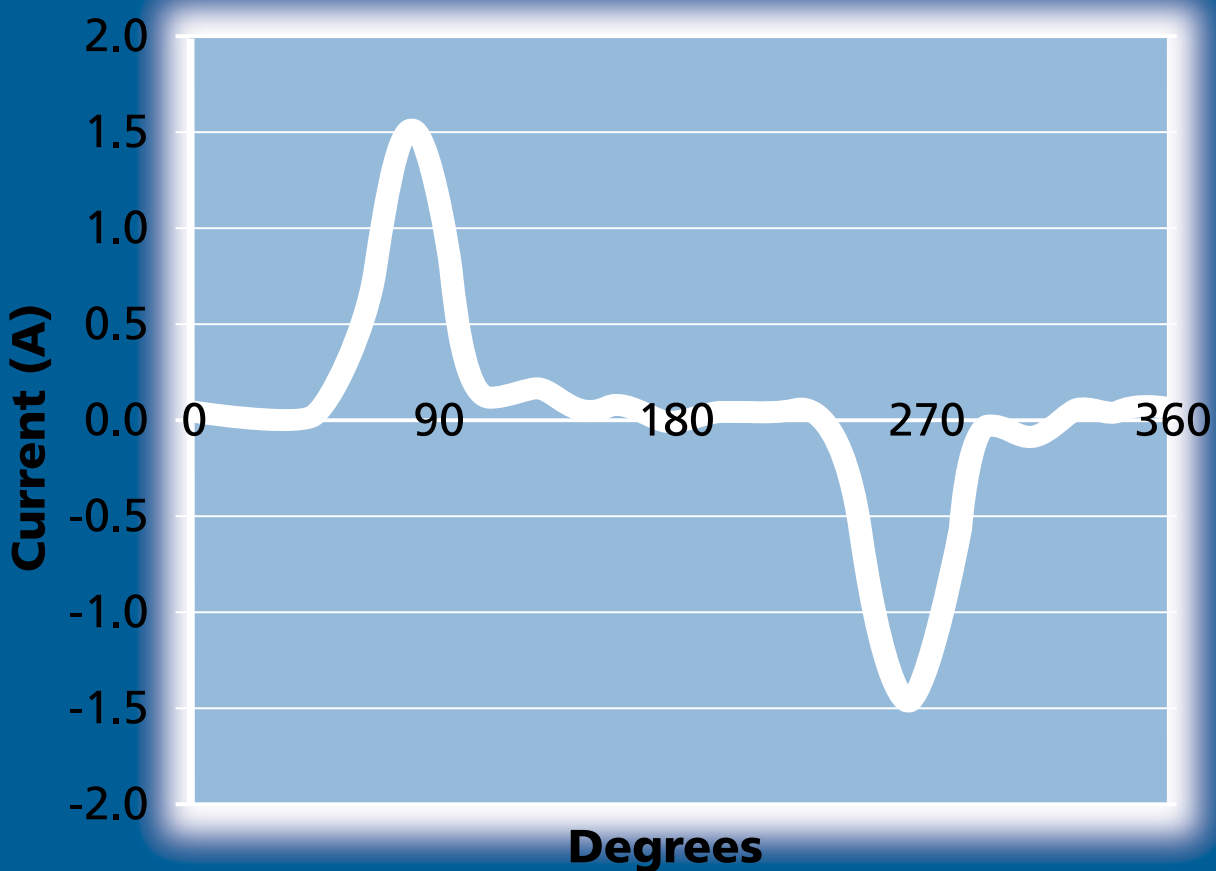




Harmonics, Transformers and K-Factors



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CDA Publication 144, September 2000

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Acknowledgments

The production of this publication is financed by International Copper Association, Ltd and Codelco Services Ltd.

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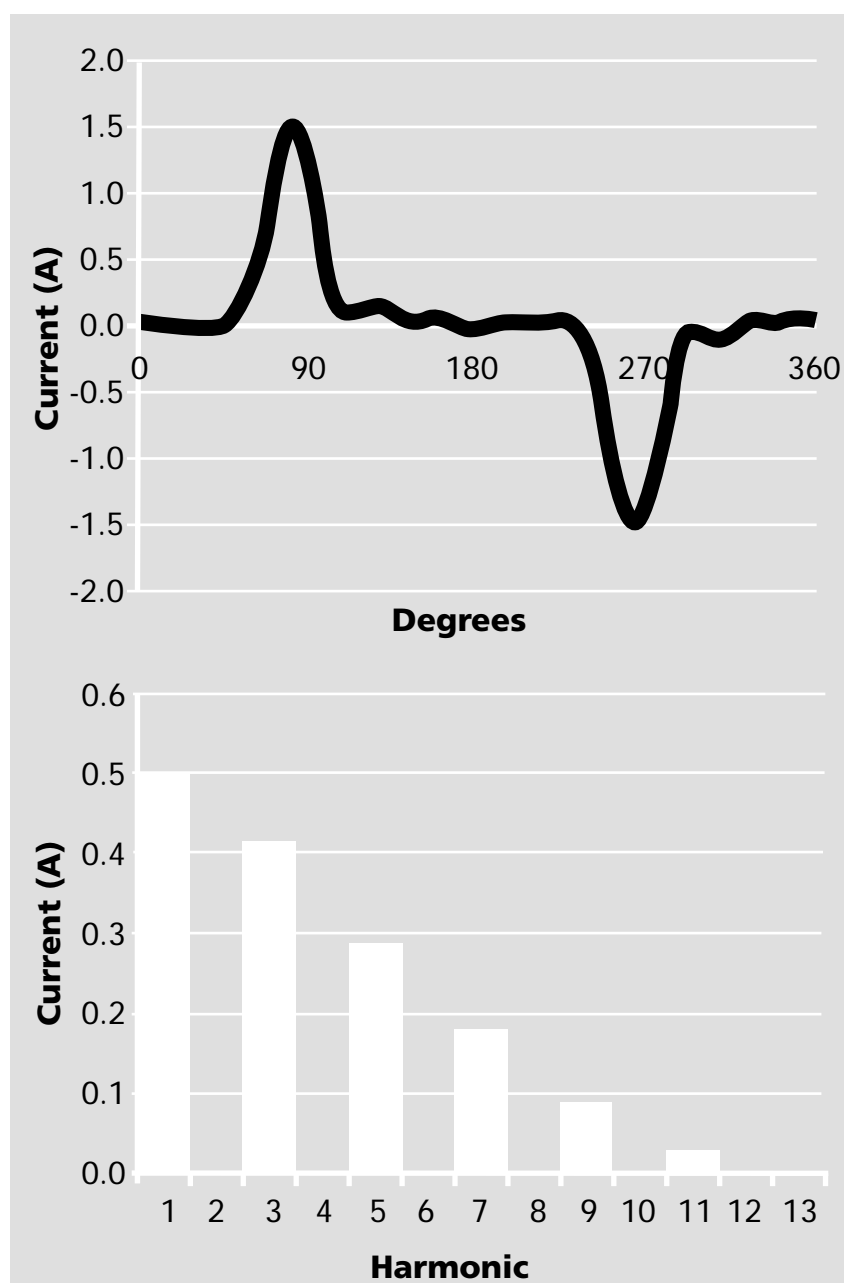
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Harmonics, Transformers and K-Factors

Harmonic currents are generated whenever a non-linear load is connected to the mains supply. The problems caused by harmonic currents include overheating of cables, especially the neutral conductor, overheating and vibration in induction motors and increased losses in transformers. Where power factor capacitors are fitted, harmonic currents can damage them and care must be taken to avoid resonance with the supply inductance. This note discusses the effects of harmonics on transformers and looks at two methods that designers can use to account for them and ensure reliability.

Losses in transformers are due to stray magnetic losses in the core, and eddy current and resistive losses in the windings. Of these, eddy current losses are of most concern when harmonics are present, because they increase approximately with the square of the frequency. Before the excess losses can be determined, the harmonic spectrum of the load current must be known.

The supply current waveform of a typical personal computer is shown below with the harmonic spectrum. This spectrum is typical of the switched mode power supplies used in modern electronic equipment such as fax machines and printers as well as PCs. Note in particular the high levels of third and fifth harmonics.



The eddy current loss at a particular harmonic is given by:

$$P_h = P_f I_h^2 h^2$$

where

P_f is the eddy current loss at the fundamental frequency f

P_h is the eddy current loss at harmonic number h

I_h is the fraction of total rms load current at harmonic number h .

The total eddy current loss is given by summing the losses for the individual harmonics and the fundamental:

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

where P_t is the total eddy current loss.

There are two distinct approaches to accounting for this increased eddy current loss in selecting a transformer. The first, devised by transformer manufacturers in conjunction with Underwriters Laboratories in the United States, is to calculate the factor increase in eddy current loss and specify a transformer designed to cope; this is known as 'K-Factor'. The second method, used in Europe, is to estimate by how much a standard transformer should be de-rated so that the total loss on harmonic load does not exceed the fundamental design loss; this is known as 'factor K'. The figures produced by each method are numerically different; 'factor K' is a total rating factor while 'K-factor' is a multiplier (although a de-rating factor can be derived from it). The fact that both methods use K as a designation can lead to confusion when talking to suppliers.

K-Factor

In US practice, where dry-type transformers are often used, the K-factor is the ratio of eddy current losses when driving non-linear and linear loads:

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

This K-factor is read directly by many power meters (e.g. Fluke 41 & 43), and the K-factor for the typical PC load seen earlier is 11.6. Once the K-Factor of the load has been determined, it is a simple matter to specify a transformer with a higher K-rating from the standard range of 4, 9, 13, 20, 30, 40, 50.

Factor K

In Europe, the transformer de-rating factor is calculated according to the formulae in BS 7821 Part 4. The factor K is given by:

$$K = \left[1 + \frac{e}{1+e} \left(\frac{I_1}{I} \right)^2 \sum_{n=2}^{n=N} \left(n^q \left(\frac{I_n}{I_1} \right)^2 \right) \right]^{0.5}$$

where

e is the eddy current loss at the fundamental frequency divided by the loss due to a dc current equal to the RMS value of the sinusoidal current, both at reference temperature.

n is the harmonic order

I is the rms value of the sinusoidal current including all harmonics given by:

$$I = \left(\sum_{n=1}^{n=N} (I_n)^2 \right)^{0.5} = I_1 \left[\sum_{n=1}^{n=N} \left(\frac{I_n}{I_1} \right)^2 \right]^{0.5}$$

I_n is the magnitude of the n th harmonic

I_1 is the magnitude of the fundamental current

q is an exponential constant that is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round or rectangular cross section conductors in both windings and 1.5 for those with foil low voltage windings.

K-Rated or De-Rated?

The great advantage of a 'K-rated' transformer is that it will have been designed with harmonic loads in mind and care will have been taken to keep losses low. For example, eddy current losses will have been reduced by the use of stranded conductors and magnetic losses will have been reduced by the use of low loss steels. The neutral point connections are usually brought out individually, so that the star point has a 300% current rating.

On the other hand, de-rating a standard transformer has a number of disadvantages. Because the transformer is oversized, the primary over-current protection level may be too high to protect the secondary, but if the protection level is reduced, the inrush current may cause tripping. A de-rated transformer is less efficient; the excess losses are still being generated and dissipated within the transformer, rather than being designed out, and a larger core than necessary, with larger losses, is being magnetised. There is also a potential maintenance problem – long after installation, changes in the needs of the facility may result in additional load being added without reference back to the initial de-rating. This may lead to overloading and consequent failure.

Diversity

Each non-linear load generates harmonics independently with the magnitude and phase angle of each harmonic depending on the design of the circuit and the instantaneous loading. When several loads are connected in parallel, for example, a number of personal computers on an office floor, the overall sum of each harmonic will be less than the sum of the individual magnitudes.

In other words, the K-factor of the overall load is less than that which would be expected from measurement of all the individual items. Similarly, when there are linear loads present, the overall K-factor is reduced because the harmonic load is a smaller proportion of the total load.

It is very difficult to predict the overall K factor of an installation; the worst case figure can be obtained by taking the harmonic spectrum of each load and summing them, including the fundamental for all linear loads. In practice, the K-factor will be less than this value, but it is impossible to predict by how much. Note that the worst case may not correspond to full load conditions.

In practice, the best course of action is to regularly monitor the overall K-factor to ensure that it remains within the design maximum.

Worked examples

The examples on the next page show the result of each method using the PC load shown earlier.

'K-Factor Calculator' software is available to perform these calculations – see 'CDA Information Service' on page 5 for details.



Factor K

Typical calculation according to BS 7821 Part 4

(taking q as 1.7 and assuming that eddy current loss at fundamental is 10% of resistive loss i.e. $e = 0.1$).

| Harmonic No. | RMS current (I_n) | $\left(\frac{I_n}{I_1}\right)$ | $\left(\frac{I_n}{I_1}\right)^2$ | n^q | $n^q \times \left(\frac{I_n}{I_1}\right)^2$ |
|--|-----------------------|--------------------------------|----------------------------------|--------|---|
| 1 | 1 | 1 | 1 | - | - |
| 3 | 0.82 | 0.82 | 0.6724 | 6.473 | 4.3525 |
| 5 | 0.58 | 0.58 | 0.3364 | 15.426 | 5.1893 |
| 7 | 0.38 | 0.38 | 0.1444 | 27.332 | 3.9467 |
| 9 | 0.18 | 0.18 | 0.0324 | 41.900 | 1.3576 |
| 11 | 0.045 | 0.045 | <u>0.0020</u> | 58.934 | <u>0.1193</u> |
| Sum = 2.1876 | | | | | $\Sigma = 14.9653$ |
| Total rms (I) = 1.479 | | | | | $\Sigma \times (I_n/I)^2 = 6.835$ |
| $(I_1/I)^2 = 0.457$ | | | | | $e/(1+e) = 0.091$ |
| $K^2 = 1 + (0.091 \times 6.835) = 1.622$ | | | | | |
| $K = 1.27$ | | | | | |
| De-rate to 78.52 % | | | | | |

K-Factor

Typical calculation according to Underwriters' Laboratories method:

| Harmonic No. | RMS current (I_n) | $\left(\frac{I_n}{I_1}\right)$ | $\left(\frac{I_n}{I_1}\right)^2$ | $\left(\frac{I_n}{I}\right)$ | $\left(\frac{I_n}{I}\right)^2$ | $\left(\frac{I_n}{I}\right)^2 \times n^2$ |
|---------------------------|-----------------------|--------------------------------|----------------------------------|------------------------------|--------------------------------|---|
| 1 | 1 | 1 | 1 | 0.6761 | 0.4571 | 0.4571 |
| 3 | 0.82 | 0.82 | 0.6724 | 0.5544 | 0.3073 | 2.7663 |
| 5 | 0.58 | 0.58 | 0.3364 | 0.3921 | 0.1538 | 3.8444 |
| 7 | 0.38 | 0.38 | 0.1444 | 0.2569 | 0.0660 | 3.2344 |
| 9 | 0.18 | 0.18 | 0.0324 | 0.1217 | 0.0148 | 1.2000 |
| 11 | 0.045 | 0.045 | <u>0.0020</u> | 0.0304 | 0.0009 | <u>0.1120</u> |
| Sum = 2.1876 | | | | | | 11.6138 |
| Total rms (I) = 1.479 | | | | | K-factor | 11.6138 |

CDA Information Service

For additional information, technical advice and details of suppliers of copper products contact:

Free Technical Helpline:

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'Harmonics in Practice' Publication - 145

Software

'Energy Efficient Cables' - D10

'Energy Efficient Busbar Design' - D11

'K-Factor Calculator' - D12

Transformers used to supply IT equipment and other non-linear loads need to be de-rated to between 60 and 80% of their nominal capacity. This technical note explains why, and how to determine the correct factor.

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