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Subject:

Neutral Currents in Three Phase Wye Systems

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- 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.

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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.

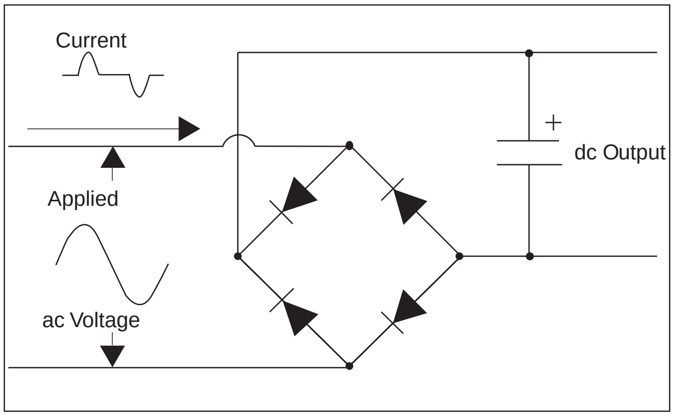

Figure 1: Electronic loads are non-linear current sources because of front-end rectification.

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.

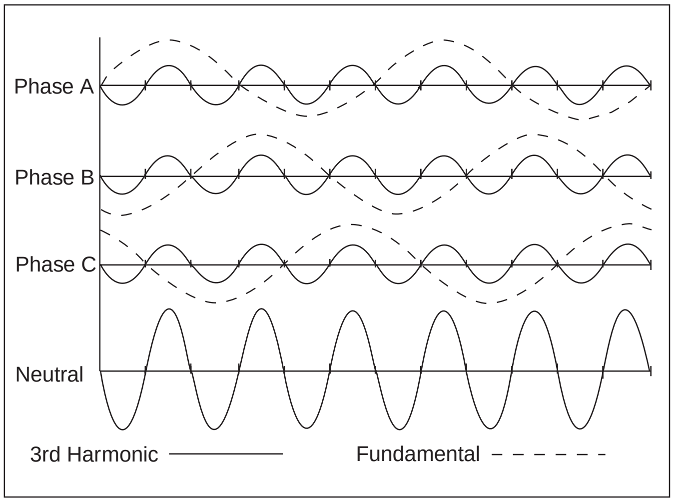

Figure 2: Third harmonic and other "triplen" harmonic components are in phase on all three phase lines in a wye-connected circuit.

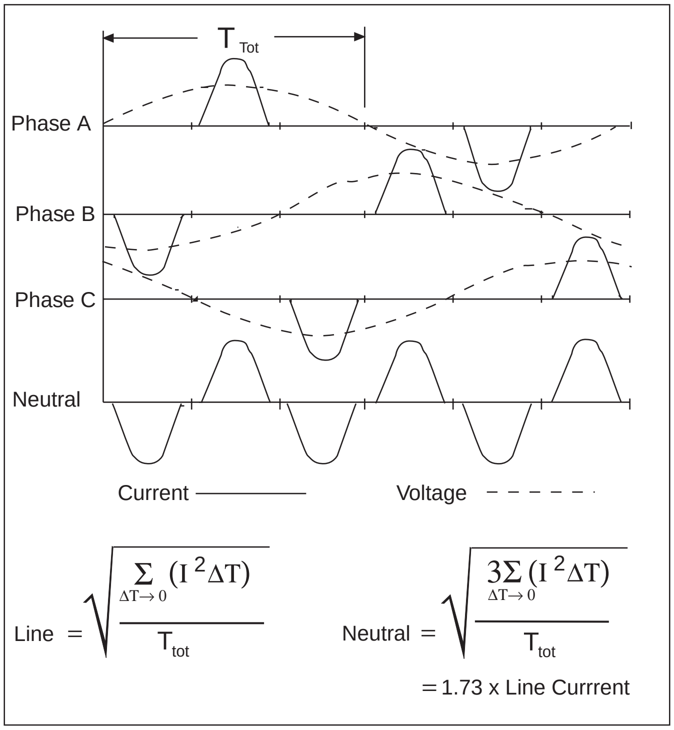

Figure 3: The theoretical maximum neutral current for rectifier type non-linear loads is 173%.

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.

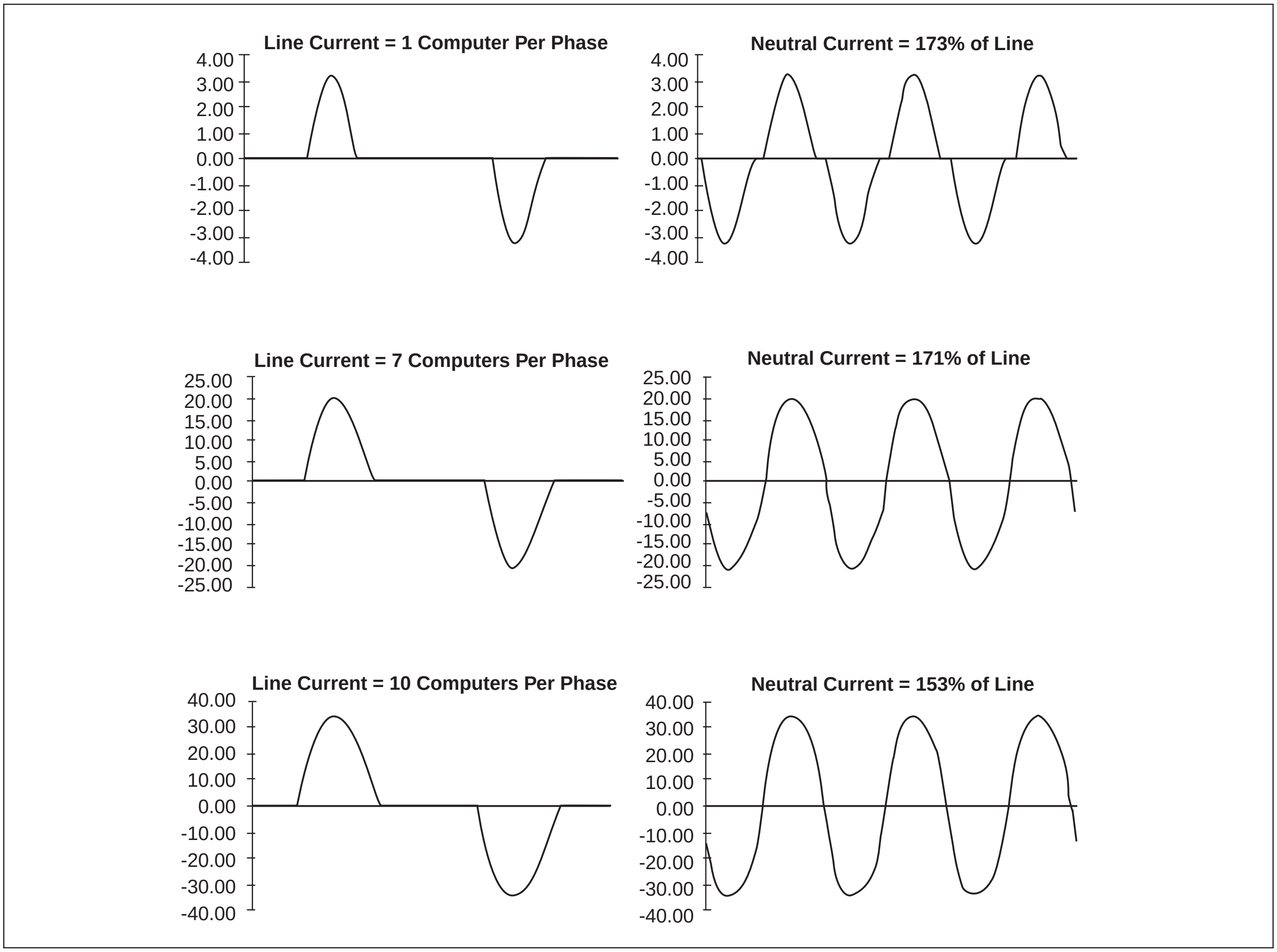

Figure 4: Both load population and the effects of source impedance on voltage tend to reduce neutral current.

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:

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

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 when harmonics other than fundamental and third are considered.

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

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

$$\sqrt{I_1^2 + I_3^2} < 1 \qquad \text{or} \qquad I_1 < \sqrt{1 - I_3^2}$$

3. Combining equations 1 and 2:

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

or

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

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:

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

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?

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

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%

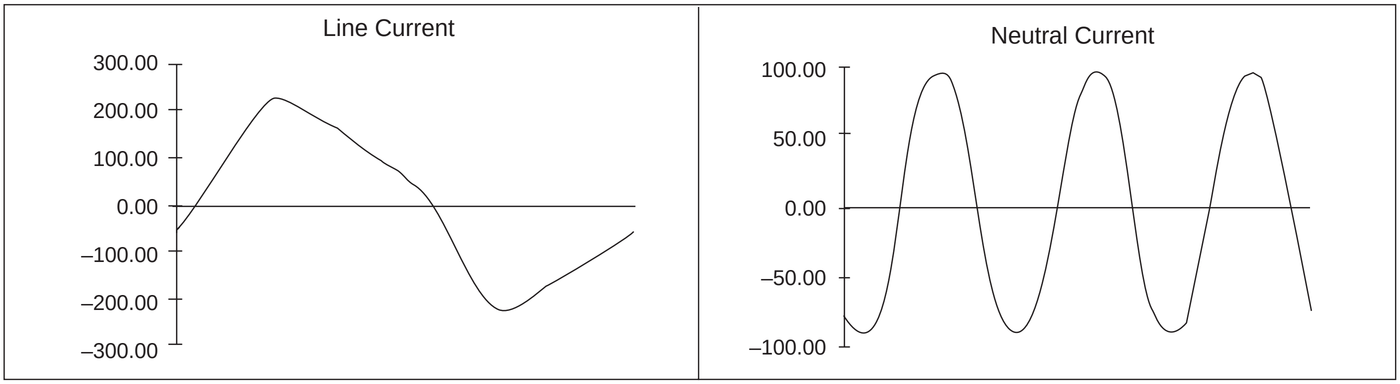

Figure 5: Current signature of a lighting panel main showing a 145A rms electronic ballast load. Line current THD is 16.7%, with a neutral current of 69.2A (47.7%). Third harmonic component is 16.2%

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

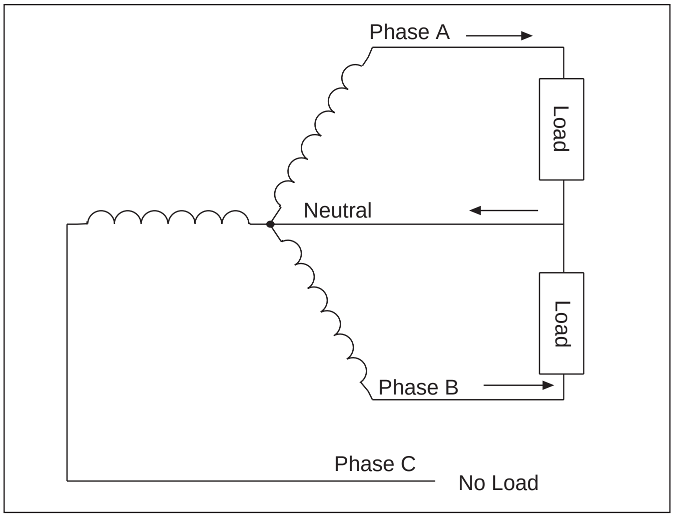

Figure 6: Unbalanced single phase non-linear loads can create elevated neutral current.

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:

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

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) =

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

   or

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

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

   Neutral Current =

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

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: %Neutral <

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

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.

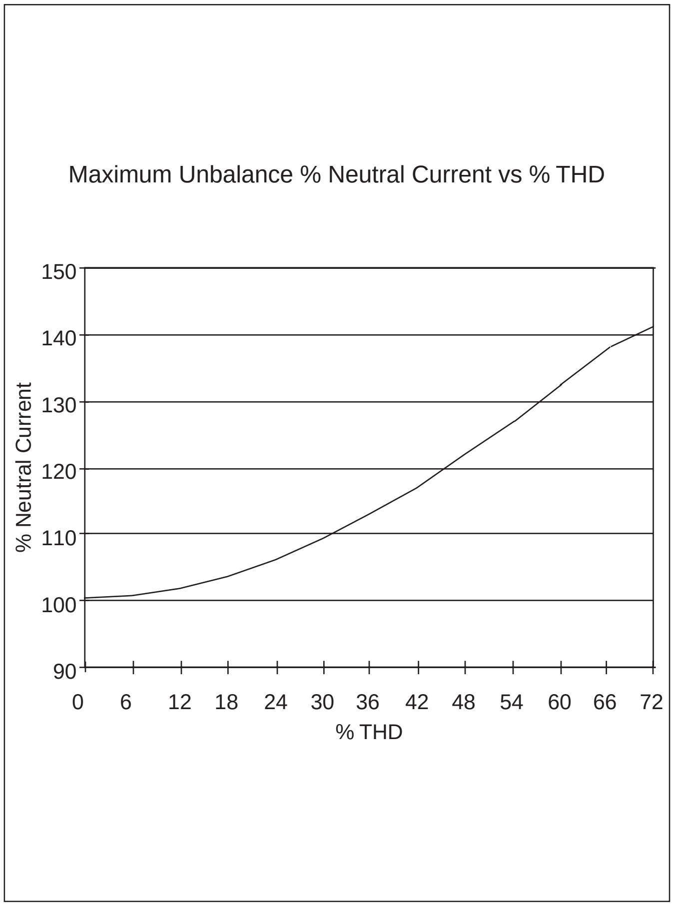

Figure 7: The maximum neutral current when the load is balanced on only two phases depends on current distortion and has a maximum value of 141.4%. This curve is derived from equation 9, page 7.

Figure 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.

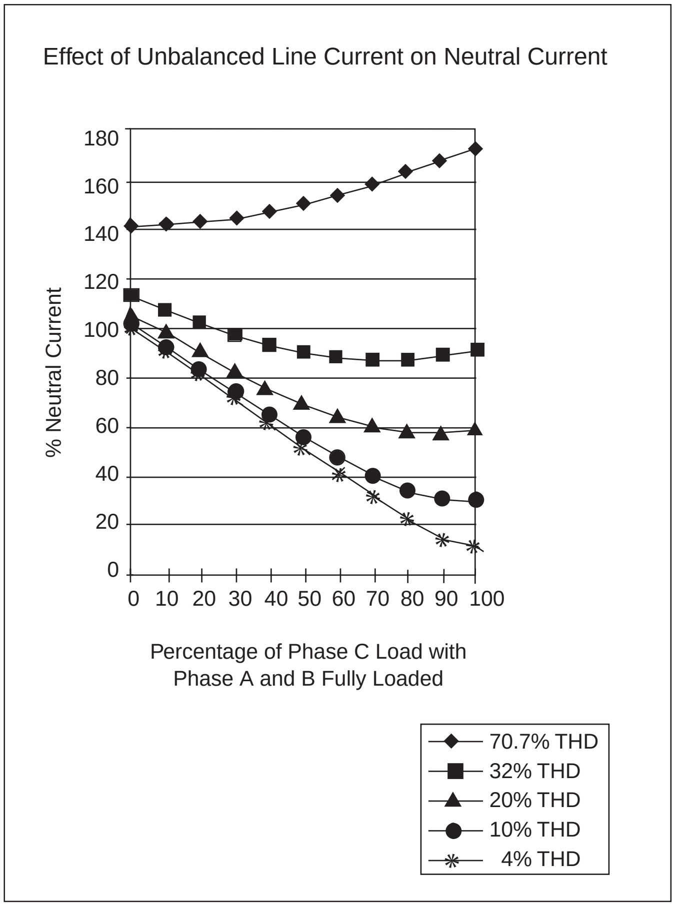

Figure 8: The unusual condition of two phases fully loaded, with one phase either unloaded, or lightly loaded, can produce greater than 100% neutral current, depending on current distortion.

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

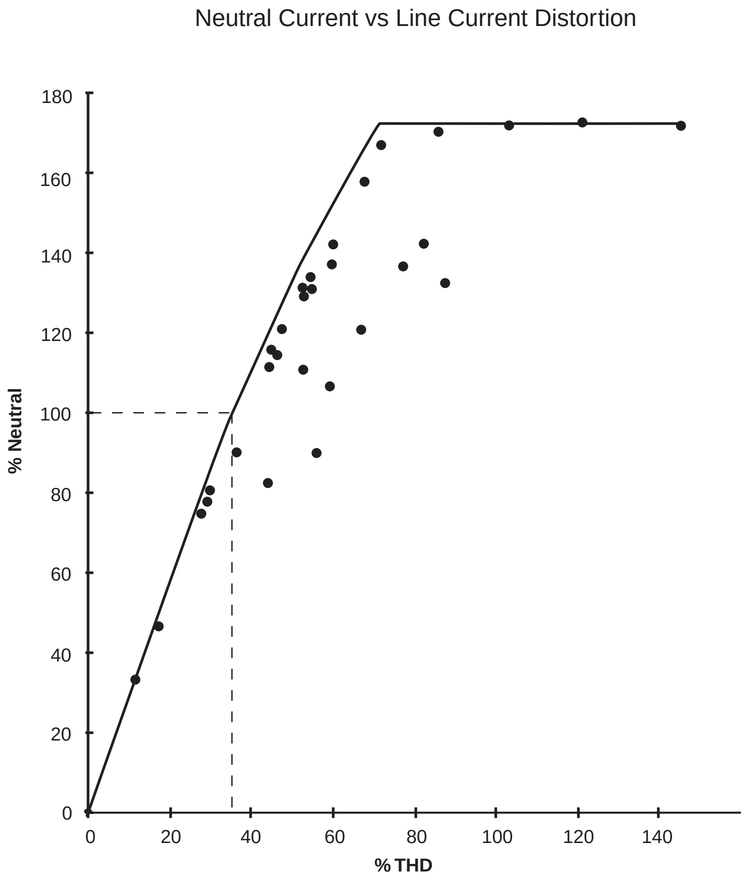

*Figure 9: **Both computer and lighting ballast "maximized" neutral contributions fall on or to the right of a curve described by equation 5, page 6, to a maximum of 173%, starting at 70.7% THD. Note that balanced loads with THD of less than 35.36% will always produce neutrals of less than 100%***

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:

%Neutral <

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

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.

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