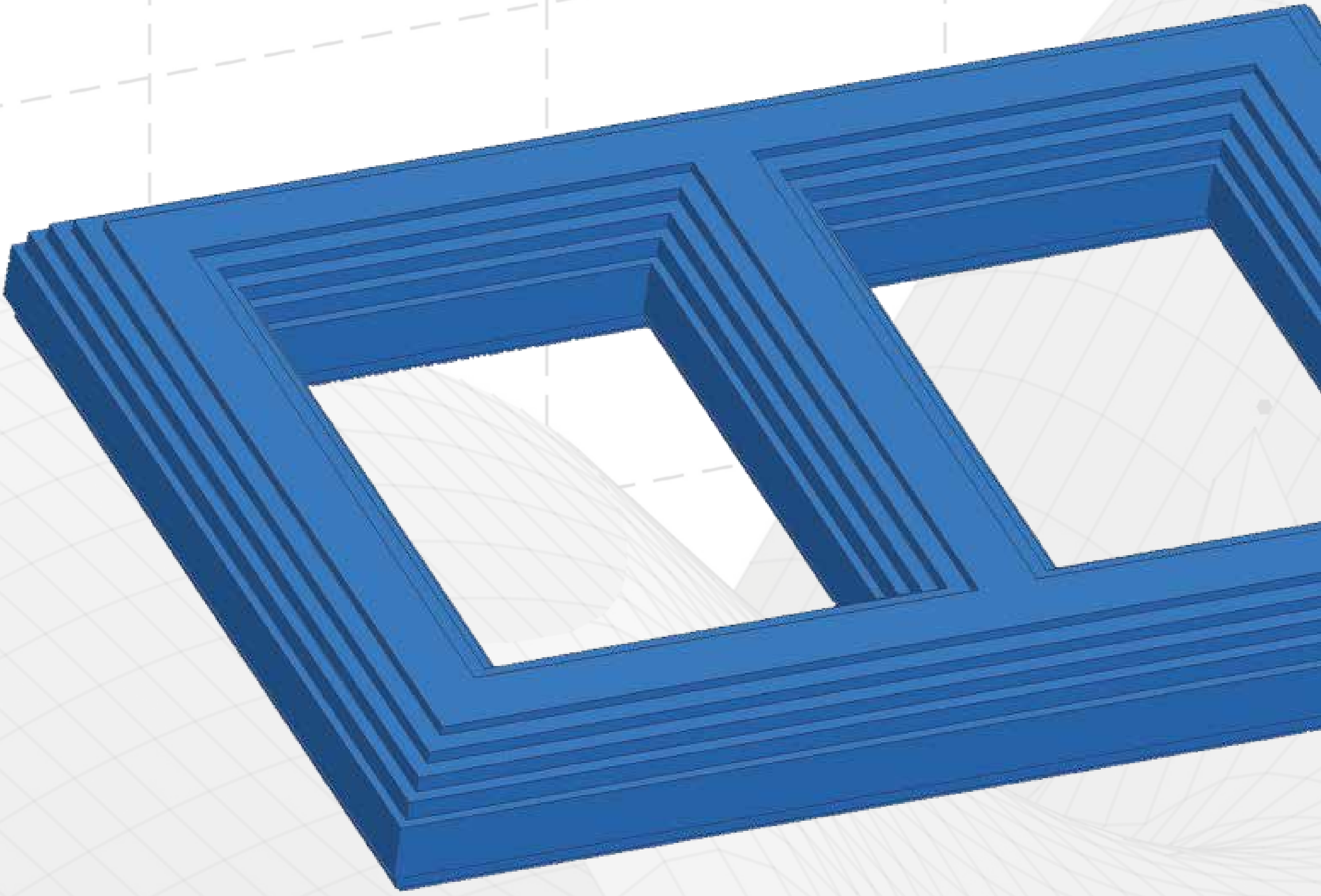

Determining transformer core losses

based on investigation of core material behaviour during test and operation – mathematical interpretation

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

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1. Introduction

No-load losses are a very important aspect of the grid operation quality, especially in sectors where the power flow is not continuous. The determination of no-load losses in power transformers is dependent mostly on its core, relying either on some initial data from the sheet manufacturers, on reference measurements of standard sheet types conducted with consideration of correction factors, or on simulation tools depending on the two previous information sources, which cannot be used for daily design.

Most of the recent research work has attempted to find the best separation in no-load losses between hysteresis losses and eddy current losses [1-3]. However, this interpretation is not sufficient for the manufacture of transformer cores because it fails 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_{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.

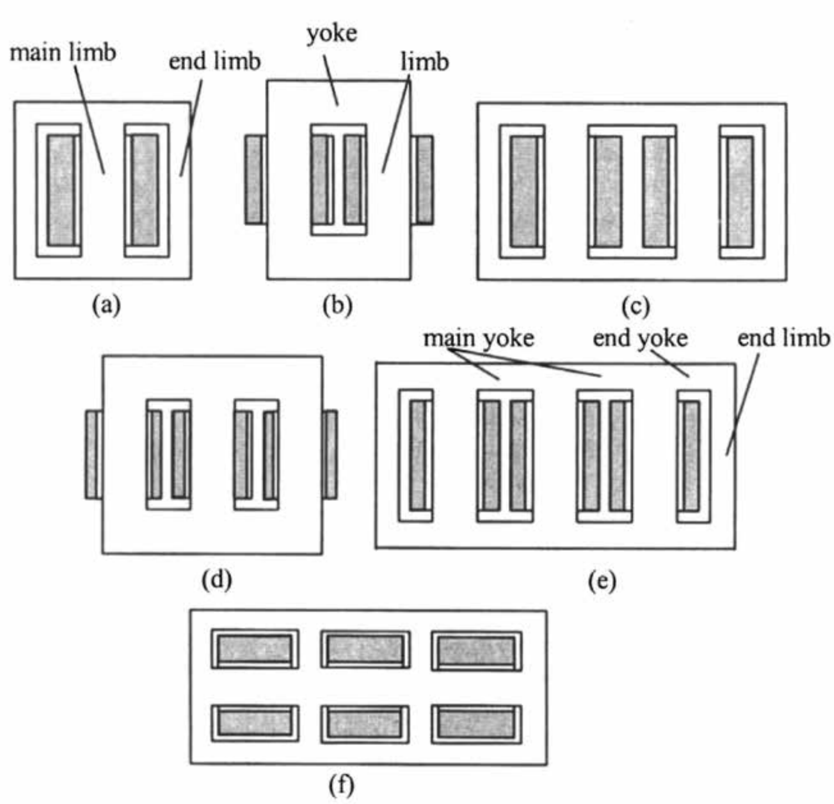
2. Basics

The magnetic circuit is one of the most important active parts of a transformer. It consists of laminated iron core and carries flux linked to windings. Energy is transferred from one electrical circuit to another through the magnetic field carried by the core. The iron core provides a low reluctance path to the magnetic flux thereby reducing magnetising current. Most of the flux is contained in the core reducing most of the stray losses in structural parts. Due to on-going research and development efforts by steel and transformer manufacturers, core materials with improved characteristics are being developed and applied with better core building technologies. In the early days of transformer manufacturing, inferior grades of laminated steel (as per today's standards) were used with inherent high losses and magnetizing volt-amperes. Later on, it was found that the addition of silicon content of about 4 to 5% significantly improves the performance characteristics due to a marked reduction in eddy losses (on account of the increase in material resistivity) and increase in permeability [4].

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.

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

> **A three-phase transformer is cheaper (by about 20 to 25 %) than three single-phase transformers connected in a bank**



(a) Single-phase three-limb core
(b) Single-phase two-limb core (very large rating)
(c) Single-phase four-limb core (reduced height for transportation)
(d) Three-phase three-limb core
(e) Three-phase five-limb core (high rating, reduced height for transportation)
(f) Three-phase shell-type core

Figure 1. Various types of core

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 sheet 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**

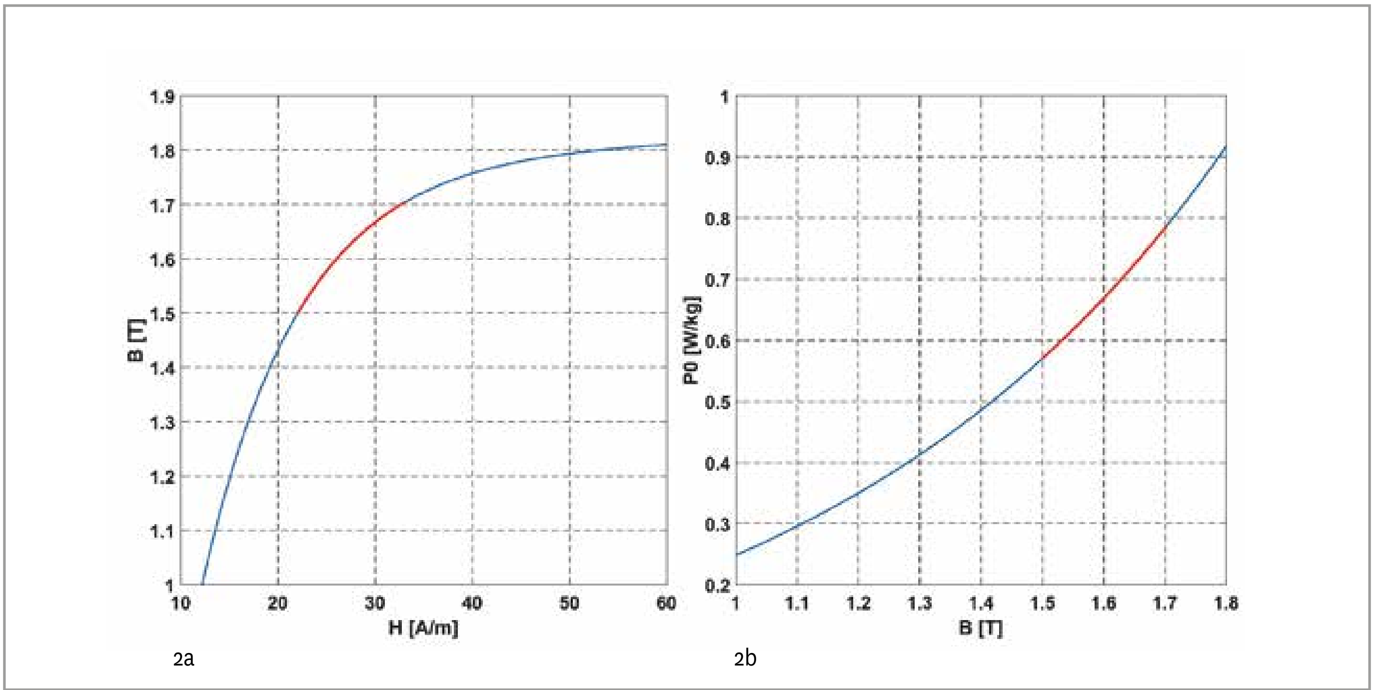


Figure 2. (a) Example of hysteresis curve (*B-H* curve); (b) The corresponding specific no-load loss curve against flux density (red coloured region for flux density between 1.5 and 1.7 T)

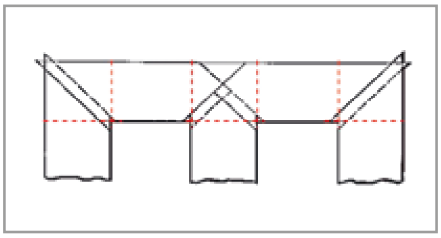


Figure 3. 45° mitre overlapped construction

" 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

Figure 3 illustrates the volume of each corner, based on which (±45° from mitre) the total weight of the corners is calculated according to a given iron density.

2.2 Definition of problem

Most of the literature discusses determining of building factor and minimizing it close to unity to be able to use the iron sheet manufacture data in terms of P_{spc} (W/kg) [7]. However, there is no evidence that the building factor is equal for all core manufacturers, not even for two different core designs using the same material. Besides, most of the core material manufacturers issue single guarantee for their product, e.g. for the specific loss value P_{spc} by a certain flux density B (Tesla) "normally at 1.7 T or 1.5 T". In the past, most transformer manufacturers would estimate P_{spc} over a so-called standard core material. This was based on a constant building and material correction factor. 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.

The problem 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.

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):

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

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}.

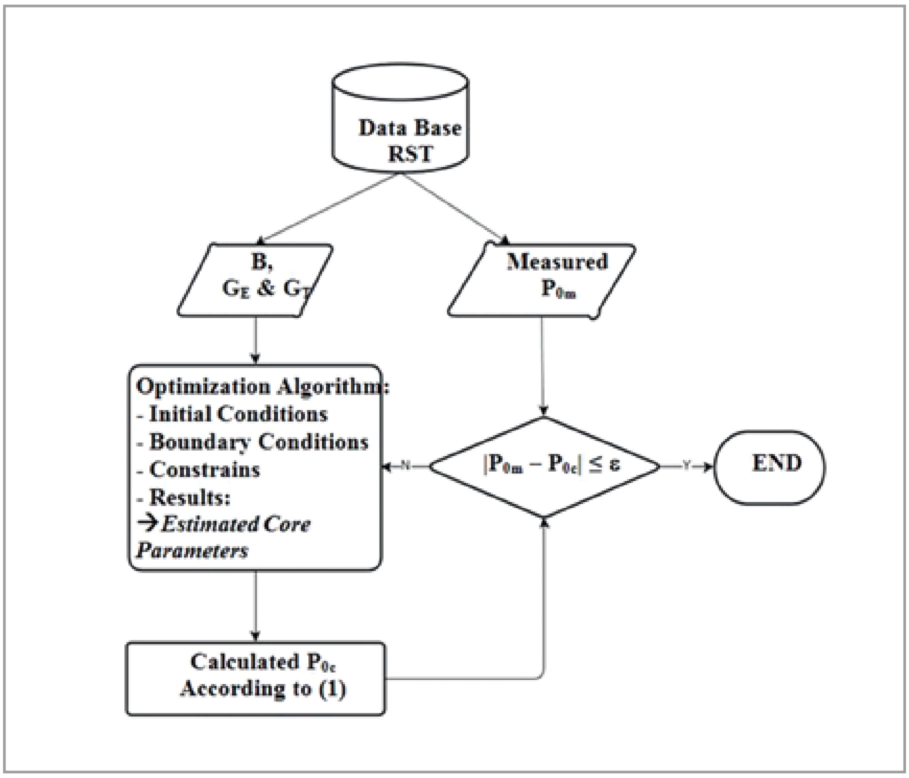


Figure 4. Flow chart for determining core parameters of Reference Sheet Type

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:

$$P_{Espc} = f_E\,(E_{1..N}, B) \cdot P_{Rspc} = f_R\,(R_{1..N}, B) \qquad (2)$$

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_{Espc} and P_{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:

$$f_E\,(E_{1..N}, B_c) > f_R\,(R_{1..N}, B_c) \qquad (3)$$

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 is 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_{Espc} and P_{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.

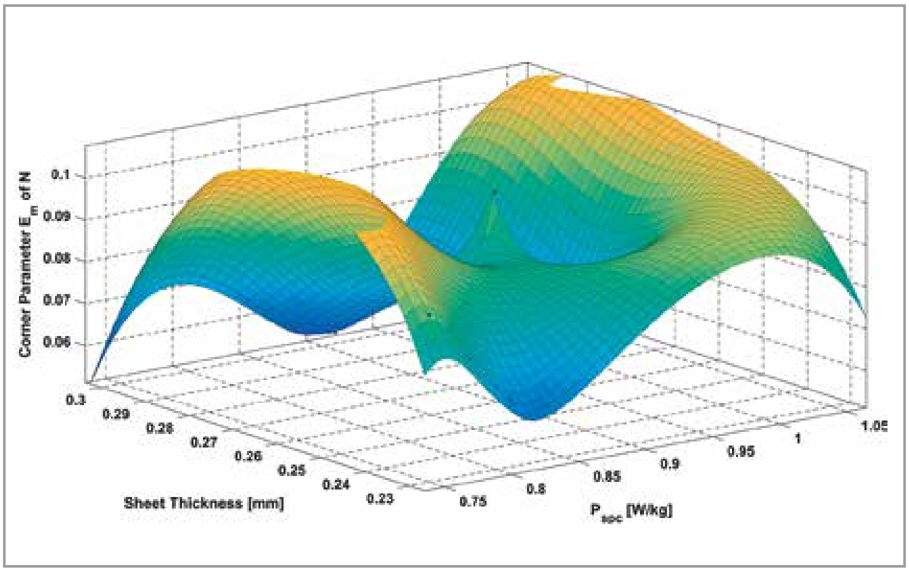


Figure 5. 3D- surface modelling to estimate core (corner) parameters of New Sheet Type

"Determining P_{spc} for RST at a certain flux density and with the given sheet thickness, a three-dimensional interpolant surface can be constructed to estimate the core parameters for NST even without any measurement history

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

Bibliography

[1] J.C. Olivares-Galván and R. Escarela-Pérez, *Separation of No-Load Losses for Distribution Transformers Using Experimental Methods*, 7th Mediterranean Conference on Power Generation, Nov. 2010.

[2] Y. Chen and P. Pillay, *An Improved Formula for Lamination Core Losses Calculations*, 2002 IEEE IAS Annual Meeting, pp 759-766.

[3] F. Zhalefar and M. Sanaye-Pasand, *International Colloquium Transformer Research and Asset Management*, Nov. 2009.

[4] S. V. Kulkarni, *Transformer Engineering Design and Practice*, 2004.

[5] M. Robert, *Transformer Design Principle with Application to Core-Form Power Transformers*, 2nd Edition, 2010.

[6] J. Martin, *The J&P Transformer Book*, 12th Edition, 1998.

[7] R. Feinberg, *Modern Power Transformer Practice*, 1979.

[8] J. John, *Power Transformers Principles and Applications*, 2002.

[9] T. McLyman, *Magnetic Core Selection for Transformers and Inductors*, May 1997.

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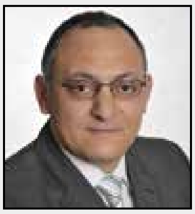

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