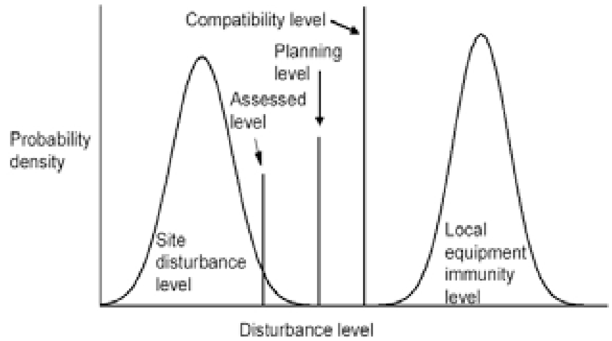


Fig.8.2: Illustration of basic voltage quality concepts with time statistics relevant to one site within the whole system

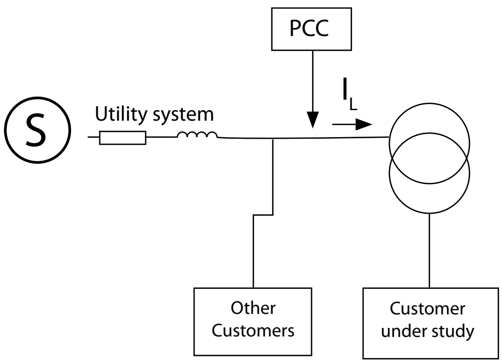
As Figure 8.2 illustrates, the probability distributions of disturbance and immunity levels at any one site are normally narrower than those in the whole power system, so that at most locations there is little or no overlap of disturbance and immunity level distributions. Interference is therefore not generally a major concern, and equipment is anticipated to function satisfactorily. Electromagnetic compatibility is therefore more probable than Figure 8.1 appears to suggest.

In this chapter, all the three technical standards are presented in brief. Each standard introduces specific harmonic limits termed as Harmonic Planning level and specific procedures. The reader/engineer is asked to read and understand all the limits and procedures dictated in these standards for actual application in assessing new equipment intended to be connected to the power supply system. Ensuring proper compatibility will prevent both long-term effects and very-short-term effects due to harmonics i.e.

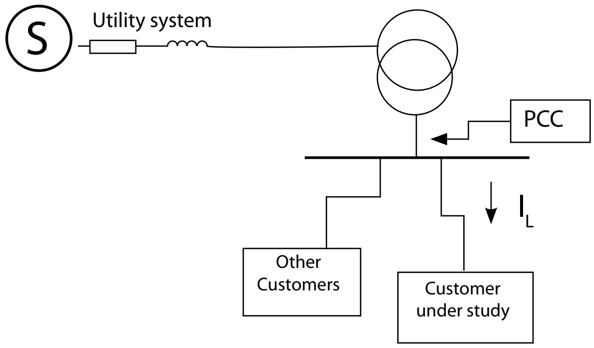
- The long-term effects relate mainly to thermal effects on cables, transformers, motors, capacitors, etc. They arise from harmonic levels that are sustained for 10 min or more.
- Very short-term effects relate mainly to disturbing effects on electronic devices that may be susceptible to harmonic levels sustained for 3 seconds or less.

8.1 ASSESSMENT OF HARMONIC EMISSION BASED ON IEEE 519:1992 [5]

IEEE Std. 519:1992, which is titled "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems", is the main document for harmonics in North America. There are a couple of concepts that must be grasped before applying the limits in this standard. The first concept is that of the Point of Common Coupling (PCC). The PCC is generally defined as the utility/customer connection point. It is this point at which the current distortion limits apply. Examples of two selections of PCC are shown in Figure 8.3. I_L is the maximum demand-load current (fundamental frequency component) at the point of common coupling. The PCC can be located at either the primary or the secondary of a supply transformer depending on whether or not multiple customers are supplied from the transformer.



a. PCC for MV customer



b. PCC for LV customers

Fig.8.3: Selection of PCC where customers can be connected

The other concept that is important is that of Total Demand Distortion (TDD) and Total Harmonic Distortion (THD). The equations for the THD & TDD have been explained in Chapter 2. The idea behind the standard is that harmonic limits are placed on a customer on the basis of current distortion relative to the total plant load. The limits do not apply to a specific non-linear load in the plant. The harmonic current limits change depend on the ratio of short circuit current to maximum demand load current at the PCC.

8.1.2 VOLTAGE DISTORTION LIMITS

The recommended THD_V values at the PCC are as follows:-

Table 8.1 IEEE 519:1992 Voltage Distortion Limits

Bus voltage (Vn) at PCC	Individual harmonic distortion (%)	Total harmonic distortion (%)
Vn ≤ 69 kV	3.0	5.0
69 < Vn ≤ 161 kV	1.5	2.5
Vn > 161 kV	1.0	1.5

Note: The values of the THD_V is based on RMS voltage values and not based on fundamental voltage values.

8.1.3 CURRENT DISTORTION LIMITS

When a customer's equipment draws current from the utility in a nonlinear or choppy manner, this is called current distortion. It always produces harmonics in the load current waveform and can produce significant harmonics in the voltage waveform at the PCC and elsewhere. IEEE 519 limits for current distortion are described in tables 7.2 to 7.4. This table applies to steady state operation of six-pulse drives and general distortion situations. For higher pulse number drives, the limits for characteristic harmonics in the tables below should be increased by a factor of $\sqrt{\frac{q}{6}}$ where q is the pulse number of the drive being considered. This can be done provided that every non-characteristic and even harmonic is less than 25% of the limits in these tables.

Table 8.2 IEEE 519:1992 Current Distortion Limits (Vn ≤ 69 kV)

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

Table 8.3 IEEE 519:1992 Current Distortion Limits (69 kV<Vn≤161 kV)

I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	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	1.25	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	20.0

Table 8.4 IEEE 519:1992 Current Distortion Limits (69 kV<Vn≤161 kV)

I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<50	2.0	1.0	0.75	0.3	0.15	2.5
≤50	3.5	1.75	1.25	0.5	0.25	4.0

All harmonic power generation equipment is limited to these values of current distortion regardless of the actual short circuit ratio, I_{SC}/I_L. I_{SC} is the short circuit current at the PCC. The load current, I_L, is defined as the average for the preceding 12 months kW portion of the currents measured at the times of monthly peak demand by the demand meter. For a balanced three-phase load I_L is calculated as $I_L = kW_{demand}/(kV_{LL}\sqrt{3})$. Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

8.1.4 ASSESSMENT PROCEDURE FOR HARMONIC GENERATING LOADS

The general procedure for applying harmonic limits involves characterizing the harmonic sources, evaluating the impact on the system and implementing methods for harmonic control (if necessary). This procedure will involve both the power utility and customers. A general two stage procedure for evaluating customer harmonic injection is shown in Figure 8.4.

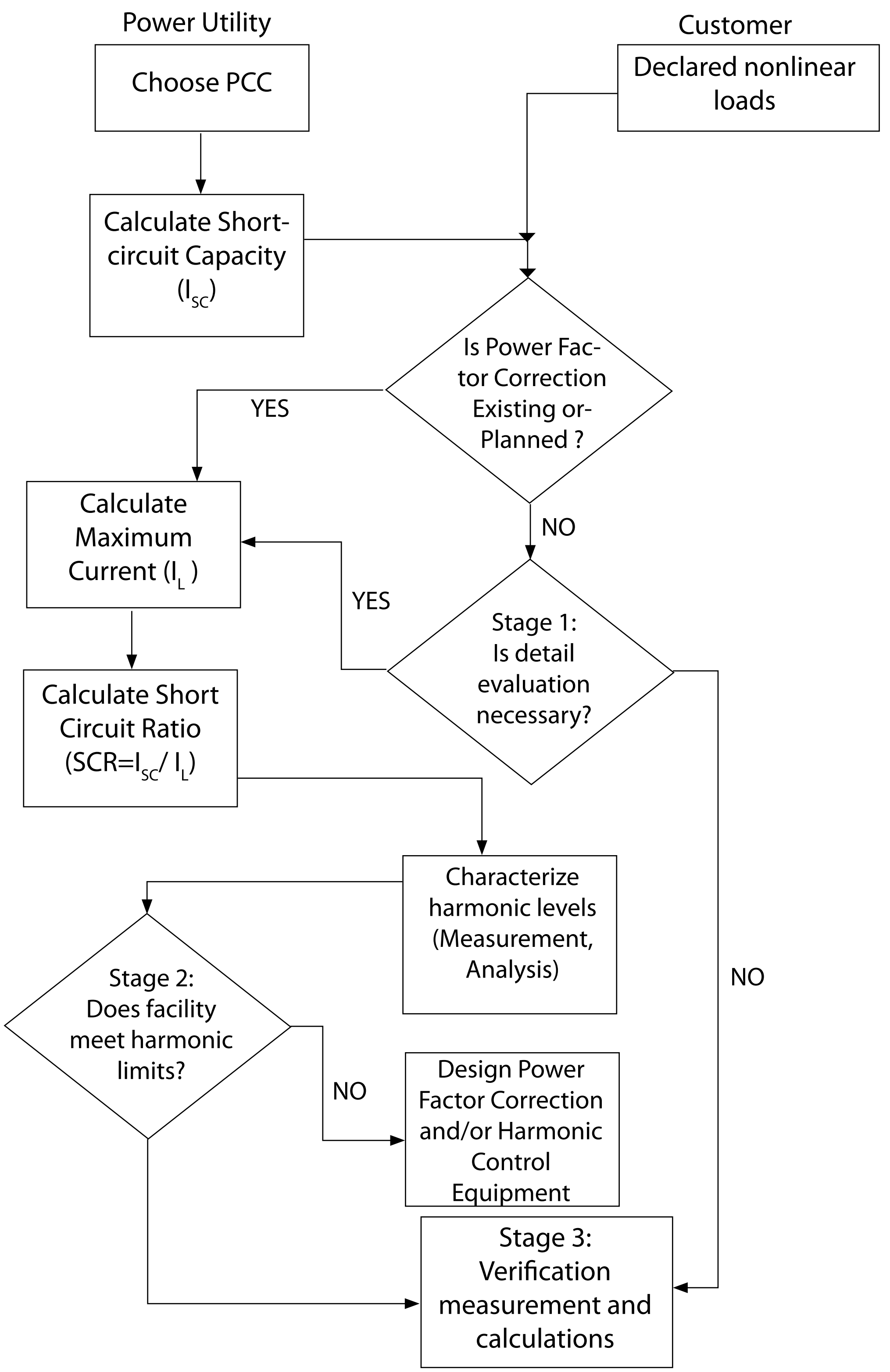


Fig.8.4: Procedure for harmonic evaluation based on IEEE 519

For detail understanding of this procedure, please refer to the IEEE 519 Technical Standard.

8.1.4.1 STAGE 1 : AUTOMATIC ACCEPTANCE

In Stage 1, harmonics from small customers or customers with only a limited amount of disturbing load can be accepted without detailed evaluation of the harmonic generating characteristics or the supply system response. One approach for this initial evaluation involves calculating a "weighted disturbing power", SDW to characterize the amount of disturbing load within the customer facility. This can be done using the weighting factors in Table 8.5 for common types of harmonic producing loads.

The weighted disturbing power is calculated as follows:

$$S_{Dw} = \sum_i S_{Di} W_i \tag{8.1}$$

where: S_{Di} is the power rating for an individual disturbing load (kVA)

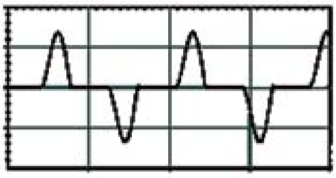
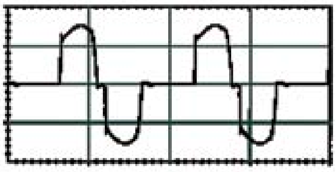
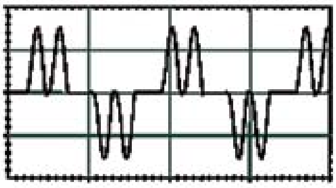
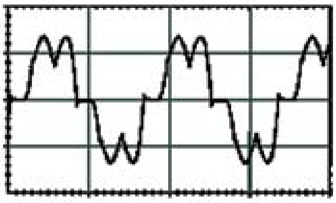
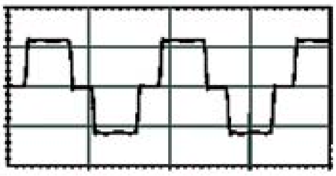
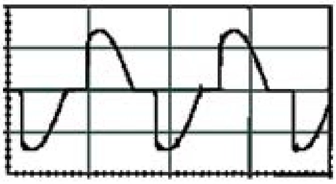
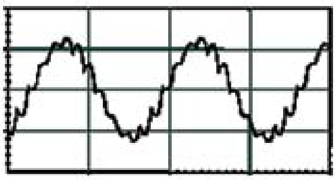
W_i is the weighting factor for the disturbing load (pu)

If the portion of the total load which is nonlinear is not known, it can be assumed that the load is harmonic producing with a weighting of 1.0. This sets a limit for the size of the customer that would require harmonic evaluation, regardless of the type of equipment used. Applying harmonic limits for very small customers can be better accomplished by promoting equipment that has reduced harmonic generation characteristics. The acceptability of the customer in Stage 1 can be evaluated by comparing the weighted disturbing power with the short circuit capacity at the point of interconnection. The following criterion is proposed:

If $S_{Dw} / S_{sc} < 0.1\%$, then automatic acceptance

A simpler Stage 1 evaluation can be performed using the percentage of the total facility load that is nonlinear. If the majority of the nonlinear load is one of the types in the first three rows of Table 8.5, a detailed harmonic evaluation should only be necessary if the load is more than 5% of the total facility load. For other types of loads, this percentage can be as high as 10%. It is important to note that a more detailed harmonic evaluation should always be performed if the customer has or is considering power factor correction capacitors. The potential for resonance concerns and harmonics from the supply system should be evaluated regardless of the percentage of nonlinear load in the facility.

Table 8.5 Weighting factors for different types of harmonic producing loads

Typical equipment connected to LV, MV or HV	Typical current waveform	Typical current THD	Weighting Factor (W_j)
Single phase power supply (rectifier and smoothing capacitor)		80 % (high 3rd)	2,5
Semi-converter		High 2nd,3rd, 4th at partial loads	2,5
6-pulse converter, capacitive smoothing, no series inductance		80 %	2,0
6-pulse converter, capacitive smoothing with series inductance > 3%, or d.c. drive		40 %	1,0
6-pulse converter with large inductor for current smoothing		28 %	0,8
AC voltage regulator		Varies with firing angle	0,7
12-pulse converter		15 %	0,5

8.1.4.2 STAGE 2: EVALUATION ACCORDING TO THE CURRENT LIMITS

Stage 2 involves application of the current limits specified in IEEE 519-1992. The current limits are dependent on the customer size, the short circuit capacity at the PCC, and the individual harmonic components involved. Harmonic limits are expressed as a percentage of the customer's average maximum demand load current.

If some type of harmonic control is needed (e.g. passive harmonic filters), the design should be a cooperative effort to avoid interaction problems between the power system and the equipment. The power utility may elect to allow conditional acceptance of harmonic injection levels from a facility that exceed the levels specified in the standard. In some cases, this could be advantageous if the costs of reducing the harmonic injection levels are prohibitive and there are no adverse impacts associated with the higher levels of harmonic current injection (i.e. they will not cause the voltage distortion to exceed allowable levels). Acceptance of higher harmonic injection levels would be subject to revision if adverse impacts are associated with these harmonics at a later date. For instance, harmonic control could be required in the future if additional facilities add harmonic generating equipment that increases the overall system distortion levels.

8.1.4.3 STAGE 3: VERIFY HARMONIC PERFORMANCE WITH MEASUREMENTS

Measurements over a period of time should be used to verify that harmonic current levels are within limits and that harmonic control equipment is performing as designed. The period of time selected should adequately characterize the time varying and statistical characteristics of the harmonic levels.

For more understanding on harmonic measurement, please refer to the subchapter 8.6.

8.2 ASSESSMENT OF HARMONIC EMISSION BASED ON ENGINEERING RECOMMENDATION ER G5/4 [27].

The intention of the Engineering Recommendation G5/4, first published in 2001, was to try to ensure that the levels of harmonics in the public electricity supply do not constitute a problem for other users taking from the same source of electrical supply. This is a primary function of Electromagnetic Compatibility (EMC) Management and Regulation, and it forms part of the

Distribution Code which is a statutory requirement placed on the UK Electricity Supply Industry. In addition, under EU legislation the supply industry has a duty to meet BS EN 50160, Voltage Characteristics of Electricity Supplied by Public Distribution Systems [25], which includes magnitudes of harmonicvoltage distortion amongst other parameters.

To facilitate the connection of non-linear equipment, ER G5/4 specifies harmonic current emission limits with the intention of limiting the overall voltage distortion to no more than the network planning levels (PL) specified in ER G5/4, which in turn are set to achieve the required compatibility level. ER G5/4 identifies consumers by their point of common coupling (PCC) to the supply, and applies limits at that point. ER G5/4 therefore applies to every consumer connected to the Public Electricity Supply (PES), including:

- Domestic
- Commercial, shop and office consumers
- Industrial customers

It forms part of the consumer's agreement to connect, and it is the responsibility of the individual consumer to ensure that the appropriate procedures to agree connection of new loads are followed. It is also very important that the consumer understands the responsibilities placed on him/her by the power utilities to avoid the possibility of having to implement costly remedial measures in the event of a problem. It is important to understand that ER G5/4 is effectively an "Installation Standard" and applies to the total harmonic generating equipment installed by a consumer. The summary of the THD_V system planning levels (PL) are shown in Table 8.6. Details of the planning levels (PL) are shown in tables 8.7 to 8.9.

Table 8.6 ER G5/4 THD_V System Planning Levels (PL)

Voltage (kV)	THD_V (%)
0.400	5.0
6.6 kV to 20 kV	4.0
>20 kV to 36.5 kV	3.0
66 kV to < 145 kV	3.0

Table 8.7 Planning Levels for Harmonic Voltages in 400V Systems

Odd Harmonics (Non-Multiple of 3)		Odd Harmonics (Multiple of 3)		Even Harmonics	
Order "h"	Harmonic Voltage (%)	Order "h"	Harmonics Voltage (%)	Order "h"	Harmonic Voltage (%)
5	4.0	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	0.7				
>25	0.2+0.5(25/h)				
The total voltage harmonic distortion level is 5%					

Table 8.8 Planning Levels for Harmonic Voltages in 6.6kV, 11kV and 20kV Systems

Odd Harmonics (Non-Multiple of 3)		Odd Harmonics (Multiple of 3)		Even Harmonics	
Order "h"	Harmonic Voltage (%)	Order "h"	Harmonics Voltage (%)	Order "h"	Harmonic Voltage (%)
5	3.0	3	3.0	2	1.5
7	3.0	9	1.2	4	1.0
11	2.0	15	0.3	6	0.5
13	2.0	21	0.2	8	0.4
17	1.2	>21	0.2	10	0.4
19	1.2			12	0.2
23	1.2			>12	0.2
25	0.7				
>25	0.2+0.5(25/h)				

The total voltage harmonic distortion level is 4%

Table 8.9a Planning Levels for Harmonic Voltages in Systems >20kV to 145kV

Odd Harmonics (Non-Multiple of 3)		Odd Harmonics (Multiple of 3)		Even Harmonics	
Order "h"	Harmonic Voltage (%)	Order "h"	Harmonics Voltage (%)	Order "h"	Harmonic Voltage (%)
5	2.0	3	2.0	2	1.0
7	2.0	9	1.0	4	0.8
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(25/h)				
The total harmonic distortion level is 3%					

Table 8.9b Planning Levels for Harmonic Voltages in 275kV and 500kV Systems

Odd Harmonics (Non-Multiple of 3)		Odd Harmonics (Multiple of 3)		Even Harmonics	
Order "h"	Harmonic Voltage (%)	Order "h"	Harmonics Voltage (%)	Order "h"	Harmonic Voltage (%)
5	2.0	3	1.5	2	1.0
7	1.5	9	0.5	4	0.8
11	1.0	15	0.3	6	0.5
13	1.0	21	0.2	8	0.4
17	0.5	>21	0.2	10	0.4
19	0.5			12	0.2
23	0.5			>12	0.2
25	0.5				
>25	0.2+0.3(25/h)				
The total voltage harmonic distortion level is 5%					

8.2.1 ASSESSMENT PROCEDURE FOR THE CONNECTION OF NON-LINEAR LOADS

The ER G5/4 defines three stages of assessment, which increase in complexity. The objective of this three stage approach is to balance the degree of detail required by the assessment process with the degree of risk that the connection of the particular equipment will result in unacceptable harmonic voltage (V_h) levels occurring on the supply system if it is connected without any mitigation measures.

Where a user wishes to install new equipment to extend an existing installation, and where agreement to connect has already been established under previous rules, it is possible that the connection of additional equipment could involve a new and lower limit being applied to the whole installation under the terms of a new agreement. This would be retrospective, and therefore difficult to enforce. In these circumstances, agreement to connect without increase in the aggregate harmonic current loading should be forthcoming, although the overall connection may be for a higher power.

Where a user wishes to replace existing equipment with new equipment of similar functionality there should be no need to repeat the application procedure, if documentary evidence exists that the levels of harmonic currents generated by the new equipment do not exceed the existing levels. The flowchart for the three stage procedures for evaluating customer harmonic injection is shown in Figure 8.5. Explanations of the mnemonics in the figure are shown below:-

PL - Planning Level
I_h – harmonic current
V_h - harmonic voltage
V_{5p} – 5^{th} harmonic voltage
DNO - Distribution network operator (power utility)

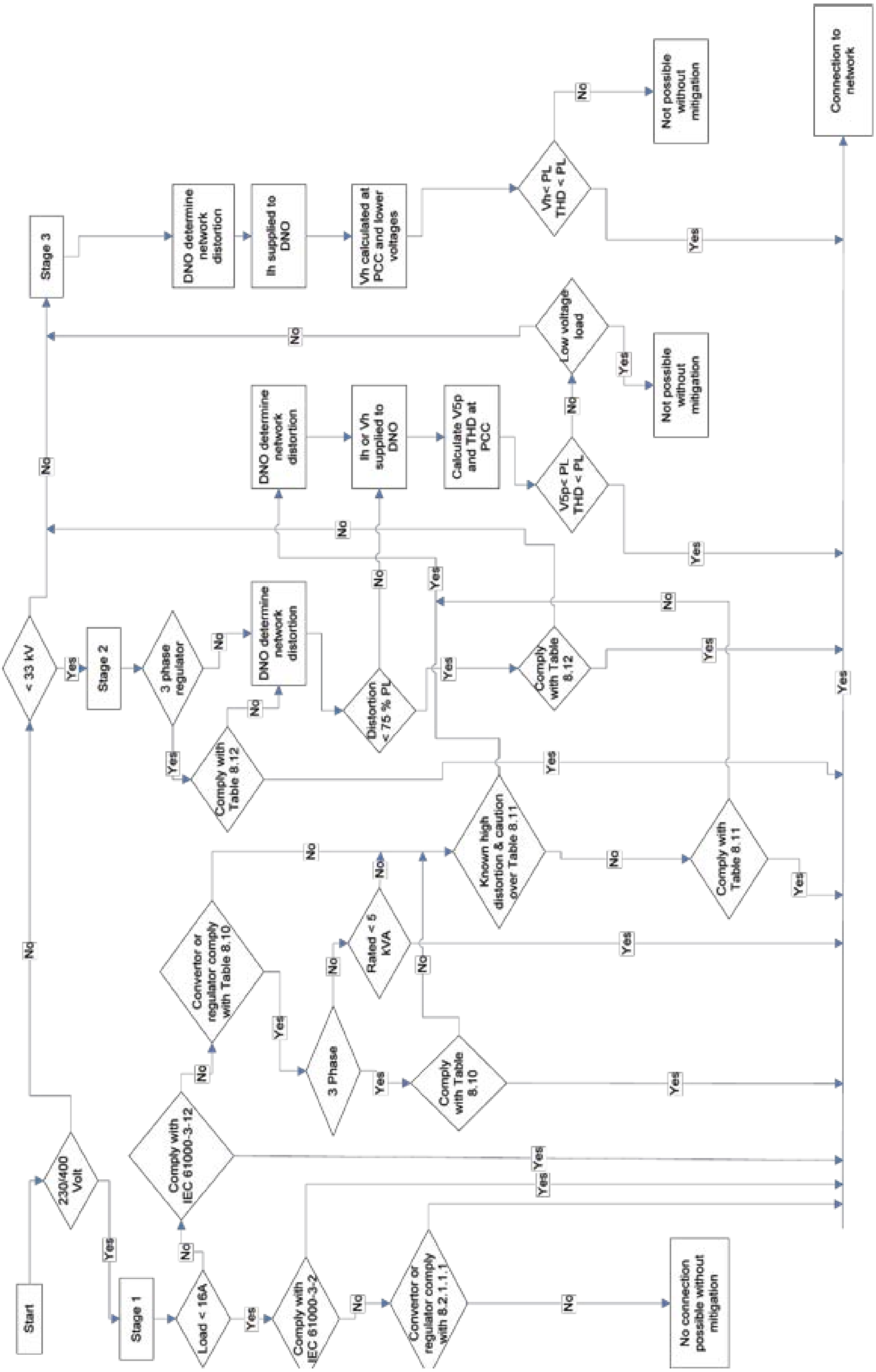


Fig.8.5 Procedure for harmonic evaluation based on ER G5/4

8.2.1.1 STAGE 1 ASSESSMENT

Stage 1 assessment applies to all 230/400 V individual items of equipment, generating plants and groups of non-linear equipment that are intended for connection to low voltage networks not known to have excessive background levels of harmonic voltage distortions.

Application for connection of all loads should be treated with caution at location where existing background levels of voltage distortion are known to be approaching the planning level (PL) in Table 8.6. A customer's non-linear equipment can be connected under a Stage 1 assessment provided at least one of the relevant conditions in 8.2.1.1.1 and 8.2.1.1.2 are met.

Aggregate load or equipment emissions which do not meet the Stage 1 criteria or where caution is required because of high background levels of distortions shall be accessed in accordance with procedures in 8.2.1.2 of Stage 2. The Stage 2 assessment shall be made at low voltage. If the predicted 5th harmonic and THD level distortion exceed Table 8.9 low voltage planning level, mitigation method is required. The prediction of THD for comparison with the Stage 2 limit requires all harmonics up to and including 50th harmonics to be taken into account in calculations.

8.2.1.1.1 CUSTOMER NON-LINEAR EQUIPMENT HAVING AN AGGREGATE LOAD OR RATED CURRENT LESS THAN OR EQUAL TO16A PER PHASE

Under the EU EMC Directive, any equipment designed for use in a domestic environment, with nominal current less than or equal to 16 A RMS (per phase), and which meets Harmonized European Standard IEC 61000–3-2, will carry a "CE mark" to meet this regulation. It may then be connected without further assessment.

Where a number of items of equipment are installed, the aggregate of the rated currents must be less than or equal to 16 A, and each individual piece of equipment must also comply with IEC 61000-3-2. Basically, this standard covers domestic equipment such as televisions, washing machines, etc. and it is these devices that are responsible for the bulk of harmonic voltage distortion throughout the network. Under this standard, drives are considered to be professional equipment, and with a total rated input over 1 kW they will be are accepted with no limits under this standard.

If the equipment is a conventional inverter load, and the combined total rating is under 5 kVA for a single-phase supply, it may again be connected without further assessment.

A customer may connect without assessment individual single and three phase convertors and regulators intended only for industrial application or overnight battery charging and which by design have negligible even harmonic emission. When a number of single phase devices are installed are installed by a customer at one location with a three phase supply, an attempt must be made to balance the non-linear loads equally between phases.

8.2.1.1.2 CUSTOMER NON-LINEAR EQUIPMENT HAVING AN AGGREGATE LOAD OR RATED CURRENT GREATER THAN 16A PER PHASE

Aggregate load or single item of non-linear low voltage equipment complying with the emission limits of Stages 1 or 2 of IEC 61000-3-12, may be connected without further assessment, subject to the fault level at the PCC being at least equal to the minimum value defined by the power utility.

A. Convertors and AC Regulators

A.1 Single phase equipment

Single phase convertors and regulators intended only for industrial applications or for overnight battery charging and which be design have negligible even harmonic emissions, may be connected without assessment if the aggregate load does not exceed 5 kVA per installation.

A.2 Three phase equipment

Table 8.10 sets out the maximum value of aggregate ratings of three phase convertor or AC regulator equipment, which may be connected to any low voltage system without further assessment.

Table 8.10 Maximum aggregate of convertor and regulator ratings which may be connected under Stage 1

System voltage at PCC	Three phase convertor ratings in kVA		Three phase regulator ratings in kVA
400 V	6 pulse	12 pulse	6 pulse thyristor
	12	50	14

8.2.1.1.3 AGGREGATE LOADS AND OTHER EQUIPMENT RATED > 16 A PER PHASE

For all installations where there are concentrations of non-linear equipment, the aggregate emission per phase should not exceed the values in Table 8.11. This restricts the total amount of equipment that can be installed by a single consumer under the Stage 1 procedure, and includes multiple equipments meeting the harmonized standard IEC 61000-3-2 and IEC 61000-3-12. One possible problem area in this procedure is where the standing voltage distortion level is already close to or above the planning level (PL). In this case, the power utility reserves the right to examine any additional load under the Stage 2 procedure.

Table 8.11 Stage 1, Maximum permissible harmonic current emission per customer for aggregate loads > 16A per phase

Harmonic order	Emission current, I_h	Harmonic order	Emission current, I_h	Harmonic order	Emission current, I_h	Harmonic order	Emission current, I_h
2	28.9	15	1.4	28	1.0	41	1.8
3	48.1	16	1.8	29	3.1	42	0.3
4	9.0	17	13.6	30	0.5	43	1.6
5	28.9	18	0.8	31	2.8	44	0.7
6	3.0	19	9.1	32	0.9	45	0.3
7	41.2	20	1.4	33	0.4	46	0.6
8	7.2	21	0.7	34	0.8	47	1.4
9	9.6	22	1.3	35	2.3	48	0.3
10	5.8	23	7.5	36	0.4	49	1.3
11	39.4	24	0.6	37	2.1	50	0.6
12	1.2	25	4.0	38	0.8		
13	27.8	26	1.1	39	0.4		
14	2.1	27	0.5	40	0.7		

8.2.1.2 STAGE 2 ASSESSMENT

If the levels of harmonics exceed those for Stage 1, the standing harmonic distortion is already close to the planning level (PL), or the point of common coupling is at medium voltage (6.6 kV to 22 kV), then a different procedure is called for.

A customer with aggregate of three phase convertor and regulator equipment ratings are less than those given in Table 8.12 may be connected without further assessment.

Table 8.12 Maximum aggregate of convertor and regulator ratings

System voltage at PCC	Three phase convertor ratings in kVA		Three phase regulator ratings in kVA
6.6, 11, 20 and 22 kV	6 pulse	12 pulse	6 pulse thyristor
	130	250	150

Connection of customers' equipment which in aggregate comply with Table 8.13 emission limits may be made without a voltage assessment provided that the levels of network distortion, measured before connection is made are less than 75% of the planning levels given in Tables 8.7 and 8.9.

Otherwise the power utility will be required to determine the network background voltage distortion. This should be a measured value, and for a balanced load application should record as a very minimum the primary odd distorting harmonics, up to the 50^{th}, plus the total harmonic distortion (THD_V) from 2^{nd} to 50^{th} harmonic.

Secondly, the background harmonic must be measured over a period of seven days to allow the results to be assessed realistically. Under ER G5/4, if the measured distortion on a network is less than 75% of the planning level (PL) in Tables 8.6 and 8.8, then a summation of currents can be used and compared with ER G5/4. Within the scope of ER G5/4, there is the provision to allow the background level to be assessed on the basis of the level that is not exceeded for 95% of the time. If the equipment will not be in continuous operation, the background should only be considered for the hours and days of the week that the equipment will be operated. As an example, taking an 11 kV point of common coupling (PCC), if the measured THD_V is less than 3% i.e. less than 75% of the planning level at 4%, and the 5^{th} harmonic distortion is less than 2.25% (75% of 3%), then we can apply the limits in Table 8.13.

The planning levels for THD_V are the same as the former ER G5/3 levels for 400 V and 11 kV networks (5% and 4%), however, maximum 5^{th} harmonic content is now introduced (4% and 3%). The values of current permitted in Table 8.13 are substantially lower than the previous ER G5/3 Stage 2 limits.

Table 8.13 Stage 2, Maximum permissible harmonic current emission per customer in Ampere, RMS per phase

Harmonic order	PCC on 6.6, 11 & 20 kV	PCC on 22 kV	Harmonic order	PCC on 6.6, 11 & 20 kV	PCC on 22 kV	Harmonic order	PCC on 6.6, 11 & 20 kV	PCC on 22 kV	Harmonic order	PCC on 6.6, 11 & 20 kV	PCC on 22 kV
2	4.9	3.3	15	0.3	0.3	28	0.2	0.2	41	0.4	0.4
3	6.6	4.4	16	0.4	0.4	29	0.8	0.8	42	0.1	0.1
4	1.6	1.3	17	3.3	2.0	30	0.1	0.1	43	0.4	0.4
5	3.9	2.6	18	0.2	0.3	31	0.7	0.7	44	0.2	0.2
6	0.6	0.6	19	2.2	1.8	32	0.2	0.2	45	0.1	0.1
7	7.4	5.0	20	0.3	0.3	33	0.1	0.1	46	0.2	0.2
8	0.9	0.9	21	0.1	0.1	34	0.2	0.2	47	0.3	0.3
9	1.8	1.5	22	0.3	0.3	35	0.6	0.6	48	0.1	0.1
10	1.4	1.4	23	1.8	1.1	36	0.1	0.1	49	0.3	0.3
11	6.3	4.7	24	0.1	0.1	37	0.5	0.5	50	0.1	0.1
12	0.2	0.2	25	1.0		1.0	38	0.2			
13	5.3	4.0	26	0.3	0.3	39	0.1	0.1			
14	0.5	0.5	27	0.1	0.1	40	0.2	0.2			

8.2.1.2.1 APPLICATION OF THE VOLTAGE DISTORTION CALCULATION

If the distortion, present before the new load is connected, exceeds 75% of the appropriate voltage planning level or the currents exceed Table 8.13 limits, then, it is necessary to determine the voltage distortion that is likely to be generated by the new load, and to predict the overall levels of voltage distortion that will result. The prediction of THD for comparison with the Stage 2 limit requires all harmonics up to and including 50^{th} harmonics to be taken into account in calculations.

In this case **the predicted harmonic currents (I_h) emission for the load as calculated by the manufacturer should be submitted to the power utility** for them to calculate the effect of the proposed new load. The harmonic currents (I_h) are used to calculate the resultant voltage distortion (V_h), however ER G5/4 uses some correction factors (k) to allow for possible system resonances in making this calculation.

Table 8.14 Values of "k"

System voltage at PCC	Harmonic order (h)			
	$h \leq 7$	$h \leq 8$	$h > 7$	$h > 8$
400 Volt	1		0.5	
6.6, 11, 20 and 22 kV		2		1

At 400V the voltages generated by harmonic currents of the 7^{th} order and above are reduced by 50%, and for 6.6 kV, 11 kV, and 22 kV systems voltages generated by harmonic currents up to the 7^{th} order are doubled. If the resultant THD_V and the level of 5^{th} harmonic remain within the planning levels, then connection should be agreed.

The customer or his consultant must supply either values of Vh or Ih to the power utility. The power utility shall use this information to estimate the supply system distortion with the new load connected. The power utility shall then compare the predicted supply distortion with the appropriate planning levels and decide whether the load is acceptable to be connected under Stage 2. If connection under Stage 2 is not acceptable, then a Stage 3 assessment should be made with the predicted harmonic distortion being calculated based on the actual harmonic impedance characteristic at point of common coupling.

8.2.1.3 STAGE 3 ASSESSMENT

If the levels of harmonics exceed those for Stage 2, or if the point of common coupling is at 33 kV or over, then a different and substantially more complex procedure is called for. In this case, measurements to determine the distortion of the local network, at least up to the 33 kV level are needed, together with detailed information on the system impedances.

This information is then used in constructing a computer model, showing the interrelationship of the consumers' network and the local supply network, to enable the effects of the new harmonic sources to be computer modeled. Currently there is little standardized methodology for undertaking this type of study, and this needs to be established between the power utility, the consumer, and the equipment supplier.

A number of proprietary programs are available for network studies; most were developed to enable the safety of a system to be established by calculating worst case fault levels, and establishing the protective equipment coordination. Each of these programs has both strengths and limitations. It is therefore important that the most effective software and correct form of study is selected and undertaken. Within the model, account may be taken of the variation of existing and predicted harmonic levels with time oday, and/or day of the week. This may be useful if a clear correlation can be established between the existing levels and the effect of the proposed load.

The Stage 3 assessment will be done by the power utility or network operator with the characteristics on the non-linear loads provided by the customer. Where the customer is connecting a system containing non-linear equipment, the power utility will be required to provide the system harmonic background at the PCC which will enable customer to evaluate his system harmonic performance.

In practice, the user will need to plan the installation in advance to be sure that it will be accepted. This means that the information, which will be used by the power utility to carry out the estimation, must be made available during the planning phase. These studies are inevitably time consuming and costly, and the apportionment of these costs must also be established. And if the results of the simulations show potential harmonic violation, then the customers must take the necessary steps to mitigate the harmonic emissions to ensure compliance with the harmonic planning limits.

8.2.1.3.1 PROCEDURE FOR ASSESSMENT OF NEW NON-LINEAR EQUIPMENT

The assessment of the connection of new non-linear loads consists of:-

a) Measuring the levels of distortion already existing in the system
b) Calculating the distortion which will be caused by new equipment
c) Predicting the new harmonic levels by the addition of a) and b).

Connection of the equipment is acceptable if the results of c) are less than the harmonic planning levels in Tables 8.6 and 8.7 for all individual harmonic orders. In Stage 3, it is recommended that in addition to an assessment based on the conditions at the PCC, assessment at other location is undertaken to establish directly the possibility of resonance effects and in particular the effects on equipment connected to the lower voltage systems. It is possible that the harmonic voltage level at the PCC will have to be set below the planning limits to take account of equipment at other locations within the same supply system, which is susceptible to the resulting voltage distortions.

8.2.1.4 HARMONICS MEASUREMENTS

Measurements can be taken of supply impedances (Z) and both harmonic currents (Ih) and harmonic voltages (V_h) using proprietary equipment. The most common form of measurement is of the voltage distortion over a period of time, and while ER G5/3 accepted measurements over 24 hours, ER G5/4 now looks to a seven day record in order to establish the worst case operating conditions.

8.3 ASSESSMENT OF HARMONIC EMISSION BASED ON IEC/TR 61000-3-6 [28]

This technical report, which is informative in its nature, provides guidance on principles which can be used as the basis for determining the requirements for the connection of distorting installations to MV, HV and EHV public power systems (LV installations are covered in other IEC documents) [28]. For the purposes of this report, a distorting installation means an installation (which may be a load or a generator) that produces harmonics and / or interharmonics. The primary objective is to provide guidance to power utilities or owners on engineering practices, which will facilitate the provision of adequate service quality for all connected customers. In addressing installations, this document is not intended to replace equipment standards for emission limits.

The system operator or power utility is responsible for specifying requirements for the connection of distorting installations to the system. The distorting installation is to be understood as the customer's complete installation (i.e. including distorting and non-distorting parts). This report gives guidance for the coordination of the harmonic voltages between different voltage levels in order to meet the compatibility levels at the point of utilisation.

8.3.1 INDICATIVE VALUES OF PLANNING LEVELS

The IEC standard defines voltage levels (Un) based on these limits:

- low voltage (LV) refers to Un ≤ 1 kV;
- medium voltage (MV) refers to 1 kV < Un ≤ 35 kV;
- high voltage (HV) refers to 35 kV < Un ≤ 230 kV;
- extra high voltage (EHV) refers to 230 kV < Un.

The indicative values of IEC planning levels for harmonic voltages are shown in Table 8.15.

Table 8.15 Indicative planning levels for harmonic voltages (in percent of the fundamental voltage) in MV, HV and EHV power systems

Odd harmonics non-multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Harmonic order h	Harmonic voltage % (MV)	Harmonic voltage % (HV-EHV)	Harmonic order h	Harmonic voltage % (MV)	Harmonic voltage % (HV-EHV)	Harmonic order h	Harmonic voltage %	Harmonic voltage % (HV-EHV)
5	5	2	3	4	2	2	1.8	1.4
7	4	2	9	1.2	1	4	1	0.8
11	3	1.5	15	0.3	0.3	6	0.5	0.4
13	2.5	1.5	21	0.2	0.2	8	0.5	0.4
$17 \le h \le 49$	$1.9 . \frac{17}{h} - 0.2$	$1.2 . \frac{17}{h}$	$21 < h \le 45$	0.2	0.2	$10 \le h \le 50$	$0.25 . \frac{10}{h} + 0.22$	$0.19 . \frac{10}{h} + 0.16$

The indicative planning levels for the total harmonic distortion are:
$THD_{MV} = 6.5\%$ and $THD_{HV\text{-}EHV} = 3\%$.

With reference to the very-short term effects, the compatibility levels for individual harmonic components of the voltage are the values given in Table 8.15 multiplied by a factor k_{hvs}, where k_{hvs} is calculated as follows:

$$K_{hvs} = 1.3 + \frac{0.7}{45}.(h-5) \qquad (8.2)$$

The compatibility level for the total harmonic distortion for very short-term effects is $THD_V = 11\%$. It is important to note that compatibility levels are not defined in IEC for HV and EHV systems.

8.3.2 ASSESSMENT PROCEDURE FOR EVALUATION AGAINST PLANNING LEVELS

The measurement method to be used for harmonic and inter-harmonic measurements is the class A method specified in IEC 61000-4-30 [29] and related IEC 61000-4-7 [14]. The minimum measurement period is one week of normal business activity. The monitoring period should include some part of the period of expected maximum harmonic levels. One or more of the following indices may be used to compare the actual harmonic levels with the planning levels. More than one index may be needed for planning levels in order to assess the impact of higher emission levels allowed for shorter periods of time such as during bursts or start-up conditions.

- The 95% weekly value of U_{hsh} (r.m.s. value of individual harmonics over "short" 10 min periods) should not exceed the planning level.
- The greatest 99 % probability daily value of U_{hvs} (r.m.s. value of individual harmonic components over "very short" 3s periods) should not exceed the planning level times the multiplying factor k_{hvs} given in Equation 8.2 with reference to the compatibility levels given for very short time effects of harmonics.

8.3.3 EMISSION LEVELS

The coordination approach recommended in this standard relies on individual emission levels being derived from the planning levels. For this reason, the same indices are applied both when evaluating actual measurements against the emission limits and against the planning levels. One or more of the following indices can be used to compare the actual emission level with the customer's emission limit. More than one index may be needed in order to assess the impact of higher emission levels allowed for short periods of time such as during bursts or start-up conditions.

- The 95% weekly value of U_{hsh} (or I_{hsh}), the r.m.s. value of individual harmonics over "short" 10 min periods, should not exceed the emission limit.
- The greatest 99 % probability daily value of U_{hvs} (or I_{hvs}), the r.m.s. value of individual harmonic components over "very short" 3s periods, should not exceed the emission limit multiplied by the factor k_{hvs} given in Equation 8.2. With reference to very short time effects of harmonics, use of the very-short time index for assessing emissions is only needed for installations having a significant impact on the system, so use of this index could be dependent on the ratio between the agreed power of the installation and the short-circuit power of the system (i.e. S_i/S_{sc}).

In order to compare the level of harmonic emissions from a customer's installation with the emission limits, the minimum measurement period should be one week. However shorter measurement periods might be needed for assessing emissions under specific conditions. Such shorter periods should represent the expected operation over the longer assessment period (i.e. a week). In any case, the measurement period must be of sufficient duration to capture the highest level of harmonic emissions which is expected to occur. If the harmonic level is dominated by one large item of equipment, the period should be sufficient to capture at least two complete operating cycles of this equipment. If the harmonic level is caused by the summation of several items of equipment, the period should be at least one operating shift.

The measurement method to be used is the class A measurement method defined in IEC 61000-4-30 [29] and associated IEC 61000-4-7 [14] for harmonics and inter-harmonics. The data flagged in accordance with IEC 61000-4-30 should be removed from the assessment. For clarity, where data is flagged the percentile used in calculating the indices defined above is calculated using only the valid (unflagged) data. When the signal to be analyzed is rapidly varying (e.g. the current drawn by an arc furnace) the measurement of (inter) harmonic groups and subgroups should be used as described in IEC 61000-4-7 rather than the harmonic components.

8.3.4 STAGES FOR EVALUATING HARMONIC LOADS

The proposed approach for setting emission limits of distorting installations depends on the agreed power of the customer, the power of the harmonic-generating equipment, and the system characteristics. The objective is to limit the harmonic injection from the total of all distorting installations to levels that will not result in voltage distortion levels that exceed the planning levels. Three stages of evaluation are defined which may be used in sequence or independently.

The flowchart for the three stage procedure for evaluating customer harmonic injection is shown in Figure 8.6.

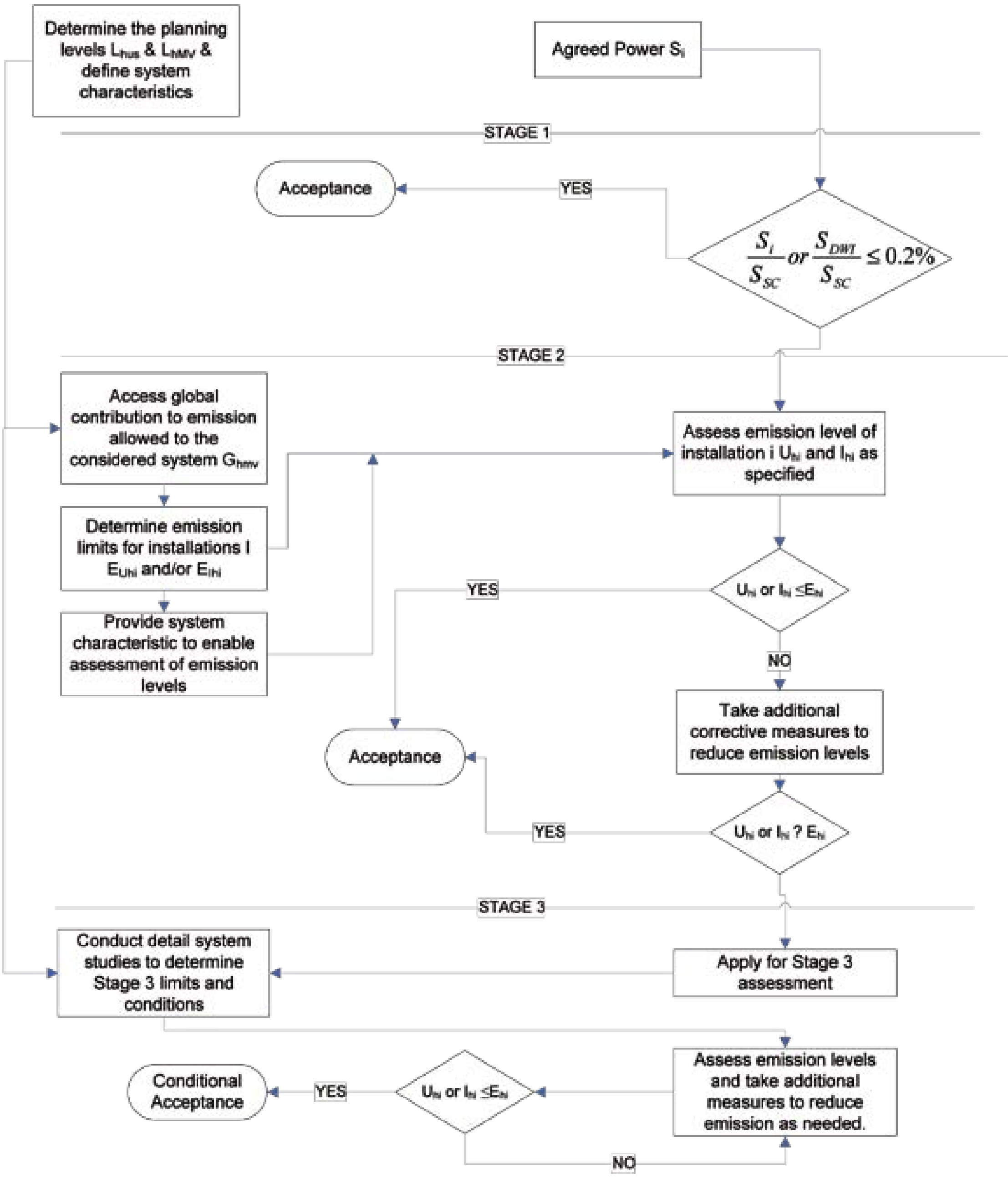


Fig.8.6 Evaluation procedure at MV system

8.3.4.1 STAGE 1: SIMPLIFIED EVALUATION OF DISTURBANCE EMISSION

It is generally acceptable for a customer to install small appliances without specific evaluation of harmonic emission by the system operator or owner. Manufacturers of such appliances are generally responsible for limiting the emissions. For instance, IEC 61000-3-2 [22] and IEC 61000-3-12 [23] are product family standards that define harmonic emission limits for equipment connected to LV systems. There are currently no emission standards for MV equipment for the following reasons:

- medium voltage varies between 1 kV and 35 kV; and
- no reference impedance has been internationally defined for medium voltage systems.

Even without a reference impedance, it is possible to define conservative criteria for quasiautomatic acceptance of small size distorting installations on MV systems (and HV systems too). Indeed if the total distorting installation, or the customer's agreed power, is small relative to the short circuit capacity at the point of evaluation, it should not be necessary to carry out detailed evaluation of the harmonic emission levels. A more refined approach is to calculate a "weighted distorting power" as a criterion to determine the acceptability at Stage 1 of the total distorting equipment connected within the customer's facility. This approach is similar to that defined in IEEE 519. In IEEE 519, the term "weighted disturbing power" is used.

The specific criteria developed for applying stage 1 evaluation is explained as follows:

A. Agreed power as a criterion

In Stage 1, the connection of small distorting installations or installations with only a limited amount of distorting equipment can be accepted without detailed evaluation of the emission characteristics or the supply system response. If the following condition is fulfilled:

$$\frac{S_i}{S_{SC}} \leq 0.2\% \qquad (8.3)$$

(S_i = agreed power of customer i and S_{SC} = short circuit power at the point of evaluation), then any distorting installation may be connected to the supply system without further examination.

Note: S_{SC} may be calculated (or measured) for the specific point of evaluation, or may be estimated for typical MV system with similar characteristics to that under consideration.

B. Weighted distorting power as a criterion

This approach involves calculating a "weighted distorting power", S_{Dwi}, to characterize the amount of distorting equipment within the customer's facility. This can be done using the weighting factors W_j in Table 8.16 for common types of harmonic producing equipment. These weighting factors for different types of harmonic producing loads are similar to the values dictated in Table 8.5 for the IEEE 519.

The weighted distorting power is calculated as follows:

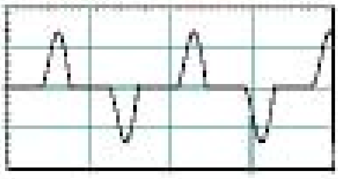
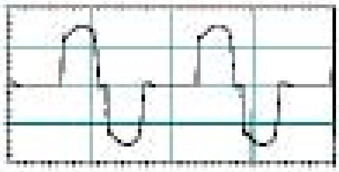
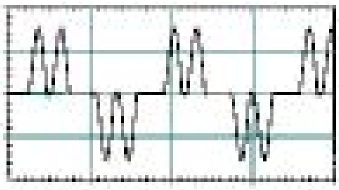
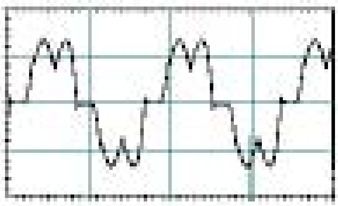
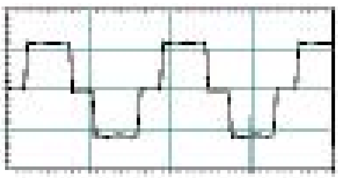
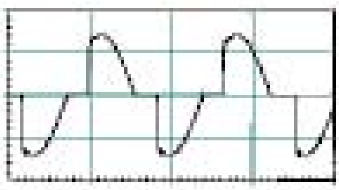
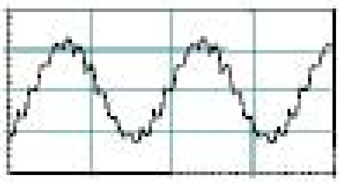
$$S_{Dwi} = \sum_{j} S_{Dj}.W_j \qquad (8.4)$$

where: S_{Dj} is the power of each distorting equipment (j) in the facility (i).

If the characteristics of the harmonic producing equipment are unknown, a weighting of 2.5 can be assumed. Acceptance of a customer's installation under stage 1 may be determined by comparing the weighted distorting power with the short-circuit power at the point of evaluation. The following conservative criterion can be used for acceptance under Stage 1:

$$\frac{S_{Dwi}}{S_{SC}} \leq 0.2\% \qquad (8.5)$$

Table 8.16 Weighting factors W_j for different types of harmonic producing equipments

Typical equipment connected to LV, MV or HV	Typical current waveform	Typical current THD	Weighting Factor (W_j)
Single phase power supply (rectifier and smoothing capacitor)		80 % (high 3rd)	2.5
Semi-converter		High 2nd,3rd, 4th at partial loads	2.5
6-pulse converter, capacitive smoothing, no series inductance		80 %	2.0
6-pulse converter, capacitive smoothing with series inductance > 3%, or d.c. drive		40 %	1.0
6-pulse converter with large inductor for current smoothing		28 %	0.8
AC voltage regulator		Varies with firing angle	0.7
12-pulse converter		15 %	0.5

8.3.4.2 STAGE 2: EMISSION LIMITS RELATIVE TO ACTUAL SYSTEM CHARACTERISTICS

If an installation does not meet Stage 1 criteria, the specific characteristics of the harmonic generating equipment within the customer's installation should be evaluated together with the absorption capacity of the system. The absorption capacity of the system is derived from the planning levels, and is **apportioned to individual customers** according to their demand with respect to the total system capacity. The disturbance level transferred from upstream voltage levels of the supply system to lower voltage levels should also be considered when apportioning the planning levels to individual customers.

The principle of this approach is that, if the system is fully utilized to its designed capacity and all customers are injecting up to their individual limits, the total disturbance levels will be equal to the planning levels taking into account transfer factors between different voltage levels and the summation of various harmonic producing installations. A procedure for apportioning the planning levels to individual customers will be implemented.

Considering the actual absorption capacity of the system, due to the phase differences of the harmonic currents as well as the system impedance and future load, higher emissions than those according to Stage 1 criteria may be granted. In this stage, the allowable global contribution to the overall level of disturbance is apportioned to each individual installation in accordance with its share of the total capacity of the supply system (S_t) to which this installation is connected. This ensures that the disturbance level due to the emissions of all customers connected to the system will not exceed the planning level.

Two approaches are presented hereafter. The first (simplified) approach is based on the allowed harmonic current as a function of the fundamental current. The second is based on the general summation law, allowing a more general method for setting emission limits for larger distorting installations.

A. Relative harmonic currents as emission limits

The permissible share of the total voltage distortion will generally not be exceeded when appropriate limits are set on the "relative harmonic currents". Table 8.17 gives an example of such limits; it applies to customers with an agreed power S_i < 1 MVA and with S_i/S_{SC} < 1%, provided that the pre-existing harmonic level allows it and if the customer does not use power factor correction capacitors and/or filters. (S_i = agreed power of customer i and S_{SC} = short circuit power at the point of evaluation).

Table 8.17 Indicative values for some odd order harmonic current emission limits relative to the size of a customer installation

Harmonic order h	5	7	11	13	>13
harmonic current emission limit $E_{Ihi} = I_{hi}/I_i$ (%)	5	5	3	3	

Where:

- E_{Ihi} is the harmonic current emission limit of order h for the customer i
- I_{hi} is the harmonic current of order h caused by the distorting installation of customer i
- I_i is the r.m.s. current corresponding to his agreed power (fundamental frequency).

NOTE: If the capacity of the system increases in the future, the emission levels of individual customers should become lower. It is important therefore, where possible, to consider future expansions of the system

B. General approach based on the summation law

B1. Global emission to be shared between customers

Consider a typical MV system as illustrated in Figure 8.7. The aim is to set emission limits at MV.

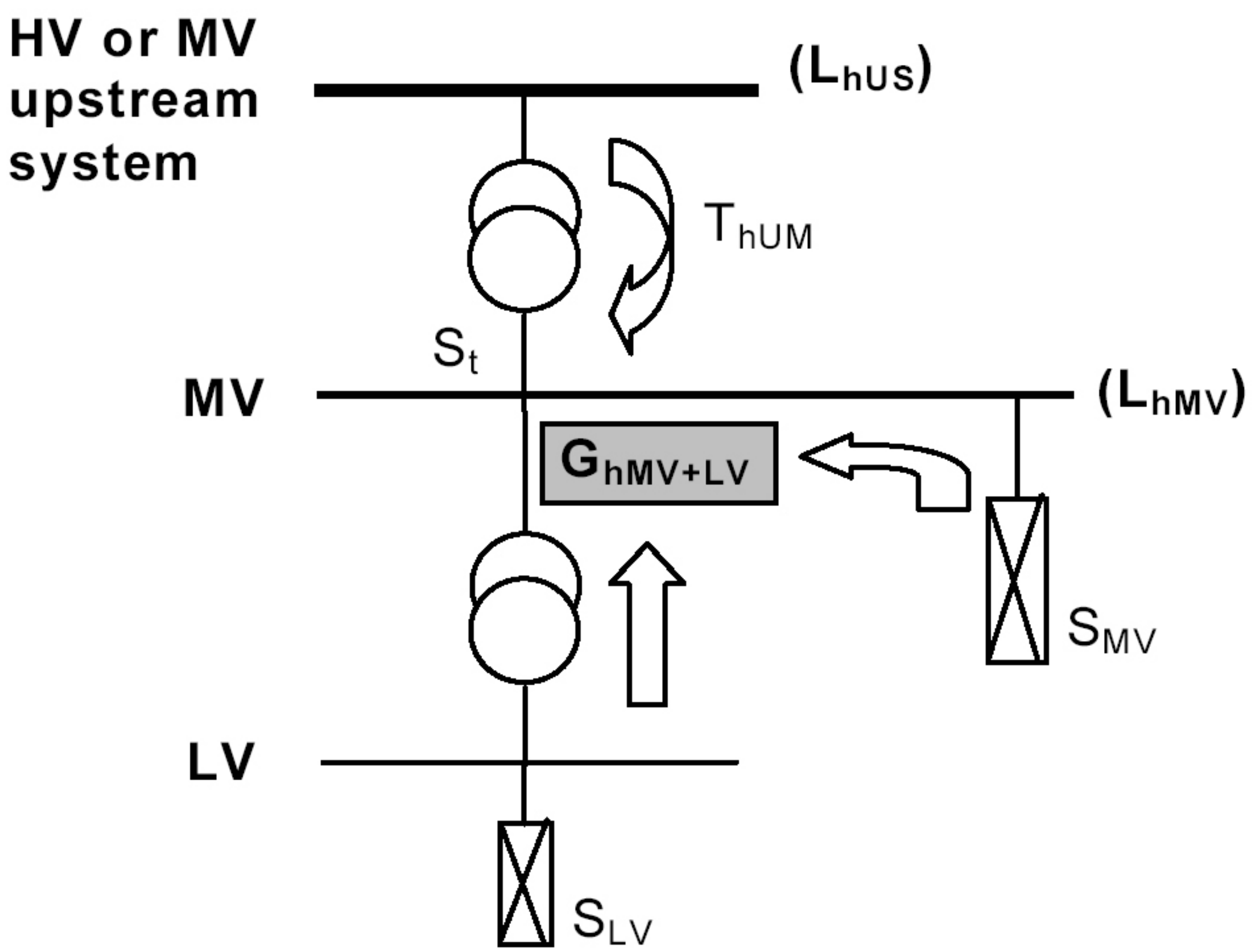


Fig.8.7 Example of a system for sharing global contributions at MV

Firstly an application of the general summation law is necessary to determine the global contribution of all harmonic sources present in a particular MV system. Indeed, for each harmonic order, the actual harmonic voltage in a MV system results from the vector summation of the harmonic voltage coming from the upstream system (note that upstream system may be a HV or another MV system for which intermediate planning levels have been set before) and of the harmonic voltage resulting from all distorting installations connected to the considered MV and LV system. This total harmonic voltage should not exceed the planning level of the MV system, given by:-

$$L_{hMV} = \sqrt[\alpha]{G^{\alpha}_{hMV} + (T_{hUM} \cdot L_{hUS})^{\alpha}} \qquad (8.6)$$

and thus the global harmonic voltage contribution that can be allocated to the total of MV and LV installations supplied from the considered MV system is given by:-

$$G_{hMV+LV} = \sqrt[\alpha]{L^{\alpha}_{hMV} - (T_{hUM} \cdot L_{hUS})^{\alpha}} \qquad (8.7)$$

Where:

- G_{hMV+LV} is the maximum global contribution of the total of MV and LV installations that can be supplied from the MV busbar to the hth harmonic voltage in the MV system (expressed in percent of the fundamental voltage)
- L_{hMV} is the planning level of the hth harmonic in the MV system;
- L_{hUS} is the planning level of the hth harmonic in the upstream system (for reasons explained before, different planning levels may be needed for intermediate voltage levels between MV and HV-EHV; this is why the general term of upstream system planning level is used);
- T_{hUM} is the transfer coefficient of harmonic voltage distortion from the upstream system to the MV system under consideration at harmonic order h. T_{hUM} can be determined by simulation or measurements. For an initial simplified evaluation, the transfer coefficients T_{hUM} from the upstream system on a MV system can be taken as equal to 1. In practice however, it may be less than 1 (e.g. 2/3), due to the presence of downstream system elements, or higher than 1 (typically between 1 and 3), due to resonance. It is the responsibility of the system operator or owner to determine the relevant values depending on the system characteristics;
- α is the summation law exponent (Table 8.18).

When the planning levels for MV systems are equal to those for the upstream systems as it is in Table 8.15 for h = 15 and 21 and higher order triplen harmonics, the application of Equation 8.7 would result in a zero contribution for the MV and LV customers. In these cases, an equitable share of emissions between the different system voltage levels should be allocated instead.

Table 8.18 Summation exponents for harmonics (Indicative values)

Harmonic order	α
$h < 5$	1.0
$5 \leq h \leq 10$	1.4
$h > 10$	2.0

B2. Individual emission limits

For each customer only a fraction of the global emission limits G_{hMV+LV} will be allowed. A reasonable approach is to take the ratio between the agreed power Si and the total supply capability St of the MV system. Such a criterion is related to the fact that the agreed power of a customer is often linked with his share in the investment costs of the power system.

$$E_{Uhi} = G_{hMV+LV} \sqrt[\alpha]{\frac{S_i}{S_t}} \quad (8.8)$$

where

- E_{Uhi} is the allowed harmonic voltage emission limit of order h for the installation (i) directly supplied at MV (%);
- G_{hMV+LV} is the maximum global contribution of the total of MV and LV installations that can be supplied from the considered MV system to the hth harmonic voltage in the MV system, as given by Equation (8.6);
- $S_i = P_i / \cos \varphi_i$ is the agreed power of customer installation i, or the MVA rating of the considered distorting installation (either load or generation);
- S_t is the total supply capacity of the considered system including provision for future load growth (in principle, S_t is the sum of the capacity allocations of all installations including that of downstream installations that are or can be connected to the considered system, taking diversity into consideration). S_t might also include the contribution from dispersed generation, however more detailed consideration will be required to determine its firm

contribution to S_t and its effective contribution to the short-circuit power as well.

- α is the summation law exponent (see Table 8.14).

It may happen at some locations that the pre-existing level of harmonics is higher than the normal share for the existing installations. In this case the emission limit for any new installations can be reduced, a reconsideration of the allocation of the planning levels between the different voltage levels could be considered, or the system harmonic current absorption capacity could be increased.

For customers having a low agreed power, Equation 8.8 may yield impractically low limitations. If the voltage emission limit at some harmonic orders becomes smaller than 0.1%, it shall be set equal to 0.1% (except if there is a risk of telephone interference, or if it corresponds to a remote control frequency for which a more severe restriction may be justified). It may be preferred to specify harmonic current limits to the distorting installation, even if the aim is to limit the harmonic voltages in the system. It will be the responsibility of the public utility to provide data concerning the frequency-dependent impedance of the system, in order to enable expressing these limits in terms of harmonic currents:

$$E_{Ihi} = \frac{E}{Z_{hi}} \qquad (8.9)$$

where:

- E_{Ihi} is the corresponding harmonic current emission limit of customer "i" at harmonic order h;
- Z_h is the harmonic impedance of the system at the point of evaluation for customer "i" assessed considering the actual purpose of converting voltage to current emission limits.

8.3.4.3 STAGE 3: ACCEPTANCE OF HIGHER EMISSION LEVELS ON A CONDITIONAL BASIS

Under some circumstances, a customer may require acceptance to emit disturbances beyond the basic limits allowed in Stage 2. In such a situation, the customer and the system operator or owner may agree on special conditions that facilitate connection of the distorting installation. A careful study of the actual and future system characteristics will need to be carried out in order to determine these special conditions.

For more details, please refer to the IEC/TR 61000-3-6 document.

8.4 RESPONSIBILITIES

In the context of this standard from the EMC point of view, the following responsibilities are defined:

- The customer is responsible for maintaining his emissions at the specified point of evaluation below the limits specified by the system operator or power utility.
- The power utility is responsible for the overall coordination of disturbance levels under normal operating conditions in accordance with technical standard requirements. For evaluation purposes the power utility should, where required, provide relevant system data such as harmonic impedance (Z_h) or the necessary data to calculate this short-circuit levels, and existing levels of harmonic distortion at the point of common coupling.
- The evaluation procedure is designed in such a way that the harmonic emissions from all distorting installations do not cause the overall system harmonic voltage levels to exceed the planning and compatibility levels. However, given specific local conditions and the assumptions that are necessary in this evaluation procedure, there is no guarantee that the recommended approach will always avoid exceeding the levels.
- Finally, the power utility and customers should co-operate when necessary in the identification of the optimum method to reduce emissions. The design and choice of method for such reduction are the responsibility of the customer.

8.5 SYSTEM HARMONIC IMPEDANCE (Z_H)

Information on the system harmonic impedance (Z_h) is a prerequisite both for the system operator or power utility for assessing emission limits and for the customer in order to assess the emission levels of the considered installation. With reference to how the harmonic impedance is to be used, it is possible to identify three different kinds:

8.5.1 IMPEDANCE FOR CONVERTING EMISSION LIMITS FROM VOLTAGE TO CURRENT

For converting emission limits from voltage into current limits, there are two ways to assess the harmonic system impedance depending on the size of the distorting installation and the system characteristics:

- For general application, a declared or generic system harmonic impedance covering different types of systems, different voltage levels, etc. may be used by the system operator or owner in order to define generic sets of emission limits based on typical system characteristics.
- Correction factors may be introduced when needed to compensate for other than generic system characteristics (e.g. an amplification factor based on typical resonance conditions for such networks). This application is generally better at lower system voltages, where damping of resonant conditions tends to be better than at HV and particularly at EHV.
- For large installations compared to system size especially at HV-EHV, the best estimate of the maximum harmonic impedance of the system over the worst operating conditions at the point of evaluation can also be used. It may also include an assessment of the impact on remote points in the network.
- In any case, exceptionally low values of harmonic impedance should be disregarded as they often relate to series resonance for which the harmonic voltage may exceed planning levels in other parts of the system. In this case, the impedance value should be disregarded and be replaced by a default value (for example Z1 * h, where h is the harmonic order and Z1 is the system impedance at the fundamental frequency).

8.5.2 IMPEDANCE FOR PRE-CONNECTION ASSESSMENT OF EMISSION LEVELS

For enabling a pre-connection assessment of the harmonic emission levels for large disturbing installations in particular, the system harmonic impedances at the point of evaluation can be obtained by simulation for various system operating conditions (including future conditions). In some cases this impedance may be based on the short-circuit impedance and in other cases (e.g. in the case of large installations) the locus of the harmonic impedance, or the data to calculate this, should be provided. Particularly, for large installations (or small S_{SC}/S_i ratio), it is important to properly assess the possibility of resonance so that filters/capacitors can be designed as to avoid problems or damage (not only system resonance, but also resonance between the considered filters or capacitors and the supply system). It is necessary to consider the range of variation of harmonic impedance not only the maximum impedance values in order to identify possible resonance. The range of variation of the phase angle of the harmonic impedance characterizes the resistive part of the impedance and defines the damping in case of resonance.

8.6 HARMONIC MEASUREMENT BEFORE CONNECTING NEW HARMONIC LOADS

Harmonics are created by nonlinear loads and devices on the power system. There are a wide variety of devices that generate harmonics and they can be connected to the power system at any voltage level. The procedures outlined in the technical standards are designed to limit harmonic currents from individual customers and equipment so that harmonic voltage levels on the overall power system will be acceptable. The approach involves a divided responsibility between the customer and the power utility.

Harmonic limits are evaluated at the point of common coupling (PCC). Measurements to evaluate compliance with the harmonic limits should therefore be made at the PCC, if possible. Measurements at other locations throughout a facility can help in the overall evaluation of harmonic concerns. For instance, measurements at nonlinear loads are used to characterize these loads as part of the overall facility load, including the time varying nature of the harmonic currents produced. Measurements for portions of a facility (e.g. individual branch circuits) can help illustrate the cancellation achieved due to harmonic injection from multiple nonlinear loads within the facility.

For many customers, the PCC will be at the high side of a step down transformer but it would be more convenient to perform measurements at the transformer low side to take advantage of existing Current Transformers (CTs) that can be used for the current measurements. The low side measurements should be quite adequate for evaluating the harmonic currents but cannot be easily used to evaluate the harmonic voltage distortion characteristics on the primary side. The harmonic currents measured on the transformer secondary can be referred to the primary side by the transformer turns ratio. However, the effect of the transformer connection on the zero sequence harmonic components must be considered.

The transformer connection will only affect the zero sequence harmonic current magnitudes. If the harmonic currents consist of only positive and negative sequence components (this may be the case for many industrial facilities that are dominated by three phase loads), then the transformer connection will only affect the phase angles of the harmonic currents. However, if the facility includes single phase loads that can generate triplen harmonics (that become zero sequence components in a balanced three phase system), the transformer connection must be considered. Delta-wye transformers will trap the zero sequence components in the delta primary winding and they will not show up in the primary system. Wye grounded-wye grounded transformers will allow these zero sequence components to flow into the primary system

8.6.1 HARMONIC VOLTAGE MEASUREMENTS

Harmonic voltage measurements can be made on low voltage systems with a direct connection to the bus. At higher voltages, potential transformers (PTs) are used to provide a lower voltage signal for the measurement equipment. PTs usually have good frequency response characteristics up to 3000 Hz. Capacitively coupled voltage transformers (CCVTs) should not be used for harmonic measurements. They use a tuned circuit for accuracy at the fundamental frequency but can have large errors at harmonic frequencies

8.6.2 HARMONIC CURRENT MEASUREMENTS

Measurements to evaluate compliance with harmonic limits require measurement of harmonic currents. The most important concept to remember when making these measurements is that the harmonic current limits are expressed in percent of a fixed current value (the average maximum demand load current). This means that the current limits are essentially fixed ampere limits at each harmonic and for the total demand distortion. In order to compare measurements with these limits, the measurements must be made in actual amperes, not percent of the fundamental current. The fundamental current is continually varying due to load variations and power factor correction changes. Harmonic currents expressed as a percentage of this changing fundamental current may be difficult to convert to actual amperes and the results can be misleading. For instance, the harmonic distortion levels expressed as a percentage of the fundamental current could be quite high during light load conditions, but the actual amperes of harmonic current may be quite acceptable.

When measuring harmonic currents within the facility, it may be important to include the phase angles of the individual harmonic components. This permits a better evaluation of harmonic cancellation between different loads within the facility. The phase angles must all be related to the same reference. This is commonly selected to be the zero crossing of the fundamental frequency voltage on phase A. Current transformer (CT) characteristics can also be important for harmonic current measurements. The frequency response characteristics of the CTs should be evaluated for the measurements being performed. The CTs should have less than 3dB of attenuation for frequencies up to 3000 Hz. Usually, the CT characteristics have a more important impact on the harmonic current phase angle than the magnitude.

8.6.3 MONITORING DURATIONS

Measurements should be performed over a period of time to characterize the variable nature of the harmonic levels. For very stable processes, measurements over a single day may be adequate to characterize harmonic level variations. More commonly, measurements should be performed over a period of at least one week during normal operation of the facility. For facilities like steel plants with arc furnaces that can have characteristics that vary from day to day, monitoring over longer durations is recommended.

Permanent monitoring of harmonic levels can be used to flag abnormal conditions and for ongoing evaluation of compliance with harmonic standards. Monitoring over some initial period of time will establish the normal harmonic variations that can be expected at a facility. If the harmonic levels fall outside these normal variations, it is an indication that something has changed either within the facility or on the power system (e.g. a filter failure, new capacitor bank, new harmonic producing load, etc.).

8.7 CONNECTION OF EQUIPMENT THAT RESULTS IN VOLTAGE NOTCHING

Voltage notching occurs during rectifier commutation when two phases of the supply are short-circuited. Voltage notches are irregularities in the voltage waveform that appears as a notch as illustrated in Figure 8.7. They are typically present in the waveform during Silicon Controlled Rectifiers (SCR's) commutation or at the time when one phase SCR is being turned off and the next one turned on. For this very small duration of time, we actually experience a short circuit between the two phases. Of course when we have a short circuit, the current goes high and the voltage goes very low. This is exactly what is experienced during a notch. The notch appears at the moment when current is actually rising very quickly but due to the shortage of the phases, the voltage is shorted and approaches zero. In the most severe cases, the notch does in fact touch the zero voltage axis. This causes the biggest problems.

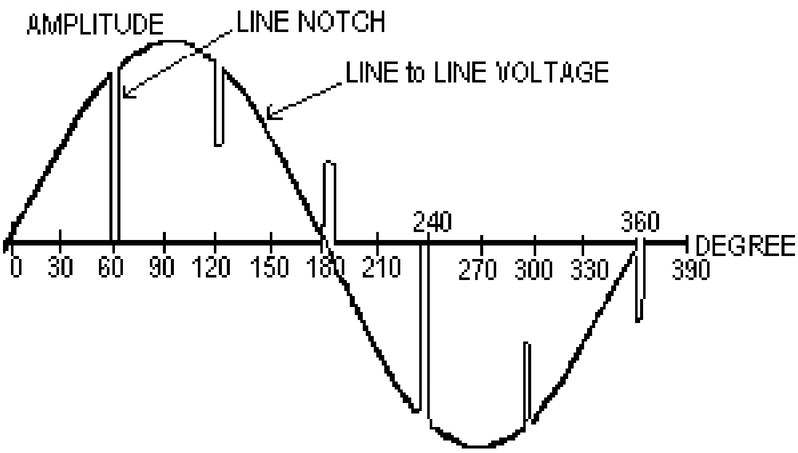


Fig.8.7 Voltage notch

Equipment that results in voltage notching can only be connected if the levels of harmonic distortion present at the PCC are less than the defined harmonic planning levels. Otherwise, a suitable mitigation method must be installed to mitigate the voltage notches.

CHAPTER 9

HARMONICS MITIGATION TECHNIQUES

9.0 OVERVIEW ON HARMONIC MITIGATION

The affect of harmonic currents on facility devices can be reduced in several ways. The first method is to isolate the harmonic loads from other sensitive equipment so that the harmonic level at the sensitive loads is lower due to the system impedance between the harmonic source and the sensitive loads. The second method is to add reactors or isolation transformers on the feeders connected to harmonic producing loads. And the last method is to add harmonic filters to divert the harmonic current from facility equipment.

9.1 ISOLATION OF THE NON-LINEAR LOADS FROM THE LINEAR LOADS

9.1.1 POSITION THE NON-LINEAR LOADS UPSTREAM IN THE SYSTEM

To limit the propagation of harmonics in the distribution network, different solutions are available and should be taken into account particularly when designing a new installation. Overall harmonic disturbances increase as the short-circuit power decreases. All economic considerations aside, it is preferable to connect the non-linear loads as far upstream as possible.

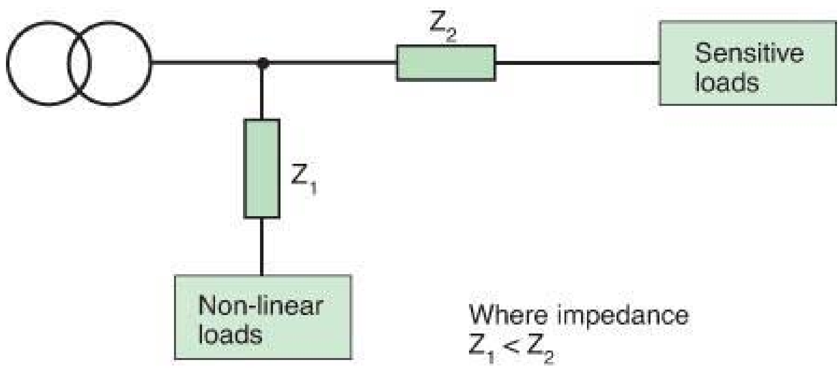


Fig.9.1 Non-linear loads positioned as far upstream as possible

9.1.2 SEPARATE THE LINEAR LOADS FROM THE NON-LINEAR LOADS

When preparing the single-line diagram, the non-linear devices should be separated from the others. The two groups of devices should be supplied by different sets of busbars.

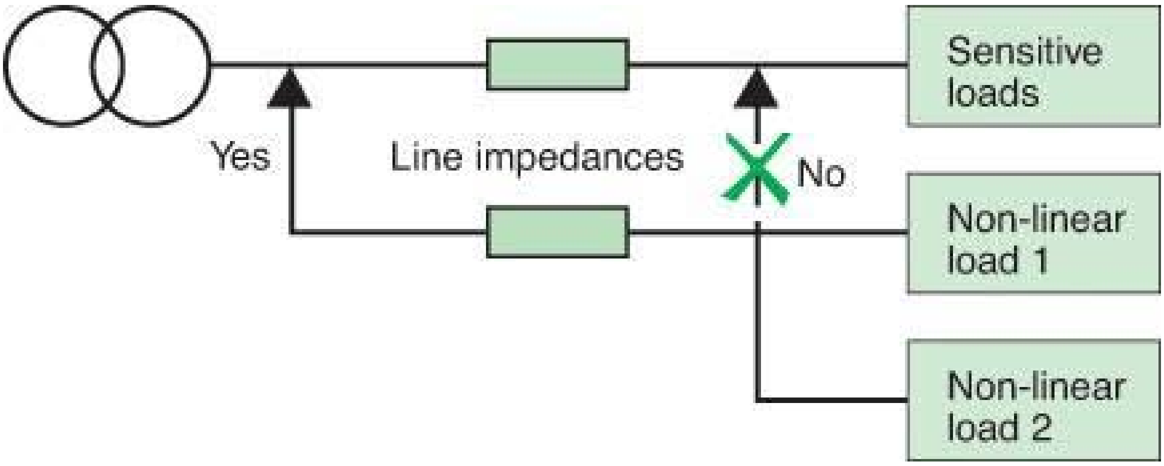


Fig.9.2 Grouping of non-linear loads and connection as far upstream as possible

9.1.3 CREATE DIFFERENT SUPPLY SOURCES FOR LINEAR AND NON-LINEAR LOADS

In attempting to limit harmonics, an additional improvement can be obtained by creating a source via a separate transformer. The disadvantage is the increase in the cost of the installation.

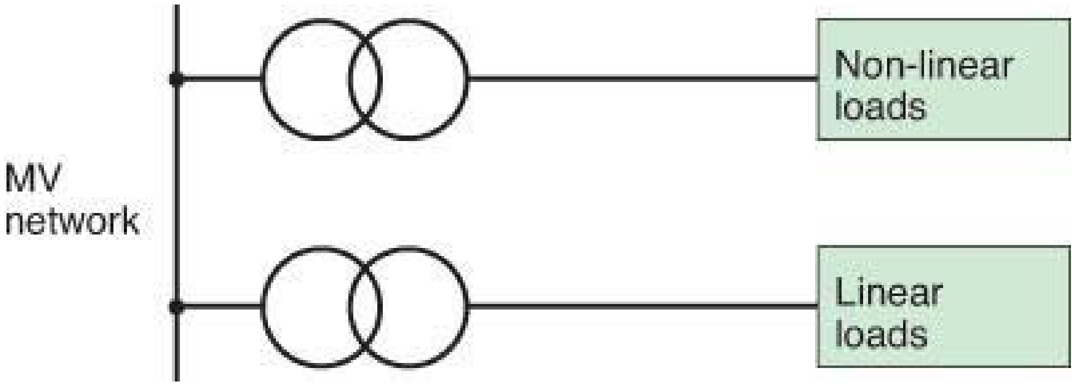


Fig.9.3 Supply of non-linear loads via a separate transformer

9.2 PRINCIPLES AND TECHNOLOGIES FOR HARMONICS MITIGATION

Various mitigation techniques of improving the input current waveform are currently available. The aim of all mitigation techniques is to make the input current more continuous so as to reduce the overall harmonic current distortion. The existing technologies for mitigating harmonics are explained in Table 9.1.

Table 9.1 Harmonic mitigation technologies

Harmonic Mitigation	Description
AC line reactors and/or DC link chokes	Since the reactor impedances (X_L) increases with frequency ($X_L = 2\pi f L$), it offers larger impedance to the flow of higher order harmonic currents. It is thus instrumental in impeding higher frequency current components, while allowing the fundamental frequency component to pass through with relative ease. (L is inductance in Henry and f is frequency in Hertz).
Passive harmonic mitigation	Passive filters consist of passive components i.e. inductors, capacitors & resistors arranged either to attenuate the flow of harmonic currents through them or shunt into them.
Phase multiplication	One of the best ways to eliminate harmonics is to use a technique known as "phase shifting." The concept of phase shifting involves separating the electrical supply into several outputs; each output being phase shifted with the other outputs with an appropriate angle for the harmonics to be eliminated. The idea is to displace the harmonic currents in order to bring them to a 180° phase shift so that they cancel each other out. Hence, an angular displacement of:- • 60° is required between two three-phase outputs to cancel the 3rd harmonic currents. • 30° is required between two three-phase outputs to cancel the 5th and 7th harmonic currents. • 15° is required between two three-phase outputs to cancel the 11th and 13th harmonic currents.
Active harmonic compensation	Active Filters are newly emerging devices for harmonic filtering, which will use Controllable Sources to cancel the harmonics in the Power Systems. The basic principle of operation of an Active Filter is to inject a suitable non-sinusoidal voltage and currents in to the system in order to achieve a clean voltage and current waveforms at the point of filtering.

9.3 THREE-PHASE AC LINE REACTORS AND DC LINK CHOKES FOR MINIMIZING HARMONICS [30]

The magnitude of harmonic currents in an individual non-linear load depends greatly on the total effective input reactance, which is comprised of the source reactance plus added line reactance. Given a six pulse rectifier with dc bus capacitor, one can predict the resultant input current harmonic spectrum based on the input reactance. The lower the source reactance, (the more stiff the power source), the higher the harmonic content will be.

Since power distribution transformers frequently have impedance ratings between 1.5% and 5.75%, one would expect that source impedance is often relatively high and that harmonics should therefore be quite low. However, transformer impedance ratings are based on transformer rated kVA, so when the transformer is partially loaded, the effective impedance of the transformer, relative to the actual load, is proportionately lower, [i.e. 1.5% impedance at 30% load = 0.5% effective impedance].

The use of AC line reactors is a common and economical means of increasing the source impedance relative to an individual load. AC line reactors are connected in series with the six pulse rectifier diodes at the input to the VFD, as shown in Figure 9.4.

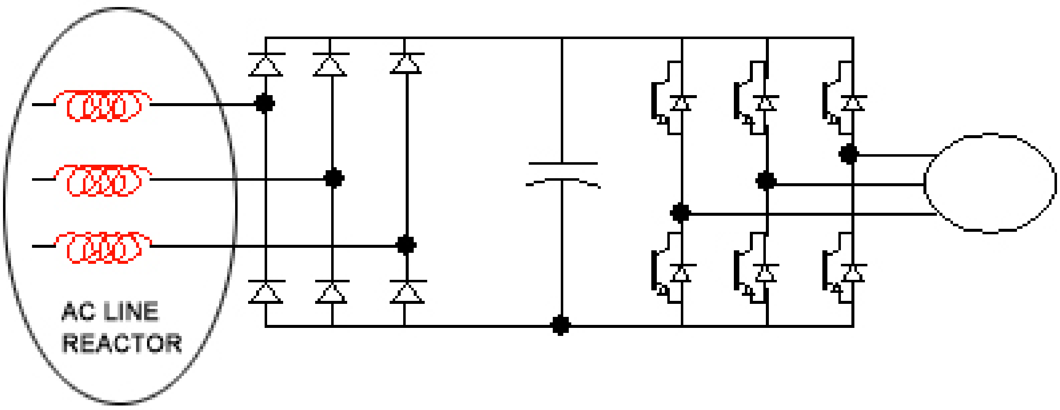


Fig.9.4 Common application of AC line reactor

It is important to note that, the oldest as well as most effective and economical harmonic mitigation strategy is the addition of inductance (typically 3% to 5% on the drive base) in the individual drive circuits. This added inductance (in the form of a reactor or transformer) directly reduces the amount of harmonic currents produced by the drive. Reactors are hardy, durable, and economical, and their application may be sufficient to reduce the harmonic distortion at the motor control center to acceptable levels. The actual distortion at the main input (metering point) will vary depending on the system impedance and the distribution of loads (linear vs. non-linear).

Reactors offer significant magnitudes of inductances, which can alter the way that current is drawn by a non-linear load such as an input rectifier bridge. The reactor makes the current waveform less discontinuous resulting in lower current harmonics. The input harmonic current distortion can be reduced significantly by the simple addition of input line reactance. The inductive reactance of an input line reactor allows 50 Hz or 60 Hz current to pass easily but presents considerably higher impedance to all of the harmonic frequencies. Harmonic currents are thus attenuated by the inductive reactance of the input reactor. Example of harmonic current due to the application of a 3 % reactor is shown in Figure 9.5.

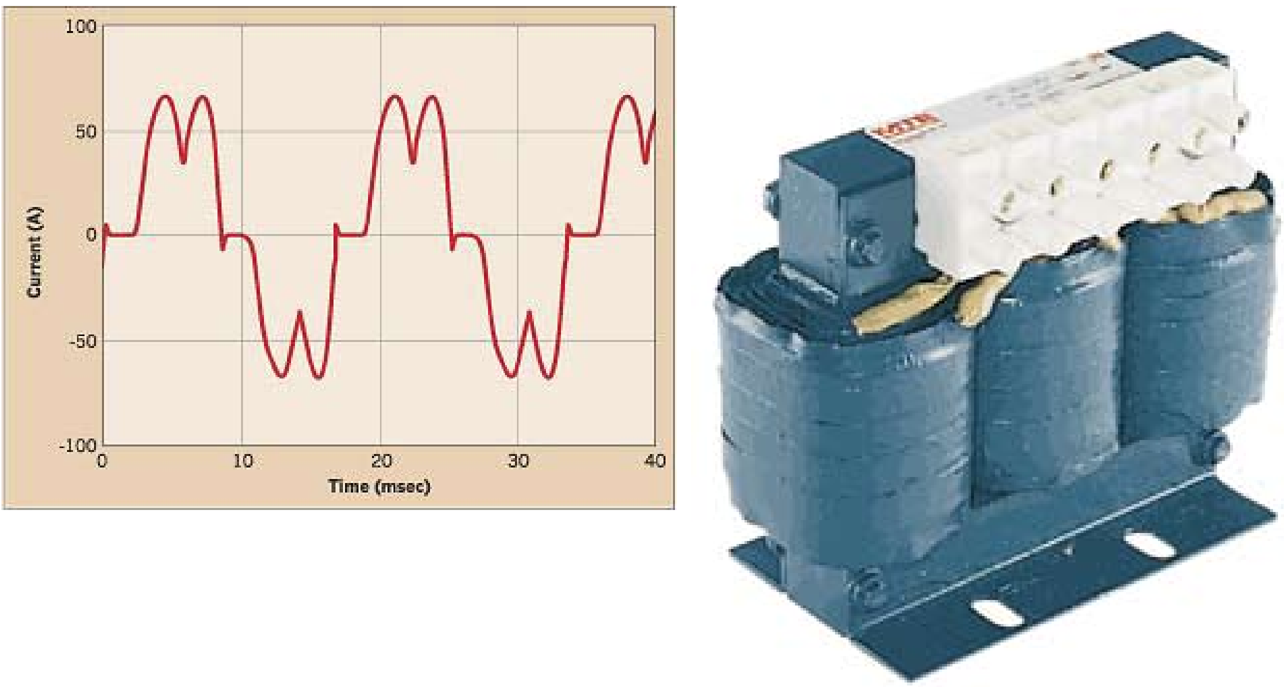


Fig.9.5 Actual input current waveform for six-pulse VFD with 3% AC line reactor

On knowing the input reactance value, one can estimate the expected current harmonic distortion. A table illustrating the expected input current harmonics for various amounts of input reactance is shown below [30].

Table 9.2 % Harmonics vs. Total Line Impedance

Reactor / Harmonics	3%	4 %	5 %	6 %	7 %	8 %	9 %	10 %
5^{th}	40	34	32	30	28	26	24	23
7^{th}	16	13	12	11	10	9	8.3	7.5
11^{th}	7.3	6.3	5.8	5.2	5	4.3	4.2	4
13^{th}	4.9	4.2	3.9	3.6	3.3	3.15	3	2.8
17^{th}	3	2.4	2.2	2.1	0.9	0.7	0.5	0.4
19^{th}	2.2	2	0.8	0.7	0.4	0.3	0.25	0.2
% THD_I	44.13	37.31	34.96	32.65	30.35	28.04	25.92	24.68
% True RMS	1.09	1.07	1.06	1.05	1.05	1.04	1.03	1.03

9.3.1 APPLICATION OF AC REACTORS FOR MOTOR PROTECTION [30]

A 3% impedance reactor is very effective at protecting against damage to or nuisance tripping of AC voltage source inverters, due to voltage spikes. Voltage spikes on the AC power system cause elevation of the DC bus voltage, which may cause the inverter to trip off and indicate an over voltage protection condition. Use a 3 % reactor to absorb these line spikes and offer protection to the rectifiers and DC bus capacitors, while minimizing nuisance tripping of the inverter.

The input impedance may consist of source impedance (upstream transformer), AC line reactor and/or DC link choke. The 8% data reflects the performance of a typical VFD when a combination of a 3% impedance DC link choke and a 5% impedance AC line reactor are used. It is easy to see how the simple addition of either a line reactor or equivalent DC link choke can have a significant effect on the input harmonic current distortion of a six pulse VFD. Reactors are by far, the most economical means of reducing input current distortion on a drive system. The single line diagrams for the installation of AC line reactors for minimizing harmonics are shown in Figure 9.6.

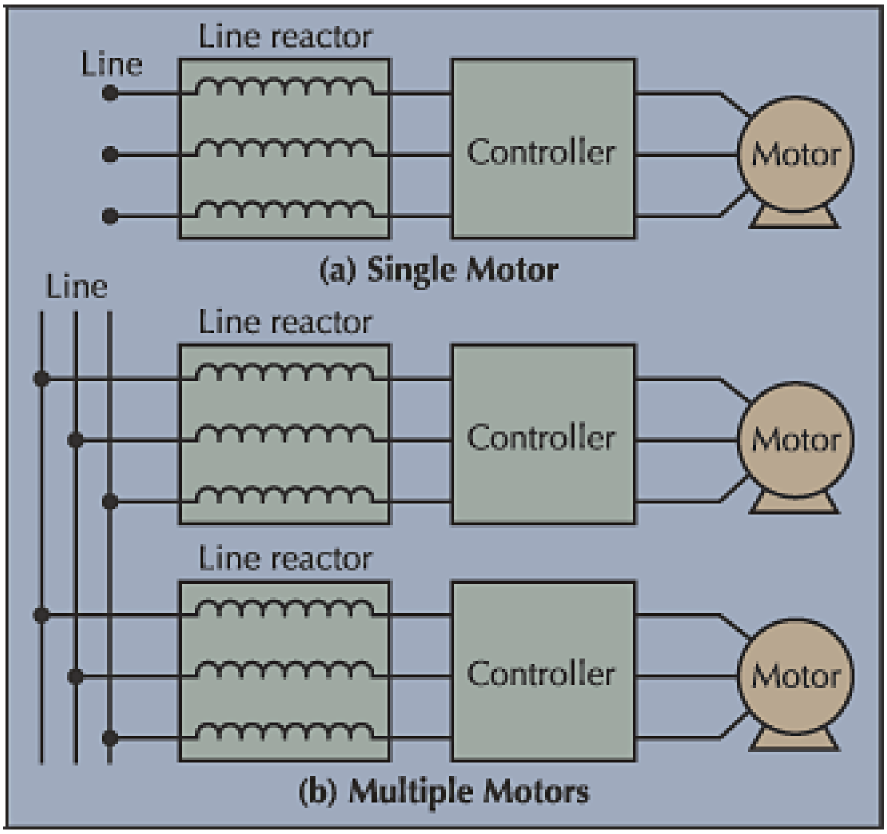


Fig.9.6 Single line diagram for installation of AC line reactors

It is important to note that whenever one is considering the impedance of a reactor, it is the effective impedance that does the work, not the rated impedance. Effective impedance is based on the actual fundamental current, which is flowing and the actual inductance of the reactor.

Effective impedance (%) [30]=

$$Z_{eff} = \frac{\sqrt{3} x 2 x \pi x f x L x I_{actualloading}}{V_{LL}} \text{ x } 100 \qquad (9.1)$$

Note:

L Inductance

f Frequency

π 3.14

I Actual current loading

V_{LL} Voltage phase to phase (400 Volt, 11 kV etc)

It is easy to predict the current distortion at the PCC when each Variable Frequency Drive (VFD) or Adjustable Speed Drive (ASD) employs the same filtering technique (such as line reactors). If 5% impedance line reactors are installed on the input of each VFD, then the input current distortion would be < 35% depending on the amount of source impedance (in addition to the line reactor). If the electrical load was entirely made up of VFDs, each having a 5% impedance line reactor, then the distortion at the PCC would simply be 35% THD_I x 100%VFD / 100% total load = 35% THD_I at the PCC. Now if the same VFDs were only 20% of the total load at the PCC, then 35% THD_I x 20% VFD / 100% Total Load = 7% THD_I at PCC.

9.3.2 APPLICATION OF DC LINK CHOKE [30]

Based on these discussions, it can noted that any inductor of adequate size placed in between the ac source and the DC bus capacitor of the VFD will help in improving the current waveform. These observations lead to the introduction of a DC link choke which is electrically present after the diode rectifier and before the dc bus capacitor. The DC link choke performs very similar to the three phase line inductance. The ripple frequency that the DC link choke has to handle is six times the input AC frequency for a six pulse VFD. The single line diagram for the installation of a DC link choke is shown in Figure 9.7.

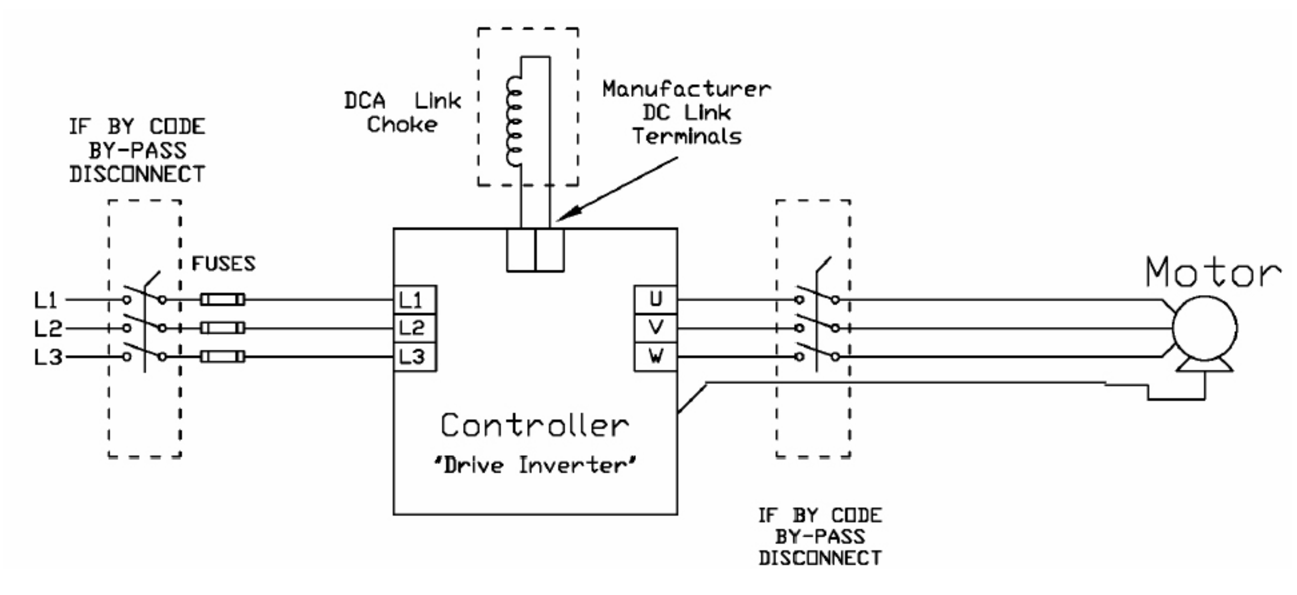


Fig.9.7 Typical electrical diagram of DC link chokes in inverter drive

However, the magnitude of the ripple current is small. One can show that the effective impedance offered by a DC link choke is about 50% of its equivalent AC inductance. In other words, a 3 % AC inductor is equivalent to a 6 % DC link choke from impedance view point. The DC link choke is less expensive and smaller than a 3-phase line AC reactor and is often included inside a VFD. It is important to note that DC link chokes are electrically after the diode bridge and so they do not offer any significant spike or overvoltage surge protection to the diode bridge rectifiers. It is thus a good engineering practice to incorporate both the DC link choke and a 3-phase AC line reactor in VFD for better overall performance. Examples of actual DC link chokes are shown in Figure 9.8.

Fig.9.8 Samples of DC link chokes for inverter drive

9.4 PASSIVE HARMONIC FILTERS

In some cases, reactors alone will not be capable of reducing the harmonic current distortion to the desired levels. In these cases, a more sophisticated filter will be required. Filters are used to restrict the flow of harmonic currents in the power systems. It is a LC circuit, which passes all frequencies in its pass bands and stops all frequencies in its stop bands. The simplest method of harmonic filtering is with passive filters. The common choices include shunt connected, tuned & detuned harmonic filters (harmonic traps) and series connected low pass filters (broad band suppressors). These filters use the reactive storage components, namely capacitors and inductors for minimizing harmonics. They play a double role: that is, eliminate harmonic currents and reduce the system load by reactive power. The filter configuration is individually designed for a given point of supply so as to obtain the required frequency–impedance characteristic of the supply system. Figure 9.9 shows a classification diagram for various types of harmonic filters.

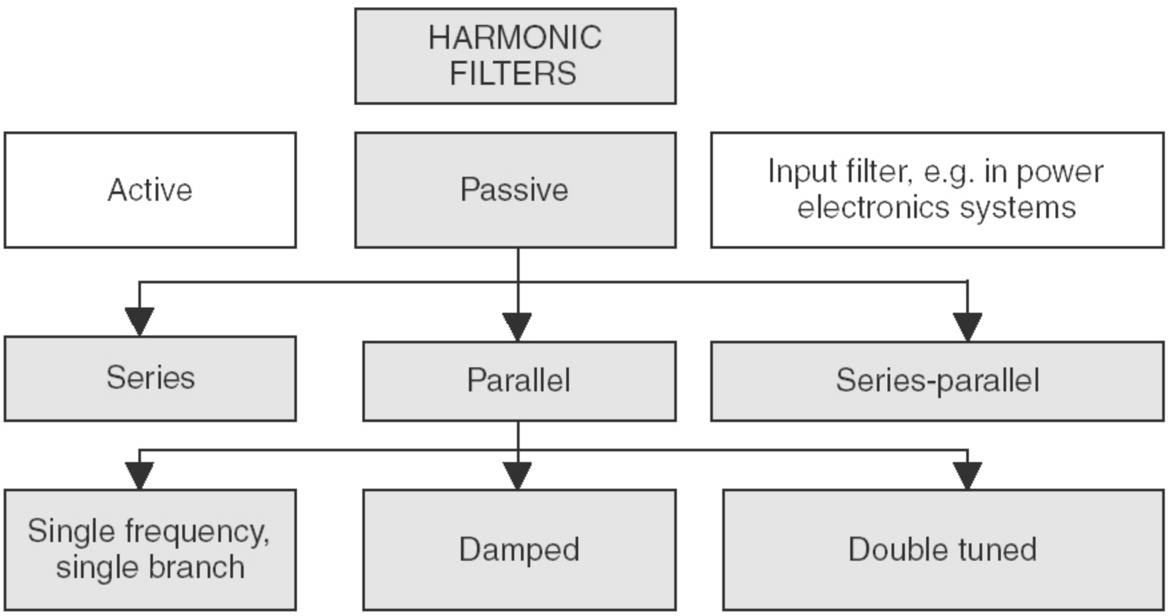


Fig.9.9 An example classification for various types of harmonic filters

Resonant filters, both single frequency and double tuned, guarantee low impedance for selected series resonance frequencies, whereas damped filters have a low impedance over a broad frequency range. Hence they are referred to as broadband filters. The most often used configuration is single-frequency resonant filters plus a broadband filter. This, of course, does not exclude other solutions which are technically advantageous and economically viable for specific applications.

Harmonic filters have been used for nearly thirty years. They consist of a capacitor and an inductor/reactor, which are tuned or detuned to a single harmonic frequency. The capacitor configuration can be either wye (Y) or delta connections. In its basic form, a filter consists of a capacitor connected in series with a reactor tuned to a specific harmonic frequency. Examples are shown in Figure 9.10. In theory, the impedance of the filter is zero at the tuning frequency; therefore, the harmonic current is absorbed by the filter. This, together with the natural resistance of the circuit, means that only a small level of harmonic current will flow in the network.

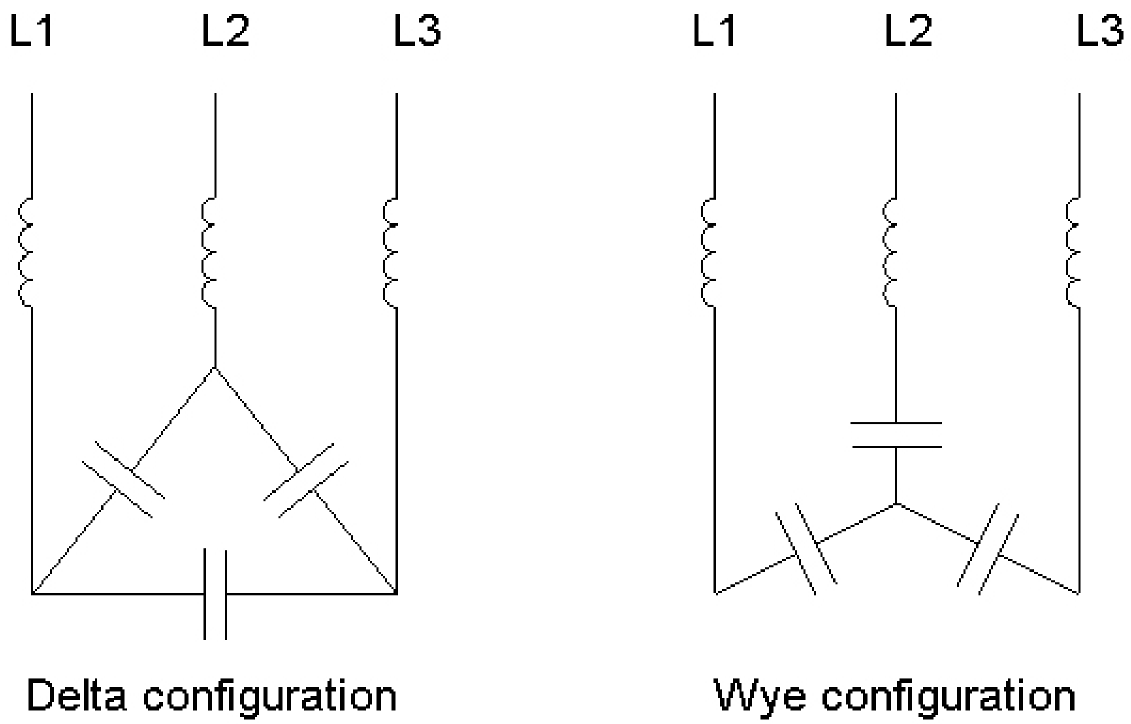


Fig.9.10 Delta & Wye connected reactors

A harmonic filter presents a low impedance path to a specific harmonic frequency regardless of its source. The trap cannot discern harmonics from one load versus another. Therefore, the trap tries to absorb all harmonics, which may be present from all combined sources (non-linear loads) on the system. This may lead to premature filter failure. If tuned harmonic filters (traps) are selected as the mitigation technique, then one may need multiple tuned filters to meet the distortion limits, which are imposed. And when employing both tuned & detuned harmonic filters, one will also need to take special precautions to prevent interference between the filter and the power system. Examples of actual harmonic filters are shown in Figure 9.11.

Fig.9.11 Typical industrial (HV) harmonic filters

Since harmonic trap type 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 of the available 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 harmonic trap type filters, one must always perform a complete system analysis. One 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 filter (trap) is installed. Field tuning of this filter may be required if adverse conditions are experienced. It is also important to note that harmonics below the filter tuning frequency may be amplified.

The most cost effective filter is generally a single-tuned passive filter and this will be applicable for the majority of cases. Filters must be carefully designed to avoid unexpected interactions with the system. The effectiveness of any filter design depends on the reactive output of the filter, tuning accuracy and the impedance of the network at the point of connection. The filter design is important to ensure that distortion is not amplified to unacceptable levels. Where there are several harmonics present, a filter may reduce some harmonics while increasing others. A filter for the 7^{th} harmonic creates a parallel resonance in the vicinity of the 5^{th} harmonic with magnification of the existing 5th harmonic; therefore, a 7th harmonic filter requires a 5th harmonic filter. Consequently, it is often necessary to use a multiple filter design where each filter is tuned to a different frequency.

9.4.1 GENERAL DESIGN OF PASSIVE HARMONIC FILTERS

When designing or applying a harmonic filter, the question that comes to the mind of many engineers is; What harmonic or frequency should the harmonic filter bank be tuned or detuned too? i.e., 4.2 (de-tuned), 4.8 (partially de-tuned) or 5.0 (tuned). To answer this question, the engineer should know why the filters are being installed in the first place.

Harmonic filters are generally installed to achieve one of the following objectives:

- Capacitors are required to improve power factor, and possible system interaction may occur with the installation of a plain capacitor bank.
- Permissible distortion limits of the power utility or technical standards are exceeded, and filters are required to reduce them.
- A combination of 1 and 2 above, whereby capacitors are required to improve power factor and with the addition of the capacitors, permissible distortion limits are exceeded.

Figure 9.12 shows schematically the set of various and mutually dependent factors that have an effect on filter design.

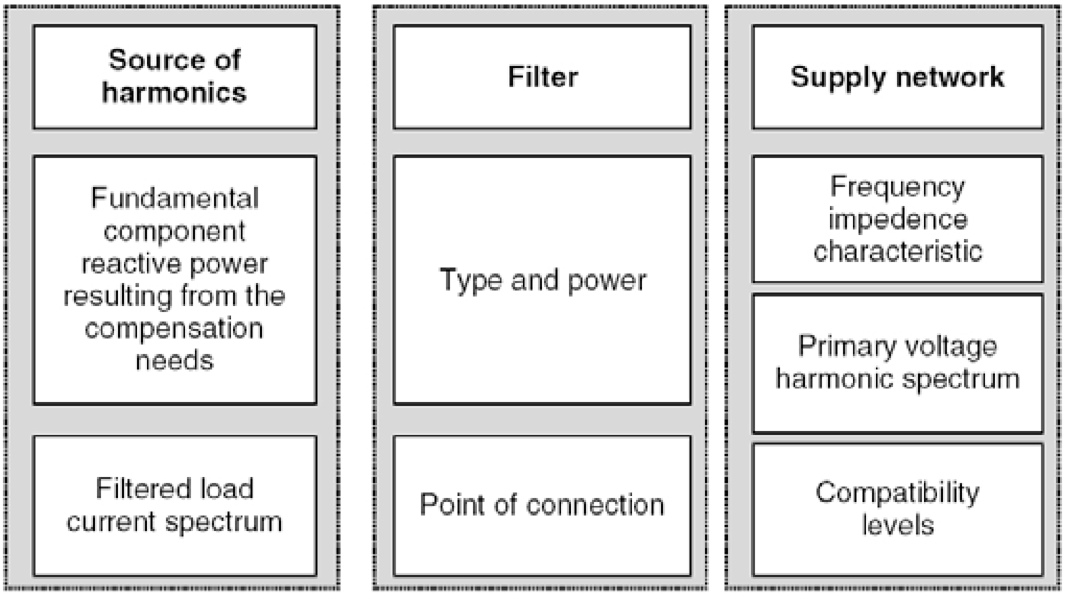


Fig.9.12 Recommended set of data for filter designing

9.4.2 DESIGN OF SINGLE HARMONIC RESONANT FILTER (SINGLE-FREQUENCY FILTER)

The equivalent circuit diagram and typical impedance characteristics of a single-frequency filter and the filter–supply network circuit are shown in Figure 9.13. The resistance R is mainly that of the reactor, since the capacitor's resistance is negligible. Most filters are designed in such a way that each frequency to be filtered has its own filtering circuit tuned to the series resonance with this frequency. Knowing the magnitudes of harmonic currents at the point of planned filter installation allows their elimination to be carried out starting from the harmonics of smallest magnitude and checking the voltage distortion factor.

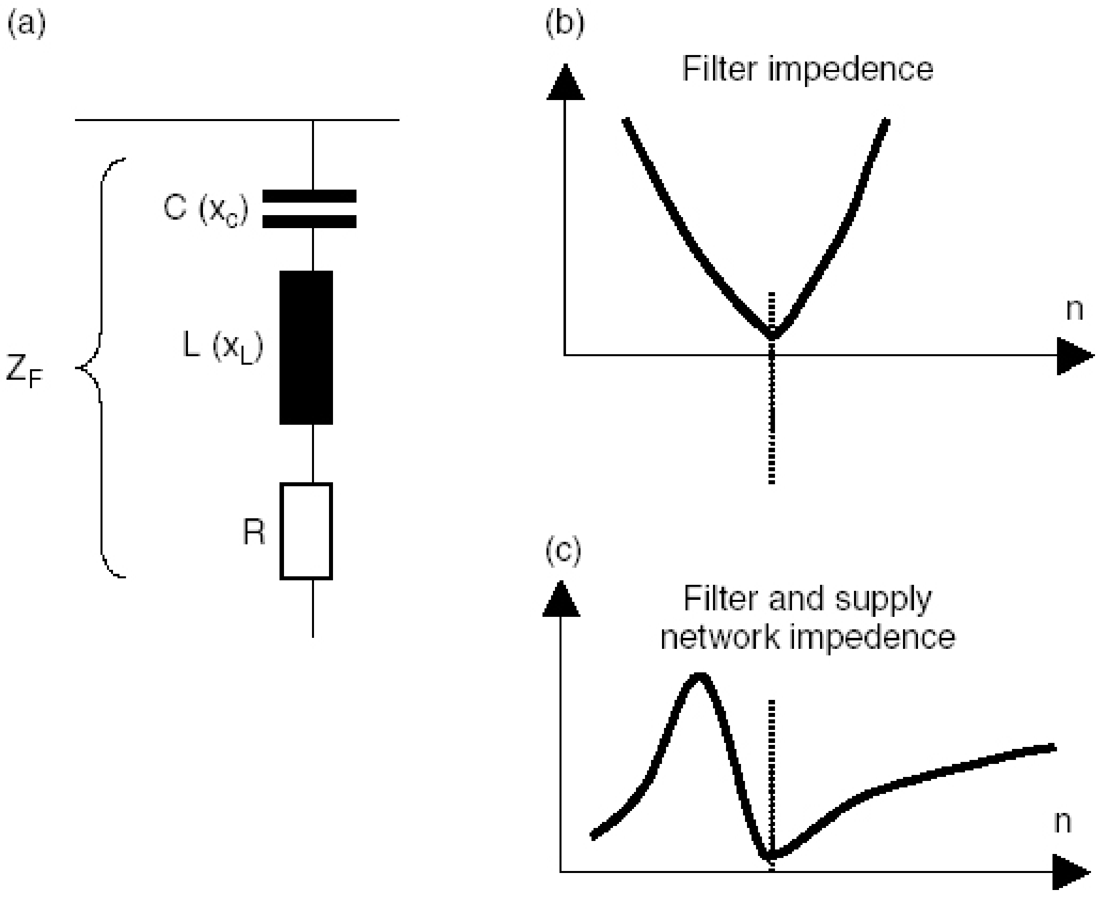


Fig.9.13 The equivalent circuit diagram of a single-frequency filter (a) and typical impedance characteristics of (b) the filter and (c) the filter with the supply network

9.4.3 TUNING THE HARMONIC FILTER

The most common select design for single tune harmonic filter is to tune at the lowest offending harmonic, usually the 5th harmonic. The impedance versus frequency plot, as seen by the harmonic source, is shown in Figure 9.14 together with the original impedance response (untuned) for comparison. Fig.9.14 (a) shows a delta-connected low-voltage capacitor bank converted into a filter by adding an inductance in series with the phases. A computer software was used to perform the impedance scan shown in Fig.9.14 (c). Details on the application of computer software for performing harmonic analysis will be explained in Chapter 10.

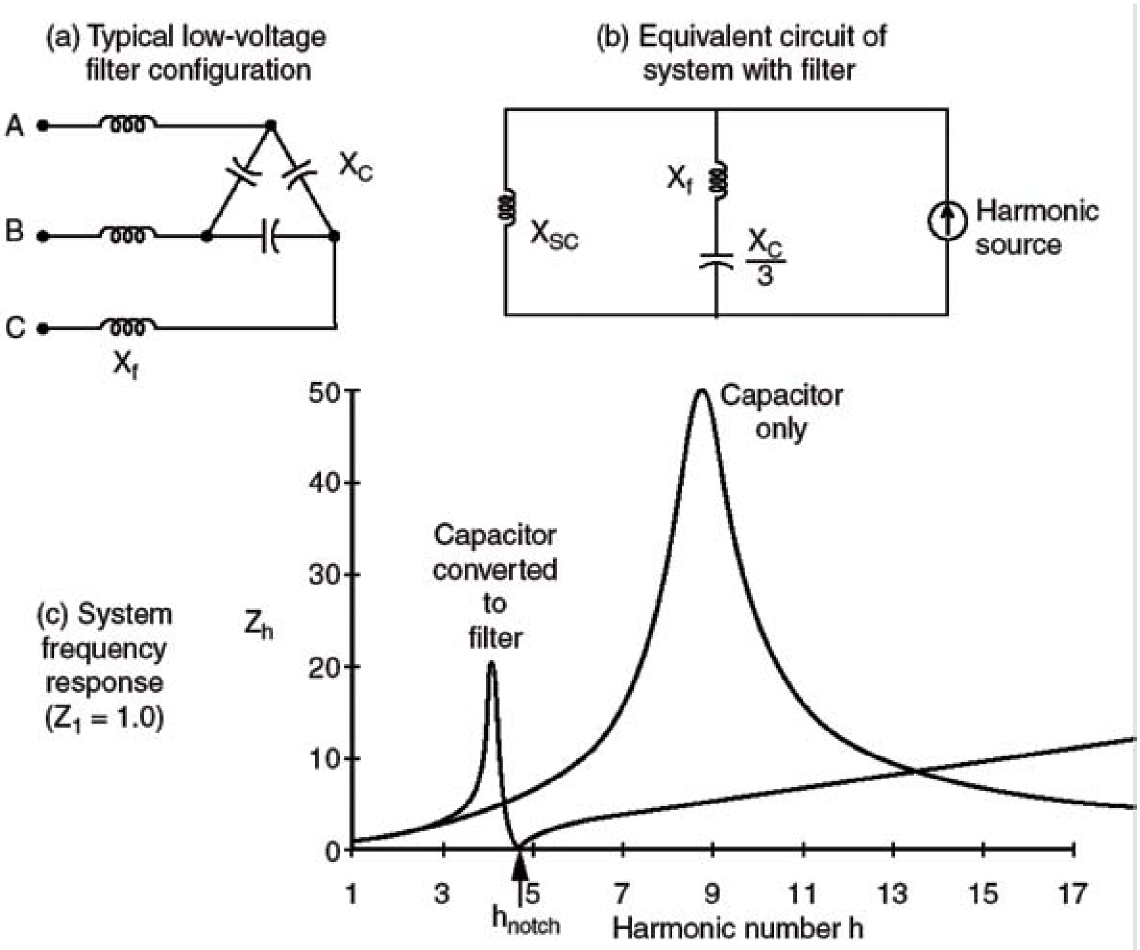


Fig.9.14 Creating a 5th harmonic notch filter and its effect on system response.

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 (Fig. 9.14c). This resonant frequency must be safely away from any significant harmonic or other frequency component that may be produced by the load. Filters are commonly tuned slightly lower than the harmonic to be filtered to provide a margin of safety in case there is some change in system parameters that would raise the notch frequency. If they were tuned exactly to the harmonic, changes in either capacitance or inductance with temperature or failure might shift the parallel resonance higher into the harmonic being filtered. This could present a situation worse than one without a filter because the resonance is generally very sharp.

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 7th harmonic filter usually requires that a 5th harmonic filter also be installed. The new parallel resonance with a 7th harmonic filter alone is often very near the fifth, which is generally disastrous.

9.4.4 SIZES OF REACTORS FOR TUNING AND DETUNING HARMONIC FILTERS

Capacitor along a reactor forms a series resonant circuit. This filter circuit can be tuned to one of the harmonic frequencies occurring in the network. When the resonant frequency of the series resonant circuit is tuned to a frequency that is similar to the harmonic occurring in the system, the filter circuit is termed as Tuned Filter. When the resonant frequency of the series resonant circuit is tuned to a frequency lower than the harmonic occurring in the system, the filter circuit is termed as Detuned Filter

The reactor to capacitance ratio p (%) reflects the ratio of reactor reactance to capacitor reactance. The resonant freq (f_R) of the series resonant filter circuit is indicated indirectly by p (%).

A. Example for tuned filter

System frequency= 50 Hz

Harmonic content: 5th harmonics (THD_V = 5.4 %)

Sample calculation for the design of tuned filter for minimizing the 5th harmonics

$$f_R = f_1 . 1/(\sqrt{p}) \quad (9.2)$$

The value of the 5th harmonics = f_R= 5x50 = 250 Hz

f_1 = 50 Hz

$$p = (f_1/f_R)^2 = (50/250)^2 = 4.00\ \% \quad (9.3)$$

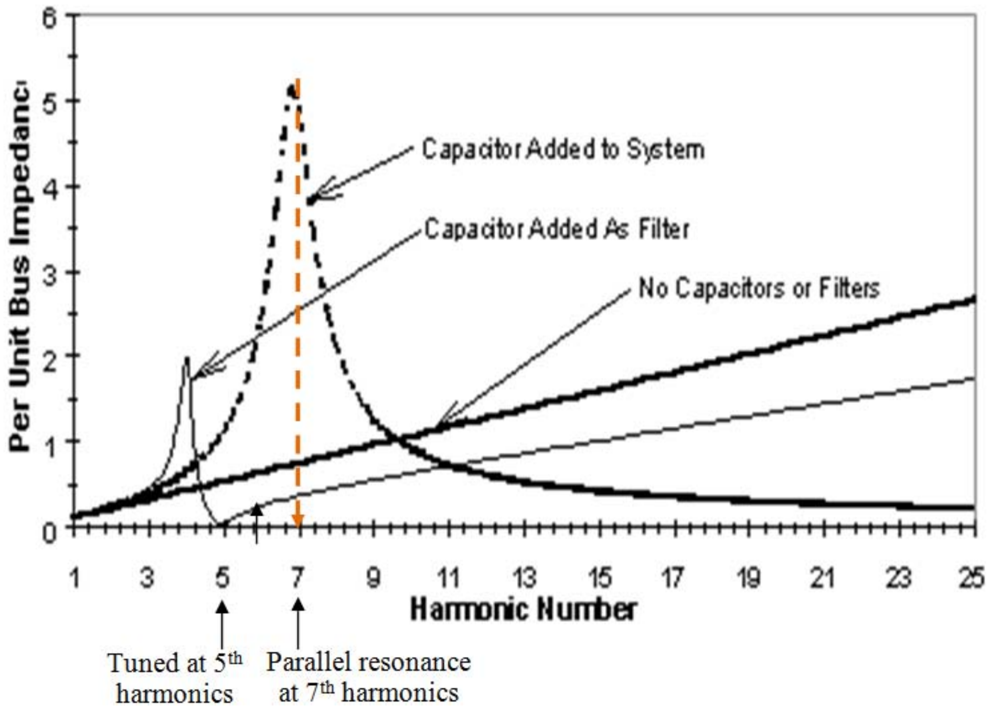


Fig.9.15 System frequency response without and with tuned reactor at 5th Harmonic

To identify the potential parallel resonance, an impedance scan must be performed. First, the related network is modeled using a computer software. Then the harmonic load is modeled as a harmonic current source. The first simulation is done with the harmonic load together with a capacitor bank. The capacitor bank is used for improving the power factor. In Figure 9.15, the impedance scan shows that a potential parallel resonance may occur at the 7th harmonic when a capacitor bank is added to the supply system.

To overcome the parallel resonance, detuned inductances (reactors) are installed in series with the capacitors. The values of the reactors are chosen based on Equation (22). A 4 % reactor is chosen to shift the potential resonance from 7th harmonic to a value less than the 5th harmonics. A notch is created at the 5th harmonic or the system response is tuned at the 5th harmonic. The overall system impedance is now much lower than during the potential resonance at the 7th harmonic.

The overall reactor sizes available for tuning purposes are shown in Table 9.3.

Table 9.3 Common sizes for tuned reactors

Tuned index at harmonic	Tuned frequency	Reactor value in %
3	150	11.11%
5	250	4.00%
7	350	2.04%
9	450	1.23%
11	550	0.83%
13	650	0.59%

If a 1.23 % reactor is chosen, the system response would be tuned to the 9^{th} harmonic or 450 kHz and a notch will be created at the 9^{th} harmonic. The harmonic filter is now designed to filter the 9^{th} harmonics.

B. Example for detuned filter

System frequency= 50 Hz

Harmonic content: 7^{th} harmonics ($THD_V = 6.9$ %)

Sample calculation to design detuned filter that detuned at 4.7^{th} harmonics

$$f_R = f_1 . 1/(\sqrt{p}) \qquad (9.2)$$

The value of the 4.7^{th} harmonics = f_R= 4.7x50 = 235 Hz

f_1 = 50 Hz

$$p = (f_1/f_R)^2 = (50/235)^2 = 4.53 \%. \qquad (9.3)$$

Other sizes for available detuned reactors are shown in Table 9.4.

Table 9.4 Common sizes for detuned reactors

Tuned index at harmonic	Detuned frequency	Reactor value in %
2.77	138.5	13.03%
3.78	189	7.00%
4.06	203	6.07%
4.4	220	5.17%
4.7	235	4.53%
4.8	240	4.34%
4.2	210	5.67%

The impact of inserting detuned reactors in series with capacitors can be seen in Figure 9.16. To identify the potential parallel resonance, an impedance scan must be performed. Two simulations were performed. The first simulation is done with the harmonic load together with a capacitor bank. The capacitor bank is used for improving the power factor. In Figure 9.16, the impedance scan shows that a potential parallel resonance may occur at the 7th harmonic when a capacitor bank is added to the supply system.

To overcome the parallel resonance, detuned inductances (reactors) are installed in series with the capacitors. The values of the reactors are chosen based on Equation (9.3). A 4.53 % reactor is chosen to shift the potential resonance from 7th harmonic to a value less than the 5th harmonics. A notch is created at the 4.7th harmonic or the system response is tuned at the 4.7th harmonic. The overall system impedance is also much lower than during the potential resonance at the 7th harmonic.

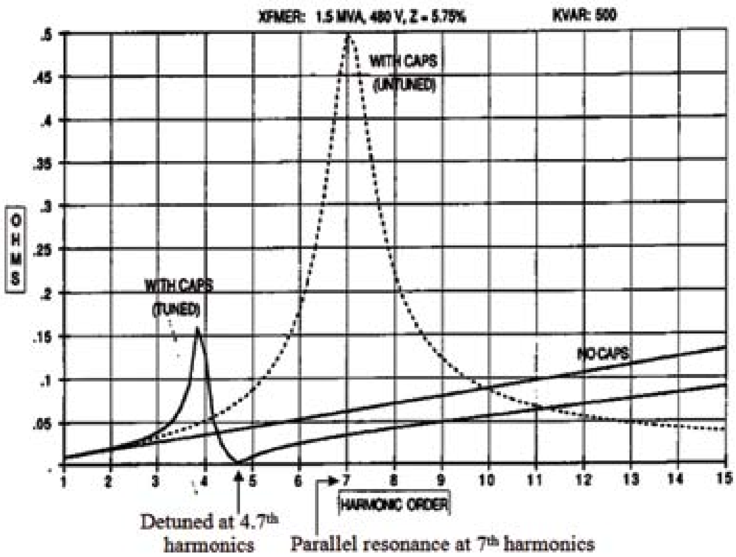


Fig.9.16 System frequency response without and with tuned reactor at 4.7th harmonic

Exercise No.1:

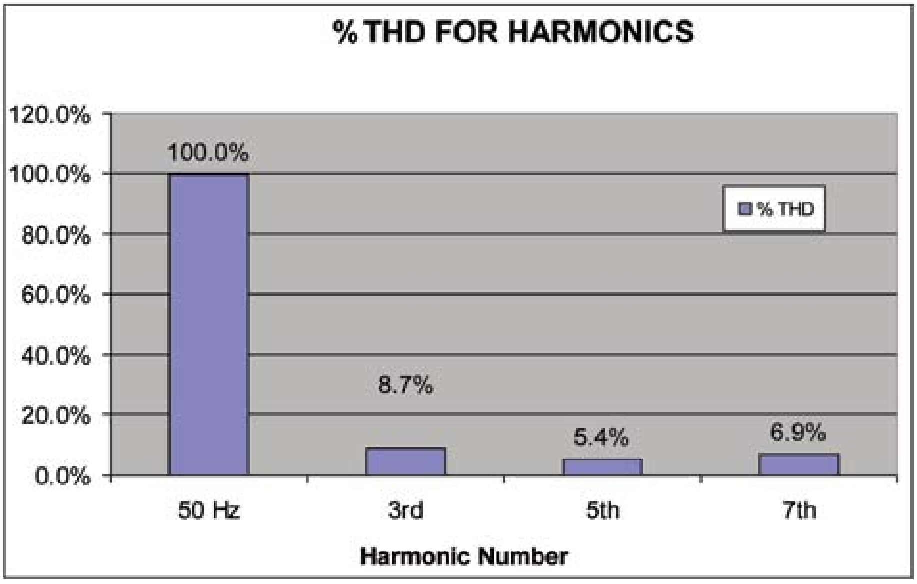


Fig.9.17 Example of harmonic background

Assuming the capacitor configuration selected for Location ABC is:

Size	300 kVar, 415 Volt
Number of steps	6 (6x50 kVar)
Size per step	50 kVar, 415 Volt

System background:

Transformer	1 MVA, 11/0.415 kV
Transformer impedance	4.75 %
Harmonic background	as shown in Figure 9.17

Questions:

1.0 What is the potential resonance frequency?

2.0 What will happen to the capacitor bank if the resonance frequency is near to the recorded harmonics?

3.0 What will happen to the transformer if the resonance frequency is near to the recorded harmonics?

4.0 What is the necessary mitigation measure?

9.4.5 PASSIVE HARMONIC FILTER PERFORMANCE

From the explanation on harmonic filters, it is apparent that tuning has a definite effect on filter performance and system interaction. The question of whether to tune, de-tune or partially de-tune is a question of economics, objective of filtering, and negative system interaction. A tuned filter cost more than a partially de-tuned filter, and likewise a partially de-tuned filter cost more than a de-tuned filter. The reason for the cost difference is the duty requirements for both the capacitors and the reactors.

Example:

The filter currents for various tuning points for the typical system in Figure 9.18 are illustrated in Table 9.5. Table 9.5 is based on 100 amps of 5^{th} harmonic current injected from the non-linear load. This current may flow back to the utility or into the harmonic filter, and is dependent upon the filter impedance and system impedance at the 5^{th} harmonic.

Table 9.5 shows that the 5^{th} harmonic filter will absorb most of the harmonic current and that very little will be absorbed by the utility. As a result, the 5^{th} harmonic filter would require a 5^{th} harmonic current rating of 99 Amps. The 4.8^{th} harmonic filter absorbs less, and would require a 5^{th} harmonic current rating of 70 Amps.

The 4.2^{th} harmonic filter absorbs very little harmonic current (20 Amps), while the utility and the remaining system absorbs the remaining 80 Amps. The conclusion here is simply tuning the filter closer to the 5^{th} harmonics requires higher reactor current ratings, (and also capacitor voltage ratings) which result in higher filter bank cost. The choice of tuning frequency is based on the objective of the harmonic filter and economics. The following guidelines may assist the engineer in determining the proper type (tuning frequency) of filter.

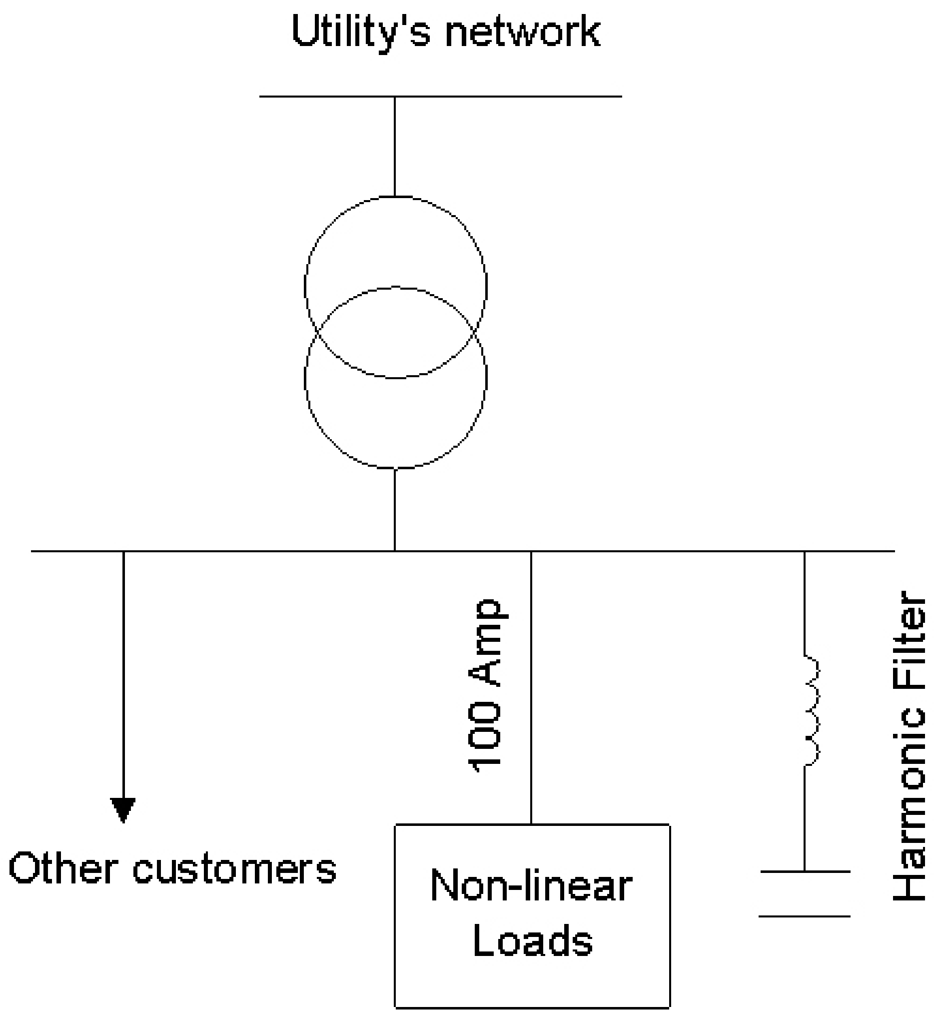


Fig.9.18 Typical industrial system with harmonic filter

Table 9.5 Filter performance

Filter type	Filter current (Amp)	Utility system (Amp)
5th	99	1
4.8th	70	30
2.2nd	20	80

9.4.6 COMPARISON BETWEEN PASSIVE HARMONIC FILTERS

A fixed detuned filter consists of a reactor connected in series with the capacitor unit. The capacitance of the capacitor is selected to reach the desired compensation power. The inductance of the reactor is selected so that the tuned or detuned frequency of the series resonance frequency formed by the capacitor and reactor is lower than the lowest harmonic frequency between the network phases. The lowest harmonic frequency present in the system is normally the 5th (250 Hz).

Below the resonant frequency of the detuned filter, such as the fundamental frequency (50 Hz) the detuned capacitor is capacitive, that is it produces reactive power. Above the resonant frequency, the detuned filter is inductive and it cannot amplify the typical harmonic frequencies such as the 5th, 7th & 11th harmonics. A fixed detuned filter also eliminates lower order harmonics from the system to some extent.

9.4.6.1 DE-TUNED FILTERS (TUNING BETWEEN 4.0 AND 4.4)

If harmonic filters are being considered only for the purpose of power factor correction, then a de-tuned filter bank is the best choice. This filter will do little for removing any harmonic distortion present on the system but will allow the installation of a large capacitor bank without any adverse system interactions. De-tuned filter banks are less costly and are more reliable than partially de-tuned and tuned filter banks. The anti-resonant frequency should be considered to assure that it does not fall near the 3rd harmonic.

9.4.6.2 PARTIALLY TUNED FILTER (TUNING BETWEEN 4.4 AND 4.8)

In some situations, a filter (or capacitor bank) is required to improve power factor, and at the same time distortion limits are exceeded. In this situation, a partially tuned filter bank is usually the best choice. A partially tuned bank offers less risk and is typically less costly than a tuned filter bank.

9.4.6.3 TUNED FILTERS (TUNING BETWEEN 4.8 AND 5.0)

If harmonic filters are being considered only for the purpose of reducing the harmonic distortion to acceptable limits, then a tuned filter bank should be considered. A tuned filter bank will require the least amount of kVar to bring the distortion down within limits, but will require the highest level of engineering design. It has the highest level of risk, since it will draw most of the harmonics present on the industrial system and local utility system. Harmonic load growth should be considered, along with ambient voltage distortion level. The application of this type of filter should include a detailed harmonic analysis by the manufacturer.

9.4.6.4 OTHER FILTER TYPES

5th harmonic filters have been the main topic of discussion. Other types of filters are some times required, i.e., 7th, 9th and 11th filter banks. Or 5th, 7th, 11th and 13th high pass. These filters are designed with optimization and with specific current distortion limits in mind. They are more costly then simple tuned filter banks but are much more effective in reducing the system distortion. They are generally applied to systems with large amounts of non-linear load.

9.5 LOW PASS HARMONIC SUPPRESSORS

Low pass harmonic filters, also referred to as broad band harmonic suppressors that offer a non-invasive approach to harmonic mitigation. Rather than being tuned for a specific harmonic, they filter all harmonic frequencies, including the 3rd harmonic. They are connected in series with the non-linear load with large series connected impedance, therefore they don't create system resonance problems. No field tuning is required with the low pass filter.

Due to the presence of the large series impedance, it is extremely difficult for harmonics to enter the filter / drive from the power source. Rather they are supplied to the drive via the filter capacitor. For this reason, it is very easy to predict the distortion levels, which will be achieved and to guarantee the results. The three Phase Low Pass Harmonic Filters are ideal for both commercial and industrial equipment such as variable frequency motor drives, pumps, fans, compressors, chillers, conveyors, cranes and many other types of electronic controls.

A low pass (broad band) harmonic filter can easily offer guaranteed harmonic current levels, right at the drive / filter input, as low as 8% to 12% THD_I. (To achieve 8% maximum current distortion one can typically select the broad band harmonic suppressor based on a hp/kW rating which is 25-30% larger than the total drive load to be supplied). In most cases, this results in less than 5% THD_I at the facility input transformer and meets most international standards.

The low pass filter, not only offers guaranteed results, it is also more economical than 12 or 18 pulse rectifier systems, active filters or in many cases even harmonic traps. They are intended for use with 6-pulse drives having a six diode input rectifier in variable torque applications. This typically means fan and pump applications. For the sake of economy, a single broad band harmonic suppressor may be used to supply several drives (VFDs). When operating at reduced load, the THD_I at the filter input will be even lower than the guaranteed full load values.

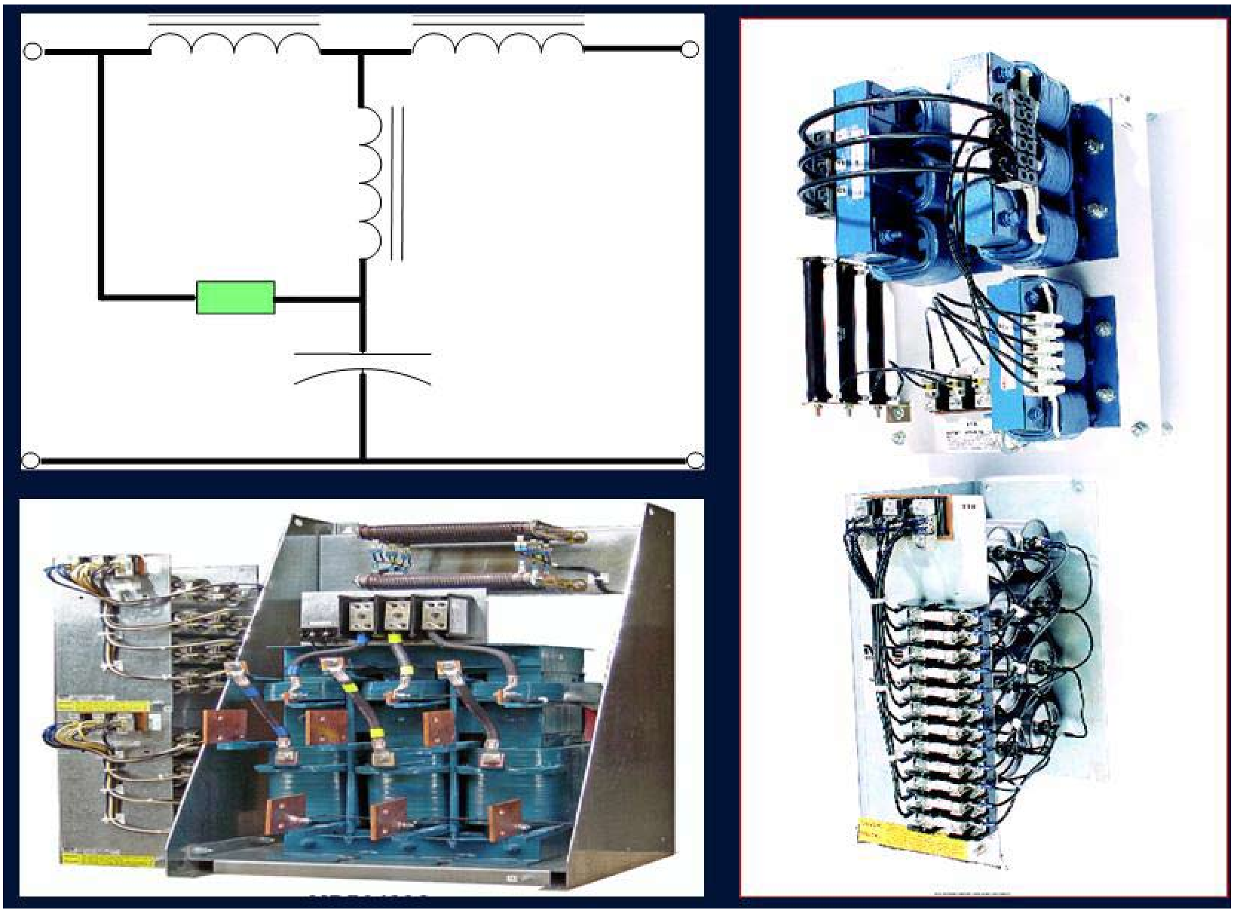


Fig.9.19 Low pass harmonic filters

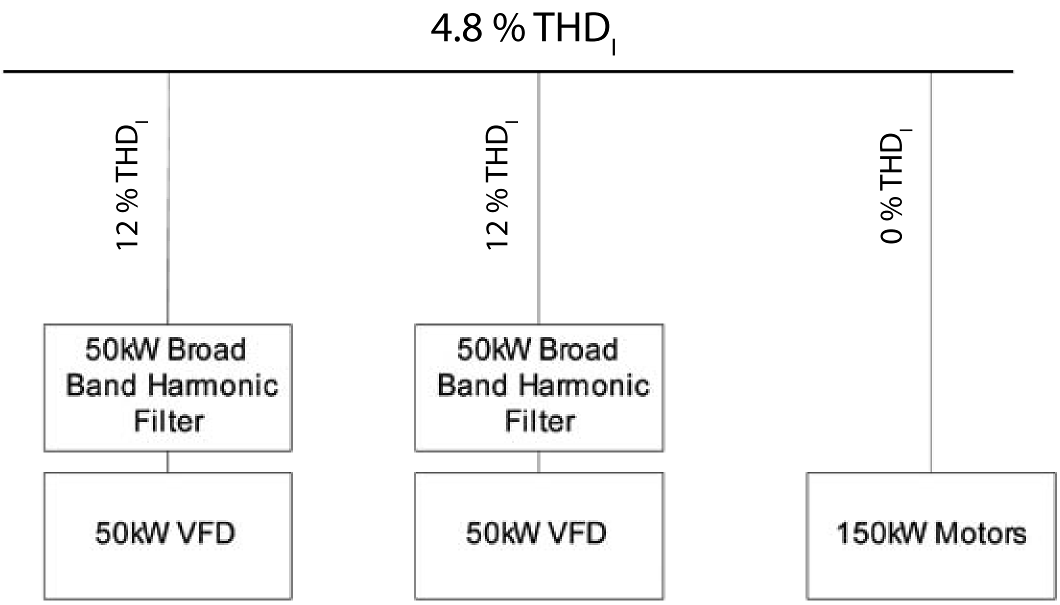


Fig.9.20 THD_I after installation of a low pass harmonic suppressors

Figure 9.20 demonstrates how 5% THD_I is accomplished at the utility PCC, or facility input transformer. It is easy to see that 12% THD_I guaranteed at the filter input, reduces to less than 5% at the PCC due to the presence of additional linear loads (motors).

The drives, in the example above, represent 100 kW of the total 250 kW load and have 12% or less current distortion. When the 150 kW motor is drawing full load current, we have the following:

100 kW / 250 kW x 12%	= 4.8%
150 kW / 250 kW x 0%	= 0%
Total harmonic distortion at PCC	= 4.8%

It is now very simple to perform harmonic analysis on a power system, because we know the worst case level of harmonic distortion whether we are employing a line reactor, combination of AC line reactor & DC link choke, or broad band harmonic suppressor.

The simple analysis will work whether we are considering the facility input PCC or a PCC defined on a particular mains bus.

- Add up the total load, at the PCC, using each of the various filtering techniques.
- Determine the percentage of this type of load compared to the total load by dividing each of these group totals by the total load.
- Multiply this result by the expected % THD_I for this particular filter technique (linear loads or motor loads = 0%, 5% line reactor = 35%, 5% line reactor & 3% DC link choke = 28%, broad band harmonic suppressor = 12% or broad band harmonic suppressor = 8%).
- Add up all of these factors to determine the percent of total harmonic distortion at the PCC s elected.

Example:

100 kW has Broad Band Harmonic Suppressor and guarantees 12% THD_I,

150 kW is motor loads with 0% THD_I.

100 kW / 250 kW x 12% = 4.8% and

150 kW / 250 kW x 0% = 0%.

The sum total is 4.8% + 0% = 4.8% THD_I at this PCC

Exercise No.2:

Capacitor size : 900 kVar Delta, 3 steps, 3.3 kV

Transformer details : 1.5 MVA, 5.25 %

Please calculate the resonance condition for 1^{st}, 2^{nd} & 3^{rd} capacitor steps.

At what step will the resonance condition happen?

What is the recommended measure to prevent the resonance conditions?

What is the type & size of reactors to be installed?

Exercise No.3:

Capacitor size : 2 Mvar Y-Y, 2 steps, 11 kV

Transformer details : 1.5 MVA, 5.25 %

Please calculate the resonance condition for 1^{st}, 2^{nd} & 3^{rd} capacitor steps.

At what step will the resonance condition happen?

What is the recommended measure to prevent the resonance conditions?

What is the type & size of reactors to be installed?

9.6 USE OF PHASE-SHIFTING TRANSFORMERS.

Phase shifting is an ideal method of controlling, reducing and eliminating harmonics currents ever present in transmission and distribution systems. The simplicity of it is that phase is shifted in increments of several outputs resulting in phase shifts which will cancel out the varying levels of harmonics. This form of phase shifting transformer is called a harmonic mitigating transformer.

A harmonic mitigating transformer attenuates triplen harmonics by utilization of a zig zag winding on its secondary. The design of a zig zag winding moves half of the turns of each secondary phase around two legs of the transformer's core. A harmonic mitigating transformer provides cancellation of magnetic flux caused by triplen harmonics by utilizing its zig zag winding with little, or no, transfer to primary windings. In the case of three phase loads, triplen harmonics are not generated but other harmonic issues result from currents flowing at 5^{th}, 7^{th}, 11^{th} or higher order harmonics. A harmonic mitigating transformer achieves attenuation of these problematic frequencies by utilizing pairs of transformers or dual secondary windings. In either scenario, two secondary are phase-shifted so that they are relative to each other. Targeted harmonics cancel each other out when the degree of relative phase shift from the secondary are close to, or are exactly, 180^{o} out of phase.

Phase shifting transformers are the second best way to address harmonic mitigation if the system's design is such that multiple 6-pulse AC drives operate at the same time and at similar load levels. However, this strategy isn't effective where different drives cycle on and off individually. The 30^{O} phase shifting transformer produces phase displacement in the current such that the 5^{th} and 7^{th} harmonics are shifted by 180°. A 15^{o} phase shifting transformer produces phase displacement in the current such that the 11^{th} and 13^{th} harmonics are shifted by 180^{o}. However, the effectiveness of these strategies is dependent on the balanced loading of the systems.

a. General Harmonic Mitigating Transformer

b. Harmonic mitigating transformers designed to reduce ripple current.

Fig.9.21 Samples of harmonic mitigating transformers

9.7 ACTIVE HARMONIC FILTER [31]

Most passive harmonic mitigation techniques discussed earlier aim to cure the harmonic problem once they had been created by non-linear loads. However, drive manufacturers are developing drives, which do not generate low order harmonics. These drives use active front ends, instead of using passive diodes as rectifiers, the active front VFD make use of active switches like IGBT's (insulated gate bipolar transistor) along with parallel diodes. The insulated gate bipolar transistor or IGBT is a three-terminal power semiconductor device, noted for high efficiency and fast switching. Today's inverters use IGBTs to switch the DC bus on and off at specific intervals. In doing so, the inverter actually creates a variable AC voltage and frequency output. The output of the drive doesn't provide an exact replica of the AC input sine waveform. Instead, it provides voltage pulses that are at a constant magnitude i.e. voltage harmonics.

To overcome such problem, the active harmonic filter was developed. Most active harmonic filter topologies are complicated and require active switches and control algorithms. These devices are non-standard products, and require and engineered solutions for the application. The cost of this type device is much more expensive than the passive harmonic filter [31].

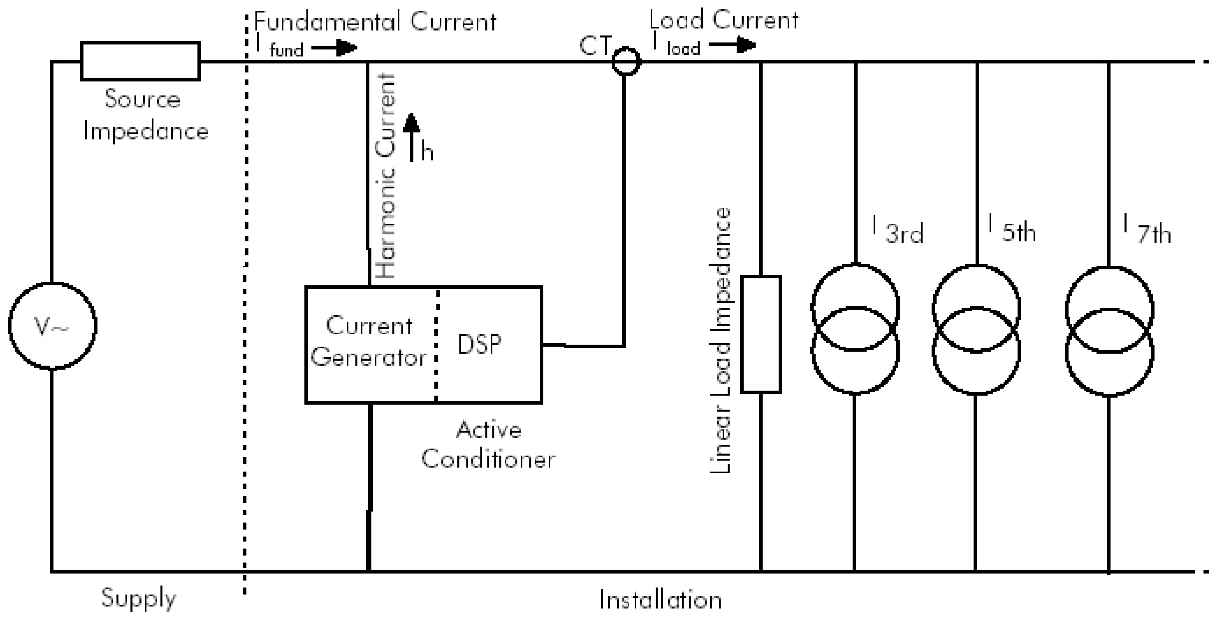


Fig.9.22 Operation of active harmonic filter

The concept of the active filter is simple; power electronics is used to generate the harmonic currents required by the non-linear loads so that the normal supply is required to provide only the fundamental current. Figure 9.22 shows the principle of a shunt device. The load current is measured by a current transformer, the output of which is analysed by a digital signal processor (DSP) to determine the harmonic profile. This information is used by the current generator to produce exactly the harmonic current required by the load on the next cycle of the fundamental waveform. In practice, the harmonic current required from the supply is reduced by about 90 %. The active filter is connected in parallel with the supply, and constantly injects harmonic currents that precisely correspond to the harmonic components drawn by the load. The result is that the current supplied by the power source remains sinusoidal. The entire low-frequency harmonic spectrum, from the second to the twenty fifth harmonic, is supported.

If the harmonic currents drawn by the load are greater than the rating of the active filter, the filter automatically limits its output current to its maximum rating; the filter cannot be overloaded and will continue to correct up to the maximum current rating. Any excess harmonic current will be drawn from the supply; the filter can run permanently in this state without damage. As the active filter relies on the measurement from the current transformer, it adapts rapidly to changes in the load harmonics. Since the analysis and generation processes are controlled by software it is a simple matter to programme the device to remove only certain harmonics in order to provide maximum benefit within the rating of the device. Example of an actual active harmonic filter is shown in Figure 9.23.

Brand A

Brand B

Fig.9.23 Examples of active harmonic filters

9.8 HYBRID REACTIVE POWER, HARMONICS & FLICKER (FSRP) COMPENSATION SYSTEM [32]

The Hybrid Reactive Power, Harmonics & Flicker (FSRP) Compensation system is one of the latest innovations for minimizing harmonic pollutions. It employs unique electronic switching mechanism (zero crossing switching mechanism) that renders the conventional capacitor system to be obsolete. This ultra-fast acquisition time (which include sensing, processing and ultimately response activities) system leverages on its active switching mechanism and passive compensation modules to offer the optimum result. In addition to reducing the harmonics and improve power factor, it's designed to be transient-free switching, non-resonant and increase the ride thru capability in the event of voltage drop. Below is a simplified design topology of the Hybrid Harmonic Filter.

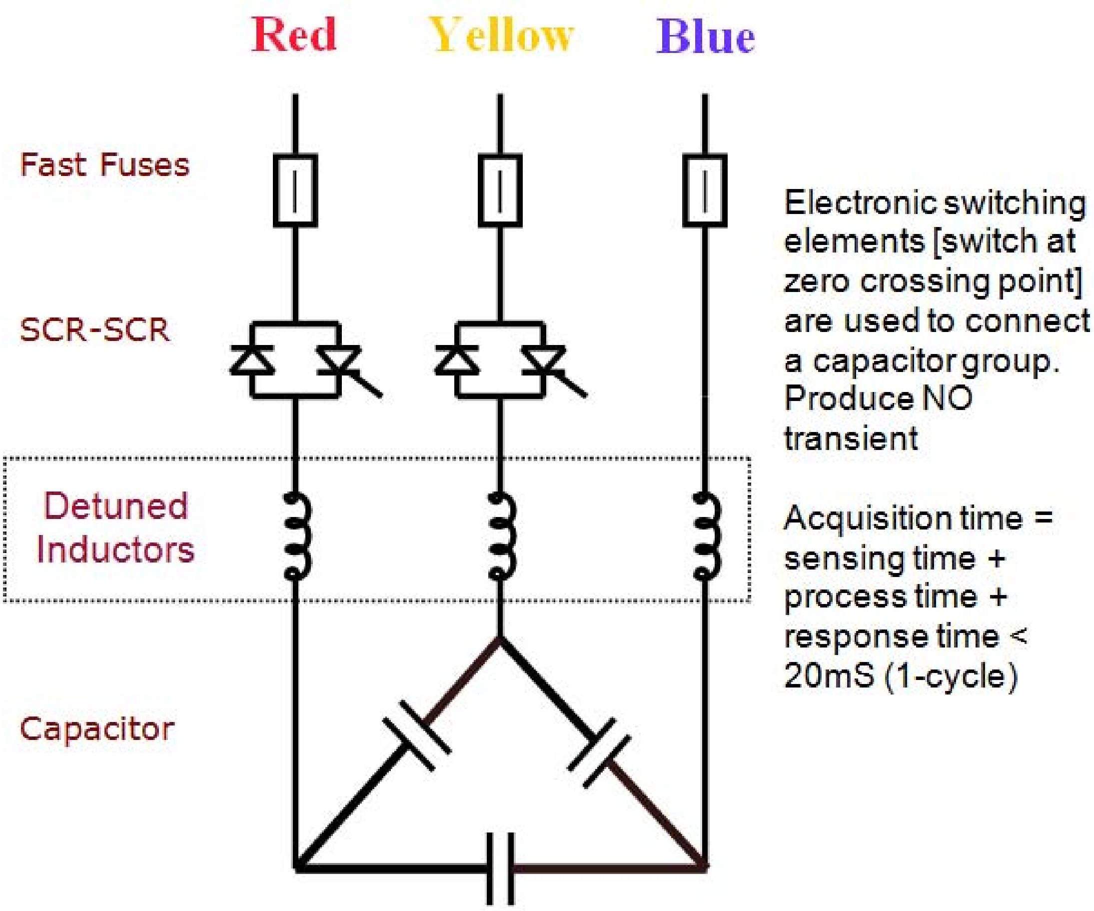


Fig.9.24 Design topology of the Hybrid Harmonic Filter

The Real Time Transient Free Hybrid Harmonic & Flicker Compensation System employs real time zero crossing switching mechanism without introducing transient into the network to provide accurate and timely reactive power compensation with total acquisition time (include sensing, processing and correction) less than 20-ms (1-cycle).

The real time reactive power, harmonic and flicker compensation system is able to switch ON/ OFF all the groups simultaneously without having delay between each groups / inter-groups.

Fig.9.25 Example for the Hybrid Harmonic Filter

CHAPTER 10

HARMONICS SIMULATION

10.0 OVERVIEW

As stated in Chapter 8, power utility's engineers are required to perform harmonic penetration studies to verify the severity of the total harmonic distortion voltage (THD_V) due to connection of new non-linear loads. Apart from verifying the new THD_V, power utility engineers can also verify the effectiveness of the harmonic mitigation measures especially the use of passive filters in mitigating harmonics. The analysis on harmonics is called the harmonic penetration study or harmonic analysis.

A harmonic analysis software can be used to model power system distortion. The deviation between the perfect sinusoid is expressed in terms of harmonic components. After the network is solved at the fundamental frequency (e.g., 50 Hz, 60 Hz), all of the network components are converted into impedances. These impedances are varied according to the harmonic number and the network is solved for each specific harmonic (e.g., 1^{st}, 3^{rd}, 5^{th}). For each device type within the network there are various ways of modeling the effect of the harmonic number on the device impedance.

The most common model for a harmonic source is the current injection model. A current injection technique is used to inject current of a certain magnitude and angle into the network. Harmonic filters may also be defined directly in the network by specifying a shunt device of this type at any node in the network. Harmonic analysis can be used to calculate the total harmonic distortion, telephone influence factor, and Thevenin impedance. In addition, a harmonic scan is also possible over a range of harmonic numbers.

In this chapter, you will learn about:

- Adding harmonic injections to the network.
- Adding harmonic filters to the network.
- Editing harmonic injections and filters.
- Specifying harmonic analysis options.
- Performing a harmonic analysis.
- Viewing results of a harmonic analysis.

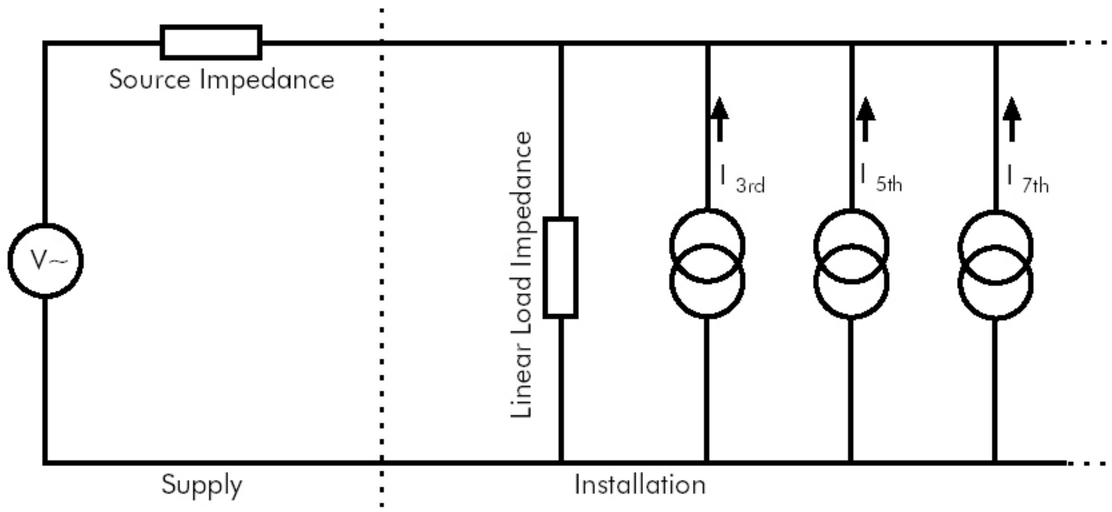
10.1 HARMONIC MODELS

10.1.1 MODELING OF SUPPLY SYSTEMS

The modeling of the supply delivery system is done similar based on the fundamental load flow concept. The source, transformer, lines & loads are modeled accordingly. Please ensure the software is able to model the fundamental (50 Hz) and harmonic components accordingly referring to the respective IEEE models for harmonics [30].

10.1.2 MODELING OF HARMONIC SOURCES

As explained in Chapter 2, the equivalent circuit of a non-linear load is modeled as harmonic current sources, one source for each harmonic frequency. In Figure 2.7, the models for harmonic current sources are shown for the 3^{rd}, 5^{th} and 7^{th} harmonics. The values of the harmonic currents are modeled either in harmonic current (Amp) or in per unit (PU) values. The values of the harmonic currents are obtained from two methods i.e. harmonic profiling using power quality recorders or data provided by the manufacturers/customers.



From Fig.2.7 Equivalent circuit of a non-linear load

A harmonic injection is a current injection that can be used to eliminate harmonics and is described by a set of "triplets" that define magnitude and angle of harmonic injection as a function of harmonic number. The magnitude of each triplet is defined in per-unit terms so the base current of the injection is also required.

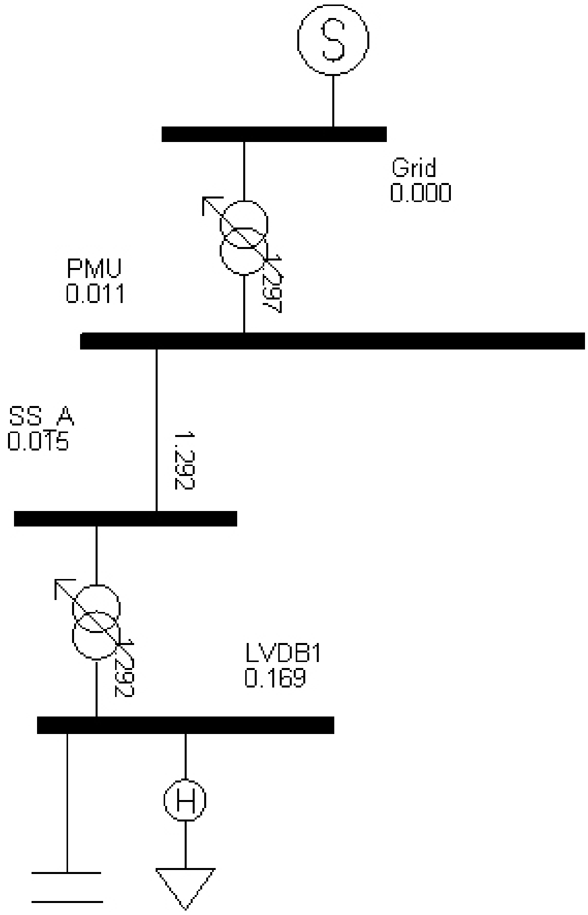
Harmonic injections specified in the network are only considered by the harmonic analysis module and are irrelevant to any other analysis. Harmonic injections can be associated with another network item, such as a static load, or can exist separately attached to a node in the network. When a harmonic injection is associated with a specific network item (static load, machine, etc.) that item is replaced by the specified harmonic injection during a harmonic analysis. A transformer branch is an exception since replacing the transformer branch by a harmonic injection would cause an islanded network to be implicitly created.

10.2 EXAMPLE ON APPLICATION OF HARMONIC ANALYSIS SOFTWARE

In this guidebook, an example on the application of a harmonic analysis software called PSS/Adept is explained. However, there also many other softwares that can also be used to perform harmonic analysis. All of these softwares would be used to evaluate the existing harmonic levels, the impact of the application of capacitor banks in the networks and the mitigation options. This next example will highlight the application of the PSS/Adept software in performing the above requirement.

Example:

The single diagram for a common distribution system is shown in Figure 10.



Label	Description
PMU	Main intake substation
SS_A	Substation A
LVDB	Low voltage distribution board

Fig. 10.1 Single line diagram for a distribution system

The details on the parameters for system in Figure 10.1 are as follows.

Table 10.1 Parameters for the distribution system

A. Source fault level

Voltage	132	kV
3ph FL	30	kA
1ph FL	10	kA
X/R Ratio		10

B. Source fault levels in per unit

Positive sequence resistance	0.0014580	pu
Positive sequence reactance	0.0145800	pu
Zero sequence resistance	0.0102052	pu
Zero sequence reactance	0.1020522	pu

C. Loads at Substation SS_A

Fundamental Loads 50 Hz (3-phase balanced)

P (kW)	Q (kVar)
300	200

Harmonic loads (currents)

Harmonic	% (THD)	PU
5	45	0.45
7	46	0.46
11	40	0.40
13	42	0.42

D. Cable & Transformer details

Component	Size	Vector Group	Length (km)	Model
132/11 kV Transformer	30 MVA	Yd11	N/A	IEEE
11/0.415 kV Transformer	1 MVA	Dyn11	N/A	IEEE
Cable from PMU to SS_A	3x240mm2	1	N/A	IEEE
Capacitor	200 kVar	N/A	N/A	IEEE

The results of the fundamental load flow & harmonic penetration are shown below:

Table 10.2 Results of the fundamental and harmonic penetration study

		Current (Amp)			Voltages (kV)			
1st Node	2nd Node	R	Y	B	R-Y	Y-B	B-R	THDV %
Grid	PMU	15.67	15.67	15.67	11.13	11.13	11.13	1.2
PMU	SS_A	15.65	15.65	15.65	11.12	11.12	11.12	1.6
SS_A	LVDB	397.58	397.58	397.58	0.440	0.440	0.440	20.40

The value of the total harmonic distortion voltage (THD_V) at the point of common coupling (PCC) at SS_A is 1.6 %. This value is less than 4 % as stated in the ER G5/4 for 11 kV networks. The graphical results are shown in Figures 10.2, 10.3, 10.4 and 10.5.

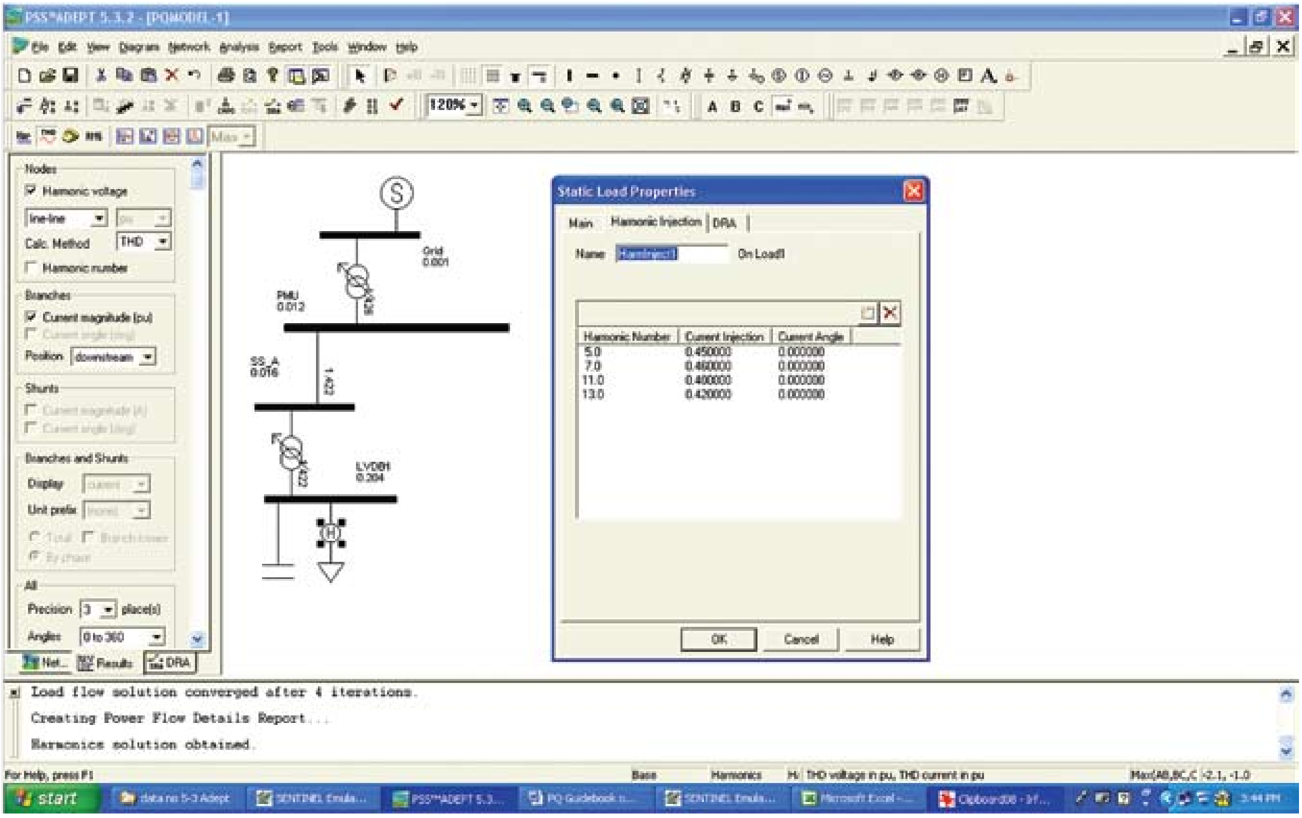


Fig. 10.2 Harmonic current sources at LVDB1

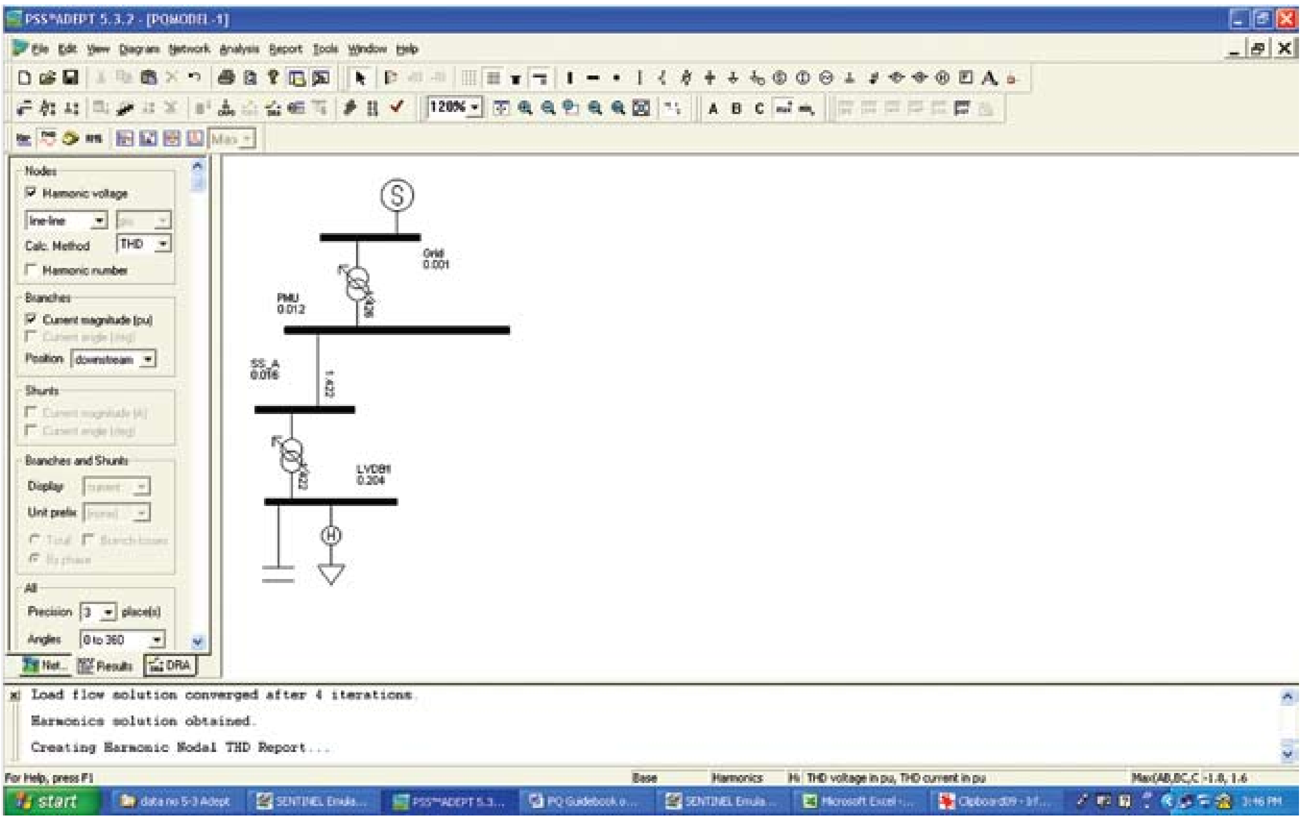


Fig. 10.3 Total Harmonic Distortion Voltage (THD_V) at LVDB1

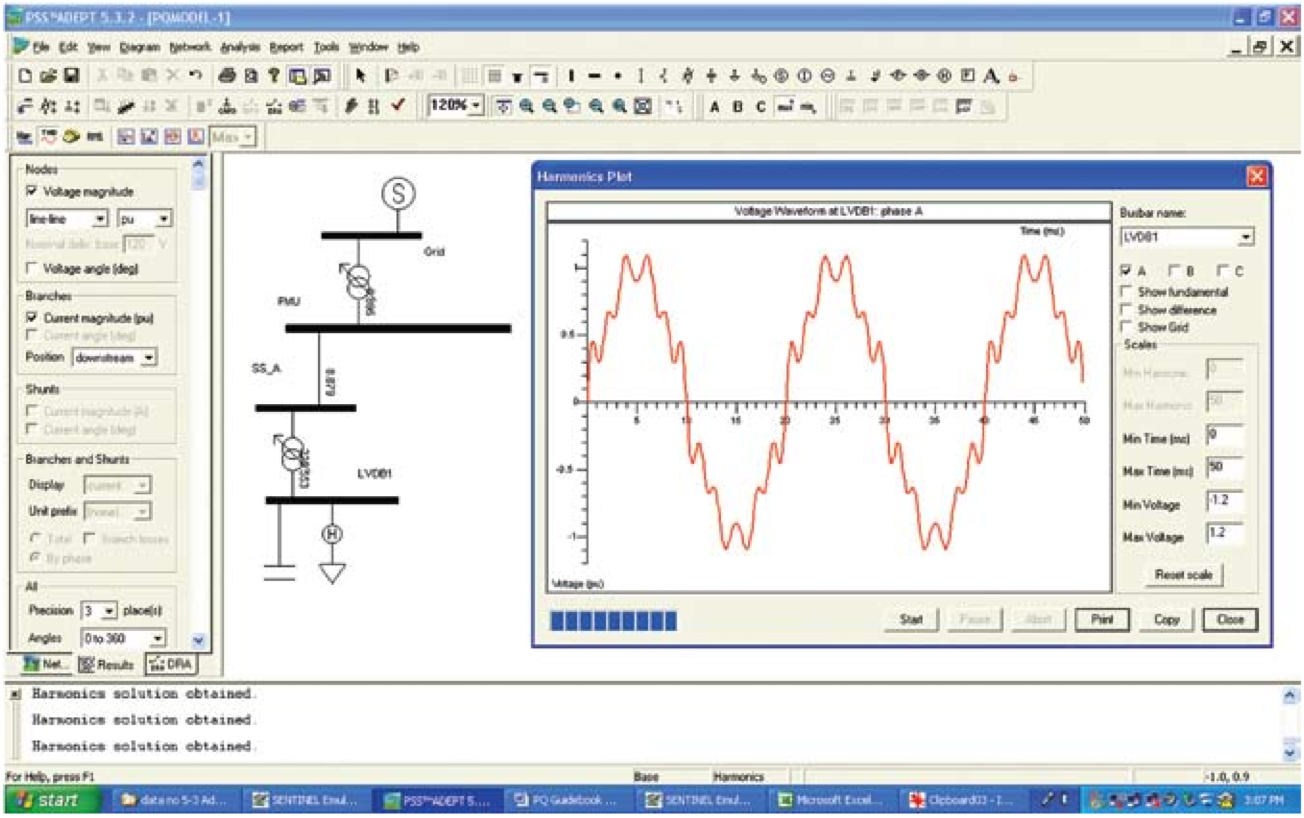


Fig. 10.4 Distorted voltages for red phase at LVDB1

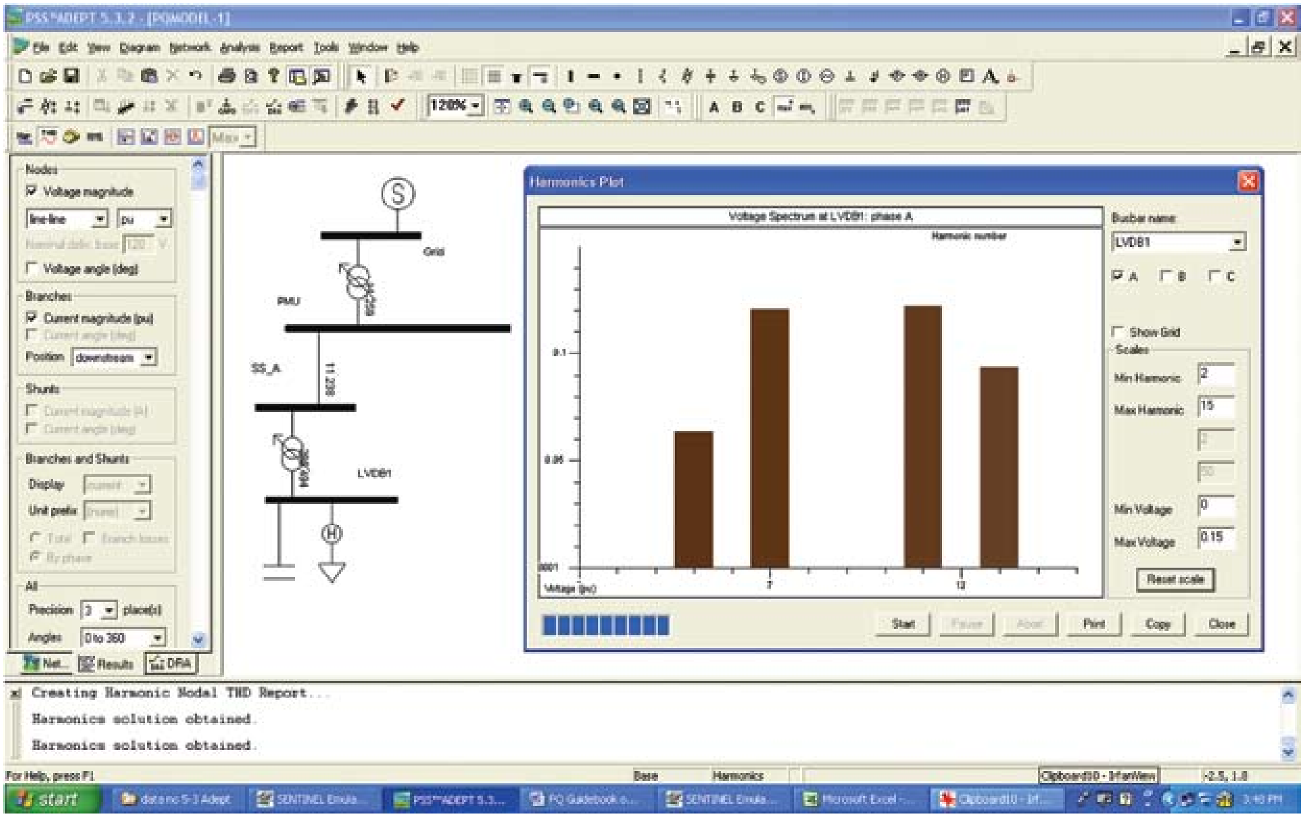


Fig. 10.5 Harmonic spectrums at LVDB1

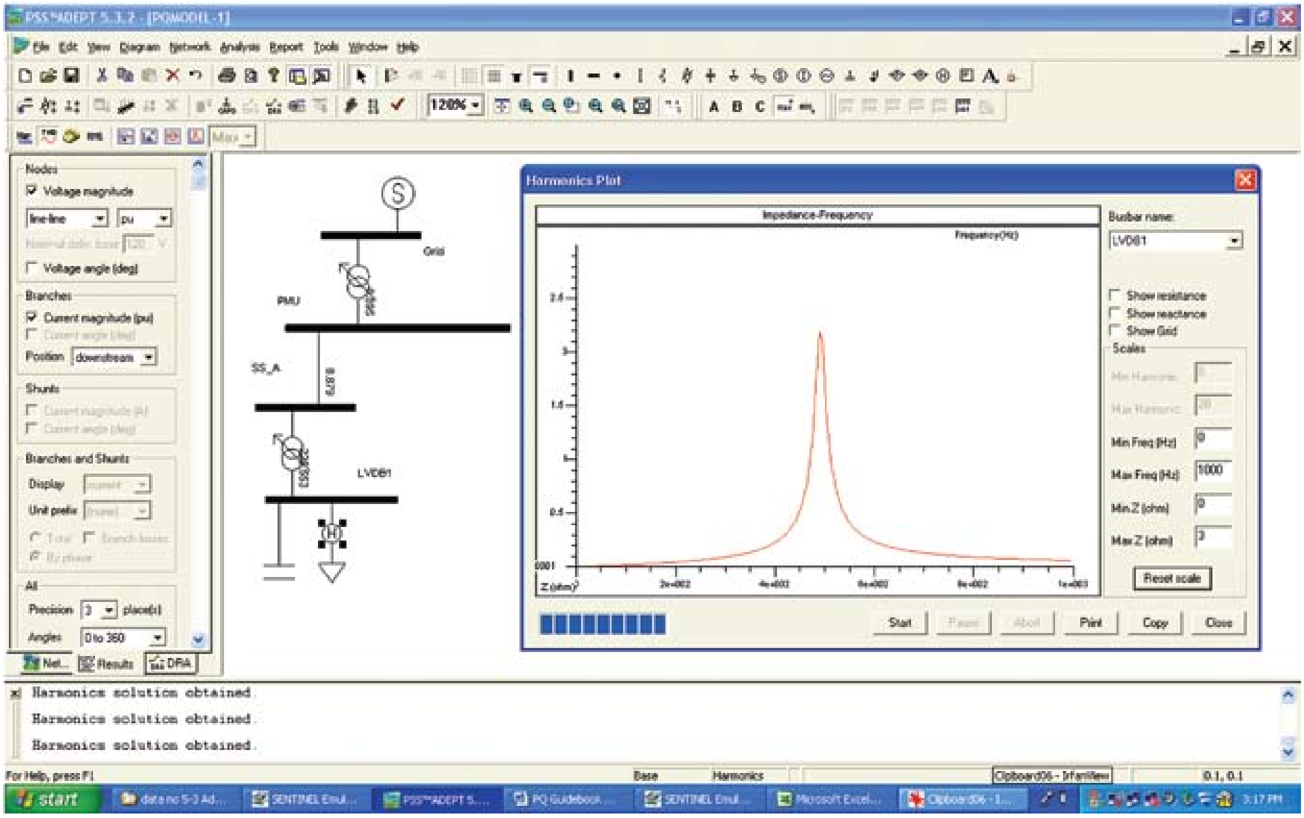


Fig. 10.6 Results of impedance scan at LVDB1 that shows parallel resonance at 9.8th harmonics

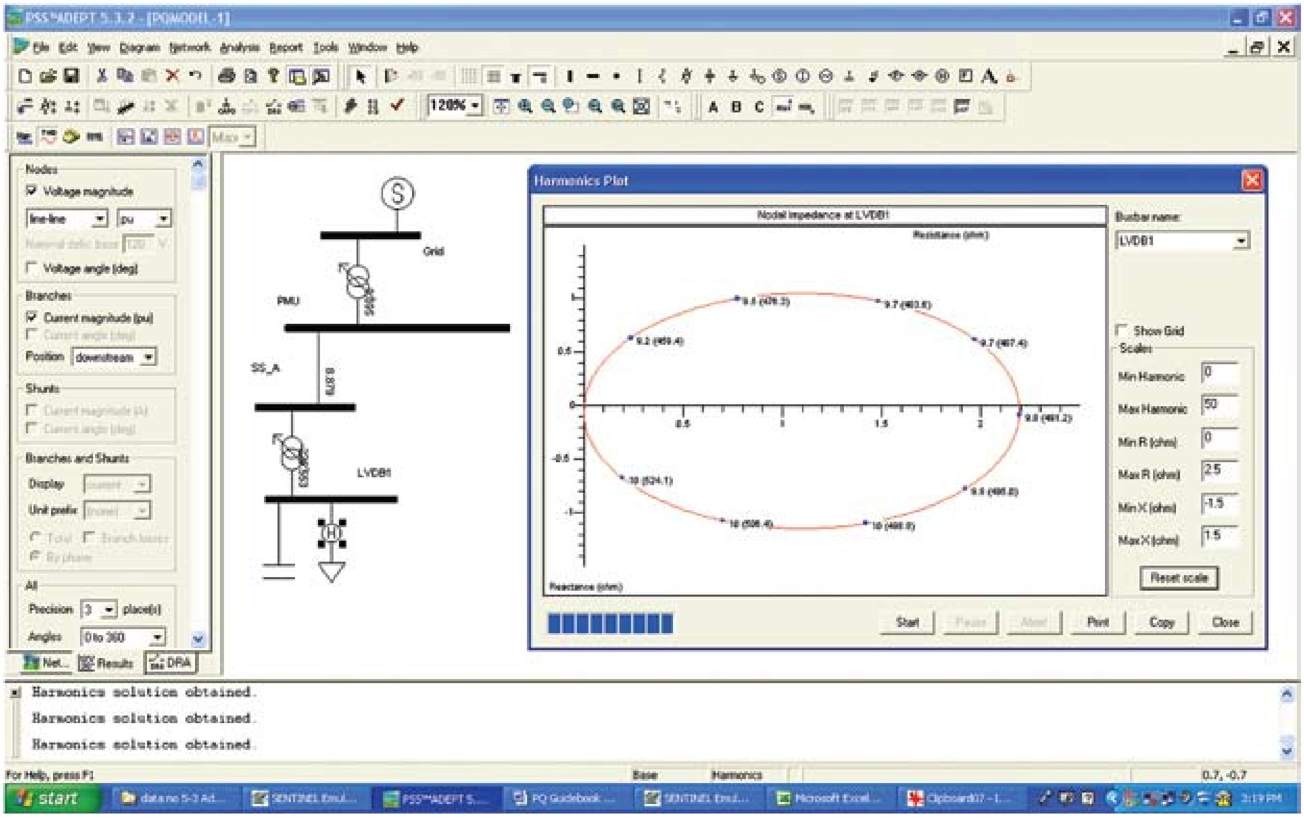


Fig. 10.7 Results of admittance scan at LVDB1 that shows parallel resonance at 9.8th harmonics

10.3 APPLICATION OF HARMONIC ANALYSIS SOFTWARE FOR EVALUATING ER G5/4

For new supply applications, utility's engineers must inform the new customers on the requirement on harmonic limits. The customers must provide the necessary harmonic current values for their non-linear loads to the engineers. These values together with the harmonic background at the point of common coupling (PCC) will be used to perform a harmonic analysis.

Assume the supply system to be evaluated is as shown in Figure 10.1. And the new customer's loads are shown in Table 10.2. The name of the new substation is SS_B. A new underground 11 kV cable (3x300mm^2) will be laid from PMU to SS_B. The length of the cable is 1 km. The new single diagram for the supply scheme is shown in Figure 10.8. The results of the harmonic analysis are shown in Figure 10.9.

Table 10.2 Loads at Substation SS_B

Fundamental Loads 50 Hz (3-phase balanced)

P (kW)	Q (kVar)
3000	1950

Harmonic loads (currents)

Harmonic	% (THD)	PU
5	35	0.35
7	26	0.26
11	21	0.21
13	18	0.18

The value of the total harmonic distortion voltage (THD_V) at the point of common coupling (PCC) at PMU is 4.4 %. This value is more than 4 % as stated in the ER G5/4 for 11 kV networks. Initially, the THD_V for the background harmonic was 1.2%. The violation in the THD_V is due to the connection of new non-linear loads at SS_B which increase the THD_V to 4.4 %.

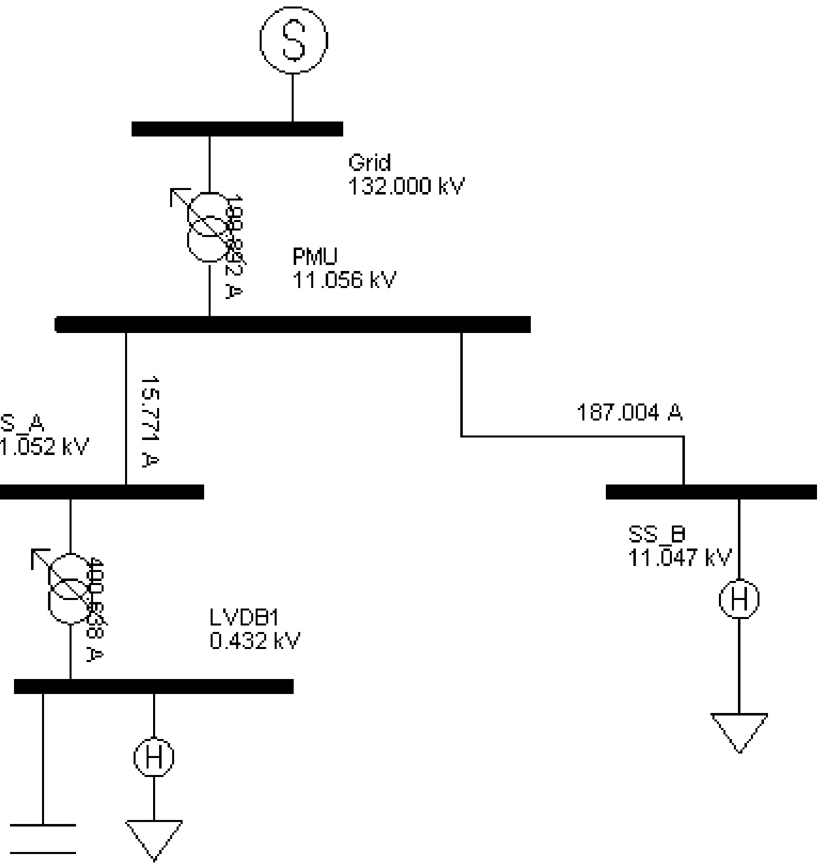


Fig.10.8 New single line diagram with new customer at SS_B

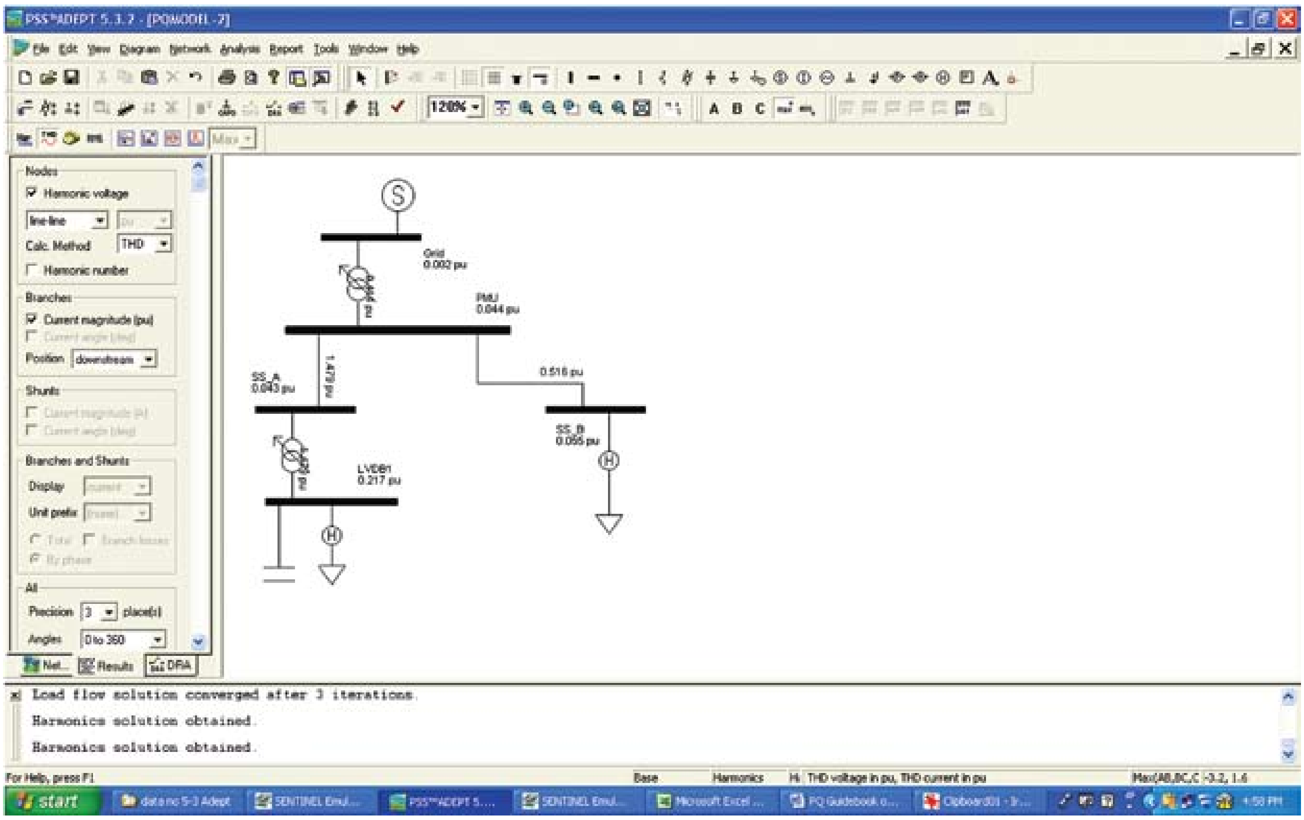


Fig.10.9 New values of Total Harmonic Distortion Voltage (THD_V)

10.4 APPLICATION OF HARMONIC ANALYSIS SOFTWARE IN DESIGNING PASSIVE FILTERS

As shown in Table 9.1, there are four techniques to filter the harmonic problems. The harmonic analysis software can be used only to evaluate the design of passive harmonic filters. A passive harmonic filter comprises of detuned/tuned reactors in series with the capacitors. The first step in the design of the passive filters is to determine the size of the capacitor bank for improving the power factor. The value of the power factor at SS_B is determined based on Equation 24.

$$pf = \frac{kW}{\sqrt{(kW^2 + kVar^2)}} \qquad (10.1)$$

The value of the power factor at SS_B is

$$pf = \frac{kW}{\sqrt{(kW^2 + kVar^2)}} = \frac{3000}{\sqrt{(3000^2 + 1950^2)}} = 0.83$$

The simplest way (not practical method) to size the capacitor bank is based on the reactive load requirement. In Figure 10.10, the reactive power requirement for SS_B is 1950 kVar. Therefore, the size of the capacitor bank is 1950 kVar. The new single line diagram in Figure 10.11 shows a passive harmonic filter installed at SS_B. A detuned reactor of 7 % (Refer Table 9.4) was chosen to detune the circuit to the 3.78^{th} harmonic frequency.

Note: For actual application, the harmonic filter/capacitor bank must be a switchable type with more than 1 step. The numbers the reactors will be dependent on the number of switching steps. And the final specifications for the filter will need to consider the potential voltage rise due to the installation of the reactors. And the customers are advised to refer to relevant technical standards on capacitors for example IEC 60831 & IEC 60871.

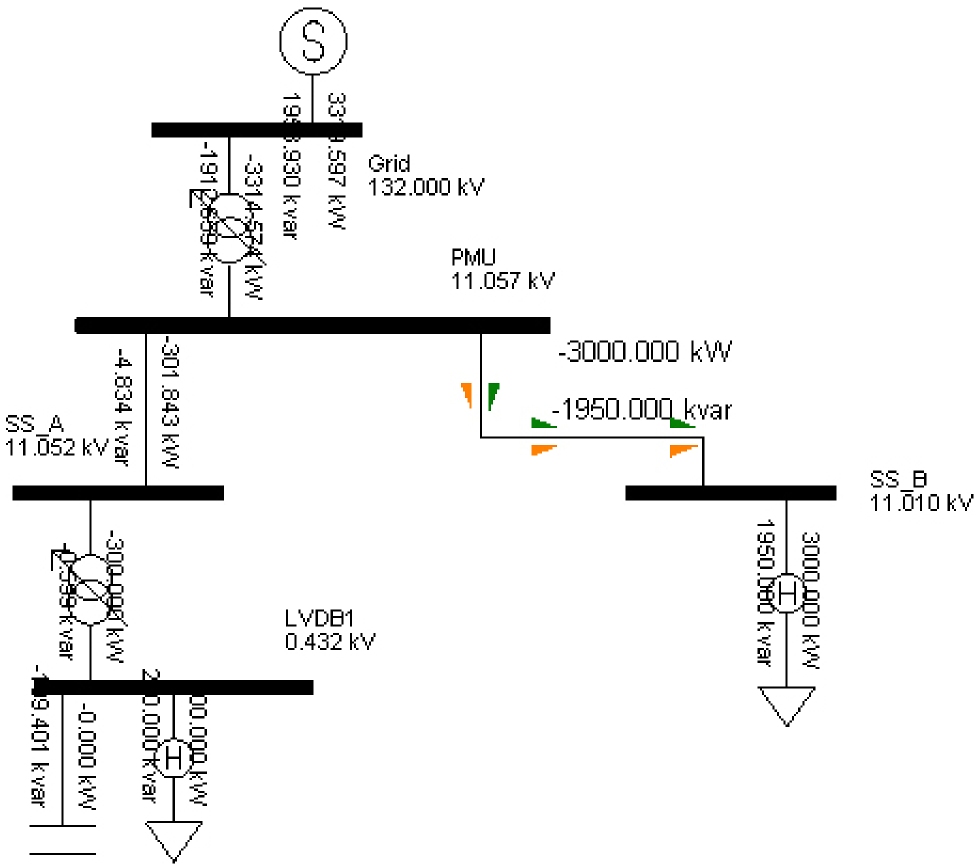


Fig.10.10 Fundamental power flow (real and reactive power)

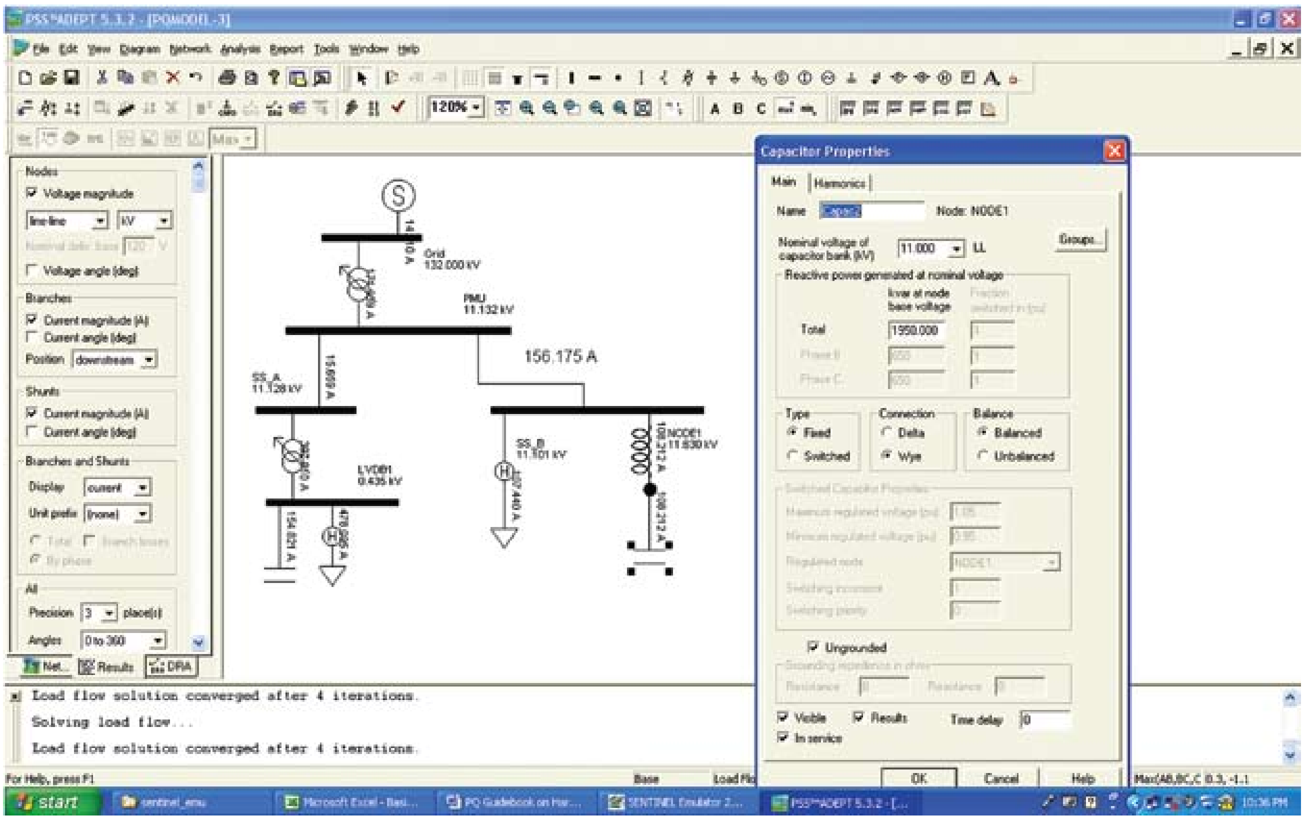


Fig.10.11 Sizing of capacitor bank with detuned reactors

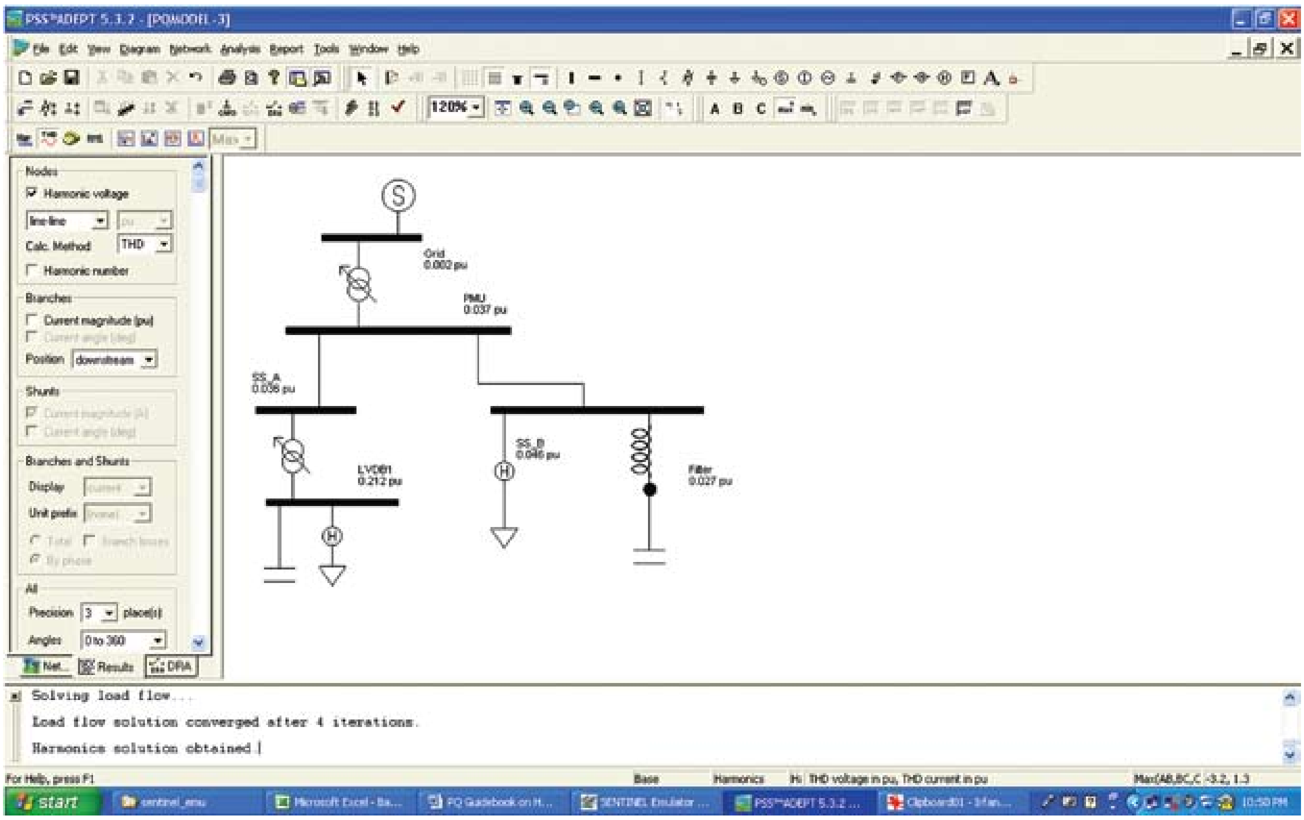


Fig.10.12 Values of THD_V for all buses with the installation of 7 % detuned filter

CHAPTER 11

SUMMARY

Harmonics are sinusoidal voltages having frequencies that are whole multiples of the frequency at which the supply system operates. Harmonic disturbances are generally caused by equipment with non-linear voltage/current characteristics or by periodic and line-synchronized switching of loads. As a result of cable transfer capacitance, line inductance and connection of power factor correction capacitors, parallel and series resonances may occur in the network and cause voltage amplification even at remote points from the distorting load. Summations of the effects of harmonics are likely and must be considered.

The presence of harmonics in low voltage electrical supply systems has been recognized for many years. It is however only in relatively recent times, that the proliferation of harmonic producing devices has increased to the extent that some serious attention needs to be given to the problem. Not generally appreciated is the fact that household television receivers are one of the most prolific generators of harmonics. A further irony is that energy efficient self ballasted fluorescent lamps produce high levels of 3^{rd} harmonic currents.

For consumer generated harmonics, harmonic currents predominate, and are aggravated in conditions where harmonic producing loads are large in comparison to the supply capacity. It is unfortunate that users are often misled by regulations that permit reduced sized neutral conductors. The increased neutral currents that result directly from the presence of harmonics should always be taken into account before any consideration is given to reduced neutrals. In many applications it is becoming increasingly necessary to allow for increased neutral currents and to overrate cables and switchgear accordingly. Whenever power factor correction capacitors are applied to a distribution network, which combines capacitance and inductance, there will always be a frequency at which the capacitors are in parallel resonance with the supply.

The net result of harmonic is possible mis-operation of sensitive electronic equipment, and overheating of phase and particularly neutral conductors. How does this happen? In a balanced 3-phase circuit (equal linear load on each phase), operating with a smooth 50 Hz sine wave voltage on each phase, the neutral carries the vector sum of the three phase currents, which is zero. But if one or more of the phase conductors is also carrying significant currents at harmonic frequencies (multiples of the 50Hz fundamental), they may not cancel by vector addition, but may add in the neutral. And it is important to note that standard test instruments cannot even measure them.

If the harmonic currents are sinusoidal, we find mathematically that the even multiples cancel. But the odd multiples, because they are in phase, are additive, and appear in the neutral, where they can cause overheating. The current in the neutral can actually be higher than that in any one of the phase conductors. (Fires in fact have been reported that resulted from harmonics.) The phase wires themselves may now be carrying a sinusoidal or non-sinusoidal 50 Hz fundamental, plus non-sinusoidal, high frequency, pulsed currents, which may result in overheating of the phase conductors. As predicted by Ohm's Law, these distorted currents will cause distorted voltage wave forms in the building wiring system, which can, in turn, cause equipment failure in other equipment.

If this condition occurs on, or close to, one of the harmonics generated by the non-linear loads, then large harmonic currents can circulate between the supply network and the capacitor equipment. Such currents will add to the harmonic voltage disturbance in the network 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. There are a number of ways to avoid resonance when installing capacitors. In larger systems it may be possible to install them in a part of the system that will not result in a parallel resonance with the supply. Varying the kVar output rating of the capacitor bank will alter the resonant frequency. With capacitor switching there will be a different resonant frequency for each step. Changing the number of switching steps may avoid resonance at each step of switching. If resonance cannot be avoided, an alternative solution is required. A reactor must be connected in series with each capacitor such that the capacitor/reactor combination is inductive at the critical frequencies but capacitive at the fundamental frequency. To achieve this, the capacitor and series connected reactor must have a tuning frequency below the lowest critical order of harmonic, which is usually the 5th. This means the tuning frequency is in the range of 145 Hz to 225 Hz, although the actual frequency will depend upon the magnitude and order of the harmonic currents present. The a ddition of a reactor in the capacitor circuit increases the fundamental voltage across the capacitor. Therefore, care should be taken when adding reactors to existing capacitors.

In view of rapidly attenuating the effects of harmonics, a triple system of technical standards and regulations is currently in force based on the documents listed below.

Standards governing compatibility between distribution networks and products

Harmonics caused by a device must not disturb the distribution network beyond certain limits. Each device must be capable of operating normally in the presence of disturbances up to specific levels. The standards to determine the necessary compatibility between distribution networks and products are:-

- Standard EN 50160 stipulates the characteristics of electricity supplied by public distribution networks
- Standard IEC 61000-2-2 stipulates the characteristics of electricity for public low-voltage power supply systems
- Standard IEC 61000-2-4 stipulates the characteristics of electricity for public medium-voltage power supply systems

Standards governing the quality of distribution networks

- Standards IEEE 519:1992, Engineering Recommendation G5/4 and IEC/TR 61000-3-6 present joint approaches between Power Utilities and customers to limit the impact of non-linear loads. What is more, Utilities encourage preventive action in view of reducing the deterioration of power quality, temperature rise and the reduction of power factor. They will be increasingly inclined to charge customers for major sources of harmonics

Standards governing equipment emission

- Standard IEC 61000-3-2 for low-voltage equipment with rated current under 16 A
- Standard IEC 61000-3-12 for low-voltage equipment with rated current higher than 16 A and lower than 75 A

All the information provided in this guidebook were extracted from many power quality reference materials i.e. guidebooks, technical standards and guidelines. The author has also documented in this guidebook his personal experience & expertise in solving harmonic related problems.

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