TESTING REVEALS SURPRISING *k*-FACTOR DIVERSITY

Bob Arthur

Harmonic cancellation and source impedance effects explain why a total load *k*-factor greater than 9 does not occur in actual office electronic loads or any similar concentration of switched-mode power supplies.

THE *total* k-factor of office load systems does *not* correlate with the relatively high values of harmonics seen at individual branch load circuits. In fact, there is not a single case (to our knowledge) of a commercial office load, operating at or near the feeder transformer's full load rating, that exceeds k-9. Demonstrations of higher k numbers have always proved to be either the result of *branch* load measurements, or drastically *underloaded feeders* where the higher k is of little or no consequence to the supply transformer.

Because there are so *many* variable factors that affect nonlinear power elements, doing an *accurate* k-factor calculation can be a very difficult task. If carefully developed, detailed estimates based on general application parameters may be sufficient. However, there are certain industry beliefs regarding the computer-intensive office that are *not* true, and which directly affect the required k-factor.

Myth. A harmonic analysis of an office with a single personal computer and video monitor will typically measure a k of 14 to 20 in harmonic intensity. For an office filled with large numbers of such PCs, a transformer with a k of 20 or 30 is needed to feed the distribution panel serving the office power. Since offices typically contain other equipment, such as copiers, printers, FAX machines, etc., the k-factor for all this equipment should be listed, weighted by their relative current contribution, and simply averaged for a total k-factor estimate.

Fact. The k-factors of electronic loads in parallel do *not* simply "average out". Fifth and higher-order harmonics in the load current from multiple single-phase electronic loads on a given feeder occur at *random* phase angles, and constantly *change* in angle during operation. This random distribution of harmonic phase angles results in a dramatic *reduction* and/or *cancellation* of higher frequency harmonics. Also, as more current flows in a feeder, the source impedance of the supplied power begins to have a mitigating effect, especially for higher frequency harmonic components in the current. Typically, by the time at least 20 devices are on line simultaneously, the combined k-factor at the bus of the distribution panel is *reduced* by a factor of three or more below the average individual device k-factor. In fact, the *higher* the number of single-phase nonlinear loads on a given distribution panel, the *lower* the k-factor.

Let's look at the testing that verifies the above statement.

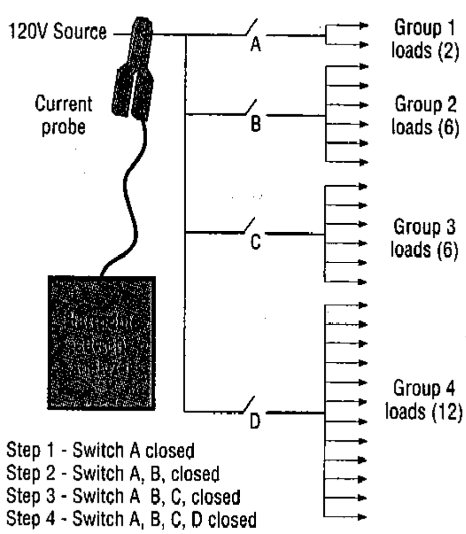


Fig. 1. Diagram shows grouped loads used in the testing analysis. All measurements were made with an harmonic analyzer with a 100A current probe.

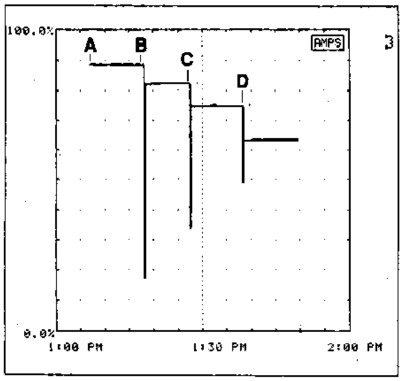
Field Tests

The testing as described here was performed by first making harmonic measurements on a single device, an IBM PS/2 computer and monitor. Additional computers, monitors, printers, and disk drives were added, with a harmonic analysis made at each step. An attempt was made to show both the effect of adding *like* equipment as well as *diverse* types and brands of devices. *No* attempt was made to dilute the effects of nonlinear loads by adding linear elements. Every one of the load elements is significantly nonlinear when analyzed individually. The results of the analysis are shown in **Figs. 1**, **2**, and **3**. Anyone with a harmonic analyzer can duplicate this testing on multiple office loads.

Fig. 1 shows the individual loads, which were arranged in four groups. Loads included IBM, NCR, and Compaq computers; IBM, NCR, and Mitsubishi monitors; a Bernoulli disk drive; and several Epson printers. Each load was maintained for 10 min.

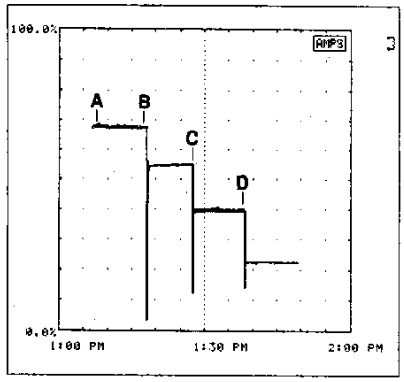
Reproductions of the harmonic analyzer

Bob Arthur is applications engineer, Transformer Business Dept., Square D Company, Oshkosh, WI.



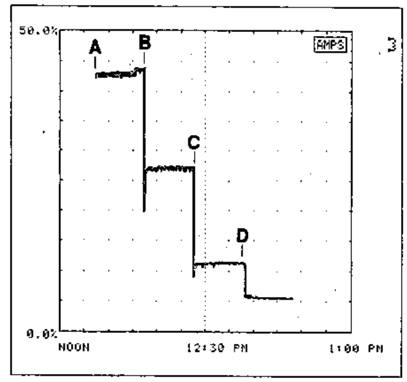
(Uncalibrated data.)

CURRENT 3rd HARMONIC (ACCUMULATED):
MAX: 89.2%
1:11 PM Sep 28 1991 (Sat)
MIN: 17.3%
1:17 PM Sep 28 1991 (Sat)



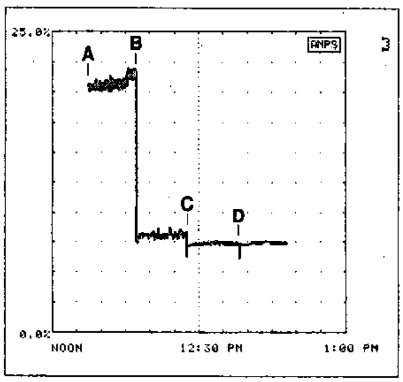
(Uncalibrated data.)

CURRENT 5rd HARMONIC (ACCUMULATED):
MAX: 68.3%
1:11 PM Sep 28 1991 (Sat)
MIN: 17.3%
1:17 PM Sep 28 1991 (Sat)



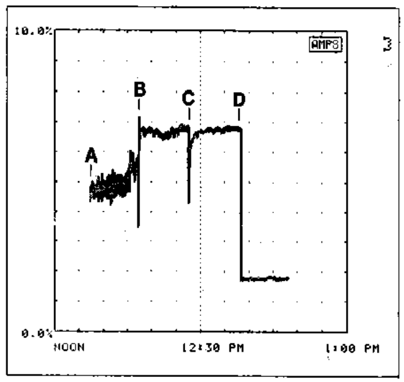
(Uncalibrated data.)

CURRENT 7th HARMONIC (ACCUMULATED):
MAX: 44.3%
12:15 PM Sep 28 1991 (Sat)
MIN: 5.4%
12:46 PM Sep 28 1991 (Sat)



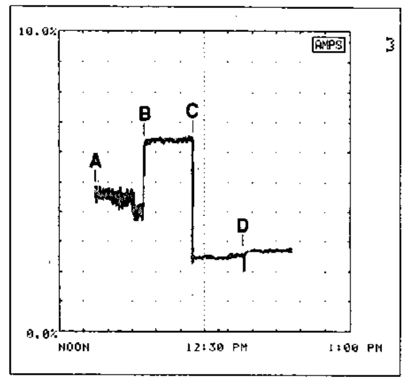
(Uncalibrated data.)

CURRENT 9th HARMONIC (ACCUMULATED):
MAX: 22.1%
12:15 PM Sep 28 1991 (Sat)
MIN: 5.4%
12:38 PM Sep 28 1991 (Sat)



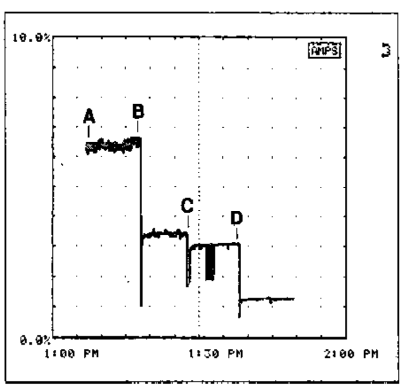
(Uncalibrated data.)

CURRENT 11th HARMONIC (ACCUMULATED):
MAX: 7.2%
12:17 PM Sep 28 1991 (Sat)
MIN: 1.7%
12:38 PM Sep 28 1991 (Sat)



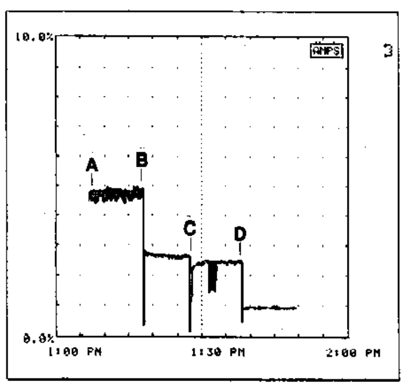
(Uncalibrated data.)

CURRENT 13th HARMONIC (ACCUMULATED):
MAX: 6.6%
12:26 PM Sep 28 1991 (Sat)
MIN: 2.0%
12:38 PM Sep 28 1991 (Sat)



(Uncalibrated data.)

CURRENT 15th HARMONIC (ACCUMULATED):
MAX: 6.8%
1:17 PM Sep 28 1991 (Sat)
MIN: 0.6%
1:38 PM Sep 28 1991 (Sat)



(Uncalibrated data.)

CURRENT 17th HARMONIC (ACCUMULATED):
MAX: 5.0%
1:16 PM Sep 28 1991 (Sat)
MIN: 0.6%
1:27 PM Sep 28 1991 (Sat)

Fig. 2. Analyzer tapes demonstrate a marked reduction of harmonics in the four groups as loads are added on. The tapes show measurements of 3rd, 5th, 7th, 9th, 11th, 13th, 15th, and 17th harmonics. In some cases, notably the 11th and 13th, the harmonics temporarily increased with a small number of loads, but the overall *k*-factor was reduced. Letters denote when specific switch is closed.

tapes (**Fig. 2**) show the effects on the third through the 17th harmonic. More importantly, the tapes clearly demonstrate the marked *reductions* of harmonics in the four groups as loads were *added.*

Reduction of the fifth and higher harmonics is thought to be primarily because of harmonic cancellation; other reduction effects are attributed to feeder impedance. In some instances, with a small number of loads connected, some harmonics temporarily *increased* instead of cancelling; however, the overall reduction in *k*-factor was significant at each load change.

Calculations for each group (**Fig. 3**) show the dramatic reduction in *k*-factor as loads are added. With 26 devices on line, the *k*-factor was reduced from the initial 13.9 to 4.6.

It's important to note in the above demonstration that the third harmonic was *reduced* from more than 88% of the fundamental to little more than 63%

Load group 1 (2 devices)

h	f_h	f_h^2	$f_h^2h^2$
1	1.000	1.000	1.000
3	0.885	0.783	7.048
5	0.673	0.452	11.310
7	0.427	0.183	8.951
9	0.203	0.041	3.329
11	0.045	0.002	0.247
13	0.047	0.002	0.367
15	0.066	0.004	0.973
17	0.045	0.002	0.591
19	0.021	0.000	0.152
21	0.014	0.000	0.083
23	0.016	0.000	0.143
25	0.015	0.000	0.142
Totals		**2.469**	**34.336**

k=34.336/2.469=13.907

Combined load groups 1, 2 (8 devices)

h	f_h	f_h^2	$f_h^2h^2$
1	1.000	1.000	1.000
3	0.826	0.682	6.142
5	0.550	0.302	7.554
7	0.273	0.075	3.660
9	0.084	0.007	0.570
11	0.068	0.005	0.565
13	0.065	0.004	0.719
15	0.034	0.001	0.263
17	0.028	0.001	0.226
19	0.028	0.001	0.282
21	0.016	0.000	0.106
23	0.016	0.000	0.128
25	0.016	0.000	0.151
Totals		**2.078**	**21.366**

k=21.366/2.078=10.282

Combined load groups 1, 2, 3 (14 devices)

h	f_h	f_h^2	$f_h^2h^2$
1	1.000	1.000	1.000
3	0.746	0.557	5.012
5	0.394	0.155	3.881
7	0.112	0.013	0.614
9	0.072	0.005	0.416
11	0.066	0.004	0.522
13	0.025	0.001	0.109
15	0.030	0.001	0.200
17	0.022	0.001	0.145
19	0.012	0.000	0.051
21	0.013	0.000	0.080
23	0.010	0.000	0.058
25	0.006	0.000	0.022
Totals		**1.737**	**12.110**

k=12.110/1.737=6.972

Combined load groups 1, 2, 3, 4 (26 devices)

h	f_h	f_h^2	$f_h^2h^2$
1	1.000	1.000	1.000
3	0.633	0.401	3.606
5	0.221	0.049	1.219
7	0.059	0.004	0.173
9	0.074	0.005	0.442
11	0.018	0.000	0.039
13	0.027	0.001	0.125
15	0.011	0.000	0.030
17	0.010	0.000	0.029
19	0.006	0.000	0.012
21	0.006	0.000	0.015
23	0.002	0.000	0.002
25	0.004	0.000	0.008
Totals		**1.460**	**6.700**

k=6.700/1.460=4.589

Fig. 3. As the number of loads increased from two to 26 devices, the *k*-factor decreased from 13.907 to 4.589. Note that the third harmonic (orange shaded area) was reduced from more than 88% of the fundamental to little more than 63% as load current increased.

as load current *increased*. (See orange shaded area.) Since the third harmonic does *not* cancel, the observed reduction is simply due to source impedance. And since the transformer feeding the office loads is usually the major ohmic impedance in the feeder, the reactance of the transformer plays a major role in controlling neutral current caused by the third harmonic.

Effect of oversizing transformers

A recent demonstration in the 208Y/120V office system at our plant illustrates the negative effect of oversizing transformers. The portion of the office in question consists totally of computer and printer loads, and is supplied by a 45kVA transformer that is only about 35% loaded.

We temporarily replaced this transformer with a 225kVA unit to observe the effect of lower ohmic resistance on the load harmonics. This transformer substitution caused the *k*-factor to *jump* from our normal value of 4.75 to a much *higher* value of 8.1. More importantly, our neutral, which was already at a high level of 120% of average line current, jumped to an unacceptable value of *over 160%*. This demonstration served to show not only that drastic oversizing of supply transformers is very *undesirable*, but also illustrated that we need to replace our existing 45kVA supply transformer with an even *smaller* unit to further reduce our neutral current.

Oversizing of transformers, or selection of unnecessarily high *k*-factor ratings of transformers, will have the effect of *increasing* neutral conductor currents and potentially damaging neutral-to-ground voltages at sensitive electronic loads.

Only at or near transformer full load is a *k*-rating necessary to prevent overheating of transformers. Since transformer losses vary with the square of current, the reduction or loss at reduced loading far outweighs the offsetting heat buildup from an increased *k* factor.

Fortunately, it's at full load where the transformer reactance has the most effect in reducing load harmonics. It's quite apparent that transformers of normal impedance and X/R values *cannot* allow a high combined electronic power supply load *k*-factor to exist, if that load is near the transformer rating. The Computer Business Equipment

Manufacturers Association (CBEMA) recommends transformer impedances of between 3 and 5%. This provides ample reactance to prevent excessive harmonic current flow and resulting high neutral current, but not so high as to cause excessive voltage distortion.

Conclusion

Misunderstandings about transformer *k* ratings come from the failure to recognize the difference between *individual branch load k*-factor values and the *total load harmonics* that appear at the feeder transformer terminals. Although some are promoting the use of tranformers with a *k* of 20 or 30 for office applications, these high ratings are based on observations of individual branch loads and cannot be justified by field data on total load *k*-factor.

When presented with isolated horror cases of very high *k*-factor industrial trouble spots, many people have overreacted by advocating unnecessarily high *k*-factor transformers for general use. Available information, however, indicates that *k*-9, or the more available *k*-13 transformers, presently are the majority choice for high concentration office loads. Our belief is that as more users measure the actual levels of *k*-factor in their systems at near full load, the *k*-4 transformer rating will become much more popular.

This is a case where more is definitely *not* better. Specifying an excessively high *k*-factor (more than 13) can create potential hazards from abnormally low impedance, a typical symptom of oversized transformers. Although a high *k*-factor does not necessarily require low reactance, the fact is that many *k*-20 and *k*-30 transformers in the marketplace fall far *below* the 3% minimum impedance recommended for computer loads. Worse yet, many have very low X/R ratios, lowering the reactive component even further.

Standard transformers with normal X/R ratios and impedance ranges of between 3 and 5% have successfully supplied mainframe computers, commercial office loads, industrial drives, and electronic ballast lighting for years. Installing abnormally low impedance, unnecessarily high *k*-factor transformers can cause even *higher* neutral currents and possibly cause malfunctions or damage sensitive load equipment.

Where *k*-rated transformers are necessary, they should be specified as close as possible to the actual load *k*-factor needed, and designed within the normal impedance range to provide the beneficial role of "softening" harmonics and reducing neutral currents that transformers have been providing all along.

The data also supports sizing transformers close to the load kVA requirements to make full use of their reactance in lowering harmonics and neutrals. This is a wise choice, since transformers run most efficiently at 70 to 80% of their capacity. This "rule-of-thumb" loading goal is further supported for controlling harmonics. The prudent use of smaller transformers, closer to the loads, and with *k* ratings closely matching the total load *k*-factor at full load, should be emphasized in planning modern electronic office systems.

• • •

Guidelines are urgently needed for multiple electronic office loads, motor drives (AC and DC), and mainframe computer installations. These guidelines will be developed through more extensive product information from equipment manufacturers as well as field measurement data bases accumulated by consultants and facility engineers. ■

For information on Electric '93 seminars on Harmonics, Derating Calculations, and/or *k*-rated transformers, circle **Reader Service Number 333.**

Please circle the appropriate Reader Service Number on the provided Reader Service Card that best describes your feelings on this article.

Very useful	Somewhat useful	Of little use
334	335	336
Easy to read	**Readable**	**Hard to read**
337	338	339

SUGGESTED READING

EC&M ARTICLES:

"Coping with Phase-to-Phase Nonlinear Loads and Harmonics," June '91 issue.
"Hands-On Approach to Solving Harmonic Problems - Parts 1 & 2" March, April, '92 issues.
"Harmonics Terminology: Fact and Fiction," February '93 issue.
"Designing Branch Circuits for the Computer-Intensive Office," February '93 issue.
For copies, phone 913-967-1801.

STANDARDS:

ANSI/IEEE C57.110-1986, *Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.*
IEEE 1100-1992, *Recommended Practice for Powering and Grounding Sensitive Electronic Equipment.*
For ordering information, phone 1-800-678-IEEE.
UL 1561 *Dry Type General Purpose, and Power Transformers*
UL 1562 *Transformers, Distribution, Dry Type—Over 600V.*
For UL ordering information, phone 708-272-8800; ext. 3331 or 2736.

Office Loads and Transformer K-Factor

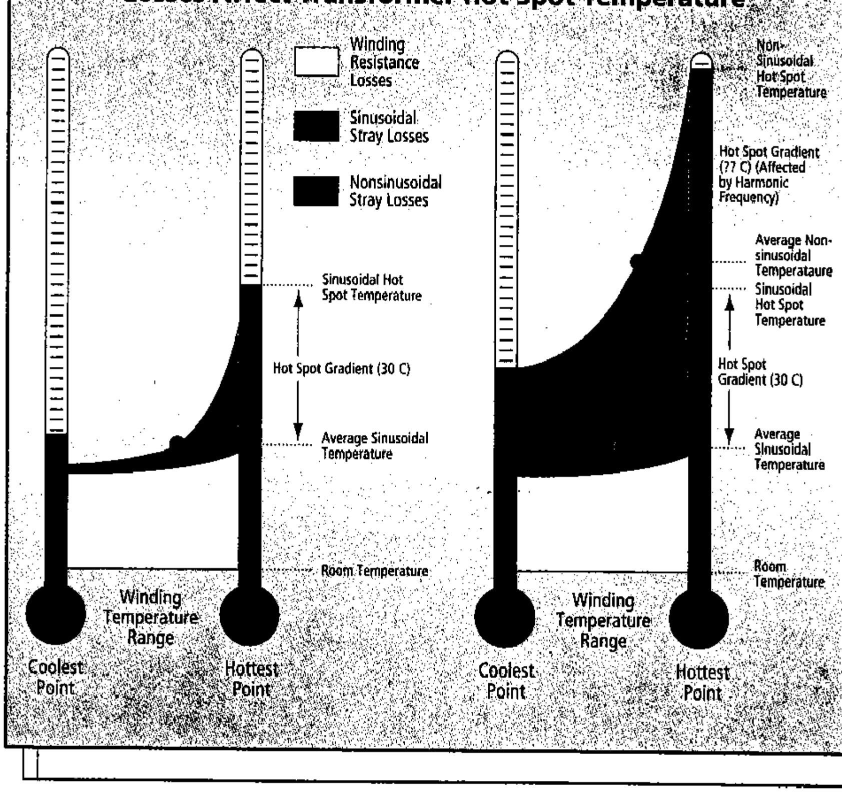
BILL PERKINS, Square D Co., Nashville; TN, and **BOB ARTHUR**, Square D Co., Oshkosh, WI

The proliferation of electronic equipment in manufacturing plants has brought to the forefront a problem that had plagued only relatively few facilities in yesteryear. The problem is the harmonic currents generated by virtually all solid-state electronic equipment. This equipment spans the gamut from personal computers and photocopiers, through solid-state motor controllers of all sizes, to dc power supplies in the megawatt range. Notable among the detrimental effects of harmonic currents is heating developed in transformers that is over and above the amount created by nonharmonic loads.

Different considerations apply than for transformers serving three-phase loads

In recent years, much attention has been devoted to a quantity known as transformer "K-Factor." Simplistically defined, a transformer's K-Factor rating describes its ability to withstand the additional heating imposed on it by loads with high harmonic content. And simplistically applied, K-Factor would appear to be a panacea for transformer burnout in the presence of high harmonic currents. The more K-Factor, the better..., right? The correct answer is "Not necessarily."

How Specific Harmonic Frequencies and Accompanying Stray Losses Affect Transformer Hot Spot Temperature



How K-Factor Is Calculated

Transformer K-Factor has its roots in ANSI/IEEE Std C57.110, "Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents," published in 1986. While the term K-Factor is relatively new, the mathematical procedure for its calculation is not. K-Factor is simply the sum of the product of the squares of the per-unit currents at each harmonic order, multiplied by the squares of the harmonic orders:

$$K = \Sigma(I_{hpu})^2 h^2$$

from $h = 0$ to infinity

Where:

K = K-Factor

I_{hpu} = per-unit harmonic current

h = harmonic order

The data in Table I are taken from IEEE/ANSI C57.110 and provide an example of how the summation $\Sigma(I_{hpu})^2h^2$ is derived for the typical harmonic distribution in the current feed-

The specific harmonic signature that the transformer is subjected to is a "wild card" affecting stray losses and resultant heating.

ing a six-pulse rectifier. The harmonic order as given in the left-hand column is the harmonic multiple of the fundamental (60-Hz) frequency. The fifth harmonic, for example, is 300 Hz (5 times 60). It should be noted that the third harmonic (180 Hz) is only generated by single-phase rectifier loads.

Table I. How K-Factor Is Derived

h	I_{hpu}	(I_{hpu}^2)	h^2	$(I_{hpu})^2h^2$
1	0.978	0.959	1	0.957
5	0.171	0.029	25	0.731
7	0.108	0.012	49	0.571
11	0.044	0.002	121	0.234
13	0.028	0.0078	169	0.133
17	0.015	0.00023	289	0.065
19	0.0098	0.00010	351	0.035

$\Sigma = 2.726$

Table II. Example of How Different Harmonic Signatures Yield the Same K-Factor

	Case 1		Case 2	
h	I_{hpu}	$(I_{hpu})^2h^2$	I_{hpu}	$(I_{hpu})^2h^2$
1	0.91	0.828	0.97	0.941
3	0.35	1.103	0.00	0.000
5	0.19	0.903	0.19	0.903
7	0.10	0.490	0.12	0.706
9	0.05	0.203	0.00	0.000
11	0.04	0.194	0.08	0.774
13	0.01	0.017	0.05	0.423
15	0.01	0.023	0.00	0.000
K-Factor		3.761		3.747

Possible Flaws in Ratings

As originally presented in ANSI/IEEE C57.110, the $\Sigma(I_{hpu})^2h^2$ harmonic summation technique was intended as a tool for derating existing small or medium-sized power transformers serving three-phase loads with high harmonic content, such as motor drives. These derating tools were not intended for derating of existing small, general-purpose transformers feeding distributed, single-phase, switched-mode power supply loads such as office equipment. The concept, however, is being increasingly misapplied in this manner.

Underwriters Laboratories first proposed using K-Factor as a transformer rating criterion in a bulletin dated December 1990. UL offered an additional listing under its existing standard UL 1561. A number of transformer experts, however, assert that UL's method of testing to verify a particular K-Factor rating might be flawed.

UL test criteria calls for first testing the transformer with 60-Hz sinusoidal current to determine total winding and core watt losses. From this total, the calculated 60-Hz I^2R winding losses are deducted to determine the stray losses. If the transformer is proposed for a particular K-Factor rating, stray losses are then multiplied by that factor and added to the 60-Hz I^2R losses.

The resultant is presumed to be the winding loss representative of the transformer when subjected to a harmonic load with K-Factor applied. If the average winding temperature rise — as determined by measuring winding resistance — does not exceed the rated average winding temperature rise, the transformer is deemed suitable for any harmonic load at the rated K-Factor or less.

Many transformer design and application engineers share the view that K-Factor does not represent an accurate analog of transformer heating. It would be nice if K-Factor rating alone would ensure that the transformer does not overheat under any combination of harmonic loads whose K-Factor summation does not exceed the transformer K-Factor rating. The heating pattern of a transformer, however, can change as the harmonic signature changes — and there are an infinite number of harmonic signature combinations that can combine to yield the same K-Factor summation. A hypothetical example is given in Table II.

Factors Affecting Heating

It is not within the scope of this article to discuss all of the many factors that affect transformer heating. A few are noted here, however, because they can affect the heating pattern of a transformer under harmonic loading — and some of these are not acknowledged in the UL test criteria for verifying K-Factor rating.

For example, the flux field in a transformer is far from uniform. And the eddy current loss in a transformer is proportional to the square of the frequency, the square of the field's breadth (90 deg to the flux field), and the fourth power of the field's depth (parallel to the flux field):

$$W \propto F^2B^2D^4$$

Where:
W = eddy current watt losses
F = frequency, Hz
B = per-unit breadth of field in a direction 90 deg to flux field
D = per-unit depth of field in direction parallel to flux field

In the case of K-Factor, overspecification can cause problems, in addition to resulting in increased costs

Any variation in frequency — or in field length or breadth — affects eddy current losses and their heating far out of proportion to the variation in frequency.

When the field is irregular — perhaps at the end turns, as can be expected even within the most rigid manufacturing tolerances — increased localized heating is expected. The effect, however, differs with different harmonic distributions, even when the K-Factors are identical. Frequency is a prominent factor in the development of eddy current heating, and frequency is a "wild card" in circuits serving multiple harmonic loads.

Transformers seldom fail because they simultaneously "failed all over;" ultimate failure from burnout is commonly at a hot spot in the winding. Standards for dry-type transformers assume a 30-deg C gradient between average winding temperature and the hottest spot in the windings.

Tests based on measuring the average winding temperature rise assume that temperatures in the winding follow a pattern such as given in the left-hand element of the illustration, "How Specific Harmonic Frequencies and Accompanying Stray Losses Affect Transformer Hot Spot Temperature." UL tests for verifying transformer K-Factor, however, presently do not consider the possible harmonic effects on eddy current loss gradients within the coils. This omission occurs because stray loss measurement and other transformer evaluation testing is all done at 60 Hz with linear loads.

The higher flux densities, design diversities, and reduced design safety factors in some of today's small dry-type transformers especially suggest that existing criteria for assigning K-Factor ratings might be inadequate for such transformers serving switched-mode power supply equipment.

Some transformer application engineers share the view that the best way to compensate for possible inadequacies in the UL K-Factor evaluation process is to specify only reduced temperature rise K-Factor transformers, either in 115 deg C or 80 deg C rise designs. Such designs can withstand elevated hot spot temperatures without exceeding the 220 deg C insulation rating.

Can You Get too Much K-Factor?

As opposed to manufacturing design practice — where, in some cases, pennies spell the difference between profit and loss — sound plant engineering practice calls for applying a contingency factor, rather than going with "just enough." In the case of K-Factor, however, overspecification can cause problems, in addition to resulting in increased costs.

> ***Frequency is a prominent factor in the development of eddy current heating***

Higher K-Factor ratings increase neutral currents, and can result in increased neutral-to-ground voltage that can cause problems on sensitive electronic loads. High K-Factors (more than 13) can result in abnormally low impedance, lowering the transformers ability to "soften" power supply aberrations. The latter condition often prevails with transformers having K-Factors of 20 or greater, and which often have impedances lower than 3%.

Consultants and transformer manufacturers occasionally recommend K-Factor ratings of 13 or higher for transformers serving office loads. However, comprehensive tests conducted on nonlinear office loads at several commercial and industrial facilities, including Square D plants, have shown that a higher-population mix of electronic office equipment actually *reduces* the total load K-Factor. The tests revealed that no office location found in these studies required a transformer K-Factor rating of more than 9.

Presuming a transformer impedance of 3% to 5%, the proper transformer kVA rating for an office application is one that permits the transformer to operate at 70% to 80% of rated kVA capacity. This kVA rating permits the transformer to operate efficiently, while leaving some excess capacity for expansion. Within this guideline, the lowest K-Factor rating should be selected that satisfies the application. In most office applications, a K-Factor of 9 to 13 suffices.

Paradoxically, smaller physical size might be an indication of a transformer's better ability to withstand the variety of harmonic signatures that it might be subjected to, because transformers with low stray losses require less oversizing to pass the UL evaluation test. If two transformers have an identical kVA and K-Factor rating, yet differ significantly in size and weight, it is probable that the smaller unit was designed for lower stray losses.❑

Reprinted from **PLANT ENGINEERING** August, 1994

Neutral Currents in Three Phase Wye Systems

Robert Arthur
Square D Company
Oshkosh, Wisconsin
(414) 426-8022

R. A. Shanahan, P. E.
Square D Company
Lexington, Kentucky
(606) 224-1914

ABSTRACT

This paper:

- Discusses current signatures of single phase non-linear loads and examines the relationship of these signatures to neutral current in wye-connected three phase electrical systems.
- Establishes formulas for estimating maximum neutral current under various total harmonic current distortion levels for both balanced and unbalanced load conditions.
- Shows that neutral conductor oversizing is not necessary in 480Y/277V systems, but may be necessary in 208Y/120V systems under unusual circumstances.

These discussions apply to 480Y/277V electrical systems in the United States and 600Y/346V lighting distribution systems in Canada.

INTRODUCTION

The increasing use of electronic devices in electrical distribution systems has raised the level of concern about the effects of "non-linear" loads on these systems. Three phase non-linear loads such as motor drives, silicon controlled rectifier (SCR) controllers, large uninterruptible power systems (UPS), and other similar devices can create their own set of distinct problems, but do not contribute to neutral current. Of special concern are single phase devices with rectifier front-end power supplies such as computers, electronic lighting ballasts, and other similar electronic devices. When these types of loads are connected line to neutral in a three phase wye-connected power system, the neutral conductors in the three phase feeders can carry surprising levels of current, even with the loads balanced on the three phases. Contrary to traditional thinking, efforts made to balance loads on the three phases that are under high current distortion conditions, may even contribute to *increased* neutral current. Since the National Electrical Code has prohibited neutral conductor overcurrent protection, proper sizing of neutral conductors is a concern when supplying large numbers of single phase non-linear loads. (An exception is when the overcurrent device opens all conductors of the circuit including the neutral.) To realistically evaluate the need for neutral oversizing, it's important to differentiate between the types of single phase electronic loads.

The first type of single phase non-linear loads includes 277V magnetic and electronic lighting ballasts, which predominate in 480Y/277V distribution systems. The electronic ballast industry has universally adopted standards that establish maximum current distortion levels. With these solutions in place, the level of concern is considerably less than that for the second type of non-linear load, which includes computers and other similar 120V devices. In contrast, these loads are major contributors to neutral current in 208Y/120V building systems. The computer industry has done very little to improve the input current waveforms from "switched-mode" power supplies. Note that delta-wye connected transformers used to step down 480V to 208Y/120V, do not transfer neutral current from the secondary to the primary. Therefore, since most systems are designed with delta-wye transformers that separate 480V and 208V systems, the neutral issues of these systems are distinctly separate.

NON-LINEAR LOAD CHARACTERISTICS

Single phase electronic-load power supplies are typically configured with a front-end full-wave bridge rectifier with significant capacitor filtering on the dc side of the rectifier. In switched-mode power supplies, the resulting dc voltage is switched at high frequency to facilitate stepdown through a relatively small, high frequency transformer. The transformer output is then rectified and filtered again to provide the required dc outputs. In other power supplies, the stepdown transformer may be ahead of the rectifier section. In this case, the dc side of the rectifier is typically passed through regulator sections to the loadside output. In either case, these loads are characterized as "non-linear" because the waveform of the input current is significantly distorted as compared to the ideal sinusoidal current waveform. The input current waveform is a result of a switching action that takes place between the rectifier diodes and the dc bus capacitors, see figure 1. The rectifier diodes are forward biased only when the input voltage exceeds both the capacitor voltage plus the forward voltage drop required by the diodes. Therefore, current exists in the ac supply side only during the peak of the source voltage waveform. During conduction, a large pulse of current occurs, which is typically comprised of capacitor charge current and load current being drawn from the dc bus. The capacitor charge current is limited by the forward resistance of the diode, the internal impedance of the dc bus capacitance, and the source impedance of the ac supply line. The resulting current signature is typically an alternate positive and negative series of short current pulses.

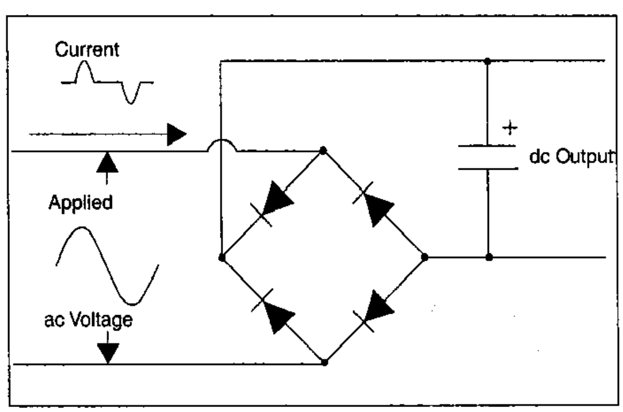


Figure 1: Electronic loads are non-linear current sources because of front-end rectification.

COMPUTER LOAD NEUTRAL CURRENT

Why do current pulses in single phase, non-linear loads increase in the three phase neutral circuit? Common explanations usually discuss the zero sequence or triplen harmonic current flow. Figure 2 shows the traditional method of illustrating third harmonic as zero sequence and its consequent additive effect in the neutral.

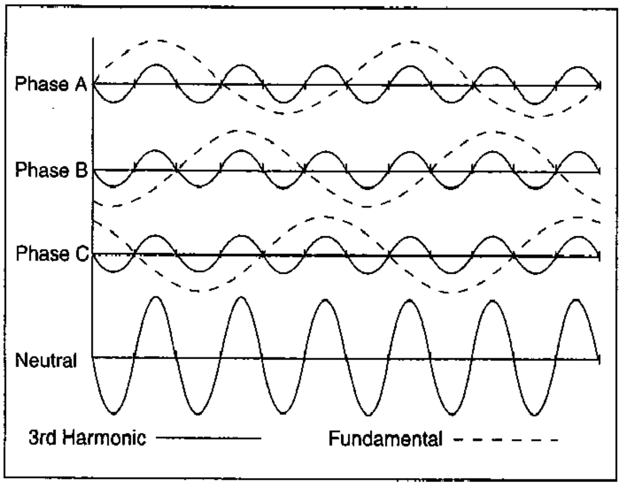
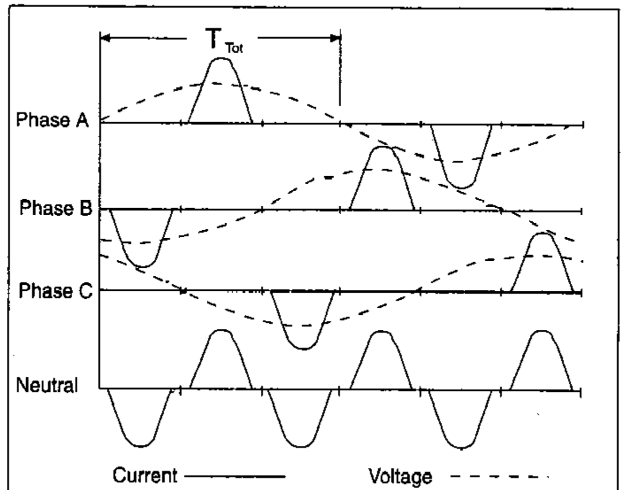


Figure 2: Third harmonic and other "triplen" harmonic components are in phase on all three phase lines in a wye-connected circuit.



$$\text{Line} = \frac{\sqrt{\sum_{\Delta T \to 0} (I^2 \Delta T)}}{T_{tot}} \qquad \text{Neutral} = \frac{\sqrt{3\sum_{\Delta T \to 0} (I^2 \Delta T)}}{T_{tot}}$$

= 1.73 x Line Currrent

Figure 3: The theoretical maximum neutral current for rectifier type non-linear loads is 173%.

Although such explanations are correct as a mathematical concept, they can be misleading. The actual current waveshapes have third harmonic components, but third harmonic sinusoids are not really flowing in the lines. Therefore, the overly simplified presentation in Figure 2 fails to show why neutral current has a maximum limit. Also, it fails to illustrate the *real* waveshape of the neutral. A more accurate and realistic visualization is possible by observing the waveshape of the currents involved.

At low current, such as in the case of single-pole branches feeding individual, unfiltered non-linear load circuits, the current pulses are typically so narrow as to be "non-overlapping" on the three phases. This means that only one phase of the three phase system carries current at any instant of time. Under these circumstances, the only return path for current is the neutral conductor. As a result, the number of current pulses accumulated in the panel neutral is three times that in the lines. The root mean square (rms) current increase, from one to three current pulses in a common time interval, is 173% (see figure 3).

NEUTRAL CURRENTS VS. LOAD CURRENT

Internal load and component differences within devices cause the diode conduction times to vary. As the number of loads increase, the diversity between individual loads widens the cumulative current pulses. In addition, as system current increases, voltage distortion from system source impedance further widens the pulses. In most systems, as few as seven unfiltered devices (even if identical) on line per phase have sufficient effect on pulse width to cause the neutral pulses to start overlapping (figure 4). During overlap periods, more than one phase is conducting at a time on the three phase lines, with some current being returned on the phase lines, and not in the neutral. The result is a reduction in neutral current as a percent of phase current. The maximum neutral current of 173% of phase current is typically seen only at lower current sub feeders in larger distribution systems. Pulse overlapping typically reduces the neutral current level to less than 130% in main service panels that are rated at higher current levels. This still may be a concern in highly loaded services. Note that these maximum levels occur only under extremely rare cases of perfect balance with all loads identical in phase relationship, power factor, and harmonic characteristics. That is why there is an extremely small number of observed loads in which neutral currents are greater than 100% of the neutral conductor rating, and these loads are restricted to subfeed panels that are either connected to comparatively large distribution systems, or prewired office partitions with shared neutrals.

In light of this relationship between current levels and pulse width, it's important to differentiate between data from installations in which neutrals have been truly overloaded, and those measurements made in systems loaded at very low percentage of capacity, where neutral current may exceed line current, but not approach neutral wire capacity. Higher neutral percentages occur more frequently in underloaded systems, but do not indicate the need to increase neutral conductor size.

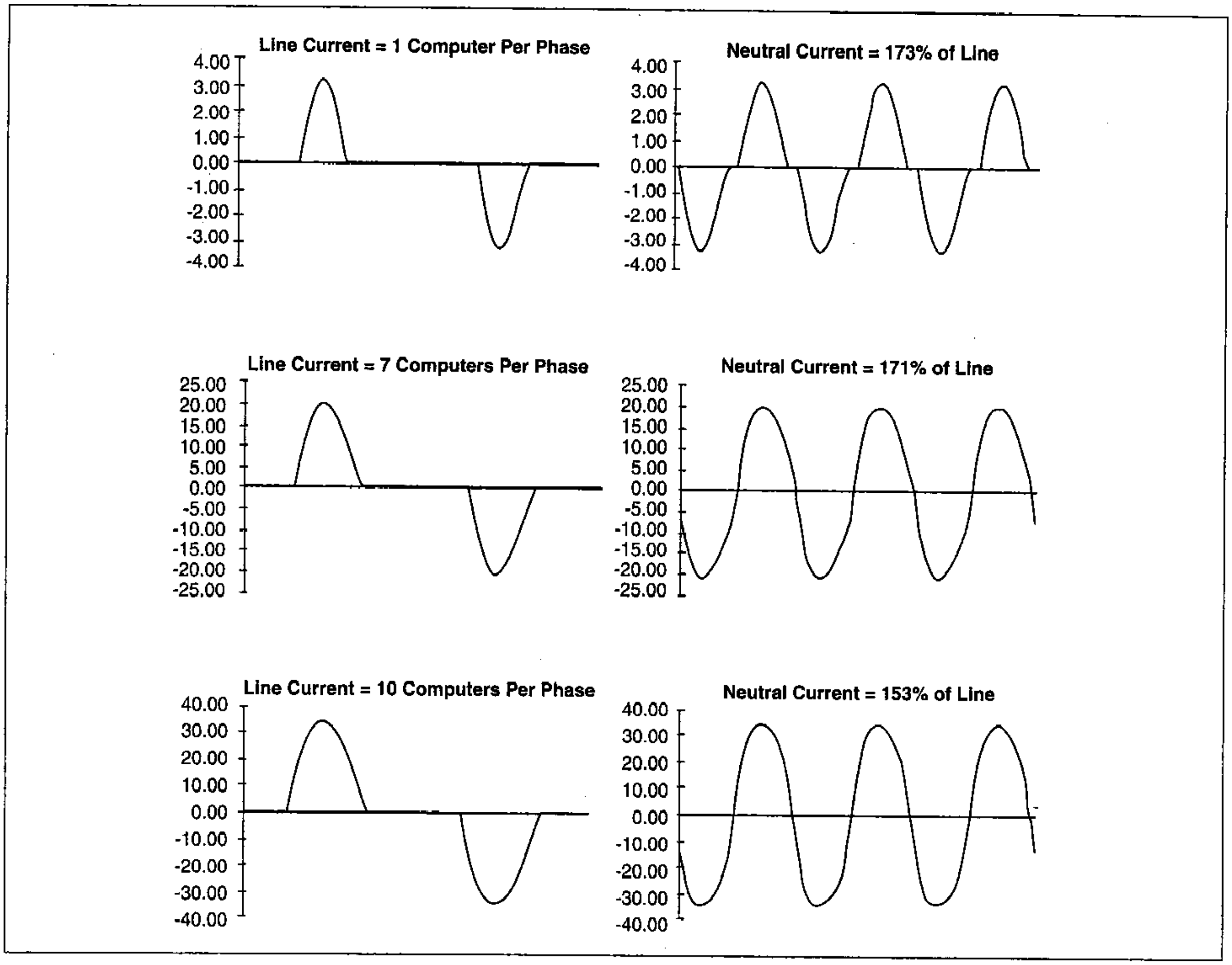


Figure 4: Both load population and the effects of source impedance on voltage tend to reduce neutral current.

NEUTRAL CURRENT AND TOTAL HARMONIC DISTORTION

Total Harmonic Distortion (THD) is a percentage representing the deviation of a waveform from the ideal sinusoid. The formula for current THD is:

$$\%THD = 100 \times \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 \ldots\ldots + I_h^2}}{I_1}$$

Where:

h = harmonic number

I_h = current at harmonic "h" in per-unit of total rms current

Every waveshape has harmonic components. In the case of a sinusoid, the harmonic component consists of the 1st harmonic, or fundamental, with no other harmonics present.

Table 1: Third harmonic in single phase non-linear load current is the major contributor to neutral current. Other harmonics, including triplens such as 9th, 15th, etc., provide insignificant contribution.

Harmonic	I_h	Harmonic	I_h
1	0.943	1	0.934
3	0.333	3	0.333
		5	0.117
		7	0.030
		9	0.039
		11	0.009
		13	0.015
		15	0.006
%THD = 35.36		%THD = 38.20	
%Neutral = 100.0		%Neutral = 100.7	

The THD of a sinusoid is 0%. Typical unfiltered single phase electronic loads produce current distortions that contain large amounts of 3rd harmonic, with decreasing percentages of 5th, 7th, 9th, 11th, 13th, 15th, and so on. Of those harmonics, only the 3rd, 9th, 15th, etc., contribute to the neutral problem. Harmonics in this sequence are identifiable as triplen harmonic numbers that are evenly divisible by 3. Because of their lower current levels and higher frequencies, the 9th, 15th and higher triplen harmonics distort the neutral current only slightly and do not have a significant effect on actual rms neutral current. Therefore, to accurately estimate the percent neutral current that would result from three identical non-linear phase currents, simply multiply the 3rd harmonic (as a percentage of total rms current), times 3 (see Table 1, page 5). Thus, a minimum of 33.33% of 3rd harmonic is required to produce a 100% neutral current.

This strong relationship between the 3rd harmonic and neutral current leads to an equally strong relationship between neutral current and line current THD. Table 1, page 5 shows that by considering the 1st and 3rd harmonics only in the THD formula, and setting the 3rd harmonic value to 33.33% to produce 100% neutral current, the minimum THD to produce this current is 35.36%. Note that if other harmonics are present, they merely raise the THD number, but do not significantly increase neutral current. For that reason, a THD of 35.36% is the minimum limit of line current distortion required to produce 100% neutral current in a balanced wye system. For a more general rule, the following guideline relationships can be calculated:

Given: I_1 = Fundamental current as a per-unit of total rms current

I_3 = Third harmonic current as a per-unit of total rms current

The %THD increases only when harmonics other than fundamental and third are considered. Other harmonics can be neglected because they do not contribute significantly to neutral current when considering **minimum** %THD:

1. Minimum %THD = $100 \times \frac{\sqrt{I_3^2}}{I_1} = 100 \times \frac{I_3}{I_1}$

2. And, since I_1 and I_3 are defined as per-unit of total rms current, then:

$$\sqrt{I_1^2 + I_3^2} \cong 1 \quad \text{or} \quad I_1 \cong \sqrt{1 - I_3^2}$$

3. Combining equations 1 and 2:

$$\text{Minimum \%THD} \cong 100 \times \frac{I_3}{\sqrt{1 - I_3^2}}$$

or

$$\text{Maximum } I_3 \cong \frac{\text{\% THD}}{\sqrt{10{,}000 + (\text{\%THD})^2}}$$

4. Since all harmonics other than 3rd have an insignificant effect on neutral current:

$$\text{\%Neutral} \cong 300 \times I_3$$

5. Note that since the maximum neutral current is 173%, the maximum 3rd harmonic is 0.577 times the total rms line current. Combining equations 3 and 4:

Maximum %Neutral ≅

$$300 \times \frac{\text{\% THD}}{\sqrt{10{,}000 + (\text{\%THD})^2}} \text{ up to 173\% neutral}$$

This relationship in equation 5 is a good guideline for estimating the maximum, balanced neutral current for THD values up to about 150%. Because third harmonic reaches its maximum at 57.7% of total rms current, equation 5 becomes increasingly inaccurate as the neutral value approaches 173%. As a result, although equation 5 estimates that a minimum of 70.7% line current THD is required to reach the 173% maximum, in practice it typically takes 80–90% THD to achieve maximum neutral levels.

For example, a lighting ballast is rated at 10% THD. What will be the maximum, balanced load neutral current on the lighting panel?

Maximum % Neutral ≅

$$300 \times \frac{10}{\sqrt{10{,}000 + (10)^2}} \cong \frac{3000}{\sqrt{10{,}100}} \cong 29.9\% \text{ of line current}$$

LIGHTING BALLASTS

Table 2: Current harmonic limits for lighting ballasts.

Harmonic	Maximum Value
Fundamental (by definition)	100%
2nd Harmonic	5%
3rd Harmonic	30%
Individual Harmonics > 11th	7%
Odd Triples	30%
Harmonic Factor (Distortion Factor)	32%

The lighting industry has established limits on harmonic currents for lighting ballasts which are outlined in ANSI Standard C82.11-1993. Table 2 is a portion of Table 3 from ANSI Standard C82.11-1993. The table is quite comprehensive in that it puts limits on specific low-order harmonics (2nd and 3rd), high-order harmonics (>11th), and odd triples. To further encourage the use of the low THD ballast designs, some utility companies offer energy saving rebates only for electronic ballasts that have THD values less than 20%. Each ballast manufacturer has a large selection in the <20% range. In reality, most of the products fall in this range, see Table 3.

Table 3 : THD ranges for various types of ballasts compared with office equipment.

Device Type	THD
Older Rapid Start Magnetic Ballast	10–29%
Electronic I.C. Based Ballast	4–10%
Electronic Discrete Based Ballast	18-30%
Newer Rapid Start Electronic Ballast	<10%
Newer Instant Start Electronic Ballast	15–27%
High Intensity Discharge (HID) Ballast	15–27%
Office Equipment	50–150%

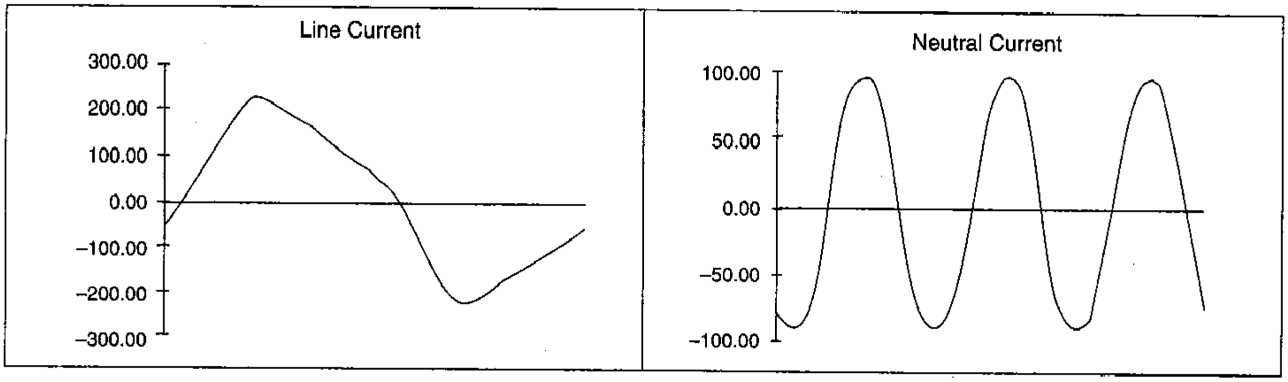


Figure 5: Current signature of a lighting panel main showing a 145A rms electronic ballast load. Line current THD is 16.7%, with a neutral current of 69.2A (47.7%). Third harmonic component is 16.2%

As pointed out previously in this paper, non-linear load current pulse widths vary with the number of loads and the magnitude of load current in the system. As pulse widths increase, the THD percentage goes down, simply because the waveform is becoming more sinusoidal. Computer load currents vary between about 40% on systems that are heavily loaded and have high load populations, to 150% THD or more, on individual load branch circuits. In comparison, the ballast industry has set a standard for electronic ballasts at 32% maximum THD. In fact, modern electronic ballasts vary from about 4% to 23% THD, showing the beneficial effect of input filters incorporated in their design (see figure 5).

UNBALANCED LINE LOADS AND NEUTRAL CURRENT

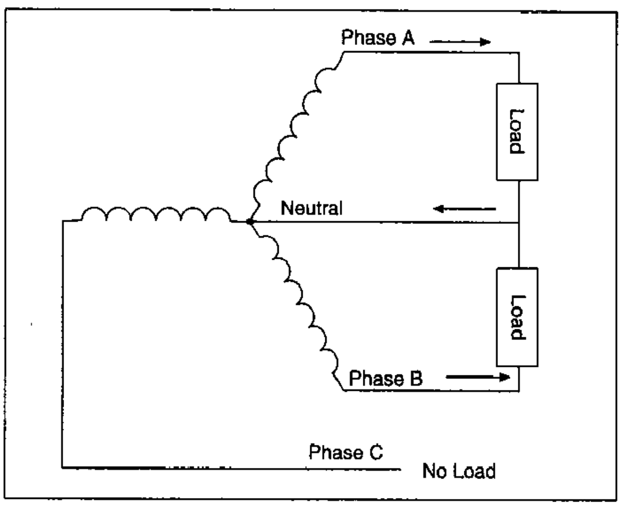


Figure 6: Unbalanced single phase non-linear loads can create elevated neutral current.

Just as balanced load neutral current is related to %THD, neutral current resulting from unbalanced non-linear loads are also related to current distortion. For linear loads, the maximum neutral current is 100%, regardless of balance. However, single phase non-linear loads, can create elevated neutral levels, particularly in severely unbalance loads (figure 6). If two phases are at full load, with no load on the third phase, the maximum neutral current can be calculated in the same way as in figure 3, page 4, but with two non-overlapping current pulses returning in the neutral for every single pulse on the line:

$$\text{Neutral} = \frac{\sqrt{2 \sum_{\Delta T \to 0} (I^2 \Delta T)}}{T_{tot}} = 1.414 \times \text{Line}$$

The maximum neutral current for an unbalanced load condition can be estimated in a way similar to the derivation of equation 5, page 6. In this case, however, the neutral carries the same magnitude as the line current of fundamental and other non-triplen harmonics, but also carries twice the triplen harmonics. We can isolate the effect of triplen harmonics using equations 6, 7, and 8.

6. Per Unit:

   Line Current (rms) =

   $$\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \ldots\ldots + I_h^2} = 1$$

   or

   $$I_1 = \sqrt{1 - I_2^2 - I_3^2 - I_4^2 + \ldots\ldots - I_h^2}$$

7. Neutral current carries the same non-triplen harmonics as the line, but twice the triplen components:

   Neutral Current =

   $$\sqrt{I_1^2 + I_2^2 + (2I_3)^2 + I_4^2 + \ldots\ldots + (I_{nontriplen})^2 + (2I_{triplen})^2}$$

8. Combining equations 6 and 7, and ignoring triplen harmonics above the third for the same reasons as shown in the balanced neutral derivation:

   $$\%\text{Neutral} \cong 100 \times \sqrt{1 + 3I_3^2}$$

9. Combining equations 8 and previously derived equation 3: Maximum %Neutral ≅

   $$200 \times \sqrt{\frac{2500 + (\%\text{THD})^2}{10{,}000 + (\%\text{THD})^2}} \quad \text{up to 141\% neutral}$$

Again, since the third harmonic maximizes at 57.7% of total rms current, the equation is not valid above the 141% maximum unbalanced neutral point.

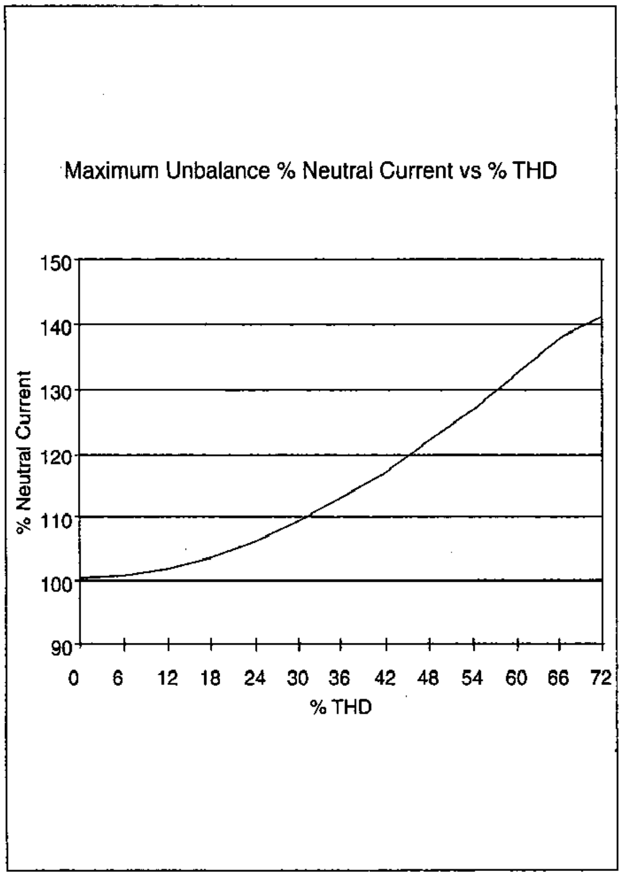


Figure 7: The maximum neutral current when the load is balanced on only two phases depends on current distortion and has a maximum value of 141.4%. This curve is derived from equation 9, page 7.

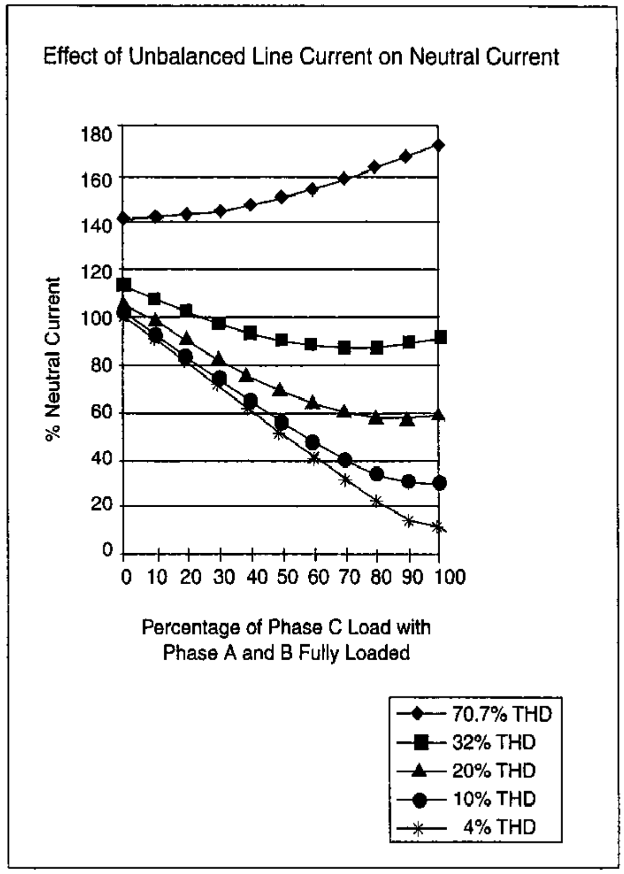


Figure 8: The unusual condition of two phases fully loaded, with one phase either unloaded, or lightly loaded, can produce greater than 100% neutral current, depending on current distortion.

Figure 7 illustrates the effect of current distortion on the maximum unbalanced current in the neutral. Although the condition of maximum unbalance under full load conditions is considered extremely unlikely, for moderate distortions even as high as the 32% limit for lighting ballasts, the neutral current would not exceed 113% of line current. Considering the improbability of the conditions required for such a current magnitude, coupled with the fact that modern lighting ballasts are far under the 32% THD maximum, the use of oversized neutrals for those applications appears unreasonable. However, for computer loads where distortions can be 40% and higher, this information reinforces the idea that oversized neutrals *may* be required for 208Y/120V systems. Figure 8 is included to show the effect of other percentages of unbalance in relation to current distortion. Note that even at the highest level of actual distortion, which is approximately 20% in typical of modern lighting ballasts, the maximum unbalanced neutral current is only 105%. Note that practical installations never approach the extreme unbalance conditions required to produce these maximums.

SITE DATA

The authors have accumulated a number of site measurements of both computer and electronic ballasts. In each case, measurements were made on installations where 100% of the loading was either computer equipment connected to 208Y/120V systems, or electronic fluorescent ballasts on 480Y/277V lighting panels. The sites in which measurements were taken were carefully chosen to represent worst case conditions, and included both Square D Company facilities and other sites, both office and concentrated electronic installations. In addition, it was decided that it would not be very constructive to evaluate actual site neutral current measurements because diversities in power factor, load equipment characteristics, unbalanced loading, and other factors can make actual neutral current measurements lower than they theoretically could be if all of the loads were the same on all three phases. To eliminate the variables, which tend to reduce neutral currents in actual installations, the authors converted each phase current waveform to an "idealized" format. Each point in figure 9 represents the

Site Data Sampling

Designation	THD (%)	Neutral (%)	RMS Amperes
Computer	121.36	173.20	1.15
Computer	146.22	172.14	3.38
Computer	103.51	172.56	4.63
Computer	86.10	171.12	8.80
Computer	87.51	133.18	16.36
Computer	68.05	158.64	16.76
Computer	67.57	121.56	20.52
Computer	59.33	107.18	20.58
Computer	44.12	82.97	21.76
Computer	72.03	167.78	27.30
Computer	82.37	143.11	29.02
Computer	55.98	90.73	29.22
Computer	82.36	142.90	33.03
Computer	59.93	142.74	35.64
Computer	76.97	137.30	37.23
Computer	44.40	112.01	38.42
Computer	36.35	90.75	40.53
Computer	54.08	134.84	42.52
Computer	52.78	111.47	43.65
Computer	46.07	115.38	46.78
Computer	52.50	131.81	48.08
Computer	47.55	121.64	49.40
Computer	54.50	131.54	50.91
Lighting	11.85	34.20	80.96
Lighting	16.71	47.70	144.98
Computer	59.24	138.01	228.63
Computer	52.66	130.06	228.75
Computer	45.19	116.09	262.38
Computer	29.26	78.74	1197.17
Computer	30.08	81.53	1228.04
Computer	27.88	75.90	1264.46

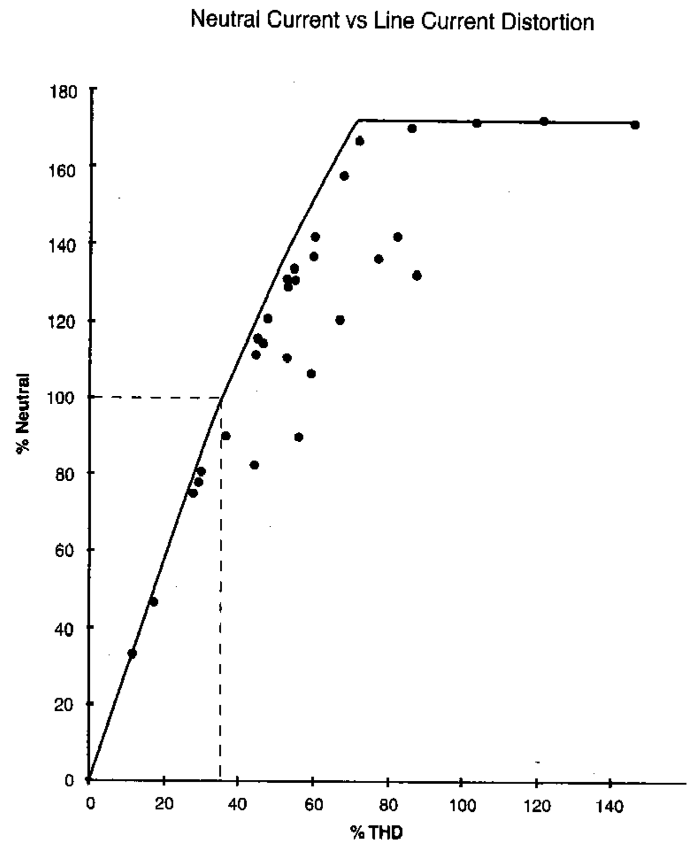


Figure 9: Both computer and lighting ballast "maximized" neutral contributions fall on or to the right of a curve described by equation 5, page 6, to a maximum of 173%, starting at 70.7% THD. Note that balanced loads with THD of less than 35.36% will always produce neutrals of less than 100%

maximum neutral magnitude if that phase current were identically copied on all three phases. Actual neutral measurements at the sites were always lower than the idealized values and, in fact, were all well below the rating of their neutral conductors. Figure 9 clearly shows that all loads fall to the right of a nearly linear relationship described by the previously derived equation 5, page 6:

Maximum %Neutral ≅

$$300 \times \frac{\%\,THD}{\sqrt{10{,}000 + (\%THD)^2}} \text{ up to 173\% neutral}$$

This relationship forms a slightly curved line, extending from the zero point (0% Neutral, 0% THD), through the 100% neutral point (35.36% THD), all the way to the 173% neutral maximum. For computers, ranging from 28% to 150% THD, the maximum neutral currents follow this curve, resulting in a range starting at 76% and reaching the maximum non-overlap point of 173% neutral when the THD reaches 70.7% or more. This curve fits very well with site measurement value tabulations. Those points far to the right of the curve contained small amounts of more linear current elements, or some phase shifted elements that caused distortions beyond those normally expected from the amount of third harmonic present.

Note that the examples of computer loads exceeding 140% are restricted to very low current site measurements, consisting of lightly loaded branch circuits with lower load population and comparatively low source impedance as a percent of actual current flow. In contrast, and of particular note, are the last three measurement examples that were taken at a Midwest insurance company. These measurements exceeded 1000A and represent close to full load for the supply transformer. Note the effect of source impedance; it keeps the neutral current well below the neutral conductor rating.

Only two electronic lighting ballast site measurements are shown, which represent that type of load. Standards limit lighting ballasts to 32% THD or less. Their actual range of 4% to 23% THD would produce neutral values of 12% to 67.2%, and would not produce neutral currents exceeding 100% under balanced conditions.

CONCLUSION

There appears to be no significant justification for increasing neutral capacity in 480Y/277V systems. The lighting industry has set THD limits, which guarantee that standard, full size neutrals are adequate. Even under very unusual situations where the phases are fully loaded and unbalanced, the neutral currents only slightly exceed 100%. Several products have appeared on the market for use in 480Y/277V systems that incorporate double neutral conductors. These products include K-Factor rated transformers with double neutral 480Y/277V secondaries, double neutral panelboards, double neutral bus duct, and even double neutral switchgear. The development of such products for use in 480Y/277V distribution is, of course, the result of specification demand. Specifiers and consultants should avoid the promotion of the myth that neutrals have problems in this voltage category. In the special case of K-rated transformers, Underwriters Laboratories (UL) and Canadian Standards Association (CSA) should reconsider their standards requirement for increased neutral terminations on 480Y/277V and 600Y/346V secondaries.

In the category of 208Y/120V systems, until the computer industry can reduce the %THD of their products, increasing the capacity of the neutral conductors on some three phase feeders will continue to be necessary. Within this category, the 200A or lower *subfeed* panels and their associated feeder cables, may be even more likely to exceed the neutral conductor rating. However, at higher current levels of the distribution system the need for these precautions lessens. In addition, *main* panels that are fully sized for the feeder transformer, even at 200A or lower, appear to benefit from the neutral current limiting effect of transformer reactance. Although theoretical levels of 113% to 130% are possible at 400A and higher, to our knowledge, no site measurements exist that exceed 100% of rating at these current levels. In practice, typical circuit loading is below 50% of maximum. In addition, the National Electrical Code (NEC) and Canadian Electrical Code (CEC) requirements for overcurrent protection tend to limit system currents to values below maximum levels. For these reasons, the incidents of neutral currents actually exceeding neutral conductor capacity are extremely rare. Normal, conservative design practices will continue to prove adequate in 400A and higher 208Y/120V panels and feeder cables, as well as most circuits below 400A.

REFERENCES

[1] M. T. Doyle, W. M. Grady, A. Mansoor, M. J. Samotyj, P. T. Staats, R. S. Thallam, *Predicting the Net Harmonic Currents Produced by Large Numbers of Distributed Single-Phase Computer Loads*, paper 95WM260-0 PWRD, presented at the IEEE/PES Winter Meeting, New York, NY, Jan 29–Feb 2, 1995.

[2] M. T. Doyle, W. M. Grady, S. Krein, A. Mansoor, R. S. Thallam, *Effect of Supply Voltage Harmonics on the Input Current of Single-Phase Diode Bridge Rectifier Loads*, paper 94SM454-9PWRD, presented at the IEEE/PES Summer Meeting, San Francisco, CA, July 24–28, 1994.

[2] R. Arthur, Testing Reveals Surprising K-Factor Diversity, *Electrical Construction and Maintenance*, (April 1993): 51–55.

Gathering Useful K-Factor Measurements

K-rated transformers can help control harmonics' damaging effects, but accurate specification depends on accurate measurements

By Robert D. Arthur, Senior Application Engineer, Square D Company, Oshkosh, Wis.

Five years ago, Underwriters Laboratories (UL) announced a listing of k-factor capabilities, but guidelines for specifying k-factor-rated transformers using these listings have yet to be developed. Although these products can help deal with harmonics' harmful effects, studies are showing their effectiveness depends on accurate measurements.

Initial promise

It was hoped k-factor ratings would help specifiers select transformers to cope with solid-state electronic equipment and the problems it can cause in a facility's electrical distribution system. K-rated transformers are now available for computers and other electronic office equipment, electronically-ballasted lighting systems and industrial process control systems drawing nonsinusoidal current. However, one important question remains: Which k-rating number to choose?

Some technical articles have proposed "cookbook" relationships between load type, load mix and total k-factor. These guidelines consistently have failed to match field measurements taken by the author. The problem: k-factor values in any given circuit are highly dependent on source impedance and the amount of current flowing in the system. Therefore, trying to pin down k-factor values is like shooting at a moving target–success depends on where you aim (clamp on) and when you pull the trigger (record the measurement).

K-factor defined

Institute of Electrical and Electronics Engineers (IEEE) Standard 1100-1992 (IEEE Recommended Practice For Powering and Grounding Sensitive Electronic Equipment) defines k-factor as:

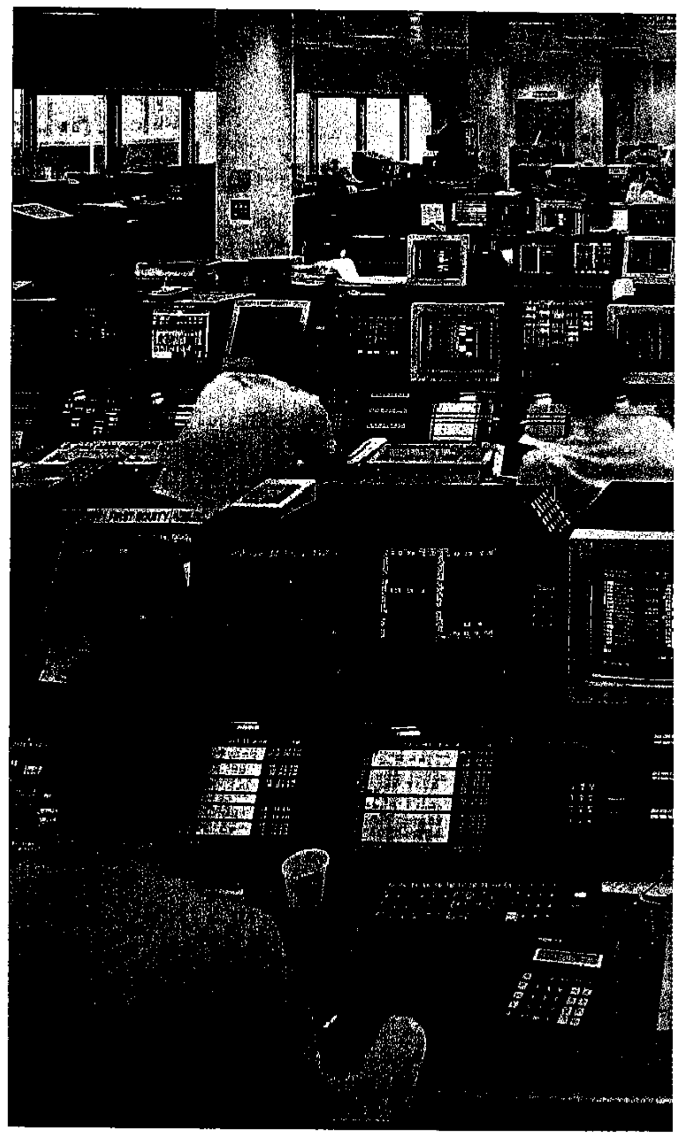
$$K = \sum_{h=1}^{h=h_{max}} I_h^2 h^2$$

where I_h = root-mean-square (rms) current at harmonic h, in per-unit of rated rms load current.

K-factor is derived using harmonic analysis instrumentation. Many available ammeters include harmonic analysis and k-factor calculation in their readouts, eliminating the need to calculate and spreadsheet harmonic levels.

Many people overlook the

K-factor transformers easily can be overspecified in high-load situations

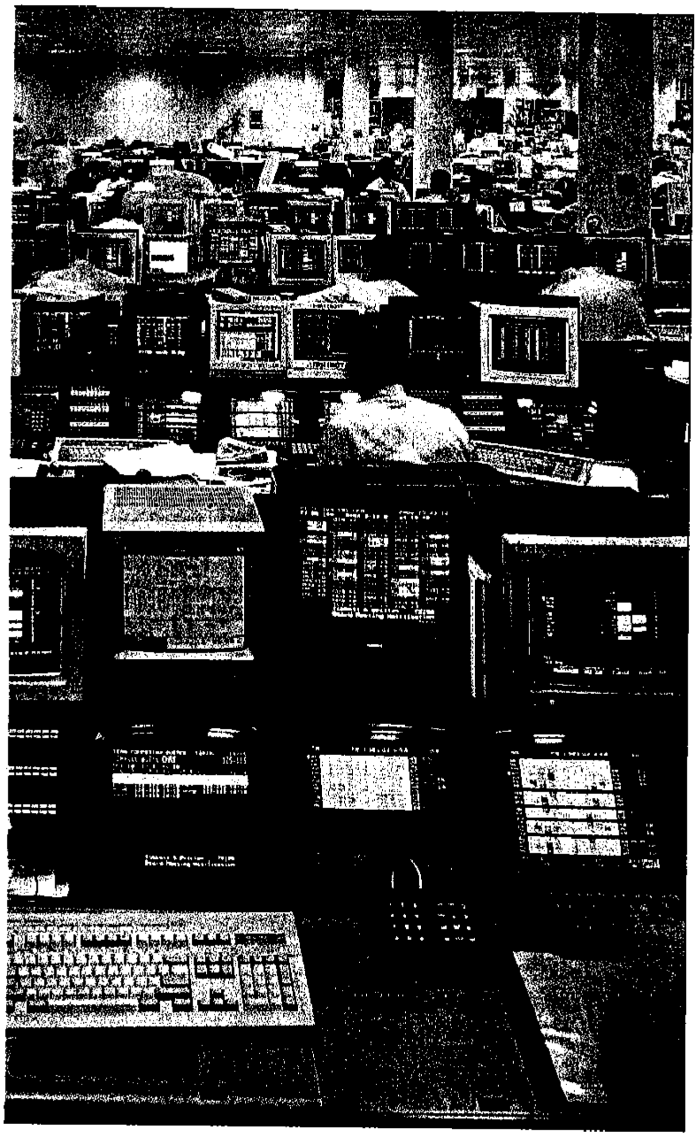


word "rated" in the definition of I_h. Data taken from individual branch-load equipment cannot be legitimately termed k-factor because measurements are taken at current levels lower than the supply-transformer rating. Typically, much lower numbers are seen at transformer terminals as transformers reach full load.

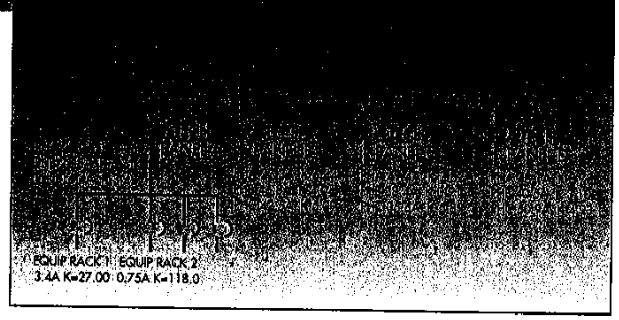
In practice, instrument k-measurements taken at other-than-rated load range from 1 for a linear load to more than 100 for some small, electronic power supply loads, and some loads have significantly greater k-factor than others. Computer factors range from 15 to as high as 45, while some office copiers and printers reach levels of 80 or more. Initial k-factor offerings were available at ratings of 4, 13, 20, 30, 40 and 50 to cover the major range of measured k-factors. The k-value of 9 was added later, but has never been accepted.

The value of measurement

Nationwide surveys taken by Square D Co. indicate average loading levels for dry-type transformers of between 35 percent for commercial facilities and 50 percent for industrial plants, so most k-factor measurements are being taken at comparatively light loads. Even worse, many readings are taken in branch circuits at even lower levels than the transformer terminal rating. The resulting higher measured values have misled many people into thinking they need very high k-numbers for their transformers.



CNBC Site Test



Measured k-ratings at CNBC illustrate possibility of overspecifying.

At the studios of cable television network CNBC in New York City, the author conducted one of many studies illustrating k-factor diversity and attenuation (see Figure 1). Here, the concentration of switched-mode power supply loads–represented by cable processing equipment–far exceeded typical office computer loads.

Despite current distortion at individual loads, k-factor levels were significantly lower at the supply transformer terminals. Figure 1 shows a partial tabulation of panel data taken at the site. Note that the measured level at the transformer was below k-6–even at about 50 percent load–although individual circuits ranged as high as k-118.

A recent study ("Predicting the Net Harmonic Currents Produced by Large Numbers of Distributed Single-Phase Computer Loads," presented at the 1995 IEEE winter meeting) illustrated the principles explained in the sidebar, "Why Harmonics Drop as Load Levels Increase." Using office computer loads, the study related measured harmonic magnitudes to source impedance using the IEEE term I_{SC}/I_L. The definition was relaxed, with I_L restated as actual–rather than rated–load current.

With that premise, the study was able to show a clear influence of source impedance on office computer load k-factor. Current distortion decreased as more computers were added to the line. The reduction in harmonic levels corresponds with the increase in current (I_L), lowering the I_{SC}/I_L ratio. Increasing source impedance (lowering I_{SC}) has a similar effect. This relationship between source impedance and k-factor appears useful in providing some general guidelines for transformers.

This study did not extend to the source impedance ratio present at transformer terminals. Transformers with impedance ranging from 3 percent to 5 percent will have full-load I_{SC}/I_L ratios from 20 to 33.3*. Fully loaded transformers will see k-factors ranging from 3 to 6. This agrees well with the numbers in the CNBC study, among others.

K-factor hazards

As a result, it appears k-factor numbers of 20, 30, 40 and

* Transformer secondary I_{SC}, or maximum available fault current (assuming infinite primary source), is equal to 1/per-unit impedance. So, for a 5% impedance transformer, fault current is 1/.05 = 20 times full load current. Thus, the I_{SC}/I_L ratio for that transformer = (20 x rated load)/rated load = 20.

True transformer k-ratings should be based only on full-load harmonics

50 have no application in normal power distribution. In fact, such high numbers also can be harmful. The Computer Business Equipment Manufacturers Association (CBEMA), in its CBEMA Information Letter 1988, recommended source impedance for power to computers be between 3 percent and 5 percent. Transformers with unnecessarily high k-factors are oversized, and typically are nameplated with unusually low impedance values.

Lower source impedance can cause much higher current distortion. Higher harmonic levels in 208Y/120 volt systems supplying office equipment, for example, accentuate high neutral-current problems, resulting in high neutral-to-ground signal noise in sensitive loads. In addition, low impedance allows higher harmonic levels to reflect upstream into primary-source power. This can cause problems in applications such as industrial drives as well as computer loads.

The inverse relationship between k-factor and impedance leads to the conclusion that the higher the transformer's k-factor, the higher the k-factor of the load may be. Thus these transformers are, in a sense, self-justifying. Using abnormally low impedance (or greatly oversized transformers) for both office computer and industrial drive isolation transformer applications hinders IEEE Standard 519 compliance efforts.

Why Harmonics Drop as Load Levels Increase

[illegible] vary with system impedance.

This guide standard establishes a ratio term—I_{SC}/I_L—which relates the available short circuit current (I_{SC}) to the rated load current (I_L). The resulting "stiffness ratio" allows IEEE to establish different recommended harmonic limits, depending on relative source impedance at points of common coupling within an electrical distribution system.

Applying Guidelines

Although k-factor increases as load decreases, overall transformer coil losses decrease with the square of the load. This reduction far outstrips the increased heating effect of higher harmonics at lighter loads. So, regardless of load current-distortion change, the maximum loss point in transformer coils is always at full load. This is why the true k-rating of a transformer must be based only on full load harmonics. American National Standards Institute (ANSI)/IEEE C57.110 "Recommended Practice For Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents" verifies this rule. This guide standard defines all parameters for derating transformers supplying nonlinear loads on the basis of rated current only.

There is strong evidence that a rough correlation exists between measured load current K and the I_{SC}/I_L ratio of the supply power. Independent studies strongly indicate that transformers with normal impedance (3 percent to 5 percent) essentially limit their own load current k-factor to a range of from 3 to 6 at full load.

The lesson of this information is that k-factor calculations are not valid unless they are derived from harmonic data at full transformer rating, otherwise results can vary. Because such measurements are seldom practical k-factor remains a problematic tool for specifying transformers. Studies should be limited to sites at or near full load. Conclusions drawn from these observations can be used as general guides. All of the office-computer load observations at or near full load made by the author have resulted in k-values less than 26. Other studies have led to the same conclusions.

Most k-rated transformers sold today are k-4 and k-13 rated, with the latter being more popular. This appears to be a wise choice for conservative specification. However, given the fact that average transformer loading is quite low, k-4—and even general-purpose—transformers are becoming increasingly popular with specifiers. The derating factor for a k-4 rated transformer supplying a k-6 load is typically so slight as to have no practical impact.

Others have noted that even with the availability of k-rated transformers, more than 90 percent of commercial and industrial office loads remain successfully supplied by standard, general purpose transformers. This is possible because of the light average-load duty that transformers typically see in these applications.

Specify with care

Most electrical system k-factor measurements are of limited use, because either current was not measured at the supply-transformer secondary main, or its magnitude was less than transformer full load. Measurement sites must be selected with care, with currents representing a high enough percentage of transformer capacity to produce meaningful results.

A large number of sophisticated instruments are now available for measuring circuit harmonics. These tools make it easy to acquire a tremendous amount of information about the power quality in electrical systems. The conditions under which this data is gathered, however, must be considered for proper specification. □

Harmonic Canceling Transformers Part 2 – Commercial Applications

Robert Arthur, Square D Company, Oshkosh, Wisconsin

It is not news to most facility engineers that commercial lighting and receptacle office power loads can cause harmonic voltage distortion. Although the majority of office buildings meet IEEE-519 voltage distortion limits at their service entrance without any special harmonic abatement, high harmonic current levels in the electrical systems supplying computers and other similar office loads can cause problems in commercial applications.

There are a vast number of products on the market that can be used to mitigate the effects of current distortions in commercial electrical systems. In last month's issue of **Power Quality Assurance** Magazine, we discussed how transformers can mitigate harmonics in industrial applications[1]. In Part 2 of this article we examine how these devices help reduce harmonics in *commercial* applications. Transformers can be used either singly or in combination to "cancel" out certain harmonic components, preventing their transfer into the primary distribution system. However, many engineers may be unfamiliar with these "harmonic canceling" transformers, particularly how they differ from standard transformers.

Using Transformers to Mitigate Harmonics in Commercial Applications

The most common applications for harmonic cancelation techniques exist in industrial systems employing large numbers of electronic motor drives, covered in Part 1. Some opportunities also exist in commercial lighting and receptacle office power loads where large numbers of single-phase devices with nonlinear load characteristics are connected line-to-neutral on three phase Wye systems. Reducing harmonics using transformers is accomplished in two ways:

Harmonic Attenuation – Transformers have reactance and resistance and, in most cases, represent the majority of impedance in the lines feeding nonlinear loads. Reactive impedance increases directly with frequency, naturally attenuating harmonics by reducing available current at higher frequencies. While this technique is fairly common in reducing the current distortion of electronic motor drives in industrial applications, it is also effective in reducing the current distortion of office computer loads.

Harmonic Cancelation – Nonlinear currents from two or more 3-phase load panels can be phase shifted from one another through various types of 3-phase transformer connections making their combined sum less distorted than their original waveforms. This reduces the distortion of current flowing into the primary power (*Figure 1*).

The vast majority of office panel loads in North America are currently served with Delta-Wye connected transformers. Depending on load level, the impedance of these transformers introduces moderate voltage distortion, which in turn reduces line and load current distortion.

Nonlinear loads connected line-to-neutral, such as in computers, copiers and other commercial office systems create severe current distortion in the form of 3rd harmonic, followed by increasingly smaller values of 5th

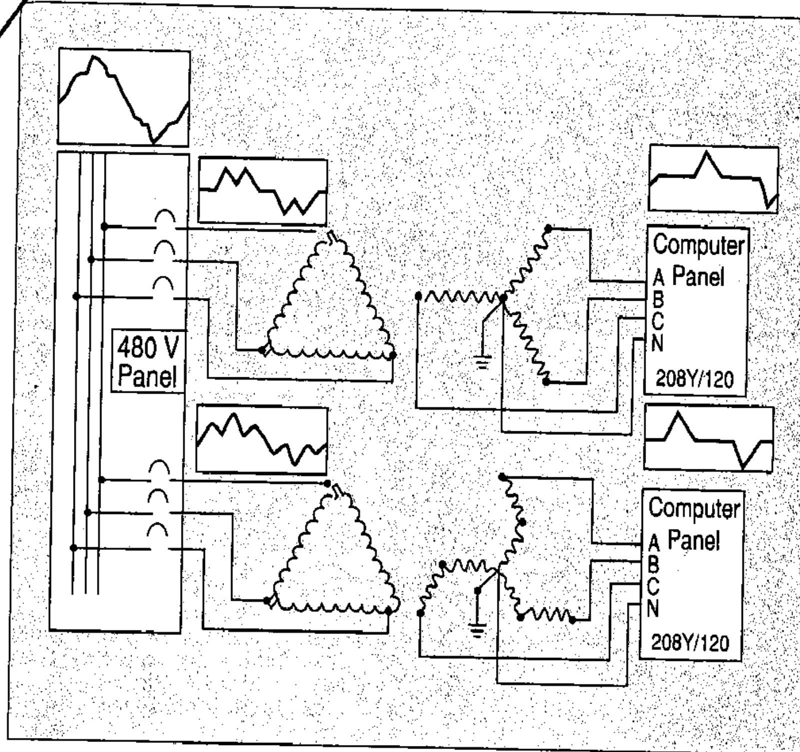


Figure 1. *Phase shifting computer load currents.*

and 7th harmonic. Thus, it is not uncommon to find current distortions over 100% in 208Y/120 office power branch circuits. For most of these applications, standard transformers are the most effective and economical choice for mitigating distortion. The vast majority of commercial office buildings meet IEEE519 limits at the service entrance without any harmonic mitigation other than provided by the standard Delta-Wye transformers within the building. However, harmonic canceling transformers are useful for solving special problems where a system study has demonstrated the need for more harmonic abatement than that afforded by standard transformers. This situation can occur when either electronic loads reach 40% of total demand at the service entrance, or HVAC adjustable frequency drive loads reach 10%. Both of these limits are rarely approached in commercial installations.

Both Harmonic canceling transformers and standard Delta-Wye connected transformers *attenuate* harmonic levels through reactance, and *cancel* harmonics through internal phase shifting. The only difference is the degree to which each function is addressed. With Delta-Wye connected transformers, the angles formed by the Delta side connection produce a good 'cancelation' effect on the 3rd harmonics, preventing them from flowing in the primary lines.

Thus, ordinary Delta-Wye transformers are very effective harmonic 'canceling' transformers, and perform superior functions in harmonic attenuation through impedance effects.

Using a transformer to cancel 5^{th} and 7^{th} harmonics in the primary system in commercial office loads is done by balancing loads across Delta-ZigZag connected transformers and Delta-Wye connected transformers feeding separate panels. If the loads on each type of transformer are balanced, then current distortion into the primary system can be reduced significantly. The 5^{th} and 7^{th} harmonic cancelation effects brought about by the 30-degree phase shift between Delta-ZigZag and Delta-Wye connected transformers depend on the load balance. Delta-Wye and Delta-ZigZag combinations work well for this application. *No special considerations are needed to address the 3^{rd} harmonic. It is taken care of automatically when converting 480V 3-wire to 208Y/120, whether using Delta-Wye or Delta-ZigZag (Figure 2).*

3rd Harmonic

Some people have misinterpreted the fact that the 3^{rd} harmonic load current is 'trapped' in the Delta side of a Delta-Wye connected transformer. Although the word 'trapped' is used a lot in IEEE and commercial publications, it was never meant to imply that there is some 'extra' circulating current going on within the Delta. All the load side harmonics flow in the primary Delta coils, causing normal I^2R loss plus a small amount of eddy current loss. The 3^{rd} and other triplen harmonics do not appear on the primary lines because they are canceled in the 60° angle at the corners of the Delta. The belief that there is some kind of 'extra' current inside the primary Delta connection gives the impression that standard Delta-Wye transformers are unsuitable for computer loads. Actually, all of the reflected currents from the secondary are accounted for in the primary line current.

One way of visualizing this is to consider the 60-degree phase angle at the corner of the Delta as causing the 'canceling' of third harmonic currents. Another way of thinking about it is to remember that harmonics are mathematical products of waveform analysis. During phase shifting, the new current wave has a different harmonic analysis, perhaps with more or less harmonic orders, but no real currents are lost or gained. It is true that the 3rd harmonic is zero sequence, and would generate circulating currents in Delta windings if it occurred simultaneously on the three load lines. The key to the misunderstanding is that all three lines of a 3-phase office load panel see the 3rd harmonic, *but they do not carry that harmonic at the same time.*

Switched-mode power supplies in electronic loads draw current during short intervals at the peak of the applied voltage cycle. Since the voltage cycles are 120 degrees apart on the three phases, these currents are never drawn at the same time. Each must return in the neutral, causing three times as many current pulses in the neutral as in the lines. That effect is why we see elevated current in neutrals.

The Importance of Impedance

Misunderstanding the 3rd harmonic has led to many incorrect assumptions about harmonic cancelation with transformers. For instance, the ZigZag connected secondary has a low zero sequence impedance compared to its line-to-line or line-neutral impedance. That characteristic gives transformers tremendous advantage in low voltage distortion when supplying zero sequence current. However, a ZigZag connected transformer carries current only on one phase at a time when supplying pure computer loads. The zero sequence impedance measurement of ZigZag connections is carried out by forcing equal current simultaneously through the three phases of the transformer. It should not expected that the improvement in voltage distortion afforded by these transformers will be as great as implied by the zero sequence impedance measurements.

It should be also pointed out that ZigZag secondaries on transformers have lower line-to-neutral impedance than line-to-line; the typical difference is around 15%. Thus, standard line-to-line nameplate impedance should never be used for short circuit studies. Some harmonic canceling transformers have nameplates with just line-to-line and zero sequence impedance. Conversion from these numbers to line-to-neutral impedance is not straightforward, and the simplified equations published by some manufacturers tend to underestimate letthough fault current potential for their products.

Pushing impedance reduction in the interest of reducing voltage distortion can have consequences. It is important to remember that lower source impedance in 3-phase power supplied to office computer loads causes higher neutral currents, and higher load current distortion (harmonics). Because lower impedance produces less harmonic attenuation on both the primary and secondary of the transformer.

Typical loading levels for low voltage transformers in the U.S. have been recently defined in NEMA Std TP 1. This standard sets the average at 35% on a daily average and 60% maximum during the day. These values are considered quite conservative in the industry, with many agreeing that actual numbers are quite a bit below these estimates. At these typical loading levels the harmonic attenuation effects of normal impedance transformers typically keep load side neutral current levels in standard load panels below 100% of panel neutral rating. The use of abnormally low impedance (<3%) transformers almost guaran-

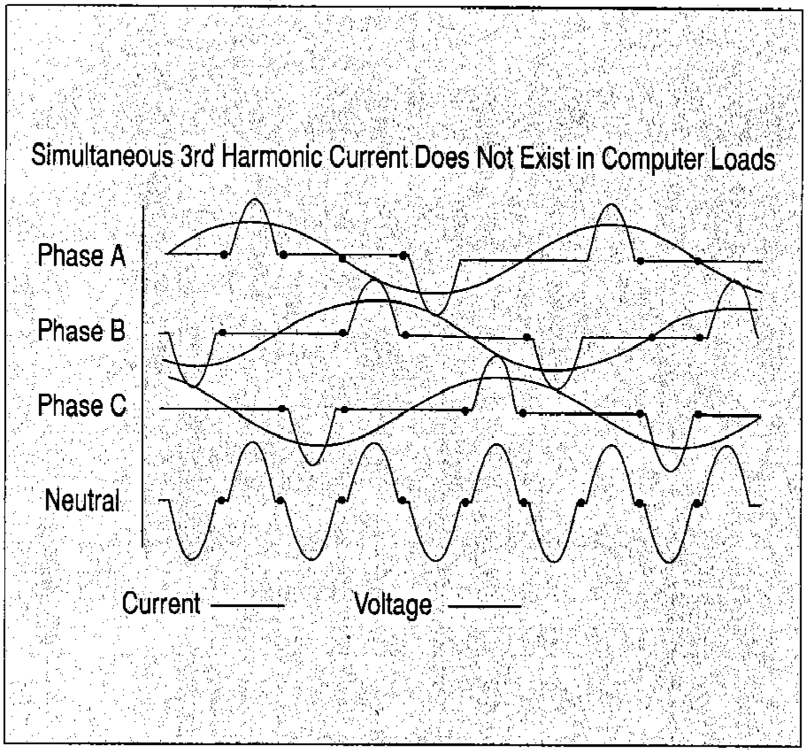


Figure 2. *Third harmonic – zero sequence?*

tees the need for special load side panels with increased neutral capacity. It is possible that higher interrupting capacity breakers may be necessary. Increased current distortion can also exaggerate the harmonic effects on main or branch breaker heating and contribute to audible noise in panels or even nuisance tripping.

Beyond the 7th Harmonic

Computer load current harmonics of a higher order than the 7th do not lend themselves well to cancelation. Even assuming a high population of identical computers, each has its own unique power requirement in every instant of time. Board level regulators draw current at different times, the state of charge of the main filter capacitors in the power supplies vary with time, and disk drives operate on and off at unique intervals. In angles of the 9th harmonic and higher measured in panels feeding distributed computer loads can be shown to vary constantly in displacement, and to such a degree that it may not be possible to effectively cancel them with transformer connections. *Therefore, using harmonic canceling transformer phase shifting techniques for mitigating higher order harmonics than the 7th will seldom have any significant benefits in commercial office load application.* Look for IEEE to publish guidelines for various combinations of electronic loads, lighting loads and adjustable frequency drive loads in commercial buildings in the upcoming IEEE 519A guide.

Note:

1. "Harmonic Canceling" Transformers: Part 1 – Industrial Applications," Robert Arthur. **Power Quality Assurance** Magazine, November 1999, page 44.

"Harmonic Canceling" Transformers: Part 1 – Industrial Applications

Robert Arthur, Square D Company, Oshkosh, Wisconsin

It is not news to most industrial plant engineers that using large numbers of ac or dc electronic motor drives (or other forms of rectifier power control) can sometimes cause harmonic voltage distortion and voltage notching. These voltage distortions can lead to the malfunction of drives, or damage to other connected equipment. Problems with harmonics remain relatively rare in industrial systems but, in some cases, can create significant problems.

Voltage distortion is the effect of distorted current flowing through distribution system impedance. Current from a branch circuit flows directly back to the service, and does not directly affect other loads. The majority of harmonic issues actually stem from the indirect effect of the voltage distortion caused by that current. A single branch load current can affect the voltage of the entire distribution system.

There are a vast number of products on the market being used to mitigate the effects of current distortions. For instance, transformers can be used either singly or in combination to cancel out certain harmonic components, while supplying power to the primary distribution system. Many engineers may be unfamiliar with harmonic canceling transformers, particularly when to use them and how they differ from standard transformers.

Mitigating Harmonics

Before deciding when and how to use harmonic canceling transformers, it is important to first understand how transformers can affect harmonics. Reducing harmonics using transformers is done in two ways:

Harmonic Attenuation: Transformers have reactance and resistance and represent the majority of impedance in the lines feeding non-linear loads. Reactive impedance increases directly with frequency, naturally attenuating harmonics by reducing available current at higher frequencies. This technique is fairly common in reducing the current distortion of electronic motor drives in industrial applications, *Figure 1*.

Harmonic Cancellation: The non-linear currents from two or more 3-phase load panels can be phase shifted from one another through various types of 3-phase transformer connections, so that their combined sum is less distorted than each of the original's waveforms. This reduces the distortion of current flowing into the primary power, *Figure 2*

IEEE 519-1992

Responding to the increasing use of adjustable frequency drives in industrial facilities, IEEE 519-1992 has set guidelines (these are not rules, they are recommended *guidelines)* for maximum current distortion present at a building service entrance. These guidelines are intended to prevent one factory from affecting the service of another, and to protect utility equipment . The determining factor in meeting IEEE 519-1992 current distortion limits is the percent of the service capacity that is used for serving non-linear loads.

Page 48 •

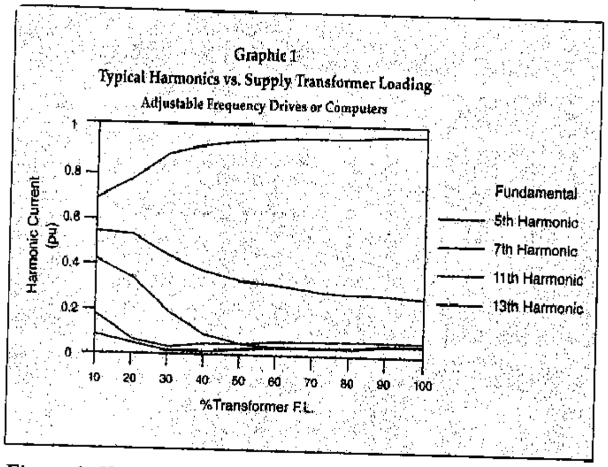


Figure 1. *Harmonic attenuation.*

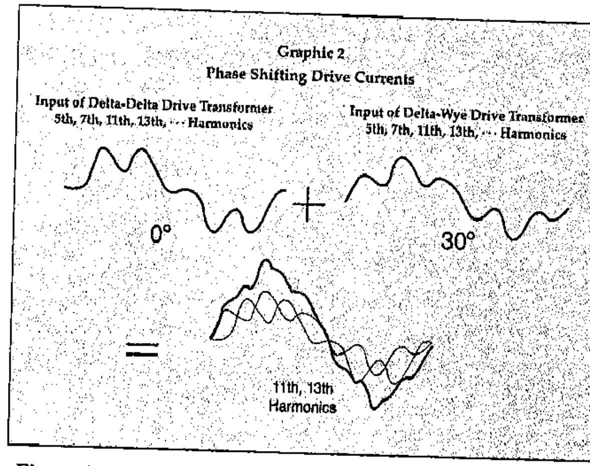
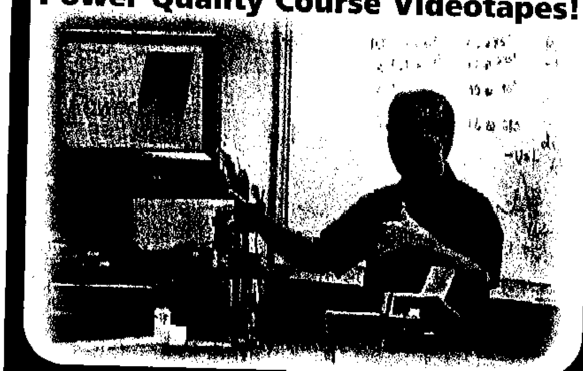


Figure 2. *Harmonic cancellation.*

Typically, an industrial facility can load up to 5% of its total service capacity with 6-pulse variable frequency drives without exceeding recommended limits. Beyond that, some form of harmonic abatement may be necessary.



Drive Distortion

Motor drive current distortion can be reduced using filters, 12-pulse or higher drives, line reactors, drive isolation transformers or harmonic canceling transformers. Both line reactors and drive isolation transformers use reactive harmonic attenuation effects to reduce the actual current distortion at the input terminals to the drives. This practice alone allows an increase of 6-pulse drive load to 20% or more of service capacity, without exceeding guideline distortions. The effectiveness of reactive harmonic attenuation varies depending on other system characteristics. Conducting careful system analysis is a good idea before applying any harmonic abatement solution to ensure the intended results.

Harmonic abatement using filtering and/or 12-, 18- or 24-pulse drive technology is becoming increasingly popular, but these are relatively expensive solutions, although every customer will see different magnitudes of savings and/or costs depending on his/her choices and starting circumstance. Using transformers for harmonic cancellation can be an attractive alternative for heavy drive users, particularly for users who already incorporate drive isolation transformers for their drives. The simplest cancellation method is to provide Delta-Delta connected transformers for some drive power, and Delta-Wye connected transformers for the remaining drives. If the sum of the drive loads on each type of drive isolation transformer is balanced, current distortion into the primary system can be reduced significantly, *Figure 3*.

The largest distortion components, by far, in 6-pulse drive current are 5th and 7th harmonics. Eliminating these harmonics can significantly improve point of common coupling current waveform distortion. The 5th and 7th harmonic cancellation effects brought about by the 30-degree phase shift between Delta-Delta and Delta-Wye connected transformers will depend on load balance. For continuous torque applications where loads are fairly constant, close load balance is easier to achieve. On the other hand, process control applications, such as punching, stamping or motion control, make it difficult to maintain consistent balance of multiple drive loads

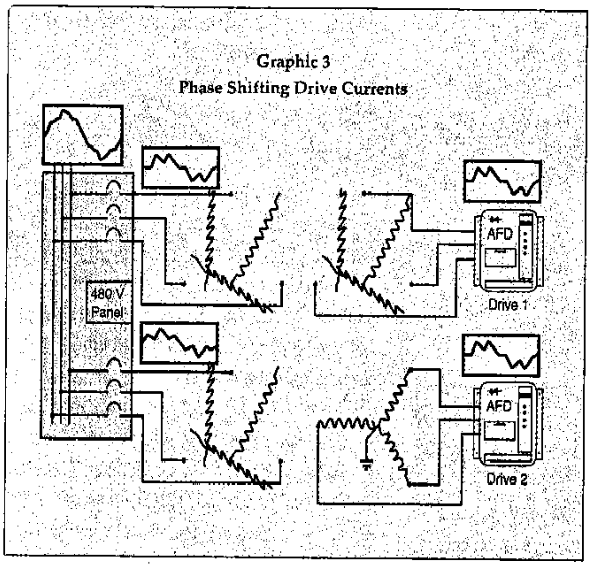


Figure 3. *Delta-Delta connected transformers can be used for some drive power, and Delta-Wye connected transformers for the remaining drives for relatively inexpensive harmonic abatement.*

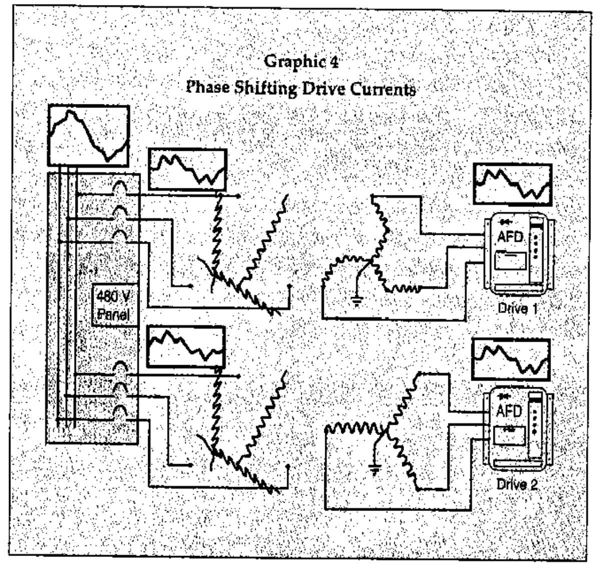


Figure 4. *Delta-ZigZag connected transformers, when used in combination with Delta-Wye connected transformers, can serve other drive loads on the same service.*

CIRCLE 127

at any given time.

In some cases, Delta-Delta connected drive isolation transformers are undesirable because the secondary cannot be grounded in a balanced way. Ungrounded power can adversely affect the operation of some drives, and can cause drives to trip on surges and impulses coupled from the primary service. For these applications, Delta-ZigZag connected transformers are available. This zero phase shift connection acts like a Wye source for the drive, providing a balanced neutral point for grounding. At the same time, they substitute for Delta-Delta transformers, providing the same harmonic abatement when used in combination with Delta-Wye connected transformers, serving other drive loads on the same service (*Figure 4*). When voltage change is not required, the use of line reactors on half the load, along with Delta-Wye connected loads on the other half, can be used.

Harmonic Canceling Transformer: a Misnomer

Since standard drive isolation transformers can be effectively used as harmonic-canceling transformers, the term "harmonic canceling transformer" becomes ill defined. In general, that term is attributed to transformer products with special connections that can address 11th, 13th and even higher harmonics in drive loads. These can be single transformers with multiple secondaries, or sets of transformers feeding multiple loads. The basic principles are the same, except that 15-degree phase shift is required to address 11th and 13th harmonics. The benefits of this additional step in harmonic reduction are dubious, however, because 11th and 13th harmonic components contribute to less than 1/5 of the total distortion in service entrance currents. The difficulties of obtaining precise balance of loads will almost always leave enough residual 5th and 7th harmonic distortion to minimize the benefit of any higher harmonic treatment. Filtering is a more cost-effective method for addressing upper order (11th and higher) harmonics compared to special "harmonic cancellation" transformers. In order for transformer phase shifting to address 5th, 7th, 11th and 13th harmonics, the loads must be separated into four separate panels, shifted 0°, 15°, 30° and 45° by either separate transformers, or one multiple output transformer. 11th and 13th harmonic filtering can typically be done for far less than half the cost of the additional separation of loads, and purchasing the additional phase shifting transformers that would be necessary.

Next Issue

In the next issue of **Power Quality Assurance** Magazine, Mr. Arthur will examine common sources of harmonics in commercial buildings and discuss means of mitigation.

For More Information Circle 206 on the Reader Info Card

FEATURE ARTICLE

Drive Isolation Transformer – Solutions to Power Quality

Bob Arthur, Square D Company, Oshkosh, Wisconsin

By now, plant and facility managers know very well that drives can cause harmonic voltage distortion and voltage notching resulting in malfunction or damage to other connected equipment. But what is not well known is that drive isolation transformers can be a simple, cost-effective solution to drives-related power quality.

Drives and Power Quality Problems

All types of drives rectify incoming power to form a DC level that is either used to directly power the motor (DC) or supply an inverter (AC). In both cases, the "front-end" rectification causes the current waveform to be nonsinusoidal, or "nonlinear" in nature. In the special case of three-phase drives using 6-pulse SCR rectifiers there are short intervals of time when more than one SCR is on, resulting in a transient "short circuit" or current peak to flow six times per line power cycle.

Distorted current flow causes nonlinear voltage to drop across the system impedance, resulting in distorted voltage. This distortion can have serious effect on other equipment connected on the same service, such as UPSs, computers, process controllers or data communication systems. Additionally, the high current peaks of DC drives can cause "notching" in the voltage, which some equipment cannot tolerate. In systems with large amounts of power factor correcting capacitors, high voltage distortion can cause resonance at system harmonic frequencies causing high series or parallel-resonant currents, which can be very damaging to the electrical system.

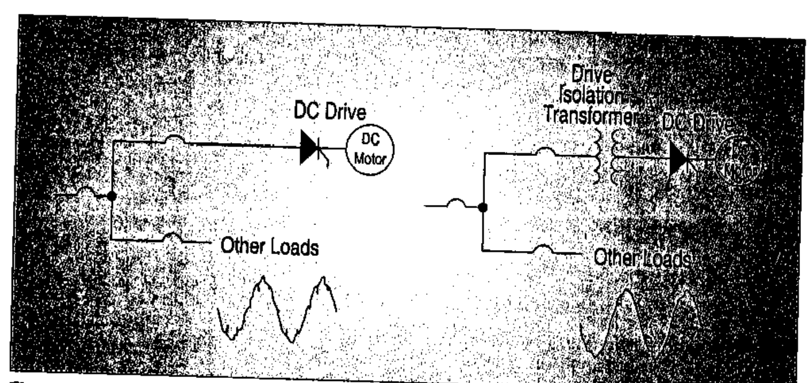


Figure 1. Use of drive isolation transformers reduces source voltage notching.

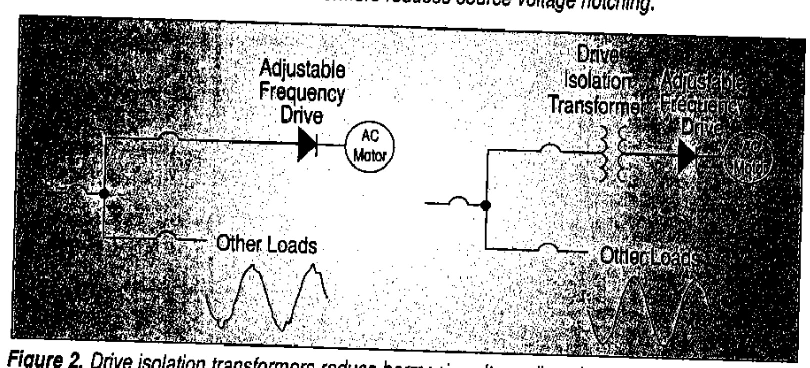


Figure 2. Drive isolation transformers reduce harmonic voltage distortion effects of adjustable frequency drives.

Drive Isolation Transformers

Adding reactance to the drive's power source is an effective technique for reducing negative effects on the electrical system. Adding reactance by using drive isolation transformers can reduce the amount of distortion present in the input current to the drive.

Using drive isolation transformers to reduce current harmonics can:

- Decrease line current waveform distortion, which improves the power factor of the drive load.
- Reduce line notching effects on the system voltage caused by SCR switching overlap (*Figure 1*).
- Reduce voltage waveform distortion effects in the feeders ahead of the transformer, which can prevent drives from affecting sensitive loads, even other drives elsewhere on the service (*Figure 2*).

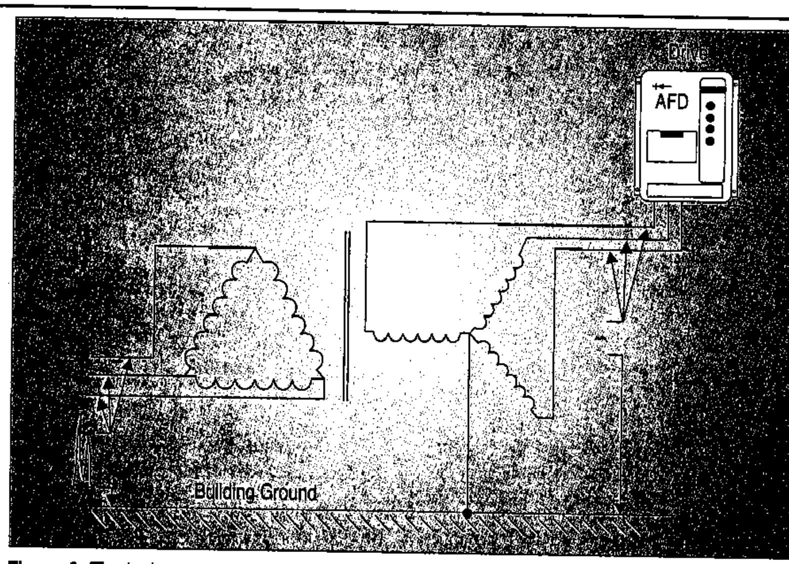


Figure 3. *The isolated secondary of a drive isolation transformer allows grounding, which eliminates common-mode transient energy.*

Unlike simple line reactors, the secondary of a drive isolation transformer represents a separately derived power supply that is electrically isolated from the primary source. If the secondary is wye connected, then it can be grounded. Grounding prevents the transfer of common-mode noise and transients, both from the primary source to the drive, and from the drive to the primary system (*Figure 3*).

Drives can also introduce large induced ground currents. This is due to rapid current changes caused by diodes, SCRs or pulse-width-modulated (PWM) outputs that couple currents capacitively through the ground back to the source. High-frequency induced ground currents are a major cause of data disruption in digital communication and can produce nuisance tripping of ground fault systems. Introducing a grounded drive isolation transformer localizes the ground current effect and prevents it from extending upstream from the transformer (*Figure 4*).

When specifying drive isolation transformers, be sure they are designed to accommodate the additional heating effects of the distorted current of both AC and DC drives. Loads incorporating static diode rectification present distorted current waveforms to the transformer windings and can create additional heating in the coils. Three-phase SCR-controlled loads introduce similar harmonic heating effects and present high-level current transients during commutation overlaps. Drive isolation transformers also need to withstand the mechanical forces in their coils that result from SCR overlap current spikes, which are typical for DC drives. Finally, the drive isolation specifier must consider thermal and mechanical stresses caused by the highly cyclic load demands of both DC and adjustable frequency drive process applications.

Many loads have characteristics similar to AC and DC drives. This is because the load inputs are either designed with three-phase static diodes or three-phase, 6-pulse, SCR bridge rectifier circuits. Drive isolation transformers can control the effects of these loads on the primary power system. General equipment applications for drive isolation transformers include: SCR-controlled heating or furnaces, three-phase rectifier input DC power supplies or three-phase switched-mode power supplies.

Isolation Transformers vs. Drive Isolation Transformers

There are no standards that differentiate transformers rated for drives from general-purpose transformers. For this reason, it is important to specify the features that differentiate them. Many manufacturers merely re-label their standard general-purpose line for use as drive isolation transformers. To ensure your equipment is truly rated for drives, make sure the manufacturer is able to prove that the drive current distortion effects do not cause coil overheating. In addition, IEEE Standard 597 requires that drives be capable of supplying 150% of rated current for one minute out of each hour. Transformers rated for drives must be capable of those same overload cycles. Since one of the major benefits of using drive isolation transformers is to provide sufficient line reactance to reduce the effects on other parts of the electrical system, minimum reactance specifications are important. (See Specification Highlights sidebar.)

Page 34 •

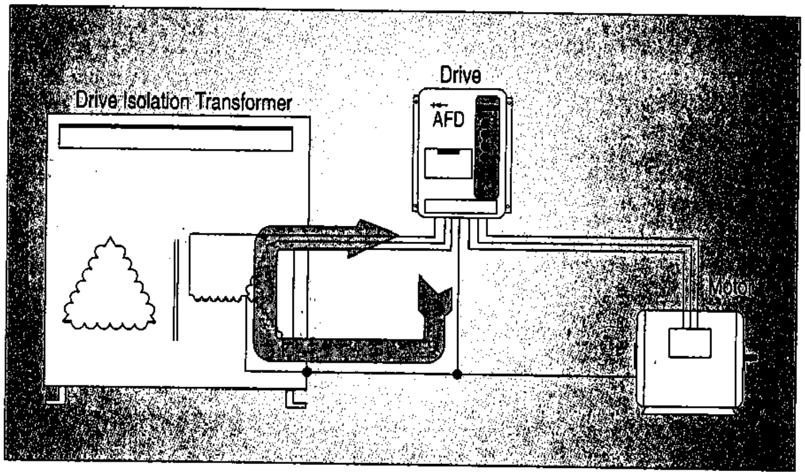


Figure 4. Induced ground current and noise from drives returns through the grounded secondary of an isolated transformer and is prevented from traveling into the primary source.

• Page 33

Finally, particularly in the case of DC drives, the manufacturer should have extensive field experience in providing coil design with adequate mechanical strength to ensure long life expectancy in high surge current applications.

If drives are causing sensitive equipment to malfunction, lighting to flicker, or other drives to act erratically, then a reactive drive isolation transformer may be an effective solution. However, a complete understanding of the problems, their causes and the effects of adding reactance to the system is essential before implementing any power solution.

Specification Highlights

Be sure drive isolation transformers you specify are:

- Evaluated according to UL Standard 1561 or 1562 for effects of harmonic heating.
- Designed for typical harmonics per IEEE 519-1992.
- Rated for 4% minimum reactance for 150°C temperature rise designs.
- Built to IEEE-597 Class B overload standard, which requires 150% of load for one minute hour.
- Designed for the mechanical stress of DC drive current spikes.
- Designed for the thermal and mechanical stress of highly cyclic process control applications.

Bob Arthur is an application staff engineer with the low voltage transformer product support division of Square D. His responsibilities include transformer product support and development.

If you found this article useful, circle 202 on the inquiry card.