Power Quality Application Guide

LEONARDO POWER QUALITY INITIATIVE

Harmonics

Selection and Rating of Transformers

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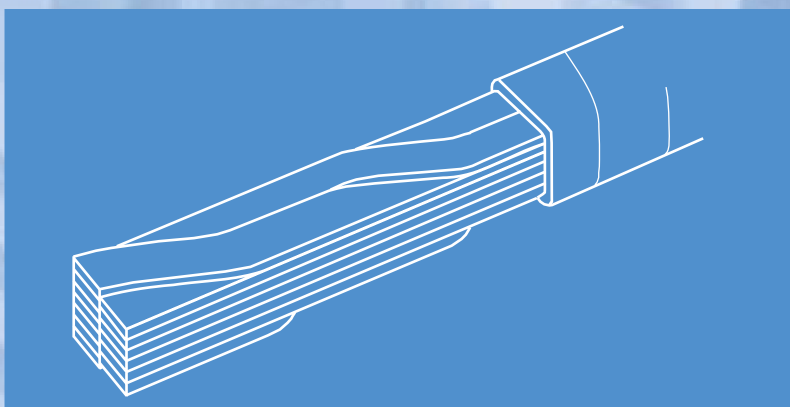

Harmonics

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Harmonics

Selection and Rating of Transformers

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Selection and Rating of Transformers

Introduction

The number of non-linear loads – which draw non-sinusoidal currents even if fed with sinusoidal voltage - connected to the power supply system is large and is continuing to grow rapidly. These currents can be defined in terms of a fundamental component and harmonic components of higher order.

In power transformers the main consequence of harmonic currents is an increase in losses, mainly in windings, because of the deformation of the leakage fields. Higher losses mean that more heat is generated in the transformer so that the operating temperature increases, leading to deterioration of the insulation and a potential reduction in lifetime.

As a result, it is necessary to reduce the maximum power load on the transformer, a practice referred to as de-rating, or to take extra care in the design of the transformer to reduce these losses.

To estimate the de-rating of the transformer, the load's K-factor may be used. This factor is calculated according to the harmonic spectrum of the load current and is an indication of the additional eddy current load losses. It reflects the excess losses experienced in a traditional wire wound transformer.

Modern transformers use alternative winding designs such as foil windings or mixed wire/foil windings. For these transformers, the standardised K-factor – derived for the load current - does not reflect the additional load losses and the actual increase in losses proves to be very dependent on the construction method. It is therefore necessary to minimise the additional losses at the design stage of the transformer for the given load data using field simulation methods or measuring techniques.

Transformer losses

Transformer losses consists of no-load (or core loss) and load losses. This can be expressed by the equation below.

$$P_T = P_C + P_{LL} \qquad (1)$$

where:

P_C = core or no-load loss

P_{LL} = load loss

P_T = total loss.

Core or no-load loss is due to the voltage excitation of the core. Although the magnetising current does include harmonics, these are extremely small compared with the load current and their effect on the losses is minimal. As a result, it is assumed in standards such as ANSI/IEEE C57.110 that the presence of harmonics does not increase the core loss.

Load losses are made up of I^2R loss, eddy current loss and stray loss, or in equation form:

$$P_{LL} = I^2R + P_{EC} + P_{SL} \qquad (2)$$

where:

I^2R = loss due to load current and DC resistance of the windings

P_{EC} = winding eddy current loss

P_{SL} = stray losses in clamps, tanks, etc.

The I^2R loss is due to the current flowing in the resistance of the windings. It is also called ohmic loss [1] or dc ohmic loss [2]. The ohmic loss is proportional to the square of the magnitude of the load current, including the harmonic components, but is independent of the frequency. It is determined by measuring the dc resistance and calculating the resulting loss using the winding currents at full load.

There are no test methods available to determine individual winding eddy current loss or to separate transformer stray loss from eddy current loss. Instead, the total stray and eddy current loss is determined by determining the total load loss and subtracting the calculated ohmic losses, i.e.,

$$P_{EC} + P_{SL} = P_{LL} - I^2 R \tag{3}$$

The eddy current loss is assumed to vary with the square of the rms current and the square of the frequency (harmonic order h), i.e.,

$$P_{EC} = P_{EC,R} \sum_{h=1}^{h=h_{\max}} \left(\frac{I_h}{I_R} \right)^2 h^2 \tag{4}$$

where:

h = harmonic order, 1,2,3, etc.

h_{max} = the greatest harmonic order to be considered

I_h = current at harmonic order h, amperes

I_R = rated current, amperes

$P_{EC,R}$ = eddy current loss at rated current and frequency.

The eddy current loss depends on the square of the conductor dimension perpendicular to the leakage flux field. At the ends of the winding the flux field bends and the larger dimension of the rectangular conductor is perpendicular to a vector component of the leakage flux field. Equalising the height of die primary and secondary windings, which can be achieved with any winding design, reduces the concentrated eddy loss at the winding ends. However, the magnitude is still greater than the middle of the winding due to this bending of the leakage flux field. Reducing conductor size reduces the percentage eddy current loss but, increases the ohmic loss. Using multiple strands per winding reduces both eddy current loss and ohmic loss, but because the conductors are of unequal length, circulating currents are generated which cause excess loss. This can be avoided by the use of continuously transposed conductors, shown in Figure 1, for the high current winding. Small transformers inherently have small conductor sizes due to low currents.

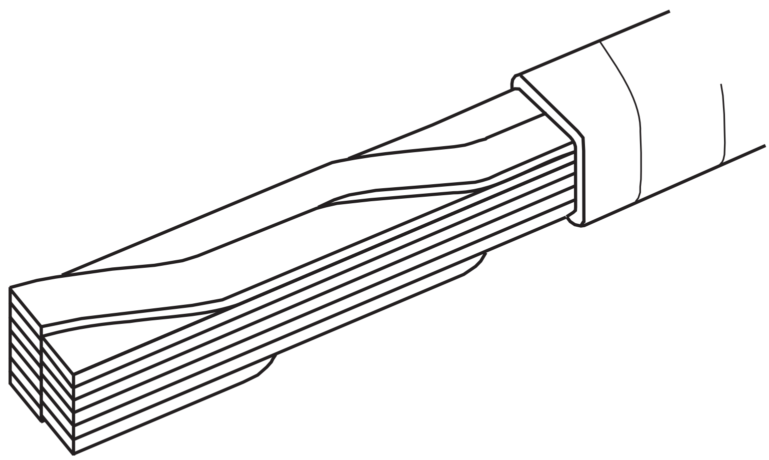

Figure 1 – Continuously transposed conductor

Stray loss occurs due to the stray flux which introduces losses in the core, clamps, tank and other iron parts. Stray loss may raise the temperatures of the structural parts of the transformer. For dry-type transformers increased temperatures in these regions do not contribute to an increase in the winding hot spot temperature. For liquid-immersed transformers, the stray loss increases the oil temperature and thus the hot spot temperature of the windings. Stray losses are difficult to calculate and it is common to assume that the losses will vary as the square of the current times the frequency (harmonic order), as shown by:

$$P_{SL} = P_{SL,R} \sum_{h=1}^{h=h_{\max}} \left(\frac{I_h}{I_R} \right)^2 h \qquad (5)$$

Transformers and K-factor

The 'K-factor'

There are different approaches to accounting for additional losses 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 the 'K-factor'.

$$K = \sum_{h=1}^{h=h_{max}} h^2 I_h^2 \qquad (6)$$

where:

h = harmonic number

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

Many power quality meters read the K-factor of the load current directly. Once the K-factor of the load is known, 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.

Note that a pure linear load – one that draws a sinusoidal current – would have a K-factor of unity. A higher K-factor indicates that the eddy current loss in the transformer will be K times the value at the fundamental frequency. 'K-rated' transformers are therefore designed to have very low eddy current loss at fundamental frequency.

The 'factor K'

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'.

$$K = \left(1 + \frac{e}{1+e} \left(\frac{I_1}{I} \right)^2 \sum_{h=2}^{h_{max}} \left(h^q \left(\frac{I_h}{I_1} \right)^2 \right) \right)^{\frac{1}{2}} \qquad (7)$$

where:

e = ratio of fundamental frequency eddy current loss to ohmic loss, both at reference temperature

h = harmonic number

I = rms of the sinusoidal current including all harmonics

I_h = magnitude of the h^{th} harmonic

I_1 = magnitude of the fundamental current

Q = 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.

The additional loss factor

The third method is called additional loss factor. A resistance factor is defined as follows:

$$K_{\Delta R}(f)=\frac{R_{AC}(f)-R_{DC}}{R_{AC}(f_1)-R_{DC}} \quad (8)$$

where:

R_{DC} = the equivalent series *DC*-resistance

R_{AC} = the series *AC*-resistance.

R_{AC} is frequency dependent, due partly to current redistribution in the winding, and is determined for each harmonic frequency. The type of construction and the placement of the windings has a major effect on the shape of the relationship between R_{AC} and frequency.

Finally, the total additional loss factor '$K_{\Delta P}$' is determined as the sum of the frequency dependent losses at each frequency arising from the R_{AC}. This requires knowledge of the harmonic current spectrum of the load.

$$K_{\Delta P}=\sum_{f>f_1} K_{\Delta R}(f)\left(\frac{I_f}{I_R}\right)^2 \quad (9)$$

where:

$K_{\Delta P}$ = additional loss factor

$K_{\Delta R}$ = resistance factor

I_f = current at harmonic frequency *f*

I_R = rated current.

To determine this factor for a given transformer, prototype or computation model, the series resistances or short circuit resistances have to be determined, either by measurement or by simulation.

Experimental tests

Additional losses in presence of current harmonics

If the harmonic spectrum is known, or can be measured or predicted, the additional losses can be easily calculated.

In principle, the process of calculation is as follows:

- Determine all the components of additional losses due to the presence of harmonics
- Determine the harmonic spectrum, either by measurement or by estimation, taking account of all harmonic generating equipment – especially electronic converters
- Calculate the contribution of each harmonic and determine the total additional loss.

In practice, it is important to use the real harmonic current magnitudes rather than theoretical values.

Table 1 shows the calculated additional losses, for harmonic currents up to order 25, for two transformers at normal environmental temperature, assuming the current harmonic spectrum to be that illustrated as the theoretical values in Figure 2.

The results demonstrate that the transformer characteristics play an important role in determining the losses with harmonic loads.

The transformers in this example were measured at slightly different temperatures (21.5°C for the first and 22.8°C for the second); this will not change the character of the result.

Loss type	First Transformer (21.5°C)	Second Transformer (22.8°C)
Additional with sinusoidal current	520 W	1721 W
Additional with non-sinusoidal current	871 W	4351 W

Table 1 – Additional losses calculated in presence of non-sinusoidal currents

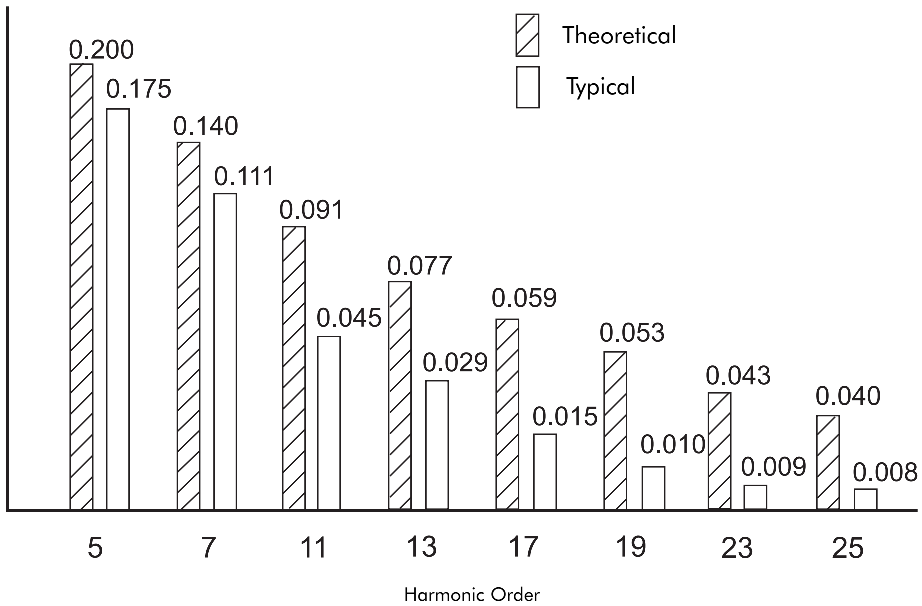

Figure 2 – Theoretical and real values of current harmonics for a six pulse converter

Calculation of the K-Factor

Table 2 shows the calculation of the K-factor for the harmonic theoretical spectrum of Figure 2 on a per unit basis.

Harmonic No	I_h/I_1	$(I_h/I_1)^2$	I_h/I	$(I_h/I)^2$	$(I_h/I)^2 \times h^2$
1	1.000	1.0000	0.9606	0.9227	0.9227
5	0.200	0.0400	0.1921	0.0369	0.9227
7	0.140	0.0196	01345	0.0181	0.8862
11	0.091	0.0083	0.0874	0.0076	0.9246
13	0.077	0.0059	0.0740	0.0055	0.9426
17	0.058	0.0034	0.0557	0.0031	0.8971
19	0.056	0.0031	0.0538	0.0029	1.0446
23	0.043	0.0018	0.0413	0.0017	0.9025
25	0.040	0.0016	0.0384	0.0015	0.9227
	Sum =	1.0838			8.3476
	Total (rms) =	1.0410			
				K-factor =	8.3476

Table 2 - Calculation of the K-factor

The first step is to calculate the rms value of total current I, 1.0410 in this case, after which the squares of the proportionate values of each harmonic current can be calculated, leading to the value of K. For such a load, a transformer with a K rating of 9 would be appropriate for a six-pulse converter.

Calculation of the Factor K

The first step in establishing factor K (Table 3) is to discover the value of e, the ratio of eddy current loss to total load loss at fundamental frequency. The transformer manufacturer should be able to provide this, otherwise it is likely to lie in the range of 0.05 to 0.1. The exponent q depends critically on the construction of the transformer and should also be available from the manufacturer. Q is likely to lie in the range 1.5 to 1.7. As before, the calculations are based on the theoretical values from Figure 2.

In practice, the transformer would need to be de-rated to 87% (1/1.15) of nominal power rating when supplying a six-pulse converter.

Harmonic No	I_h/I_1	$(I_h/I_1)^2$	h^q	$(I_h/I_1)^2 \times h^q$
1	1.000	1.0000	1.0000	1.0000
5	0.200	0.0400	15.4258	0.6170
7	0.140	0.0196	27.3317	0.5357
11	0.091	0.0083	58.9342	0.4880
13	0.077	0.0059	78.2895	0.4642
17	0.058	0.0034	123.5274	0.4155
19	0.056	0.0031	149.2386	0.4680
23	0.043	0.0018	206.5082	0.3818
25	0.040	0.0016	237.9567	0.3807
	Sum =	1.0838	[a] =	3.7511
	Total (rms) =	1.0410	$[a] \times (I_1/I)^2$ =	3.4611
			e/(e+1) =	0.091
	$(I_1/I)^2$ =	0.9227		
			K^2 =	1.315
			K =	1.15

Table 3 - Calculation of the Factor K

Transformer design consideration

Introduction

Many transformer manufacturers have developed designs rated for non-sinusoidal load currents while optimising their production costs. The design process involves an analysis of the eddy current loss distribution in the windings and calculation of the hot spot temperature rise. Eddy current losses due to the leakage flux distribution are concentrated in the ends of the winding. Analysis of the eddy loss distribution may be performed using finite element or other type computer programs. Specialised software programs are commercially available.

For larger transformers, above about 300 kVA, a combination of testing and analysis may be the only economically practical approach. Thermal studies should be conducted using embedded thermocouples installed in test windings of prototype transformers to measure hot spot temperature to refine mathematical models to calculate the hot spot temperature.

Electromagnetic analysis

The subject of harmonics has received much publicity in recent times leading to the belief that the industry is only just beginning to understand the effect of harmonics and to calculate the increased eddy current losses. In fact, the study of the effects is quite old, with eddy current losses in conductors in a magnetic field dating from 1906. Many early investigations were highly mathematical and the flux plots given in these early papers were every bit as detailed, and probably as accurate, as those produced by modern computer programs.

With the availability of computers, methods were developed to compute electrical fields and eddy current losses in transformers. Many commercial computer programs are currently available and a list is given in the 1989 IEEE Spectrum article by Cendes [5]. These computer programs produce elegant plots, however their accuracy cannot be proven.

Thermal analysis

Although hot spot temperature is an important performance parameter to be met by the manufacturer, there are currently no defined test methods, nor is there a requirement that this parameter be measured on production or prototype transformers. This is important since temperature is fundamental in determining the life of the equipment.

The hot spot temperature in dry-type transformers is sometimes a contentious issue. Hot spots, the positions of the highest temperature, occur naturally due to the non-uniform heat generation and the fact that the rate of heat transfer to the environment is not uniform; dry-type transformers have unique heat-transfer characteristics that are not well understood. Most manufacturers of dry-type transformers simply add 30 deg C to the average temperature rise (calculated using empirical equations) and claim this is according to standards. In fact, IEEE Standard C57.12.01- 1989 requires that both average winding temperature rise and hot spot temperature are limits to be met at rated kVA. The difference between these two limits happens to be 30 deg C but the use of 30 deg C as a 'rule of thumb' was not intended.

Conclusion

Non-sinusoidal currents cause excessive heating in transformers due to the increase in the losses, especially the eddy current losses.

Where existing or standard transformers are used to supply non-linear loads, they should be de-rated in a manner appropriate to their construction.

For new installations, specially constructed (or K rated) transformers should be selected if possible, otherwise appropriate de-rating should be used.

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