Power System Harmonics

What are power system harmonics?

Ideally, voltage and current waveforms are perfect sinusoids. However, because of the increased popularity of electronic and other non-linear loads, 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 1)*. 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. The term expresses the distortion as a percentage of the fundamental (pure sine) of voltage and current waveforms.
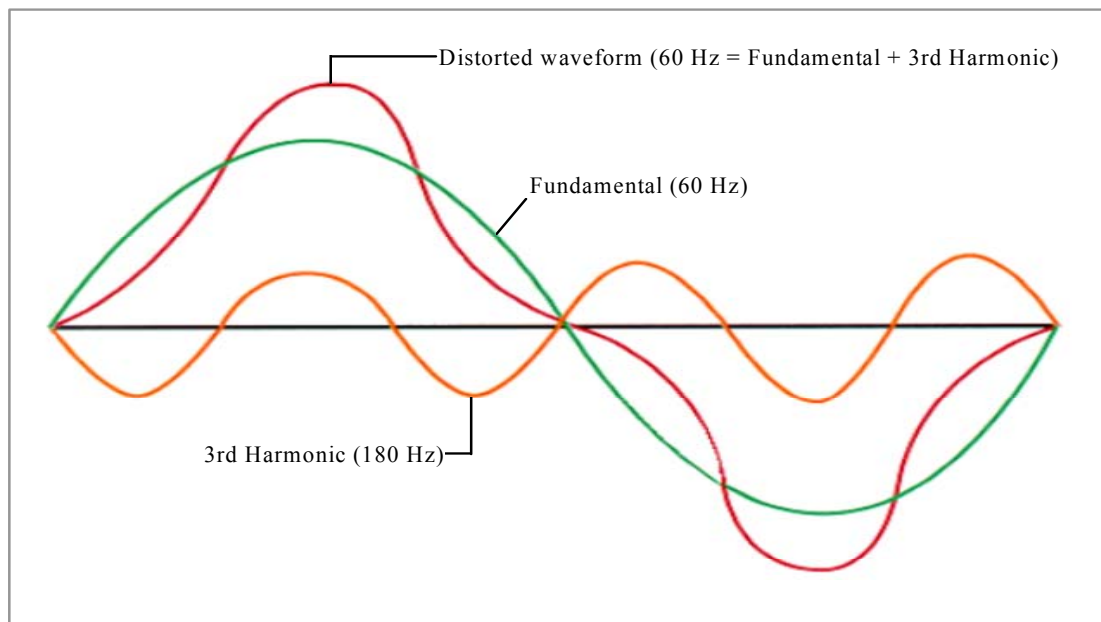
Distorted waveform (60 Hz = Fundamental + 3rd Harmonic)

Fundamental (60 Hz)

3rd Harmonic (180 Hz)

Figure 1: Distorted Waveform Composed of Fundamental and 3rd Harmonic. THD approximately 30%

Why are voltage and current harmonics a problem?

Current harmonics are a problem because they cause increased losses in the customer and utility power system components. Transformers are especially sensitive to this problem and may need to be derated to as much as 50% capacity when feeding loads with extremely distorted current waveforms (current total harmonic distortion above 100%).

ANSI/IEEE C57.110-1986 (IEEE Recommended Practice for Establishing Transformer Capacity When Supplying Nonsinusoidal Load Currents) states that a transformer subject to nonsinusoidal load current having more than 5% total harmonics distortion needs to be derated. However, when current THD is below 15%, the derating of the transformer would be so small that it can be neglected. On the other hand, when current THD exceeds 15%, the transformer capability should be evaluated by a professional using IEEE recommendations. It is important to clarify that these IEEE recommendations do not apply to transformers especially designed to feed nonsinusoidal loads. Underwriters Laboratories (UL) tests and rates this special type of transformer, also called a "K-factor" transformer.

Loads with highly distorted current waveforms also have a very poor power factor; because of this, they use excessive power system capacity and could be a cause of overloading. Voltage source electronic adjustable speed drives (ASD) often have a total power factor[1] of approximately 65% because of the highly distorted current. This total power factor could be corrected to approximately 85% using line-side chokes (reactors) on the drive. The chokes limit the rate of rise and the peak value of the line current, dramatically reducing the current THD.

In addition, current harmonics can distort the voltage waveform and cause voltage harmonics. Voltage distortion affects not only sensitive electronic loads but also electric motors and capacitor banks. In electric motors, negative sequence harmonics (i.e. 5th, 11th, 17th), so called because their sequence (ABC or ACB) is opposite of the fundamental sequence *(see Figure 2),* produce rotating magnetic fields. These fields rotate in the opposite direction of the fundamental magnetic field and could cause not only overheating but also mechanical oscillations in the motor-load system.
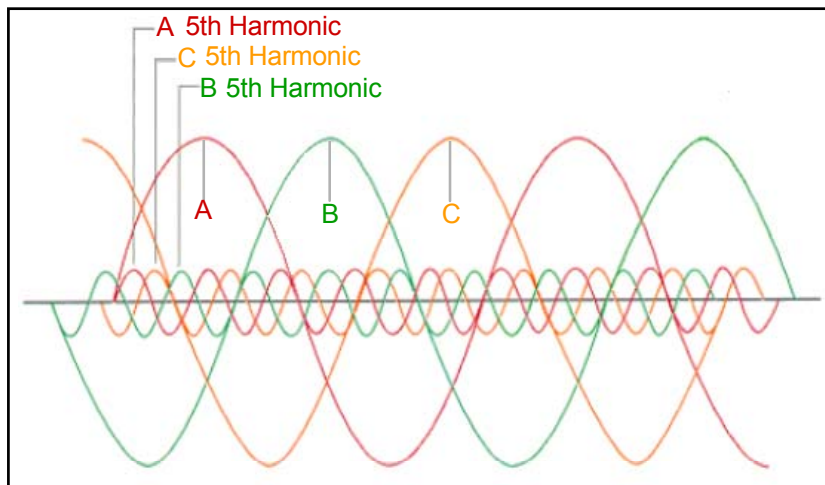

Figure 2: Balanced 3-Phase voltage with 5th harmonic. Note the inverted sequence of the 5th harmonic.

[1] Defined by kW divided by KVA, not the cosine of the angle between the fundamental of the voltage and the fundamental of the current which is close to unity on ASDs and often advertised by vendors.

The problem with capacitor banks, on the other hand, is that the reactance (impedance) of a capacitor bank decreases as the frequency increases[2]. This causes the bank to act as a sink or trap for higher harmonic currents from the surrounding customer and/or utility system. The effect is increased current, increased heating and dielectric stresses that could lead to capacitor bank failure.

Single-phase load harmonics vs. three-phase load harmonics

Single-phase non-linear loads, like personal computers, electronic ballasts and other electronic equipment, generate odd harmonics (i.e. 3rd, 5th, 7th, 9th, etc.). The troublesome harmonics for single-phase loads are the 3rd and odd multiples of the 3rd (9th, 15th, etc.). These harmonics are called "triplens" and because the A-phase triplen harmonics, B-phase triplen harmonics and C-phase triplen harmonics are all in the phase with each other. They will add rather than cancel on the neutral conductor of a 3-phase 4-wire system. This can overload the neutral if it is not sized to handle this type of load.

Additionally, triplen harmonics cause circulating currents on the delta winding of a delta-wye transformer configuration. When current triplen harmonics on the neutral of a 3-phase 4-wire system reach the transformer, they are reflected to the delta-connected primary where they circulate. The result is transformer heating similar to that produced by unbalanced 3-phase current.

On the other hand, 3-phase non-linear loads like 3-phase ASDs, 3-phase DC drives, 3-phase rectifiers, etc., for not generate current triplen harmonics (3rd, 9th, 15th, etc.). These types of loads generate primarily 5th and 7th current harmonics and a lesser amount of 11th, 13th, and higher order.

How do you check for harmonic currents?

When non-linear loads are a considerable part of the total load in the facility (more than 20%), there is a chance of a harmonics problem. Another consideration is the amount of current distortion produced by the non-linear loads. Electronic ballasts, for example, come with current THD ranging from 6% to 100%. It is important to avoid electronic ballasts with more than 20% current THD. PWM[3] ASDs typically produce close to 100% current THD, which can be reduced to less than half by installing inexpensive 3% impedance line-side reactors (chokes).

Another important way to check for harmonic currents is to measure the current in the neutral of a 3-phase 4-wire system. If the neutral current is considerably higher than the value predicted from the imbalance in the phase currents, there is a good possibility of heavy presence of triplen harmonics.

Other signs of current harmonics include inexplicable higher-than-normal temperatures in the transformer, voltage distortion and high crest factor.

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[2] Harmonics have higher frequency than the fundamental (60Hz); the 5th harmonic, or example, has a frequency of 300 HZ.
[3] Pulse Width Modulation is the most common technology used in ASDs under 200HP.

What is crest factor?

The crest factor of any waveform is the ratio of the peak value to the RMS value.[4] In a perfect sine wave, the crest factor is 1.414. Crest factors different than 1.414 indicate distortion in the waveform. Typically distorted current waveforms have crest factors higher than 1.414 *(see Figure 3)*, and distorted voltage waveforms have crest factors lower than 1.414. Distorted voltage waveforms with crest factors lower than 1.414 are called "flat top" voltage waveforms.
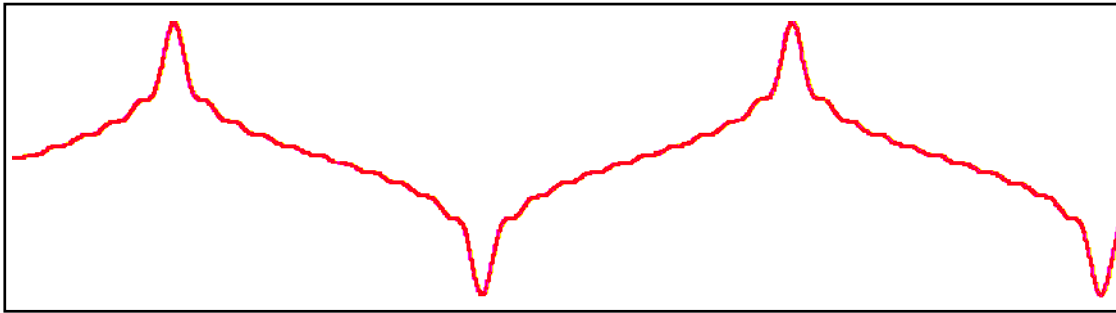

Figure 3. Typical current waveform for a single-phase non-linear load with a switched-mode power supply. This kind of waveform is characterized by high crest factors, usually between 2.2 and 3.0

The Computer and Business Equipment Manufacturers Association (CBEMA) recommends a method for derating transformers based on the current crest factor. CBEMA defines the transformer harmonic-derating factor (THDF) as the ratio of 1.414 to the transformer current crest factor. The derated KVA of the transformer would be the nominal KVA of the transformer multiplied by the THDF. This method, however, should only be applied when the distortion in the current is caused by single-phase, non-linear loads (like personal computers) and other office equipment. Also, when using this method, the crest factor measurements should always be made in the secondary of the transformer. A more complete method for transformer derating is the one described by ANSI/IEEE C57.110-1986.

What kind of equipment is needed to measure distorted waveforms?

A digital oscilloscope is needed to measure the wave shape, THD and amplitude of each harmonic. However, if we simply want to measure the RMS value of the waveform, a "True-RMS" multimeter will suffice.

The term "True-RMS" is used because not all instruments give correct readings when measuring distorted waveforms. The majority of low-cost portable instruments are "average responding-RMS calibrated." These instruments give correct readings for distortion-free sine waves and will typically read low when the current waveform is distorted. Most portable instruments with true RMS capabilities are labeled or listed as such in their owner manuals.

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[4] Typically when we measure voltage and current, we are measuring RMS values.

Does having harmonics in the power system always mean trouble?

Harmonics only mean trouble if the power system is not designed to handle them. High harmonic neutral currents are a problem only if the neutral is not properly sized. Current harmonics are not a problem to a transformer if it is derated appropriately. Even some voltage distortion below 8% THD at the point of utilization) is acceptable as long as sensitive equipment is not affected. However, it is always important to be aware of the presence of harmonics and to try to minimize them by purchasing low distortion electronic ballasts and reactors for PWM ASDs. This will not only keep the harmonics in check and improve the power factor in the facility, but will also save energy by reducing losses on power system components. In addition, any time there is a considerable increase of non-linear loads, it is important to check power system components to prevent problems.

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