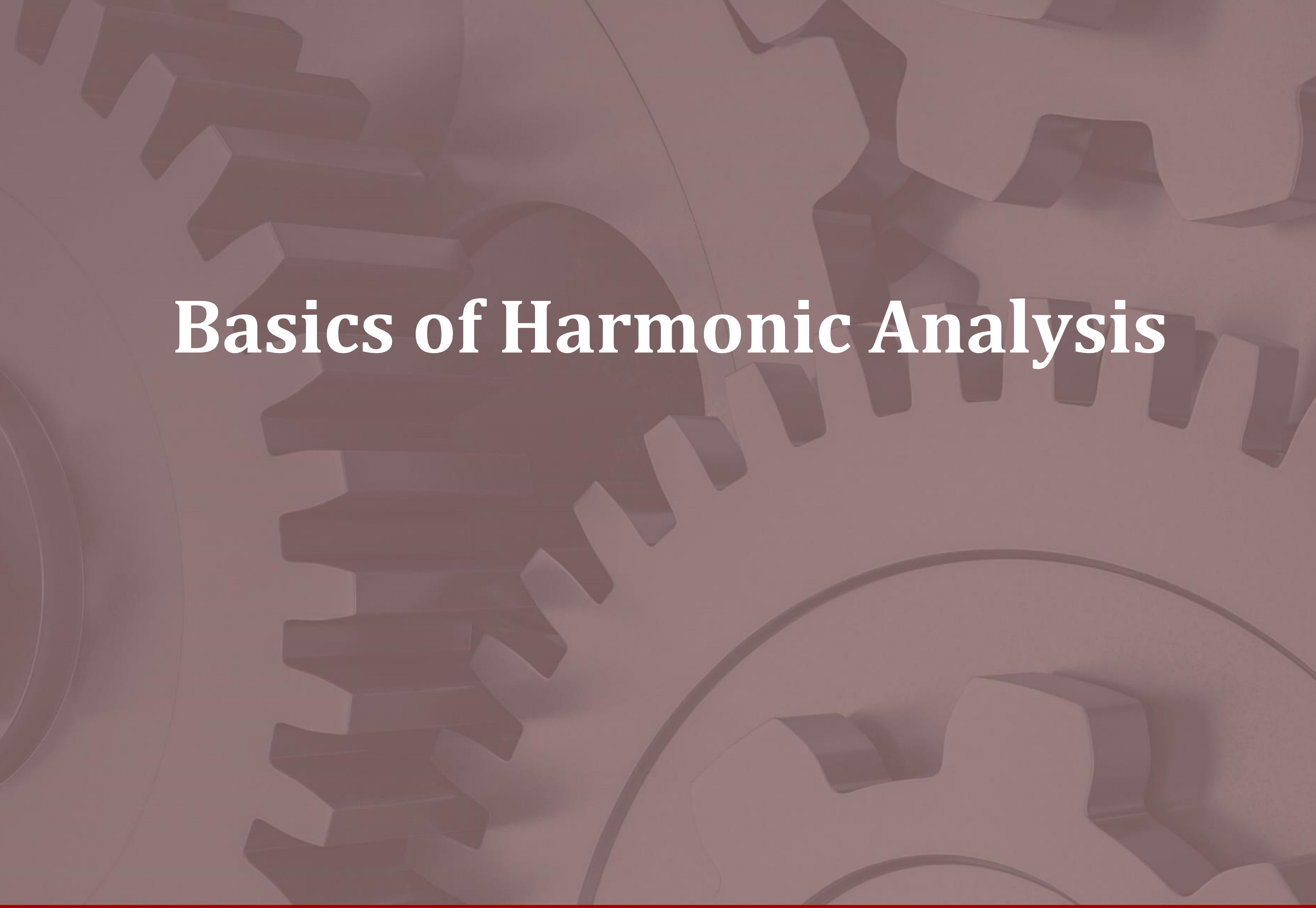

Basics of Harmonic Analysis

An Online Continuing Education Course for Engineers

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Basics of Harmonic Analysis

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Introduction

In this course we will discuss the underlying concepts of harmonic analysis in relation to industrial and commercial power systems. Also included will be the reasons we require this analysis, the recognition of problems that may arise in the process, methods of correcting and preventing these issues, the data required to perform this analysis, and the benefits of technology in performing a harmonic analysis study.

The main source of power system harmonics has traditionally been the static power converter, used as a rectifier in many industrial processes. The static power converter is now used, however, in a number of different applications. These include adjustable speed drives, frequency changers for induction heating, switched-mode supplies, and many more. Increasingly, semiconductor devices are being used as static switches, to adjust the amount of voltage being applied to a load. Some applications for this include light dimmers, electronic ballasts for discharge lamps, soft starters for motors, and static var compensators. Any device with a nonlinear voltage current like an arc furnace or saturable electromagnetic device can also be included.

Nonlinear loads represent a growing portion of the total load of a commercial or industrial power system. This means harmonic studies are an important part of any system design and operation. Fortunately, the software available to assist us with harmonic analysis has grown also.

If we model power system impedances as a function of frequency, we can determine the effect of harmonic contributions produced by nonlinear loads on voltage and current in a power system. The majority of harmonic analysis software will offer the ability to do as follows:

- Calculate harmonic bus voltages and branch current flows produced by harmonic sources in a network

- See resonances in an existing or planned system

- Calculate the effects of harmonics on voltage or current waveform distortion, telephone interference etc. through performance indices. This can also aid in choosing or finding capacitors and passive filters to produce optimal system performance.

We will discuss the details of applicable standards and system modelling, particularly in industrial and commercial systems running at low or medium voltages. The basics are applicable also to higher voltage systems and other system applications. In this course, we will not cover active filters as part of a design, but some references will be made to their use and application.

From the beginning we may say that harmonic filter design is linked closely to power-factor (PF) requirements in a system, based on utility tariffs. Both must therefore be considered together.

Many studies on PF compensation have previously been made without considering possible resonances or harmonic absorption by capacitors.

Background

By definition, any device or load that doesn't draw a sinusoidal current when excited by a sinusoidal voltage of the same frequency is a nonlinear load. Most commonly these are switching devices like solid-state converters which force conduction of currents for particular periods. They can also include saturable impedance devices like transformers with nonlinear voltage vs. impedance characteristics. Nonlinear loads are also considered sources of harmonic currents, in which harmonic frequencies are classed as integer multiples of the system frequency. Arc furnaces, cycloconverters, and other specific nonlinear loads can have non-integer harmonic frequencies as well as the integer harmonics expected in the system.

By definition, harmonics are a part of every fundamental current cycle. When calculating them, they are considered part of the steady-state solution. But harmonics can vary from cycle to cycle, as exceptions will always occur. These are classed as time-varying harmonics. These are not dealt with in this chapter, nor quasisteady-state or transient solutions (as in magnetization inrush current of a transformer).

In industrial application studies, the nonlinear load or harmonic source is classed as an ideal current source without a Norton's impedance (i.e. assume infinite Norton impedance), providing a constant current, regardless of the system impedance seen by the source. This is generally a reasonable assumption and tends to yield acceptable results. A Norton equivalent current source can still be used when a nonlinear device acts as a voltage source, such as with pulse-width-modulated or PWM inverters, as most computer software works on the current injection method.

Networks are solved for current and voltage individually at each frequency, as a system is subjected to current injections at multiple frequencies. Then, the total voltage or current can be found through a root-mean-square or arithmetic sum via the principle of superposition.

Different types of nonlinear loads with generate different harmonic frequencies. Most will produce odd harmonics, with small, even harmonics, but loads like arc furnaces produce the entire spectrum: odd, even, and non-integer, also known as interharmonics. In general, the harmonic amplitude will decrease as the harmonic order or frequency increases.

Depending on harmonic voltage drops in various series elements of the network, distortion of the voltage waveform is produced due to the effects of harmonic current propagation through the network (including the power source). Voltage distortion at a bus depends on the equivalent source impedance – smaller impedance means better quality voltage. Note that nonlinear loads of harmonic sources are not power sources, but the cause of active and reactive losses of power in a system.

The Purpose of Harmonic Study

Nonlinear loads represent a growing propagation in commercial buildings and industrial plants, in the range of thirty to fifty percent of the total load. This means we need to examine the effects of harmonics within a system and the impact they have on a utility and neighbouring loads, to prevent any complaints, equipment damage, or loss in production.

The list below represents a number of situations in which a harmonic study may be necessary, including recommendations for mitigation of harmonic effects.

a) IEEE Std. 519-1992 compliance, defining the current distortion limits that should be met in the utility at the point of common coupling or PCC. As a basis for the system design, limits of voltage distortion are also defined. These are intended to provide a good sine wave voltage in the utility, but users are expected to use them as a basis for the design of a system. If current distortion limits are met, voltage distortion limits should also, allowing for unusual and exceptional circumstances.

b) Harmonic related problems in the past, including failure of power-factor compensation capacitors; overheating of transformers, motors, cables, and other such equipment; and misoperation of protective relays and control devices.

c) Expansion in which significant nonlinear loads are added or a significant capacitance is added to a plant.

d) Designing a new power system or facility in which the power factor compensation, load-flow, and harmonic analyses need to be studied in one integrated unit, in order to determine reactive power demands, harmonic performance limits, and how to meet these requirements. If system problems appear to be caused by harmonics, it becomes important to determine resonant frequencies at points which are causing problems. Parallel system resonance can also occur around the lower harmonic orders (3, 5…) with banks of power-factor correction capacitors. This can be critical if a harmonic current injection at that frequency excites the resonance.

Frequently you will find systems where taking harmonic measurements as a tool for diagnostics rather than performing detailed analysis studies will be a much more practical task. Measurements can also be used to verify system models before performing a detailed harmonic analysis study. Arc furnace installations are a situation in which this is especially desirable. Careful consideration must be given to procedures and test equipment to make sure harmonic measurements will produce reliable results. These may produce the cause of a problem, meaning a simpler study or even the elimination of the need for a study.

General Theory

Harmonic Sources

Harmonic sources are all considered nonlinear loads, as when a sinusoidal voltage is applied, they draw non-sinusoidal currents. This may be caused by the inherent characteristics of the load as in arc furnaces, or due to a switching circuit like a 6-pulse converter, which forces conduction for particular periods. There may be many such harmonic sources throughout an industrial or commercial power system.

Harmonic studies require that the performer has knowledge of harmonic currents produced by the involved nonlinear loads. An analytical engineer has three main choices.

- Measuring harmonics produced at each source
- Calculating harmonics produced via a mathematic analysis in applicable situations, e.g. converters or static var compensators
- Using typical values from published data on similar applications
  all three of these methods are used in practice and acceptable results are produced by each.

System configuration and loads are continually changing. This means that the harmonics also change, and studying all possible conditions would be a difficult task. Instead, designs are based on the "worst-generated" harmonics, by finding the worst operating condition available. However, even with this case, harmonic flows through various parts of a network can be different, depending on tie breakers or transformers involved. Even with the "worst-generated" case, this means we must also analyse the "worst operating case(s)".

When multiple harmonic sources are connected to the same or different buses, another difficulty arises in the analysis. Phase angles between same order harmonics are usually unknown. This means that we generally have to turn to arithmetic addition of harmonic magnitudes, assuming the sources are similar, with similar operating load points. If sources are different, or operate at different load points, this approach can produce more conservative filter designs or distortion calculations. For common industrial applications, determining phase angles of harmonics and vectorial addition is often not very cost-effective and can be over-complicated, but this can be resolved by simplifying assumptions through field measurements or previous experience. When accuracy is more important, such as in high-voltage dc transmission and other utility applications, more advanced techniques are employed.

Industrial harmonic studies are usually based on the assumption that a positive sequence analysis applies, and a system is balanced. This means they are represented on a single-phase basis. If the system or load is extremely unbalanced, or a four-wire system exists with single-phase loads, this warrants a three-phase study. This situation makes it appropriate and preferred to find the harmonics generated in all three phases. A three phase study, however, may not serve the full purpose of the study if harmonic generation is assumed to be balanced, while the system is unbalanced. The cost of one of these studies can be much higher than a single-phase study, so should only be used if it is justifiable to produce this expense for the purpose.

Effects of Harmonics

Harmonic effects are only described here in terms of an analytical study of a harmonic system. These harmonics influence system losses, operation, and performance, making them ubiquitous in a power system. If they are not contained within acceptable limits, harmonics can damage both power and electronic equipment, resulting in costly system outages.

Harmonic effects are caused by both voltage and current, but the effects of current are more often seen in conventional performance. However, degradation of insulation can be caused by voltage effects, shortening equipment life. The list below describes some common harmonic effects.

- Losses in equipment, cables, lines, etc.
- Rotating equipment produces pulsating and reduced torque
- Increased stress in equipment insulation causing premature aging
- Rotating and static equipment producing increased audible noise
- Waveform sensitive equipment being misoperated
- Resonances causing significant amplification of voltage and current
- Inductive coupling between power and communication circuits causing communication interference

Common harmonic studies including harmonic flows and filter design tend not to involve an in-depth analysis of harmonic effects when limits of a standard or user are met, but in some specific cases, a separate study is required for harmonics penetrating into rotating equipment, affecting communication circuits, or causing misoperation of relays.

Resonance

Elements of a power system circuit are predominantly inductive. This means the inclusion of shunt capacitors for power-factor correction or harmonic filtering can cause inductive and capacitive elements to transfer cyclic energy at the natural resonance frequency. Inductive and capacitive reactance is equal at this frequency.

When viewed from a bus of interest, commonly the bus where a nonlinear source injects harmonic currents, the combination of inductive (L) and capacitive (C) elements can result in either a series resonance (L and C in series) or a parallel resonance (L and C in parallel). The following sections will show that a series resonance results in low impedance, while a parallel resonance will result in a high impedance. The net impedance in either series or parallel is resistive. It is essential that the driving-point impedance (as seen from the bus of interest) is examined in a harmonic study, to determine the frequencies of series and parallel resonances, and their resulting impedances.

PF correction capacitors are commonly used in practical electrical systems to offset utility-imposed power factor penalties. The combination of capacitors and inductive elements in the system can result either in series or parallel resonance, or a combination of both, depending on the system configuration, which can result in an abnormal situation. Parallel resonance is more common as capacitor banks act in parallel with inductive system impedance, which can be a problem when the resonant frequency is close to one of those generated by the harmonic sources.

Series resonance can result in unexpected amounts of harmonic currents flowing through certain elements. Excessive harmonic current flow can cause inadvertent relay operation, burned fuses, or overheating of cables.

Parallel resonance may produce excessive harmonic voltage across network elements. Commonly, this will cause capacitor or insulation failure.

Series Resonance

Figure 1 shows an example of a series resonant circuit, with each element described in terms of its impedance. Equations (1) and (2) express the equivalent impedance of the circuit and current flow. This circuit is in resonance when X_L is equal to X_C (inductive reactance equal to capacitive reactance). Equation (3) gives the resonant frequency at which $X_L = X_C$

$$\bar{Z} = R + j(X_L - X_c) \qquad \text{Eq. (1)}$$

$$\bar{I} = \frac{\bar{V}}{R + j(X_L - X_C)} \qquad \text{Eq. (2)}$$

$$= \frac{V}{R}\ at\ resonance\ (X_L = X_C)$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad \text{Eq. (3)}$$

The magnitude of the cu ificant due to the relatively low values of series

Figure 2. Equivalent imp quency where R = 2 Ω , L = 3.98 mH, and C = 3 pedance at low frequencies appears capacitive and only becor frequency increases. That resonance occurs at 420 Hz.