Electrical Harmonics: An Introduction and Overview of What That Means to You

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Introduction:

The purpose of this paper is to attempt to explain the basic elements of electricity and electrical circuits such as current, voltage, harmonics and power factor. Through comparisons to basic plumbing and simple graphs, it is hoped that the reader will have a better understanding of some of the basic elements related to electrical power and what can impact their power bill.

An analogy to help understand electrical terms is plumbing and water pipes. If we use plumbing as an analogy for electricity we can equate “voltage” to water pressure, “current” to rate of flow, and “resistance” to size of pipe. Assume you have a tank of pressurized water connected to a hose for watering the garden. If we increase the pressure (more voltage) in the tank we can project that more water (more current) will come out of the hose. This is the same as saying that if we increase the voltage, more current will flow. The size of the hose you have attached to the tank can either hinder if it is small (meaning higher resistance) or if it is larger, water flows more freely (meaning less resistance).

The three most basic units in electricity are voltage (**V**), current (**I**, uppercase "i") and resistance (**R**). Voltage is measured in ***volts***, current is measured in ***amps*** and resistance is measured in ***ohms***. There is a basic equation in physics and electrical engineering that states how the three terms relate. It says that the current is equal to the voltage divided by the resistance.

$$I = V/R \quad \text{or} \quad \text{Amps} = \text{Volts/Ohms}$$

Now let’s use a water wheel as a way to explain electrical power. Take a flume (i.e. water pipe) and point it at a waterwheel like the ones that were used to turn grinding stones in watermills. You can increase the power generated by the waterwheel in two ways. If you increase the pressure of the water coming out of the flume, it hits the waterwheel with a lot more force and the wheel turns faster, generating more power. This can happen due to gravity if the original water source is coming into the flume from a reservoir at a higher elevation. Alternatively, you can increase the flow rate by using a larger flume, the waterwheel turns faster because of the weight of the extra water hitting it. What that means in electrical terms is that if we increase voltage or current, we increase electrical power. You can visualize this by looking at the water wheel image to the right.

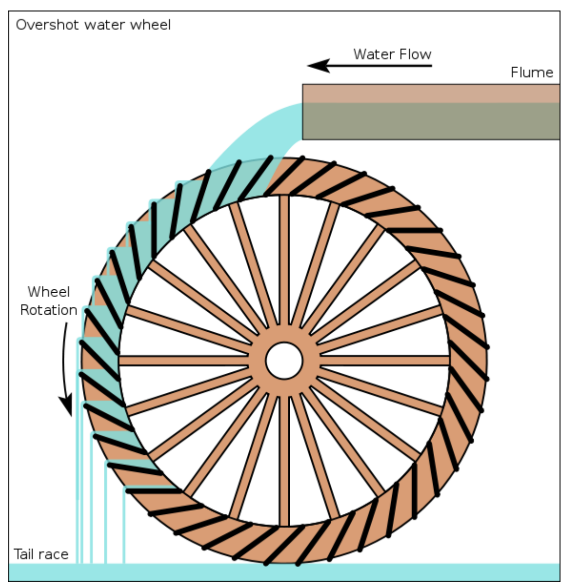

Figure 1: Traditional Water Wheel

Electrical power is measured in **watts**. In an electrical system power (**P**) is equal to the voltage multiplied by the current.

$$P = V \times I \quad \text{or} \quad \text{Watts} = \text{Volts} \times \text{Amps}$$

Understanding Alternating Current:

An alternator is an electromechanical device that converts mechanical energy to electrical energy in the form of alternating current. Alternating Current (AC) is created by the magnet of an electromechanical alternator as it moves toward and away from coils surrounding the magnetic rotor of the alternator. The voltage produced by the stationary coils by the motion of the rotating magnet is proportional to the rate at which the magnetic flux is changing perpendicular to the coils (Faraday's Law of Electromagnetic Induction). That rate is greatest when the magnet poles are closest to the coils, and least when the magnet poles are furthest away from the coils. Mathematically, the rate of magnetic flux change due to a rotating magnet follows that of a sine function, so the voltage produced by the coils follows that same function.

If we were to follow the changing voltage produced by a coil in an alternator from any point on the sine wave graph to that point when the wave shape begins to repeat itself, we would have marked exactly one *cycle* of that wave. This is most easily shown by spanning the distance between identical peaks, but may be measured between any corresponding points on the graph. The degree marks on the horizontal axis of the graph represent the domain of the trigonometric sine function, and also the angular position of a simple two-pole alternator shaft as it rotates. Figure 2 illustrates this below.

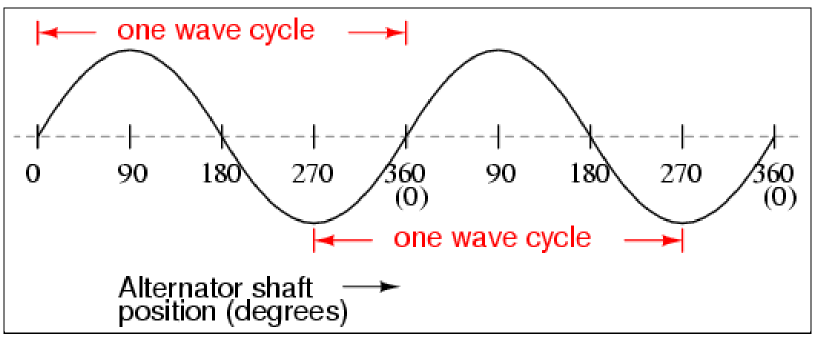

Figure 2: Alternator voltage as function of shaft position (time).

Since the horizontal axis of this graph can mark the passage of time as well as shaft position in degrees, the dimension marked for one cycle is often measured in a unit of time, most often seconds or fractions of a second. When expressed as a measurement, this is often called the *period* of a wave. The period of a wave in degrees is *always* 360, but the amount of time one period occupies depends on the rate voltage oscillates back and forth.

A more popular measure for describing the alternating rate of an AC voltage or current wave than *period* is the rate of the back-and-forth oscillations. This is called *frequency*. The modern unit for frequency is the Hertz (abbreviated Hz), which represents the number of wave cycles completed during one second of time. In the United States of America, the standard power-line frequency is 60 Hz, meaning that the AC voltage oscillates at a rate of 60 complete back-and-forth cycles every second.

The voltage-time graph in Figure 3 below shows some of the other properties of an electrical signal.

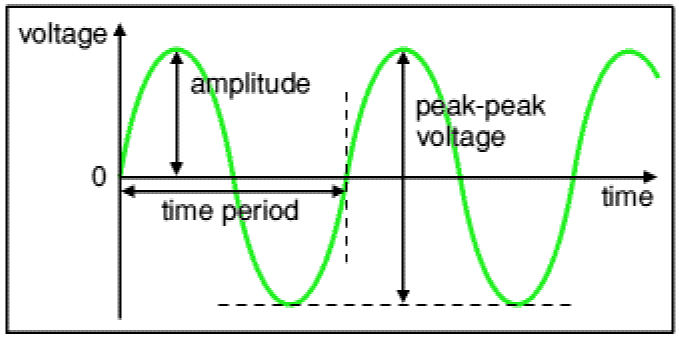

Figure 3: Characteristics of a voltage wave form

- **Amplitude** is the maximum voltage reached by the signal. It is measured in **volts**, **V**.
- **Peak voltage** is another name for amplitude.
- **Peak-peak voltage** is twice the peak voltage (amplitude). When reading an oscilloscope trace it is usual to measure peak-peak voltage.

The value of an AC voltage is continually changing from zero up to the positive peak, through zero to the negative peak and back to zero again. Clearly for most of the time it is less than the peak voltage, so this is not a good measure of its real effect. Instead the **root mean square voltage** (V_{RMS}) is used. The root mean square voltage is NOT really the average! In fact the average voltage (or current) of an AC signal is zero because the positive and negative parts exactly cancel out! For sinusoidal voltage wave forms, the root mean square voltage is really approximately 0.7 of the **peak voltage** (V_{peak}):

$$\mathbf{V_{RMS} = 0.7 \times V_{peak}} \quad \text{and} \quad \mathbf{V_{peak} = 1.4 \times V_{RMS}}$$

These equations also apply to **current** and are only true for sine waves. For a normal 120V AC circuit it turns out that the actual peak voltage is about 168 volts but it is read with a Watt meter as approximately 120 volts (or 0.7 x 168).

Electrical engineers frequently use oscilloscopes to view the waveforms of electrical current and voltage. A typical display whereby the current and voltage are in-phase and delivering maximum power is illustrated in Figure 4.

In AC circuits, **electrical impedance** is the measure of the opposition that a circuit presents to the passage of a current when a voltage is applied. In that respect it represents a complex ratio of voltage to the current in an AC circuit. It is similar to the basic concept of resistance that includes magnitude but also has implications as to phase.

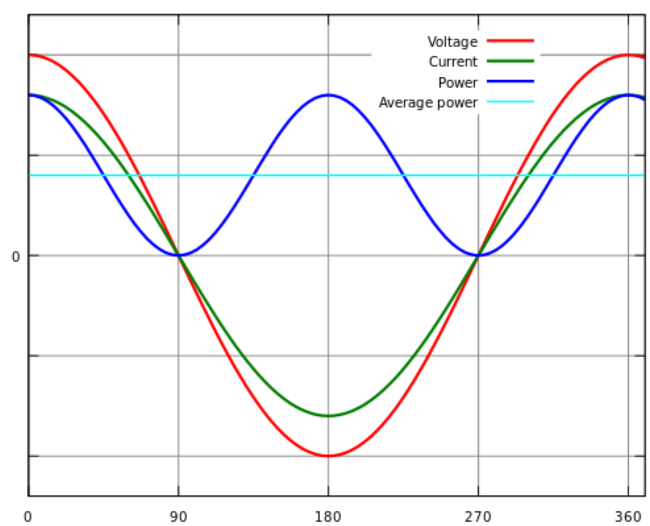

Figure 4: In-Phase Voltage and Current Wave Forms

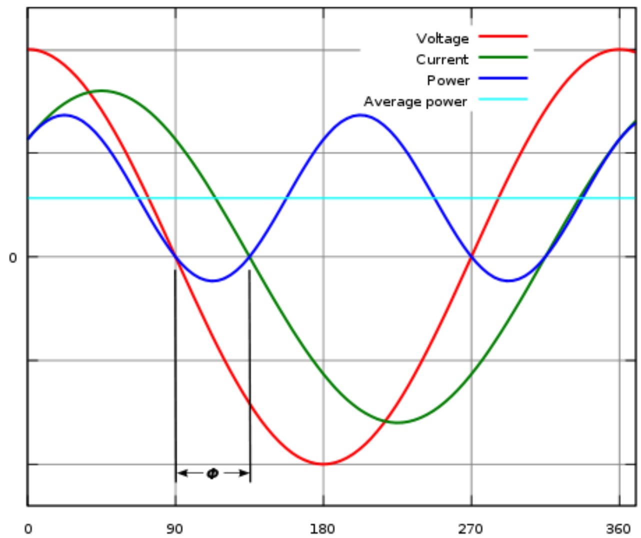

Figure 5: Out-of-Phase Voltage and Current Wave Forms

The impact of impedance on voltage and current wave forms results in them either being in-phase or not. When impedance causes voltage and current to be out of phase, the result is less real power gets to the load attached to the circuit. Figure 5 illustrates what this might look like when current and voltage are out of phase by 45 degrees. This results is about 30% less real power being delivered to the load on the circuit.

If both the voltage and the current waveforms were sinusoidal, it would be possible to measure phase angle simply by reading the time difference between zero crossings of the waveforms on an oscilloscope. In fact, the phase angle is defined as the angle between the fundamental voltage and current as seen in Figure 5 above. The real power (sometimes called active power) that the load on the circuit can actually use is measured in Watts with a Watt meter.

When a sinusoidal voltage is applied to a certain type of load, the current drawn by the load is proportional to the voltage and impedance and follows the envelope of the voltage waveform. These loads are referred to as **linear loads** (loads where the voltage and current follow one another without any distortion to their pure sine waves). Examples of linear loads are resistive heaters, incandescent lamps, and constant speed induction motors.

A **nonlinear load**, on the other hand, is a load that does not oppose the applied voltage with constant impedance. The result is a nonsinusoidal current waveform that does not conform to the waveform of the applied voltage. Nonlinear loads have high impedance during part of the voltage waveform, and when the voltage is at or near the peak the impedance is suddenly reduced. The reduced impedance at the peak voltage results in a large, sudden, rise in current flow until the impedance is suddenly increased resulting in a sudden drop in current. Because the voltage and current waveforms are no longer related, they are said to be "nonlinear." These nonsinusoidal current pulses introduce unanticipated reflective currents back into the power distribution system, and the currents operate at frequencies other than the fundamental 60 Hz.

Ideally, voltage and current waveforms are perfect sinusoids. However, because of the increased popularity of computers, personal electronics and fluorescent lighting, these waveforms quite often become distorted. This deviation from a perfect sine wave can be represented by harmonics—sinusoidal components having a frequency that is an integral multiple of the fundamental frequency (see Figure 6). Thus, a pure voltage or current sine wave has no distortion and no harmonics, and a non-sinusoidal wave has distortion and harmonics. To quantify the distortion, the term total harmonic distortion (THD) is used and expresses the distortion as a percentage of the fundamental voltage and current waveforms.

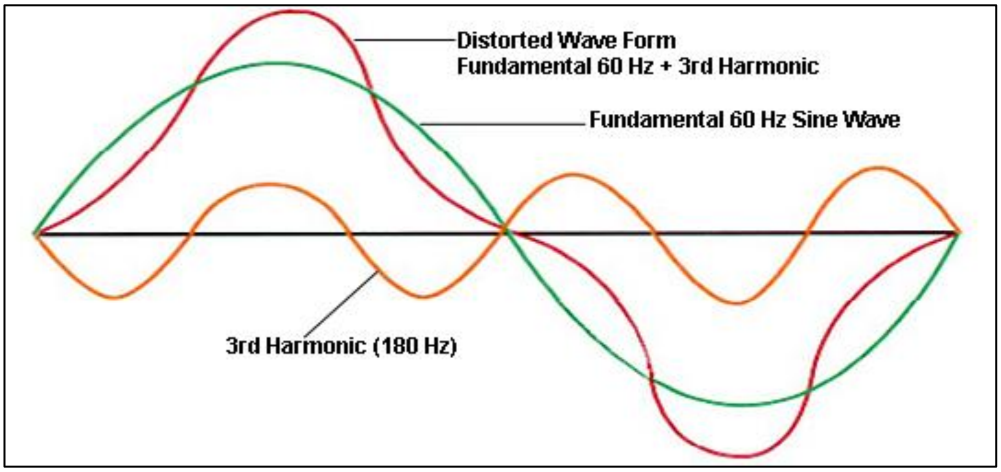

Figure 6: Distorted Waveform Composed of Fundamental and 3rd Harmonic. THD approximately 30%

While motor drives and commercial power supplies are most often blamed for harmonics, the most likely culprits in the typical power system is "switched-mode-power-supplies" such as those seen in personal computers and other electronically driven devices. Current harmonics are a problem because they cause increased losses in the customer and utility power system components. Single-phase non-linear loads, like personal computers, electronic ballasts for fluorescent lights and other electronic equipment, generate odd harmonics (i.e. 3^{rd}, 5^{th}, 7^{th}, 9^{th}, etc.). The troublesome harmonics for single-phase loads are the $3^{rd}$and odd multiples of 3 (9^{th}, 15^{th}, etc.). These harmonics can also be out of phase with the primary current as seen in Figure 7 that results in complex and unusual wave forms. Therefore, nonsinusoidal waveforms consist of, and can be broken down into, some finite number of pure sine waves.

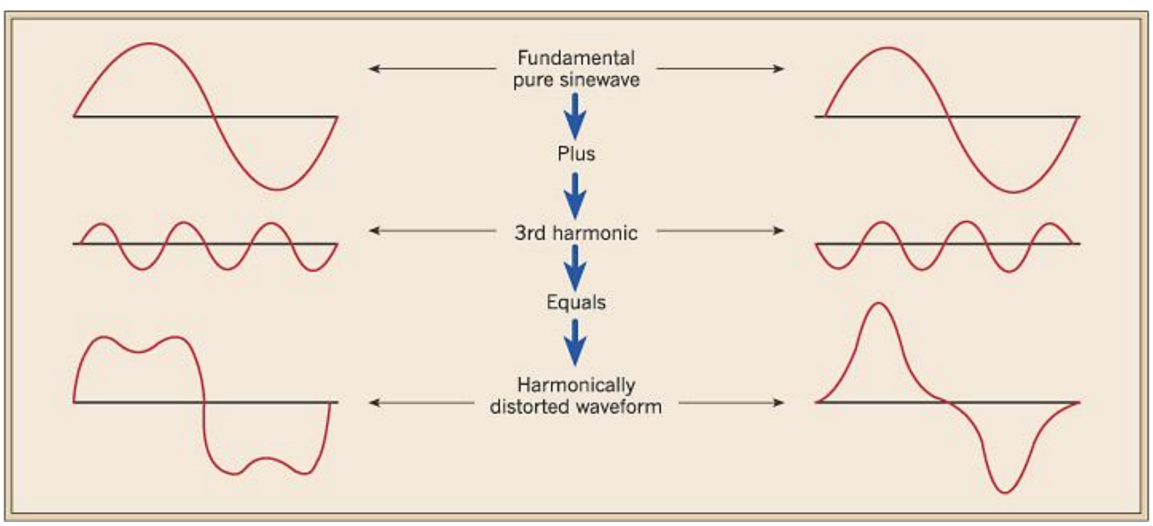

Figure 7: Distorted Wave Forms based on wave forms with different frequency, amplitude and timing.

As the current distortion is conducted through the normal system wiring, it creates voltage distortion according to Ohm's Law. While current distortion travels only along the power path of the non-linear load, voltage distortion affects all loads connected to that particular bus or phase. Each harmonic current in a facility's electrical distribution system will cause a voltage at the same harmonic to exist when the harmonic current flows into an impedance. This results in voltage harmonics appearing at the load bus. For example, a 3^{rd} harmonic current will produce a 3^{rd} harmonic voltage, a 9^{th} harmonic current will produce a 9^{th} harmonic voltage, etc.

While motor drives and commercial power supplies are most often blamed for harmonics, the most likely culprits in the typical power system is "switched-mode-power-supplies" such as those seen in personal computers and other electronically driven devices. The typical office can have as much as 50% of its load being determined by devices of this type. Operation of these devices represents a double-edged sword. Although they provide greater efficiency, they can also cause serious consequences to power distribution systems — in the form of harmonic distortion.

Electronic equipment (switching power supplies) draws current differently than non-electronic equipment. Instead of a load having a constant impedance drawing current in proportion to the sinusoidal voltage, electronic devices change their impedance by switching on and off near the peak of the voltage waveform. Switching loads on and off during part of the waveform results in short, abrupt, nonsinusoidal current pulses during a controlled portion of the incoming peak voltage waveform. These abrupt pulsating current pulses introduce unanticipated reflective currents (harmonics) back into the power distribution system. As mentioned earlier these currents operate at frequencies other than the fundamental 60 Hz. Harmonic currents can be likened to the vibration of water in a water line when a valve is open and closed suddenly.

Current distortion affects the power system and distribution equipment. It may directly or indirectly cause the destruction of loads or loss of product. From the direct perspective, current distortion may cause transformers to overheat and fail even though they are not fully loaded. Conductors and conduit systems can also overheat leading to open circuits and downtime.

Another indirect problem introduced by current distortion is called resonance. Certain current harmonics may excite resonant frequencies in the system. This resonance can cause extremely high harmonic voltages, possibly damaging sensitive electronic equipment. As the current distortion is conducted through the normal system wiring, it creates voltage distortion according to Ohm's Law. While current distortion travels only along the power path of the non-linear load, voltage distortion affects all loads connected to that particular bus or phase.

Voltage distortion directly affects loads. Distorted voltage can cause motors to overheat and vibrate excessively. It can also cause damage to the motor shaft. Even non-linear loads are prey to voltage distortion. Equipment ranging from computers to electronically-ballasted fluorescent lights may be damaged by voltage distortion.

The actual problems of any building will vary, depending on the types and number of installed harmonic producing loads. Most buildings can withstand nonlinear loads of up to 15% of the total electrical system capacity without concern, but, when the nonlinear loads exceed 15% some non-apparent negative consequences can be expected. For buildings that have nonlinear loading of more than 25%, particular problems can be become apparent. The following is a short summary of most problems caused by harmonics:

1. Blinking of Incandescent Lights - Transformer Saturation
2. Flickering of Fluorescent Lights - Transformer Saturation
3. Computer Malfunction or Lockup - Voltage Distortion
4. Electronic Equipment Shutting down - Voltage Distortion
5. Static or Interference on Voice or Sound Communication - Harmonic Noise
6. Circuit Breakers Tripping - Inductive Heating and Overload
7. Fuses Blowing for No Apparent Reason - Inductive Heating and Overload
8. Motor Failures (overheating) - Voltage Drop
9. Overheating of Metal Enclosures - Inductive Heating

Miles per gallon is commonly used to measures the fuel efficiency of our cars. With electricity, the measurement of efficiency is called the **power factor**. Today, the average home in America operates at a power factor of 0.77, or in other words, twenty three percent of the electricity is wasted. Power factor is an important measurement for two main reasons. An overall power factor of less than 1 means that an electricity supplier has to provide more generating capacity than actually is required due to the

Power factor takes into account both the phase and wave-shape contributions to the difference between true and apparent power. Power factor relates watts to volt-amperes:

Where: kW = kVA x PF   or   VA = V_{RMS} x A_{RMS}
kW = true power (sometimes called active power or real power) in watts measured with a wattmeter
kVA = apparent power, the product of rms volts and rms amps and cannot be used by the load on the circuit so is either fed back into the power system or released as heat
PF = power factor

Alternatively, Power factor is defined as the ratio of real power to apparent power. This definition is often mathematically represented as:

$$PF = kW/kVA$$

where the numerator is the active (real) power and the denominator is the (active+ reactive) or apparent power.

To illustrate further let's suppose we want to fill a water tank with water, one bucket at a time, by climbing a ladder, carrying a bucket of water and pouring the water into the tank. Once we pour the bucket of water into the tank, we have to go down the ladder to get more water. In this one cycle of going up the ladder and coming down we have done some work or the energy required to go up is more than the energy required for coming down.

If the ladder was climbed with an empty bucket (no real load or work), and and then came down with the same bucket there would not have been any work performed. The energy for upward and downward motion is the same. Though I have not done any work – worth paying for – it required some energy. That is, the energy that it takes to go up and down a ladder carrying nothing either way requires reactive power, but no real power. The energy that it takes to go up a ladder carrying something and come down without carrying anything requires both real power and reactive power.

Reactive power does not contribute to the work being done to any load attached to a circuit even though it is being provided to that load. The higher the percentage of reactive power, the less real work is being done and as a result a lower power factor.

Electrical engineers use circuits that force the current waveform to be near sinusoidal and in-phase with the voltage to decrease harmonics and increase power factor. These circuits are known as power-factor correction circuits. These can be beneficial if you can answer yes to any of the following questions:

- Is your furnace, central air conditioner or heat pump more than three years old?
- Do you have a well?
- Do you have a pool?
- Do you have a hot tub or jacuzzi?
- Do you have a number of appliances in your home?
- Do you have more than one refrigerator or freezer?
- Do you have an air conditioner?
- Are any of your major appliances (refrigerator, freezer, washer, dryer, dishwasher) not energy star rated?

Use of power correction circuits or devices is becoming increasingly popular due to the recent use of smart meters being used by power companies. A tariff is now being applied to electrical bills based on power factor. Since one of the leading causes of low power factor is the presence of reactive power due to harmonics, it is becoming increasingly important to look at what harmonics are and how to decrease the amount of reactive power and increase the amount of real power in the electrical system.

Summary:

The purpose of this paper has been to introduce the reader to some of the basic principles and terms used in understanding AC (alternating current) circuits as well as the concept of harmonic distortion and its impact on those types of circuits. In addition, with the advent of smart meters and the accompanying charges related to low power factor due to electrical distortion caused by harmonics, it is important for consumers and businesses to understand what harmonics due and how it impacts the efficiency of their electrical system so as to not be charged due to low power factor. Hopefully this paper has contributed to a better understanding of electrical harmonics and why it’s important to consider modern energy management systems that incorporate power correction circuits.

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