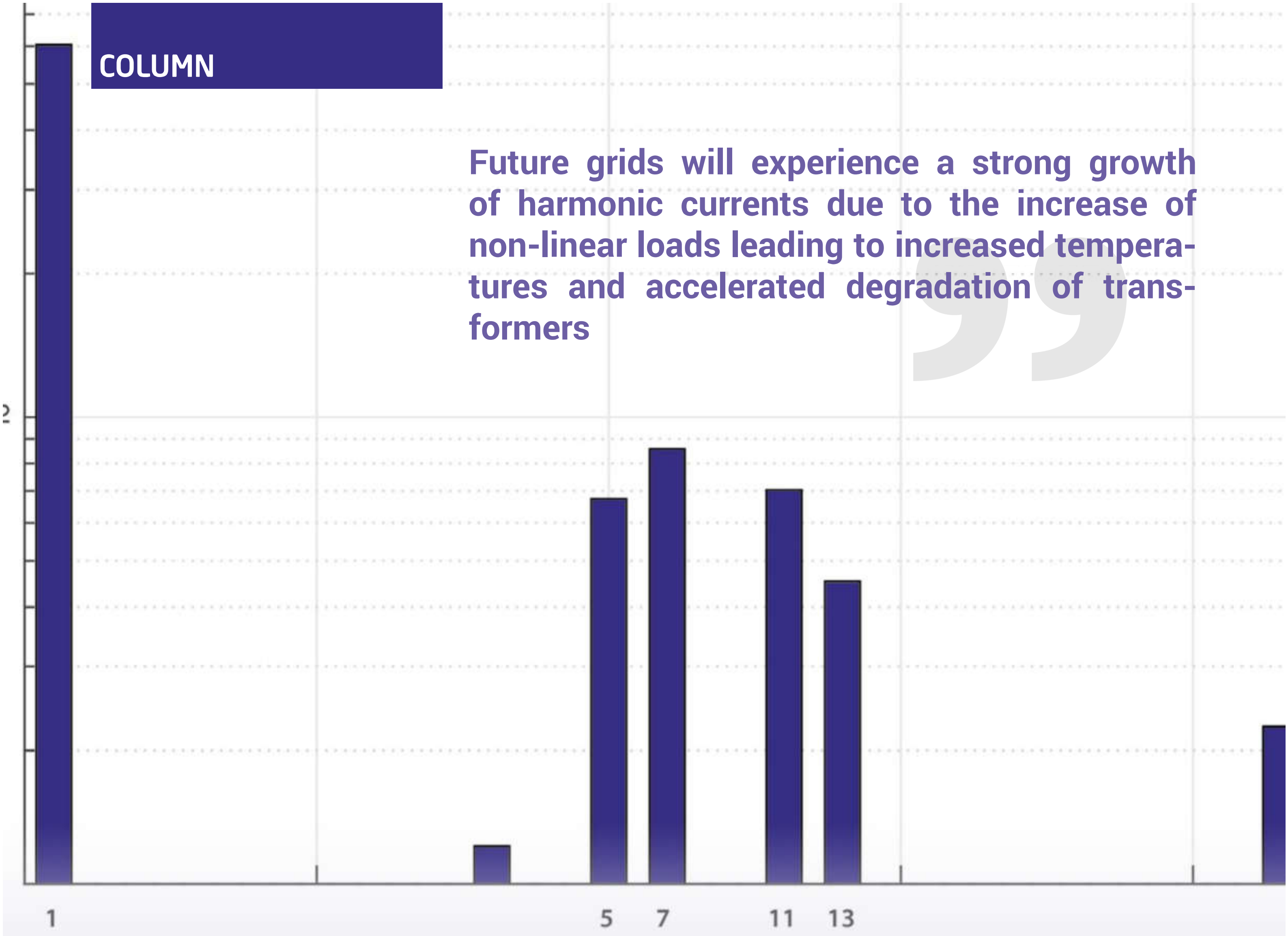
Future grids will experience a strong growth of harmonic currents due to the increase of non-linear loads leading to increased temperatures and accelerated degradation of transformers



Operation of transformers:

Impact of harmonic loading on transformer losses

ABSTRACT

Due to the increasing number of electronic devices with non-sinusoidal power supplies applied in today's grids, transformers are being subjected to enhanced internal heating. Also, additional heating of transformer coils is caused by current waveform distortions due to non-linear loads, which in turn induce additional harmonic components to the fundamental (power frequency) current. The additional heat production, together with the normal heat from the transformer under load, leads to accelerated insulation degradation and reduction of the transformer lifespan. This paper discusses possible mitigation solutions for harmonics on transformers, ranging from specification of the transformer to monitoring and operational measures.

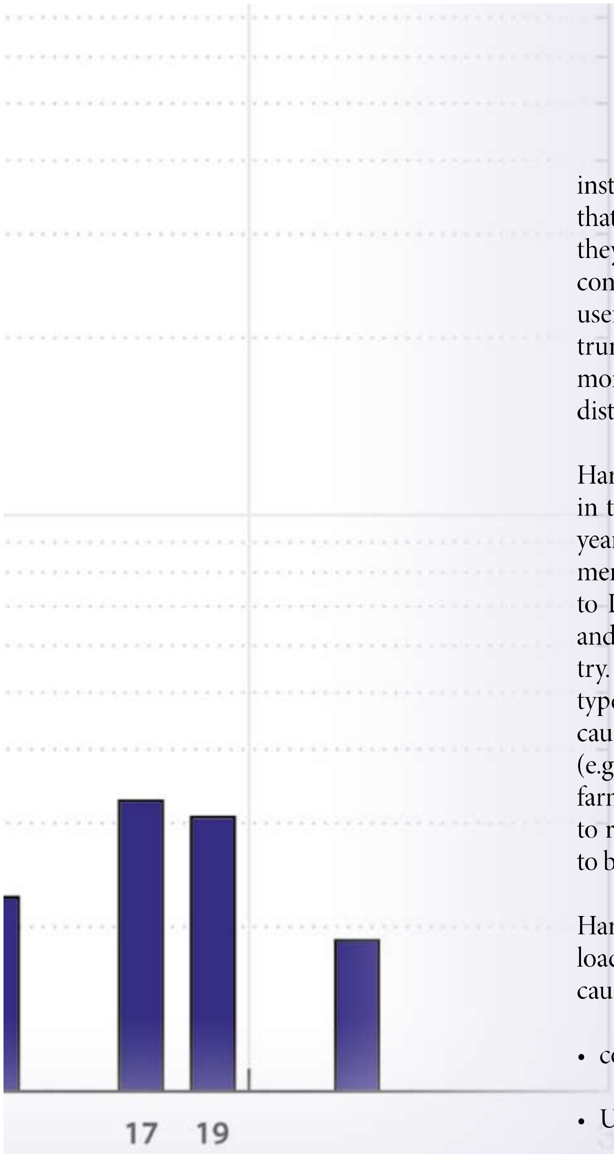
KEYWORDS

harmonic loading, additional heating, loss of transformer life

1. Introduction

Among various power quality problems, it is mainly the presence of harmonics in the network that interacts adversely with the network components and causes inconveniences to the network operators and consumers or producers connected to the grid. The operation of power electronic devices produces harmonic currents that lead to additional harmonic power flow and increase the network's total apparent power demand while decreasing the true power factor of the network. Large harmonic currents can also cause overloading and additional power losses in network components. It may lead to high thermal stresses and early aging of the transformer.

In the future electricity infrastructure, which is characterized by the usage of multiple power electronics devices, harmonics can become a problem for the network manager. Various costs due to harmonics include operational costs (e.g. increased power losses), aging costs (e.g. reduced lifetime cost) and costs due to equipment's maloperation. This paper presents the sources of harmonic loading, the impact of harmonics loading on the losses of a transformer, the additional rise of the transformer temperature and the



additional loss of life due to the elevated temperature. Also, mitigation of the impact of harmonic loading on the transformer is discussed.

2. Harmonics sources

In the last decade, there has been a growing concern about harmonic distortion and the effects of harmonics in power systems. In Europe, the transmission and distribution grids are designed to carry the fundamental 50 Hz frequency current. Harmonic frequencies are integer multiples of the fundamental supply frequency, i.e. for a fundamental of 50 Hz, the third harmonic would be 150 Hz and the fifth harmonic would be 250 Hz.

When talking about harmonics in power installations, it is the harmonic currents that cause most of the concern, because they are responsible for the detrimental consequences. Although it would be more useful to analyze the impact of the spectrum of the current harmonics, it is common to include only the total harmonic distortion (THD) figures.

Harmonic currents have been occurring in the electricity supply system for many years. Initially they were produced by the mercury arc rectifiers used to convert AC to DC current for railway electrification and for DC variable speed drives in industry. More recently, the range of equipment types and the number of equipment units causing harmonics have risen sharply (e.g. due to electrical vehicle charging, PV farms and windfarms), and will continue to rise, so a careful study of the impact is to be considered [2].

Harmonics are generated by non-linear loading. Typical non-linear loads are caused by [1]:

- computers
- UPS systems
- variable speed drives
- inverters
- magnetization current of transformers

Harmonic currents cause additional losses in the transformer, resulting in a higher temperature, and a reduction of the transformer lifetime. The additional losses depend on the harmonic spectrum of the load current, and on the transformer design.

The triple harmonics (3rd, 9th, 15th, etc.) are the major cause of heat production because the phase currents add in the neutral conductor. The magnitude of the harmonic current produced by the triples can cause the neutral conductor to overheat. Distribution transformers are configured with a delta-wye (Dy) connection to reduce the effects of harmonics. The triple harmonics are trapped and circulate in the delta primary of the transformer. Thus the harmonic content reflected back to the source (the medium-voltage network) is reduced. The circulating harmonics in the delta connected winding of the transformer create heat because of their higher frequencies.

Next to problems with the triple harmonics, a transformer feeding a converter or inverter can also experience problems with other harmonics. The typical harmonics (h) in a semiconductor bridge can be calculated by using the formula: $h=p\cdot k\pm1$. Here p is the pulse number of the bridge (6, 12) and k is an integer (1, 2 …, n).

For a 6 pulse bridge the typical harmonics are: 5, 7, 11, 13, 17, 19, 23, 25, etc. For a 12 pulse bridge the typical harmonics are: 11, 13, 23, 25, etc.

3. Transformer losses

Losses in transformers can be separated into three categories:

a. no-load losses

b. load losses

c. cooling losses (caused by fans or pumps for the cooling of the transformer)

In the following, we will discuss the no-load losses and the load losses in more detail.

3.1. No-load losses

Even without feeding a load, a transformer experiences losses. A magnetizing current is required to compensate for the losses due to energy dissipation while the alternating flux in the core is being maintained. This loss is known as the core loss, no-load loss or iron loss. The core loss is present whenever the transformer is energized, and represents a constant and therefore significant energy drain on any electrical system. In addition, the alternating fluxes also generate alternating forces in the iron core and thereby acoustic noise.

The core loss consists of two components: the first one, the hysteresis loss, is proportional to the frequency and depends on the area of the hysteresis loop in the

> **The growing impact of harmonics on transformer degradation calls for mitigating measures in the specification, design, operation and monitoring of transformers**

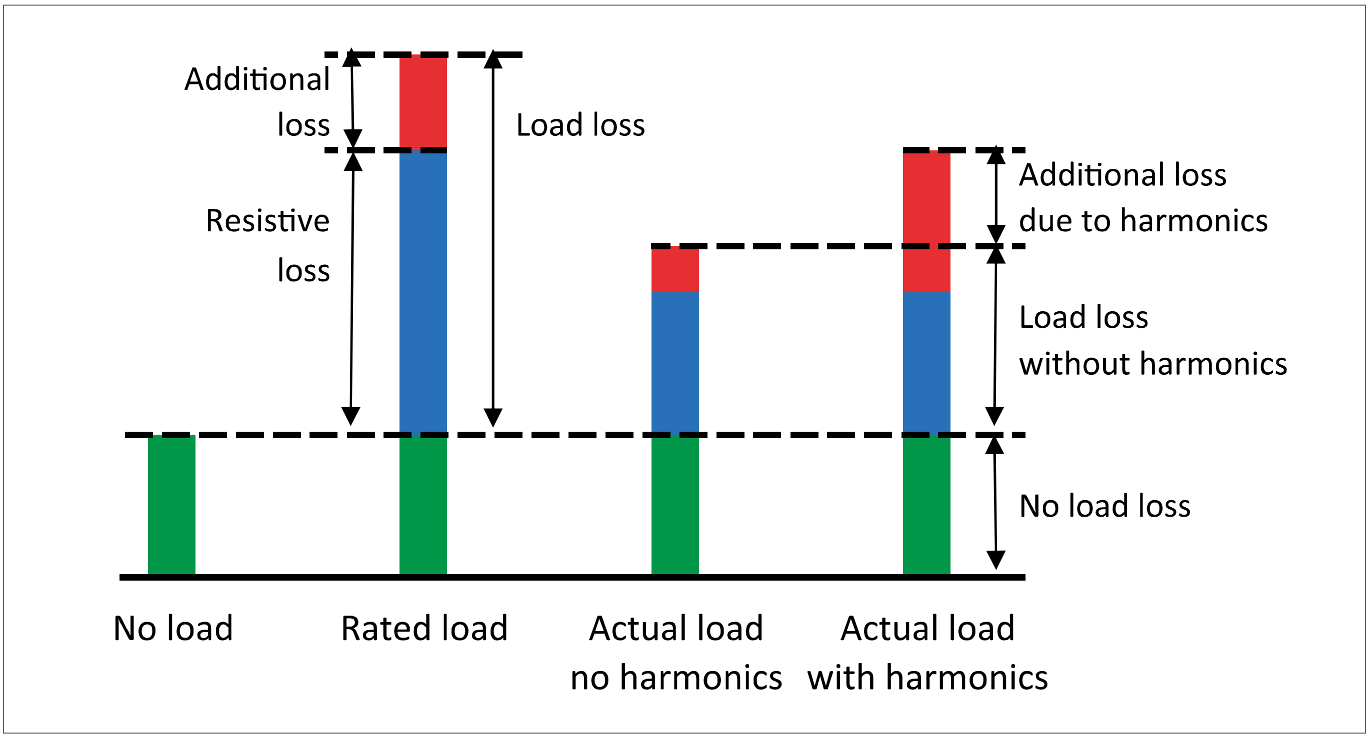


Figure 1. Extra losses due to harmonics

> **Current harmonics cause additional eddy current losses in the winding and conductive structural elements, while core losses are affected by harmonics only in relation to voltage distortion**

B-H diagram. It is therefore typical for the materials used, and depends on the peak flux density. The second component is the eddy current loss that is dependent on the square of the frequency, the square of the thickness of the material and the resistivity.

Minimizing hysteresis losses therefore implies application of a material having a minimum area of hysteresis loops, while minimizing eddy current loss is achieved by building a laminated core with thin layers of high resistivity.

3.2. Load losses

The load loss of a transformer is the part generated by the load current, and it varies with the square of the load current. It consists of three contributing causes:

- resistive loss within the winding conductors and leads
- eddy current loss in the winding conductors
- eddy current and stray losses in the tanks and structural steelwork

The latter two categories are also referred to as “extra losses”.

Resistive loss follows Ohm's law and can be decreased by reducing the number of winding turns, by increasing the cross-sectional area of the turn conductor, or by a combination of both.

Eddy currents arise from the fact that not all the flux produced by one winding is captured by the other winding. This leakage flux also adds to the short-circuit reactance or impedance of a transformer. The transformer impedance is a valuable tool for the system designer to determine system fault levels to meet economic limitations of the connected plant.

The path of eddy currents in winding conductors is complex. The magnitude and location of this leakage flux depends on the geometry and construction of the transformer. Leakage flux in the transformer windings results in radial and axial flux changes at any given point in space and any moment in time. These fluxes induce voltages which cause currents to flow perpendicular to the original fluxes. The magnitude of these currents can be reduced by increasing the resistance of the path through which they flow, and this can be effected by reducing the total cross-sectional area of the winding conductor, or by subdividing this conductor into a large number of strands insulated from one another (in the same way as laminating the core steel reduces eddy-current losses in the core). However, the former alternative increases the overall winding resistance and thereby the resistive losses. Conversely, if the overall conductor cross-section is increased in order to reduce resistive losses, it results in an increase of the eddy current losses. This can only be mitigated by a reduction in strand cross-section and an increase in the total number of strands. It is costly to wind a large number of conductors in parallel and therefore a manufacturer may wish to limit the total number of parallel strands. Also, an increased number of strands increases the amount of insulation material, thus

> **Advanced thermal modeling fine-tuned by measurement or augmented by incorporating a hotspot sensor may be used to estimate the effects of harmonic currents on the loss of lifetime**

yielding a less favorable winding-space factor. It is evident that in a transformer with a low reactance, winding eddy currents are less of a problem than in high reactance transformers.

At very high currents (e.g. >1000 A), fluxes generated at the main leads can give rise to eddy current losses in the adjacent tank structure.

Higher frequency components in the load current (harmonics) cause additional losses because harmonics do not fully penetrate in the conductor due to the skin effect. This causes the effective cross sectional area of the conductor to decrease, thereby increasing the resistance and the I^2R losses, which in turn heats up the conductors and anything connected to them.

Harmonic currents also increase the eddy current losses in transformers. In case of harmonics, the eddy current losses are of prime cause of concern because they increase approximately with the square of the frequency. The no-load losses are transformer core losses, which are affected by harmonics only in relation to voltage distortion, but not in relation to current distortion. Consequently, the increase in no-load losses due to harmonics is usually negligible. Load losses, on the other hand, are significantly affected by harmonic currents.

As described earlier, load losses consist primarily of resistive (or I^2R or ‘copper’) losses and extra (eddy current) losses. Due to harmonics, not only the eddy current losses but also the resistive losses increase. By definition, the loss increase due to the presence of harmonics is usually also designated as “extra losses”, Fig. 1.

4. Calculation of the hot spot rise

The insulation system of a transformer consists of paper and oil. Both suffer from (thermo-chemical) aging, but paper degradation is usually considered more critical because it is (virtually) irreversible. Any (unexpected) increase in the load results in a rise of the temperature and consequently affects the thermal decomposition of the paper. Due to the fact that the temperature distribution in a winding is not uniform, the hottest section of the transformer (the so-called “hotspot”) will subsequently be suffering the most.

The hotspot temperature cannot be measured if no hotspot sensor is built in beforehand, and is usually estimated from a thermal model, the loading guide (as described in IEC 60076-7 [3] or IEEE C57.91-2011 [4]). The estimation is based on the thermal diagram shown in Figure 2.

The model calculates the relevant oil temperatures and the hotspot temperature as a function of load (current) and ambient temperature using a number of transformer characteristics. These characteristics may be derived from the transformer heat run test or, if not available, default values for different transformer designs may be taken from the standard.

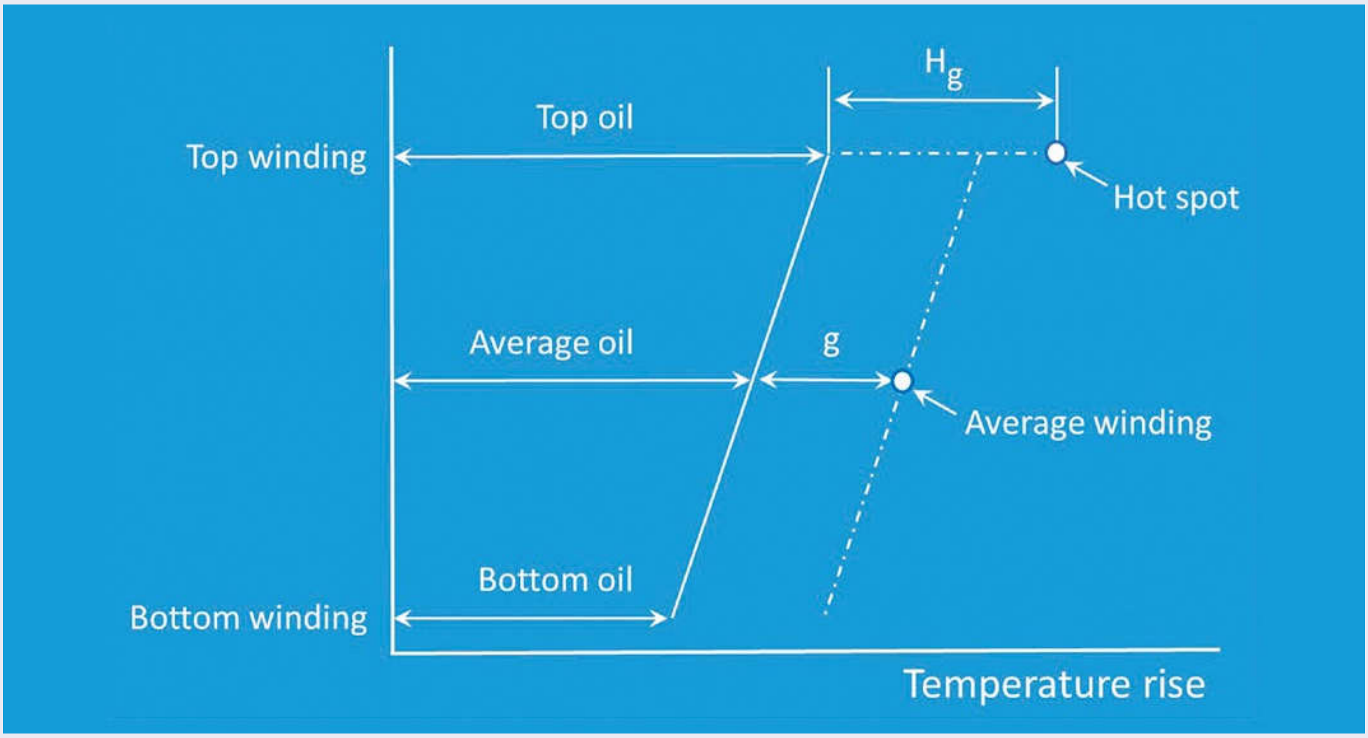


Figure 2. Loading guide thermal diagram

Table 1. K-factor for different types of loads

K factor	Load type
1	Resistance heating, motors, distribution transformers
4	Welders, induction heaters, fluorescent lighting
13	Telecommunication equipment
20	Mainframe computers, variable speed drives, desktop computers

For new-build transformers, harmonic loading should be incorporated in the specification and design of transformers

In case harmonic currents are present, their effect on the hotspot temperature is accounted for by adjusting the load current, thus yielding a hotspot temperature including the effect of harmonics.

5. Thermal aging of transformers

The actual lifetime of a transformer depends on a number of parameters and possible events such as over-voltages, short-circuit currents and emergency overloading. In this contribution we primarily focus on the additional aging due to harmonic currents as compared to power frequency currents. The presence of harmonics introduces an additional thermal input, thereby causing the hotspot temperature to rise above the power frequency value.

In the loading guide thermal model, the hotspot temperature is used to determine the aging rate of the insulating paper and, consecutively, the loss-of-life of the transformer.

As a matter of fact, the loading guide thermal model does not estimate the actual lifetime but the relative loss-of-life; in other words: the loss-of-life as compared to a reference. There are two references, one for Kraft paper and one for thermally upgraded paper:

1. The reference for Kraft paper assumes an indicative lifetime of about 30 years at a continuous hotspot temperature of 98 °C, and is stipulated by IEC.
2. The reference for thermally upgraded paper assumes an indicative lifetime of about 20 years at a continuous hotspot temperature of 110 °C, and is stipulated by IEEE.

Recent insights indicate that 110 °C is a realistic value for all kinds of paper under optimum conditions, whereas 98 °C is considered a more practical and realistic temperature considering that conditions are never optimal due to the presence of water and oxygen. It should be noted that there is agreement to the model as such, but there is still a debate about the indicative lifetimes.

Since harmonics introduce additional losses and therefore additional heat dissipation in transformers, harmonics may have a large influence on the lifetime of the transformer, resulting in an increased loss of life, or lifetime consumption. With the thermal model it is possible to estimate the additional loss of lifetime due to harmonics.

The consequence of an increased hotspot temperature in the winding, caused by harmonics and resulting in an increased loss of life poses a risk of premature failure. This risk may either be of an immediate short-term nature or may only be evident after cumulative deterioration of the transformer over many years.

6. Mitigation

To reduce the effect of harmonic currents on transformer degradation and lifetime several mitigation measures can be taken. During the specification or selecting of the transformer, harmonic loading must be considered, and transformers may be designed so that they can manage the additional heat production. For transformers loaded with harmonics, a factor K representing the increase in eddy current loss can be used. In the US practice, the K-factor is used to account for the eddy current losses when driving non-linear and linear loads:

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

The presence of harmonics increases the K-factor indicating that the transformer must be designed to sustain additional heating. Table 1 gives indicative values for different types of loads.

Next to purchasing a transformer with an adequate K-factor, it is also possible to specify the harmonics spectrum of the current at the rated load and demand from the manufacturer that the design is able to handle that.

During the design of the transformer, it is possible to calculate the influence of harmonics by calculating the additional losses caused by harmonic transformer loading. As described earlier, the load losses in transformers are subdivided into DC (I^2R) losses, eddy current losses in windings and connections, and stray losses in conductive structural parts of the transformer.

The design can contribute to the reduction of additional transformer losses due to harmonics e.g. by the choice of material used in the transformer (copper vs. aluminum windings, iron construction vs. non-ferro metal or stainless steel construction). For large transformers, often the wires in the windings are separated into small sections in parallel. The smaller the wire, the lower the extra losses will be. To reduce the effect of transformer aging, one may use thermally upgraded paper and/or reduce the temperature rise within the transformer. A particular point of interest is field control near the hotspot in order to avoid multi-factor stress.

When harmonics are expected during operation, the risk may be monitored by incorporating a hotspot sensor in the design, in order to monitor the hotspot temperature and predict the additional loss-of-life. A special point of attention in that case is to ensure that the sensor itself does not introduce field non-uniformities. If a hotspot sensor is used, it is also possible to use that information for a more accurate thermal model of the transformer.

Normally losses are measured at the power frequency (50 Hz). To find out whether harmonics have a significant impact, it is recommended to measure transformer losses both at DC, at the standard sinusoidal power frequency current and at a frequency higher than power frequency. By combining these three measurements, it is possible to establish the eddy current losses in the windings and in the structural parts. This information can be used to fine-tune the thermal model of the transformer and calculate the hotspot temperature during operation. Fine-tuning the model does however require a heat run test to establish the proper transformer characteristics for such a fine-tuned thermal model.

For transformers already in operation it is, of course, not possible to adjust the design or perform additional tests. In case harmonics are likely to occur, it is recommended to monitor the (harmonic) loading and adjust loading limits accordingly.

Further monitoring may be used to observe whether heat induced degradation effects are occurring at higher rates than expected. Dissolved gas analysis (DGA) may be applied to track thermal defects, and furfural analysis may provide evidence for accelerated paper aging.

> **For transformers in service, the impact of harmonics may be mitigated by a combination of load control and transformer monitoring**

Concluding remarks

In the future grid, transformers will increasingly be subjected to harmonic loading (e.g. due to the growth of PV- and windfarms, power electronics, power storage systems, and loading facilities for electrical vehicles). If no preventive action is taken, this will lead to enhanced degradation, a shorter life time expectation and, eventually, an increased failure rate.

For new-build transformers, harmonic loading should be increasingly incorporated in the specification and design of transformers. In the manufacturing process more focus may be needed on controlling the hotspot temperature, with the aid of advanced thermal modeling techniques. Also the use of built-in hotspot sensors may be considered, but care must be taken to avoid detrimental effects.

For transformers in service, advanced thermal modeling may be used to estimate the effects of harmonic degradation, and the impact of harmonics may be mitigated by a combination of load control (to prevent overheating), and on transformer monitoring (to timely detect temperature defects and enhanced thermo-chemical aging).

Bibliography

[1] W.T.J. Hulshorst, J.F. Groeman, *Energy saving in industrial distribution transformers*, KEMA (now DNV GL), www.leonardo-energy.org, 2002

[2] R Godina, E. M. G. Rodrigues, J. C. O. Matias, J. P. S. Catalão, *Effect of Loads and Other Key Factors on Oil-Transformer Ageing: Sustainability Benefits and Challenges*, http://www.mdpi.com, Volume 8, Issue 10, 2015

[3] IEC standard 60076, Power Transformers, Part 7, *Loading guide for oil-immersed power transformers*, 2005

[4] IEEE standard C57.91-2011, *IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators*, 2011

Acknowledgement

The author gratefully acknowledges the assistance of Walter Hulshorst B.Sc. of DNV GL. He has delivered valuable contributions to the field of transformer technology and the impact of harmonics.

Author

Dr. Jos Wetzer from the Netherlands is senior principal consultant „Asset Management“ with DNV GL Energy, stationed in Arnhem, The Netherlands. He obtained a M.Sc. degree in Electrical Engineering (cum laude) and a Ph.D. degree in Technical Sciences, both from the Eindhoven University of Technology. After obtaining his Ph.D. degree he worked as an associate professor at the Eindhoven University of Technology for 14 years. His activities included research, education and consultancy in the field of High-Voltage Engineering and EMC. In 1998 he joined KEMA (now DNV GL) as a senior consultant, in the field of condition assessment, asset management and EMC. From 2001 to 2006 he held a management position, and from 2006 on he has been active as a (senior) principal consultant, and has served numerous clients in Europe, North America, the Middle East and Asia Pacific on asset management issues. From 2004 to 2007 he also held a position as a part-time professor at the Eindhoven University of Technology in the Netherlands, engaged in Asset Management of Electrical Infrastructures. His expertise includes asset and maintenance management, condition assessment and diagnostics, dielectrics and electrical insulation, electromagnetic fields and EMC. He has published over 150 scientific and professional publications.