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Common power quality factors affecting transformers

Application Note

Commercial buildings commonly have a 208/120 V transformer in a delta-wye configuration to feed receptacles. Single-phase, non-linear loads connected to the receptacles produce triplen harmonics, which add up in the neutral. When this neutral current reaches the transformer, it is reflected into the delta primary winding where it causes overheating and transformer failures.

Another transformer problem results from core loss and copper loss. Transformers are normally rated for a 60 Hz phase current load only. Higher frequency harmonic currents cause increased core loss due to eddy currents and hysteresis, resulting in more heating than would occur at the same 60 Hz current.

Transformers supplying non-linear loads should be checked periodically to verify operation within acceptable limits. Transformers are also critical to the integrity of the grounding system.

Factors

1. Transformer loading (kVA)

Start by measuring kVA and determine wether the transformer load is balanced.

- Connect voltage probes on Phase 1 and Neutral and clamp current probe on same phase. Repeat for Phase 2 and 3.
- Use a single phase power quality analyzer to read kVA of each phase and sum all three for total transformer kVA.
- Or, connect all four current clamps and all five test leads for the three phase power quality analyzer to read kVA for each phase and the total.
- Compare actual load kVA to nameplate kVA rating to determine % loading.

When using a single phase analyzer on a balanced load, a single measurement is sufficient. Transformers loaded at less than 50 % are generally safe from overheating. However, as loads increase, measurements should be made periodically. At some point the transformer may require derating.

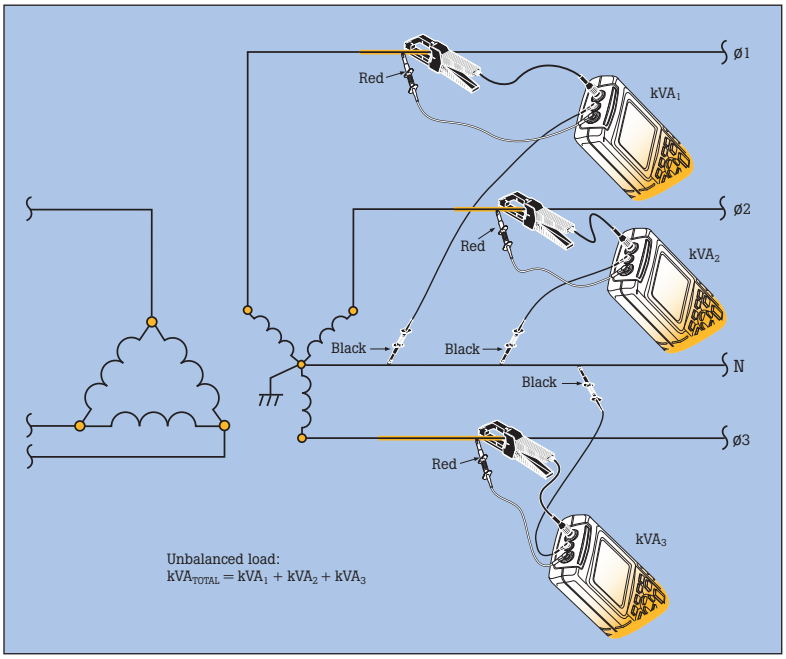

Figure 1. Measuring transformer load (unbalanced) using a single phase power quality analyzer.

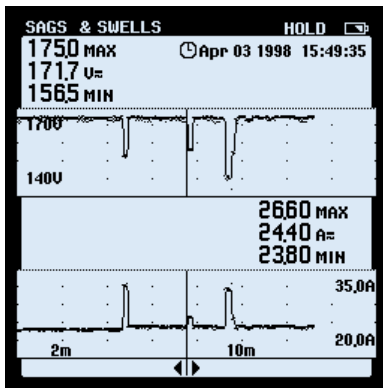

Figure 2. Harmonic spectrum.

2. Harmonic spectrum

The harmonic spectrum of the secondary (load) current will give us an idea of the harmonic orders and amplitudes present:

- In a transformer feeding single-phase loads, the principal harmonic of concern is the 3rd. The 3rd will add arithmetically in the neutral and circulate in the delta primary of a delta-wye transformer. The good news is that the delta-wye tends to isolate the rest of the system from the 3rd (though not the 5th, 7th or other non-triplen harmonics). The bad news is that the transformer pays the price with additional heat.

Table 1: Measurements at the distribution transformer

Measurement	Look for
1. kVA	Transformer loading. If loading exceeds 50 %, check for harmonics and possible need for derating.
2. Harmonic spectrum	• Harmonic orders/amplitudes present: 3rd harmonic (single-phase loads) 5th, 7th (primarily three-phase loads) • Resonance of higher order harmonics • Effectiveness of harmonic trap filters
3. THD	Harmonic loading within limits: Voltage %THD < 5 % Current %THD < 5-20 % (Table 2)
4. K-factor	Heating effect on transformer from harmonic loads
5. Ground currents	• Objectionable ground currents are not quantified but are prohibited by the NEC • Neutral-ground bond in place • ESG (Electrical Safety Ground) connector to ground electrode (typically building steel) in place

- In a transformer feeding three-phase loads which include drives or UPS systems with 6-pulse converters, the 5th and 7th harmonic will tend to predominate. Excessive 5th is of particular concern because it is negative sequence. It will tend to produce counter-torque and overheating in polyphase motors.
- Harmonic amplitudes normally decrease as the frequency goes up. If one frequency is significantly higher in amplitude than lower frequencies, we can suspect a resonant condition at that frequency. If such a condition is detected, be sure to take readings at capacitor banks to see if the caps are experiencing overcurrent/overvoltage conditions.
- Before-and-after harmonic spectrum measurement is extremely valuable to determine if harmonic mitigation techniques, like trap filters, which are tuned to specific frequencies, are sized properly and are working as expected.
- Different harmonic frequencies affect equipment in different ways (see below).

Harmonic Sequences

Name	F	2nd	3rd	4th	5th	6th	7th	8th	9th
Frequency	60	120	180	240	300	360	420	480	540
Sequence	+	–	0	+	–	0	+	–	0

Rule: If waveforms are symmetrical, even harmonics disappear.

Effects of Harmonic Sequences

Sequence	Rotation	Effects (from skin effect, eddy currents, etc.)
Positive	Forward	Heating of conductors, circuit breakers, etc.
Negative	Reverse	Heating as above + motor problems
Zero	None	Heating, + add in neutral of 3-phase, 4-wire system

Harmonics are classified as follows:

1. Order or number: Multiple of fundamental, hence, 3rd is three times the fundamental, or 180 Hz.
2. Odd or even order: Odd harmonics are generated during normal operation of nonlinear loads. Even harmonics only appear when there is dc in the system. In power circuits, this only tends to occur when a solid state component(s), such as a diode or SCR, fails in a converter circuit.
3. Sequence:
   - Positive sequence. Main effect is overheating.
   - Negative sequence. Create counter-torque in motors, i.e., will tend to make motors go backwards, thus causing motor overheating. Mainly 5th harmonic.
   - Zero sequence. Add in neutral of 3-phase, 4-wire system. Mainly 3rd harmonic.

3. Total Harmonic Distortion

Check for THD of both voltage and current:

- For voltage, THD should not exceed 5 %
- For current, THD should not exceed 5-20 % (see Odd Harmonics table)

IEEE 519 sets limits for harmonics at the PCC (Point of Common Coupling) between the utility and customer (EN50160 is the European standard). IEEE 519 is based on THD measurements taken at the PCC. Technically, the PCC is the primary of the utility supply transformer (although there are cases where the PCC is at the secondary if the secondary feeds a number of customers). In practice, these measurements are often made at the secondary of the customer's main transformer, since that is the point most easily accessible to all parties (and also since that is generally a Low Voltage measurement).

Some PQ practitioners have broadened the concept of PCC to include points inside the facility, such as on the feeder system, where harmonic currents being generated from one set of loads could affect another set of loads by causing significant voltage distortion. The emphasis is on improving in-plant PQ, rather than on simply not affecting utility PQ.

3a. Voltage THD

THD has a long history in the industry. The underlying concept is that harmonic currents generated by loads will cause voltage distortion (E=IZ) as they travel through the system impedance. This voltage distortion then becomes the carrier of harmonics system-wide: if, for example, the distorted voltage serves a linear load like a motor, it will then create harmonic currents in that linear load. By setting maximum limits for voltage distortion, we set limits for the system-wide impact of harmonics.

Table 2: IEEE 519 limits for harmonic currents at the point of common coupling (All percentages are % of IL, maximum demand load current)

	Odd Harmonics					
SCR=Isc/IL	**<11**	**11-17**	**17-23**	**23-35**	**>35**	**TDD**
<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 %

SCR = Short circuit ratio (Isc/I_L)
Isc = Available short circuit current at PCC
$\mathbf{I_L}$ = Maximum demand load current (rms amps)
TDD = Total demand distortion

Note: IEEE allows these limits to be exceeded for up to one hour per day, while IEC allows them to be exceeded for up to 5 % of the time.

The concept of $\mathbf{I_L}$, maximum demand load current, is key to using Table 2. For existing facilities, I_L is calculated by averaging the maximum demand current for 12 consecutive months (information available in billing records). For new installations, $\mathbf{I_L}$ must be estimated. Transformer rating could be used and would be the most conservative estimate (i.e., it would result in the lowest SCR), since it assumes that the transformer would be used at full capacity.

Voltage distortion, however, depends on source impedance, i.e., on system capacity. It was quite possible for the first (or second or third) customer to inject significant harmonic currents into the system and not cause voltage THD to exceed 5 %. The entire responsibility for harmonic mitigation could fall on the last customers unlucky enough to push V-THD over 5 %, even if their particular harmonic load was relatively small–literally the straw that broke the camel's back.

3b. Current THD

To restore some fairness to this situation, standards for maximum current harmonics were added, since current harmonics were under the control of the local facility and equipment manufacturer (remember, harmonic "loads" act as "generators" of harmonics). This emphasis on the mitigation of current harmonics at the load, including the not-too-distant requirement that the load generate virtually no harmonics, has become the prevailing regulatory philosophy. It puts the burden of responsibility on the local site and on the equipment manufacturers.

For equipment manufacturers, IEC 1000-3-2, published in 1995, is the applicable standard. It specifies maximum current levels out to the 40th harmonic. Its expected effective date is projected to be early 2001. To certify for CE, a requirement for the European market, manufacturers will have to meet this standard. This edict will have a major effect on power supply design.

For the facility, IEEE 519 is the standard (EN 50160 in Europe). The limits set in IEEE 519 for harmonic currents depend on the size of the customer relative to the system capacity. (See Table 2.)

The SCR (Short Circuit Ratio) is a measure of the electrical size of the customer in relation to the utility source. The smaller the customer (higher SCR), the less the potential impact on the utility source and the more generous the harmonic limits. The larger the customer (smaller SCR), the more stringent the limits on harmonic currents.

3c. TDD and THD

TDD (Total Demand Distortion) is the ratio of the current harmonics to the *maximum* load (I_L). It differs from THD in that THD is the ratio of harmonics to the *instantaneous* load. Why TDD instead of THD? Suppose you were running a light load (using a small fraction of system capacity), but those loads were nonlinear. THD would be relatively high, but the harmonic currents actually being generated would be low, and the effect on the supply system would in fact be negligible. So who cares? TDD acknowledges this, and allows harmonic load to be referenced to the maximum load: if harmonic load is high at maximum load, then we have to watch out for the effect on the supply source. So where does that leave current THD as a useful measurement. *The closer the current THD reading(s) is taken to conditions of maximum load, the closer it approximates TDD.*

Table 3

Inspection of Transformer Ground	Explanation
Check for *N-G bond.*	A high impedance N-G bond will cause voltage fluctuation.
Check for grounding conductor and integrity of connection to building steel (exothermic weld).	Fault currents will return to the source via these connections, so they should be as low impedance as possible.
Check for tightness of all *conduit* connections.	If the conduit is not itself grounded, it will tend to act as a "choke" for higher frequencies and limit fault current (remember that fault currents are not just at 60 Hz but have high-f components).
Measure for *ground currents* on the grounding conductor.	Ideally there should be none, but there will always be some ground current due to normal operation or leakage of protective components (MOVs, etc.) connected from phase or neutral to ground. However, anything above an amp should be cause for suspicion (there is no hard and fast rule, but experienced PQ troubleshooters develop a feel for possible problems).

A final word on measuring THD: the one place not to apply the specs is at the individual harmonic-generating load. This will always be a worst-case distortion and a misleading reading. This is because as harmonics travel upstream, a certain amount of cancellation takes place (due to phase relationships which, for practical purposes, are unpredictable). Measure at a PCC, or at the source transformer.

4. K-factor

K-factor is a specific measure of the heating effect of harmonics in general and on transformers in particular. It differs from the THD calculation in that it emphasizes the frequency as well as the amplitude of the harmonic order. This is because heating effects increase as the square of the frequency.

A K-4 reading would mean that the stray loss heating effects are four times normal. A standard transformer is, in effect, a K-1 transformer. As with THD, it is misleading to make a K-factor reading at the load or receptacle because there will be a certain amount of upstream cancellation; transformer K-factor is what counts. Once the K-factor is determined, choose the next higher trade size. K-factor rated transformers are available in standard trade sizes of K-4, K-13, K-20, K-30, etc. K-13 is a common rating for a transformer supplying office loads. The higher ratings tend to be packaged into PDUs (Power Distribution Units) which are specially designed to supply computer and other PQ-sensitive installations.

5. Ground currents

Two prime suspects for excessive ground current are illegal N-G bonds (in subpanels, receptacles or even in equipment) and so-called isolated ground rods:

- Subpanel N-G bonds create a parallel path for normal return current to return via the grounding conductor. If the neutral ever becomes open, the equipment safety ground becomes the only return path; if this return path is high impedance, dangerous voltages could develop.
- Separate isolated ground rods almost always create two ground references at different potentials, which in turn causes a "ground loop" current to circulate in an attempt to equalize those potentials. A safety and equipment hazard is also created: in the case of lightning strikes, surge currents travelling to ground at different earth potentials will create hazardous potential differences.

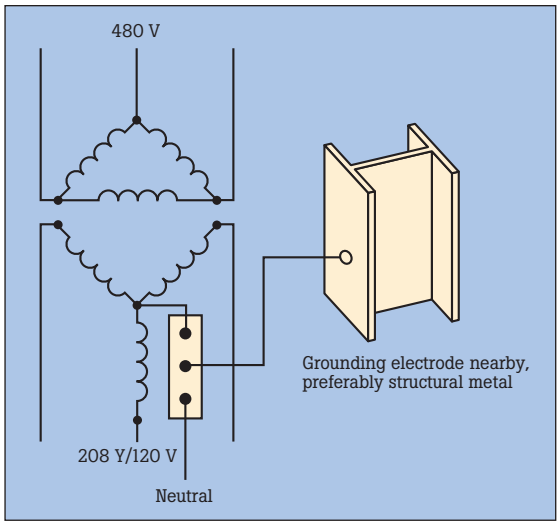

Figure 3. Transformer grounding.

Transformer grounding

The proper grounding of the transformer is critical. (Table 3.3.) NEC Article 250 in general and 250-26 in particular address the grounding requirements of the SDS.

- A ground reference is established by a grounding connection, typically to building steel (which, in turn, is required to be bonded to all cold water pipe, as well as any and all earth grounding electrodes). Bonding should be by exothermic weld, not clamps that can loosen over time. The "grounding electrode conductor" itself should have as low a high-frequency impedance as possible (not least because fault current has high frequency components). Wide, flat conductors are preferred to round ones because they have less inductive reactance at higher frequencies. For the same reason, the distance between the "grounding electrode conductor connection to the system" (i.e., N-G bond at the transformer) and the grounding electrode (building steel) should be as short as possible: in the words of the Code, "as near as practicable to and preferably in the same area..."
- The neutral and ground should be connected at a point on the transformer neutral bus. Although permitted, it is not advisable to make the N-G bond at the main panel, in order to maintain the segregation of normal return currents and any ground currents. This point at the transformer is the only point on the system where N-G should be bonded.

Solutions

There are a number of solutions for transformer-related PQ problems:

- Install additional distribution transformers (Separately Derived Systems)
- Derate transformers
- Install K-rated transformers
- Used forced air cooling

1. Separately Derived System (SDS)

The distribution transformer is the supply for a Separately Derived System (SDS), a term which is defined in the NEC (Article 100). The key idea is that the secondary of this transformer is the new source of power for all its downstream loads: this is a powerful concept in developing a PQ distribution system. The SDS accomplishes several important objectives, all beneficial for PQ:

- It establishes a new *voltage reference*. Transformers have taps which allow the secondary voltage to be stepped up or down to compensate for any voltage drop on the feeders.
- It *lowers source impedance* by decreasing, sometimes drastically, the distance between the load and the source. The potential for voltage disturbances, notably sags, is minimized.
- It achieves isolation. Since there is no electrical connection, only magnetic coupling, between the primary and secondary, the SDS isolates its loads from the rest of the electrical system. To extend this isolation to high frequency disturbances, specially constructed "isolation transformers" provide a shield between the primary and secondary to shunt RF (radio frequency) noise to ground. Otherwise, the capacitive coupling between primary and secondary would tend to pass these high-frequency signals right through.
- A new ground reference is established. Part of the definition of the SDS is that it "has no direct electrical connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system." (NEC 100) The opportunity exists to segregate the subsystem served by the SDS from ground loops and ground noise upstream from the SDS, and vice versa.

2. K-rated transformers

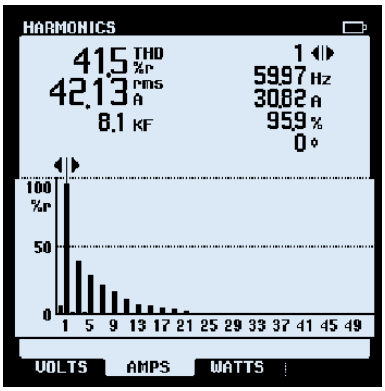

Figure 4. Typical K-factor in commercial building.

Harmonics cause heating in transformers, at a greater rate than the equivalent fundamental currents would. This is because of their higher frequency. There are three heating effects in transformers that increase with frequency:

- **Hysteresis.** When steel is magnetized, magnetic dipoles all line up, so that the North poles all point one way, the South poles the other. These poles switch with the polarity of the applied current. The higher the frequency, the more often the switching occurs, and, in a process analogous to the effects of friction, heat losses increase.
- **Eddy currents.** Alternating magnetic fields create localized whirlpools of current that create heat loss. This effect increases as a square of the frequency. For example, a 3rd harmonic current will have nine times the heating effect as the same current at the fundamental.
- **Skin effect.** As frequency increases, electrons migrate to the outer surface of the conductor. More electrons are using less space, so the effective impedance of the conductor has increased; at the higher frequency, the conductor behaves as if it were a lower gauge, lower ampacity, higher impedance wire.

The industry has responded with two general solutions to the effects of harmonics on transformers: install a K-factor rated transformer or derate a standard transformer. Let's look at pros and cons of the K-factor approach first. K-factor is a calculation based on the rms value, %HD (harmonic distortion) of the harmonic currents, and the square of the harmonic order (number). It is not necessary to actually perform the calculation because a harmonic analyzer will do that for you. The important thing to understand is that the harmonic

order is squared in the equation and that is precisely where the high- frequency heating effects, like eddy current losses, are taken into account.

K-rated transformers are designed to minimize and accommodate the heating effects of harmonics. K-rated transformers do not eliminate harmonics (unless additional elements like filters are added). They accommodate harmonics with techniques such as the use of a number of smaller, parallel windings instead of a single large winding: this gives more skin for the electrons to travel on. The primary delta winding is up-sized to tolerate the circulating third harmonic currents without overheating. The neutral on the secondary is also up-sized for third harmonics (typically sized at twice the phase ampacity).

Application issues with K-factor transformers

K-rated transformers have been widely applied, but there are certain issues with them. Many consultants do not see the need for using transformers with a rating higher than K-13 although K-20 and higher might be supplied as part of an integrated Power Distribution Unit (PDU). Also, early applications sometimes overlooked the fact that K-rated transformers necessarily have a lower internal impedance. Whereas a standard transformer has an impedance typically in the 5-6 % range, K-rated transformers can go as low as 2-3 % (lower as the K-rating increases). In retrofit situations, where a standard transformer is being replaced by a K-rated transformer of equivalent kVA, this may require new short circuit calculations and re-sizing of the secondary overcurrent protective devices.

3. Derating standard transformers

Some facilities managers use a 50 % derating as a rule-of-thumb for their transformers serving single-phase, predominantly nonlinear loads. This means that a 150 kVA transformer would only supply 75 kVA of load. The derating curve, taken from IEEE 1100-1992 (Emerald Book), shows that a transformer with 60 % of its loads consisting of SMPS (switched-mode power supplies), which is certainly possible in a commercial office building, should in fact be derated by 50 %.

The following is an accepted method for calculating transformer derating for single-phase loads only. It is based on the very reasonable assumption that in single-phase circuits, the third harmonic will predominate and cause the distorted current waveform to look predictably peaked.

Use a *true-rms meter* to make these current measurements:

1. Measure rms and peak current of each secondary phase. (Peak refers to the instantaneous peak, not to the inrush or "peak load" rms current).
2. Find the arithmetic average of the three rms readings and the three peak currents and use this average in step 3 (if the load is essentially balanced, this step is not necessary).
3. Calculate Xformer Harmonic Derating Factor:
   xHDF = (1.414 * IRMS) / IPEAK
4. Or, since the ratio of Peak/RMS is defined as Crest Factor, this equation can be rewritten as:
   xHDF = 1.414 / CF
   If your test instrument has the capability, measure the CF of each phase directly. If the load is unbalanced, find the average of the three phases and use the average in the above formula.

Since a sine wave current waveform has a CF=1.414, it will have an xHDF=1; there will be no derating. The more the 3rd harmonic, the higher the peak, the higher the CF. If the CF were 2.0, then the xHDF=1.414 / 2 =.71. A CF=3 gives us an xHDF =.47. A wave with CF=3 is about as badly distorted a current waveform as you can expect to see on a single-phase distribution transformer.

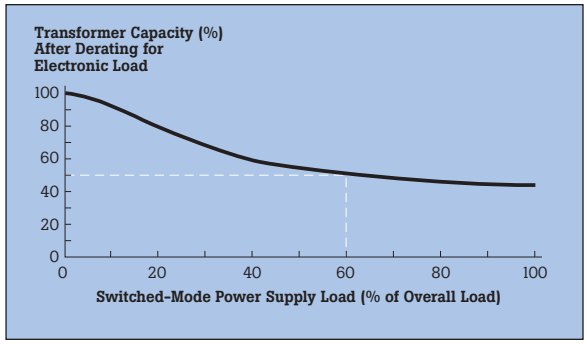

Figure 5. Transformer derating curve (IEEE 1100-1992)

Caution: This method does not apply to transformers feeding three-phase loads, where harmonics other than the third tend to predominate and CF is not useful as a simple predictor of the amount of distortion. A calculation for three-phase loads is available in ANSI/IEEE C57.110. However, there is some controversy about this calculation since it may underestimate the mechanical resonant vibrations that harmonics can cause, and that accelerate transformer wear above and beyond the effects of heat alone.

4. Forced air cooling

If heat is the problem, cooling is the solution. Break out the fan, turn it on the transformer and use forced air cooling. Some experienced hands figure that's worth 20-30 % on the up side. In any case, it can only help.

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