Derating method for dry type power transformers based on current distortion parameters

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ABSTRACT

Harmonic loads on a transformer cause losses and unwanted heating. This leads to reduced lifetime and unexpected downtime caused by insulation failure. Many publications deal with the life time estimation of transformers. Life time estimation of transformers based on ambient, surface, winding and hotspot temperature is constrained by lack of data such as measurements from inside the transformer. In order to protect the transformer against overload when harmonics are present, derating of the transformer is applied. Derating is usually performed based on the K-factor in the EU and K-rating is used in the US. This information is not always available in current measurement equipment, especially panel meters. Panel meters typically measure only basic power quality parameters and in many cases they calculate only the THD(I). The K-factor is only calculated in dedicated power quality analyzers. This makes a quick assessment of the required derating difficult. Consequently this paper offers an interesting point of view. This paper presents the use of THD(I) as a parameter for derating of dry type transformers next to and in relation with the K-Factor. But it also gives the opportunity to determine the US K-factor based on THD(I). The relation of these parameters is determined based on field data from the industry on a large number of transformers and load conditions.

Keywords— Transformer derating, power quality, transformers, energy efficiency, monitoring systems, THD(I), K-factor

INTRODUCTION

A transformer is a crucial piece of equipment in a power distribution system. The availability has to be very high. For this reason an assessment of the harmonic load and by extension the total loading capability of the transformer is important.

It is commonly known that harmonic loads applied on transformers cause extra losses in both winding and iron and consequently leading to a decreased efficiency [2]. Reducing the maximum load called derating has been proposed in many publications and different approaches exist [5],[11].

For transformers, the IEEE C57.110 [1] provides a method to derate the transformer when supplying non-linear loads. This transformer derating is based on additional eddy current losses due to harmonic currents but neglects the no-load losses. Voltage distortion on high voltage side will also lead to increased eddy current losses but they are neglected with respect to the influence of low voltage side since the resulting high voltage currents are small.

In many cases a temperature measurement is present in the transformer but this does not give any information on the harmonic load condition over time. In an ideal situation a permanent monitoring system with event analysis should be present at transformer level in order to optimize its availability. Using adequate monitoring systems one can perform predictive maintenance on the electrical installation and intervene before the transformer is switched off due to overload or insulation breakdown because of degradation of insulation and due to increased partial discharge. This way increasing the lifespan of the transformer.

In the IEEE C57.110 [1], the harmonic loss factor (FHL) is used in order to assess the harmonic load on the transformer and to determine the required derating. The same standard also describes the relation with the K-factor. In other publications the K-factor is used in order to determine the appropriate derating [3],[4]. In practical situations these factors are not always known or cannot be calculated since this requires more complex measurement equipment. The only parameter that is widely available is the Total Harmonic Distortion of the current (THD(I)). This paper makes an assessment of the required derating factors based on the THD(I) instead of the K-factor or harmonic loss factor – FHL allowing quick evaluation of the transformer load and a reliable method to evaluate if further action is required.

TRANSFORMER LOSSES

Transformer losses are categorized as load losses and No-load losses [1]. The No-load losses are independent of the load of the transformer and are better known as the excitation losses. These losses are present when the transformer is energized and are influenced by the voltage distortion. No-load losses consists primarily of core loss, which is a function of the magnitude, frequency, and wave shape of the excitation voltage. Next to the voltage distortion the nonlinearity of the transformer core will introduce significant harmonics into the excitation current [17] Where the IEEE C57.12.91 [16] states that No-load losses also vary with temperature and are particularly sensitive to differences in waveform; therefore, no-load loss measurements vary markedly with the waveform of the test voltage for dry type transformers. The IEEE C57.12.90 [15] states otherwise for liquid filled transformers. The eddy-current component of the no-load loss varies with the square of the rms value of excitation voltage and is substantially independent of the voltage waveform [15]. No load losses are not included in further evaluation.

The load losses vary with both the load magnitude and load nature applied to the transformer. Load losses are subdivided into I^2R losses and “stray losses.”

$$P_{SL} = P_{LL} - I_{rms}^2 R \tag{1}$$

Where:

P_{LL}	the load loss (watts)
P_{SL}	the stray loss (watts)
I_{rms}	current (amperes)
R	Resistance (ohm)

“Stray losses” can be defined as the losses due to stray electromagnetic flux in the windings, core, core clamps, magnetic shields, enclosure or tank walls, …. The stray losses is on his turn subdivided into winding stray losses (P_{EC}) and stray losses in components other than the windings (P_{OSL}). The winding stray losses includes winding conductor strand eddy-current losses and losses due to circulating currents between strands or parallel winding circuits. All of this losses may be considered to constitute winding eddy-current losses (P_{EC}). The total load losses can then be stated as in following equation:

$$P_{LL} = P + P_{EC} + P_{OSL} \tag{2}$$

Where:

P_{LL}	the load loss (watts)
P	the I^2R loss portion of the load loss (watts)
P_{EC}	the winding eddy-current loss (watts)
P_{OSL}	the other stray loss (watts)

LOSSES DUE TO HARMONICS

Effect of harmonics on I²R losses

If the rms value of the current is increased due to harmonics, the I²R losses will also increase accordingly. In the IEEE C57.110 a simplified method of determining the effect of joule losses is included this being the fundamental form of joule losses:

$$P_{jrms} = I_{rms}^2 . R_{rms} \tag{3}$$

Where:

P_{jrms}	the I^2R losses portion of the load losses (watts)
I_{rms}	the rms current (amperes)
R	the winding resistance (ohm)

This expression does not fully take into account the increase due to harmonic current and is therefore a simplified method. The skin- and proximity effect are taken into account which will, in the presence of higher harmonics, play a role in the total resistance. In order to take these effects also into account following expression should be used and is valid if the THD(I) is less than 50% [12] which is usually the case at transformer level.

$$P_{jrms} = I_{rms}^2 . R_{dc} . \left(1 + y_s + y_p\right)_{50Hz} \tag{4}$$

Where:

P_{jrms}	the Joule losses portion of the load losses (watts)
I_{rms}	the rms current (amperes)
R_{dc}	the winding DC resistance (ohm)
ys	increase in resistance due to skin effect
yp	increase in resistance due to proximity effect

Harmonic effect on eddy current losses

Due to harmonic currents, winding eddy current losses are proportional to the square of the load current and approximately proportional to the square of the frequency. The proportionality to the square means that the major part of the winding losses and temperature increase is caused by eddy current losses.

$$P_{EC} = P_{EC-R} . \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_{rms}}\right)^2 . h^2 \tag{5}$$

Where

P_{EC}	the winding eddy-current losses (watts)
$P_{EC\text{-}R}$	the winding eddy-current losses under rated conditions (watts)
h	the harmonic order
h_{max}	the highest significant harmonic number
I_h	the rms current at harmonic “h” (amperes)
I_{rms}	the rms current under rated frequency and rated load conditions (amperes)

Harmonic effect on other stray losses

Next to the eddy current losses, other stray losses (P_{OSL}) in the core, clamps and structural parts will also increase. However, these losses will not increase at a rate proportional to the square of the frequency, as in the winding eddy losses. Studies have shown that the eddy-current losses in bus bars, connections, and structural parts increase by an exponent factor of 0,8 or less of the harmonic [1]. The effects of these losses will also vary depending on the type of transformer. The temperature rise in these non-winding parts will generally not be very critical for dry-type transformers [1]. However, these losses must be properly accounted for in liquid-filled transformers [1]. In dry type transformers the main effect will thus occur from the eddy current losses (P_{EC}). Further in this paper only the eddy current losses are taken into account since the focus in this paper is on dry type transformers.

DC component

It is generally known that a DC current in the transformer will increase the core losses and cause additionally heating. The effect off small DC currents (up to the rms magnitude of the transformer excitation current at rated voltage [1]) is off little importance in the increase of iron losses. However this can cause core saturation, resulting in leakage flux and flux distortion leading to inter-harmonics [13]. Since it is of little concern on the iron losses this is not further evaluated in this paper.

TRANSFORMER LOSSES IN PER-UNIT

In order to make calculations, predictions, etc. it is important that the calculations are performed on a per unit base. Equation (1) can be written in pu.

$$P_{\mathrm{LL-R}}\,(\mathrm{pu}) = 1 + P_{\mathrm{EC-R}}\,(\mathrm{pu}) + P_{\mathrm{OSL-R}}\,(\mathrm{pu}) \qquad (6)$$

Where:

$P_{\mathrm{LL-R}}(\mathrm{pu})$	the per-unit load losses under rated conditions
$P_{\mathrm{EC-R}}(\mathrm{pu})$	the per-unit winding eddy-current losses under rated conditions
$P_{\mathrm{OSL-R}}(\mathrm{pu})$	the per-unit other stray losses under rated conditions

So far the equations take into consideration the rated current. The rated current is the current on the nameplate of an electrical machine (this is in-fact full load current). For example for a 2500 kVA transformer the rated current is 3608A @ 400V and 65,61 @ 22 kV.

The above mentioned equations are considered taken at rated currents which seldom are encountered in the field. To be applicable for evaluation at loaded current following considerations are made [1]:

1. The eddy current losses are approximately proportional to the square of the frequency. This assumption will cause any subsequent equations to be accurate for small conductors and low harmonics, providing a conservative calculation, for a combination of larger conductors and higher harmonics.
2. The eddy losses are a function of the current in the conductors. Any equation for losses can then be expressed in terms of the rms load current *I*.
3. Superposition of eddy losses will apply, which will permit the direct addition of eddy losses due to the various harmonics.

The more general written equation taking into account the measured currents will be (where the second term is the UL K-factor)

$$P_{EC} = P_{EC-0}\,.\sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2 .\,h^2 \qquad (7)$$

Where

P_{EC}	the winding eddy-current losses (watts)
P_{EC-O}	the winding eddy-current losses at the measured current and the power frequency (watts)
h	the harmonic order
h_{max}	the highest significant harmonic number
I_h	the rms current at harmonic “h” (amperes)
I_{rms}	the rms load current (amperes)

HARMONIC LOSSES FACTOR AND K-FACTOR

Harmonic losses factor

It is convenient to define a single number that may be used to determine the capabilities of a transformer in supplying power to a load. F_{HL} is a proportionality factor applied to the winding eddy losses, which represents the effective rms heating as a result of the harmonic load current [1].

$$F_{HL} = \frac{P_{EC}}{P_{EC-0}} = \frac{\sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2 .\,h^2}{\sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2} \qquad (8)$$

where

F_{HL}	the harmonic losses factor for winding eddy currents
h	the harmonic order
h_{max}	the highest significant harmonic number
I_h	the rms current at harmonic “*h*” (amperes)
I	the rms load current (amperes)

The heating due to other stray losses is generally not a consideration for dry-type transformers [1]. These losses can have a substantial effect on liquid-filled transformers but this evaluation is not part of this publication.

K-factor

K-factor [14] is a weighting of the harmonic load currents according to their effects on transformer heating. The higher the K-factor, the greater the effects of harmonics on the heating will be. The K-factor can thus be used in order to assess the harmonic loads on transformer and to derate the transformer. The disadvantage of the K-factor is that it is not always measured which makes it a less suitable parameter for derating. The expression of the K-factor is

$$K = \frac{1}{I_R^2}\sum_{h=1}^{hmax}(i_h * h)^2 \qquad (9)$$

Where:

I_R	the rated current (ampere)
I_h	the rms current at harmonic h (ampere)
h	the harmonic order

Or if this expression is expressed in pu of the rated current:

$$K = \sum_{h=1}^{hmax}(i_h * h)^2 \qquad (10)$$

Where:

I_h	the rms current at harmonic h in pu of rated current (ampere)
h	the harmonic order

The US K-factor is based on the harmonic losses and is defined to the rated current but since measurement devices do not know the rated current, the calculated K-factor is de facto related to the measured current thus in reality the K-factor measured is equal to the harmonic losses factor.

$$K = F_{HL} = \frac{\sum_{h=1}^{hmax}(i_h * h)^2}{\sum_{h=1}^{hmax} {i_h}^2} \qquad (11)$$

Where:

F_{HL}	the harmonic losses factor for winding eddy currents
K	*US K-Factor*
h	the harmonic order
h_{max}	the highest significant harmonic number
I_h	the rms current at harmonic "*h*" (amperes)

DERATING OF EXISTING TRANSFORMERS

Derating factor

For dry type transformers a derating factor can be determined based on the K – factor (FHL-factor) [1].

$$\text{Derating factor: } \sqrt{\frac{1+P_{ec-r}}{1+\frac{\sum_{h=1}^{\infty} I_h^2 h^2}{\sum_{h=1}^{\infty} I_h^2}.P_{ec-r}}}\ [\text{pu}] \qquad (12)$$

$$\text{Derating factor: } \sqrt{\frac{1+P_{ec-r}}{1+K\ .P_{ec-r}}}\ [pu] \qquad (13)$$

Which can be applicable on both power and current to determine the maximum power and current.

Where:

P_{ec-r}	the maximum transformer per unit eddy current losses factor (typically between 0,05 and 0,15 pu for dry type transformers)
h	harmonic order
I_h	harmonic current (referred to the fundamental current) (amperes)

Derating of existing transformers based on THD(I)

Based on > 20 transformer measurements in the industry a calculation is made of the F_{HL}, K-factor and derating factor. The main difficulty in this evaluation is that the K-factor is a weighted value in function of the harmonic where the THD(I) is not. The THD is referred to the fundamental. For the calculations a eddy current factor is used of 0,1. The value of the eddy current factor is important since the difference between 0,1 and 0,15 will lead to > 5% difference in derating factor. Figure 1 gives the relation between the K-factor and the derating factor that should be applied based on K-factor calculation.

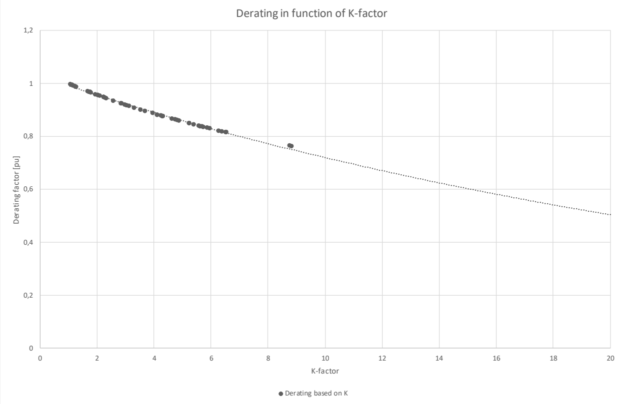

Figure 1: relation between the K-factor and derating factor for dry type transformers

These factors are then related to the measured THD(I). Based on the relation between the parameters, the derating factor due to harmonics under normal operation condition in function of the THD(I) can be determined. Figure 2 gives the relation between the THD(I) and derating factor.

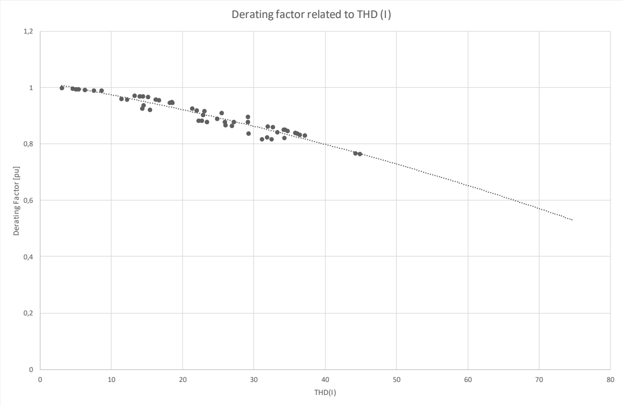

Figure 2: relation between the K-factor and derating factor for dry type transformers

When all these relations are established they can be combined in one graph of which the derating can be determined based on THD(I) and / or K-factor.

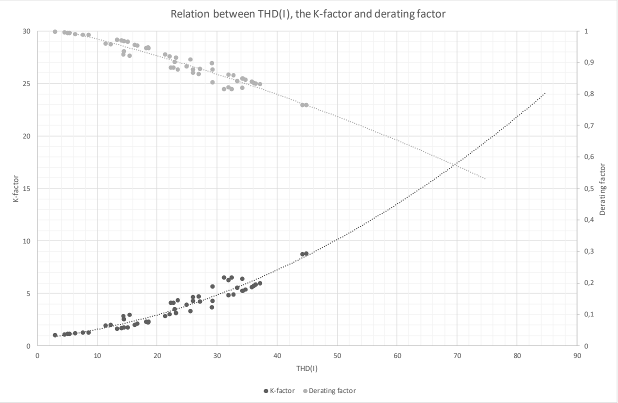

Figure 3: relation between the K-factor, THD(I) and derating factor for dry type transformers

Attention should be paid to the fact that this derating does not take into account environment temperatures higher than 40°C and does not take into account that dry type transformers should not be loaded more than 80%. If these conditions are present additional derating should be applied.

CONCLUSION

Harmonic current leads to additional load on transformers which are associated with additional losses. This means that, because of these harmonic currents the transformer can be overloaded even while the load current is below the nominal current. In order to prevent these overload conditions transformers need to be derated. The derating is generally based on the harmonic load factor or the K-factor which are both parameters that are not always available. In this paper the relation between these factors and a common available parameter (THD(I)) is evaluated and derating factors are determined. Next to this derating the relation with the US K-factor is made which allows to determine this factor based on THD(I) This evaluation is made based on real life measurements on multiple transformers with different load levels so representing a real industrial relevance.

When applying this with permanent monitoring systems one can perform predictive maintenance on the electrical installation in general and more specific the transformer preventing unexpected downtime of the installation.

FURTHER RESEARCH

At this point this paper only includes dry type transformers. Further research is performed to extend this principle to liquid filled transformers.

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