Sizing Neutrals for Transformers

Correctly sizing neutrals for transformer secondaries is essential for handling harmonics

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K-rated transformers are typically used where anticipated loads include nonlinear power supplies. They don't remove harmonic distortion from the system. Rather, they handle the added current and heating effects resulting from nonlinear loads without damage.

Underwriters Laboratories has established ratings of 1, 4, 9, 13, 20, 30, 40 and 50 as standard K-factor ratings. K-rated transformers include neutral lugs that allow for 200% neutral connections; smaller parallel windings on the secondary side of the transformer to compensate for the skin effect associated with high frequency harmonics; transposed delta winding conductors; and electrostatic shielding between the primary and secondary windings.

Harmonic load currents cause additional heating, primarily in the form of additional winding eddy current losses. ANSI/IEEE C57.110 provides methods to de-rate a transformer for a given harmonic load profile. ANSI found that a non-K-rated transformer would have to be de-rated to about 70% in an environment requiring K-13 load factors.

The actual K rating of a transformer describes the ratio of linear and nonlinear load that it can handle. As the amount of nonlinear load increases in respect to the linear load, higher K-rated transformers will be required. A specific K-factor rating indicates that a transformer can supply its rated kVA load output to a load of specified amount of harmonic content. K-factor is a scale of the harmonic currents with respect to their effects on transformer heating based on ANSI/IEEE C57.110. A. For example, the following data is from the Federal Pacific website (www.federalpacific.com/university/kfactor/chapter2.html):

- K-4 transformer will handle 100% plus 50% nonlinear load.
- K-13 transformer will handle 100% plus 100% nonlinear load.
- K-20 transformer will handle 100% plus 125% nonlinear load.
- K-30 transformer will handle 100% plus 150% nonlinear load.

The transformer will be able to operate without overheating within its rating while supplying a nonlinear load percentage. For instance, for a K-13 transformer, the total current from the frequencies above 60 Hz (fundamental) is equal to the total current from the fundamental frequency.

Each of the K ratings noted above (4, 13, 20 and 30) have an associated harmonic profile. Utilizing the harmonic content load profile, the total harmonic distortion (THD) can be calculated by the following equation:

$$\%THD = 100 * \sqrt{(I_2^2 + I_3^2 + I_4^2 + I_5^2 \ldots\ldots + I_h^2)} / I_1$$

This is the square root of the sum of the square of all harmonic currents present in the load, excluding the 60 Hz fundamental. The total harmonic distortion for each of the K-ratings above can be used to calculate the total balanced and unbalanced neutral current with the following formulas:

Balanced: % Neutral current

$$< 300 * \frac{\%\ THD}{\sqrt{(10{,}000 + (\%\ THD)^2)}}$$

(Cannot exceed 173% of neutral.)

Unbalanced: % Neutral current

$$< 200 * \frac{\sqrt{(2{,}500 + (\%\ THD)^2)}}{(10{,}000 + (\%\ THD)^2)}$$

(Cannot exceed 141% of neutral.)

The per unit harmonic currents used for the calculations in the accompanying charts are arbitrary. But when the per unit harmonic current is squared and multiplied by the harmonic frequency number squared for each of the harmonic frequencies and the sums of these values added together, they equal the K-factor number. Differing amounts of per unit harmonic currents can exist at the various harmonic frequencies for the same K-factor level, but using the figures noted should give a good approximation of the anticipated level of THD associated with various K-rated transformers. Actual harmonic current levels at the various harmonic frequencies would have to be evaluated to determine the actual THD for a specific location in a distribution system. Charts 1 through 4 show the calculations for various ratings.

LOW AND HIGH

At lower levels of harmonic content, the unbalanced situation will produce more neutral current. As harmonic content increases to the K-13 level, the unbalanced neutral content is about equal to the balanced neutral content. As one approaches even higher levels, the balanced situation will produce more neutral current than in the unbalanced situation. The additive effects of the harmonics coupling on the neutral from all three-phase conductors start to have more of an effect than the canceling effect on the neutral of the balanced system.

As one can see from the charts, 200% neutrals from the secondary side of a 480-208/120-volt, delta-wye, 3-phase, 4-wire transformer to the 208/120-volt distribution panel are not always required. Theoretically the maximum neutral current can only be 173% of the phase conductors based on worst case condition of rectifier conduction angles of 60 degrees. Even in the widely used K-13 transformer, the associated load profile dictates only a maximum of a 126% neutral current. It may be prudent to provide 200% neutral feeders from the transformer to the distribution panel in an environment requiring a K-30 transformer where the calculated maximum neutral current can be as high as 171% of the phase conductors.

The neutral current can theoretically be as much as 173%—based on worst case condition of rectifier conduction angles of 60 degrees—of the balanced ungrounded conductor (phase) current due to nonlinear loads. *The National Electrical Code* (NEC) does not have any specific codes that call for the neutral conductors to be larger than the ungrounded conductors.

During the 1996 NEC code cycle, an ad hoc subcommittee studied many installations and hundreds of feeders involving 3-phase 4-wire, wye-connected systems with nonlinear loads. They found that only about 5% had neutral current ampacities exceeding 125% of the phase conductors. As a result, the subcommittee indicated that there was not enough evidence to require neutral conductors to be oversized by any typical factor.

[CHART 1]

Neutral Current with K-4 Transformer

The per unit harmonic current for the various harmonics are:

1st	1.0	**9th**	0.056	**17th**	0.029	**25th**	0.020
3rd	0.1667	**11th**	0.045	**19th**	0.026		
5th	0.100	**13th**	0.038	**21st**	0.024		
7th	0.071	**15th**	0.033	**23rd**	0.022		

$$\%THD = 100 * \sqrt{(0.1667^2 + 0.1^2 + 0.07143^2 + 0.0556^2 + 0.045^2 + 0.038^2 + 0.033^2 + 0.029^2 + 0.026^2 + 0.024^2 + 0.022^2 + 0.020^2) / 1} = \mathbf{23.2\%}$$

Balanced: $\%\ Neutral < 300 * 23.2 / \sqrt{10{,}000 + (\%\ 23.2)^2} = \mathbf{68\%}$

Unbalanced: $\%\ Neutral < 200 * \sqrt{(2{,}500 + (\%\ 23.2)^2) / (10{,}000 + (\%\ 23.2)^2)} = \mathbf{107\%}$

[CHART 2]

Neutral Current with K-13 Transformer

The per unit harmonic current for the various harmonics are:

1st	1.0	**9th**	0.111	**17th**	0.059	**25th**	0.040
3rd	0.333	**11th**	0.091	**19th**	0.053		
5th	0.200	**13th**	0.077	**21st**	0.048		
7th	0.143	**15th**	0.067	**23rd**	0.043		

$$\%THD = 100 * \sqrt{(0.333^2 + 0.200^2 + 0.143^2 + 0.111^2 + 0.091^2 + 0.077^2 + 0.067^2 + 0.059^2 + 0.053^2 + 0.048^2 + 0.043^2 + 0.040^2) / 1} = \mathbf{46.3\%}$$

Balanced: $\%\ Neutral < 300 * 46.3 / \sqrt{10{,}000 + (\%\ 46.3)^2} = \mathbf{126}\%$

Unbalanced: $\%\ Neutral < 200 * \sqrt{(2{,}500 + (\%\ 46.3)^2) / (10{,}000 + (\%\ 46.3)^2)} = \mathbf{124\%}$

NEC dictates that the demand calculations for a system will be based on 100% of the non-continuous load plus 125% of the continuous load. The phase conductors are sized based on the system demand calculations. Since the neutral conductors are typically sized at a minimum—the same as the phase conductors—they are sized to handle 125% of the continuous current. Per NEC, a continuous load is where maximum current is expected to last for three or more hours.

GOOD JUDGMENT

There are times when applying a 200% neutral to the secondary of every K-rated transformer can be avoided by using logic and mathematical formulas to determine the actual size of the required neutral conductor. Reducing the size of neutral conductor from the secondary of the 480-208/120-volt delta-wye 3-phase, 4-wire transformer to the 120/208-volt distribution panel will not provide much cost savings if the panel is close to the transformer. But if the electrical distribution contains several feed-through panels or extended lengths of 208-volt 3-phase feeders to distribution panels, reducing the size of neutral conductors can provide installation cost savings.

It is not uncommon to feed four to six receptacles for computer loads from a single 20-amp, 1-pole breaker. This individual branch can be fed independently with a single hot and a neutral or can be combined with two other branch feeders in what is called a “full boat.” This full boat “homerun” can be brought back to the branch breaker panel from a common point between the three branch circuit feeders. The neutrals can remain separate, but it’s common to use a single common neutral—as long as breakers are of an “a, b, c” orientation and there is only one phase conductor for each phase angle—back to the branch panel.

For this common situation, the phase conductors are #12 American wire gauge and the neutral is #10 awg. In the case of a common neutral in the homerun for three branch breakers, the neutral is sized at 160% of the maximum phase current. This calculation is based on the increased number of current-carrying conductors as defined in NEC Table 310.15(B)(2)(a) and results in an 80% de-rating as described below in the bus duct section of this article. Per NEC Section 110-14 (C), ampacity reduction of THHN (90°C) conductor is based on the conductor’s ampacity as listed in the 90°C column of Table 310-16 and not on the temperature rating of the terminals. The ampacity of a conductor is the current rating (in amps) that it can carry continuously, after applying conductor ampacity reduction factors for conductor bundling and ambient temperature. Therefore, a #10 neutral conductor’s ampacity rating at 90°C is 40 amps. At an 80% de-rating

[CHART 3]

Neutral Current with K-20 Transformer

The per unit harmonic current for the various harmonics are:

1st	1.0	**9th**	0.139	**17th**	0.074	**25th**	0.050
3rd	0.417	**11th**	0.114	**19th**	0.066		
5th	0.25	**13th**	0.096	**21st**	0.06		
7th	0.179	**15th**	0.083	**23rd**	0.054		

$$\%THD = 100 * \sqrt{(0.417^2 + 0.25^2 + 0.179^2 + 0.139^2 + 0.114 + 0.096^2 + 0.083^2 + 0.074^2 + 0.066^2 + 0.06^2 + 0.054^2 + 0.050^2)/1} = \mathbf{57.9\%}$$

Balanced: $\%\ \text{Neutral} < 300 * 57.9 / \sqrt{(10{,}000 + (\%\ 57.9)^2)} = \mathbf{150\%}$

Unbalanced: $\%\ \text{Neutral} < 200 * \sqrt{(2{,}500 + (\%\ 57.9)^2) / (10{,}000 + (\%\ 57.9)^2)} = \mathbf{132\%}$

[CHART 4]

Neutral Current with K-30 Transformer

The per unit harmonic current for the various harmonics are:

1st	1.0	**9th**	0.167	**17th**	0.088	**25th**	0.060
3rd	0.5	**11th**	0.136	**19th**	0.079		
5th	0.3	**13th**	0.115	**21st**	0.071		
7th	0.214	**15th**	0.1	**23rd**	0.065		

$$\%THD = 100 * \sqrt{(0.5^2 + 0.3^2 + 0.214^2 + 0.0556^2 + 0.045^2 + 0.038^2 + 0.033^2 + 0.029^2 + 0.026^2 + 0.024^2 + 0.022^2 + 0.020^2) / 1} = \mathbf{69.4\%}$$

Balanced: $\%\ \text{Neutral} < 300 * 69.4 / \sqrt{(10{,}000 + (\%\ 69.4)^2)} = \mathbf{171\%}$

Unbalanced: $\%\ \text{Neutral} < 200 * \sqrt{(2{,}500 + (\%\ 69.4)^2) / (10{,}000 + (\%\ 69.4)^2)} = \mathbf{141\%}$

K - 4:	K - 13:	K - 20:	K - 30:
In a balanced situation, the neutral current can be a maximum of **68%**. In an unbalanced situation, the neutral current can be a maximum of **107%** of the phase conductors. Based on the neutral being **107%** of the phase conductors, entire bus duct assembly would have to be de-rated to about **79%**.	In a balanced situation, the neutral current can be a maximum of **126%**. In an unbalanced situation, the neutral current can be a maximum of **124%** of the phase conductors. Based on the neutral being **126%** of the phase conductors, entire bus duct assembly would have to be de-rated to about **75%**.	In a balanced situation, the neutral current can be a maximum of **150%**. In an unbalanced situation, the neutral current can be a maximum of **132%** of the phase conductors. Based on the neutral being **150%** of the phase conductors, the entire bus duct assembly would have to be de-rated to about **70%**.	In a balanced situation, the neutral current can be a maximum of **171%**. In an unbalanced situation, the neutral current can be a maximum of **141%** of the phase conductors. Based on the neutral being **171%** of the phase conductors, entire bus duct assembly would have to be de-rated to about **66%**.

the neutral is capable of handling 32 amps. The 32 amps divided by 20 amps (capable of running through a 20-amp overcurrent protective device) = 160%. Note that at very high levels of harmonics, the high-frequency currents tend to travel on the skin of the conductor, which will increase the resistance of the conductor. In these cases, a separate neutral may be advisable.)

A Square D study found that the maximum theoretical neutral current of 173% is typically seen on a single sub-feeder; pulse overlapping of multiple branch feeders reduces the neutral current at the distribution panels to less than 130%. Based on this analysis, I question a design that feeds individual 20-amp, 1-pole "full boat" homeruns with a #10 neutral conductor. This will only provide a 160% neutral-carrying capability and specifically requires a 200% neutral from the secondary of the 480-208/120-volt delta-wye 3-phase, 4-wire transformer to the 120/208-volt distribution panel where neutral levels can be significantly reduced from that at an individual load.

USING BUS DUCT

If bus duct is used for distribution on the secondary side of the transformer, it must be sized according to the anticipated amount of neutral current. With bus duct, harmonics found in the neutral conductor heat up the entire assembly, which must be de-rated based on current in the neutral.

Even if the anticipated neutral current is not analyzed, NEC specifies a certain amount of de-rating for the assembly if nonlinear load is served. NEC indicates various numbers of current-carrying conductors in a raceway or cable and their associated de-rating percentages. For one to three current-carrying conductors, there is no de-rating. For four to six current-carrying conductors, the conductors are de-rated to 80% of their values.

NEC indicates that "on a 4-wire, 3-phase wye circuit, where the major portion of the load consists of nonlinear loads, harmonic currents are present in the neutral conductor; the neutral shall therefore be considered a current carrying conductor."

In a typical bus-duct distribution with 3-phase conductors and a neutral conductor, if the neutral is not considered a current-carrying conductor, the complete assembly can be rated at 100%. If the neutral is considered a current-carrying conductor, the assembly must be de-rated to 80%.

There is another disadvantage, in addition to extra cost, to oversizing transformers to deal with harmonics. A higher K-rated transformer than is required can cause the transformer's primary-side overcurrent protective device to trip when energized.

System designers ran into trouble some years back when use of K-13 transformers was proliferating. A K-13 is sometimes just a larger transformer with a smaller rating to compensate for and deal with harmonics. The same 45-amp breaker typically on the primary side of a regular 30-kVA transformer may trip when protecting a 30-kVA K-13 transformer.

For sizing of the primary side overcurrent protective device for K-13 or higher transformers, I recommend multiplying the input full load amps of a transformer by 125% and going to the next common size up. In addition, if you are using a breaker with no instantaneous trip setting adjustment, you should ensure that the default setting is set for 10 times the continuous current rating. When an instantaneous setting is available, it usually has a setting from five to 10 times the continuous current rating. A setting in the higher end of the scale can allow for the inrush of the transformer during startup without tripping the primary-side overcurrent protective device.

In addition, NEC, Section 450-3 (b) allows the primary breaker to be rated at 250% of the rated primary current of the transformer when the transformer has an overcurrent protective device on the secondary side rated no more than 125% of the rated secondary current of the transformer. If a larger breaker above the commonly sized 125% of the rating of the transformer is utilized on the primary side of the transformer as required to permit larger starting inrush currents and not trip, additional expense involved in the breaker and larger primary side feeder will be required. As a final step, I recommend an overcurrent protective device coordination study to ensure the electrical distribution system will work before it is too late, after construction is complete and the engineer is stuck with an angry owner. END