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K-factor & Transformers

Transformers serving heavy nonlinear loads are subject to increased winding temperatures due to the harmonic currents generated by those loads. This overheating can result in a shortened service life for the transformer. For example, operating a transformer at 10 degrees C above its insulation rated class will cause approximately a 50% reduction in the life of the transformer. If the over temperature gets high enough or lasts long enough, the insulation with fail which in turn will result in a transformer failure. K-factor rated transformers are designed to compensate for the presence of harmonic loading thereby preventing excess heating.

The definition for the K-factor as provided by the IEE Std. C57.110-2008 (IEEE Recommended Practice for Establishing Transformer Capacity When Supplying Nonsinusoidal Load Currents) states:

"A rating optionally applied to a transformer indicating its suitability for use with loads that draw non-sinusoidal currents.

$$\textbf{The K}-\textbf{FACTOR} = \sum_{h=1}^{\infty} I_h(pu)^2 h^2$$

where

$I_h(pu)$ = the rms current at harmonic "h" (per unit of rated rms load current);
h = the harmonic order."

Confused? – The object of this paper is to demystify the subject thereby providing a basic understanding as to the impact of K-factor on transformer design and operation.

Although transformers are inherently very efficient, there are losses associated with their design and loading. These losses are made up of core, winding (I^2R), and eddy

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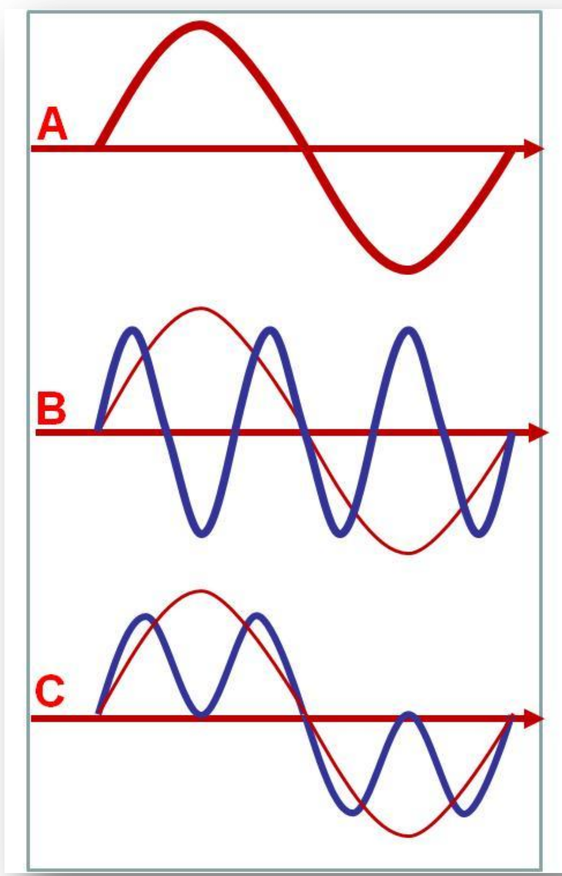
currents. Although core loss and winding loss values are largely constant and directly dependent on the quality and amount of material used, eddy currents can vary depending on load profiles.

In a transformer, the primary windings induce voltage in the secondary windings through an expanding and contracting magnetic field. Eddy currents are stray currents of electricity that are created by induction in conductors. These counter-electromotive forces (emf) are induced in opposition to the original field thereby creating opposition to current flow (resistance) which translates to losses.

Eddy current losses are expressed as a percentage of the transformer's normal winding (I^2R) as determined by Ohms law. They are a phenomena that increase in severity as the frequency of the current increases.

In an electrical power system, harmonics are current and voltage with frequencies that are integer multiples of the fundamental power frequency. That is, in a power system with a fundamental frequency of 60Hz, the second harmonic is 120Hz, the third harmonic is 180Hz, and so on. Harmonics have no useful purpose, yet contribute to losses and lower system efficiency. Harmonics return over the neutral and are dissipated as heat in connecting cables and transformers. These frequencies are referred to as non-sinusoidal loads. The presence of non-sinusoidal harmonic content in the current waveform will have the effect of increasing eddy current losses in the transformer leading to "harmonic distortion" of the fundamental power frequency waveform.



In the image to the right "A" depicts a single 60HZ cycle waveform (fundamental power frequency). "B" represents a 3rd harmonic (180HZ) waveform. The resultant waveform as shown in "C" provides an example as to the impact that the harmonic load may have on the fundamental waveform. Although the example depicts an unlikely 3rd harmonic magnitude, it provides a graphic depiction as to the impact that non-sinusoidal content can have on the fundamental waveform. The magnitude of the distortion is dependent on the number and magnitude of the total harmonic load profile.

Examples of loads for various K-factor ratings

Load	K-factor
Incandescent lighting (with no solid state dimmers)	K-1
Electric resistance heating (with no solid state heat controls)	K-1
Motors (without solid state drives)	K-1
Control transformers/electromagnetic control devices	K-1
Motor-generators (without solid state drives)	K-1
Electric-discharge lighting	K-4
UPS w/optional input filtering	K-4
Induction heating equipment	K-4
Welders	K-4
PLC's and solid state controls (other than variable speed drives)	K-4
Telecommunications equipment	K-13
UPS without input filtering	K-13
Multi-wire receptacle circuits in general care areas of health care, facilities and classrooms of schools, etc.	K-13
Multi-wire receptacle circuits supplying inspection or testing equipment on an assembly or production line	K-13
Mainframe computer loads	K-20
Solid state motor drives (variable speed drives)	K-20
Multi-wire receptacle circuits in critical care areas and operating/recovery rooms of hospitals	K-20
Multi-wire receptacle circuits in industrial, medical, and educational laboratories.	K-30
Multi-wire receptacle circuits in commercial office spaces	K-30
Small mainframes (mini and micro)	K-30
Other loads identified as producing very high amounts of harmonics (especially in higher orders)	K-40

The table to the right provides an example of environments in which various K-factor rated transformers would be used. A transformer "K-factor" rating conveys its ability to manage varying degrees of nonlinear loads without exceeding the rated temperature rise limits. For any given nonlinear load, if the harmonic current components are known, the K-factor can be calculated and compared to the transformer's nameplate K-factor. As long as the load K-factor is equal to or less than the transformer's rated K-factor, the transformer does not need to be de-rated. The higher the K-factor, the more non-linear loads the transformer can handle. The actual formula to determine K-factor takes into account the frequency and current intensity of each individual harmonic.

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The identification, measurement, and determination of the presence of non-sinusoidal frequency loads is essential in determining the impact on a transformer load. ANSI/IEEE C57.110, is the guide for determining the heating effects of nonlinear loads. It developed an equation for calculating these heating effects. By squaring the frequency and the per-unit current and multiplying them together, the guide arrived at a number without a designation. Originally it was going to be called C for “constant”, but was decided against because of possible confusion with “centigrade”. The letter K for “Konstant” was selected and Underwriters Laboratory used this designation in the original submission of a low voltage dry type transformer. K since became the standard measure of the ability of a transformer to withstand nonlinear loads.

The K-factor is a number derived from a numerical calculation based on the summation of harmonic currents generated by the non-linear load. The higher the K-factor, the more significant the harmonic current content.

Standard K-factor transformers come in K-factors of 4, 9, 13, 20, 30, 40, and 50. After K-factor load calculations are made, a transformer rated equal to or higher than the result is specified. It is more economical to purchase a K- factor transformer than to use a de-rated oversized transformer.

As a “rule of thumb”:

- 0% electronic, 100% electrical – standard (K-1 rated) transformer
- 25% electronic, 75% electrical – K-4 rated transformer
- 50% electronic, 50% electrical – K-9 rated transformer
- 75% electronic, 25% electrical – K-13 rated transformer
- 100% electronic, 0% electrical – K-20 rated transformer

  “electronic” = Nonlinear Loads

  “electrical” = Inductive and Resistive Loads

K-factor rated transformers are preferred over oversized (de-rated) conventional transformers because they are designed to supply nonlinear loads, are equipped with 200% rated neutral bus, and are likely to be smaller and less expensive. Disadvantages of an over-sized standard transformer may include the requirement for a higher short-circuit rating on circuit breakers and a higher inrush current. Derating a standard transformer is only a temporary fix that often translates into lower efficiency operation.

To calculate the K-factor, multiply the square of the percentage of harmonic current by the square of the harmonic order and add the results. For example, if a load is 60% of the fundamental, 65% of the third harmonic, 30% of the fifth harmonic, and 35% of the seventh harmonic, the resulting K-factor would be 12.3

$$(.60^2 * 1) + (.65^2 * 3^2) + (.30^2 * 5^2) + (.35^2 * 7^2) =$$
$$.36 * 1 + (.42 * 9) + (.09 * 25) + (.12 * 49) =$$
$$.36 + 3.8 + 2.25 + 5.88 = \underline{12.3}$$

In this example, a transformer with a K-factor of 13 should be specified. The K-factor rating defines the transformer's ability to withstand odd-harmonic currents while operating within its insulation class. When the K-factor is unknown, a transformer may be selected by using the above “Examples…” table as a guide.

For existing installations, one can validate the K-factor load by using a 3 phase analyzer such as pictured below.

Such a device can also be used to check the impact of adding additional load devices on K-factor loading so as to insure that the existing transformer can be used.

So, what changes must be made to a transformer design in order to accommodate the additional losses caused by non-sinusoidal loads? The most notable is that the capacity of the transformer neutral is increased a minimum of 200% of the transformer kva rating. This is to accommodate the presence of triplen harmonics. The triplen harmonics are defined as the odd multiples of the 3rd harmonic (ex. 3rd, 9th, 15th, 21st etc.). Triplen harmonics are of particular concern because they are zero sequence harmonics, unlike the fundamental, which is positive sequence. The consequence of this fact is that the magnitude of these currents on the 3 phases are additive in the neutral which if not accommodated for, can lead to significant heating.

For K-factor rated transformers, PCT routinely utilizes round coil construction with cruciform cores which allow for 360 degree cooling ducts. This approach minimizes the potential for localized heating within the coils since the cooling fluid flows freely throughout the core/coil assembly.

With the additional loss requirements identified via the K-factor rating, additional cooling radiators may be added to insure that while delivering nameplate capacity, the temperature limit will not be exceeded. In extreme cases (K-20 and above), winding conductor current densities and/or core material flux densities may be adjusted.

Round coil construction

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