Understanding Power System Harmonics

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Harmonics – Past to Present

Power systems are designed to operate at frequencies of 50 or 60Hz. However, certain types of loads produce currents and voltages with frequencies that are integer multiples of the 50 or 60 Hz fundamental frequency. These higher frequencies are a form of electrical pollution known as power system harmonics.

Power system harmonics are not a new phenomenon. Concern over harmonic distortion has ebbed and flowed during the history of electric power systems. Steinmetz published a book in 1916 that devoted considerable attention to the study of harmonics in three-phase power systems. His main concern was third harmonic currents caused by saturated iron in transformers and machines, and he was the first to propose delta connections for blocking third harmonic currents.

Later, with the advent of rural electrification and telephone service, power and telephone circuits were often placed on common rights-of-way. Harmonic currents produced by transformer magnetizing currents caused inductive interference with open-wire telephone systems. The interference was so severe at times that voice communication was impossible. This problem was studied and alleviated by filtering and by placing design limits on transformer magnetizing currents.

Today, the most common sources of harmonics are power electronic loads such as adjustable-speed drives (ASDs) and switch-mode power supplies. These loads use diodes, silicon-controlled rectifiers (SCRs), power transistors, and other electronic switches to chop waveforms to control power or to convert 50/60Hz AC to DC. In the case of ASDs, the DC is then converted to variable-frequency AC to control motor speed. Example uses of ASDs include chillers and pumps.

Due to tremendous advantages in efficiency and controllability, power electronic loads are proliferating and can be found at all power levels – from low voltage appliances to high voltage converters. Hence, power systems harmonics are once again an important problem.

Harmonic Distortion and Definitions

Power electronic loads control the flow of power by drawing currents only during certain intervals of the 50/60Hz period. Thus, the current drawn by the load is no longer sinusoidal and appears chopped or flattened. The nonsinusoidal current can interact with system impedance to give rise to voltage distortion and, in some cases, resonance.

In a ‘stiff’ power system, where the available fault current is high (thus the system impedance is low), the voltage distortion is usually small and does not present a power quality problem. However, in a weak system, where the system impedance is high, voltage distortion can be high and may cause problems.

Unlike transient events such as lightning that last for a few microseconds, or voltage sags that last from a few milliseconds to several cycles, harmonics are steady-state periodic phenomena that produce continuous distortion of voltage and current waveforms. These periodic nonsinusoidal waveforms are described in terms of their harmonics, whose magnitudes and phase angles are computed using Fourier analysis. The analysis permits a periodic distorted waveform to be decomposed into an infinite series containing dc, fundamental frequency (e.g. 60Hz), second harmonic (e.g. 120Hz), third harmonic (e.g. 180Hz), and so on. The individual harmonics add up to reproduce the original waveform. The highest harmonic of interest in power systems is usually the 25th multiple, which is in the low audible range. Positive and negative half cycles of power systems voltages and currents tend to have identical waveshapes so that their Fourier series contain only odd harmonics. A DC term is usually not present.

The most common measure of distortion is total harmonic distortion, THD. THD applies to both current and voltage and is defined as the rms value of harmonics divided by the rms value of the fundamental, and then multiplied by 100%. THD of current varies from a few percent to more than 100%. THD of voltage is usually less than 5%. Voltage THDs below 5% are widely considered to be acceptable, but values above 10% are definitely unacceptable and will cause problems for sensitive equipment and loads.

It is not generally known that power factor is closely linked to harmonics. The traditional d*isplacement* power factor is the cosine of the relative phase angle between fundamental voltage and current. However, *true* power factor is average power divided by the product of rms voltage and rms current. Harmonics increase rms voltage and, especially, rms current. Table 1 shows the theoretical maximum true power factor of a distorting load as a function of current THD. The table assumes the optimum case, i.e., the displacement power factor is 1.0.

Table 1 – Maximum true power factor of a nonlinear load.

Current THD	Maximum true pf
20%	0.98
50%	0.89
100%	0.71

When a three-phase power system is balanced, harmonics fall into the phase sequence pattern shown in Table 2.

Table 2 – Harmonic phase sequence in a balanced three-phase power system.

Harmonic	Phase Sequence
1	+
2	–
3	0
4	+
5	–
6	0
…	…

Thus, the traditional rule that “balanced power systems can have no negative- or zero-sequence components” is not valid when harmonics are present. It is important to note that harmonic multiples of three (i.e., triplens) are zero-sequence. This fact accounts for neutral conductor overheating that is explained in a following section.

Harmonic Sources

There are two general categories of harmonic sources: saturable devices and power electronic devices. Saturable devices produce harmonics due mainly to iron saturation, as is the case for transformers, machines, and fluorescent lamps (with magnetic ballasts). For economic reasons, most transformers and motors are designed to operate slightly past the knee of the iron core saturation curve. The resulting magnetizing currents are peaked and rich in the third harmonic. Unless blocked by a delta transformation, a synchronous machine will produce a third harmonic current of approximately 30% of the fundamental.

Fluorescent lamps with magnetic ballasts are usually rather benign sources of harmonics. Their current distortion is due to the arc and to the ballast. Typically distortions are dominated by the third harmonic with a magnitude in the range of 15% to 30% of the fundamental. Figure 1a shows the harmonic current of a fluorescent lamp with a standard magnetic ballast.

Power electronic loads draw power only during portions of the applied voltage waveform. These loads include switch-mode power supplies, fluorescent lights (with electronic ballasts), voltage source converters, pulse-width modulated converters, to mention just a few. Figure 1b shows the line current of a fluorescent lamp with an electronic ballast that employs a switch-mode power supply. Desktop computers, video monitors, and televisions have similar waveforms. The current THD is approximately 100%.

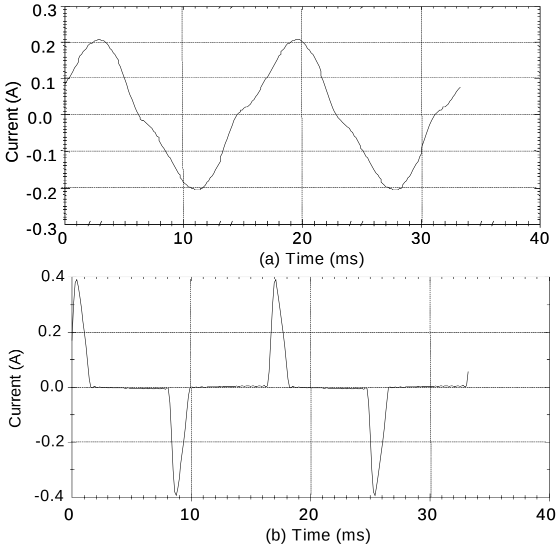

Figure 1 – Current waveforms of fluorescent lamp with (a) a magnetic ballast and (b) with an electronic ballast.

Figure 2 shows the current and harmonic spectrum of a typical voltage source PWM converter for ASD applications. The input to the PWM drive is typically a three-phase version of the single-phase switch-mode power supply. The rectifier feeds directly from the ac bus to a large capacitor on the dc bus. With little intentional inductance, the capacitor is charged with very short pulses creating the distinctive ac-side current waveform with very high distortion. The current THD is usually in the 40 – 60% range.

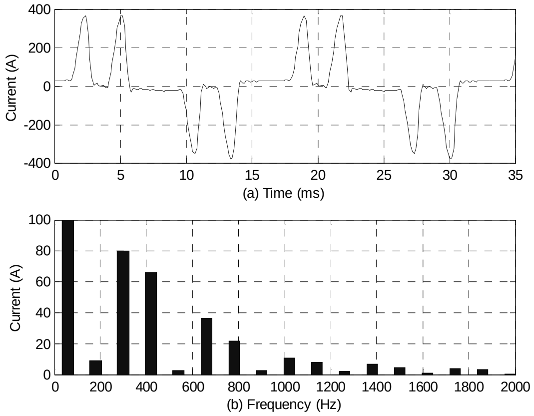

Figure 2 – Current waveform and harmonic spectrum of a PWM converter.

System Response Characteristics

All circuits containing both capacitance and inductance have one or more natural resonant frequencies. When one of these frequencies corresponds to an exciting frequency being produced by nonlinear loads, harmonic resonance can occur. Voltage and current will be dominated by the resonant frequency and can be highly distorted. Thus the response of the power system at each harmonic frequency determines the true impact of the nonlinear load on harmonic voltage distortion.

Resonance can cause nuisance tripping of sensitive electronic loads and high harmonic currents in feeder capacitor banks. In severe cases, capacitors produce audible noise, and they sometimes bulge.

To better understand resonance, consider the simple parallel and series cases shown in the one-line diagrams of Figure 3. Parallel resonance occurs when the power system presents a parallel combination of power system inductance and power factor correction capacitors at the nonlinear load. The product of harmonic impedance and injection current produces high harmonic voltages.

Series resonance occurs when the system inductance and capacitors are in series, or nearly in series, with respect to the nonlinear load point.

For parallel resonance, the highest voltage distortion is at the nonlinear load. However, for series resonance, the highest voltage distortion is at a remote point, perhaps miles away or on an adjacent feeder served by the same substation transformer. Actual feeders can have five or ten shunt capacitors each, so many parallel and series paths exist, making computer simulations necessary to predict distortion levels throughout the feeder.

In the simplest parallel resonant cases, such as an industrial facility where the system impedance is dominated by the service transformer, shunt capacitors are located inside the facility, and distances are small. In these cases, the simple parallel scenario shown in Figure 3a often applies.

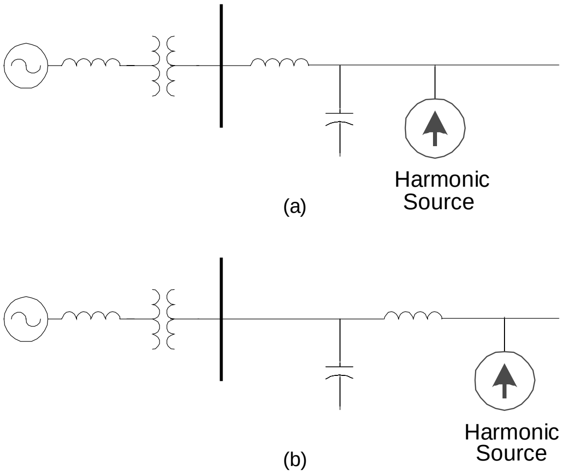

Figure 3 – Examples of (a) parallel and (b) series resonance.

Harmonic Impacts

Harmonics have a number of undesirable effects on power system components and loads. These fall into two basic categories: short-term and long-term. Short-term effects are usually the most noticeable and are related to excessive voltage distortion. On the other hand, long-term effects often go undetected and are usually related to increased resistive losses or voltage stresses.

Short-term effects can cause nuisance tripping of sensitive loads. Some computer-controlled loads are sensitive to voltage distortion. For example, one documented case showed that a voltage distortion of 5.5% regularly shut down computerized lathes at a large pipe company heat treatment operation. While voltage distortions of 5% are not usually a problem, voltage distortions above 10% will almost always cause significant nuisance tripping or transformer overheating.

Harmonics can degrade meter accuracy. This is especially true with common single-phase induction-disk meters. In general, the meter spins 1-2% faster when a customer produces harmonic power. However, the greater issue in metering is the question of how active power, and especially reactive power, should be defined and measured when distortion is present. Debate on these definitions continues today.

Blown capacitor fuses and failed capacitor cans are also attributed to harmonics. Harmonic voltages produce excessive harmonic currents in capacitors because of the inverse relationship between capacitor impedance and frequency. Voltage distortions of 5% and 10% can easily increase rms currents by 10% to 50%. Capacitors may also fail because of overvoltage stress on dielectrics. 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.

Harmonics can also cause transformer overheating. This usually occurs when a dedicated transformer serves only one large nonlinear load. In such a situation, the transformer must be derated accordingly. Derating to 0.80 of nameplate kVA is common.

Overloaded neutrals appear to be the most common problems in commercial buildings. In a three-phase, four-wire system, the sum of the three phase currents returns through the neutral conductor. Positive and negative sequence components add to zero at the neutral point, but zero sequence components are additive at the neutral.

Power system engineers are accustomed to the traditional rule that “balanced three-phase systems have no neutral currents.” However, this rule is not true when power electronic loads are present. Their zero sequence harmonics (i.e., primarily the 3rd harmonic and “triplens”) sum in the neutral wire and can overload the neutral conductor. Figure 4 illustrates this problem.

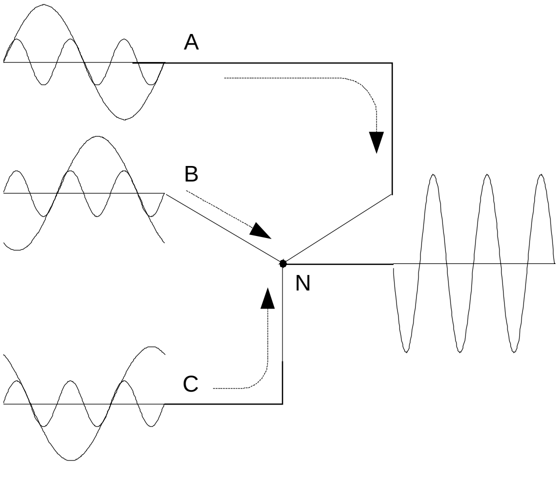

Figure 4 – Overloaded neutral conductors serving single-phase nonlinear loads.

Many PCs have 3rd harmonic currents greater than 80%. In these cases, the neutral current will be at least 3 • 80% = 240% of the fundamental a-b-c phase current. Thus, when PC loads dominate a building circuit, it is good engineering practice for each phase to have its own neutral wire, or for the shared neutral wire to have at least twice the current rating of each phase wire.

Overloaded neutral currents are usually only a local problem inside a building, for example at a service panel. At the building service entrance, the harmonic currents produced by PCs, ASDs, and other nonlinear loads are not totally additive because of phase angle diversity in their phasor currents. Research has shown this diversity to be inversely proportional to frequency, so that the 3rd harmonic currents are almost totally additive, but harmonic currents above the 15th add to only about 0.20 of their individual magnitude sums.

In addition to phase angle diversity, harmonic currents are diluted by the addition of many linear loads in the building, including air conditioners, pumps, fans, and incandescent lights. Thus, the net current distortion of a large building is usually less than 10-15%.

Control of Harmonics

Based on the above discussion, the two common causes of harmonic problems are

- Nonlinear loads injecting excessive harmonic currents,
- The interaction between harmonic currents and the system frequency response.

When harmonics become a problem, commonly-employed solutions are

- Limit harmonic current injection from nonlinear loads. Transformer connections can be employed to reduce harmonics in a three-phase system by using parallel delta-delta and wye-delta transformers to yield net 12-pulse operation, or delta connected transformers to block triplen harmonics.
- Modify system frequency response to avoid adverse interaction with harmonic currents. This can be done by feeder sectionalizing, adding or removing capacitor banks, changing the size of the capacitor banks, adding shunt filters, or adding reactors to detune the system away from harmful resonances.
- Filter harmonic currents at the load or on the system with shunt filters, or try to block the harmonic currents produced by loads. There are a number of devices to do this. Their selection is largely dependent on the nature of the problems encountered. Solutions can be as simple as an in-line reactor (i.e., a choke) as in PWM-based adjustable speed drive applications, or as complex as an active filter.

Harmonic controls can be exercised at the utility and end-user sides. IEEE 519 attempts to establish reasonable harmonic goals for electrical systems that contain nonlinear loads. The objective is to propose steady-state harmonic limits that are considered reasonable by both electric utilities and their customers. The underlying philosophy is that

- customers should limit harmonic currents, since they have control over their loads,
- electric utilities should limit harmonic voltages since they have control over the system impedances, and
- both parties share the responsibility for holding harmonic levels in check.

It is important to remember that IEEE 519 is a recommended practice and not an actual standard or legal document. It is intended to provide a reasonable framework within which engineers can address and control harmonic problems. It has been adopted by many electric utilities and by several state public utility commissions.

Conclusions

Harmonic distortion is not a new phenomenon. Concern over harmonic distortion emerged during the early history of ac power systems. Widespread applications of power electronic-based loads continue to increase concerns over harmonic distortion. Harmonic problems have sparked research that has led to much of the present-day understanding of power quality problems.

The current drawn by electronic loads can be made virtually distortion-free (i.e., perfectly sinusoidal), but the cost of doing this is significant and is the subject of ongoing debate between equipment manufacturers and electric utility companies in standard-making activities. Two main questions often arise during these consensus-building discussions:

1. What are the acceptable levels of current distortion produced by nonlinear loads?
2. Who should be responsible for controlling harmonics, the end users or the utility companies?

IEEE 519 provides an excellent groundwork to addresses both concerns.

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