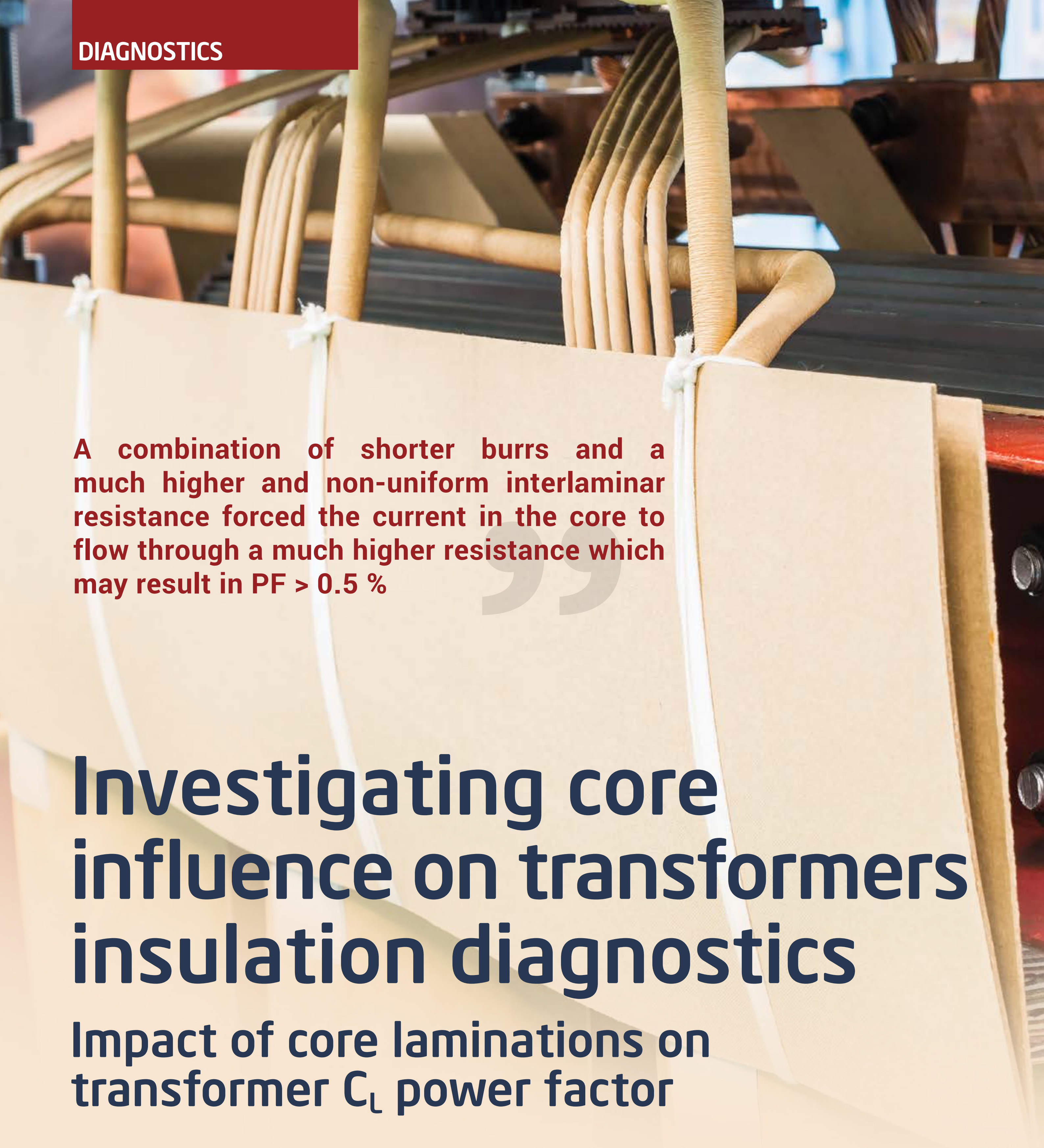

A combination of shorter burrs and a much higher and non-uniform interlaminar resistance forced the current in the core to flow through a much higher resistance which may result in PF > 0.5 %

Investigating core influence on transformers insulation diagnostics

Impact of core laminations on transformer C_L power factor

ABSTRACT

In a healthy power transformer, the power factor (PF) of the low-voltage winding insulation to the ground (C_L) is expected to be less than 0.5 %. In recent cases, the C_L PF measured during the factory testing exhibited high values close or above 0.5 %. Investigations have determined that the issue might be related to a higher than usual core steel interlaminar resistance, occurring due to a combination of shorter burrs and higher non-uniform insulation resistance between laminations. This article describes the phenomena and proposes a test protocol to differentiate the problem from other issues that cause high C_L PFs, such as moisture or contamination / deterioration of the insulation.

KEYWORDS:

core interlaminar resistance, insulation, insulation power factor, transformer diagnostics

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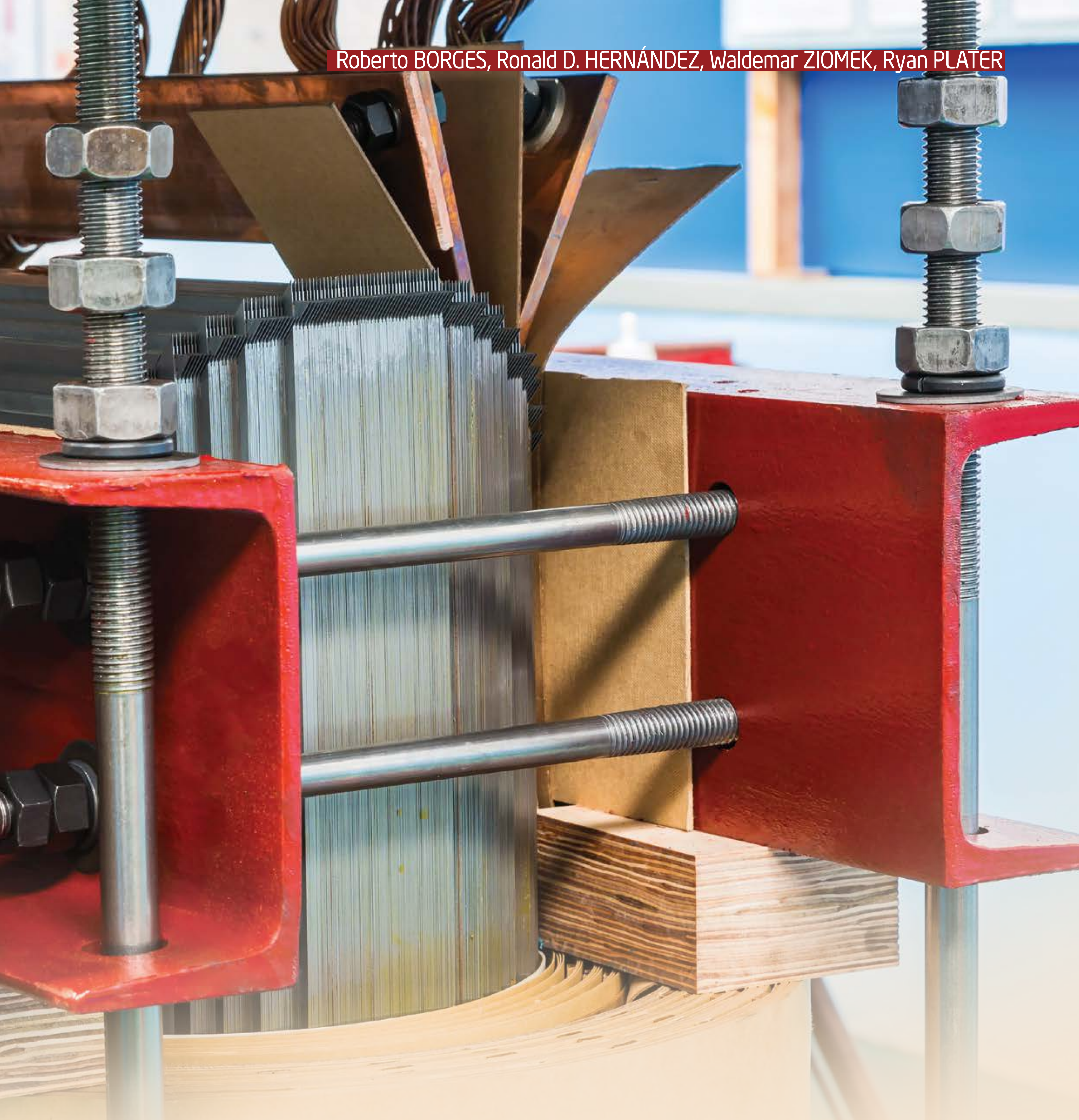

Note: Image shown is for illustration purposes only.

1. Introduction

Historical data suggests that oil-filled power transformers should have insulation PF of 0.5 % or less at 20 °C for all main insulation segments, e.g., C_H, C_{HL} and C_L, to be considered in good condition. Normally, the effect of the core design would be negligible during PF measurements, as it is effectively grounded across the complete core stack. In most cases, a single-core ground lead, placed between two adjacent laminations, typically located in the centre of a core, is used to obtain an effective grounding of all core laminations. The interlaminar resistivity should be high enough to avoid circulating currents between core laminations during service, but additionally, it should be low enough to allow an effective core stack grounding. A combination of proper interlaminar resistivity and suitable burrs height at the core steel lamination edges is usually sufficient to produce a low-resistance path for currents flowing to the ground during the C_L measurement. This results in PF < 0.5 % for units with healthy C_L insulation.

Elevated PF caused by excessive core lamination insulation was first reported in 1979 in [1]. Moreover, in recent cases, a combination of shorter burrs (i.e., shorter than interlaminar space) and a much higher and non-uniform interlaminar insulation resistance forced the current in the core to flow through a much higher resistance. This condition may result in PF > 0.5 %, thus misrepresenting the

Modern slitting and cutting machines can produce burrs as short as 0.002 mm, which, combined with improvements in the insulating coatings, yield a higher interlaminar insulation resistance

condition of a healthy insulation segment. The analysis presented hereby addresses the C_L PF issue based on experience with core-type transformers.

2. Core losses and the effect of burrs

Considerable research and development have been applied to magnetic steel and core design to reduce the core losses. Different alloys and steel production processes are used to increase the permeability of the material, reducing the hysteresis losses. Meanwhile, reduction of the eddy current losses is achieved by building the core using very thin laminations. The insulating coating is applied to the laminations to increase the interlaminar resistivity and reduce the interlaminar eddy currents and associated losses [2].

Another factor that impacts the eddy losses, as well as the magnetic properties of the steel laminations, is the presence of burrs at the edges. Burrs are a sub-product of slitting or cutting processes and usually have a sharp edge that follows the direction of the blade movement. Fig. 1 shows a microscopic image of the burrs on the edges of a core lamination. The height and length of the burrs depend on the type and wear of the slitting or cutting blade as well as on the steel alloy used to produce the lamination [3].

The height of the burrs is an important parameter. When a core is stacked, the burred edges are aligned on the external core surface, while in the core joints, burrs follow a step-lapped construction. Longer burrs can bridge the insulating coating, which may result in short circuits between adjacent laminations. Ultimately, this will cause additional interlaminar eddy currents, thus increasing the total core losses.

Fig. 2 shows the step-lapped design edges for the typical core joint construction. Laminations are shown in grey while coating in orange. From left to right, various burr heights affect the insulation between the laminations (thickness has been exaggerated for illustration purposes) in different ways. The core on the left (Fig. 2a) exhibits shorted laminations as the burrs are long enough to go through the coating. The middle sketch (Fig. 2b) shows a standard situation where the burr's height is not sufficient to short the laminations. Modern slitting and cutting machines can produce burrs as short as 0.002–0.004 mm. Shorter burrs, combined with improvements in the insulating coatings (Fig. 2c), yield a higher interlaminar insulation resistance, which, in turn, allows for less core losses. However, as recent experience suggests, these enhancements impact the C_L insulation PF measurements.

3. Core influence on power factor measurements

During a C_L PF test, an AC voltage is applied between the low-voltage winding conductor and the grounded tank and core. The C_L insulation is made up of contributions from two insulation segments in parallel, depicted in Fig. 3 as capacitances C_{Lb} and C_{LC}. Here, the capacitance C_{Lb} includes the insulation from the low-voltage winding to the grounded tank along with the overall insulation of all low-voltage bushings and cables. The capacitance C_{LC} represents the insulation between the low-voltage winding and the

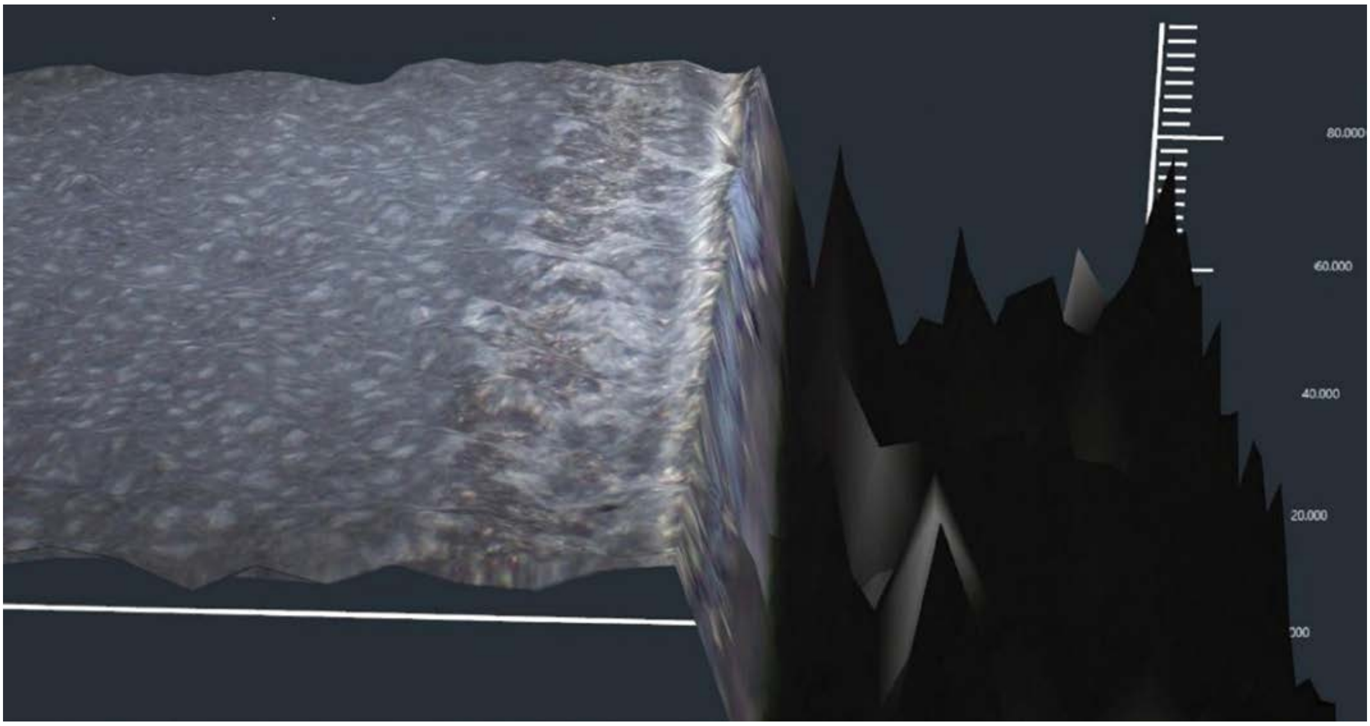

Figure 1. Microscopic view of burrs on the edge of core lamination

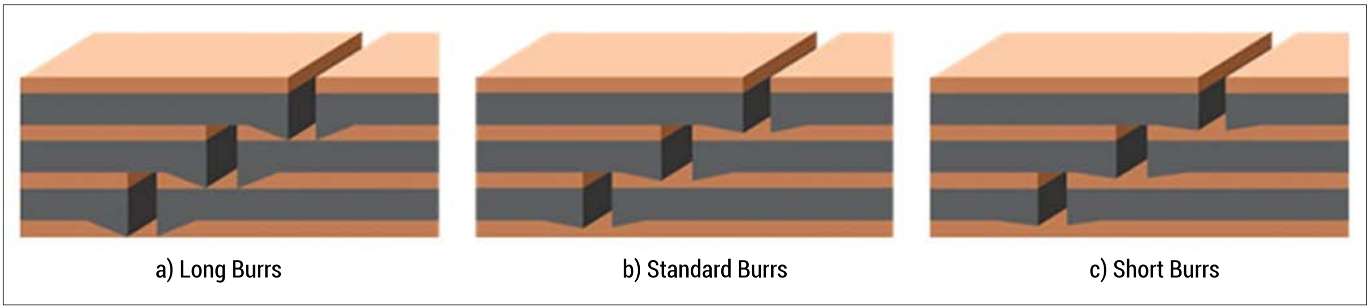

Figure 2. Expanded view of step-lapped edges of stacked cores

grounded core. The capacitance C_L is the combination of these two components, i.e., $C_L = C_{Lb} + C_{LC}$.

Once the current that flows through C_{LC} reaches the core surface, it then follows two paths: one portion goes through the interlaminar insulation (I_{across}) and the other flows on the surface ($I_{surface}$) through the burrs at the edges of laminations towards the grounding lead (Fig. 4). Both currents will re-unite when reaching the core ground lead, normally sandwiched between two neighbouring laminations in the centre of the core. This current, in addition to the current through C_{Lb}, becomes a part of the total current measured during the PF test on C_L insulation.

Shorter and fewer burrs increase the surface resistance through the edges of the laminations, sometimes to levels high enough to galvanically isolate some laminations, which now – also due to high interlaminar resistance – are under a floating potential, different from ground potential. Having laminations under different voltages impacts $I_{surface}$, generating higher dielectric losses and ultimately resulting in a higher C_L PF. At the same time, I_{across} flows through the interlaminar insulation. The improvements in insulating coatings can create very high resistances in the range of several tens to hundreds of MΩ that are faced by the current on its way towards the core grounding point. This high resistance is unevenly distributed across the core steps (i.e., groups of laminations of the same width). As a result, stray capacitances are generated between electrically floating laminations, which can absorb and retain electric charges with high resistances producing long R_C time constants. This process influences the real power supplied by the test instrument, resulting in a different loss angle and, therefore, affecting the PF as well [4].

Experiments performed on transformers exhibiting high core interlaminar resistance suggested that the degree of its effect on the PF measurements might depend on the design and size of the unit

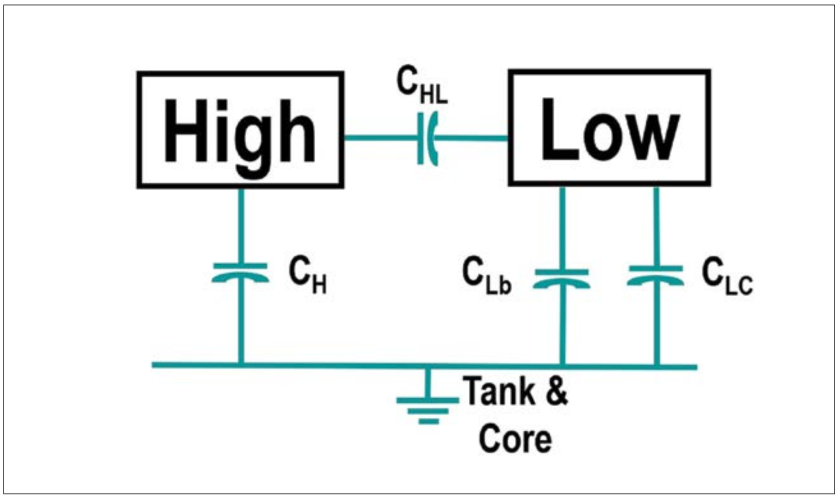

Figure 3. Dielectric circuit of a two-winding transformer showing C_L components

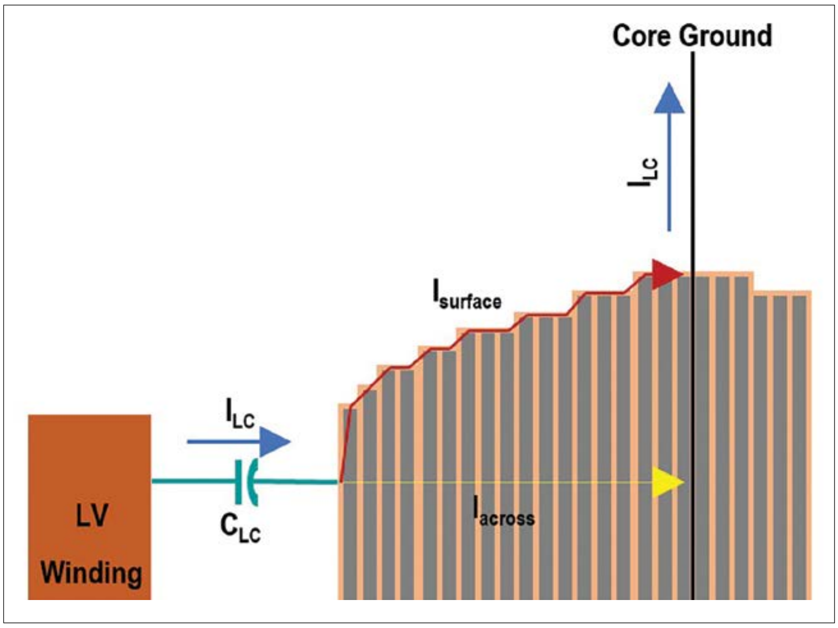

Figure 4. Current components through the core

C_L Variable frequency power factor (VFPF) traces on new units from the manufacturers analysed in this study exhibited an upswing in the higher frequency range caused by the high core interlaminar resistance

Core laminations under the influence of high interlaminar resistance are no longer at the same potential (ground potential) and can be represented as shown in the dotted square (Fig. 5). Here, R_{LC} is the interlaminar resistance faced by currents flowing through C_{LC} when being tested. C_{Lam} represents the capacitance between a series of electrically floating core laminations, and R_C represents the interlaminar resistance faced by currents during a C_C (core to ground insulation) test. The capacitance C_{HC} represents the capacitive coupling between the high-voltage winding and the core. Experiments performed on transformers exhibiting high core interlaminar resistance suggested that the degree of its effect on the PF measurements may depend on the design and size of the unit.

4. Recognizing high interlaminar resistance

It is well known that the PF test is a common diagnostic tool used to detect moisture, carbonization, and other forms of contamination of windings, bushings and liquid insulation in power and distribution transformers. The traditional diagnostic criteria used to analyse the test results would not be sufficient to identify changes in the C_L PF due to the presence of uncommonly high interlaminar resistance. For this reason, we are proposing a protocol that could assist to differentiate between the contamination and / or deterioration issues associated with the insulation and the high PFs caused by high interlaminar resistance.

The test protocol includes different connection schemes based on [5–7] to evaluate the insulation systems exhibiting high PF values. In a core type two-winding transformer, this would typically be the insulation of the winding closer to the core, e.g., C_L. However, depending on the design of the unit, other insulation segments can also be affected, and their evaluation is equally important.

It is essential to note that the presence of accessible core ground lead(s) is necessary to perform the evaluation. When ungrounded, the core ground lead would serve as an additional test point that allows the breakdown of the C_L insulation into three components, i.e., C_{Lb}, C_{LC} and C_C, which can be tested separately. In that, C_C represents the insulation between the core and the grounded tank. By assessing the C_{Lb} PF, it is also possible to evaluate the condition of low-voltage bushings without taps.

The dielectric circuit of a two-winding core type transformer with ungrounded core ground lead(s) is depicted by Fig. 5.

The testing protocol evaluating the condition of C_L, C_{Lb}, C_{LC} and C_C is as follows:

1. With core lead(s) directly grounded, perform 60 Hz overall PF and 15–400 Hz Variable Frequency Power Factor (VFPF) tests on the C_L insulation. This will serve as a benchmark for future reference.
2. With core lead(s) ungrounded, perform 60 Hz PF and 15–400 Hz VFPF tests on the C_{Lb}, C_{LC} and C_C segments.
   - Test diagrams are shown in Fig. 6. The top diagram is intended to measure C_{LC} and C_{Lb} (requires test modes UST R for C_{LC} and GAR RB for C_{Lb}). The diagram at the bottom allows the measurement of C_C using test mode GAR RB.
3. Reconnect the core ground lead(s) for normal operation and perform a 60 Hz overall PF test on C_L to confirm that the core ground leads have been properly grounded.

A comparison of PF test results among the three C_L insulation components will then reveal whether a high interlaminar resistance is affecting a C_L PF measurement. For instance, in new units with healthy insulation and high core interlaminar resistance, the C_{Lb} PF at 60 Hz is expected to be low and less than 0.5 %, while the segments directly associated with the core, i.e., C_{LC} and C_C are expected to exhibit higher PFs. This, however, may not be enough to differentiate the phenomenon of high core interlaminar resistance from contamination or deterioration of the insulation. Here, the analysis of the VFPF test results plays an important role as abnormal behaviour of the traces compared with typical VFPF measurements can indicate the presence of high core interlaminar resistance, as discussed in the following case studies.

5. Case studies

A total of seven transformers of different sizes, designs and manufacturers were tested during the investigation. All of

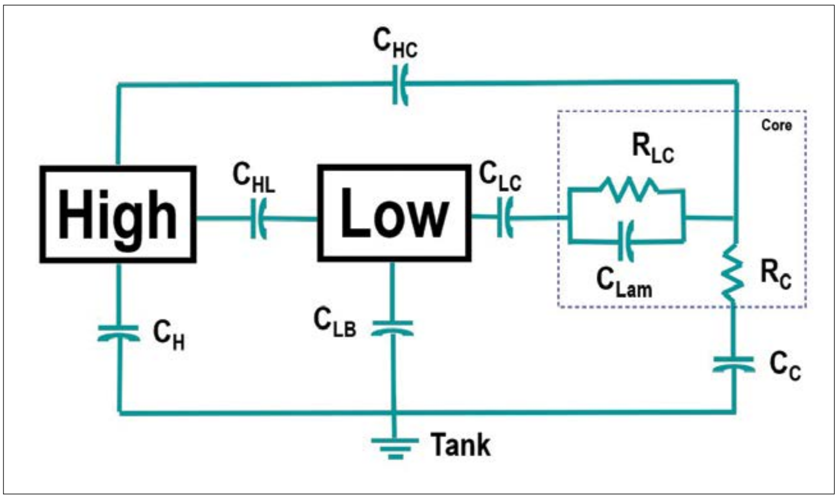

Figure 5. Dielectric circuit of a two-winding transformer showing insulations segments associated with the core

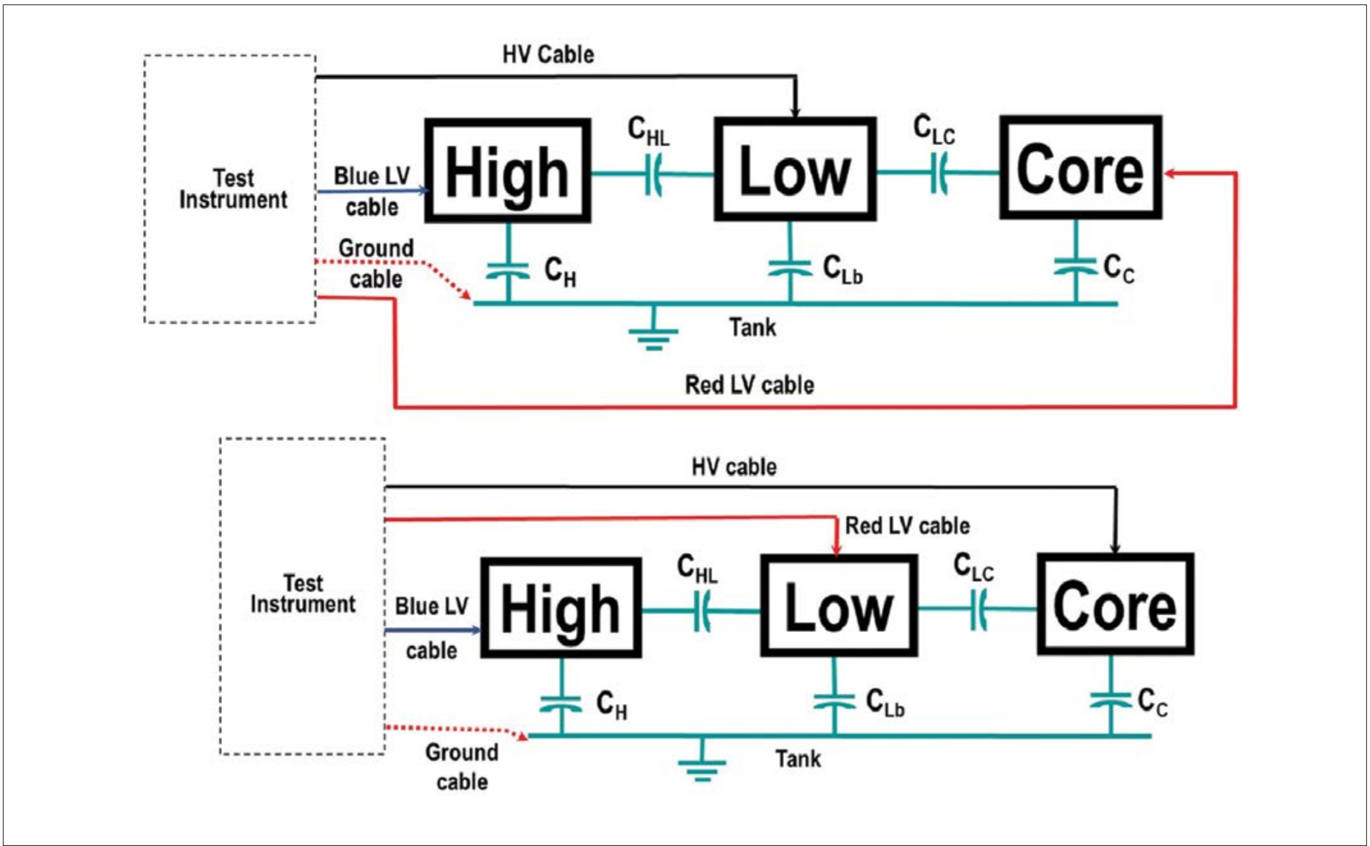

Figure 6. Setup for PF measurement on C_{Lb} and C_{LC} (top diagram), and C_C (bottom diagram)

them exhibited an influence of the core laminations on the C_L PF measurements [7].

One of the units was a 138–13.8 GrdY kV, 118 MVA power transformer manufactured by PTI Transformers LP that exhibited high C_L PF when tested in the factory. This unit was originally produced with a single core ground lead. After internal analysis, including numerous diagnostic tests, examination of the core lamination insulation test certificates and direct measurements of the core step resistance, it was determined that the high C_L PF was due to a high core interlaminar resistance. The problem was solved by installing two additional core ground leads, located symmetrically from the core centre, close to the smallest core items [4]. This caused a reduction of the measured PF to the expected lower values. All core ground leads were accessible for testing in the factory. This provided the opportunity to apply the test protocol using different core ground leads configurations to identify whether / how the PF and VFPF measurements were affected by the high interlaminar resistance.

Steps 1, 2 and 3 of the test protocol were performed using two different core ground configurations: a single-core ground (test data is influenced by interlaminar resistance) vs. three core ground leads (influence resistance on test data is reduced) grounded or connected to the high-voltage terminal of the test set, as described by the protocol. Even though the PF measurements on C_L were not above 0.5 % for a single core ground configuration, the tests showed that the higher PF values (in some cases close to 0.5 %, which was uncommon for PTI transformers, typically measuring PF in 0.2–0.35 % range) came down to more acceptable values when using a configuration with three core ground leads.

Table 1 shows the measured PFs at 60 Hz on the C_L, C_{LC} and C_C segments. When comparing a single-core ground vs. three core ground connected conditions, it is observed that the measured PFs are higher when only a single core ground lead is grounded. By adding extra core ground leads, most of the core sheets are brought to the ground potential, thus significantly shortening the current path. This reduces resistance for test currents from the point of entering the core to the ground. However, in most cases, testing crews would have access to only one core ground lead, brought to the exterior of the transformer through a bushing. Under these conditions, the regular 60 Hz PF test would not allow to differentiate if the high PFs are due to high interlaminar resistance or other phenomena.

Table 1. Case study 1 - measured PF at 60 Hz on C_L, C_{LC} and C_C insulations

Lead Config.	C_L PF (%)	C_{LC} PF (%)	C_C PF (%)	T (°C)
1 core-gnd (high interlaminar resistance)	0.46	0.908	1.421	26
3 core-gnd (low interlaminar resistance)	0.35	0.396	0.548	26
ΔPF (%)	**-0.11**	**-0.512**	**-0.873**	

It is important to point out that the level of impact of the high core interlaminar resistance on both the VFPF traces and 60 Hz PF measurements may depend on the size and design of the unit

VFPF was performed on the C_L, C_{LC} and C_C segments, and comparisons between a single core ground vs. three core ground connected conditions are shown in Fig. 7. Here, the higher interlaminar resistance of the single-core ground connected condition results in higher PFs on all three segments. The difference between the traces is more pronounced at the higher frequencies, marked by an upswing exhibited by the single-core ground traces. This behaviour is not typical of VFPF traces and could be attributed to high interlaminar resistance. The upswing is due to a change of the phase angle of the measured current, which depends on the frequency and core interlaminar resistance; the angle becomes smaller with the increase in frequency, leading to higher PFs.

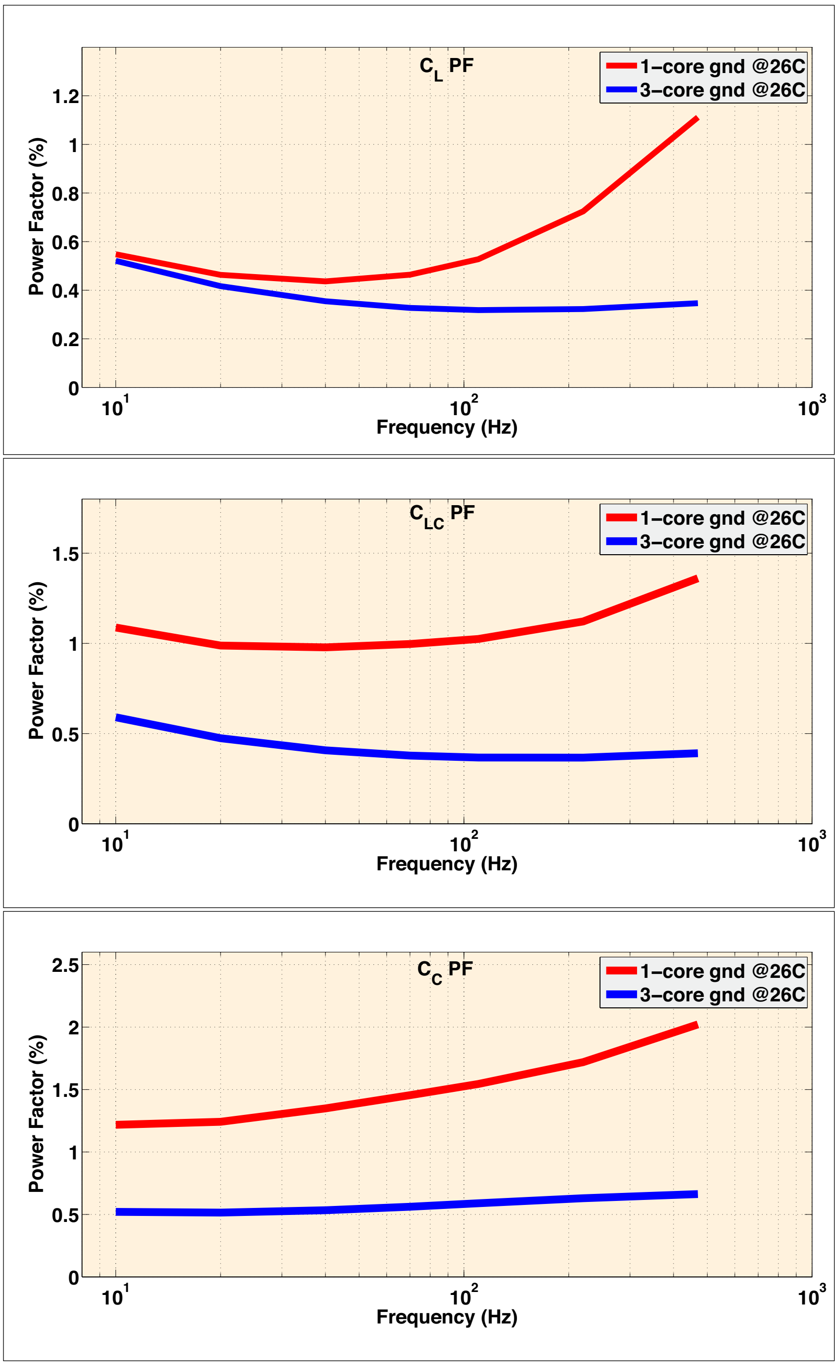

Figure 7. Case study 1 - VFPF traces on 1-core ground (high interlaminar resistance) vs. 3-core ground (low interlaminar resistance) connected on C_L, C_{LC} and C_C

A second case study of the effect of high core interlaminar resistance is observed in Fig. 8. The traces correspond to a single-phase 247–17.6 kV, 320 MVA transformer (by a different manufacturer). Once again, the VFPF traces on C_L and C_{LC} show the impact of high interlaminar resistance, which is reflected in the high PF measurements (see Table 2 for 60 Hz PF values) and the upswing present in the high-frequency range. Meanwhile, the C_{Lb} PF at 60 Hz was less than 0.5 %, which confirms the usefulness of the proposed test protocol to differentiate the phenomenon of high core interlaminar resistance from contamination or deterioration of the insulation. It is worth noting the behaviour of the C_{Lb} trace that exhibits a monotone decrease towards negative values at higher frequencies. Traces exhibiting a similar monotone decrease behaviour were encountered on every one of the units tested for this investigation, and, in some instances, the PF at 60 Hz even presented negative values. Understanding this phenomenon is the subject of ongoing research [8].

6. Conclusions

Traditional diagnostic criteria used to analyse dielectric test results may not be sufficient to identify changes in PF due to the presence of high core interlaminar resistance. A testing protocol is proposed to help differentiate the contamination or deterioration issues associated with the insulation condition from the presence of high core interlaminar resistance. The protocol allows identifying the influence

Table 2. Case study 2 - Measured PF at 60 Hz on C_L, C_{LC} and C_{Lb} insulations

Insulation	PF (%)	Temp (°C)
C_L	0.603	10
C_{LC}	0.530	10
C_{Lb}	0.351	10

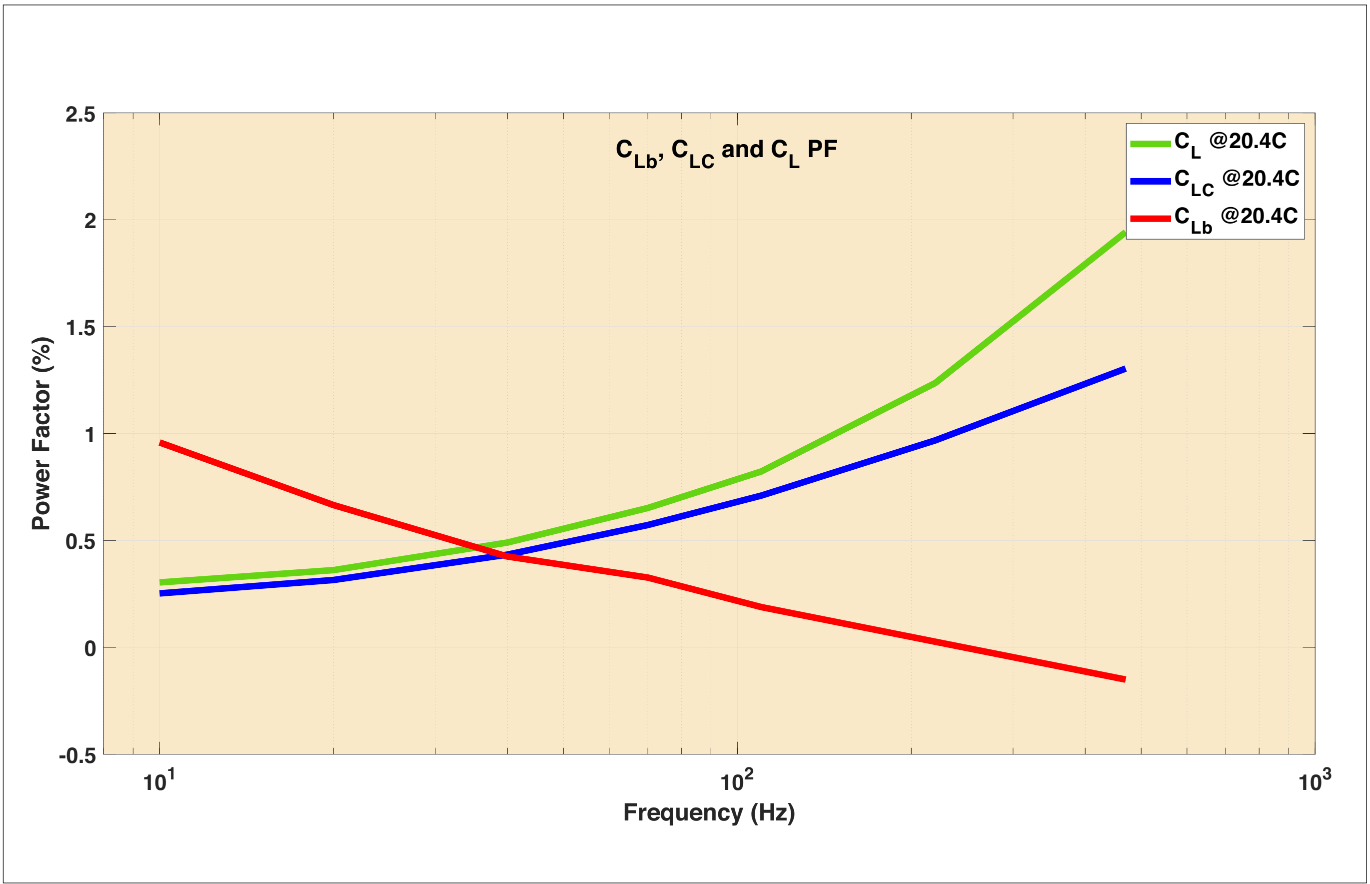

Figure 8. Case study 2 - VFPF traces on C_L, C_{LC} and C_{Lb}

of high interlaminar resistance on the transformer insulation PF measurement, mainly by examining the higher frequency range of PF vs. frequency traces.

The C_L VFPF traces on new units from various manufacturers analysed in this study exhibited an upswing in the higher frequency range, caused by the high interlaminar resistance. As part of that frequency range, the 60 Hz PF was impacted as well.

Splitting the C_L insulation into smaller segments by ungrounding the core ground lead(s), according to the test protocol, yielded interesting and promising results. The behaviour of VFPF traces on C_{LC} and C_C is similar to the one observed in the C_L insulation, where the effect of the high interlaminar resistance creates an upswing in the higher frequency range. However, in most cases, the upswing caused by high interlaminar resistance is more pronounced on the smaller insulation segments C_{LC} and C_C.

The effects of high interlaminar resistance are also observed on PF and VFPF measurements performed on the C_{Lb} insulation. In this case, PF readings at 60 Hz

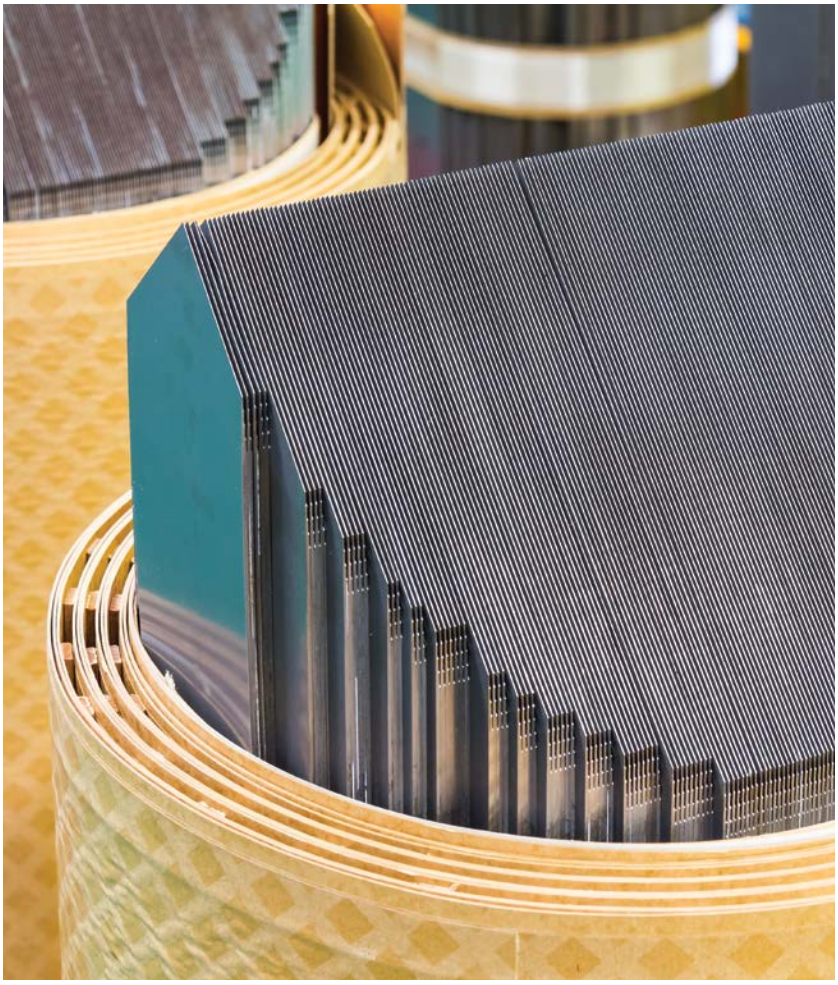

Figure 9. Transformer core detail (image shown is for illustration purposes only)

are expected to be very low and negative in some instances, and the VFPF traces show a monotone decrease in measured PF with the increase of frequency. The causes of this behaviour are being currently investigated.

Finally, it is important to point out that the level of impact of the high core interlaminar resistance on both the VFPF traces and 60 Hz PF measurements may depend on the size and design of the unit.

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