

K-Factor Transformers and Nonlinear Loads

SUMMARY

Harmonic currents generated by nonlinear loads can cause problems in the power system. Transformers are particularly vulnerable to overheating and premature failure. To protect against transformer overheating caused by harmonics, designers can specify derated equipment, i.e., oversized transformers that will run at a fraction of their rated capacity, or K-factor transformers specifically designed to accommodate harmonic currents. K-factor transformers are preferred because they have additional thermal capacity of known limits, design features that minimize harmonic current losses, and neutral and terminal connections sized at 200% of normal. K-factor transformers allow operation up to nameplate capacity without derating.

In recent years, there has been an increased concern about the effects of nonlinear loads on the electric power system. Nonlinear loads are any loads which draw current which is not sinusoidal and include such equipment as arc furnaces, gas discharge lighting, solid state motor drives, battery chargers, UPS systems, and the increasingly common electronic power supply. While nonlinear loads are not new, their increased use means a larger percentage of any power system tends to be nonlinear. Additionally, nonlinear loads were once thought to be a concern only to industrial power systems where large static power converters are used. Such is not the case today. With the widespread application of electronics to virtually every electrical load, nonlinear loads are also prevalent in commercial and even residential power systems.

Nonlinear loads generate harmonic currents which flow from the load toward the power source, following the paths of least impedance. Harmonic currents are currents which have frequencies that are whole number multiples of the fundamental (power supply) frequency. The harmonic currents superimposed on the fundamental current result in the non-sinusoidal current waveforms associated with nonlinear loads.

Harmonic currents adversely affect virtually every component in the power system, creating additional dielectric, thermal, and/or mechanical stresses. The harmonic currents flowing through the power system impedances result in harmonic voltage drops which are observed as harmonic voltage distortion. Very severe voltage distortion can result when the power system's inductive and capacitive reactances happen to be equal (parallel resonance) at one of the nonlinear load's significant harmonic current frequencies (typically the 5th, 7th, 11th or 13th harmonic).

Even without resonance, harmonic currents cause losses in normal power system components. Wiring experiences additional heating beyond the normal I^2R , due to skin and proximity effects. With one notable exception, however, the derating of wiring for harmonics is minimal and can be ignored if normal wire sizing methods are employed. That exception is the heating of the neutral conductor due to the additive nature of triplen harmonics (3rd, 9th, 15th, etc.) on three-phase, four-wire systems serving nonlinear loads with line-to-neutral connections.^(1,2)

With transformers, harmonic load currents cause additional heating, primarily in the form of additional winding eddy current losses. ANSI/ IEEE C57.110⁽³⁾ provides methods to derate a transformer for any given harmonic load profile. This standard considers the winding eddy current losses (P_{ec}) to be proportional to the harmonic current squared times its harmonic number squared. This relationship has been found to be accurate for the lower power frequency harmonics, but results in an overestimation of losses for higher harmonics (generally greater than the 11th).⁽⁴⁾ A typical derating curve is shown in Figure 1.

Transformers directly supplying single-phase power supplies may require deratings of 30% to 40% to avoid overheating.⁽¹⁾ Underwriters laboratory (UL) recognized the potential safety hazards associated with using standard transformers with nonlinear loads and developed a rating system to indicate the capability of a transformer to handle harmonic loads. The ratings are described in UL1561⁽⁵⁾ and are known as transformer K-Factors. K-Factor is a weighting of the harmonic load currents according to their effects on transformer heating, as derived from ANSI/IEEE C57.110. A K-Factor of 1.0 indicates a linear load (no harmonics). The higher the K-Factor, the greater the harmonic heating effects:

$$K\text{-Factor} = \sum(I_h)^2 h^2$$

where I_h is the load current at harmonic h , expressed in a per-unit basis such that the total RMS current equals one amp, i.e.,

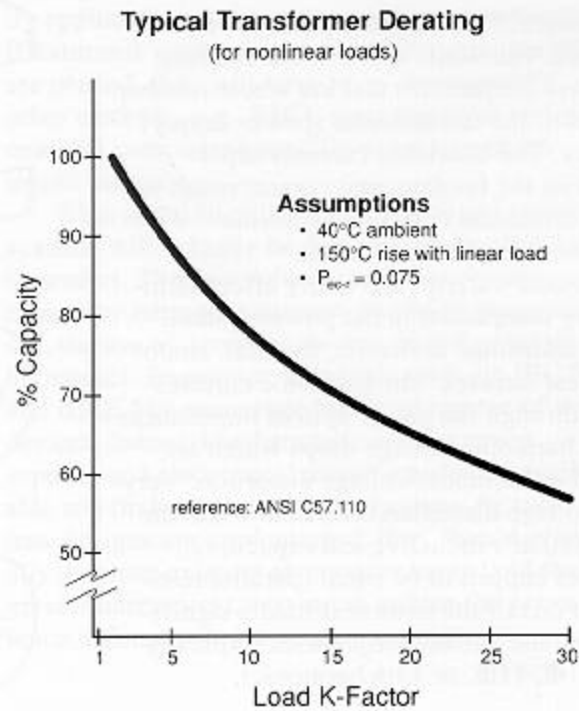
$$\sum(I_h)^2 = 1.0$$

One problem associated with calculating K-Factor is selecting the range of harmonic frequencies that should be included. Some use up to the 15th harmonic, others the 25th harmonic, and still others include up to the 50th harmonic. For the same load, each of these calculations can yield significantly different K-Factors because even very small current levels associated with the higher harmonics, when multiplied by the harmonic number squared (e.g., $50^2 = 2500$), can add significantly to the K-Factor. Based on the underlying assumptions of C57.110, it seems reasonable to limit the K-Factor calculation to harmonic currents less than the 25th harmonic. Sample calculations are shown in Figure 2.

Figure 2.

K-Factor Calculation for a Typical Nonlinear Load					
h (harmonic number)	I_h (nonlinear load current)	$(I_h)^2$	$i_h = (I_h) / (\sum(I_h)^2)^{1/2}$	$(i_h)^2$	$(i_h)^2 h^2$
1	100.0%	1.000	0.792	0.626	0.626
3	65.7	0.432	0.520	0.270	2.434
5	37.7	0.142	0.298	0.089	2.226
7	12.7	0.016	0.101	0.010	0.495

Figure 1



9	4.4	0.002	0.035	0.001	0.098
11	5.3	0.003	0.042	0.002	0.213
13	2.5	0.001	0.020	0.000	0.066
15	1.9	0.000	0.015	0.000	0.051
17	1.8	0.000	0.014	0.000	0.059
19	1.1	0.000	0.009	0.000	0.027
21	0.6	0.000	0.005	0.000	0.010
23	0.8	0.000	0.006	0.000	0.021
25	0.4	0.000	0.003	0.000	0.006
Total		1.596		1.00	6.33

In establishing standard transformer K-Factor ratings, UL chose ratings of 1, 4, 9, 13, 20, 30, 40, and 50. From a practical viewpoint, individual loads with K-Factors greater than 20 are infrequent at best. Office areas with some nonlinear loads and large computer rooms normally have observed K-Factors of 4 to 9. Areas with high concentrations of single-phase computers and terminals have observed K-Factors of 13 to 17.

When multiple nonlinear loads are powered from the same source, lower total harmonic current levels may be expected due to phase-shifts and cancellations. In one study of commercial buildings,⁽⁶⁾ single phase loads with current distortions of 104% THD (total harmonic distortion) resulted in only a 7% THD at the service entrance when added with other loads in the building. Additional studies of typical loads are beginning to provide information which should aid in the development of additional rules-of-thumb to use when direct load measurements are not available.

K-Factor transformers are designed to be operated fully loaded with any harmonic load having a K-Factor equal to or less than its K-Rating. For example, a K-13 transformer can be fully loaded with any harmonic load having a K-Factor up to K-13. If the load has a K-Factor greater than 13, then the transformer cannot be safely operated at full load and would require derating.

K-Factor transformers differ from standard transformers. They have additional thermal capacity to tolerate the heating effects of the harmonic currents. Beyond that, well-designed K-Factor transformers will also minimize the winding eddy current losses through the use of parallel conductors and other winding techniques. The K-Factor indicates the multiple of the 60 Hz winding eddy current losses that the transformer can safely dissipate: Transformer load losses consist of winding I²R losses plus stray losses. Using UL1561 test methods, stray losses are assumed to be primarily winding eddy current losses for transformers 300 kVA and smaller. For example, a transformer having winding I²R losses of 2000 watts and 60 Hz stray losses of 100 watts would, with a K-20 rating, be required to dissipate the 2000 watts of I²R losses plus 20 times the 60 Hz stray losses of 100 watts for a total load loss of 4000 watts without exceeding the maximum winding temperature rise. The result is a larger, more expensive transformer.

For K-Factor transformers, UL also requires that the neutral terminal and connections be sized to accommodate twice the rated phase conductor size (double the minimum neutral capacity) of standard transformers.

Standard transformers, i.e., those not marked with a K-Factor rating, may have some tolerance to nonlinear loading, but their capability is unknown to the user and is not certified by a third party such as UL. Currently, marking a transformer with a K-Factor rating is not required by UL. Due to a conservative design or application, some unmarked transformers may therefore have enough extra thermal capacity to tolerate additional harmonic load heating. This is particularly true for 80°C or 115°C rise transformers built with 220°C insulation materials which can safely withstand a 150°C winding temperature rise.

Additional overcurrent protection should be considered for all transformers supplying nonlinear loads. The National Electrical Code allows primary-only overcurrent protection at 125% of the transformer's primary full load amps. With three-phase transformers, the triplen harmonics are cancelled in the delta winding and do not appear in the input current. The output current and transformer loading is greater than is apparent from the input current. Therefore, the transformer can be overloaded without the primary overcurrent protection ever tripping. Adding transformer secondary overcurrent protection helps, but it still does not protect the transformer from the heating effects of harmonic currents. The use of supplemental protection in the form of winding temperature sensors can be used to provide alarm and/or system shutdown in the event of overload, excessive harmonic current, high ambient temperature, or inadequate cooling.

The use of derated standard transformers instead of K-Factor transformers carries some disadvantages.

First is the issue of managing the derating when the transformer nameplate indicates greater capacity. Initially, the transformer may be operated at the reduced loading, but in the future, the loading may be increased without considering the intended derating.

Second, if smaller overcurrent protection is used to intentionally limit the loading, nuisance tripping may occur due to the transformer inrush current. Larger overcurrent protection may be required for the oversized (derated) standard transformer resulting in larger conductor requirements with the associated higher feeder costs.

Third, transformers designed specifically for nonlinear loads minimize losses due to the harmonic currents. They operate with the nonlinear loads more efficiently and generate less heat that needs to be dissipated.

Because transformers are the power system component most affected by nonlinear loads, they were the first to receive a harmonics capability rating system. K-Factor ratings are based on the heating effects of harmonics and are not necessarily applicable to other power system components. If harmonic rating systems for other components are needed, they will have to be developed by other methods, e.g., THD, crest factor, or some new and component-specific weighting of harmonic currents.

What is the likelihood that additional rating systems will actually be developed? That's hard to predict. The best solution to the problems caused by harmonic currents would be preventive, i.e., the use of components that do not generate harmonics. Impending standards such as IEC 555 and IEEE 519 encourage the development of such devices. Indeed, low-harmonic-current power supplies and electronics ballasts are already available and finding increasing application. As such new designs are implemented, they should gradually displace existing electronics loads (and their greater harmonics), serving to reduce the prevalence of harmonic currents over the long-term.

Short-term, however, projections show harmonics levels in power systems increasing as more electronic loads are added. Whether this will provide sufficient impetus for new ratings systems for other power system components is problematical. One thing is sure, though. Until the day that harmonic currents actually diminish, K-Factor transformers will play an important role in coping with the problems harmonics create.

¹ Computer Business Equipment Manufacturers Association (CBEMA). *Three-Phase Power Source Overloading Caused by Small Computers and Electronic Office Equipment*. ESC-3 Information Letter, 1987.

² Gruzs, T. M. "A Survey of Neutral Currents in Three-Phase Computer Power Systems." *IEEE Transactions On Industry Applications*, Vol. 26, No. 4, July/August 1990.

³ The Institute of Electrical and Electronics Engineers. *Recommended Practice for Establishing Transformer Capability when Supplying Nonsinusoidal Load Currents*. ANSI/IEEE C57.110-1986, New York, 1986.

⁴ IEEE P-1100 Working Group. *Recommended Practice for Powering and Grounding Sensitive Electronic Equipment*. Draft. 1992.

⁵ Underwriters Laboratories. *Proposed Requirements and Proposed Effective Dates for the First Edition of the Standard for Dry-Type General Purpose and Power Transformers, UL1561*. Santa Clara CA, 1991.

⁶ McGranaghan et al. "Analysis of Harmonic Distortion Levels in Commercial Buildings." PQA '91, Paris, France, October 1991.

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