ABSTRACT
By identifying the characteristic equation of the specific no-load losses of each iron sheet based on the core configuration, it is possible to reach a high level of accuracy in detecting no-load losses over a wide range of flux density. The method is applicable and frequently used for reference as well as for new sheet types that appear on the market. The results presented in this paper are based on one year experience, showing that the total weight and volume of transformers have clearly been reduced.

KEYWORDS
transformers, core parameter, core corners, Reference Sheet Type (RST), New Sheet Type (NST), building factor
No-load losses are a very important aspect of the grid operation quality, especially in sectors where the power flow is not continuous. Recent no-load loss research attempts to find the best separation between hysteresis- and eddy current losses have not been sufficient because they fail to consider the building factor, which differs for materials and manufacturing processes.

In this article, a new approach is introduced to determine the total no-load losses in core-form power transformers to identify the specific no-load losses $P_{\text{spc}}$ (W/kg) during transformer operation and test. The separation in this approach is based on the geometry of the core (separation between the losses in linear and non-linear regions of the core). The work is based on 50 Hz operation; however, converting the result to any other frequency is simply done by the inverse proportional factor referenced to 50 Hz. The method is using the history of each iron sheet type during transformer no-load test (reference sheet starting from 20 different designs) to define the characteristic equation (W/kg vs. Tesla). For a new iron sheet (new in market), a 3D-interpolant surface is constructed using sheet manufacture data and reference sheet information to detect the expected characteristic equation for the particular new sheet without a single measurement.

The core construction mainly depends on technical specifications, manufacturing limitations, and transport considerations. It is economical to have windings of all three phases in one core frame. A three-phase transformer is cheaper (by about 20 to 25%) than three single-phase transformers connected in a bank. But from the spare unit consideration, users find it more economical to buy four single-phase transformers as compared to two three-phase transformers. Also, if the three-phase rating is too large to be manufactured in transformer works (weights and dimensions exceeding the manufacturing capability) and transported, there is no option but to manufacture and supply single-phase units. In Figure 1, various types of core construction are shown.
The convenient range of operating flux density lies typically between 1.5 and 1.7 T. Most of iron sheet manufacturers specify the guaranteed specific no-load losses [W/kg] according to one of these two rated flux densities for certain grade. For each iron sheet type there is a standard identification card, which normally includes the specific no-load losses at a certain flux density and the sheet thickness in mm. Since a combination of different sheet types in one core is possible, the only condition for that is to have the same sheet thickness or, in another words, the same grade. For example, M080-23P has specific no-load losses of 0.8 W/kg where M075-23P has 0.75 W/kg. However, both of them have the same sheet thickness of 0.23 mm or the same grade of 23. In Figure 2a one can see that this region lies between the linear region and the saturation region, which means that any slight change in flux density will cause a big change in the material properties. These changes can be clearly seen in Figure 2b, illustrated by the sharp and quick change in the resulting specific no-load losses of the material. The situation becomes more complicated when the construction of different core types is concerned as another component is added to hysteresis losses, which is eddy current losses.

This leads to consideration of the kind of losses separation based on the core configuration rather than the type of losses themselves. Dealing with the losses separately in direct rolling and cross rolling direction offers solution to this problem.

2.1 Stacked cores in core-form transformers

In larger power transformers, stacked cores are more common. However, this type has gaps at the corners where the magnetic flux changes direction, resulting in poorer magnetic characteristics locally [5]. While the iron sheet manufacturers have constantly been trying to improve the magnetic properties of their products, for a long time there has been research to improve the flux path quality in the transition area between the limb and the yoke (core corners marked with red dotted squares in Figure 3).

The turning of the flux, which is necessary at the top and bottom corners of the core limbs, is causing noticeable increase of the total core losses. This effect is noticeable in that a tall, slim core will have a lower loss than a short, squat core of the same weight and flux density since the former arrangement requires less deviation of the flux. The relationship between the core loss of a fully assembled core and the product of core weight multiplied by specific loss of the “raw sheets” is known as the building factor [6]. In order to limit the extent to which the flux path cuts across the grain direction at the intersection of limbs and yokes, corners of laminations are cut on a 45° mitre. The core sheets at these mitred corners must be overlapped so that the flux can transfer to the adjacent sheet rather than cross the air gap which is directly in its path (see Fig. 3). The corners volumes and weights are depicted by the marked dotted squares in Figure 3.

In order to reduce no-load losses steel manufacturers have been trying to improve the magnetic properties of materials, while transformer manufacturers have been trying to improve the flux path quality in the transition area between the limb and the yoke.
The increase of the loss costs for the grid and the need for low no-load loss transformers have made any empirical method no longer sufficient to satisfy the current market demands.

3. New approach

In order to determine the losses separately in the corners, a characteristic equation of no-load losses in the corners ($P_{Espc}$) needs to be specified, and another one for the rest of the core ($P_{Rspc}$). In other words, the core parameters of the specific no-load losses must be defined separately for the corners and the rest of the core (limb & yoke). To reach this target, it is required to have a starting point, which is the information obtained from the history of built and tested transformers. The available information includes:

- Core material types
- Core corners and core total weights
- No-load loss measurements

3.1 Mathematical interpretation

If the specific no-load losses $P_{Espc}$ and $P_{Rspc}$ are known at the desired flux density $B$ in Tesla, the total no-load losses of the core will be mathematically described as in (1):

$$P_0 = G_E + P_{Espc} + (G_T - G_E) \cdot P_{Rspc}$$  (1)

Where:

- $P_0$ is the total no-load losses of the core in W,
- $G_E$ is the corners weight in kg,
- $G_T$ is the total core weight in kg.

For the same core design of two transformers with different core material, it is noticed that there is a difference in measured $P_0$. This difference could cause that the customer will accept one transformer and refuse the other because of the operating restrictions or guaranteed values. This means that each iron core material should have its own $P_{Espc}$ and $P_{Rspc}$. 
3.2 Core parameters

There is no rule to define the form of the characteristic equations of the core. The physical base shown in (2) reads as follows:

\[ P_{\text{Espc}} = f_E(E_{1..N}, B) \quad P_{\text{Rspc}} = f_R(R_{1..N}, B) \]  

Where:
- \( f_E() \) is the characteristic equation of the core corners,
- \( f_R() \) is the characteristic equation of the core limb and yoke,
- \( E_{1..N} \) represents the corners core parameters,
- \( R_{1..N} \) represents the limb and yoke core parameters,
- \( B \) is the flux density in Tesla.

More important than the form of \( P_{\text{Espc}} \) and \( P_{\text{Rspc}} \) versus \( B \) are the physical constrains, which limit the region where the core parameters are investigated. One of these constrains refers to a certain flux density \( B_c \):

\[ f_E(E_{1..N}, B_c) > f_R(R_{1..N}, B_c) \]  

According to equation (3), at any operating flux density of the transformer, the specific no-load losses in the corners are higher than in the rest of the core.

3.3 Procedure

This approach consists of two parts. The first one deals with Reference Sheet Type, which has been in use for a long time and has a long enough history of no-load loss measurements. The second one deals with Pre-New Sheet Type on the market, where the only information available is the manufacturer data concerning the specific no-load loss at a certain flux density (for example: 0.81 W/kg at 1.5 T).

a. Reference Sheet Type (RST)

The history of no-load loss measurements forms the basis for the separation between \( P_{\text{Espc}} \) and \( P_{\text{Rspc}} \) through using the corners and rest weights data, as well as the measurements of no-load losses, as input into optimisation algorithm to detect the core parameter as shown in Figure 4. This procedure is executed continuously until an acceptable tolerance between the estimated and measured no-load losses is reached. By reaching this tolerance, the desired core parameter is registered for the core material under investigation. Figure 4 illustrates the flow chart of determining the core parameter for Reference Sheet Type (RST).

Let us consider a case of a transformer with the following data:
- 50 MVA, 110 kV
- Core total weight 26.7 tons
- Core corner weight 6.3 tons
- Operating flux density 1.5 T

The customer guarantee value for no-load losses was 18.75 kW. The core was built according to one of the reference sheets having the grade 27. The traditional calculation based on the manufacturer data and experience yielded 18.69 kW, which did not allow any further chance to optimise the core in order to avoid exceeding the limits set by the guarantee. However, the measurement showed that the sheet quality was better than estimated, yielding a value of 18.13 kW (-3% of the estimation).

Using the new approach, which deals with the core corner separately from the rest of the core, a more accurate value of 18.22 kW was obtained, which means that there

"The approach taken in this paper is to define the characteristic equation of the core material based on the core configuration in two areas: the corners and the rest of core.

The new approach provides more accurate no-load loss values, thus allowing a further opportunity for optimisation of core dimensions and weight, and material and cost savings in order to avoid exceeding the guarantee limits and penalty consequences."
was still an opportunity for optimisation of core dimensions and weight, as well as for the material and cost saving before reaching the guarantee value (the difference between the new estimation and the limit was about 3%).

b. Pre-New Sheet Type (NST)

Iron sheet manufacturers conduct constant research to improve the quality of their material. This is usually done during the material handling by reducing the specific no-load losses of the material. As a result, transformer manufacturers continuously receive new offers for materials with an improved no-load loss characteristics. In these cases, there is no measurement history available. However, the acquired knowledge of RST could be used to estimate the behaviour of the core built on the basis of NST. By determining \( P_{spc} \) for RST at a certain flux density (for example, 1.5 T) and with the given sheet thickness by the manufacturer, a three-dimensional interpolant surface can be constructed to estimate the core parameters for NST even without any measurement history, as shown in Figure 5.

In the second part of this paper, the results and practical experience with the application of the new approach will be presented.

Bibliography


Authors

Ahmed Gamil completed a M.Sc. in electrical power engineering in 2004 and has worked in transformer protection and monitoring systems as well as software development through different positions at AREVA, Siemens and German Research Association (DFG). His work involved simulation of network short circuit and transformer analysis under lightning impulse voltage as well as programming of offline/online monitoring systems. Today he works for SGB Regensburg, Germany, in R&D sector and leads different development projects in power transformer design. He is also an active participant in international conferences such as CIGRE and CIEME.

Franz Schatzl graduated from the University of Vienna in the field of electrical power engineering in 1998. In 1999 he joined Siemens Transformers Austria (STA) AG as an electrical design engineer. He was responsible for special applications such as low noise transformers and the use of alternative liquids. From 2007 to 2009 he oversaw the electrical design department. Since 2010 he has been Technical and R&D Manager at SGB Regensburg in Germany in the power transformer division. Franz is also member of IEC and CIGRE working groups and is author of several papers on different power transformer subjects.

www.transformers-magazine.com