Evaluation of the Impact on Non-Linear Power On Wiring Requirements for Commercial Buildings

Final Report

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THE FIRE PROTECTION RESEARCH FOUNDATION
Research in support of the NFPA mission

FIRE RESEARCH

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FOREWORD

The recent movement toward lighting systems, solid state technology, and renewable energy technologies has resulted in an increase in non linear power to building wiring systems. Non-linear power has an impact on various safety provisions of the *National Electrical Code,* including, for example: (a) harmonics in neutral conductors; (b) load calculations; (c) integration of non-linear loads on multi-wire branch circuits; and (d) over-current protection and AFCI and GFCI devices. This project's goals was to provide users of the NEC and NFPA 70B with guidance on this issue. The study reviews research relevant to safety and serviceability issues, provides case study examples of harmonic surveys, and provides guidance and recommended further studies to inform the NEC and NFPA 70B.

The content, opinions and conclusions contained in this report are solely those of the author.

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EVALUATION OF THE IMPACT ON NON–LINEAR POWER ON WIRING REQUIREMENTS FOR COMMERCIAL BUILDINGS

Prepared for

THE FIRE PROTECTION RESEARCH FOUNDATION

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Executive Summary

The results presented in this interim report show how a high penetration of non-linear loads will affect the applicability of the provisions in NEC and NFPA 70B. The focus of this study is on third-harmonic-producing load with a secondary focus on other harmonic-producing loads.

This report contains fundamental information on harmonics and concern associated with the presence of harmonics in distribution systems. Additionally, a literature search was conducted to inform on (1) sources of harmonics in distribution systems, (2) their effects on equipment with regard to thermal loading, current/voltage distortion, and neutral voltage elevation, and (3) techniques that can be used to mitigate harmonics in distribution systems. Literature related to performance and safety thresholds to identify the safety and serviceability issues due to nonlinear loads on electric wiring systems in commercial buildings was also reviewed. The background information and the results of the literature search are presented in Chapter 2 through Chapter 6. Additionally, we summarized the latest versions of the pertinent standards in the Appendix.

The findings of the literature search form the bases of the review of specific articles in NEC and NFPA 70B. The reviewed articles are:

- NEC 210 (Branch Circuits)
- NEC 215 (Feeders)
- NEC 220 (Branch-Circuit, Feeder, and Service Calculations)
- NEC 310 (Conductors for General Wiring)
- NFPA 70B-10 (Electrical Equipment Maintenance)

In Chapter 7, we issue recommendations for changes on these articles. We also identified additional research to quantify changes in NEC and NFPA 70B. Our recommendations for additional research to be addressed in a follow-on project are summarized below:

- Conduct a study to determine appropriate harmonic limits for which the neutral has to be considered a current-carrying conductor and include the limits determined in the study in the NEC (see Section 7.1.4)

- Conduct a study studies to determine appropriate values for Y_C (see Section 7.1.5).
- Conduct a study that determines sizing requirements for neutral conductors. The neutral sizing requirements should be based on statistically significant data from measurements of neutral currents in different environments (office buildings, residential building, etc.) (see Section 7.1.12).

Four case studies will be presented in the final report, which will be issued by April 20, 2011. The case studies will illustrate survey and testing protocols that are suggested in NFPA 70B, Section 10.2.4.

Abbreviations and Acronyms

ASD: Adjustable Speed Drive

CCFL: Cold Cathode Fluorescent Lamp

CFL: Compact Fluorescent Lamp

EIA: Energy Information Administration

IEA: International Energy Agency.

IEC: International Electrotechnical Commission

IHD: Individual Harmonic Distortion

PC: Personal Computer

PWM: Pulse-Width Modulation

RMS: Root-Mean Square

TDD: Total Demand Distortion

THD: Total Harmonic Distortion

TV: Television

VSD: Variable Speed Drive

Glossary

Cold Cathode Fluorescent Lamps (CCFL)

A gas discharge lamp with an electron emitting electrode that is not independently heated to emit electrodes (cold cathode).

Individual Harmonic Distortion (IHD)

A value that is a measure of the harmonic contamination of a signal by a given harmonic. The Individual Harmonic Distortion (IHD) is the ratio of the given harmonic to the fundamental multiplied by 100%. The IHD can be calculated for currents and voltages.

Pulse-Width Modulation (PWM) Drive

A drives that controls the speed of a motor with power transistors that rapidly switching current flow to the motor on and off. Feedback systems can be employed to control the armature voltage of the motor and/or frequency and thereby the motor speed.

Total Demand Distortion (TDD)

IEEE 519 defines TDD as “the total root-sum-square harmonic current distortion, in percent of the maximum demand load current (15 or 30 min demand).”

Total Harmonic Distortion (THD)

A value that is a measure of the harmonic contamination of a signal. According to IEEE 519, the Total Harmonic Distortion (THD) is the ratio of RMS of the individual harmonic content to the RMS of the fundamental multiplied by 100%. The THD can be calculated for currents and voltages.

Variable Speed Drive (VSD)

Drives that vary the speed of an AC or DC motor by varying the voltage and/or frequency of the motor.

1 Introduction

The nature of the aggregate electrical load served by utilities has evolved over the last decade and is changing even more rapidly as "new" end-use loads proliferate on distribution systems. With the increasing use of variable speed drives, electronic ballasts, switched-mode power supplies and other electronic equipment, the utility load is becoming more active and non-linear. As a result, the harmonic distortion levels in distribution systems are increasing. 5th & 7th harmonics have been a feature of electronic loads for a while and effective methods have been developed to mitigate them (e.g. multi-pulse power converters, transformer phase-shifting principle, active and passive filtering, etc.). With more phase-to-neutral connected electronic loads, distribution utilities are finding that in many cases the dominant harmonic is the 3rd, which causes high neutral currents and neutral-to-ground voltages in addition to substantial increase in voltage distortion. Current harmonic distortion can have a serious impact on distribution systems because a transformer that needs to supply fundamental currents to non-linear loads will not be able to provide the rated fundamental current (transformers are RMS current-limited) resulting in reduced system capacity. Voltage harmonic distortion, which can be created by current harmonic distortion, can have a detrimental effect on the loads within a facility. For instance, in three-phase systems, the fifth harmonic can cause a negative torque to an induction motor that attempts to drive the motor in a direction opposite to normal operating direction. This causes the motor to draw more current, which can result in the tripping of protective devices or motor failure due to overheating.

This study investigates how a high penetration of non-linear loads will affect the applicability of the provisions in NEC and NFPA 70B. The focus of this study is on third-harmonic-producing load with a secondary focus on other harmonic-producing loads. The main objectives of this study are to

- investigate the relevant “new” and existing end-use loads influencing the power quality by means of harmonic distortion,
- assess how current penetration levels of harmonic-producing loads affect safety and serviceability,
- analyze the impact of harmonic-producing and harmonic-influenced loads, with regard to thermal loading, current/voltage distortion, and neutral voltage elevation,

- illustrate, using case studies, survey and testing protocols that are suggested in NFPA 70B, Section 10.2.4.

2 Background Information

In this section, we provide fundamental information on harmonics and concern associated with the presence of harmonics in distribution systems.

2.1 What are harmonics?

Harmonics are sinusoidal voltages and currents with frequencies that are integer multiples of the fundamental frequency (60 Hz in the United States). The value of the multiplier corresponds to the harmonic order. In three-phase systems, harmonics can be either positive, negative, or zero sequence, depending on the phase shift between the three phases. The harmonics of order 4, 7, 10, 13, … are usually positive sequence because they follow the sequence of the fundamental, that is, in balanced systems the phase B current lags the phase A current by 120° and the phase C current leads the phase A current by 120°. The harmonics of order 2, 5, 8, 11, … are usually negative sequence because the sequence order is opposite of the sequence order of the fundamental, that is, in balanced systems the phase B current leads the phase A current by 120° and the phase C current lags the phase A current by 120°. The harmonics of order 3, 6, 9, 12, … are usually zero sequence, that is, the phase shift between phase A, phase B, and phase C is zero. Note that in an unbalanced system each harmonic can have positive, negative, and zero sequence components.

Harmonic distortion in the electric power system predominately originates from loads in which the current is not linearly related to the voltage (see Section 0). Harmonic with odd multiples of the fundamental frequency are usually considered to be particularly troublesome since many sources inject currents with odd harmonic frequencies. If there is a system resonance formed by the system impedance that coincides with harmonic load currents the harmonic current can be amplified resulting in higher voltage and current distortion levels (see Section 2.6). A 3^{rd} harmonic resonance would probably be the worst resonance (see Section 2.5). Delta transformer windings block zero-sequence harmonic currents. However, delta transformer windings are not so common in distribution systems and instead Wye connections, which do not block zero-sequence harmonics, dominate on grounded-Wye circuits. Note that a three-phase diode or thyristor converter will produce third harmonic when there is a fundamental voltage imbalance present (negative sequence). The third harmonic produced in this case is not zero sequence; in fact, it is impossible for a Graetz bridge (or most 3-phase IGBT bridges) to produce zero sequence because they lack a neutral connection. A 5^{th} harmonic resonance can easily be excited by six-pulse rectifiers and other power electronic loads while a 7^{th} harmonic resonance is commonly produced by non-linear loads such as saturable transformers. Seventh harmonic resonances are typically not as troublesome as 5^{th} harmonic resonances because the magnitudes of 7^{th} harmonic currents from non-linear sources are usually smaller than the magnitudes from 5^{th} harmonic current sources and system damping, that is, the reduction of the magnitude of the harmonic by the impedance in the system, is usually larger.

Harmonics other than the fundamental are generally undesirable in a power system and cause distorted currents and voltages. For example, Figure 2-1 shows a voltage waveform that was recorded at a capacitor bank in a manufacturing plant, which was excited by a circuit resonance. In this case, adjustable speed drives were tripping on overvoltage conditions and the bank was experiencing frequent capacitor failures.

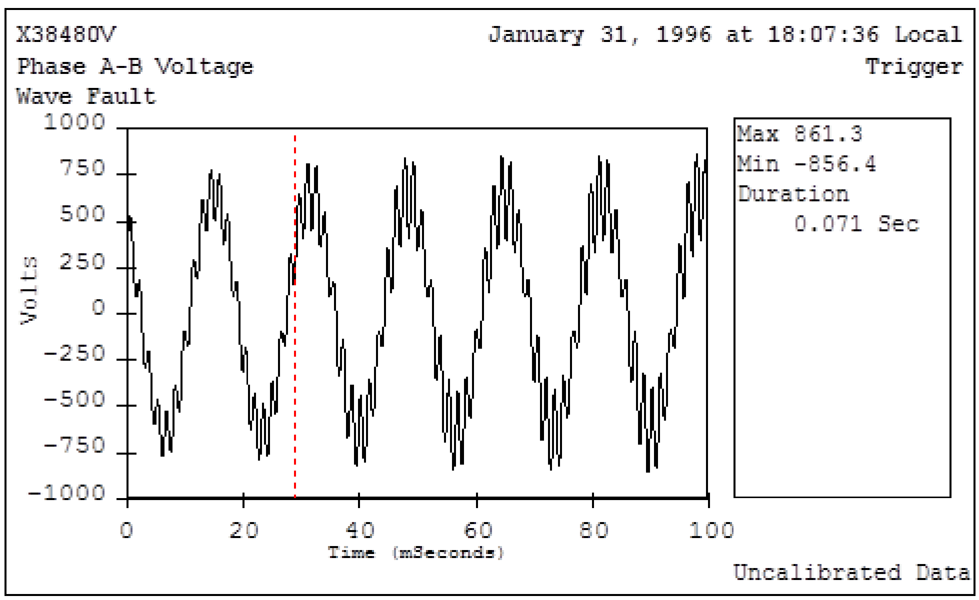

Figure 2-1: Example of a voltage waveform contaminated with harmonics.

We found claims in the literature that the direct effect of current harmonic distortion on loads within a facility is minimal and/or negligible since the distorted current is path-dependent and does not flow into loads other than the load that causes them (EC&M, 2010; IAEI, 2003). However, we do not entirely agree with these claims because loads can be sinks for harmonic currents produced elsewhere, and this can result in cross-distortion consequently resulting in increased production of harmonics by the affected load at other frequencies (usually two orders above and below). On the other hand, current harmonic distortion can have a serious impact on distribution systems because a transformer that needs to supply fundamental currents to non-linear loads will not be able to provide the rated fundamental current (transformers are RMS current-limited) resulting in reduced system capacity. Also, harmonic currents can increases joule heating losses (I^2R) considerably due the skin effect, which results in an increased resistance for higher frequencies. Voltage harmonic distortion, which can be created by current harmonic distortion, can have a detrimental effect on the loads within a facility. For instance, in three-phase systems, the fifth harmonic can cause a negative torque to an induction motor that attempts to drive the motor in a direction opposite to normal operating direction. This causes the motor to draw more current, which can result in the tripping of protective devices or motor failure due to overheating. Section 4 includes more detailed information regarding effects of harmonics in power systems.

Note that the harmonic distortion level is closely linked to the true power factor as discussed in the following section.

2.2 True Power Factor vs. Displacement Power Factor

Power is the rate at which electricity is produced/consumed and is defined as the product of the voltage and current. In AC systems the voltage and the current are time dependent and the AC power is in general a complex value. For undistorted waveforms, that is, the voltages and currents are only composed of the fundamental frequency, the total power is the apparent power $S_{Fundamental}$, the real part of $S_{Fundamental}$ is the real power P and the imaginary part of $S_{Fundamental}$ is the reactive power Q (Figure 2-2).

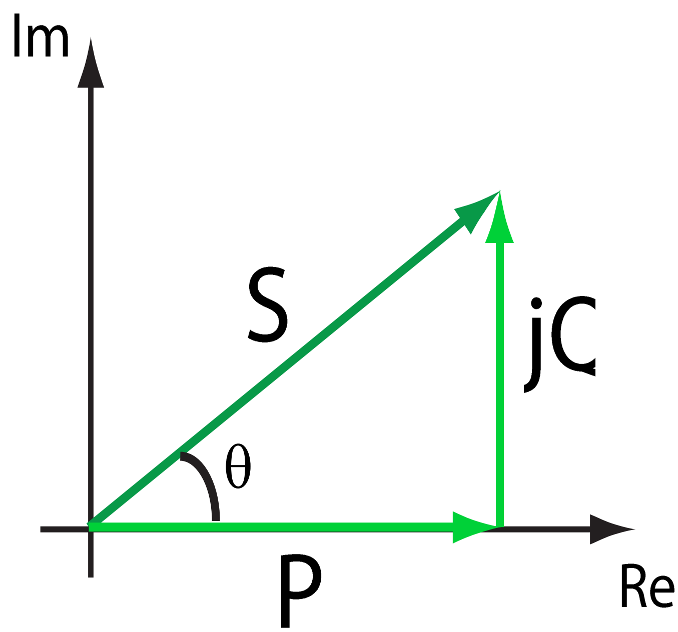

Figure 2-2: The power triangle for the fundamental frequency consisting of real power P, reactive power Q, and apparent power S.

From Figure 2-2 it is apparent that for undistorted voltages and currents, the active power, reactive power, and apparent power are related following equations:

$$P = S_{Fundamental} \cdot \cos\theta \tag{2.1}$$

$$Q = S_{Fundamental} \cdot \sin\theta \tag{2.2}$$

$$S_{Fundamental} = \sqrt{P^2 + Q^2} \tag{2.3}$$

In general, the power factor is a number between 0 and 1 and is a measure for the amount of “useful” power (i.e., the component of the total power that is consumed by purely resistive loads) transferred. For undistorted waveforms, the power factor only depends on the displacement of current and voltage. Consequently, for the special case of fundamental-frequency waveforms, the power factor is called displacement power factor and is the ratio of real power and fundamental-frequency apparent power:

$$PF_{Displacement} = \frac{P}{S_{Fundamental}} \tag{2.4}$$

Equivalently, the displacement power factor is the cosine of the displacement angle of the fundamental-frequency current and voltage, which is apparent when combining Equation (2.1) and Equation (2.4):

$$PF_{Displacement} = \cos\theta \tag{2.5}$$

The maximum average power transferred is for a purely resistive load, which has a power factor of one (Figure 2-3). The transferred average power is zero and the power factor is zero for a purely inductive load (Figure 2-4) and a purely capacitive load. A load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred, which results in (1) increased energy lost due to joule heating (I^2R) and (2) larger equipment requirements (generator, conductors, transformer, switchgear). Therefore, it is desirable to have a power factor as close to one as possible, which can be achieved with power factor correction methods. For instance, induction motors are generally inductive[1] loads (most loads in a utility system are inductive) and can have a very poor power factor.

It is not correct to use the displacement power factor for distorted voltages and currents because they are composed of multiple-frequency components and the phase shift θ only reflects the shift between voltages and current of a single frequency (i.e., the fundamental frequency). For distorted waveforms, the general definition of the power factor must be applied, that is, the power factor is the ratio of real power and the total transferred power S_{Total} (including fundamental and harmonic components). This "true" power factor is

$$PF_{True} = \frac{P}{S_{Total}} \tag{2.6}$$

Note that harmonic distortion typically only marginally increases the real power P. On the other hand, harmonic distortion may result in a substantially increase of

[1] "inductive" means that the impedance of the load contains an inductive component in addition to a resistive component. "capacitive" means that the impedance of the load contains an capacitive component in addition to a resistive component.

apparent power S_{Total}. Consequently, the presence of harmonics may result in a substantially lower power factor (Dugan et al., 2002).

The total harmonic voltage distortion (THD_v) is usually less than 10% (Grady and Santoso, 2001). Assuming the THD_v is close or equal to 0 the true power factor and displacement power factor can be shown to have following relationship:

$$PF_{True} = \frac{PF_{Displacement}}{\sqrt{1 + THD_I^{\,2}}} \tag{2.7}$$

where THD_I is the total harmonic current distortion, which is explained in the next section.

The true power factor is an accurate measure of how much “useful” (active) power is delivered to the customer and what fraction of the total (apparent) power is delivered as reactive power. Note that reactive power is not per se “useless” power – some loads, such as induction motors, consume reactive power. However, the extra current that needs to be generated by the plant to feed the reactive portion of the loads occupies system delivery capacities and produces additional losses The true power factor is a more accurate parameter than the displacement power factor for sizing equipment used for the power delivery (transformers, transmission lines, etc.) because power frequency currents as well as currents with other frequencies (mostly harmonic frequencies) flow through the equipment. On the other hand, when calculating the voltage drop due to reactive power in the system the displacement power factor must be used as the voltage drop is calculated for the fundamental (50 or 60 Hz) frequency only. Some non-linear loads, such as Compact Fluorescent Lamps, can have a displacement power factor close to unity and a much lower true power factor. The low true power factor of these loads is due to the presence of harmonic distortion.

A number of power factor correction methods exist to raise the power factor close to unity and the choice of method depends on whether the goal is to increase the displacement power factor or the true power factor. For instance, capacitors can be utilized to compensate for inductive motor loads. This will improve the displacement power factor by ‘shifting’ the voltage and current back into phase, that is, reducing the phase difference between current and voltage (see Figure 2-4) so that the load looks like a resistive load (see Figure 2-3). However, capacitors essentially only compensate for fundamental frequency reactive power – capacitor banks do not work to raise a true power factor that is low due to excessive harmonics in the system and, in fact, can decrease the power factor by creating resonance points, that is, a low-impedance path for harmonics at the resonance frequency (Dugan et al., 2002). True power factors can be increased by passive power factor correction, that is, low-pass filters composed of passive components (capacitors and inductors) or by active power factor correction, that is, electronic devices that control the amount of power drawn by a load.

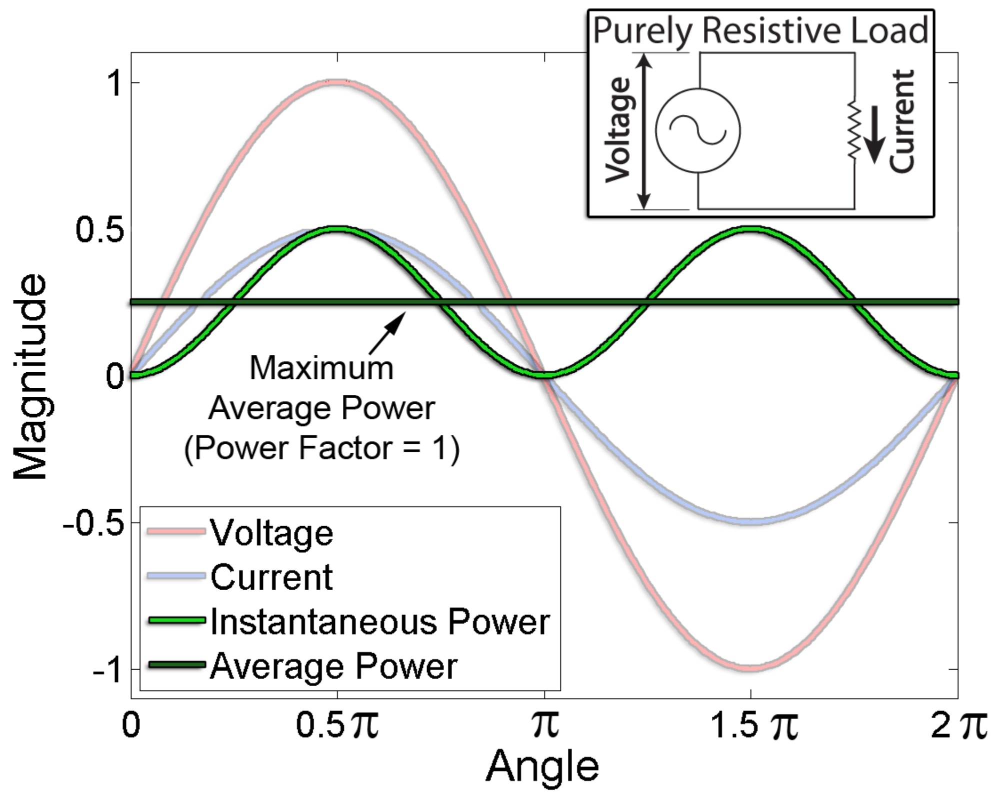

Figure 2-3: Instantaneous and average powers for a purely resistive load.

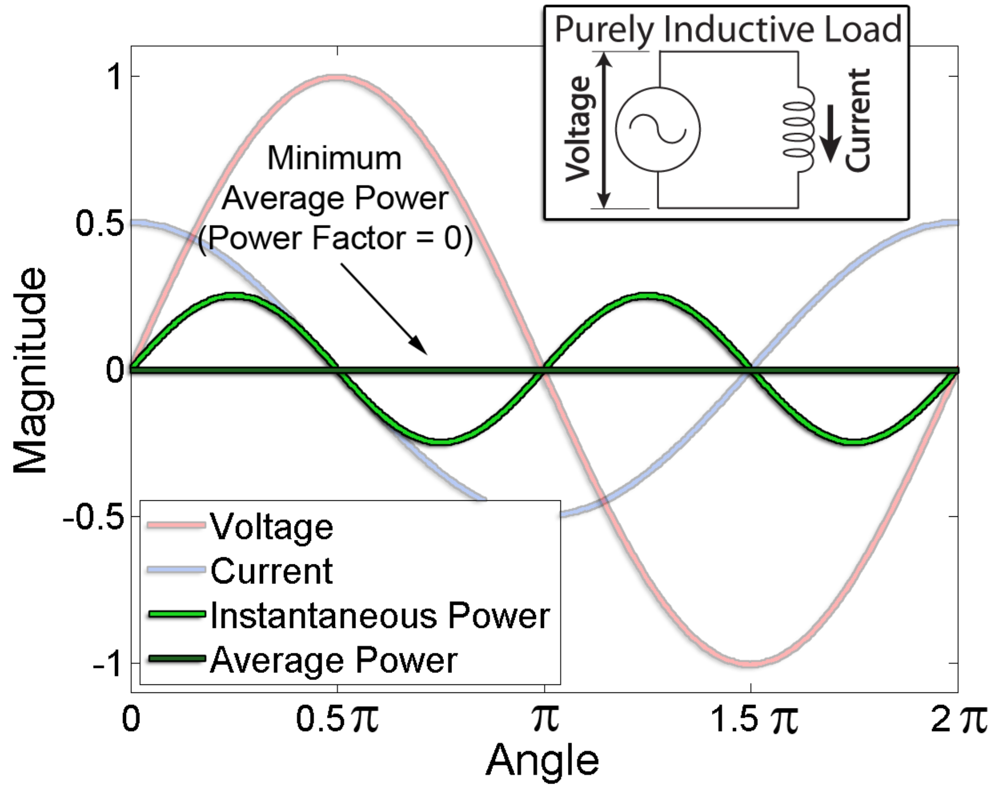

Figure 2-4: Instantaneous and average powers for a purely inductive load.

2.3 Quantifying Harmonic Distortion

The measure for the degree of harmonic contamination of a waveform by a single harmonic is the Individual Harmonic Distortion (IHD) level, which is the ratio of the magnitude of a given harmonic to the magnitude of the fundamental multiplied by 100%. The measure for the degree of harmonic contamination of a waveform by all harmonics is the Total Harmonic Distortion (THD) level. The THD is the ratio of RMS of the individual harmonic content of a signal to the fundamental multiplied by 100%:

$$THD = \frac{\sqrt{\sum_{i=2}^{n} {H_i}^2}}{H_1} \cdot 100\% \tag{2.8}$$

where H_1 is the fundamental harmonic (e.g., 60-Hz voltage or current) and H_n is the n^{th} harmonic. The THD is a measure for the potential heating effect of the harmonic components in a distorted waveform. A measure for the potential heating effect of all components is the Root-Mean-Square (RMS) value of the voltage/current, which is the square root of the sum of squares of all individual components (that is, the fundamental and the harmonic components for a harmonically distorted waveform):

$$RMS = \sqrt{\sum_{i=1}^{n} {H_i}^2} = H_1 \cdot \sqrt{1 + THD^2} \tag{2.9}$$

It is important to note that the THD and RMS value is a useful quantity for assessing heat losses; for instance, if a harmonic voltage is applied across a resistive load the THD quantifies how much heat will be generated by the harmonic components and the RMS quantifies how much heat will be generated by all components. However, these quantities do have their limitations; for instance, neither quantity is a good measure for the voltage stress in a capacitor due to a distorted waveform because the voltage stress depends on the peak value of the voltage, not the average value (Dugan et al., 2002).

Current distortion levels can be characterized by a THD value, as has been described above. However, that can sometimes be misleading due to the fact that a high THD value for input current may not be of significant concern if the load is light, since the magnitude of the harmonic current is low, even though its relative distortion to the fundamental frequency is high (Arrillaga et al., 1985). Since electrical power supply systems are designed to withstand the rated or maximum load current, the impact of current distortion on the system will be more realistic if the assessment is based on the designed values, rather than on a reference that fluctuates with the load levels. This problem can be avoided by referring THD to the fundamental of the peak demand load current rather than the fundamental of the present sample. That is called Total Demand Distortion (TDD) and is defined as follows:

$$TDD = \frac{\sqrt{\sum_{i=2}^{i_{max}} {I_i}^2}}{I_L} \tag{2.10}$$

where I_L is the rms value of the peak, or maximum, demand load current at the fundamental frequency component measured at the point of common coupling (PCC), i is the harmonic order, and I_i is the rms load current at the harmonic order i. Two ways, to measure I_L can be found in literature. In case of a new facility, I_L can be estimated based on the predicted load practice. In case the load is already in the system, I_L can be the average of the 12-months peak demand readings.

Traditionally, only active (“useful”) power P and reactive power flow Q is accounted for in a power flow analysis and, according to the fundamental-frequency power triangle shown in Figure 2-2, the apparent power S is composed of P and Q only:

$$S_{Fundamental} = \sqrt{P^2 + Q^2} \tag{2.11}$$

2.4 Harmonic Distortion Limits

IEEE 519-1992 recommends limiting the voltage THD at the Point of Common Coupling to below 5%. The current IHD and THD limits are based on load size (quantified by the load current I_L) with respect to the size of the power system to which the load is connected (quantified by the short-circuit current I_{SC}). The IEEE 519 recommended current distortion values for single consumers for various short-circuit current to load current ratios are shown in Table 2-1. Harmonic current and voltage distortion limits are also specified in the IEC standards 61000 parts 3-2 and 3-4 for equipment with rated currents of below 16 A and above 16 A, respectively.

Table 2-1: IEEE 519-1992 individual and total odd harmonic current limits given in percent of load current. Even harmonics are limited to 25% of the odd harmonic limits.

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

Note that IEEE 519 is not a mandatory standard but rather a document that provides information on recommended practices for engineers to control harmonics in order to avoid a number of undesirable effects and impacts on the operation of loads and system equipment. According to IEEE 519, the responsibility to limit harmonics lies both with the end-user and utilities. The end-user has control over the harmonic current through the load he/she connects to the system; the resulting harmonic voltage is typically the responsibility of the utility. However, what complicates things is that the harmonic distortion present in the system is determined by both the injected harmonic current and the system impedance and, consequently, harmonic current on some equipment in the power system such has transformers and capacitors may need to be limited during, for instance, resonant conditions even if the harmonic voltage is within IEEE 519 limits. Vice versa, exceeding the harmonic current distortion limits does not always result in a violation of harmonic voltage limits – a single user may exceed the harmonic current distortion limits without causing excessive harmonic voltages in the system. Consequently, the recommended harmonic current limits in IEEE 519 can be overly restrictive in some situations, which is important to be aware of when utilizing the current limits to govern decision regarding the installation of expensive mitigation equipment to limit harmonic currents (Ribeiro, 2008).

2.5 What is so special about third harmonics?

Many electronic loads, such as Personal Computers (PCs) and Compact Fluorescent Lamps (CFLs), produce, among other low-order harmonics, third harmonic currents (see Section 0). Some environments, such as commercial buildings, are particularly prone to excessive third harmonic distortion due to a large number of third-harmonic producing loads being used in these environments.

What distinguishes third harmonics and other zero-sequence (harmonics that are integer multiples of three) harmonics from all other harmonics is that zero-sequence harmonics in balanced four-wire, three-phase systems add arithmetically in the neutral conductor. On the other hand, balanced fundamental current and balanced non-zero-sequence harmonic currents cancel in the neutral conductor. For instance, Figure 2-5 shows three-phase balanced load currents that are composed of fundamental currents and third harmonic currents that have 50% of the magnitude of the fundamental. The vector addition illustrated in Figure 2-6 shows that the fundamental currents, which phases are shifted by 120°, cancel in the neutral. The third-harmonic currents, which are in-phase, sum in the neutral resulting in third-harmonic currents with a magnitude of 150% (3 times 50%) of the fundamental. This behavior can also be easily shown mathematically. The neutral current i_N is the sum of the individual phase currents i_A, i_B, and i_C:

$$i_N = i_A + i_B + i_C \tag{2.12}$$

For currents of fundamental frequency ω_1 the fundamental-frequency neutral current i_{N1} is

$$i_{N1} = I_{A1}\cos(\omega_1 t) + I_{B1}\cos(\omega_1 t + 120°) + I_{C1}\cos(\omega_1 t - 120°) \tag{2.13}$$

where I_{A1}, I_{B1}, and I_{C1} are the peak values of the respective phase A, phase B, and phase C fundamental currents. In balanced systems, these peak values are identical ($I_{A1} = I_{B1} = I_{C1} = I_1$) and the neutral fundamental current is zero for all times (see also the left hand side of Figure 2-6):

$$i_{N1} = I_1[\cos(\omega_1 t) + \cos(\omega_1 t + 120°) + \cos(\omega_1 t - 120°)] = 0 \tag{2.14}$$

Equation (2.14) can be generalized to account for harmonics of order n:

$$i_{Nn} = I_n[\cos(n\omega_1 t) + \cos(n\omega_1 t + n120°) + \cos(n\omega_1 t - n120°)] \tag{2.15}$$

For 2nd order harmonics (n=2) and all other even-order, non-zero-sequence harmonics, Equation (2.15) becomes zero:

$$i_{N2} =$$

$$I_2[\cos(2\omega_1 t) + \cos(2\omega_1 t + 240°) + \cos(2\omega_1 t - 240°)] =$$

$$= I_2[\cos(\omega_2 t) + \cos(\omega_2 t - 120°) + \cos(\omega_2 t + 120°)] =$$

$$= 0$$

Similarly, for 5th order harmonics (n=5) and all other odd-order non-zero-sequence harmonics, Equation (2.15) becomes zero:

$$i_{N5} =$$
$$= I_5[\cos(5\omega_1 t) + \cos(5\omega_1 t + 600°) + \cos(5\omega_1 t - 600°)] =$$
$$= I_5[\cos(\omega_5 t) + \cos(\omega_5 t - 120°) + \cos(\omega_5 t + 120°)] =$$

$$0$$

On the other hand, for 3rd order harmonics (n=3) and all other zero-sequence harmonics, the individual phase currents are in phase and add arithmetically in the neutral:

$$i_{N3} =$$
$$= I_3[\cos(3\omega_1 t) + \cos(3\omega_1 t + 360°) + \cos(3\omega_1 t - 360°)] =$$
$$= I_3[\cos(\omega_3 t) + \cos(\omega_3 t) + \cos(\omega_3 t)] =$$

$$= 3\, I_3 \cos(\omega_3 t)$$

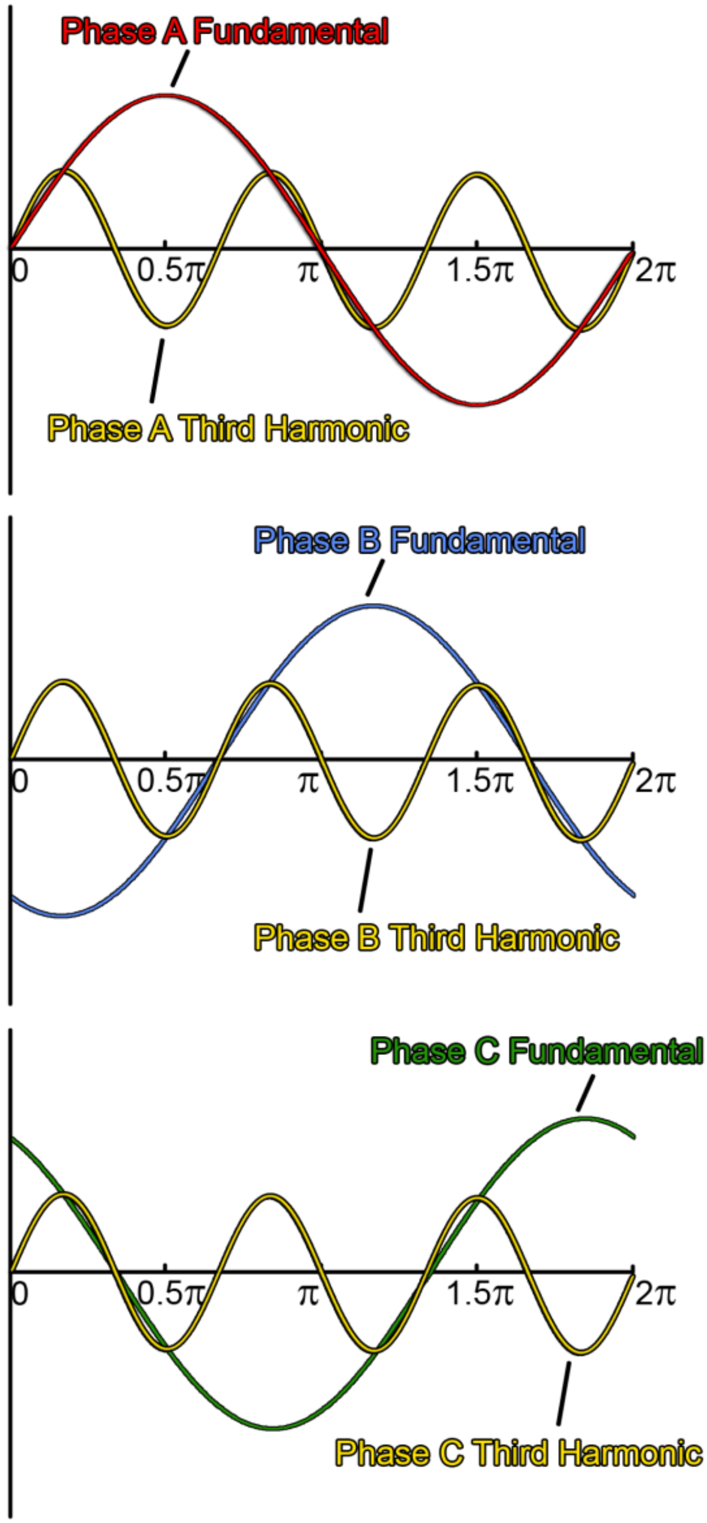

Figure 2-5: Fundamental and third-harmonic components in the phase conductors of a three-phase system.

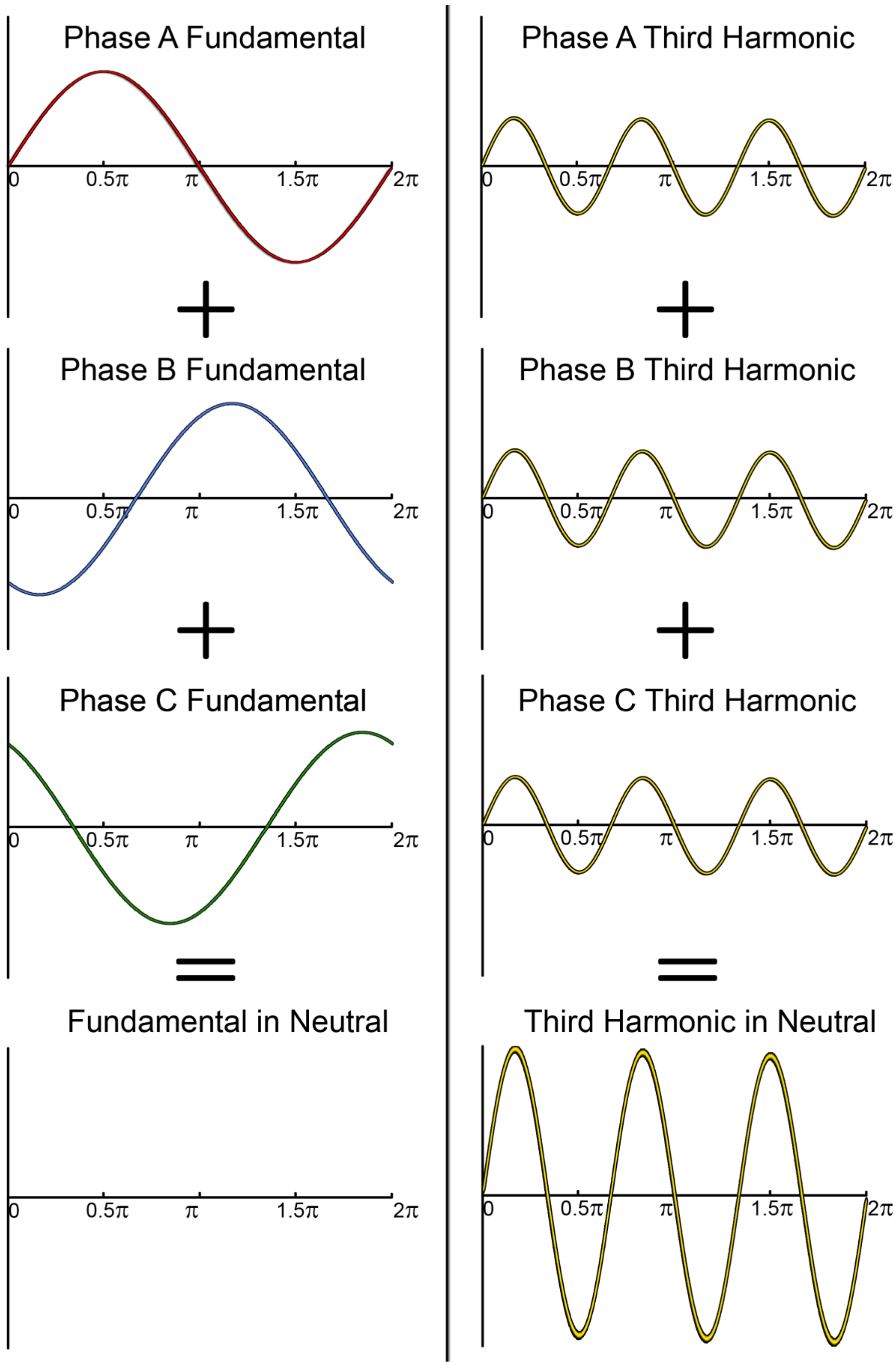

Figure 2-6: Illustration of the calculation of the neutral current for the fundamental components (left-hand side) and third-harmonic components (right-hand side).

2.6 What are resonances?

All power systems have inductive and capacitive elements. Examples for elements that primarily inductive are transformers and overhead transmission lines. Underground cables and power factor correction capacitors are primarily capacitive elements. The impedances Z_L of an inductive element with inductance L and the impedance Z_C of a capacitive element with capacitance C vary with frequency ω:

$$Z_L = \omega L \tag{2.16}$$

$$Z_C = \frac{1}{\omega C} \tag{2.17}$$

A resonance exists for the frequency for which the inductive impedances are equal.

$$Z_L = Z_C \tag{2.18}$$

The resonant frequency $\omega_{resonant}$ can be calculated by combining the equations above:

$$\omega_{resonant} = \sqrt{\frac{1}{LC}} \tag{2.19}$$

The order of the resonant harmonic $h_{resonant}$ is

$$h_{resonant} = \frac{1}{2\pi\, f_{fundamental}} \sqrt{\frac{1}{LC}} \tag{2.20}$$

where $f_{fundamental}$ is the fundamental frequency (60 Hz in the United States).

Depending on the data available, system resonances can also be computed or estimated using one of the following equations (Dugan et al., 2002):

$$h_{resonant} = \sqrt{\frac{X_C}{X_{SC}}} \tag{2.21}$$

where X_C is the capacitor reactance, and X_{SC} is the system short-circuit reactance.

$$h_{resonant} = \sqrt{\frac{MVA_{SC}}{MVAr_{cap}}} \tag{2.22}$$

where MVA_{SC} is the system short circuit MVA and $MVAr_{cap}$ is the MVAr rating of the capacitor bank.

$$h_{resonant} \approx \sqrt{\frac{100\ kVA_{tx}}{kVAr_{cap}\ Z_{tx}}} \tag{2.23}$$

where kVA_{tx} is the kVA rating of the step-down transformer, $kVAr_{cap}$ is the kVAr rating of the capacitor bank, and Z_{tx} is the percentage impedance of the step-down transformer.

In general there are two types of resonant conditions- (1) series resonance conditions and (2) parallel resonance conditions. Under series resonance conditions, inductive and capacitive elements are connected in series. For resonant-frequency currents, the inductive and capacitive impedances in the circuit are equal in magnitude and cancel each other because they are 180° apart in phase. In this case, the current flow is only limited by the resistance of the circuit. Under parallel resonance conditions, inductive and capacitive elements are connected in parallel. For resonant-frequency currents, the inductive reactance and the capacitance reactance are equal resulting in an impedance peak (that is, frequencies below the resonant frequency will lower the inductive reactance and frequencies above the resonant frequency will lower the capacitive reactance; in both cases the total impedance of the parallel circuit will be lower). The “sharpness” of the impedance dip/peak will be governed by the resistance in the circuit. A measure for the sharpness it the quality factor Q of the circuit; circuits with a low Q will have wide dips/peaks and circuits with a high Q will have narrow dips/peaks.

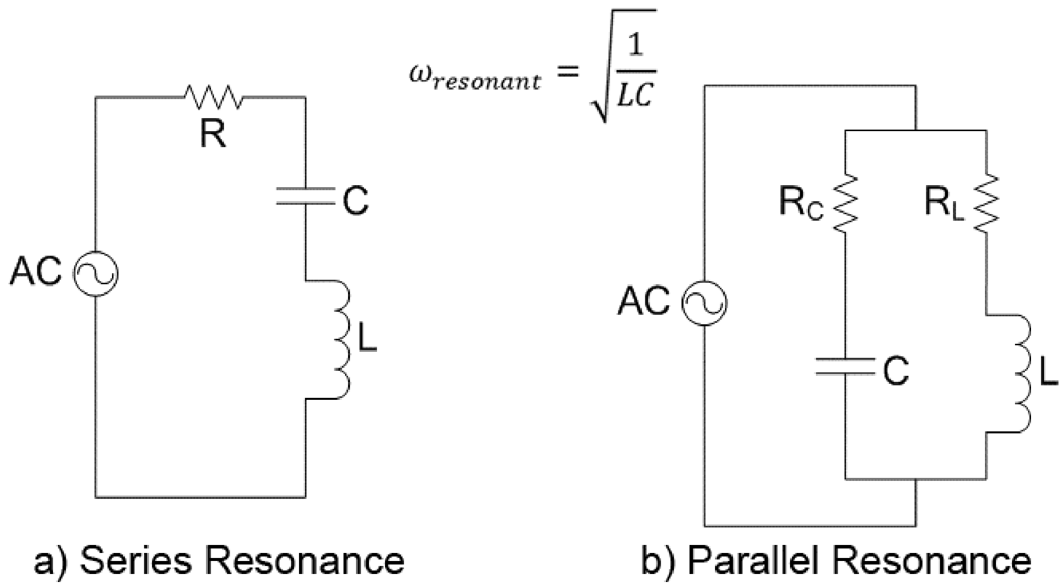

Figure 2-7: Simple circuits illustrating series resonance and parallel resonance.

Depending on the relative locations of the inductive and capacitive elements in the power system, there will be series resonances resulting in impedance dips and, if excited by harmonic sources, large current or parallel resonances resulting in impedance peaks and, if excited by harmonic sources, large voltages. The simple circuits shown in Figure 2-7 have only one inductive element and one capacitive element and consequently there will be only a single resonant frequency or, equivalently, a single impedance dip or peak. However, a circuit that is a more realistic representation of a power system has a number of branches that have many inductive and capacitive elements. For these circuits, a number of combinations exist for which the individual inductive and capacitive reactances are equal and for each combination a resonance frequency exists causing and impedance dip or peak. Figure 2-8 and Figure 2-9 show impedance dips under parallel resonance conditions and impedance peaks under series resonance conditions, respectively. The plots were created by performing a frequency scan on a simulated power system with different numbers of capacitor banks (one capacitor bank through six capacitor banks) in the system. Note that the increasing number of capacitor banks causes a shift of the resonance dips/peaks shift towards lower-order harmonics.

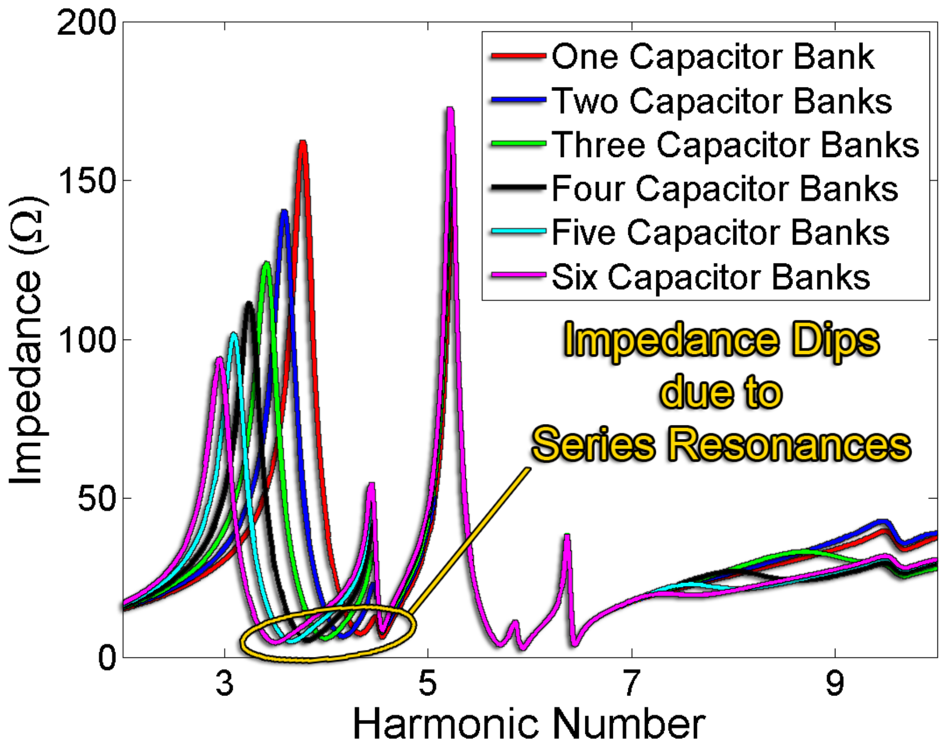

Figure 2-8: Impedance dips during series resonance conditions for different numbers of capacitor banks in the circuit.

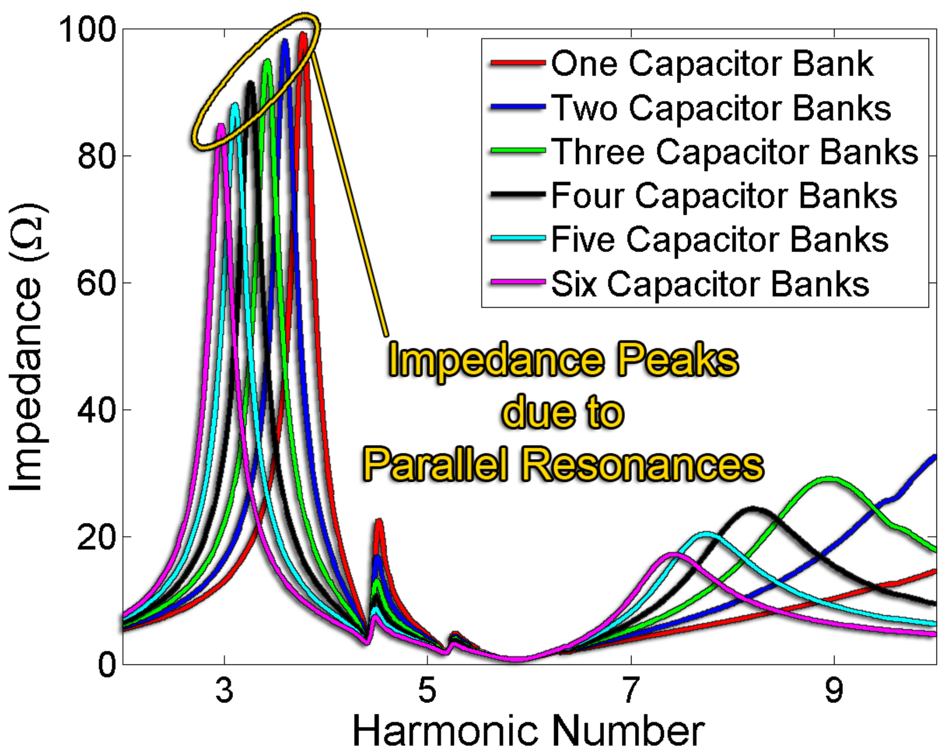

Figure 2-9: Impedance peaks during parallel resonance conditions for different numbers of capacitor banks in the circuit.

3 Harmonic Sources

Harmonics in a power system are produced by loads in which the consumed current is not proportional to the applied voltage. Examples for these so-called non-linear loads are diodes, saturated transformers, and rectifiers used in, for instance, Variable-Speed Drives (VSDs). The harmonic currents injected into the system by non-linear loads varies to some degree with the distortion of the applied voltage – there is some experimental evidence that the harmonic current is higher if the voltage that supplies the non-linear load has less distortion and lower for supply voltages with more distortion (Mansoor et al., 1995, Nassif and Xu, 2009).

3.1 Compact Fluorescent Lamps (CFLs)

A Compact Fluorescent Lamp (CFL) is a fluorescent lamp with a more compact design than a fluorescent tube. A CFL consists of a gas-filled tube and an electronic ballast or, less commonly, a magnetic ballast to control the current flow through the gas. The electric current flowing through the gas, (typically mercury vapor) results in the emission of invisible ultraviolet light, which excites a phosphor coating on the tube resulting in the emission of visible light. The phosphor coating is usually a mix of different phosphors, with each phosphor emitting one color. High-quality CFLs have typically three to four different phosphors to approximate white light. The electronic ballast is a small circuit composed of rectifiers, a filter capacitor, and a high-frequency resonant series DC-to-AC inverter, which produces frequencies of about 40 kHz or higher. CFLs are produced in three different configurations: (1) Self-ballasted CFL have the ballast integrated into the lamp and are designed to replace incandescent lamps without requiring any modifications to the existing screw base, (2) pin-based CFLs have a modular design, i.e., the lamp can be detached from the ballast, so a burned out lamp can be replaced without having to replace the ballast, and (3) hard-wired systems where the ballast and the lamp socket are permanently wired into a fixture (MGE, 2009). Hard-wired systems are similar to pin-based lamps in that they also feature a modular design. The typical lifespan of CFLs is between 6,000 and 15,000 hours, although a CFL will emit significantly less light at the end of its lifetime since the output of CFLs degrades exponentially over time. The Cold Cathode Fluorescent Lamp (CCFL), which is commonly used in LCD televisions and computer monitors for backlighting, are a type of CFL.

The shift away from incandescent lighting towards energy-efficient lighting raises concerns (especially with the utilities) regarding how a wide-scale use of energy-efficient lighting will affect the power quality. Incandescent lamps are almost purely resistive loads resulting in a power factor close to unity. On the other hand, the true power factor of CFLs depends on the quality of the electronic ballast and ranges between 0.5 and 0.9 for Low-Power-Factor (LPF) CFLs and is above 0.9 for High-Power-Factor (HPF) CFLs. Good quality ballasts that have circuitry to correct for poor power factor (e.g., a capacitor to shift phase angle) can achieve power factors of 0.95 or greater (Parsons Brinckerhoff Associates, 2006). Typically, pin-based (modular) CFL are HPF devices but self-ballasted CFL, which are the common energy-efficient replacements for incandescent lamps, often have a poor power factor (MGE, 2009; Conner, 2009). Cunill-Sola and Salichs (2007) measured the power factor of nine CFL below 25 Watt, which are increasingly used in household installations, and found power factors ranging from 0.56 to 0.65. Also, there is some concern that the power factor of the electronic ballast degrades substantially over the lifetime of the CFL (Parsons Brinckerhoff Associates, 2006). CFLs without filters or with low-quality filters have a poor true power factor because they are highly non-linear loads, which produce significant harmonics. The true power factor can be calculated from the displacement power factor and the Total Harmonic Distortion (THD) using the following equation (see also Section 2.2):

$$PF_{True} = \frac{PF_{Displacement}}{\sqrt{1 + {THD_I}^2}} \tag{2.24}$$

Since the displacement power factor of CFLs is close to unity, the true power factor for CFLs mainly depends on the THD and therefore reflects the degree of harmonic distortion due to CFL loads. Consequently, similar to the true power factor, the current Total Harmonic Distortion (THD) varies considerably with the quality of the ballast and can range from 30% THD for ballasts with harmonic filters (De Almeida, 1993) to well over 100% THD for less sophisticated ballasts (Verderber et al., 1993). Watson et al. (2009) classified four different types of CFL circuits: (1) basic, no filtering, (2) basic, with filtering, (3) valley-fill or equivalent, and (4) active power-factor control. Watson et al. analyzed a large number of CFLs and measured their harmonic distortion levels. Typical spectra for each of the four categories of CFL ballast circuits are shown in Figure 3-1. The THD/true power factor for each spectrum is 174%/0.5, 123%/0.6, 31%/0.95, and 8%/0.99 for circuits of type 1, type 2, type 3, and type 4, respectively.

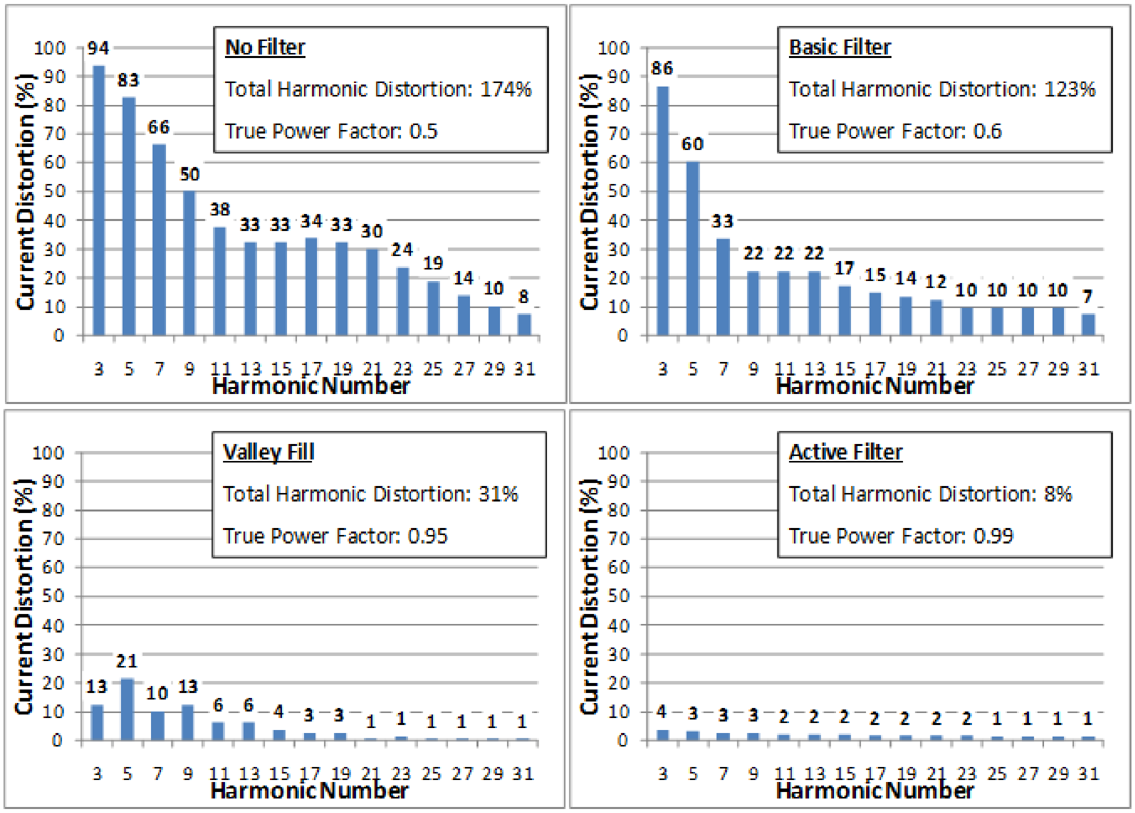

Figure 3-1: Experimentally determined harmonic current spectrum for a CFL ballast circuit with no filter, a basic filter, a valley-fill filter, and an active filter (data adopted from Watson et al., 2009).

Cunill-Sola and Salichs (2007) measured the THD of nine CFL below 25 Watt, which are increasingly used in household installations, and found high THD levels ranging from 91% to 117%.

It is not clear what impact the growing use of CFL and other energy efficient lights has on the power quality. No power quality problems are expected for a low penetration level of CFLs (Parsons Brinckerhoff Associates, 2006; Verderber et al., 1993). Verderber et al. (1993) found in a computer simulation that there is little effect on a building's power quality if the CFLs comprise less than 10% of the building's load and even with CFL lighting comprising 25% of the building's load, the THD voltage levels is below the IEEE 519 limit of 5%. On the other hand, Verderber et al.'s simulation results show that if the CFL load is above 27% of the total load and each CFL has 115% current THD, then the IEEE 519 THD voltage distortion limit of 5% will be exceeded. For the latter scenario, Verderber et al. recommend low-cost passive filter circuits to suppress harmonic distortion.

Koroveris et al. (2004) simulated the effect of replacing incandescent lights with CFLs in a weak system (a power system on Aegean, a small Greek island, fed by a photovoltaic station of 25 kW) for four CFL penetration scenarios and found that the voltage THD increased from 3.2% (only incandescent lights) to 8% for the light CFL penetration scenario and 30.8% for the worst-case scenario.

Gothelf (1997) conducted an experimental study on the power quality impact of CFL in a residential district in the suburbs of Stockholm, Sweden. Gothelf measured harmonic currents and voltages with up to 106 CFLs of three different types installed in 17 houses. The operation of the 106 CFLs caused an increase of the 3rd harmonic current by 1.34 A from slightly below 5 A to slightly above 6 A. The operation of the 106 CFLs caused an increase of the 5th harmonic current by 0.67 A from about 3.5 A to slightly above 4 A. The changes in the other harmonic currents (up to the 25th) were negligible. Gothelf measured that the Total Harmonic Voltage Distortion (THD) was lower for the case with the CFLs (THD slightly below 1.6%) than for the case without CFLs (THD slightly below 1.8%) – a result that is somewhat counter-intuitive and inconsistent with the significant increase of 3rd and 5th harmonic currents. Gothelf speculated that the reduction of harmonic voltage distortion is attributable to harmonic cancellation of harmonics from CFLs and other harmonic sources in the system. We think that, considering the relatively small THD reduction by 0.2%, the decrease may not be significant and is possibly due to the normal fluctuation of the harmonic voltage level over time.

Rönnberg et al. (2010a, 2010b) conducted an experimental study to investigate the harmonic impact of changing the lighting in a medium sized hotel (76 rooms) from incandescent lamps to CFL and LED lamps. The energy-efficient lighting had a displacement power factors ranging from 0.5 to 0.6. Laboratory measurements conducted by Rönnberg et al. (2010a) showed that the replacement lights were a significant source of third harmonics. The 563, forty Watts incandescent lamps used in the hotel before the change were replaced with 447, seven Watts LED lamps and 116, eight Watts CFL. Five-hundred-thirty-three of the lights were located in the guest rooms and are consequently subjected to large variation of usage due to factors such as hotel occupancy and seasonal variation. The experimental study compared harmonic distortion levels in Ampere of the currents flowing in the phase conductors (including third harmonic distortion and THD) before and after the change to energy-efficient lighting and found that (1) the harmonic distortion levels before and after the change were below IEC 61000-3-12 limits and (2) no significant change in harmonic distortion levels were observed. Note that neutral currents before and after the switch were not compared in the paper. The authors do not give an explanation for the perhaps unexpected result that the harmonic distortion levels do not change significantly, but caution that they were not able to remove completely factors such as seasonal variations from their comparison. However, they note that, in their case study, these variations appear to have a stronger impact on harmonic distortion levels than the impact of the switch to energy efficient lighting. Our interpretation of the study results is that the low impact of the light switching on harmonic distortion levels is possibly related to the fact that the total power consumption of the energy efficient light is much smaller than the power consumption of the incandescent light (7/8 Watts vs. 40 Watts) and consequently the harmonic currents injected by the energy efficient lightings are small if measured in Ampere (even though the harmonic currents are large if measured as a percentage of the rated current of the light). Consequently, lighting after the change is a smaller load compared to the total load of the hotel and their impact on harmonic distortion level will be less significant. Rönnberg et al. do not give information on the total load mix of the hotel, but, based on the experimental result that significant third harmonic currents were measured even before the switch to third-harmonic producing energy-efficient lighting, we can assume that a significant fraction of the load were composed of third-harmonic producing non-lighting load and, consequently, the inclusion of additional third-harmonic producing loads (i.e., the energy-efficient lighting) will be less visible.

Note that some harmonic cancellation may occur in a residential area with high penetration of CFLs due to the phase shift introduced by having the CFLs at different locations in the systems and slightly different harmonic characteristics of CFLs from different manufacturers. Harmonic cancellation would likely not affect lower harmonics significantly as they experience very little phase shift. On the other hand, higher harmonics, which experience a larger phase shift when installed at different locations in the system, may be subjected to significant harmonic cancellation.

3.2 Power Electronic Devices

Switched-Mode Power Supplies (SMPSs) are electronic devices that are employed to regulate the voltage and current from a source (typically the power grid) to supply power to single-phase or three-phase loads. During the last decades there has been a trend towards using SMPSs instead of traditional linear power supplies. Linear power supplies are large, heavy, and inefficient devices due to the use of a mains transformer and a dissipative series regulator. On the other hand, SMTPs are usually more efficient and can be built much smaller and lighter than linear transformers of the same rating.

The operating principle of an SMPS is as follows: In the rectifier stage a diode bridge and a capacitor to convert the AC input voltage (typically from the mains) to DC voltage. The DC voltage is switched on and off at very high frequencies (typically between 50 kHz and 1 MHz). Voltage regulation is achieved by varying the duration of the 'on' time and the 'off' time. The high-frequency voltage passes through a high-frequency transformer or inductor. Note that most of the cost-savings, form-factor advantages, and weight advantages of SMPSs over linear power supplies come from the fact that the high-frequency transformer in SMPSs is much smaller than the mains transformer used in linear power supplies.

The rectifier stage in simple SMPSs consists of a simple full-wave rectifier and a capacitor. These SMPSs draw current from the supply in short pulses to recharge the capacitor. As a result, the input current to the SMPS has a high harmonic content.

Single-phase SMPSs are commonly employed in electronic equipment such as computers, printers, copiers, and cell phone power supplies. The harmonic content for a single-phase SMPS is characterized by a high contribution of third harmonics, which can cause problems due to neutral overloading in particular in older buildings where the neutral is more likely to be undersized. The harmonics can be reduced with a passive or an active power factor correction stage. A passive power factor correction stage can be a passive band-pass filter that is tuned to pass only the power-frequency. In an active power factor correction stage the power drawn by a load is actively controlled with an electronic converter, such as a boost, buck, or buck-boost converter, which is usually installed between the diode bridge and the capacitor.

Three-phase electronic converters are commonly used in HVDC links, motor drives, static VAr compensators, and cycloconverters. These converters have different harmonic characteristics than single-phase converters in that they do not generate significant third harmonics. In order to control the power in three-phase converters, a

Pulse-Width Modulation (PWM) scheme is commonly employed, which are generally a three-phase version of the control scheme used in single-phase SMPSs, that is, the power supplied to the load is controlled by the durations of the 'on' and 'off' stages of the switches. The dominant harmonics h depend on the number of pulses p used in the converter and can be calculated using the following equation:

$$h = p \cdot n \pm 1 \tag{2.25}$$

where n = 1, 2, 3, 4 …

For instance, for a 6-pulse converter (p=6) the dominant harmonics are 5th, 7th, 11th, 13th … For a 12-pulse converter (p=12) the dominant harmonics are 11th, 13th, 23rd, 25th, …. Under ideal operation conditions, that is, balanced voltages, equal commutating reactances, and equally spaced firing pulses in the converter bridge, the magnitude of the harmonics decrease with increasing harmonic order h by the factor 1/h.

It is difficult to accurately determine the harmonic current characteristic of residential appliances with VSDs due to the large variety of appliances (clothes dryers and washers, heat pumps, etc.). Even for appliances of a given category, the harmonic current characteristic can vary considerable. For instance, the information shown in Table 2 suggests that the current THD for heat pumps with Adjustable Speed Drives (ASD) can vary between 16% and 123% (IEEE 519, 2004).

Single-phase, capacitor-run induction motors employed in refrigerator compressors, air conditioners, heat pumps, and blowers can act as a sink for low-order harmonics. The capacitor and the auxiliary winding may create a series resonance that can be a preferred path for low-order harmonics already in the system. For instance, Collins et al. (2008) demonstrated in an experiment with four- and eight-pole induction motors with various capacitor sizes that some motor impedances can create a third-harmonic resonance. Our interpretation of this experimental study is that the interaction of the capacitor motors with the system is typically not detrimental to the power quality of the system since the capacitor motor is a sink (not a source) for the harmonic currents. On the other hand, damage to the capacitor motor due to excessive harmonic currents for which the motor creates a resonance condition may be of concern.

Table 3-1: Harmonic current characteristics for conventional heat pumps and heat pumps with Adjustable Speed Drives (source: IEEE 519, 2004).

Appliance	Load Current RMS (A)	Current THD (%)	Individual Current Harmonic Distortion (%)			
			3rd	5th	7th	9th
Conventional Heat Pump #1	23.8	10.6	8.0	6.8	0.5	0.6
Conventional Heat Pump #2	25.7	13.2	12.7	3.2	0.7	0.2
ASD Heat Pump #1	14.4	123.0	84.6	68.3	47.8	27.7
ASD Heat Pump #2	27.7	16.1	15.0	4.2	2.3	1.9
ASD Heat Pump #3	13.0	53.6	48.8	6.3	17.0	10.1

3.3 Harmonics Produced by Magnetic Core Saturation

Harmonics can originate from saturable devices that have a steel core, such as transformers, iron-core reactors, and motors. Increased current flow through a transformer results in an increased flux density in the steel. The flux density is proportional to the transformer voltage. Initially, the current and the flux/voltage are more-or-less linearly related as illustrated in Figure 3-2. Under this condition, the transformer current will be essentially undistorted. At sufficiently large currents, magnetic saturation of the steel core occurs, that is, the magnetizing capability of the steel is inhibited and the magnetic flux density in the steel levels off resulting in leveling off of the transformer voltage. Magnetic saturation occurs when the so-called “knee point” of the transformer’s magnetizing characteristic is exceeded (see Figure 3-2). For transformers operation above the “knee point” the voltage-current relationship is non-linear resulting in distorted current waveforms that are mainly contaminated with third-harmonics currents.

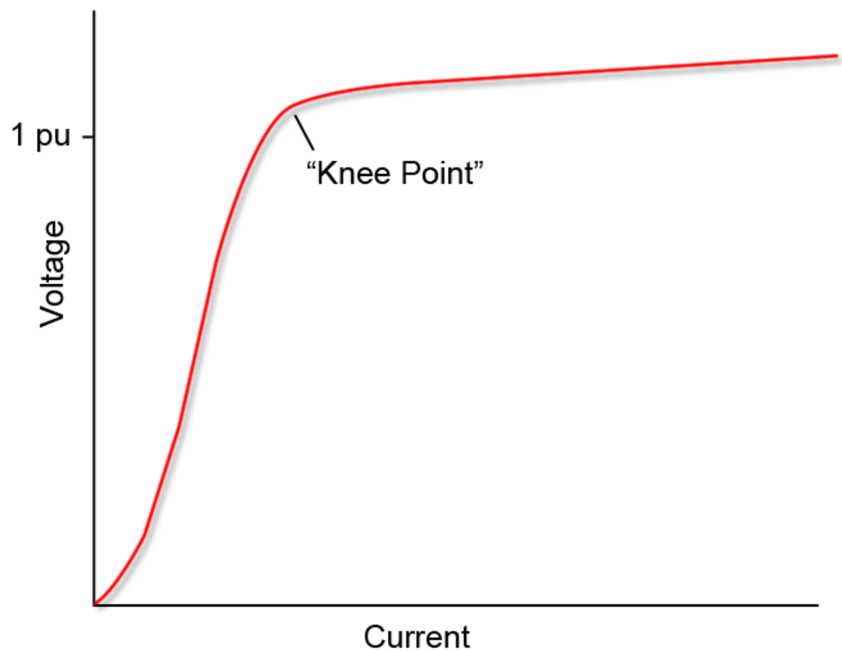

Figure 3-2: Magnetizing characteristic of a transformer.

Magnetic core saturation in transformers can produce steady-state harmonics and transient harmonics. In general, symmetric core saturation results in odd harmonics and asymmetric core saturation results in odd and even harmonics. The magnitude of the harmonics generated by transformer saturation depends on the saturation level of the magnetic core and on the transformer design (IEEE TF, 2004).

The origins and characteristics for harmonics produced by saturation effects are summarized below.

- **Normal transformer operation**: For economic reasons, transformers are often operated just below the "knee point" and the excitation current may graze the bottom of the "knee" resulting in slightly distorted waveforms. The magnitude of the harmonic components in the transformer exciting current during normal operation is relatively low – typically less than one percent of the rated full-load current (Dugan et al., 2002). However, utility distribution systems often have a large number of transformers and their combined harmonic pollution during normal operation may result in significant harmonics. Harmonic current distortion, in particular due to zero-sequence harmonics, is often noticeable on distribution systems during early morning hours when the load is low and the voltage rises. The increased voltage causes harmonic currents due to saturation and the harmonic currents are relatively large compared to the low load current, which makes the harmonic currents particularly visible (Dugan et al., 2002).
- **Temporary Overvoltage (TOV):** TOVs can be caused by load rejection or excessive control action (CIGRE, 1990). TOVs typically have a duration in the

order of milliseconds and may cause transformers to operate in their saturated region resulting in the production of harmonics during this time.

- **Unbalanced Transformer Loads:** Unbalanced transformer loads will result in an uneven distribution of the magnetizing current among the phases, which may result in the saturation of one phase, even if the line voltage is within normal limits (IEEE TF, 2004).
- **Low Frequency Currents:** The presence of low-frequency currents can drive a transformer into saturation. The additional flux generated by these currents will causes an offset that will "push" one half-cycle of the power-frequency magnetizing current closer to saturation. Low-frequency currents can be produced by Adjustable Speed Drives (Wang and Liu, 1993). Also, low-frequency (typically 0.001 Hz to 0.1 Hz) geo-magnetically induced currents, that is, currents that flow on the earth surface due to solar magnetic disturbances, can reach peak values of up to 200 A (Lu et al., 1993) and enter grounded wye transformers thereby biasing transformers towards half-cycle saturation.
- **Transformer Inrush Currents:** Inrush currents during transformer energization can be large enough to cause asymmetric core saturation, which results in harmonics. The duration of the inrush current depends on the size of the transformer – the inrush current duration for large transformers may exceed 30 seconds (Heydt, 1991) and consequently the transformer inrush current is sometimes viewed as steady-state process for which a Fourier series exists[1].

3.4 Rotating Machines

Harmonics generated in synchronous machines can have the following origins:

- **Non-sinusoidal flux distribution:** A non-sinusoidal flux distribution in synchronous machines can cause odd-harmonic voltages. However, synchronous machines are usually designed in such a way that the harmonics due to this effect are minimized to the extent that they are negligible (Arrillaga et al., 1985).
- **Frequency conversion process:** Synchronous machines can generate harmonics under unbalanced conditions. A negative-sequence current in the armature due to the imbalance may induce a second-order harmonic in the rotor, which in turn can induce a third-order harmonic back into the armature due to saliency effects. Similarly, unbalanced harmonics of order h in the armature can create harmonics of order h+2. The effect of frequency conversion in synchronous machines can (1) cause the machine itself to generate harmonics and (2) cause synchronous machines to generate harmonics in response to external harmonic

[1] Calculating the Fourier series to determine harmonic components requires periodic signals, which inrush current is not (inrush current is composed of a sinusoid and a term that decays exponentially), but signals with sufficiently long duration can be approximated as periodic.

sources (Xu et al., 1991). Harmonics due to frequency conversion can be particularly significant for salient pole machines that are located near HVDC terminals (IEEE TF, 2004).

- **Saturation:** Synchronous machines can cause harmonics due to magnetic saturation in the stator and rotor cores, and in the stator and rotor teeth (see Section 3.1). This effect is typically negligible in large machines (IEEE TF, 2004).

Harmonics generated in induction motors can have the following origins:

- **Stator winding configuration:** The stator windings in induction motors are located in slots. The spatial displacement of the windings will result in a distorted Magnetomotive Force (MMF) even if the applied stator voltage is undistorted. Harmonics caused by this effect are called "space harmonics". However, induction motors are usually designed in such a way that space harmonics are minimized to the extent that they are negligible (IEEE TF, 2004).
- **Startup:** The stator current and rotor current in induction motors during start up and during changing load conditions vary at high frequency, which results in the generation of harmonic currents (IEEE TF, 2004).

Generally, the harmonics generated by induction motors are much smaller than the harmonics from other sources, such as arc furnaces and power electronic devices. Consequently, the harmonic contribution from induction motors is often neglected. However, it is important to include the impedance characteristics of induction motors in a harmonic analysis since the motor impedance will impact the resonance characteristics of the system (IEEE TF, 2004).

3.5 Arc Furnaces

Arc furnaces use electric arcs for melting and refining metals. The arcs can be generated by AC voltage or DC voltage. Both AC and DC arc furnaces produce harmonics, but the harmonics generated by a DC furnace are mostly due to the AC/DC converter and not primarily due to the arcing process (IEEE TF, 2004). AC arcs are ignited and extinguished during each half-cycle of the supply voltage. After arc ignition, the voltage drops abruptly and the arc current is mainly limited by the impedance of the power system (cables, leads, and transformers) and, to a lesser degree, limited by the impedance of the arc. The arc current in arc furnaces often reaches current magnitudes in excess of 60 kA (Dugan et al., 2002). The current chopping and igniting process during each half-cycle causes significant harmonic distortion. The harmonic spectrum of arc furnace current is continuous with the second harmonic and odd harmonics being dominant. Higher-frequency components are attenuated due to the damping from the system impedances – if the furnace is operated from a stiff bus, harmonics above the 23rd, or so, experience rapid attenuation (Heydt, 1991) and may be neglected in a harmonic analysis. Balanced zero-sequence harmonics generated by three-phase arcs can be canceled through the transformer connection. However, the three-phase current consumed by arc furnaces during the melting phase is often unbalanced so that significant zero-sequence harmonics are created. The imbalance and resulting zerop-sequence harmonics are reduced during the refining stage in arc furnaces (Dugan et al., 2002).

4 Effects of Harmonics

4.1 Effect of Harmonics on Wiring Requirements

The presence of harmonic currents can significantly increase the heating in conductors. The increased heating is caused by two mechanisms: (1) the additional load due to the harmonic currents and (2) the current redistribution within the conductor.

A measure for the additional load inside the conductor is the difference between the true RMS value of the current flowing through the conductor and the RMS value of the fundamental-frequency current component. Assuming the current is composed of fundamental-frequency and harmonic components only (i.e., no DC component and no subharmonics), the difference will be attributable to the harmonic load only.

Additional heating inside conductors is caused by the current redistribution. The current redistribution is mainly due to the skin effect, that is, the tendency of higher-frequency current to flow on the outside of conductors thereby effectively decreasing the size of the current-carrying portion of the conductor, which in turn increases the resistance and the joule heating. The skin effect increases with increasing frequency making it particularly significant for high-order harmonic currents. To a lesser degree, the current is also redistributed by a proximity effect due to electromagnetic coupling between current-carrying adjacent conductors and between the current-carrying conductor and other objects such as metal sheaths and conduit (IEEE TF, 1993).

In Baggini (2008) the author shows that issues related to the skin effect can be significant even at lower harmonics. When considering a typical cylindrical copper conductor with a diameter of 0.7874 inch (20 mm), the AC resistance to DC resistance ratio can theoretically reach 1.35 for the 3rd harmonic component and 2.07 for the 9th harmonic component. Figure 4-1 shows the resistance ratio as a function of frequency.

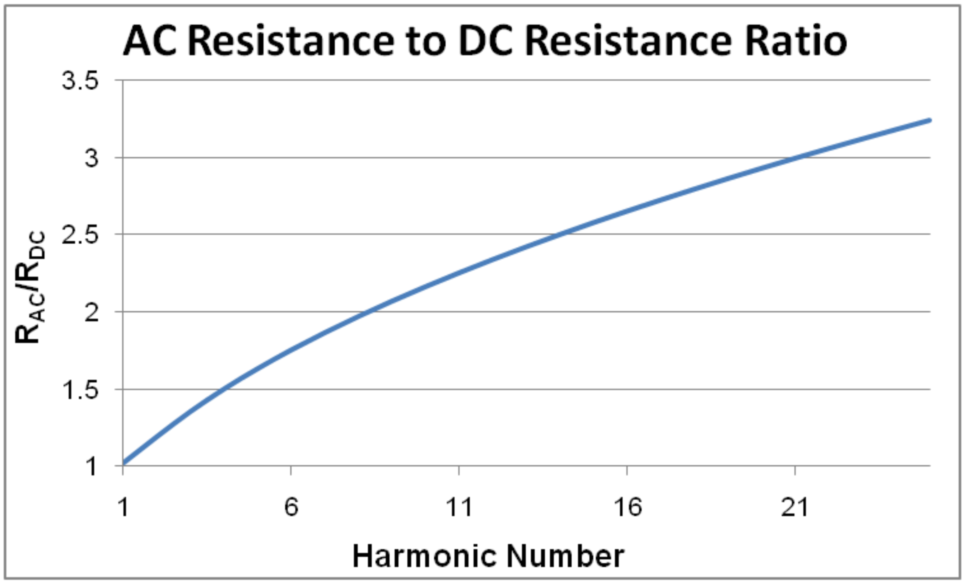

Figure 4-1: R_{AC}/R_{DC} ratio as a function of frequency (harmonic number).

While harmonic currents cause additional heating irrespective of the type of conductor, the neutral conductor in 3-phase, 4-wire distribution systems deserves special consideration. This is because zero-sequence harmonics (that is, harmonics that are integer multiples of three) add arithmetically in the neutral conductor as opposed to balanced fundamental current and balanced non-zero-sequence harmonic currents, which cancel in the neutral conductor (see Section 2.5).

The 3rd harmonic currents flowing in neutral conductors in addition to currents from system imbalance may result in overloaded neutral conductors. This is even more problematic if only load balance was accounted for when sizing neutral conductors and the 3rd harmonic load is neglected resulting in undersized neutral conductors in relation to the phase conductors.

Third harmonic currents can be particularly troublesome in commercial building, where many loads produce 3rd harmonic current. For instance, many Personal Computers (PCs) produce 3rd harmonic currents greater than 80% of the fundamental current. For a balanced three-phase load consisting entirely of PCs, the neutral conductor will carry 240% (three times 80%) 3rd harmonic current. Measurements performed in commercial buildings in which a large fraction of the load is 3rd-harmonic producing show neutral currents that are between 1.5 and 2.1 times larger than the phase currents (Baggini, 2008 and Grady et al., 2001). Overloaded neutral currents are often only a local problem inside a building, for example at a service panel. Because of phase angle diversity in phasor currents, the zero-sequence harmonic currents produced by non-linear loads are not completely additive in the neutral.

McGranaghan (1998) compares the RMS phase current I_{phase} with the RMS neutral current $I_{neutral}$ for a three-phase load drawing fundamental frequency current $I_{fundamental}$ and a third harmonic current with 70% of the fundamental I_3 :

$$I_{phase} = \sqrt{I_{fundamental}{}^2 + I_3{}^2} = \sqrt{1.0^2 + 0.7^2} = 1.22$$

$$I_{neutral} = I_3 + I_3 + I_3 = 0.7 + 0.7 + 0.7 = 2.1$$

$$\frac{I_{neutral}}{I_{phase}} = \frac{2.1}{1.22} = 1.72$$

In the example above, the neutral rating should be at least 1.72 times the rating of the phase conductor rating. The example makes a case for oversizing the neutral to twice the ampacity of the phase conductor. Obviously, under-sizing the neutral is not advisable.

4.2 Undesired operation of breakers and fuses

Harmonic currents influence the operation of protective devices. Fuses and circuit breakers are prone to nuisance operation when subjected to nonlinear currents. Load currents and low-level fault currents may contain a high percentage of harmonic distortion. The harmonic content of high-level fault currents is usually negligible.

Lembo et al. (1981) describe 15 kV-breaker failures due to harmonic currents. Currents with 50% distortion factor limited the breaker blowout coil's ability to force the arc into the arc chute. Furthermore, the prolonged interruption also delayed fault current dissipation and caused re-ignition after fast reclosure. Vacuum interrupters are less sensitive to harmonic current distortion than air magnetic breakers.

Peak sensing circuit breakers have a reduced trip time if the harmonics add to the peak of the current waveform and an increased trip time if the harmonics subtract from the peak. (Lee et al, 1995) Generally, high-frequency harmonics increase the peak resulting in a faster trip time. Increased heat dissipation in equipment can be caused by increased RMS values of distorted current. With increasing frequency, the resistance in the equipment increases, causing heat to build up. Premature tripping of thermal circuit breakers may be caused by the generated heat.

Brozek (1990) describes how harmonic distortion affects the current sensing ability of thermal magnetic breakers. The instantaneous mechanism of some breakers is a solenoid that dissipates additional heat due to losses for frequencies above the fundamental. That heat then raises the temperature of the thermal device reducing the trip point. Because fuses are thermally triggered, they are inherently RMS overcurrent devices. Farahani et al. (2010) investigate the thermal behavior of fuses during harmonic conditions using computer simulations. They demonstrate that increasing levels of current THD result in an increase of the internal temperature of the fuse. For instance, in Farahani et al.'s simulation an undistorted current flowing through a fuse caused a hot point temperature of 211°C. The temperature was increased by 29.8°C to 240.8°C for a current that had a THD of 40% potentially leading to undesired tripping of the fuse.

4.3 Elevated Neutral to Earth Voltages

Elevated neutral-to-earth voltage (NEV) in distribution systems has long been a power quality concern NEV may result in unacceptable step and touch potentials in publicly and privately accessible locations. NEVs are created by unsymmetrical networks, unbalanced loads, and the practice of grounding the neutral conductor at multiple points throughout the power system. Conventional NEV analysis on three-phase systems focuses on the residual neutral return due to the unbalance on the system and loading at the fundamental frequency. However, the increasing prevalence of power-electronic devices, especially the single-phase nonlinear loads on Y-connected commercial/residential distribution circuits, calls for an evaluation of elevated NEV, including the effect of harmonic distortion. (Collins et al, 2009)

Studies have shown increased NEV levels at buses of multi-grounded distribution systems. In Balda et al. (1997) neutral-to-earth voltage measurements taken on the primary side of a distribution transformer at a bus located at the end of a multi-grounded feeder revealed potential difference between the neutral point and the local ground of 0.26 pu on a 120 V base (i.e. 31.2 V). This high neutral voltage was caused by the flow of the neutral current in the neutral conductor and the ground impedance due to both linear load unbalance and the nonlinear characteristics of electrical equipment throughout the feeder – measurements showed that the predominant harmonics were the 2nd, 3rd, 4th, and 5th harmonics.

4.4 Metering

Harmonics can affect the performance of metering equipment and thereby impact the billing charges of the customer. Reading of energy, reactive power, and voltampere meters are used to calculate the billing charges for customers and to determine extra punitive charges for low power factor loads. Therefore, the consumers' billing is based on the definitions of three basic electrical quantities: the apparent, active and reactive power, S, P and Q, respectively. (Emanuel, 2002) When the practical issues of measuring the defined quantities and indices began to be considered, it was soon clear that the traditional instruments (mainly active and reactive energy meters) used under sinusoidal conditions to evaluate the energy consumption, both from a quantitative and qualitative point of view, were inadequate. (Domijan et al., 1996) They are however, increasingly being operated in the field under waveform conditions, which are not pure sinusoids. Under these conditions the measuring method implemented in the revenue meter is critical. Field data indicates that the difference in kVA demand meter readings can be as large as 30% for distorted waveforms. The differences are mainly due to the different definitions of apparent power implemented in revenue meters. (Arseneau et al., 2004) The open and widely-discussed question in the metering community is the question how active power and especially reactive power, should be defined and measured when distortion is present. For example, distortion of the current waveforms can result in significantly different demand and power factor charges depending on the type of meters used. As a result, a meter change can sometimes trigger a power factor penalty where previously there had been none.

4.5 Other Effects of Harmonics

Transformer Overheating

Voltage harmonics produce additional losses in the transformer core as the higher frequency harmonic voltages cause hysteresis loops, which superimpose on the fundamental loop. The additional loops caused by the harmonics increase the magnetization power requirements and core losses. (Sankaran, 2002). Harmonic currents cause additional losses in the transformer windings and other structural parts. Delta connected transformers prevent the flow of zero-sequence harmonics by capturing them in the delta winding. This is a problem for transformer manufacturers due to the extra losses to be taken into account.

Failed capacitor banks

Capacitor banks are commonly found in commercial and industrial power systems to correct for low power factor conditions. Capacitor banks are designed to operate at a maximum voltage of 110% of their rated voltages and at 135% of their kVAr rating. (Sankaran, 2002) Excessive harmonic voltages and currents can cause voltages and currents rise above the maximum thresholds resulting in failures, such as (1) blown fuses, (2) reactive power overload, (3) overvoltage, and (4) increased dielectric losses (Mehrdad et al.). Harmonic voltages can produce excessive harmonic currents in capacitors. This effect is enhanced because of the inverse relationship between capacitor impedance and frequency, that is, the impedance is lower for a voltage with a higher frequency resulting in increased currents. Voltage distortions of 5% and 10% can easily increase RMS currents by 10% to 50%. The decreased impedance for higher frequencies causes capacitor banks to behave like a sink for harmonic currents – stray harmonic currents are absorbed by the capacitor, which can result in overloads and subsequent blown fuses and/or failure of the bank. Overvoltage stress on dielectrics may accelerate the aging and eventually cause failure of the capacitors. A 10% harmonic voltage for any harmonic above the 3rd increases the peak voltage by approximately 10% because the peak of the harmonic usually coincides, or nearly coincides, with the peak of the fundamental voltage (Grady and Santoso, 2001). Capacitor banks can create resonance conditions (see Section 2.6). Excessive harmonic currents may be created during series resonance conditions when the capacitive elements in a circuit are in series with the inductive elements and the individual reactances cancel at the resonant frequency. In this case, the flow of resonant-frequency currents is only limited by the resistive circuit component. Excessive harmonic voltages may be created during parallel resonance conditions when the capacitive elements in a circuit are in parallel with the inductive elements and the voltage drop across both reactances is maximum at the resonant frequency. Parallel resonant conditions may cause insulation failure in capacitor banks, cables, and transformers. (Sankaran, 2002 and Baggini, 2008)

Communication system interference

Power system harmonic frequencies can induce noise into communication systems where power lines are coupled to communication lines. With new developments in hardware and software techniques, harmonic disturbances in communication systems have become less significant. However, even though this type of interference poses a lesser problem nowadays it is still present.

Relay malfunction

Relay operations differ significantly in the presence of harmonic interference. The response not only depends on the device type and manufacturer, but also varies with each piece of equipment tested, as well as with changes in the characteristic features of the spectrum.

Effects in adjustable speed drives

The presence of harmonics in rotating machines can influence the torque, primary I^2R losses, secondary I^2R losses, core losses, losses due to skew-leakage fluxes, and losses due to end-leakage fluxes.

5 Mitigation of Harmonics

This chapter addresses common techniques that can be employed to reduce or suppress harmonics in distribution systems. In general, solutions to harmonic problems are categorized as preventive and remedial.

Preventive solutions:

Preventive (precautionary) solutions are techniques that are primarily employed to reduce harmonics in the system before harmonic problems occur. These techniques include

- phase cancellation or harmonic control in power converters.
- developing procedures and methods to control, reduce or eliminate harmonics in power system equipment; mainly capacitors, transformers and generators.

Remedial solutions:

Remedial (corrective) solutions are techniques that are employed in response to an existing harmonic problem. These techniques include

- use of filters.
- circuit detuning, for instance, relocation of capacitor banks to shift resonance away from the aggravating harmonics.

5.1 Filters

Filters can be employed to reduce excessive harmonics. Filters are usually categorized as passive filters and active filters.

Passive filters, as the name implies, use passive components such as resistors, inductors, and capacitors. A combination of passive components is tuned to the disturbing harmonic frequency forming a low-impedance branch to ground for the disturbing harmonic. Due to the lower impedance of the filter in comparison to the impedance of the source, the harmonic frequency current will circulate between the load and the filter. This keeps the aggravating harmonic current away from the source and other loads in the power system. In effect, under ideal conditions, the harmonic current flows only in the filter circuit and does not occur in the supply network. If other harmonic frequencies are to be filtered out, additional tuned filters are applied in parallel. Some harmonic generating loads, such as an arc furnace, require multiple harmonic filters, as they generate large quantities of harmonic currents at several frequencies.

Active filters use power electronic components to compensate for harmonic currents in a power system. The filter samples the distorted current and, using power electronic switching devices, draws a current from the source of such magnitude, frequency composition, and phase shift to cancel the harmonics in the load. These two levels of harmonics cancel each other out at the point of common coupling.

Passive filters are relatively inexpensive (compared to active filters) devices that, if designed properly, can reliably reduce excessive harmonics in distribution systems to safe levels. However, passive filters have a number of shortcomings, which are listed below (Baggini, 2008 and Clark et al, 1997):

- An electric power system with passive filters is a weakly damped LCR circuit which, in order to exclude resonance phenomena, requires a careful analysis of the frequency characteristics at the design stage.
- The effectiveness of the filter strongly depends on the supply network impedance at the point of connection. Normally its exact value is not known and it varies with changes in network configuration.
- Filters are subject to detuning due to variations in the supply frequency and changes in LC component values (e.g. due to the effect of capacitor ageing and/or changes in distribution system).
- Only selected harmonics of dominant magnitude are filtered. The load non-characteristic harmonics, which may occur in the load supply current, are not filtered.
- Undesirably large bus voltages can result from using and oversized filter, and an undersized filter can become overloaded.

Active filters do not have the shortcomings listed above and are therefore, in theory, technically superior to passive filters. However, active filters are complex electronic devices and the development of practical ways to utilize active filters has been an arduous process, and has already spanned well over twenty years. Nevertheless, many research teams continue to refine techniques, as problems remain to be solved. (e.g., Detjen et al., 2001, Basic et al., 2001, and Singh et al., 1999) The factor of cost efficiency has been and continues to be a major obstacle in realizing these methods; despite that obstacle, some manufactures have already put active filters for power conditioning on the market. (Akagi, 2005) In our opinion, active filters are generally superior in performance compared to traditional passive filter designs, but the substantial additional costs associated with active filters are preventing widespread use of active filters in distribution systems.

5.2 Other Mitigation Devices and Strategies

Transformers

Harmonics can be reduced through the ingenuity of transformer connection. Delta-connected transformers prevent the flow of zero-sequence harmonics. The same benefit can be obtained using a Zig-Zag wound transformer. The transformer phase-shifting principle, using a Δ-Δ and a Δ-Y transformer to supply harmonic producing loads in parallel, is also used to achieve cancellation of the 5^{th} and the 7^{th} harmonic currents.

Power converter

Increasing the number of pulses in the converter system is the most common way to reduce the converter current distortion factor and therefore to mitigate the adverse effects of harmonics in a power system. An equivalent, multi-pulse mode of operation can be achieved by means of connecting in series, or in parallel, converters with a smaller number of pulses and ensuring an appropriate phase shift between the voltages supplying the bridges. Converters are rarely increased beyond eighteen pulse types as they become very difficult and costly to manufacture. Research in this field continues in order to refine techniques necessary to address the cost, size and reliability problems related to high-pulse power converter integration.

Capacitor banks

The simplest method to provide some level of harmonic control and also accomplish power factor correction is to employ an existing capacitor bank as a part of a filtering system. Additionally, by relocating the capacitors the source-to-capacitor inductive reactance changes; thus reducing/eliminating harmonics by avoiding parallel resonance with the supply impedance.

Rotating Machines

Harmonics in three-phase electrical machines can be eliminated/reduced through coil spanning, which reduces 5^{th} and 7^{th} harmonics, and delta connected transformers, which eliminates zero-sequence harmonics in balanced systems. Generally, harmonics produced by rotating machines are relatively small compared to harmonics produced by other sources and are consequently often ignored in a harmonic analysis. (Wakileh, 2001)

6 Case Studies

Using case studies, in this section we, illustrate survey and testing protocols that are suggested in NFPA 70B, Section 10.2.4. The case studies incorporate measurements of phase and neutral currents and voltages conducted at various commercial and industrial facilities in the USA and Europe. The following tables give an overview of the companies at which the data were obtained, including information about the transformer configuration and the nominal voltage and frequency. The data have been acquired with power quality and energy/carbon monitoring devices.

(Comp.1): Office building in Knoxville TN.

Summary	3P4W 120/208Vac
Power Configuration	Wye/Star
Nominal Line-to-Neutral Voltage	120V
Nominal Line-to-Line Voltage	208V
Nominal Frequency	60Hz

(Comp.2): Manufacturing facility in Alameda, CA

Summary	3P4W 277/480Vac
Power Configuration	Wye/Star
Nominal Line-to-Neutral Voltage	277V
Nominal Line-to-Line Voltage	480V
Nominal Frequency	60Hz

(Comp.3): Office building in Santa Clara CA

Summary	3P4W 208/120Vac (400A)
Power Configuration	Wye/Star
Nominal Line-to-Neutral Voltage	120V
Nominal Line-to-Line Voltage	208V
Nominal Frequency	60Hz

(Comp. # 4): Manufacturing facility in Karlsruhe Germany

Summary	3P4W 230/400Vac
Power Configuration	Wye/Star
Nominal Line-to-Neutral Voltage	230V
Nominal Line-to-Line Voltage	400V
Nominal Frequency	50Hz

(Comp. # 5): Manufacturing facility in Ober-Grafendorf Austria

Summary	3P4W 230/400Vac
Power Configuration	Wye/Star
Nominal Line-to-Neutral Voltage	230V
Nominal Line-to-Line Voltage	400V
Nominal Frequency	50Hz

(Comp. # 6): Machine shop in Oakland CA

Summary	3P4W 240/139Vac
Power Configuration	Wye/Star
Nominal Line-to-Neutral Voltage	139V
Nominal Line-to-Line Voltage	240V
Nominal Frequency	60Hz

(Comp. # 7): Research laboratory in Berkeley CA

Summary	3P4W 277/480Vac
Power Configuration	Wye/Star
Nominal Line-to-Neutral Voltage	277V
Nominal Line-to-Line Voltage	480V
Nominal Frequency	60Hz

The exact load fleet at the different locations is unknown. However, it is assumed that the preliminary consumers at the office locations are computers, lighting, UPSs, etc. The manufacturing facilities are assumed to utilize rotating machines, robots, conveyors, etc. No information about possible harmonics mitigation technologies at the chosen locations is available to the authors.

Throughout this section the various locations will be referred to as Comp. 1, Comp. 2, Comp. 3, etc.

6.1 Case study 1 – True rms ammeter

When problems occur in a commercial facility, that are possibly attributable to the presence of harmonics (e.g. overloaded neutrals, transformer heating, frequent operation of breakers and fuses, etc.) it is advisable to get information about the loads used in the building. This can be done by, for instance, walking around the inspected facility to take a look at types of equipment used. In case personal computers, printers, adjustable speed drives, solid-state heater controls, and certain lighting are used, there is a good chance harmonics are present. Another step toward identifying possible presence of harmonics is the transformer heat check. After locating the transformer feeding all the non-linear loads described above, it can be inspected for excessive heating (it is important to make sure the cooling vents are unobstructed).

The next step in identifying the possible presence of harmonics, current readings with an average responding ammeter and a true rms responding ammeter can be conducted. It is a common practice, when harmonics are present that the average responding meter will generally yield readings lower than the rms meter readings. True-rms refers to “root-mean-square”. An average responding meter usually uses a rectifier to convert alternating current into direct current, while a true rms responding meter measures the actual rms value of the current and voltage. Figure 6-1 illustrate parameters that characterize distorted and undistorted current waveforms, and that can be obtained by these meters. The same type of parameters can be used to characterize voltage waveforms.

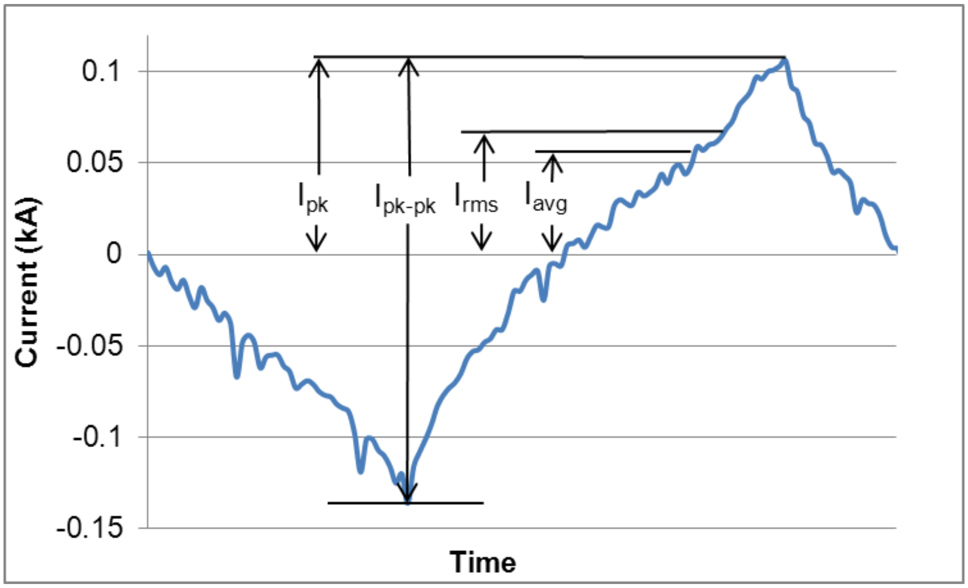

Figure 6-1: Common measurement parameters (Comp.1).

Peak current (I_{pk}) and peak-to-peak current ($I_{pk\text{-}pk}$) are illustrated in the figure. I_{avg} is the average of all the instantaneous absolute values in one complete cycle of the waveform. This is illustrated further in Figure 6-2. Note that the waveforms in Figure 6-1 and Figure 6-2 are similar with the only difference being that the waveform in Figure 6-2 shows absolute values, that is, the negative values in Figure 6-1 are displayed as positive values in Figure 6-2.

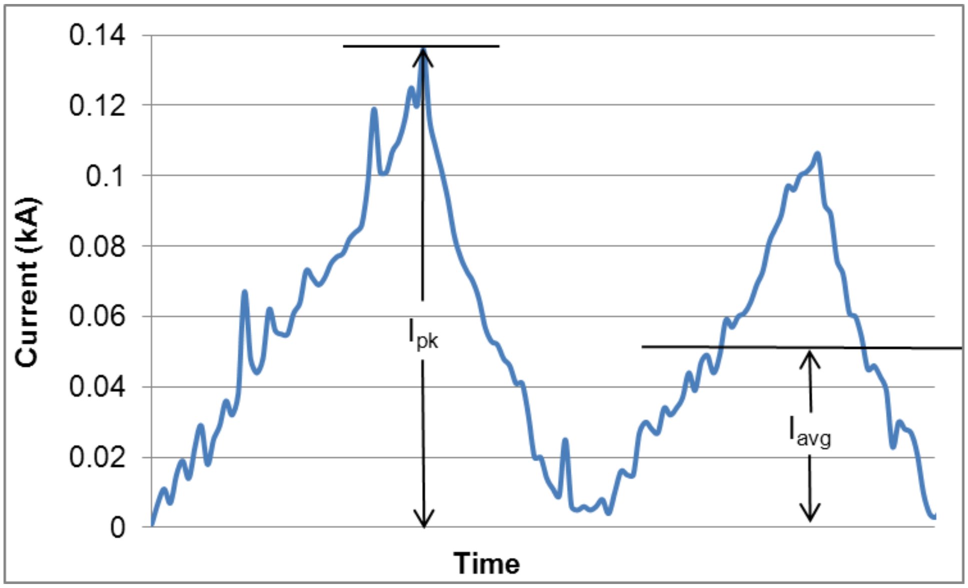

Figure 6-2: Absolute value of the waveform (Comp.1).

For a pure, undistorted sine wave the average is equal to I_{pk} x 0.637. I_{rms} can be derived by squaring every point in the waveform, finding the average value of the squares, then finding the square root of the average. With pure sine waves, a couple of shortcuts can be taken (i.e. $I_{rms} = I_{pk} \times 0.707$ or $I_{rms} = I_{avg} \times 1.111$). These scaling factors apply only to pure sine waves - for every other type of signal, using this approach produces incorrect answers. Inexpensive peak-responding or average-responding meters employ these scaling factors to calculate V_{rms} and, consequently, are inaccurate for waveforms that are not pure sine waves. Such a meter is not really designed for measuring distorted signals and can produce errors as high as 40% or more – depending on the meter and signal. Note, the average responding meters not always yield readings lower than the rms meter readings, when harmonics are present. In some cases harmonics can lead to unusual distortions of the waveform providing higher average responding meter readings.

Figure 6-3 shows a snapshot of 3 phase current waveforms measured at various locations in USA and Europe. All 4 of the shown locations have a distinguished shape depending on the different phase loading and harmonic distortion. Note that the magnitudes and fundamental frequencies of the measured currents are at different levels due to diversities in company profiles, locations, and times of measurements.

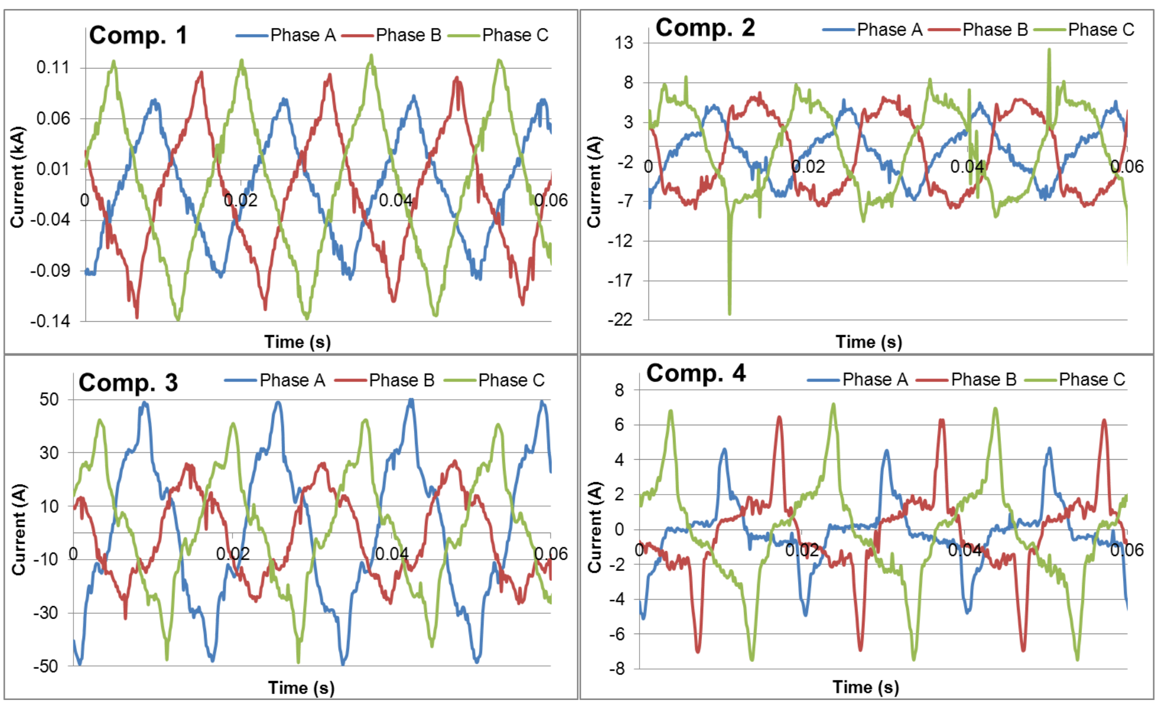

Figure 6-3: Snapshot of phase currents measured at different locations (Comp.1, Comp.2, Comp.3, and Comp.4).

The relative harmonic distortion, of the phase currents, normalized to the fundamental is shown in Figure 6-4.

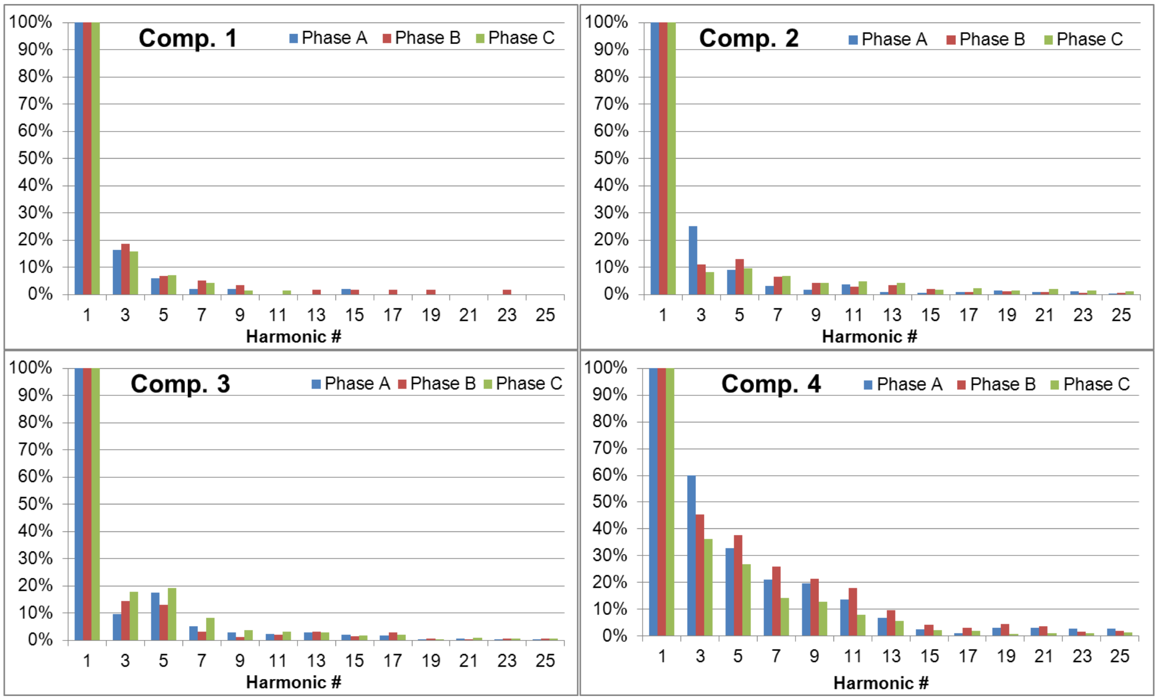

Figure 6-4: Harmonic spectra of the phase currents shown in Figure 6-3 (Comp.1, Comp.2, Comp.3, and Comp.4).

In order to evaluate the proposed approach of using two different ammeters to identify the presence of harmonic distortion we evaluated the waveforms, shown in Figure 6-3, using both principles described above (i.e., true rms and average responding). Table 6-1 summarizes the obtained results together with the relative difference of the two measurements.

Table 6-1: Summary of readings of an average responding ammeter, a true rms responding ammeter, and relative comparison of the readings from the two meters.

	Phase Current rms Measurements								
	Average responding (A)			True RMS Responding (A)			Difference (%)		
Location	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Comp.1	48.00	57.00	67.00	51.00	61.00	71.00	6.17	6.22	6.05
Comp.2	3.02	5.11	5.24	3.28	4.92	5.29	7.88	-3.95	0.96
Comp.3	26.92	15.86	19.71	27.47	15.65	21.59	2.02	-1.38	8.68
Comp.4	1.32	1.95	2.49	1.78	2.36	2.88	25.68	17.29	13.84

The readings for the Phase B currents at Comp.2 and Comp.3 sites revealed that despite the presence of harmonics, the average responding meter provided readings higher than the rms meter. That does not dispute the proposed approach, as mentioned above. It illustrates such a case when the waveform distortion has an unusual character leading to a higher average responding meter reading. In general, when the two used meters are showing significantly different readings the measured waveform is not a pure sine wave. Therefore, a distortion of some kind is present and additional investigating steps need to be taken.

In case only one true-rms responding meter is present, it can be used to perform the "crest factor" test in order to identify the presence of harmonics in the system. The crest factor (CF) of a waveform is the ratio of the peak value to the rms value (FC = I_{pk}/I_{rms}). For a sine wave, the crest factor is 1.414. In case the used meter has a "peak" function, the crest factor can be easily calculated. A crest factor other than 1.414 indicates a distortion of the measured waveform. Typically for single-phase cases, the greater the difference from 1.414, the higher the distortion. In case of voltage harmonics, the crest factor is usually below 1.414, which sometimes is referred to as "flat top". In case of current harmonics, the crest factor is usually higher than 1.414. Table 6-2 shows the crest factors for the current and voltage waveforms of the four locations mentioned above. As expected, all of the current crest factors are higher than 1.414 indicating presence of current harmonics. The crest factors calculated from the voltage waveforms are either very close to 1.414 or slightly higher, which leads to the conclusion the voltage harmonic distortion level is low.

Table 6-2: Summary of voltage and current crest factor calculations.

	Crest Factor					
	Voltage			Current		
Location	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Comp.1	1.413	1.406	1.413	1.85	1.98	1.92
Comp.2	1.409	1.417	1.418	2.18	1.60	3.34
Comp.3	1.437	1.438	1.437	1.86	1.90	2.18
Comp.4	1.410	1.403	1.405	2.81	3.02	2.59

6.2 Case study 2 – Neutral

Balanced zero-sequence harmonics (3^{rd}, 6^{th}, 9^{th}, 12^{th}, etc.) in a four wire, three-phase system add arithmetically in the neutral conductor. Therefore, by taking measurements of the neutral current with a true-rms responding ammeter could prove or dispute the presence of harmonics in the system.

The ability to estimate the expected current in the neutral conductor based on the rms values of the phase currents requires extensive knowledge of the system load. Additionally to the knowledge of the magnitude rms values the knowledge of the angle shifts between the individual phase currents is important. For example, based on the power factor of the single phase loads served from a three phase system the angle shift between the phase currents can deviate from the common 120 degrees, thus preventing cancelation of the phase currents in the neutral conductor. Balancing the phase load currents in a 208Y/120 volt three phase system (i.e., making load current magnitudes equal in each phase) will normally reduce neutral current to zero if load currents have an undistorted sinusoidal wave shape. However, the odd multiples of the 3rd harmonic will not cancel each other in the neutral.

Figure 6-5 shows a snapshot of the neutral current waveforms measured at various locations in USA and Europe. The corresponding harmonic distortions of the neutral current waveforms are shown in Figure 6-6. Table 6-3 summarizes the rms values of the neutral current measurements at the different locations.

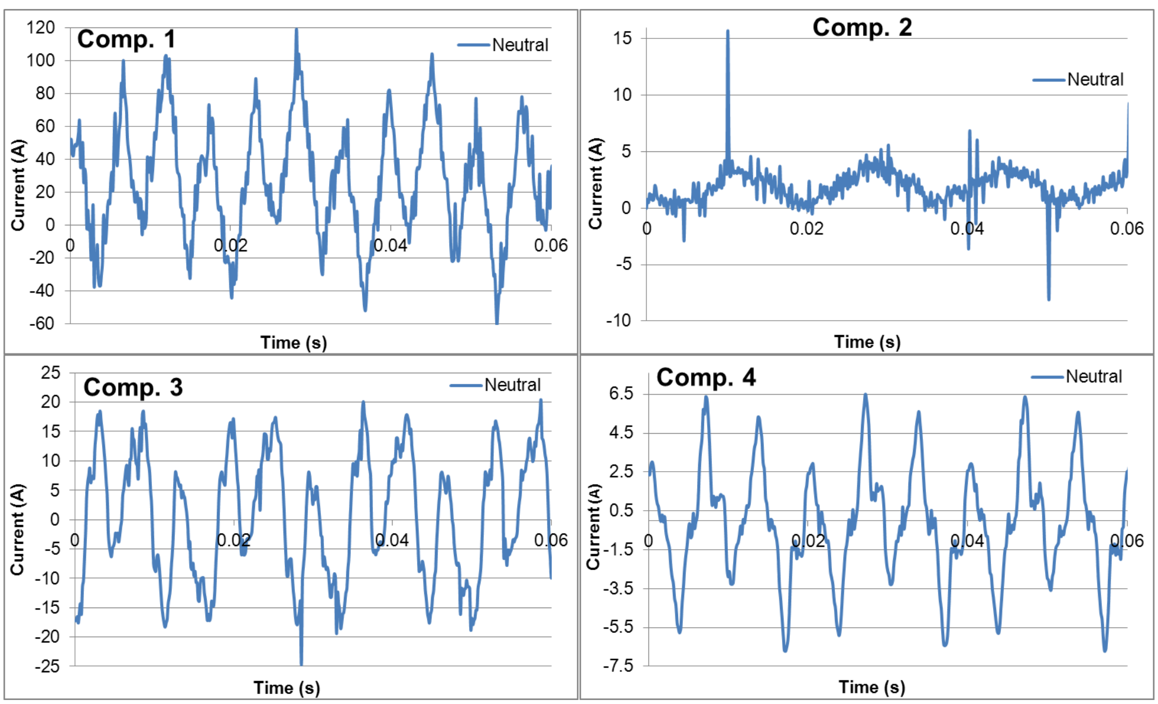

Figure 6-5: Currents in the neutral conductor measured at different locations in USA and Europe (Comp.1, Comp.2, Comp.3, and Comp.4).

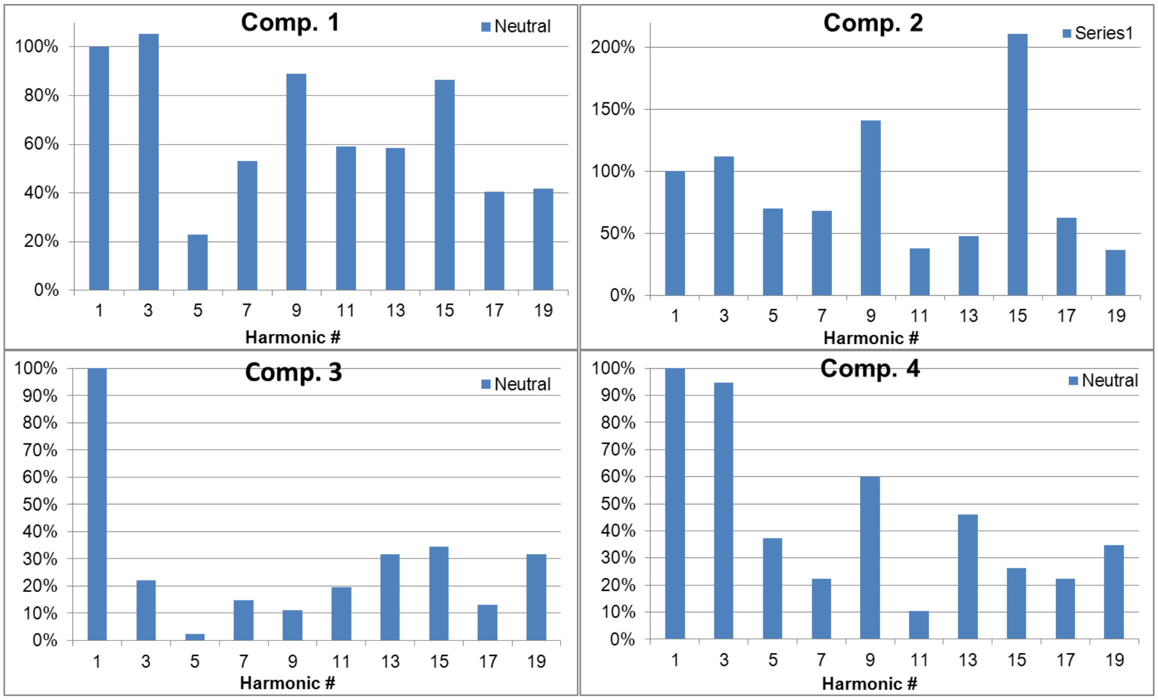

Figure 6-6: Harmonic spectra of the currents in the neutral conductor measured at different locations in USA and Europe (Comp.1, Comp.2, Comp.3, and Comp.4).

Assuming that no knowledge about the nature of the loads exists, an explicit conclusion about the presence of harmonics can only be made in case of Comp.4 measurements. This conclusion is made, based on the fact that the rms value of the neutral current is higher than any of the phase readings. However, when considering the harmonic spectra shown in Figure 6-6, it is clear that all four sites contain significant odd zero-sequence harmonics (i.e. 3rd, 9th, and 15th) in their neutral currents. At this point, a simple frequency measurement would help. A frequency of 60 Hz would suggest that the phases are out of balance, while higher frequencies would suggest a strong presence of harmonics. Therefore, any frequencies, of the neutral current, above 60 Hz combined with relatively high magnitude rms readings almost always imply high harmonic distortion.

Table 6-3: Summary of neutral current measurements.

Location	Neutral (A)	Phase A	Phase B	Phase C
Comp.1	36.00	51.00	61.00	71.00
Comp.2	2.58	3.28	4.92	5.29
Comp.3	10.56	27.47	15.65	21.59
Comp.4	2.91	1.78	2.36	2.88

Presence of zero-sequence harmonics can sometimes be detected by measuring the neutral-to-ground (N-E) voltage at the equipment. The neutral ground voltage is usually in the 0.20 V 0.30 V range at the panel, while the actual value depends on the distance to the transformer. According to NFPA 70B-10.2.4.3, any rms reading above 2 V should be noted, and can be used as an indicator for the presence of excessive harmonic distortion levels.

Figure 6-7 shows snapshots of the neutral-to-ground voltage waveforms measured at various locations in USA and Europe.

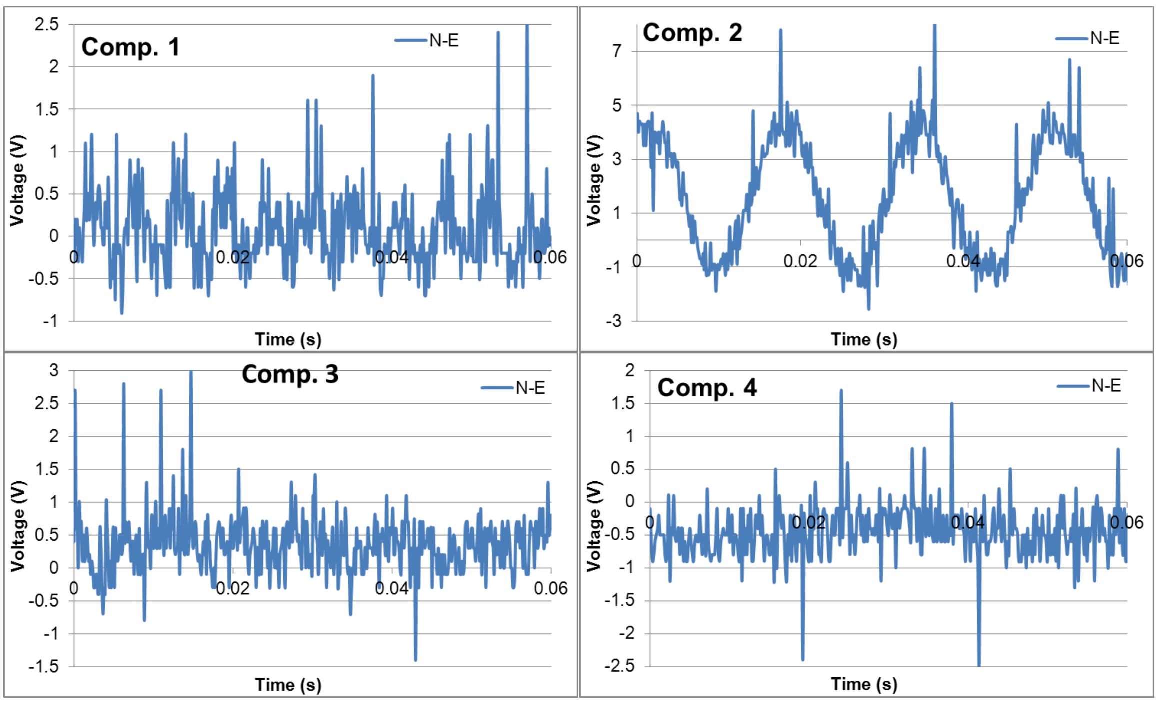

Figure 6-7: Neutral-to-ground voltages measured at different locations in USA and Europe (Comp.1, Comp.2, Comp.3, and Comp.4).

Table 6-4 shows the rms values of the neutral-to-ground votlage measuremtns. Here it is interesting to note that only Comp.2 site is showing N-E rms values higher than 2 V, which could be attributed to an number of factors (e.g., quality of connectors, length of the run, etc.). The remaining three sites have their N-E rms values in the range of 0.5 V to 0.6 V. This leads to the conslusion that any N-E rms reading above 0.5 V should result in further investigations.

Table 6-4: Neutral-to-ground rms values for the different locations.

Location	N-E rms (V)
Comp. 1	0.53
Comp. 2	2.61

Comp. 3	0.57
Comp. 4	0.57

Figure 6-8 shows an example where N-E rms readings are significantly above the 2 V mark. However, the corresponding neutral current is relatively small, as is shown in Figure 6-9. The corresponding N-E rms reading and neutral current rms reading are summarized in Table 6-5.

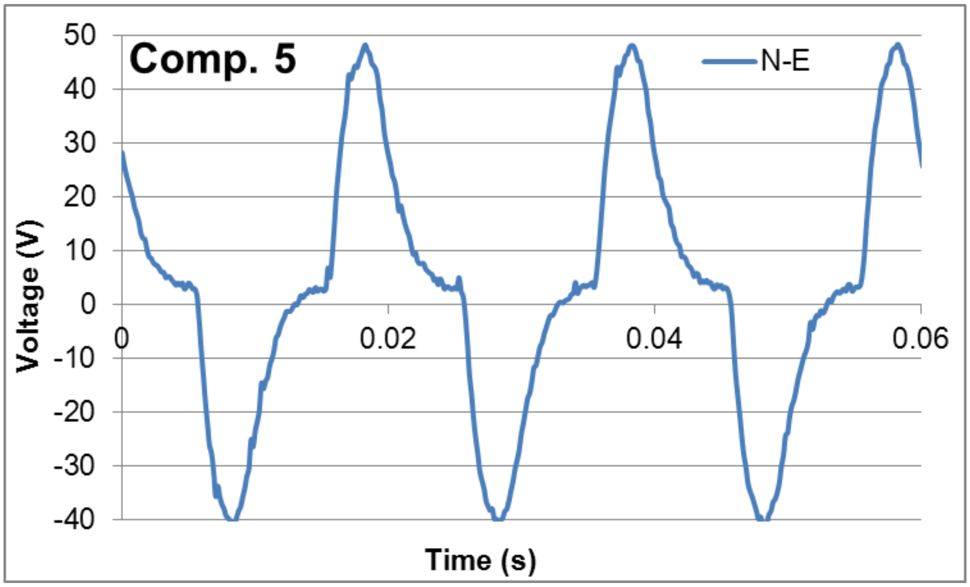

Figure 6-8: Neutral-to-ground voltage measured at Comp.5.

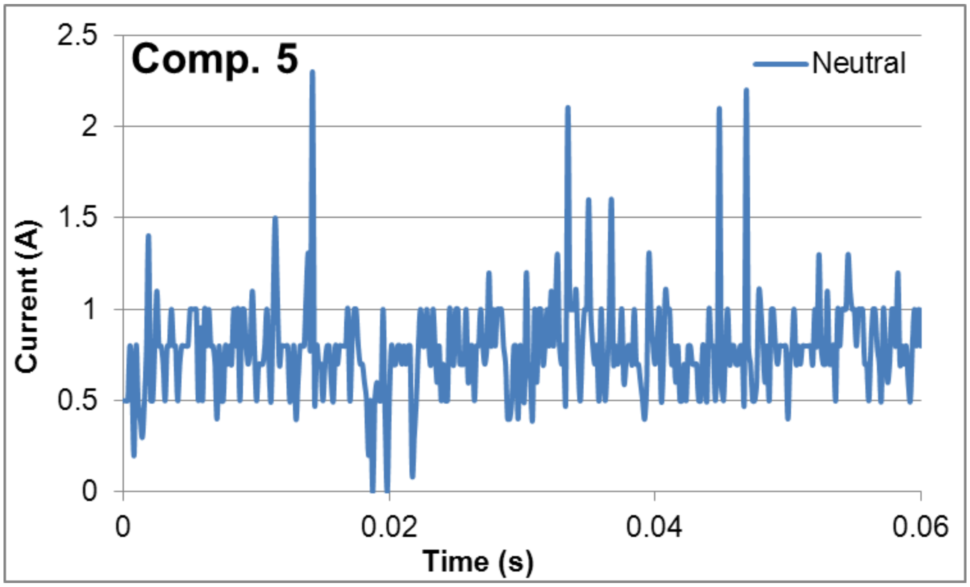

Figure 6-9: Current in the neutral conductor measured at Comp.5.

It is obvious that at 24.58 V rms, the N-E voltage has an origin others that just the harmonic distortion in the phase currents. Therefore, in this case it would be misleading to entirely rely on the N-E rms reading in order to prove or dispute the presence of harmonics.

Table 6-5: Neutral-to-ground voltage rms and neutral current rms at Comp.5 site.

Location	N-E rms (V)	Neutral rms (A)
Comp. 5	24.58	0.785

However, if considering the relative amplitudes of the harmonic spectra of the phase currents it becomes obvious there are significant power quality issues in this system (Figure 6-10).

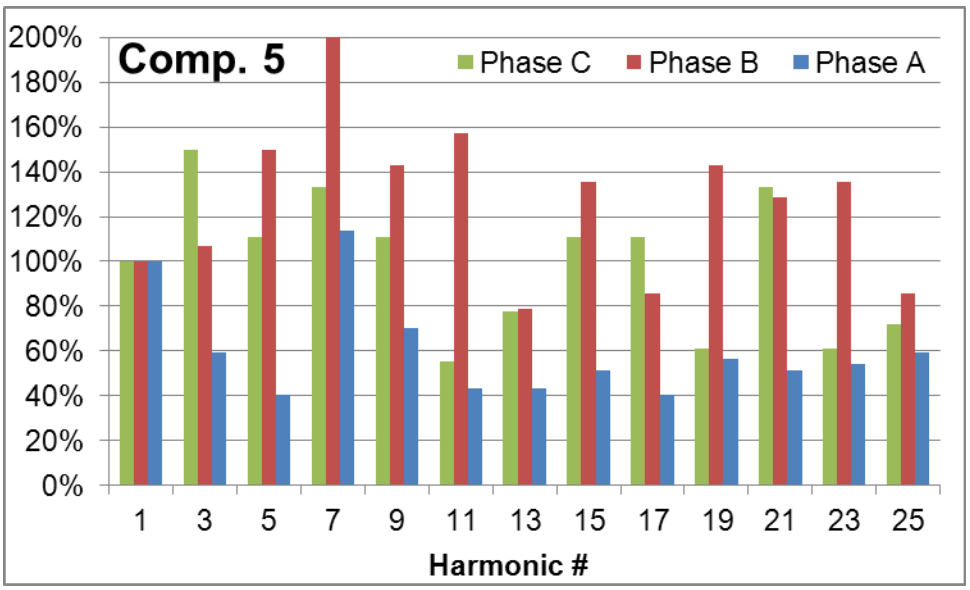

Figure 6-10: Harmonic spectra of the current in the neutral conductor measured at Comp.5.

In our example, we determined that significant harmonics are present, which warrants a more in-depth analysis of the situation by, for instance, employing harmonic analyzers.

6.3 Case study 3 – Power Quality Analyzer

It is important to note that harmonic values will often change during the day, or the time of the year, as different loads are turned on and off within the facility, or in other facilities on the same electric utility distribution system. A power quality monitor can record the harmonic values over a period of time for a more in-depth system analysis. The phase voltages and currents, real and reactive powers, total harmonic distortion for phase voltages and total demand distortion for phase currents as well as the neutral-to-ground voltage and neutral current should be monitored. Figure 6-11 shows a collection of such measurements over an extended time period. In this case, the shown data were collected over a period of one week (March 14, 2011 – March 21, 2011) with samples taken every 5 minutes. Figure 6-12 shows the neutral current readings of the same power quality device - instantaneous values of the neutral current are shown on the right, the rms values of the neutral current are shown on the left).

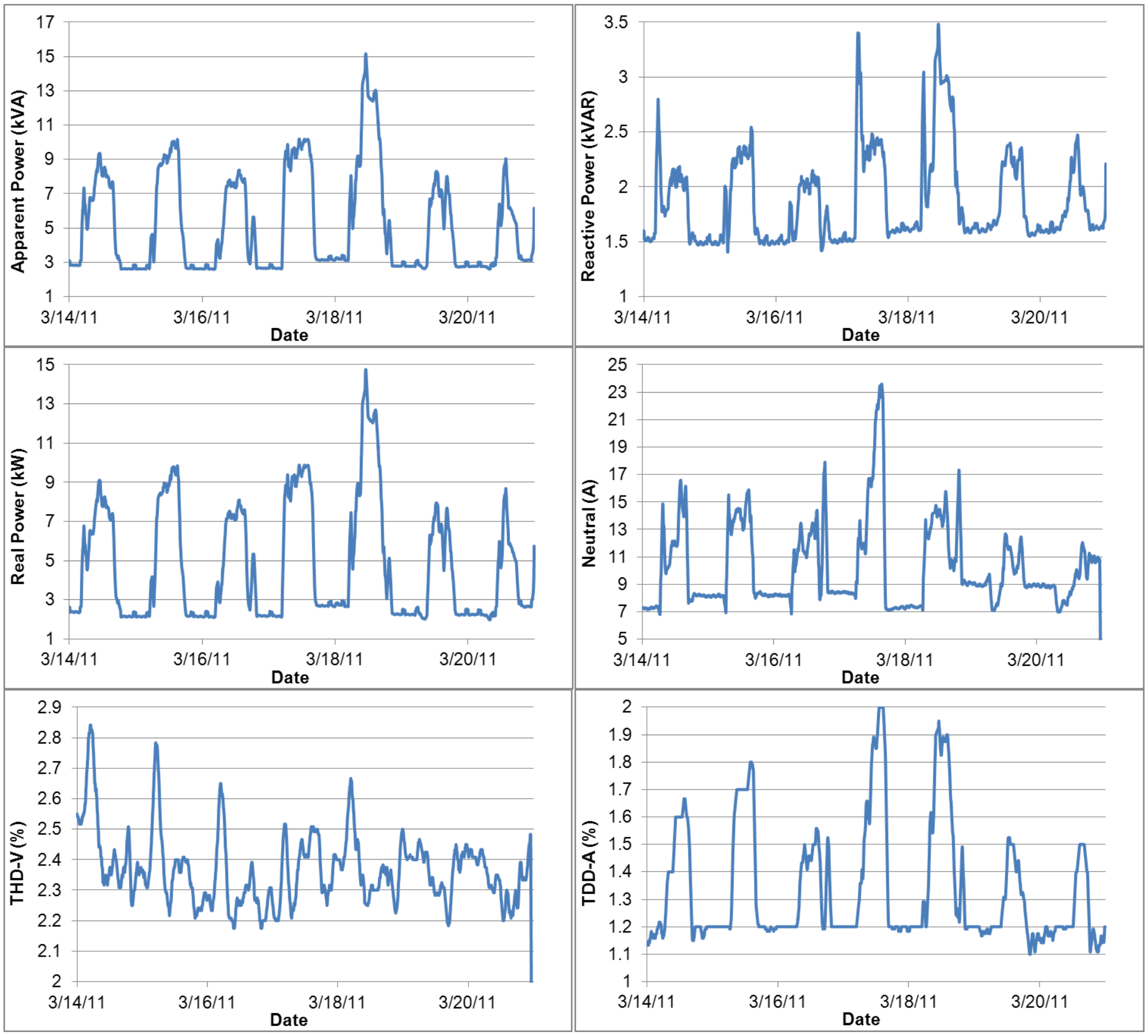

Figure 6-11: Summary of the data collected by a power quality device at Comp.3 site over a period of 7 days.

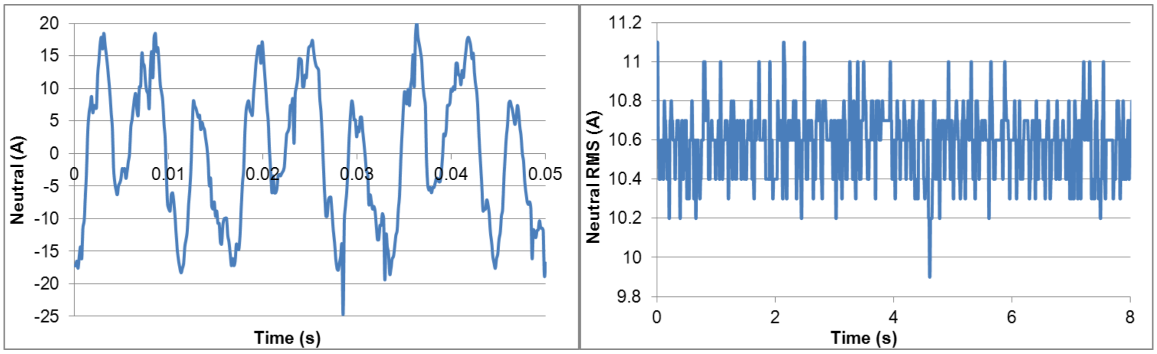

Figure 6-12: Summary of high resolution data (left-130 µs instantaneous values, right-8 ms rms values) measured at Comp.3.

The in-depth systems analysis can be initiated by observing the changes in load, harmonic distortion, and their relationship over a complete load cycle (e.g., 24h week day for a commercial/industrial facility). Figure 6-13 shows phase currents (H1) and harmonics (H3, H5, H7, H9) from Comp. 6 measured for the duration of an entire day. The individual harmonic currents in percent of the instantaneous fundamental current are shown in Figure 6-14. It can be seen that during night hours the harmonics are relatively high normalized to instantaneous phase currents. On the other hand, during the day hours (operating hours) the relative relationship between instantaneous phase current and harmonic currents is small. As mentioned in Section 2.3 a high distortion value for input current may not be of significant concern if the load is light, since the magnitude of the harmonic current is low, even though its relative distortion to the fundamental frequency is high.

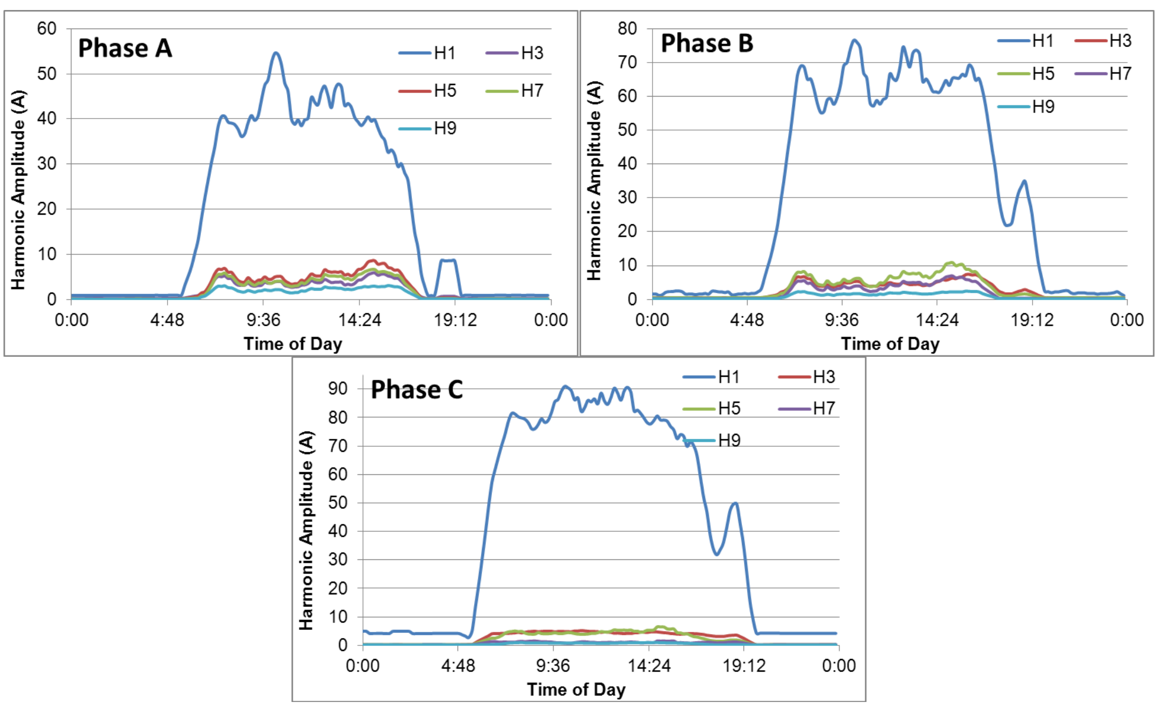

Figure 6-13: 3 Phase current harmonics distribution throughout the day at Comp. 6

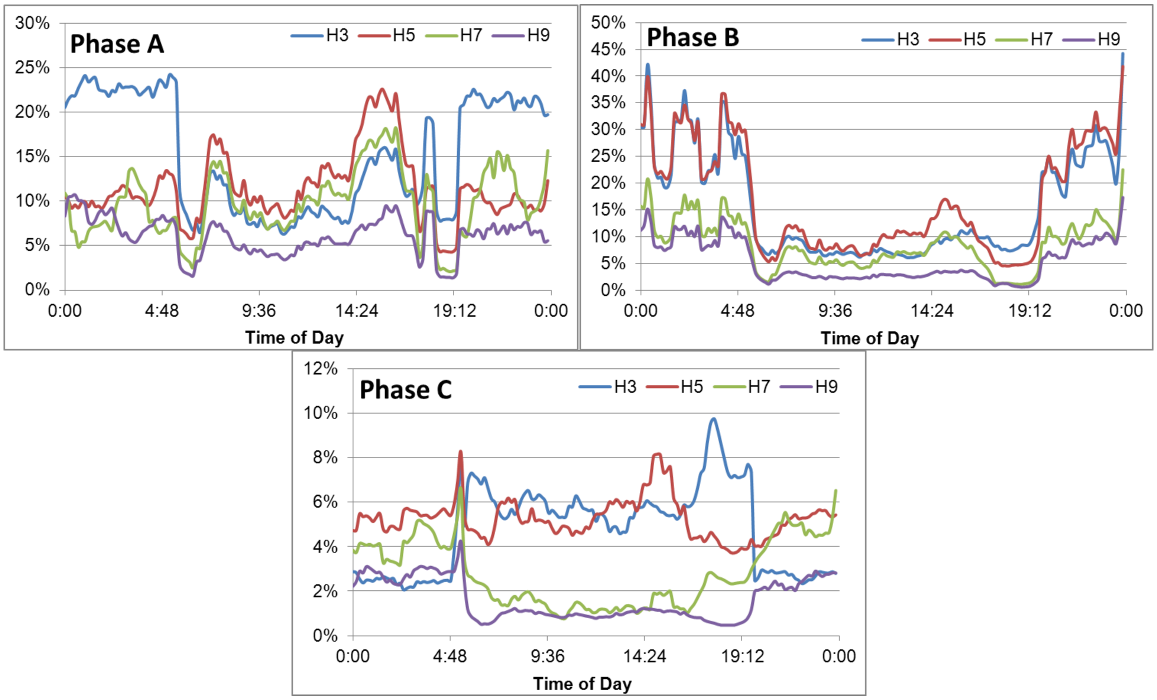

Figure 6-14: 3 Phase current harmonics relative distribution throughout the day at Comp. 6

Monitoring the total demand distortion (see Section 2.3) over an extended time period can provide insight to the harmonic distortion, relative to rated demand. The harmonic analyzer used to collect data sets, present in this report was programed to record the total demand distortion (TDD) for all phase currents, combined and individually. Moreover, the same analyzer also recorded the combined and individual total harmonic distortion (THD) for the phase voltages. Figure 6-15 shows the combined total demand distortion of the phase currents measured at Comp.6 throughout a 24 h period. The combined total harmonic distortion of the phase voltages is shown in Figure 6-16. It is important to avoid quick conclusions on harmonic distortion based on limited data. Therefore, before making any decisions to mitigate the distortion, it is important to consider and review an extensive compilation of power quality data sets.

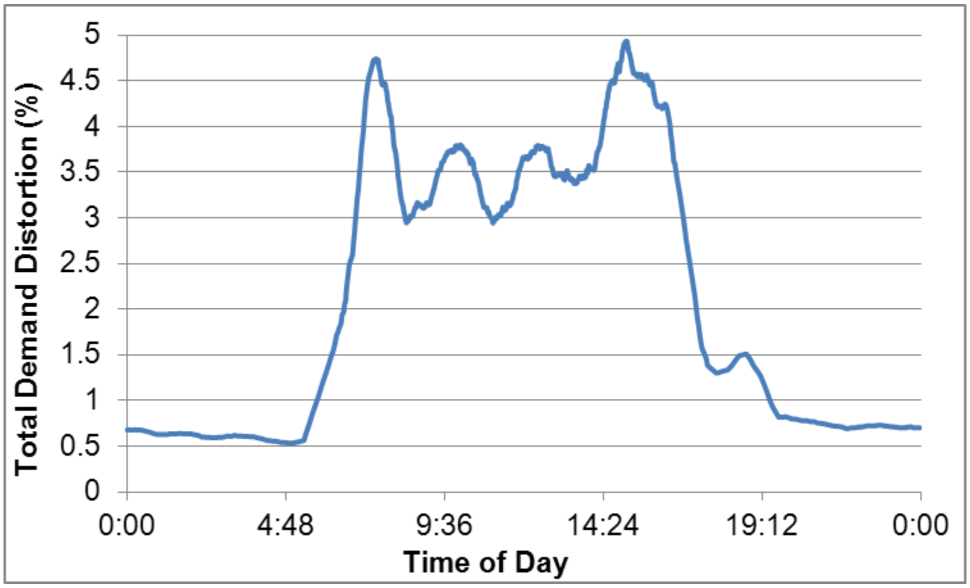

Figure 6-15: Combined total demand distortion of the phase currents for an entire day at Comp.6.

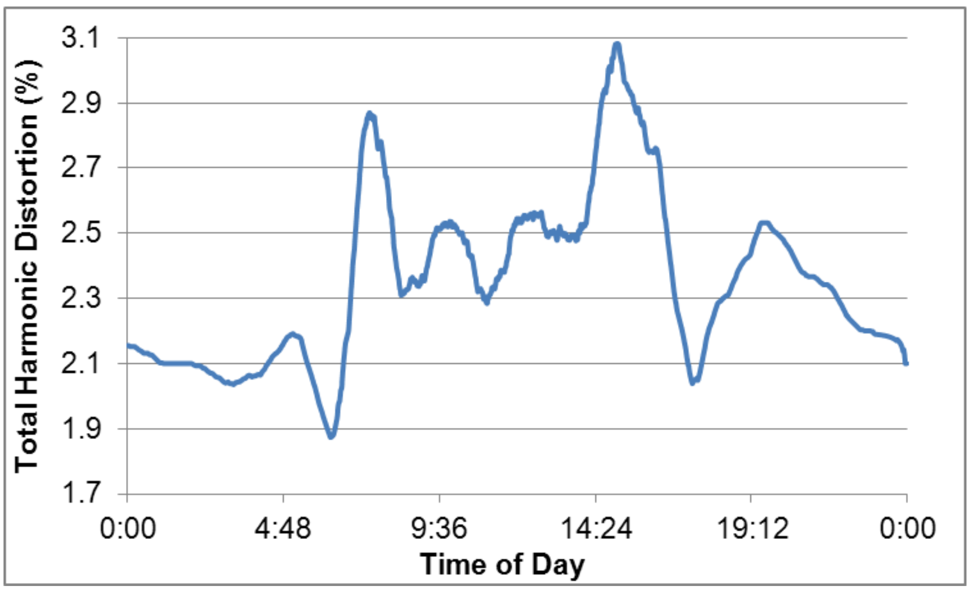

Figure 6-16: Combined total harmonic distortion of the phase voltages for an entire day at Comp.6.

Correlating measured parameters can provide some additional insight. For instance, Figure 6-17 shows the TDD as a function of apparent power (kVA) measured at Comp. 6. The figure shows how the TDD changes with the loading of the system and questions like ”How serious is the harmonic distortion when operating at rated load” and “Which loads provide most distortion?”, etc. can be answered.

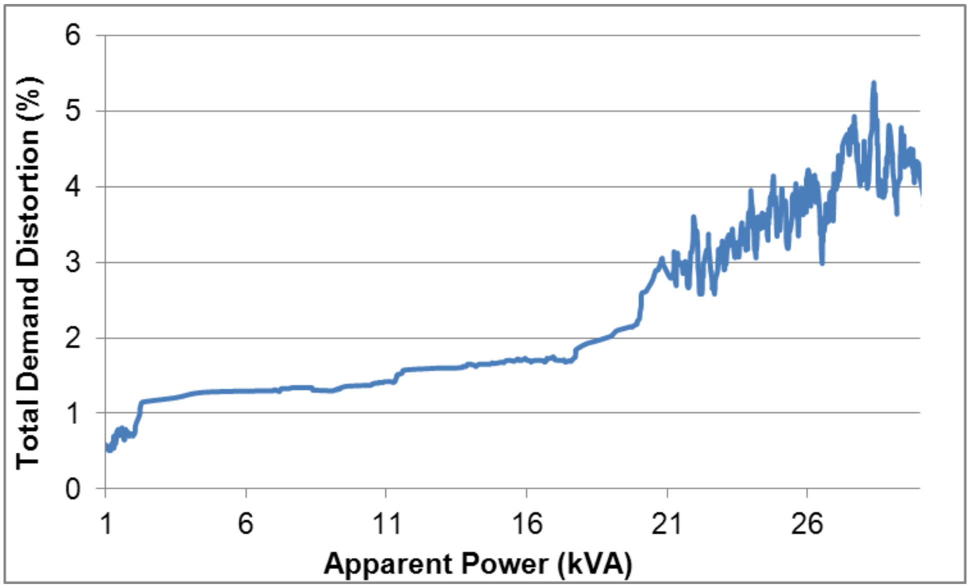

Figure 6-17: Total demand distribution as a function of apparent power at Comp. 6

To provide a small summary of the TDD readings collected for this project, Figure 6-18 shows the TDD as a function of apparent power (kVA) measured at various locations in USA and Europe. The TDD data set recorded at Comp.2 is the only one maintaining a constant level over the measured period. This is due to the fact that the provided apparent power had increased merely by one kVA over the same period of time, leading to small changes in instantaneous phase currents.

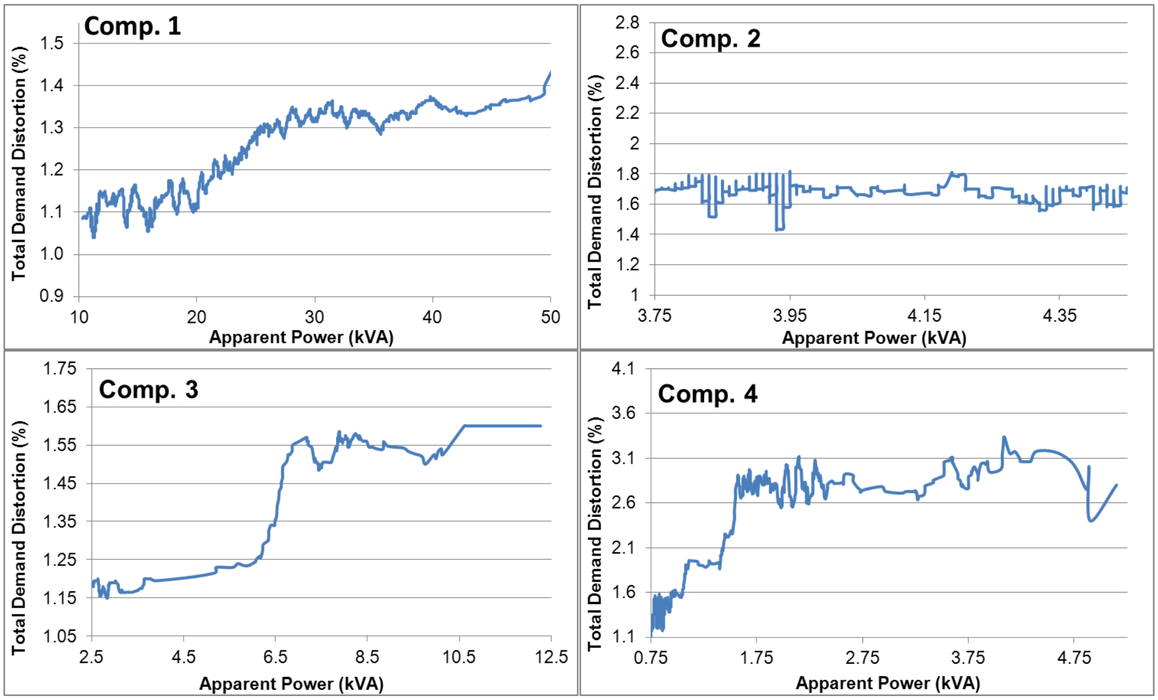

Figure 6-18: Total demand distribution as a function of apparent power (Comp. 1, Comp. 2, Comp. 3, Comp. 4)

6.4 Case study 4 – Derating

There are numerous ways to address some typical harmonic problem in a power system. In case of overloaded neutrals in a three-phase, four-wire system, the 60Hz portion of the neutral current can be minimized by balancing the loads in each phase. The zero sequence harmonics caused neutral currents can be reduced by adding harmonic filters. Moreover, additional neutral wires can be installed (e.g. one neutral for each phase) or the existing neutral can be replaced by an oversized wire to be shared by all three phases.

One way to protect a transformer from harmonics is to size it so that the transformer rating exceeds the maximum amount of power-frequency load placed on it, which is called "derating". One of the most common derating methods is described in ANSI/IEEE standard C57.110-2008. The standard defines the harmonic loss factor for winding eddy currents (F_{HL}) as, "a proportionality factor applied to the winding eddy losses, which represent the effective rms heating as a result of the harmonic load current. F_{HL} is the ratio of the total winding eddy current losses due to the harmonics, (P_{EC}), to the winding eddy current losses at the power frequency, when no harmonic currents exist (P_{EC-O})". Moreover, the same standard defines the harmonic loss factor for other stray losses (FHL-STR) as, losses that "can have a substantial effect on liquid-filled transformers, by causing additional heating of the cooling liquid". Equations (6.1) and (6.2), given in IEEE Std. C57.110-2008, define the two harmonic loss factors as follows:

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2 h^2}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2 h^2}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2} \tag{6.1}$$

where

F_{HL}	is the harmonic loss factor for winding eddy currents
h	is the harmonic order
h_{max}	is the highest significant harmonic number
I_h	is the rms current at harmonic "h" (amperes)
I	is the rms load current (amperes)
I_1	is the rms fundamental load current (amperes)

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2} \qquad (6.2)$$

where

$F_{HL\text{-}STR}$ is the harmonic loss factor for other stray losses

h is the harmonic order

h_{max} is the highest significant harmonic number

I_h is the rms current at harmonic "h" (amperes)

I is the rms load current (amperes)

I_1 is the rms fundamental load current (amperes)

Harmonic loss factors can be calculated in terms of the harmonics normalized to the total rms current (I) or to the first or fundamental harmonic (I_1).

The per-unit value of nonsinusoidal load current that will make the result of the per-unit load loss calculation equal to the design value of loss density in the highest loss region for rated frequency and for rated current operation is given by:

$$I_{max}(pu) = \sqrt{\frac{P_{LL-R}(pu)}{1 + F_{HL} \cdot P_{EC-R}(pu)}} \qquad (6.3)$$

where

$I_{max}(pu)$ is the max permissible rms nonsinusoidal load current under rated conditions

$P_{LL\text{-}R}(pu)$ is the per-unit load loss under rated conditions

F_{HL} is the harmonic loss factor for winding eddy currents

$P_{EC\text{-}R}(pu)$ is the per-unit winding eddy-current loss under rated conditions

In other words, the equation above provides the maximum permissible per-unit nonsinusoidal load current with a given harmonic composition. However, it is somewhat impractical because it requires extensive loss data from the transformer manufacturer plus a complete harmonic spectrum of the load current.

The per-unit load loss under rated conditions required in equation (6.4) is given in the IEEE Std. 57-110-2008 as:

$$P_{LL\text{-}R}(pu) = 1 + P_{EC\text{-}R}(pu) + P_{OSL\text{-}R}(pu) \tag{6.4}$$

where

$P_{LL\text{-}R}(pu)$ is the per-unit load loss under rated conditions

$P_{EC\text{-}R}(pu)$ is the per-unit winding eddy-current loss under rated conditions

$P_{OSL\text{-}R}(pu)$ is the per-unit other stray loss under rated conditions

Following is an example that illustrates the use of the equations (6.1-6.4). Note that the example was obtained from IEEE Std. C57.110-2008. However the transformer and load data were adjusted based on the measurements from the Comp.3 site:

Given a nonsinusoidal load current with the following harmonic distortion, determine the maximum load current that can be continuously drawn (under standard conditions) from an IEEE standard dry-type transformer having a rated full load current of 400A and whose winding eddy-current loss under rated conditions ($P_{EC\text{-}R}$) at the point of maximum loss density is 15% of the local I^2R loss. Table 6-6 shows the tabulated calculation of the harmonic loss factor (F_{HL})

Table 6-6: Tabulated calculation of the harmonic loss factor (F_{HL}) at Comp.5.

h	$\frac{I_h}{I_1}$	$\left(\frac{I_h}{I_1}\right)^2$	h^2	$\left(\frac{I_h}{I_1}\right)^2 h^2$
1	1.0	1.0	1	1.0
3	0.097	0.00934	9	0.08403
5	0.175	0.03077	25	0.76913
7	0.051	0.00261	49	0.12812
9	0.028	0.00081	81	0.06544
11	0.023	0.00055	121	0.06636
13	0.028	0.00079	169	0.13368
15	0.019	0.00038	225	0.08520
17	0.017	0.00029	289	0.08237
19	0.00303	0.0000092	361	0.00330
∑		1.05		2.52

From equation (6.1) the harmonic loss factor becomes:

$$F_{HL} = \frac{2.52}{1.05} = 2.39$$

From equation (6.4), the per-unit load loss under rated conditions, with the simplification that no other stray losses besides the winding eddy-current losses are present, becomes:

$$P_{LL\text{-}R}(pu) = 1 + 0.15 = 1.15$$

Leading to the maximum permissible per-unit nonsinusoidal load current with the given harmonic compensation, from equation (6.3):

$$I_{max}(pu) = \sqrt{\frac{1.15}{1 + 2.39 \cdot 0.15}} = 0.92$$

$$I_{max} = 0.92 \text{ x } 400 = 368 \text{ A}$$

With the given nonsinusoidal load current harmonic composition, the transformer capability is approximately 92% of its sinusoidal load current capability, or 368 A.

Figure 6-19 shows the maximum permissible per-unit nonsinusoidal load current with the given harmonic compensation based on the data form Comp. 6 site over a period of 24 hours. In our example, throughout the day I_{max} (pu) varies between 85% and 99%. Higher permissible nonsinusoidal load current is observed during the day hours (operation hours), when the power consumption is close to its rated value. Therefore, a decision to derate a transformer based on this method should be made after consideration of various load conditions (e.g. rated condition).

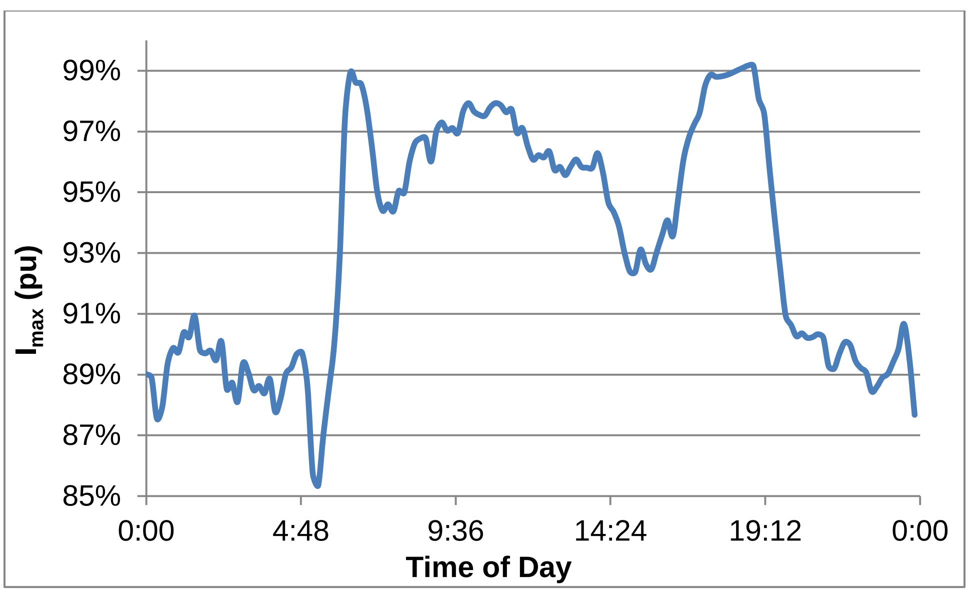

Figure 6-19: Maximum permissible per-unit nonsinusoidal load current with the given harmonic compensation based on the data form Comp. 6.

Another form of transformer protection is by using the widely recognized rating method called K-factor. The K-factor indicates the suitability of the transformer for non-sinusoidal load currents. “K-rated” transformers are optimized to better withstand harmonics, mechanical stress damage and overheating. K-rated transformers have the following features: (Wakileh, 2001)

- They have lower than normal flux densities and can; thus, tolerate over-voltages coupled with circulating harmonic currents.
- They employ an electromagnetic shield between the primary and secondary windings of each coil, thus attenuating higher frequency harmonics.
- They provide a neutral with twice the size of a phase conductor, to account for increased neutral current due to flow of zero-sequence harmonics.
- Windings are designed with several smaller sizes parallel conductors, therefore reducing skin effect at higher frequency harmonics.
- They use insulated and transposed conductors resulting in reduced losses.

It is widely known that harmonic distortion can generate additional heat, which can decrease the lifetime of a transformer. As noted above the K-rated transformers are specially designed to manage distorted waveforms and have lower eddy current losses. On the other side, derating of a common transformer is a simple oversizing leading to dissipation of the harmonic caused heat. However, a K-factor transformer may cost approximately twice as much as a standard transformer and weigh 115% more than a standard transformer.

The K-factor may be universally applied to all sizes of transformers and is defined on a per unit basis as follows:

$$\mathrm{K-factor} = \sum_{h=1}^{h_{max}} \left(I_{h(pu)}^2 \cdot h^2 \right) = \sum_{h=1}^{h_{max}} \left[\frac{I_h}{I_R} \right]^2 h^2 \qquad (6.5)$$

where

I_h(pu) is the RMS current at harmonic h, in per unit of transformer’s rms rated load current

h is the harmonic order

I_h is the rms current at harmonic “h” (amperes)

I_R is the rms fundamental current under rated frequency and rated load conditions (amperes)

According to IEEE Standard C57.110.2008, "the numerical value of the K-factor equals the numerical value of the harmonic loss factor only when the square root of the sum of the harmonic currents squared equals the rated secondary current of the transformer."

Following is an example that illustrates the use of the equation (6.5).

Given a nonsinusoidal load current with the following harmonic distortion, determine the maximum load current that can be continuously drawn (under standard conditions) from an IEEE standard dry-type transformer having a rated full load current of 400A. Table 6-7 shows the tabulated calculation of the K-factor.

Table 6-7: Tabulated calculation of the K-factor at Comp.5.

h	$\frac{I_h}{I_R}$	$\left(\frac{I_h}{I_R}\right)^2$	h^2	$\left(\frac{I_h}{I_R}\right)^2 h^2$
1	0.157	0.025	1	0.025
3	0.021	0.00045	9	0.00403
5	0.027	0.00071	25	0.01774
7	0.009	0.000079	49	0.00388
9	0.004	0.000018	81	0.00146
11	0.004	0.000016	121	0.00190
13	0.005	0.000021	169	0.00353
15	0.003	0.0000078	225	0.00175
17	0.003	0.0000103	289	0.00299
19	0.001	0.00000029	361	0.00011
∑				0.06

From the fifth column follows:

K-factor = 0.06

How to interpret the number above? K-rated transformers have associated K-factor ratings, which range between 1 and 50. The higher the K-factor, the more heat from harmonic currents can be handled. A standard transformer designed for linear loads is said to have a K-factor of 1, whereas a transformer with a K-factor of 50 is designed for the harshest harmonic distorted environment. The cost of a transformer increase with the K-factor, which makes transformers rated with K-factor of 50 extremely expensive and rare. Table 6-8 shows a short overview of K-factor ratings based on the percentage of the non-linear load.

Table 6-8: Short overview of K-factor ratings.

Level of Distortion	K-factor
Harmonic current producing equipment < 15%	K-1
Harmonic current producing equipment < 35%	K-4
Harmonic current producing equipment < 75%	K-13
Harmonic current producing equipment < 100%	K-20

Figure 6-20 shows the K-factor for the given harmonic compensation based on the data form Comp. 6 site over a period of 24 hours. It is clearly to see that throughout the day K-factor varies between 0 and 1.8, in this case. Higher K-factor is observed during the day hours (operation hours), when the power consumption is close to its rated value. Therefore, a decision to derate a transformer based on this method should be made after consideration of various load conditions (e.g., rated condition).

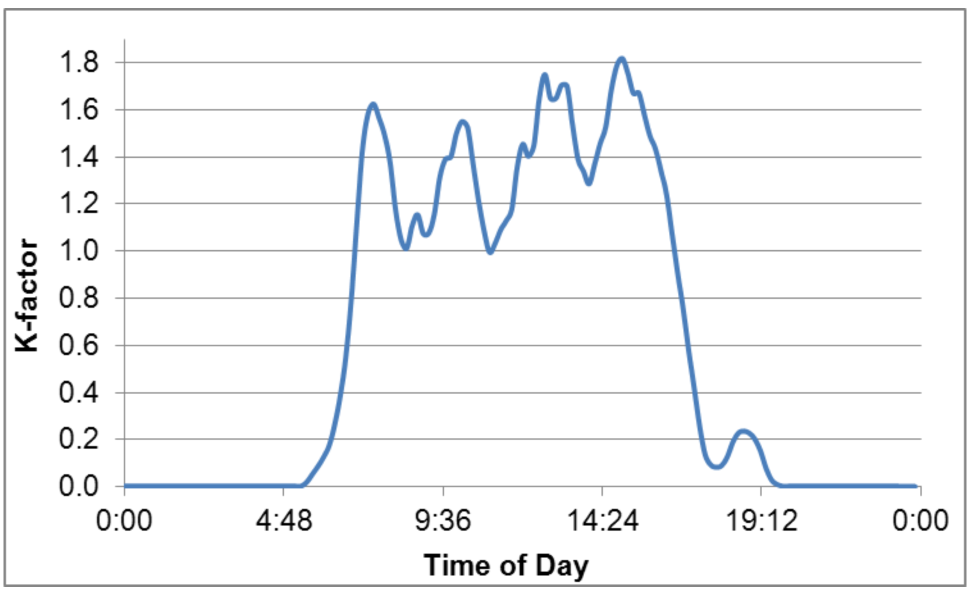

Figure 6-20: K-factor for the given harmonic compensation based on the data form Comp.6.

A rather simple method is recommended by the Computer & Business Equipment Manufacturers Association. It involves several straightforward measurements that can be done with commonly available test equipment. It has been noted in the literature and electric test equipment application notes to give reasonable results for 208/120 V receptacle transformers. Following equation shows the proposed harmonic derating factor (HDF):

$$\mathrm{HDF} = 1.414\frac{\mathrm{I_{rms}}}{\mathrm{I_{peak}}} \tag{6.6}$$

where

I_{rms} is the true-rms phase current

I_{peak} is the instantaneous peak phase current

This equation generates a value between 0 and 1. In case the phase current is purely sinusoidal, I_{peak} would be 1.414 times I_{rms} leading to a unity HDF. In this case no transformer derating would be required.

Following is an example that illustrates the use of the equation (6.6) using measurements from Table 6-9.

Table 6-9: Current readings measured at Comp.6.

Phase	True-RMS (A)	Instantaneous Peak (A)
A	27.47	51.00
B	15.65	29.70
C	21.59	46.95
3 Phase Average	21.57	42.55

From equation (6.6) the harmonic derating factor becomes:

$$\mathrm{HDF} = 1.414\frac{21.57}{42.55} = 71.7\%$$

The results indicate that with the level of harmonics present the transformer should be derated to 71.7% of its rating to prevent overheating.

Figure 6-21 shows the harmonic derating factor based on the data form Comp.3 site over a period of 7 days. In this example, throughout the week HDF varies between 23% and 98%. Therefore, a decision to derate a transformer based on this method should be made after consideration of various load conditions (e.g. rated condition)

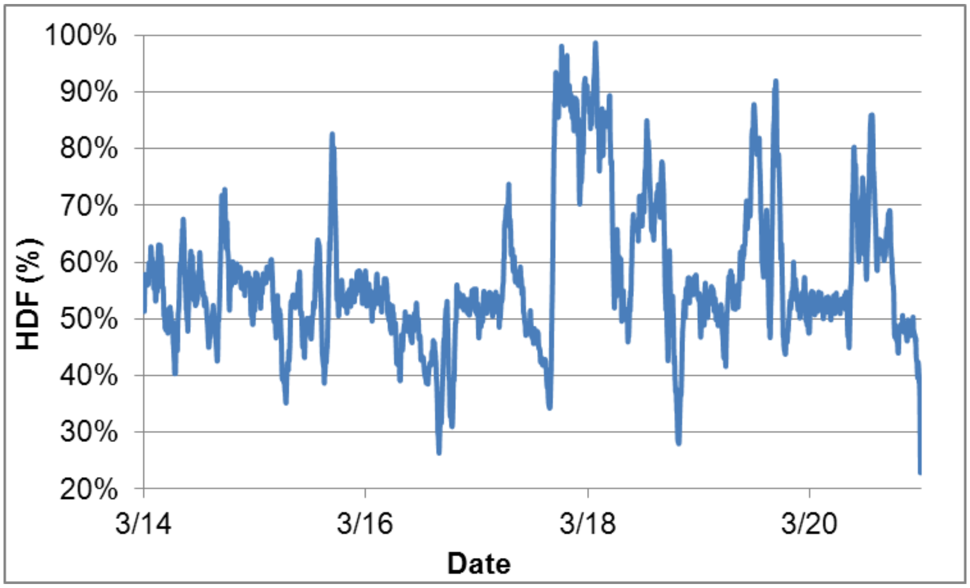

Figure 6-21: Harmonic derating factor based on the data form Comp.3.

7 Review of Applicability of NEC and NFPA 70B

7.1 Recommended Changes, Content

7.1.1 210.19(A) Informational Note

CURRENT CONTENT:

210.19(A) Informational Note No. 4:

> Informational Note No. 4: Conductors for branch circuits as defined in Article 100, sized to prevent a voltage drop exceeding 3 percent at the farthest outlet of power, heating, and lighting loads, or combinations of such loads, and where the maximum total voltage drop on both feeders and branch circuits to the farthest outlet does not exceed 5 percent, provide reasonable efficiency of operation. See Informational Note No. 2 of 215.2(A)(3) for voltage drop on feeder conductors.

RECOMMENDATION: Add Informational Note No. 5 in 210.19(A):

“Where the major portion of the load consists of nonlinear loads, harmonics currents may increase the resistivity of the conductor leading to higher voltage drops”

SUBSTANTIATION: High harmonic penetration might cause temperature increase in the conductor, which increases the resistance and the voltage drop (Sankaran 2002 and De La Rosa 2006).

7.1.2 215.2(A) Informational Note

CURRENT CONTENT:

215.2(A)(4)Informational Note No.2:

(4) Individual Dwelling Unit or Mobile Home Conductors. Feeder conductors for individual dwelling units or mobile homes need not be larger than service conductors. Paragraph 310.15(B)(6) shall be permitted to be used for conductor size.

Informational Note No. 1: See Examples D1 through D11 in Informative Annex D.

Informational Note No. 2: Conductors for feeders as defined in Article 100, sized to prevent a voltage drop exceeding 3 percent at the farthest outlet of power, heating, and lighting loads, or combinations of such loads, and where the maximum total voltage drop on both feeders and branch circuits to the farthest outlet does not exceed 5 percent, will provide reasonable efficiency of operation.

Informational Note No. 3: See 210.19(A), Informational Note No. 4, for voltage drop for branch circuits.

RECOMMENDATION: Add Informational Note No. 4 in 215.2(A)(4):

"Where the major portion of the load consists of nonlinear loads, harmonics currents may increase the resistivity of the conductor leading to higher voltage drops"

SUBSTANTIATION: High harmonic penetration might cause temperature increase in the conductor, which increases the resistance and the voltage drop (Sankaran 2002 and De La Rosa 2006).

7.1.3 NEC 310.15(B)(5)(a)

CURRENT CONTENT:

(a) A neutral conductor that carries only the unbalanced current from other conductors of the same circuit shall not be required to be counted when applying the provisions of 310.15(B)(3)(a).

RECOMMENDATION: Make the following change "… that carries only the unbalanced current from other conductors and that is in the same raceway or cable as the phase conductors of … ".

SUBSTANTIATION: We agree with this statement in the context of determining the number of current carrying conductors for determining the ambient temperature adjustment factor if all three phases and the neutral are in the same raceway. We think that the rationale is that the ambient temperature is essentially the same if (1) the phases carry the full rated current and (2) one of the phases carries less-than-rated current and the difference flows through the neutral (due to the imbalance). However, if the phase conductors and the neutral conductor are in different raceways, the neutral conductor should be considered current-carrying as the heat due to the neutral current will add to the ambient temperature. In practice, this seems to be an unlikely scenario and we do not feel strongly about implementing this recommended change.

7.1.4 NEC 310.15(B)(5)(c)

CURRENT CONTENT:

> (c) On a 4-wire, 3-phase wye circuit where the major portion of the load consists of nonlinear loads, harmonic currents are present in the neutral conductor; the neutral conductor shall therefore be considered a current-carrying conductor.

RECOMMENDATION: Conduct a study to determine appropriate harmonic limits for which the neutral has to be considered a current-carrying conductor and include the limits determined in the study in the NEC.

SUBSTANTIATION: The criterion regarding when to consider the neutral as a current-carrying conductor is somewhat vague (at what point does a major portion of the load consists of nonlinear loads?). See Section 4.1 of this report. This issue has also been pointed out in 1996 task group report (page 954, “Concerns for Neutral Conductor Sizing”).

7.1.5 NEC 310.60 (D)

CURRENT CONTENT: Neher-McGrath formula

> **(D) Engineering Supervision.** Under engineering supervision, conductor ampacities shall be permitted to be calculated by using the following general equation:

$$I = \sqrt{\frac{T_c - (T_a + \Delta T_d)}{R_{dc}(1+Y_c)R_{ca}}} \times 10^3 \text{amperes}$$

RECOMMENDATION: Add the following Informational Note:

“The ‘component ac resistance resulting from skin effect and proximity effect’ (Y_C) should be selected with respect to harmonic distortion.”

Conduct a study to determine appropriate values for Y_C.

SUBSTANTIATION: The skin effect is strongly dependent on the frequency of the current – the higher the frequency of the current, the larger the non-uniformity of the current distribution, which will result in additional conductor heating and higher conductor resistance. This effect will be of particular importance for high-order harmonics. Moreover, harmonic current distortion may lead to higher hysteresis losses if the duct is made out of steel or other magnetic material. For additional information, see Section 4.1.

It is apparent from Figure 4-1 that the frequency-dependence of the skin effect has to be taken into account when derating conductors in harmonic-rich environments. The current version of the code does not account for the frequency-dependence of the skin effect and we assume skin effect is calculated based on power-frequency currents. Ideally, the derating factor for the skin effect should be derived based on the actual dominant harmonic(s) in a given network. However, in order to issue a general recommendation for the derating factor that would be suitable to be included in the NEC code, we think it would be appropriate to base the derating factor on typical harmonic distortion levels. The typical distortion levels should be determined from a large number of measurements in commercial and residential building. We are not aware of any recent study that statistically characterize harmonic spectra and distortion levels in commercial and residential building, but do recommend such a study to determine appropriate derating factors.

7.1.6 NEC 450.3, Informational Note No.2

CURRENT CONTENT:

> Informational Note No. 2: Nonlinear loads can increase heat in a transformer without operating its overcurrent protective device.

RECOMMENDATION: Change to "Harmonic currents in the system can increase heat in a transformer without operating its overcurrent protective device."

SUBSTANTIATION: Nonlinear loads are not the exclusive source of harmonics in a power system. IEEE Std 519-1992, *Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*, recognizes that the primary sources of harmonic currents are nonlinear loads located on the end-user side. However, harmonics can also be produced on the utility side by transformer saturation or rotating machines (see Section 3). For instance, Kennedy (2000) identifies the utility as a possible source of harmonic voltages and currents. Therefore, we think that using 'harmonic current' instead of 'non-linear loads' in the Informational Note No. 2 is more appropriate as it avoids the subject of where the harmonics are coming from.

7.1.7 NEC 450.5(A)(4)

CURRENT CONTENT:

> **(4) Rating.** The autotransformer shall have a continuous neutral-current rating that is sufficient to handle the maximum possible neutral unbalanced load current of the 4-wire system.

RECOMMENDATION: Add the following Informational Note: "In some instances, neutral harmonic currents may add to the neutral unbalanced load current."

SUBSTANTIATION: When excessive neutral harmonic currents are present, the neutral conductor ampacity may be subsequently amplified by zero sequence currents exceeding the maximum possible neutral unbalanced load current (De La Rosa, 2006).

7.1.8 NFPA 70B 10.1.1

CURRENT CONTENT: Currently 18 items are listed in the Special Terms section.

RECOMMENDATION: Include the following item:

10.1.1.19 Elevated Neutral-to-Earth Voltage (NEV). Electrical potential difference between the neutral conductor and the grounding conductor as a result of unsymmetrical networks, unbalanced loads, harmonic distortion, and/or the practice of grounding the neutral conductor at multiple points throughout the power system.

SUBSTANTIATION: Harmonic distortion can lead to Elevated Neutral-to-Earth Voltages (NEV) affecting power quality and creating potential hazards to humans and animals. With the increasing prevalence of power-electronic devices, NEVs are becoming more of a concern and should be included in this part of the document.

7.1.9 NFPA 70B 10.2.2.1.1

CURRENT CONTENT: Currently 11 items are listed as possible problems created by harmonics.

RECOMMENDATION: Include the following item

Effects on revenue-meter accuracy

SUBSTANTIATION: The definitions for active, reactive, and apparent powers that are currently used in the majority of the revenue meters are based on the assumption of power-frequency current and voltage waveforms (see *IEEE 1459, Standard Definitions for the Measurement of Electric Power Quantities under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions*). In case of harmonic distortion the meters may produce falsified readings (see Section 4.4).

7.1.10NFPA 70B 10.2.2.1.1

CURRENT CONTENT: Currently 11 items are listed as possible problems created by harmonics.

RECOMMENDATION: Include the following item

Excessive Elevated Neutral – to Earth Voltage (NEV)

SUBSTANTIATION: Elevated neutral-to-earth voltage (NEV) in distribution systems can cause nuisance and potential hazard to humans and animals.

7.1.11NFPA 70B 10.2.2.3.1

CURRENT CONTENT:

10.2.2.3.1 On a 3-phase delta-wye-connected transformer, third harmonics generated by the transformer secondary loads are reflected into the primary in the form of circulating currents in the delta-connected primary. It is therefore especially important to use a true rms-reading ammeter when checking a transformer's secondary line, neutral, and, where practical and safe, primary winding current, for possible overload.

RECOMMENDATION: On a 3-phase delta-wye-connected transformer, zero-sequence harmonics (harmonics with multiples of the 3^{rd} harmonic such as 3^{rd}, 6^{th}, 9^{th}, …)

generated by the transformer secondary loads can be reflected into the primary in the form of circulating current in the delta-connected primary.

SUBSTANTIATION: The 3rd harmonic has usually the highest amplitude of all zero-sequence harmonics but is not the only one responsible for circulating currents in the delta side of the transformer (See Section 2.5 and De La Rosa, 2006).

7.1.12 Wiring requirements for Neutral conductor

CURRENT CONTENT: The NEC code provides no information regarding the sizing of the neutral conductor in the presence of harmonics. Some footnotes related to this issue are in the NEC handbook, but no recommendations are included in the handbook, either.

RECOMMENDATION: Conduct a study that determines sizing requirements for neutral conductors. The neutral sizing requirements should be based on statistically significant data from measurements of neutral currents in different environments (office buildings, residential building, etc.)

SUBSTANTIATION: See Section 4.1 of this report. Further substantiation will be presented in a case study that is part of the Task-4 effort of this study.

7.2 Recommended Changes, Editorial

7.2.1 210.19(A)(1)Informational Note No.4

CURRENT CONTENT:

> Informational Note No. 4: Conductors for branch circuits as defined in Article 100, sized to prevent a voltage drop exceeding 3 percent at the farthest outlet of power, heating, and lighting loads, or combinations of such loads, and where the maximum total voltage drop on both feeders and branch circuits to the farthest outlet does not exceed 5 percent, provide reasonable efficiency of operation. See Informational Note No. 2 of 215.2(A)(3) for voltage drop on feeder conductors.

RECOMMENDATION: Last sentence should be:

“See Informational Note No. 2 of 215.2(A)(4) for voltage drop on feeder conductor.”

SUBSTANTIATION: No Informational Note in 215.2(A)(3). The reference surely refers to 215.2(A)(4).

7.2.2 450.9 Informational Note No. 1:

CURRENT CONTENT:

> Informational Note No. 1: See ANSI/IEEE C57.12.00-1993, *General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers*, and ANSI/IEEE C57.12.01-1989, *General Requirements for Dry-Type Distribution and Power Transformers*.

RECOMMENDATION: See ANSI/IEEE C57.12.00-2010, *General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers*, and ANSI/IEEE C57.12.01-2005, *General Requirements for Dry-Type Distribution and Power Transformers, Including those with Solid-Cast and/or Resin Encapsulated Windings*.

SUBSTANTIATION: Updated version of ANSI/IEEE Std C57.12 is available.

7.2.3 450.9, Informational Note No. 2

CURRENT CONTENT:

> Informational Note No. 2: Additional losses may occur in some transformers where nonsinusoidal currents are present, resulting in increased heat in the transformer above its rating. See ANSI/IEEE C57.110-1993, *Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents*, where transformers are utilized with nonlinear loads.

RECOMMENDATION: Additional losses may occur in some transformers where nonsinusoidal currents are present, resulting in increased heat in the transformer above its rating. See ANSI/IEEE C57.110-2008*, Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents,* where transformers are utilized with nonlinear loads.

SUBSTANTIATION: Updated version of IEEE Std C57.110 is available.

7.3 Summary of recommendations that require a follow-up study

In the previous sections, we identified the following items that require further studies:

- Conduct a study to determine appropriate harmonic limits for which the neutral has to be considered a current-carrying conductor and include the limits determined in the study in the NEC (see Section 7.1.4)
- Conduct a study studies to determine appropriate values for Y_C (see Section 7.1.5).
- Conduct a study that determines sizing requirements for neutral conductors. The neutral sizing requirements should be based on statistically significant data from measurements of neutral currents in different environments (office buildings, residential building, etc.) (see Section 7.1.12).

Appendix: IEEE Standards Related to Harmonics

IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems (IEEE 519-1992)

Scope:

This recommended practice intends to establish goals for the design of electrical systems that include both linear and nonlinear loads. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling; and observance of the design goals will minimize interference between electrical equipment.

Introduction:

Nonlinear loads change the sinusoidal nature of the ac power current (and consequently the ac voltage drop), thereby resulting in the flow of harmonic currents in the ac power system that can cause interference with communication circuits and other types of equipment. When reactive power compensation, in the form of power factor improvement capacitors, is used with these nonlinear loads, resonant conditions can occur that may result in high levels of harmonic voltage and current distortion when the resonant condition occurs at a harmonic associated with nonlinear loads.

IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents (ANSI/IEEE C57.110-2008)

Scope:

This recommended practice applies to liquid-filled and dry-type power and distribution transformer capability when subject to nonsinusoidal load currents.

Introduction:

This recommended practice provides calculation methods to conservatively evaluate the feasibility for an existing installed dry-type or liquid-filled transformer, to supply nonsinusoidal load currents as a portion of the total load. This recommended practice also provides necessary application information to assist in properly specifying a new transformer expected to carry a load, a portion of which is composed of nonsinusoidal load currents. A number of examples illustrating these methods and calculations are presented. Reference annexes provide a comparison of the document calculations to calculations found in other industry standards. Suggested temperature rise calculation methods are detailed for reference purposes.

IEEE Recommended Practice for Monitoring Electric Power Quality (IEEE 1159-2009)

Scope:

This recommended practice encompasses the monitoring of electrical characteristics of single-phase and polyphase ac power systems. It includes consistent descriptions of conducted electromagnetic phenomena occurring on power systems. The document presents definitions of nominal conditions and deviations from these nominal conditions that may originate within the source of supply or load equipment, or from interactions between the source and the load. Also, this document presents recommendations for measurement techniques, application techniques, and interpretation of monitoring results.

Introduction:

The use of equipment that causes and is susceptible to various electromagnetic phenomena has heightened the interest in power quality. An increase in operational problems has led to a variety of attempts to describe the phenomena. Because different segments of the technical community have used different terminologies to describe these electromagnetic events, this Recommended Practice will provide users with a consistent set of terms and definitions for describing these events. An understanding of how power quality events impact the power system and end-use equipment is required in order to make monitoring useful. Proper measuring techniques are required to safely obtain useful accurate data. Appropriate location of monitors, systematic studies, and interpretation of results will enhance the value of power quality monitoring. The purpose of this Recommended Practice is to assist users as well as equipment and software manufacturers and vendors by describing techniques for defining, measuring, quantifying, and interpreting electromagnetic disturbances on the power system.

IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions (IEEE 1459-2010)

Scope:

This recommended practice provides definitions of electric power to quantify the flow of electrical energy in single-phase and three-phase circuits under sinusoidal, nonsinusoidal, balanced, and unbalanced conditions. The standard is meant to provide definitions extended from the well-established concepts. It is meant to serve the user who wants to measure and design instrumentation for energy and power quantification.

Introduction:

The definitions for active, reactive, and apparent powers that are currently used are based on the knowledge developed and greed on during the 1940s. Such definitions served the industry well, as long as the current and voltage waveforms remained nearly sinusoidal. Important changes have occurred in the last 50 years. This standard lists new definitions of powers needed for the following particular situations:

- When the voltage and current waveforms are nonsinusoidal
- When the load is unbalanced or the supplying voltages are asymmetrical
- When the energy dissipated in the neutral path due to zero-sequence current components has economical significance

Electromagnetic compatibility (EMC) - Part 3-12: Limits C Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and <=75 A per phase (IEC 61000-3-12)

Introduction:

This part of IEC 61000 deals with the limitation of harmonic currents injected into the public supply system. The limits given in this International Standard are applicable to electrical and electronic equipment with a rated input current exceeding 16 A and up to and including 75 A per phase, intended to be connected to public low-voltage a.c. distribution systems of the following types:

- nominal voltage up to 240 V, single-phase, two or three wires;
- nominal voltage up to 690 V, three-phase, three or four wires;
- nominal frequency 50 Hz or 60 Hz.

Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current <= 16 A per phase) (IEC 61000-3-2)

Introduction:

This part of IEC 61000 deals with the limitation of harmonic currents injected into the public supply system. It specifies limits of harmonic components of the input current which may be produced by equipment tested under specified conditions. This part of IEC 61000 is applicable to electrical and electronic equipment having an input current up to and including 16 A per phase, and intended to be connected to public low-voltage distribution systems.

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