PRINT ME

SAVE AS

PQTN COMMENTARY

Commercial Office Wiring
Nonlinear Loads
Harmonic-Related Heating

Power Quality Testing Network

Published by the EPRI Power Electronics Applications Center   No. 1   December 1996

Harmonic Currents in Building Wiring

Introduction

The increasingly abundant use of electronic appliances is changing the design requirements for building wiring. This change is especially true in commercial office buildings where three-phase circuits serve multiple single-phase electronic appliances. Prior to the 1980s, electrical wiring in office buildings was designed to serve a relatively light plug load (watts per electrical outlet) and a demand load (average building load over a specified period) of about five to six watts per square foot. Today, the increased use of electronic office appliances has significantly increased the demand load because these appliances tend to remain turned on a high percentage of the time. Additionally, multi-outlet power strips have made possible a significant increase in the number of appliances per outlet and thus a higher average plug load.

Although most electronic appliances are energy-efficient, they typically have a low power factor when all the harmonic frequencies are taken into account. The resulting harmonic currents increase the amps per watt drawn by electronic appliances. An abundance of harmonic current, coupled with a high demand load and heavy plug loads, may consume any spare current-carrying capacity designed into the building transformers and conductors. In an extreme case, the electrical system in a commercial building may be overburdened if it is not designed to accommodate numerous electronic appliances. Moreover, the National Electric Code does not dictate design procedures to protect wiring carrying harmonic-rich current.

The concern about such a potential overburden has increased within the last few years. Articles describing harmonic currents as monsters that devour wiring and transformers whet the concern. Literature about harmonics is replete with misinformation about how harmonic currents affect the power system. This PQTN Commentary is intended to present facts based upon measurements and experience and thereby dispel some of the myths about harmonic currents in building wiring.

Harmonic-Generating Loads

The modern office is brimming with electronic appliances that draw non-sinusoidal currents. These nonlinear plug-in appliances include personal computers, printers, monitors, fax machines, and photocopiers. Nonlinear equipment such as fluorescent lamps with electronic ballasts and high-efficiency HVAC (heating, venting, and air-conditioning) systems are also sources of harmonic currents in commercial buildings.

Branch-Circuit Appliances Table 1 on page 2 lists the current characteristics of single-phase appliances found in a typical commercial office building. For single-phase electronic appliances, the harmonic current may be higher than the fundamental current, indicating a total harmonic distortion of greater than 100 percent. Most of these appliances generate odd-numbered harmonics (third, fifth, seventh, and so on). Note that, generally, the higher the harmonic number, the less the current produced. Harmonic currents are highest when many single-phase nonlinear loads such as computers are connected to a few branch circuits. In fact, multiple computer work stations and the like are responsible for the higher levels of current in modern wiring systems.

As shown in Table 1, the current drawn by single-phase electronic appliances is typically rich in third harmonic. The presence of even-numbered harmonics is not at all typical and indicates either a malfunction of the appliance—which should be identified and removed or replaced—or an appliance with a half-wave rectifier such as an electric hand tool.

The relative power consumption of the electronic appliance and the percent of total harmonic distortion (THD) determine how much the appliance contributes harmonic current to the building wiring system. While some office loads may have a high percent of distortion, the actual amount of harmonic current they contribute to the building wiring may be insignificant. For example, the personal computer with 150 percent current THD draws less than one amp of harmonic current. In contrast, the microwave oven with only 45 percent current THD draws almost four amps of harmonic current. Many small electronic appliances, such as computers, may contribute very little to the total harmonic current in a wiring system. A few amps of very distorted current mixed with tens of amps of slightly distorted current should not overburden typical building wiring.

The power-circuit design of an electronic appliance determines its current distortion characteristics. For

Table 1. Current Characteristics of Single-Phase Appliances Found in a Typical Office Building

Load	*Operating State*	*Total Current (A)*	*60-Hz Current (A)*	*Harm. Current (A)*	*Total Harmonic Distortion*	*Harmonic Distortion Component*			
						3rd	*5th*	*7th*	*9th*
Fax Machine	Idle	0.25	0.16	0.20	130%	88%	68%	44%	24%
	Printing	3.75	3.74	0.22	6.0%	5.0%	2.0%	2.0%	0.3%
	Sending	0.25	0.16	0.19	120%	87%	65%	39%	18%
Clock Radio	On	0.05	0.05	0.02	47%	19%	5.0%	6%	1.0%
386 IBM-Comp. PC	On	1.00	0.63	0.77	120%	88%	67%	43%	21%
486 IBM-Comp PC	On	1.00	0.56	0.83	150%	93%	80%	61%	42%
Pentium PC	On	0.69	0.49	0.48	98%	79%	51%	22%	8.0%
Macintosh PC	On	1.00	0.60	0.80	130%	90%	72%	50%	32%
Laptop PC	On	0.16	0.09	0.13	140%	92%	78%	60%	40%
PF-Corrected PC	On	0.75	0.74	0.14	19%	13%	12%	6.0%	2.0%
13-Inch Monitor	On	0.57	0.40	0.41	100%	81%	53%	24%	3.0%
17-Inch Monitor	On	0.61	0.40	0.46	110%	87%	61%	35%	17%
Phone Switch	On	0.12	0.11	0.04	40%	34%	18%	7.0%	4.0%
Photocopier	Idle	1.00	0.59	0.81	140%	88%	74%	11%	39%
	Copying	10.50	10.35	1.76	17%	5.0%	13%	7.0%	1.0%
VCR	Playing	0.19	0.11	0.16	150%	91%	77%	62%	47%
Video System	On	0.93	0.60	0.71	120%	86%	65%	42%	21%
Coffee Maker	Idle	0.85	0.85	0.03	3.0%	2.0%	3.0%	1.0%	0.3%
	Brewing	11.70	11.69	0.35	3.0%	2.0%	3.0%	1.0%	0.5%
Microwave Oven	Cooking	9.00	8.21	3.69	45%	43%	12%	4.0%	2.2%
Water Cooler	Cooling	4.46	4.45	0.22	5.0%	4.0%	2.0%	1.0%	0.6%
Pencil Sharpener	Idle	0.03	0.02	0.02	97%	37%	4.0%	11%	14%
	Sharpening	0.75	0.75	0.07	10%	9.0%	1.0%	1.0%	0.8%
Electric Typewriter	On	0.11	0.10	0.03	33%	30%	10%	7.0%	4.0%
Incand. Lamp	On	0.45	0.45	0.01	3.0%	2.0%	2.0%	1.0%	0.4%
Electronic Fluoresc.	On	0.12	0.08	0.09	120%	85%	64%	40%	22%
Elect. Fluor. (PFC)	On	0.13	0.13	0.02	15%	3.9%	9.2%	3.7%	3.1%
Magnetic Fluoresc.	On	0.31	0.31	0.04	13%	12%	3.0%	2.0%	0.8%
Desk Fan	On	0.03	0.03	0.00	11%	10%	3.0%	0.0%	0.1%
UPS #1	PC Load	4.40	4.39	0.35	8.0%	7.0%	2.0%	3.0%	0.4%
UPS #2	PC Load	4.80	3.59	3.19	89%	75%	43%	15%	7.0%
UPS #3	PC Load	8.00	7.55	2.64	35%	34%	5.0%	3.0%	2.0%
UPS #4	PC Load	7.00	4.31	5.52	130%	89%	71%	49%	27%
Laser Printer	Idle	0.26	0.16	0.21	130%	90%	73%	52%	30%
	Printing	0.40	0.27	0.30	110%	85%	61%	34%	10%

example, each of the four uninterruptible power supplies (UPSs) in Table 1 has a different front-end rectifier design. Consequently, the current harmonic distortion of each UPS ranges from eight to 130 percent. The typical computer, monitor, printer, and fax machine—all staples of the modern workplace—use switch-mode power supplies (SMPSs), which draw current as shown in Figure 1. The waveform of SMPS current tends to be very peaked and contains mostly third harmonic.

The current harmonic distortion of one personal computer shown in Table 1 is less than 20 percent because its power supply employs power-factor-correction and harmonic-elimination circuitry, a design that was probably influenced by International Electro-technical Commission standards. Low-harmonic designs are expected to be used extensively in the near future.

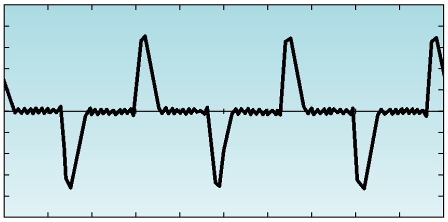


Figure 1. Current Waveform of a Typical Switch-Mode Power Supply

Lighting and Three-Phase Loads In most cases, lighting and HVAC systems are connected to individual branch circuits, separating them from other loads in the building. Lighting in a modern office building provides a wide range of current waveforms and harmonic distortion. Energy-efficient fluorescent lighting is beginning to dominate all other types of lighting in commercial buildings. Both magnetic and electronic ballasts serving four-foot fixtures can generate harmonic currents, but levels are significantly lower than the typical computer. Industry standards for four-foot fluorescent lighting require less than 30 percent current THD and a power factor greater than 0.9. Figure 2 shows the current waveform of a typical electronic ballast with a THD of 22 percent. Although compact fluorescent lamps are as efficient as four-foot lighting systems, their current distortion can be significantly higher.

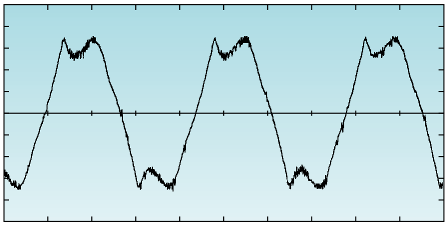


Figure 2. Current Waveform of a Typical Electronic Ballast

HVAC loads are usually three-phase loads operating at either 208 or 480 volts and have predominantly motor-type (inductive) loading characteristics. Some of the newer HVAC systems incorporate adjustable-speed drives (ASDs)—whose input power supplies are basically three-phase diode-bridge rectifiers—which inject harmonic currents back into the power distribution system. For three-phase loads, an unbalanced voltage will cause an increase in harmonic distortion, which is mostly fifth and seventh harmonic with little, if any, third harmonic. The current drawn by each phase of an ASD-driven HVAC system has the characteristic two-pulse waveform shown in Figure 3.

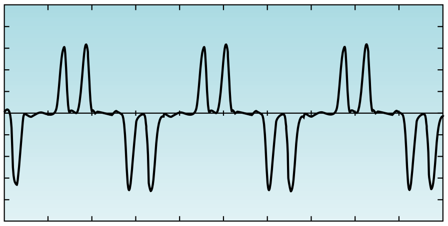
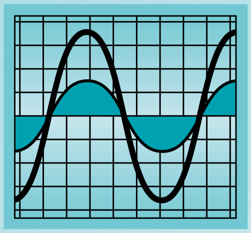


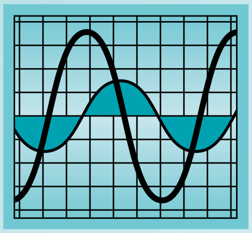
Figure 3. Current Waveform of a Typical Adjustable-Speed Drive

Loads and Their Current Waveforms



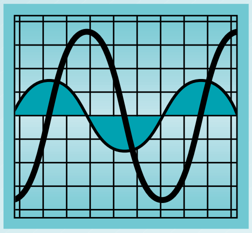
Resistive

For a resistive load such as an incandescent light bulb or resistive heater, current and voltage are in phase and no harmonic currents are present. If the three phases of a five-wire, wye-connected wiring configuration were balanced with purely resistive loads, the current in a shared neutral conductor would cancel out.



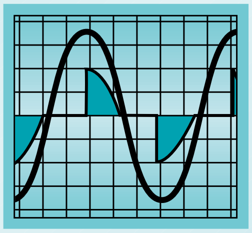
Inductive

For a purely inductive load, the current lags behind the voltage by 90 electrical degrees. However, even a highly inductive load such as a motor has some resistance, so that the current will lag behind the voltage by less than 90 degrees. As with resistive loads, currents drawn by inductive loads balanced across all three phases would cancel out in a shared-neutral conductor.



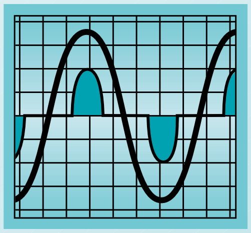
Capacitive

For a purely capacitive load, the current leads the voltage by 90 electrical degrees. Like the purely inductive load, a capacitive load uses no real power. By themselves, capacitors are used to offset the effects of heavy inductive loading. Currents drawn by capacitive loads balanced across all three phases would cancel out in a shared-neutral conductor.



Phase-Controlled Turn-On Devices

The simplest example of a phase-controlled turn-on device is a light dimmer, which uses a triac to control the starting point on the voltage sine wave at which the light draws current. This type of device generates harmonic currents including triplens that will combine in the neutral conductor, even with a balanced load.



Electronic Power Supply

The full-wave rectifier with a bulk capacitor is the basic front-end circuit for almost all new electronic office appliances. Such appliances draw current only when the input voltage exceeds the voltage level of the bulk capacitor, typically during the middle third of each half cycle. The resulting current pulses contain a large amount of triplen harmonics.

Wiring Configurations in Commercial Buildings

The effect of harmonic currents on the building wiring depends heavily upon the configuration of the wiring. Figure 4 is a typical wiring schematic for a commercial building. Large three-phase loads such as HVAC are served from motor-control centers or main power panels at 480 volts. Lighting is often served from its own panel at single-phase 277 volts. And the 120-volt office plug loads are served by load centers or sub panels that are fed by dry-type step-down transformers located inside the building.

Although much of the harmonic current flowing from appliances to the utility system will eventually cancel, harmonic current flowing in the branch circuits serving nonlinear loads may actually add in neutral conductors. Moreover, high levels of distortion, particularly in branch circuits serving 120-volt receptacles, can cause a voltage drop. If the circuit is robust, current distortion is higher but the voltage may be relatively unaffected. Conversely, if the circuit is relatively weak, voltage distortion will be higher and current distortion will be lower.

The plug loads in commercial office buildings are typically single-phase and connected from line to neutral, which can be either a separate neutral conductor or a neutral conductor shared by other loads in the circuit. The most common wiring configuration is a four or five-wire circuit with a shared-neutral conductor, three phase conductors, and either a separate ground wire or a metal con-duit ground (see Figure 5). Because of lower installation and operating costs, this configuration is often preferred over separate neutral conductors.

A balanced three-phase system with a shared-neutral conductor is also the most efficient configuration. Circuit losses can be as much as 40 percent lower with the shared-neutral configuration because the fundamental return currents cancel in the neutral conductor between appliances. Circuit voltage drop is also lower. However, harmonic currents in this type of configuration may overload the neutral conductor, particularly if the conductor is undersized. Buildings wired before 1990 are most at risk for overloaded neutral conductors because until 1990, the National Electric Code permitted the shared-neutral conductors of a three-phase system to be one wire size smaller than the phase conductors.

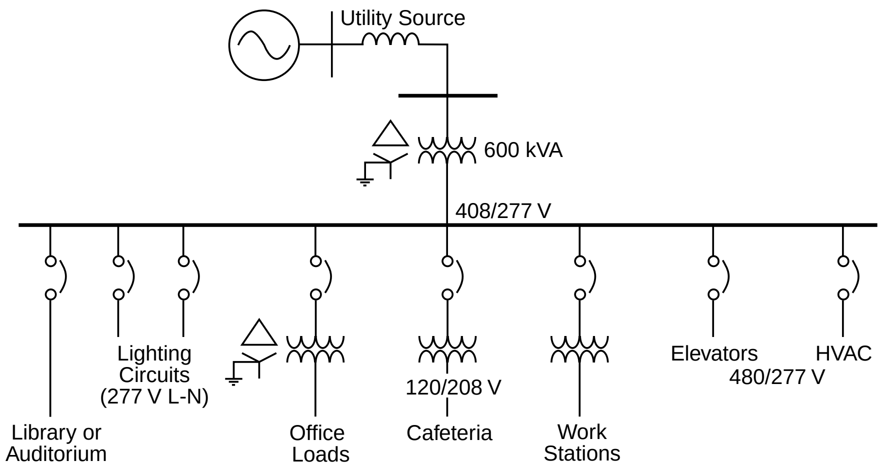
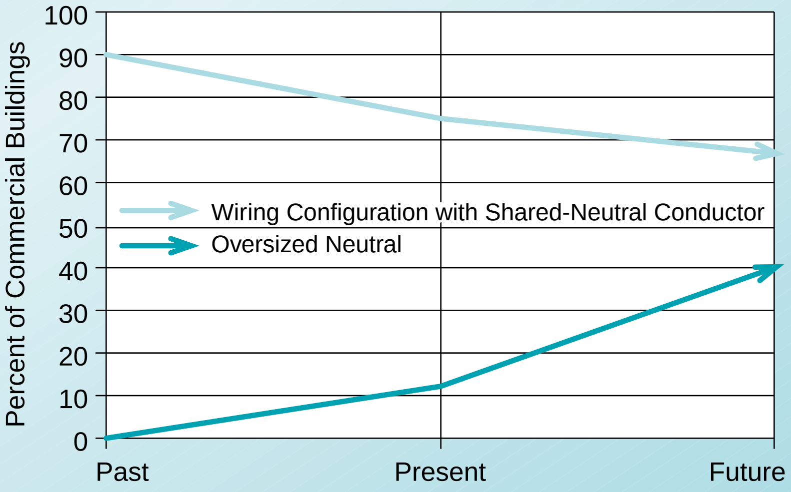


Figure 4. Typical Power Wiring for a Large Commercial Building

Are Concerns About Harmonic Current Influencing Wiring Design?

Results from a 1995 survey of architects, electrical engineers, electrical contractors, and facility electrical designers reveal that concerns about harmonic currents in building wiring have influenced the design of wiring configurations in new commercial buildings. When asked about their wiring practices in the 1970s and 1980s, the respondents said that 90 percent of the buildings for which they designed the wiring had five-wire, three-phase branch circuits with a shared-neutral conductor. The respondents indicated that they currently design that same wiring configuration for 75 percent of the buildings, while they indicated that only 67 percent of their future buildings will have such a wiring design. The trend toward oversizing neutral conductors is also a cogent indicator of how concerns about harmonic currents are influencing wiring designs. None of the respondents oversized neutral conductors in the 1970s and 1980s. However, 12 percent of the building wiring currently designed by the respondents have oversized conductors—mostly one size larger than the phase conductors—and 40 percent of the respondents' future buildings will have oversized conductors.



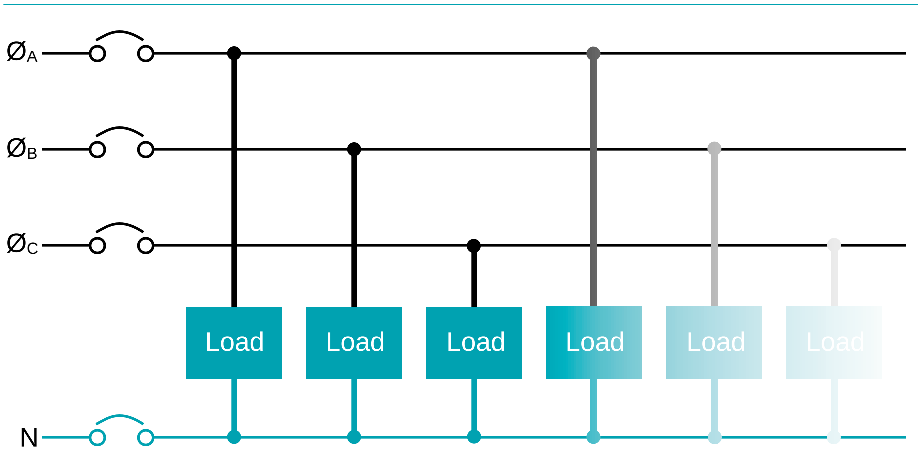


Figure 5. Single-Phase Branch Circuits with a Shared-Neutral Conductor

The most common wiring configurations for lighting loads are 120-volt connected line-to-neutral and 277-volt connected line-to-neutral. Both of these systems can create non-canceling harmonic currents in the phase conductors and in the shared-neutral conductor of lighting panels. However, bulk lighting systems rarely draw harmonic current greater than 30 percent of the fundamental current. One reason for the low current distortion levels of commercial office lighting is ANSI/IEEE C82.11, an American fluorescent lighting standard that limits the amount of harmonic current to less than 32 percent.

Harmonic Effects on Building Wiring

The primary effect of harmonic loading on the building wiring is increased current, as much as double for wiring with highly distorted currents. Highly distorted current also reduces the power factor and the spare current capacity of conductors. Because conductor heating depends upon the square of the current, building power system losses will also increase.

Losses in Conductors Because conductors are resistive, any current flowing through them will generate heat. The amount of energy lost through heat by a conductor at a particular frequency depends upon the amount of RMS current flowing through the conductor and resistance of the conductor at that frequency. Harmonic currents usually add to the RMS current flowing in building wiring, thus increasing the amount of energy loss. For highly nonlinear loads such as personal computers, the RMS current due to harmonics is nearly as high as the fundamental current.

The ac resistance at a particular frequency is the sum of dc resistance, skin-effect resistance, and proximity-effect resistance. The dc resistance can be obtained from any cable handbook. It is a function of the length, area, and constant of resistivity, which depends upon the conductor material.

Skin effect is the tendency of an alternating current to travel on the outer surface, or skin, of a conductor, thus reducing the effective cross-sectional area. The larger the wire diameter and the higher the frequency, the greater the skin effect. For wire sizes typical of commercial office buildings and for lower harmonic frequencies, skin effect is not a significant factor.

Proximity effect is caused by the linking of magnetic flux from parallel conductors and nearby metal parts. Proximity effect increases as the conductor area increases, the frequency increases, and the conductors get closer to each other, which is usually determined by insulation thickness. Like the skin effect, the proximity effect is not very significant, probably less than one percent of the total ac resistance for branch-circuit wiring. However, the effect increases in transformers, panels, and service conductors.

Figure 6 shows the ratio of the ac to dc resistance—which indicates how much skin and proximity effects are contributing to the conductor resistance—for four different-size cables: 500 kcmil, 4/0 AWG, 1/0 AWG, and 12 AWG, all of which are typically used in building wiring. For Figure 6, the calculation of the proximity effect is based upon conductors separated by insulation type THHN, which is a relatively thin heat-resistant thermoplastic rated at 90°C and often used in building wiring systems. The skin and proximity effects of the four different conductors range from practically none, in the case of the 12 AWG conductor, to a significant increase in resistance, in the case of the larger conductors.

Because both skin and proximity effects increase as the frequency increases, the higher-order harmonics create more conductor heating for the same amount of RMS current. Fortunately, the content of higher-order harmonic current (above the 11th

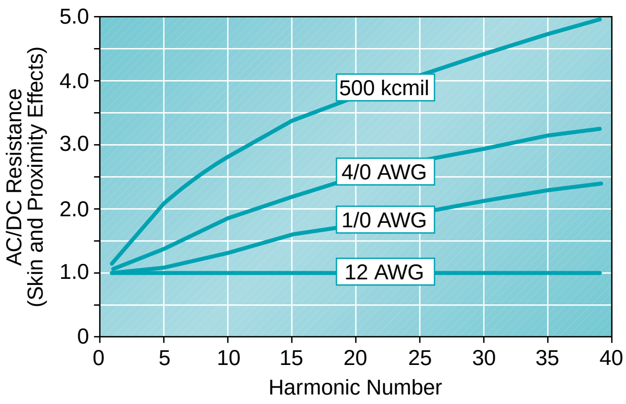


Figure 6. Conductor Resistance Contributed by Skin and Proximity Effects as a Function of Harmonic Number and Conductor Size

PQTN COMMENTARY No. 1

Case Study: The Cost of Harmonic Losses in an Airline Reservation Center

Situation

An airline reservation center with 240 computer workstations in an office building showed signs of harmonic overloading near the workstations, and the building tenant wanted to add more equipment. The measured voltage distortion at some receptacles was above seven percent, and the transformer that served computer workstations seemed hot. However, out at the service entrance, the electrical-system components were cool, and the voltage distortion was less than three percent.

The figure on the opposite page shows the electrical wiring schematic of the reservation center and the waveforms and measurements at various points in the building wiring. The total load of the reservation center was about 300 kilowatts, distributed among three three-phase, 480-volt feeders and a single-phase, 277-volt feeder. The 240 computer workstations and other electronic office appliances were found to be a major source of harmonics. These loads were served by a dry-type, 480-volt-to-120/208-volt, 112.5-kVA step-down transformer fed by one of the four 480-volt feeders. The cable from the secondary of the transformer to the sub-panel that served the workstations (Cable 3 in the figure) included a shared-neutral conductor (four wires), whereas the branch-circuit cables (Cable 4) included separate neutral conductors for each phase (six wires).

Comparing the current measurements with cable and transformer ratings indicated that the neutral conductor of Cable 3 was 40 percent overloaded. Although the 112.5-kVA transformer seemed to be running hot, it was rated for class F insulation (180º max.), which can normally run hot. To determine the extent and cost of harmonic-related losses, a detailed analysis was conducted.

Analysis: Losses and Energy Costs of Wiring to Workstation Area

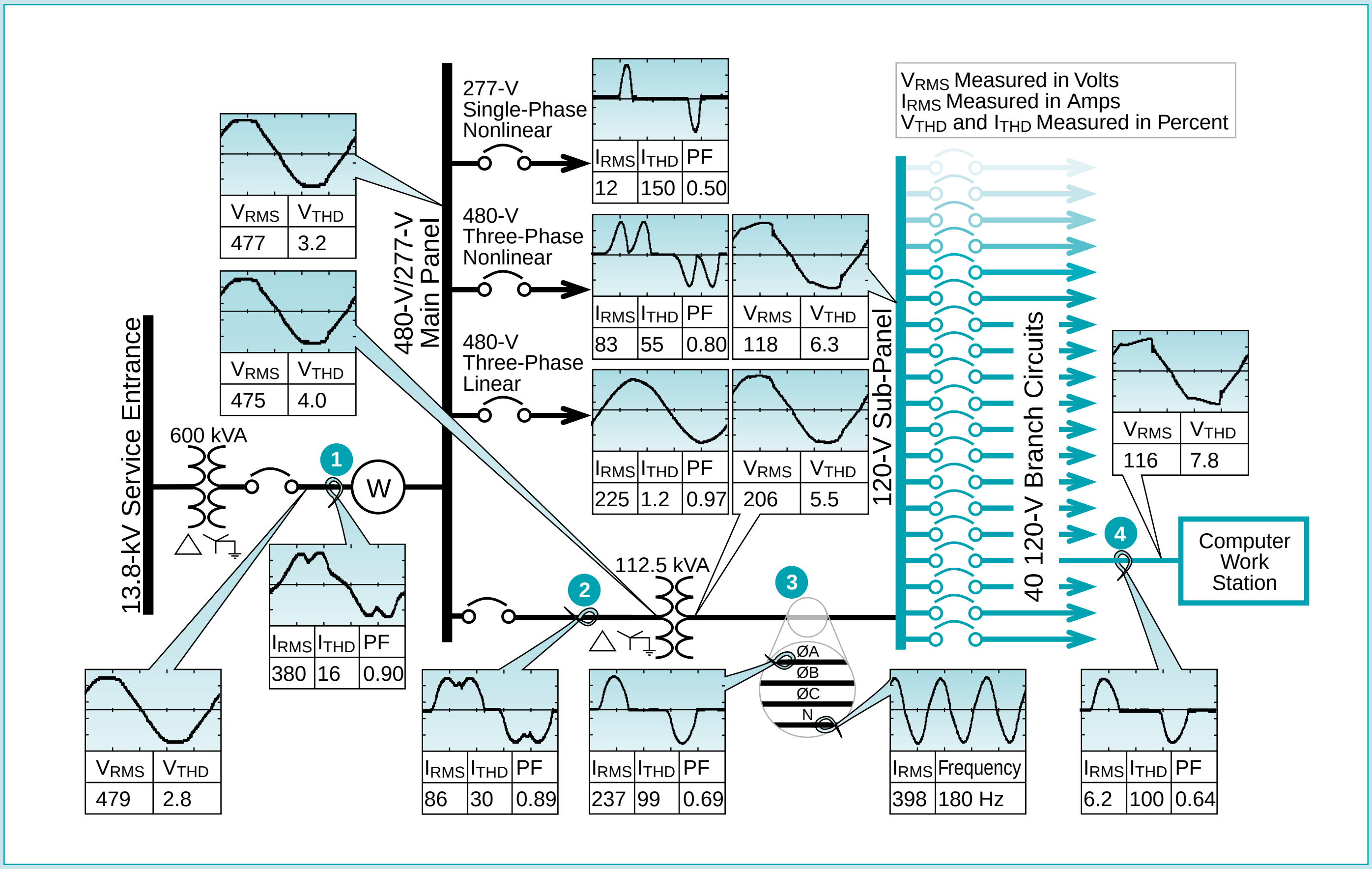
The table below shows the results of the analysis. For each segment of the power system serving the workstation area, both cable and transformer losses were calculated. This calculation takes into account the specific mix of harmonics and the proximity and skin effects on cables, as well as eddy currents in transformer windings. For the 112.5-kVA transformer, only load-related losses were calculated. For comparison, the building wiring losses and energy costs of a 60-kilowatt linear workstation load were also calculated.

To calculate the cost of energy, the workstations were assumed to operate 12 hours per day and 365 days per year with electric energy at 10¢ per kilowatt-hour. The highly distorted current of the workstations increased the energy loss in building wiring by about 2.3 times. The annual losses due to harmonics was 4,696 watts at a cost of $2,057.

This case illustrates an important point about shared-neutral conductors. In electrical wiring not carrying distorted currents, a shared-neutral configuration will always reduce the wiring losses because some of the phase currents will cancel in the neutral. For a perfectly balanced system with sinusoidal currents, the losses of a shared-neutral configuration are exactly half that of a configuration with three separate neutral conductors. However, when currents are distorted, the losses in a shared-neutral configuration increase and the savings decrease. In this case, the 350-kcmil cable with 100 percent current distortion had slightly higher losses with a shared-neutral, four-conductor cable than if separate neutral conductors were used. The additional losses in the neutral conductor can be attributed to triplen harmonics. However, if the current distortion is low in triplen harmonics, a shared-neutral conductor will likely always have lower wiring losses.

Cable Segment/ Transformer	*Conductor Size*	*Conductor Length*	*Rated Current**	*Measured Current*	*Current Loading*	*I_{THD}*	*Actual Segment Loss*	*Expected Linear-Load Loss*
Cable ①	8-500 kcmil	50 Feet	688 A	380 A	55%	16%	178 W	167 W
Cable ②	3-1/0 AWG	150 Feet	150 A	86 A	57%	30%	259 W	235 W
Xformer Primary			143 A	86 A	60%	30%	4322 W	1575 W
Secondary			311 A	237 A	76%	99%		
Cable ③, Phases	3-350 kcmil	50 Feet	280 A	237 A	85%	99%	357 W	140 W
Cable ③, Neutral	1-350 kcmil	50 Feet	280 A	398 A	142%	N/A	377 W	0 W
Cable ④	6-12 AWG	200 Feet	21 A	6.2 A	30%	100%	2647 W	1327 W
Total Load-Related Losses							8140 W	3444 W
Annual Cost of Load-Related Losses							$3565	$1508

*Rated current is based upon 86º F, conductors in conduit with required deratings for fill, and continuous loading.



Recommendations to Remedy the Overloaded Neutral Conductor

Option 1: Derate workstation panels and the 112-kVA transformer based upon the K factor of the load current. If another transformer in the building has spare loading, derate the 112-kVA transformer by 30 percent to 78 kVA and relocate 20 workstations to the different transformer. Then, replace the neutral conductor of Cable 3 with a conductor that is one wire size larger (400 kcmil), or add a 350-kcmil neutral conductor in parallel with the existing neutral conductor. Since 1996, NEC Article 310-4 permits, by exception, running a parallel neutral conductor for No. 2 AWG and larger wire diameters when the procedure is conducted under the supervision of a qualified engineer.

Option 2: Add another transformer and panel close to the workstations and split workstation loads between the two transformers. Divide up harmonic-generating workstation loads and mix with other loads to dilute harmonic currents. Also try to balance all loads between the three power phases.

Option 3: Install filters to trap harmonic currents close to computer workstations by adding six-amp, series-connected, parallel-resonant filters at receptacles where several computers and peripherals can be plugged in. Or, add a three-phase, zig-zag transformer with a five-percent series reactor (sized according to the manufacturer) in the neutral conductor located at the source side of the computer workstation load panel.

harmonic) is usually quite small and accounts for little if any additional heating of wiring in commercial buildings.

Loading of Shared-Neutral Conductors In three-phase, four-wire wye-connected circuits, odd triplen harmonic currents add algebraically in the shared neutral conductor. Exactly how much neutral current may flow in a three-phase, four-wire system has been the subject of debate and confusion. Some say that the current in a shared-neutral conductor can never exceed 1.73 times the largest phase current, others say that 2.7 is attainable, and still others say that 3.0 is possible.

A shared-neutral current of 2.7 times the phase current is possible, but to obtain this value, a very unlikely load mix is required: One phase must be loaded with a purely resistive load, the second loaded with only an inductor, and the third phase with only a capacitor (see Figure 7). Each element—the resistor, the capacitor, and the inductor—must draw the same amount of RMS current and must be in the correct phase sequence.

A neutral current of 3.0 times the greatest phase current could theoretically be achieved if all three circuits from the phase conductors were perfectly in phase and of the same polarity. However, this scenario does not occur because the three phase voltages from the service entrance are 120 degrees out of phase with each other.

As shown in Figure 8, the phase currents of linear loads can cancel in a shared-neutral conductor, whereas the non-overlapping phase currents of nonlinear loads add in a shared-neutral conductor. Because there is no addition or subtraction of non-overlapping phase currents, two characteristics can be proven mathematically: 1) The effective heating of the neutral current (I_{RMS}) is exactly $\sqrt{3}$ times the individual phase currents. Therefore, the losses in the neutral conductor $(I_N^2R_N)$ will be three times the losses of each phase conductor. 2) A frequency-based

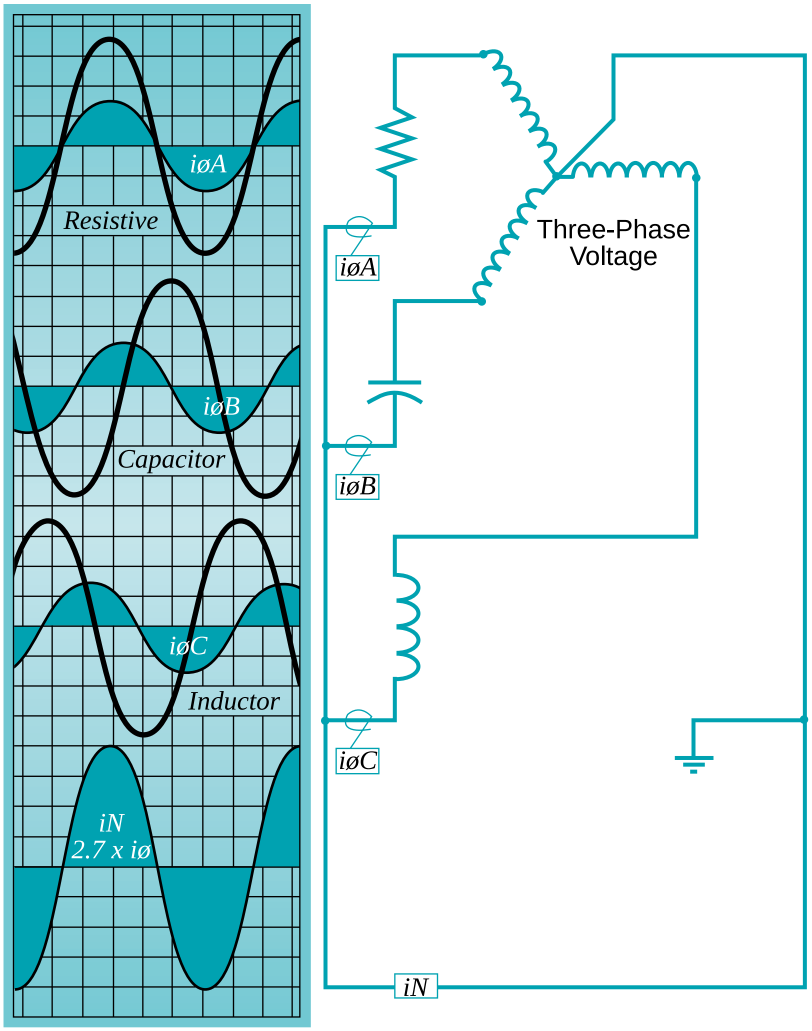


Figure 7. Configuration to Yield a Neutral Current of 2.7 Times the Maximum Phase Current

Calculating Shared-Neutral Current

The following calculations work for practical systems where pulse-shaped load currents in the three phases do not overlap. Assume that all nonlinear-load current areas in Figure 8 (a_1 through a_6) are the same shape and duration.

The phase current is: $I_{\text{Ørms}} = \sqrt{\frac{\text{area of } i^2(t)}{T}} = \sqrt{\frac{a^2+a^2}{T}} = \sqrt{\frac{2a^2}{T}}$

The neutral current is: $I_{\text{Nrms}} = \sqrt{\frac{\text{area of } i^2(t)}{T}} = \sqrt{\frac{a_1^2+a_2^2+\ldots a_6^2}{T}} = \sqrt{\frac{6a^2}{T}}$

The relationship between the phase and neutral currents is:

$$\frac{I_{\text{Ørms}}}{I_{\text{Nrms}}} = \frac{\sqrt{\frac{2a^2}{T}}}{\sqrt{\frac{6a^2}{T}}} = \frac{\sqrt{1}}{\sqrt{3}} \approx \frac{1}{1.73}$$

The shared RMS neutral current is:

$$I_{\text{Nrms}} = \sqrt{3} \times I_{\text{Ørms}} \approx 1.73 \times I_{\text{Ørms}}$$

analysis, also called a Fourier analysis, of the neutral current will show only triplen harmonic components. All the fundamental and non-triplen harmonics cancel when the current pulses add in the neutral. This is a unique characteristic of pulse-shaped currents.

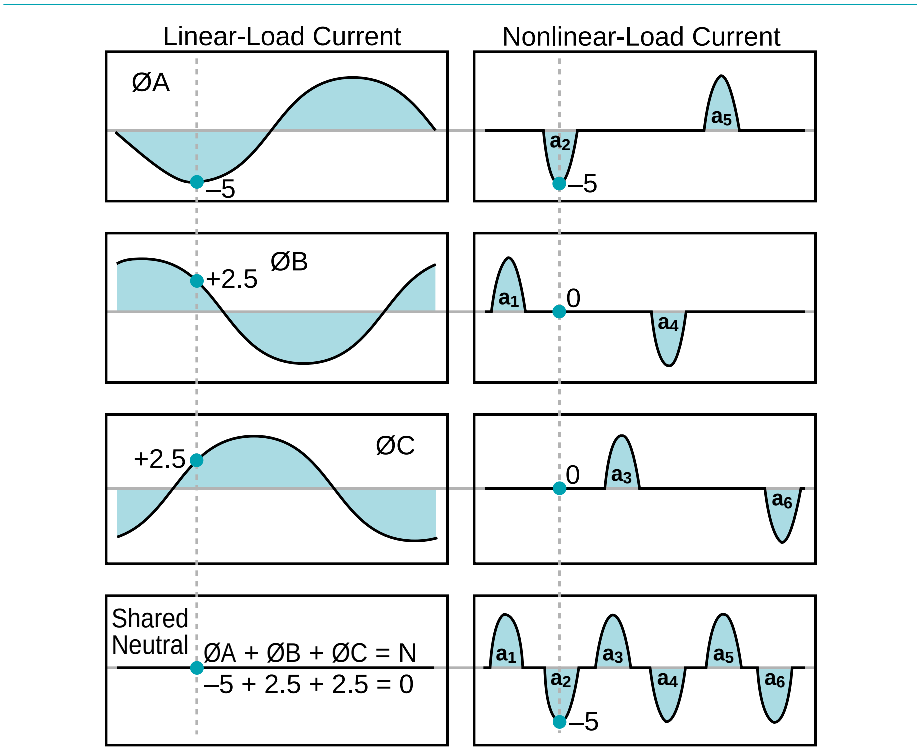


Figure 8. Addition of Linear- Compared to Nonlinear-Load Currents in a Shared-Neutral Conductor

Losses in Transformers Nonlinear loading may increase heating in transformers because the RMS current is usually higher per watt with nonlinear loads. Additionally, the higher frequencies in non-sinusoidal current will heat transformer components more than an equivalent amount of sinusoidal current.

Step-down transformers connected in a delta-wye configuration and serving single-phase electronic appliances can act as a filter, protecting the upstream part of the building wiring. The primary windings of the transformer trap the triplen harmonic currents, resulting in some interesting phenomena. For example, the RMS current out of the transformer may be higher than the current in, even with the turns ratio taken into account. Current distortion at the transformer output may be more than double the distortion at the input. However, the extra work performed by the transformer as it traps triplen harmonic currents increases transformer losses.

As shown in Figure 9, the shape of the output current may be significantly different from the input current. Table 2 shows the harmonic components, total RMS current, current distortion, power factor, and K factor (discussed later) of the input and output currents shown in Figure 9. Note that the 3rd and 9th harmonic components are absent from the input current, significantly reducing the total RMS current and harmonic distortion, and improving the power factor.

To understand how harmonic current affects transformers, consider some basic principles of transformer losses. There are two types of transformer losses: “no-load” and “load.” No-load losses depend upon the design of the transformer and the amplitude and distortion of the source voltage. No-load losses occur in the primary winding and core material when the transformer is energized. An increase in either input voltage distortion or magnitude causes these losses to increase. However, voltage distortion at the transformer primary is typically low, usually less than five percent. No-load losses related to harmonics are therefore usually insignificant.

In contrast, load losses due to harmonics are usually significant. These losses are related to current in both the primary and secondary windings. Load loss is the sum of all current-related losses, including copper losses (I^2R_{AC}) and eddy-current losses. Copper losses depend upon the load current and ac resistance of the windings (dc, skin-effect, and proximity-effect resistances).

Table 2. Details of Input and Output Currents of Transformer Shown in Figure 9

Harmonic Number	*Input Current (A)*	*Output Current (A)*
1	0.65	0.65
3	0.00	0.52
5	0.42	0.42
7	0.29	0.29
9	0.00	0.13
11	0.12	0.12
13	0.10	0.10
I_{RMS}	0.84	1.00
I_{THD}	82%	116%
PF	0.77	0.65
K-Factor	17.5	16.3

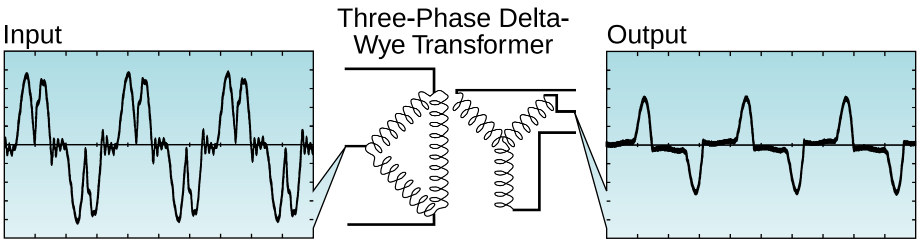


Figure 9. Input and Output Current of Three-Phase, Delta-Wye Transformer Feeding Computers

Eddy-current losses, also called stray losses, are particular to transformers. They occur when ac fields between windings induce additional winding currents that depend upon the harmonic components of the load current. Eddy-current losses are similar to proximity losses in wiring, but are intensified by ac fields and close coupling of metal parts. AC fields are generated in the windings, core, core clamps, copper shields, tank walls, and other structural parts of the transformer.

When the currents flowing in the windings of a transformer are rich in harmonics, the induced eddy-current losses in the windings increase significantly, and may be many times higher than the eddy-current loss due to 60-cycle current. Table 3 shows the load losses for a typical delta-wye transformer. The total losses nearly triple for nonlinear loads with the same real power (watts).

The additional transformer heating caused by load current distortion is addressed in the American National Standard C57.110-1986, which recommends practices for determining transformer capability when the transformer serves nonlinear loads.

Underwriters Laboratory (UL), working with transformer manufacturers, has defined a similar way to determine transformer capability called “K factor,” which indicates the level of distortion in current and is used for rating transformers. K factors follow an I^2H^2 function, where I is simply RMS current and H is the harmonic number of the current. If the current is sinusoidal, its K factor is unity (one). This relationship between RMS current and harmonic number is more accurate for lower harmonics (3rd, 5th, 7th), but overestimates heating for higher harmonics, particularly the heating of windings with large cross-sections.

Harmonic Currents Can Increase Electricity Bills

Harmonic current generated by electronic appliances causes additional reactive power demand on the building wiring system. Reactive power is a measure of the rate at which energy oscillates in a power system with no net gain or loss. This oscillation occurs when the current is out of phase with the voltage at any of the frequencies present. Reactive current at 60 Hz is necessary to provide magnetization to the power system and connected loads. A correct level of reactive current is also critical to voltage regulation. However, the components of reactive current related to harmonic current represent a less useful form of reactive power.

Unlike real power, reactive power by definition is neither gained nor lost. However, its oscillation or transfer within the power system does contribute to system losses, primarily I^2R line losses. These oscillations can also cause a line-voltage drop.

To reduce these effects, electric utilities employ *reactive-power compensation* and may pass on the cost of compensation to the end user in the form of a power-factor penalty.

Table 3. Typical Transformer Losses with Linear and Nonlinear Loads

Type of Load Loss	*Losses (Watts)*	
	Linear Load *pf=1.0, I_{THD}=0%*	*Nonlinear Load* *pf≈0.64, I_{THD}=100%*
Copper Loss = $\Sigma I_h^2 R_{AC}$	1500 W	2986 W
Eddy-Current Loss $P_{EC} = \Sigma I_h^2 h^2$	75 W	1336 W
Total Load Loss $P_{LL} = \Sigma I_h^2 R + P_{EC}$	1575 W	4322 W
Assumptions: Three-phase delta-wye transformer is rated at 112 kVA; load is 60 kW.		

The UL Standards 1561 and 1562 apply the UL rating system to dry-type power transformers to indicate their suitability for distorted current. The transformer rating system indicates a transformer’s ability to serve a nonlinear load without exceeding its rated temperature-rise limits. The standard UL K-factor ratings are 4, 9, 13, 20, 30, 40, and 50, which define the level of distortion expected in the transformer’s load current. The higher the number, the greater the distortion. For this rating system to work properly, the harmonic content of the load

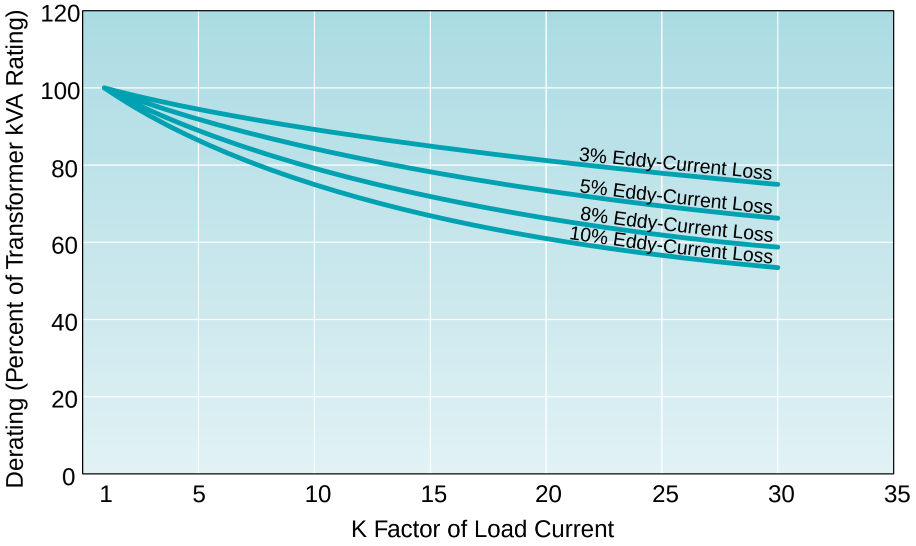


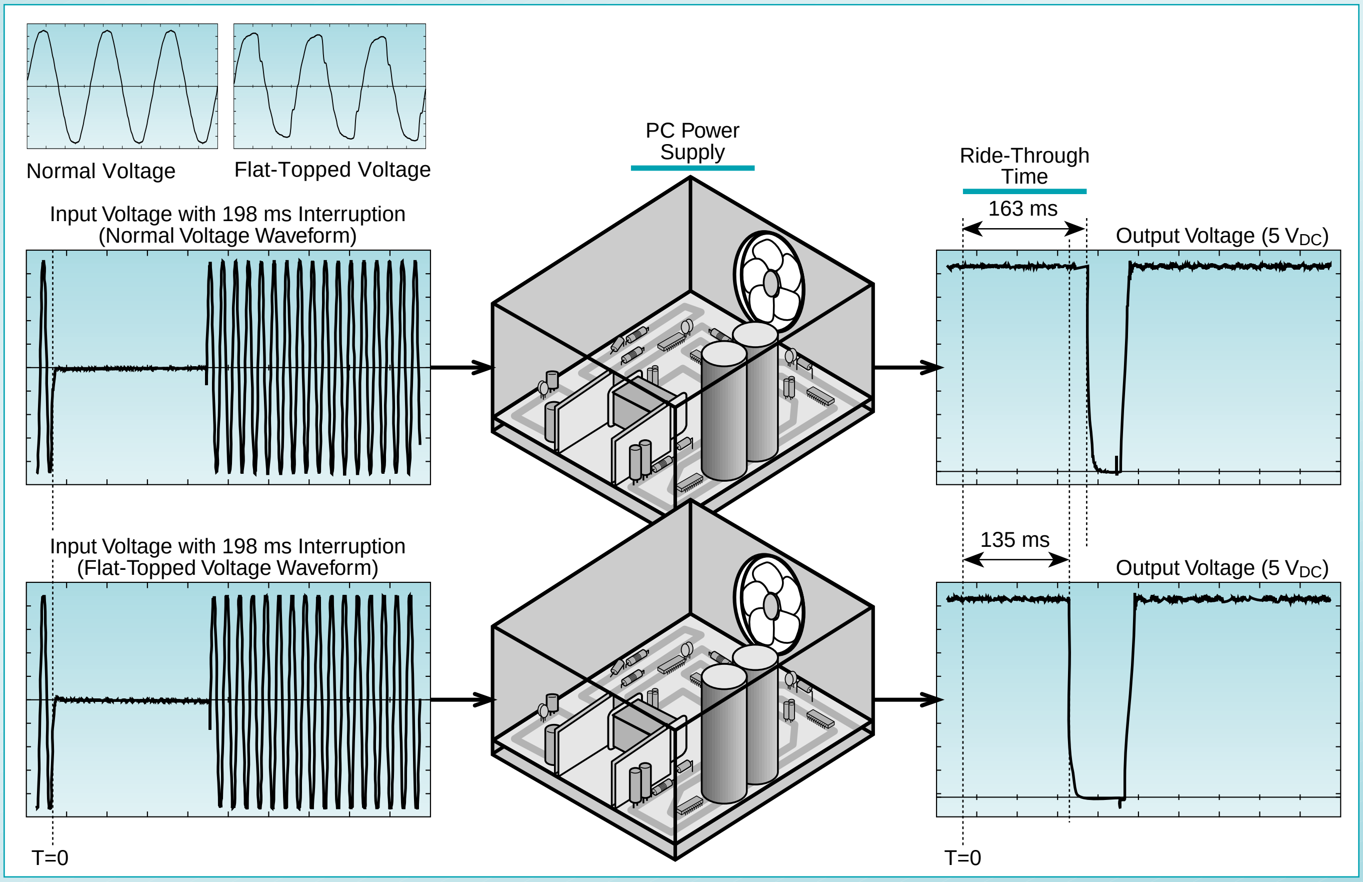
Figure 10. Transformer Derating Based Upon Eddy-Current Losses and Current Distortion

Harmonic Currents Can Affect Voltage Distortion and Ride-Through

When high levels of non-sinusoidal current flow through building wiring, the voltage at the point of use can be distorted by nonlinear or frequency-dependent drops in voltage. Distortion levels depend upon the power system impedance—how “stiff” the voltage source is. The voltage in a very stiff power system, which has a low impedance, is less likely to be distorted by harmonic currents.

In typical commercial buildings, the voltage distortion is nearly always significantly lower than the current distortion. For example, 50 to 100 percent current distortion may cause up to a ten percent voltage distortion at or near 120-volt receptacles. Although voltage distortion might be characterized as a second-order effect, relatively low voltage distortion can cause additional heating of motors and equipment malfunctions.

When electronic appliances draw current during the peak of the voltage sine wave, the voltage can drop, resulting in the most common type of voltage distortion called “flat-topping.” A lower peak voltage reduces stored energy in the capacitor of a switch-mode power supply, thus reducing the ability of some electronic power supplies to ride through low-voltage conditions.



current must first be analyzed to determine a K factor. Then, the K factor of the transformer must be matched to the K factor of the current. If the K factor of the load current is greater than the transformer’s rated K factor, the transformer must be derated. As illustrated in Figure 10, derating is based upon the eddy-current losses of the transformer measured at 60 Hz and the expected distortion of the load current. For example, to stay within its rated temperature-rise limits, a conventional transformer, which has a K-factor rating of 1, may need to be derated to serve nonlinear loads.

Circuit-Breaker and Connector Heating Harmonic currents affect circuit breakers and connectors in subtle ways. Generally, harmonic currents heat circuit breakers and related connectors. Peak harmonic current and vibrations induced by harmonic currents can also heat connectors and contacts. Additionally, voltage distortion resulting from current distortion can heat the coils of a circuit breaker. When circuit breakers are subjected to continuous nonlinear-load current near their rated thermal trip, a transient or small increase in loading may trip them. When reset, they are likely to be cooler, so the cycle may begin again. Consequently, some overload problems go unnoticed for a long time until more definite symptoms appear.

Loose connectors exacerbate the effects of heating caused by harmonic current and may routinely run hot. Loose connectors may cycle between hot and cold as the load changes state—for example, as appliances are turned on or the heater elements of printers and copiers cycle on and off. This cycling loosens the connectors even more, which contributes to resistance and thus heating.

Conclusion

Are concerns over harmonic currents in building wiring justified? Harmonic current may contribute to wiring overload in older buildings with undersized neutral conductors and under-rated step-down transformers. Even so, much of the concern over harmonic effects of electronic appliances has been exaggerated by inaccurate claims—for example, that the harmonic currents combining in neutral conductors can be two to three times the amount of current in the phase conductors.

More a hobgoblin than a wire-eating menace, harmonic current does not usually pose a threat in modern office buildings designed for electronic appliances. Today, most design engineers recognize and account for the real effects of harmonic-generating appliances on the load-serving capacity of building wiring.

The trend toward oversizing neutral conductors is just one example of a business world prepared to handle the by-products of the electronic appliances responsible for enormous increases in productivity and efficiency. By installing neutral conductors sized one gage larger than the phase conductors, building designers and engineers can adequately mitigate the effect of harmonic currents on shared-neutral conductors. Additionally, a rating system for sizing transformers in a world of harmonic currents has been in place for several years and has been effective in measuring and reducing the potential for overloading transformers. In the end, the total energy losses caused by harmonic currents tend to go unnoticed in the power bill because of the increased energy efficiency of many harmonic-generating loads.

Appliance manufacturers have not been idle. With every new generation of electronic appliance, they have an opportunity to improve their products. For example, manufacturers are beginning to incorporate power-factor-correction circuits into their power supplies. Therefore, future generations of energy-efficient electronic appliances may generate such low levels of harmonic current that even buildings with modestly sized neutral conductors and transformers can carry the currents drawn by office appliances.

Reducing Harmonic Currents

Certain loading strategies and wiring-system characteristics reduce harmonic currents in building wiring. For example, large linear loads tend to dilute the effects of many smaller nonlinear loads (Figure A). Also, mixing different types of nonlinear loads provides diversity in current shapes, which will usually reduce the combined harmonic current (Figure B). Even in shared-neutral wiring, the potential for harmonic overload is greatly reduced if there is a variety of load types on a single power panel. In addition, high circuit impedance at harmonic frequencies will attenuate harmonic currents and distortion (Figure C).

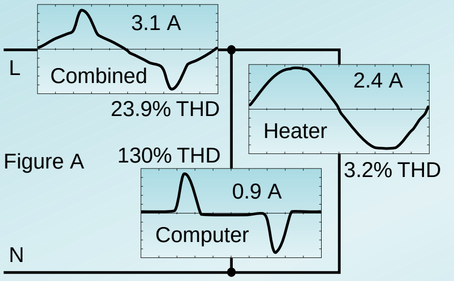


Figure A

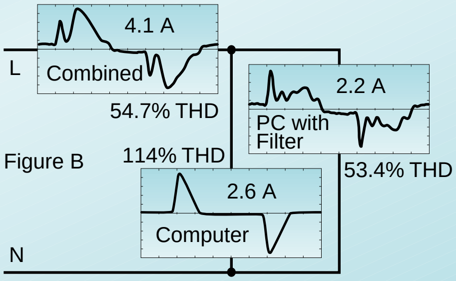


Figure B

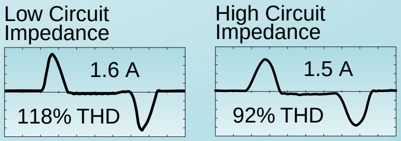


Figure C

The Power Electronics Applications Center (PEAC) is a center of the Electric Power Research Institute, a nonprofit institute that conducts research on behalf of electric utilities. PEAC's mission is to support electric utilities in their efforts to understand and resolve power quality problems and system compatibility issues; to help utilities solidify durable, beneficial relationships with their customers, manufacturers, and standards organizations; and to empower them with knowledge via power quality training and publications. This PQTN Commentary is one of many publications available to qualified utilities and their customers.

For mor information about PEAC products and services, contact Steve Rector, EPRI-Knoxville, at 423-974-8307 or Gene Sitzlar, System Compatibility Research, at 423-974-8288, fax 423-974-8289.

Power Electronics Applications Center
10521 Research Drive, Suite 400
Knoxville, Tennessee 37932
423-974-8288, fax 423-974-8289

For ordering information,
call PEAC (423) 974-8288.

Copyright © 1996 Electric Power Research Institute

TC-107163

Printed with soy inks on recycled paper (at least 50% recycled fiber, including at least 10% postconsumer waste) in the United States of America.