Rise-of-temperature method for building factor distribution in 1-phase model transformer core interior considering high DC bias

Franz HOFBAUER, Helmut PFÜTZNER, Georgi SHILYASHKI, Damir ŠABIĆ

Edin MULASALIHOVIĆ, Viktor GALABOV

Institute of Electrodynamics, Microwave and Circuit Engineering (EMCE),

University of Technology, Vienna (Austria)

(franz.hofbauer@tuwien.ac.at)

Abstract – Loss distributions of transformer cores are affected by z-flux effects if considered for the core surface. Here we propose the application of a thermal sensor which is inserted to the core interior through one of 16 channels of 2 mm width. Measurements were made on a 1-phase core assembled from laser-scribed SiFe. Throughout the core, the local building factor *BF* proved to increase towards the periphery which can be interpreted by interactions of highest anisotropy and non-linearity. Additional DC superposition yields non-uniform increases of *BF* at different core positions. Local losses tend to become more balanced – measurement locations with a priori high *BF* experience lower percentage increases, being more robust with respect to DC components.

Keywords: Core Loss, DC bias, Building factor distribution, Rise-of-temperature method

1 Introduction

Earlier studies of loss distributions in model transformer cores were performed by a large amount of thermal sensors arranged between inner laminations of the core (e.g. [1]). However the technique involves (i) very high effort, (ii) differences of sensor sensitivities and (iii) artefacts from interlaminar air gaps. The alternative to scan the core surface by a single sensor has the drawback that the losses may deviate from inner ones, mainly due to planar eddy currents as resulting from z-flux - especially if the core is DC biased [2]. Here we propose a novel procedure where a single sensor is inserted into channels that provide access to inner regions of the core. The width of channel is restricted to 2 mm in order to prevent effects on the distribution of flux.

Results of the distribution of the local building factor *BF* are presented for a 1-phase core with the impact of additive DC bias taken into consideration. DC bias in power transformer cores results from several sources which can be classified by the strength of the DC/AC excitation ratio r_{DC}. Moderate DC bias (r_{DC} = 1) is caused by HV-DC lines using the earth as return path inducing long-term DC currents into HV-AC mains and residual DC-components of solid-state inverters interconnecting HV-DC and HV-AC systems. High DC bias (r_{DC} = 5) may arise through the influx of solar-wind caused geomagnetically induced currents (GICs) as a short time phenomenon.

2 Methodologies

The measurements were performed on a 400 mm x 320 mm single-phase transformer model core stacked from 70 layers of highly grain oriented SiFe laminations (23ZH90) of 80 mm width. Local no-load losses *P* were determined at 16 core positions with the initial-rise-of-temperature method utilizing a thermistor sensor of type EPCOS G 540 which was chosen for high sensitivity to small temperature changes and fast response time due to low heat capacity. The active thermistor is mounted at the tip of a 1 mm glass column, a thermally insulated compensation thermistor arranged in a balanced Wheatstone bridge circuit, allows for compensation of ambient temperature fluctuations. For a local measurement, the active sensor was inserted in a 2 mm wide hole drilled through the 10 outermost laminations, being pressed to the 11th lamination by a spring for enforced thermal contact (Fig.1). Thus information about the core interior is obtained, avoiding the above mentioned side-effects. A second identical sensor being fixed in the centre of the left limb serves as a reference, assuming a local building factor BF = 1.0 here.

Magnetization time was restricted to 10 s to reduce global heat-up of the core and to confine thermal balancing to a small area during the measurement process, considering the thermal conductivity of the material. The minimum time delay for sufficient cooling between consecutive measurements was monitored and adapted depending on the excitation currents to counteract on the adverse effect of the heating of the windings especially at high flux densities.

Superposition of DC bias on AC excitation was simulated by adjusting the DC current in the secondary windings at defined DC/AC excitation ratios $r_{DC} = (N_{DC} \cdot I_{DC})/(N_{AC} \cdot I_{AC})$, with N the number of turns, I_{DC} the DC current intensity and I_{AC} the AC current intensity for $I_{DC} = 0$. To achieve an even flux distribution and to provide access to measurement locations in the limbs, the primary excitation winding is split to six coils and the secondary winding to two coils, with a ratio of $N_{AC}/N_{DC} = 108/60$. r_{DC} was varied between 1 as possible for long term bias, up to 5 as it is considered by industry as being representative for distinct GICs. Measurements were taken for peak induction values B_{NOM} = 1.5 T up to 1.8 T.

3 Results for mere AC magnetization

Fig.2a shows the measured local distribution of the building factor $BF = P_{LOC}/P_{REF}$ of the core magnetized with B_{NOM} = 1.7 T (50 Hz) at r_{DC} = 0. P_{LOC} is the local loss value registered at an individual location. As reference, P_{REF} is the nominal loss of the material which can be assumed to arise at the reference region, in approximation.

In detail, this measurement reveals mean values of *BF* of 1 for the limbs, 0.9 for the yokes, and about 1.2 for the corner overlaps, with distinct asymmetries (Fig. 2, left). *BF* shows minimum values (mean value 1) for the inner flux path I, higher ones (mean 1.1) for the middle path II and maximum ones (mean 1.2) for the peripheral path III. Flux densities of B_{NOM} = 1.5 T and B_{NOM} = 1.8 T yield a similar distribution of *BF*, with maximum mean values of 1.2 on flux path III (Fig. 2, right).

This tendency is contradictory to expectations from path length differences. To clarify the observations, local flux densities were measured with search coils arranged to intersect the width of the core along the flux paths. As an interpretation, due to the extreme anisotropy, path I will show strongly reduced flux since the air triangles of the corners affect the entire path. Path II shows maximum flux which however is almost sinusoidal. Here, the fundamental component of 50 Hz is close to the nominal value and the higher harmonics are less distinct than at the other paths. Path III shows reduced flux which however tends to be strongly distorted, as a main reason for high *BF* (Fig.3). Since the classical eddy current losses are proportional to the squared product of the *B*-components with their corresponding frequencies, an overall higher mean *BF* value in flux path III for all measured B_{NOM}-values is the result [3].

Maximum values at corners can be attributed to saturation for local induction values that exceed the "critical" induction B_c [4]. The inevitable air gaps at the lap joints represent high reluctance paths between neighbouring laminations and are bypassed by the local flux via gap bridges until approaching saturation at B_c. At this value, the flux takeover mechanism is altered and the gap has to take up as much of the excess flux as does the gap bridge. Thus, the excessive local flux density contributes to an increased local loss figure.

4 Results for DC bias

A moderate DC field of $r_{DC} = 1$ affects the *BF* distribution on the model core, with the highest impact on the inner path I and the middle path II. In the depicted case of $B_{NOM} = 1.7$ T, path I shows strongest increases of 17% mean value. Lower increases result for path II with 10% and especially path III with an increase of only 2% (Fig.4a, left). The loss value at the reference point P_{REF} is increased by 10 % compared to the non biased case. A lower induction of $B_{NOM} = 1.5$ T, yields overall higher percentage increases, the mean value of path I being 23%, 19% in path II and 8% in path III. At an induction of $B_{NOM} = 1.8$ T, the influence of the moderate DC bias on the *BF* is limited, with an average increase of ΔBF of less than 5% (Fig.4a, right). These results indicate that the superposition with moderate DC bias affects especially lower induction values and raises the local losses mainly at those regions with a priori low *BF.*

The superposition with a high DC field of $r_{DC} = 5$ tends to increase the *BF* at every location considerably, however in uneven ways, contrary to a priori given values. In the case of $B_{NOM} = 1.7$ T, path I shows strongest increases of 45% mean value. Much lower increases result for path II with 25% and path III with 21% (Fig.4b). Similar to the case of r_{DC} = 1, at an induction of B_{NOM} = 1.5 T an overall higher percentage increase can be observed, the mean value of path I being 57%, 39% in path II and 22% in path III. On the other hand, B_{NOM} = 1.8 T yields a lower average increase, with a mean value of 32% at path I, and about 15% at path II and III (Fig.4b).

5 Discussion

The comparison of Fig.4a) and Fig.4b) indicates that losses increase with rising DC bias in a distinctly non-linear way, corresponding to a tendency of saturation. While the ratio of r_{DC} is 1:5 for all induction values, the ratio of average *BF*-increases is in the order of 1:2 to 1:3 for an induction of B_{NOM} = 1.5 T and 1.7 T, respectively. In summary, a balancing tendency is given. As a general experience, DC bias tends to affect mainly those regions which are characterized by low induction and ideal magnetization performance, respectively. Regions of a priori high *BF* tend to be more "robust" with respect to DC components.

Concerning the practical relevance, it has to be stressed that high values of r_{DC} are restricted to GICs which have a limited duration in the order of days. Thus even strong increases of the local *BF* are of minor energetic relevance. However, the measurements with r_{DC} = 5 show the influence of high DC bias on the non-uniform *BF* distribution in a clear way. On the other hand, the case of moderate DC bias may arise for a longer period of time. The effects tend to be weaker, but their long-term character is of importance because in industrial practice even single percent variations of *BF* are capitalized. In the future this will show increased significance due to the tendency that very large 3-phase machines are being replaced by three 1-phase machines in increasing ways.

6 Conclusions

By means of the initial rise-of temperature method, the local distribution of the local building factor *BF* was measured at 16 positions in a single-phase model transformer core assembled from highly grain oriented SiFe. A novel sensor design overcomes the drawbacks of previous measurement setups by inserting the thermistor sensor into measurement channels which provide access to inner regions of the core. To investigate the impact on the local *BF* in different regions of the core, the case of mere AC excitation was compared with that of additional moderate and high DC magnetization, respectively. The results yield the following main conclusions:

(1) For mere AC excitation, lowest *BF* arise in the inner flux path due to reduced flux densities caused by the air triangles in the corners, which affect the entire path.

(2) Highest *BF* in the outer peripheral path is caused by flux distortion.

(3) The superposition with DC magnetization yields an overall increase of the *BF* in a non-linear way, depending on the strength of the DC bias and on the region of the core. In a tendency of balancing, DC bias affects especially those regions with a priori low induction and ideal magnetization performance, respectively.

As result, the superposition with DC magnetization yields an overall increase of the *BF* in a non-linear way, depending on the strength of the DC bias and on the region of the core. In a tendency of balancing, DC bias affects especially those regions with a priori low induction and ideal magnetization performance, respectively.

Acknowledgements: The authors thank for support from the Austrian Science Funds FWF (Project No. P21546-N22) as well as from ABB Transformers.

References

[1] A.J. Moses, B. Thomas, J.E. Thompson, Power loss and flux density distributions in the T-joint of a three phase transformer core*, IEEE Trans. Magn.* **8**-4 (1972), 785-790.

[2] E.Mulasalihovic, H.Pfützner, P. Zanolin, G. Shilyashki, V. Galabov, Effects of moderate DC-magnetization on 3-D loss distributions of a 3-phase model transformer core, *Proc. 1&2-D Magn. Meas. & Test* (2012), 59-60.

[3] G.F. Mechler and R.S. Girgis, Calculation of spatial loss distribution in stacked power and distribution transformer cores, *IEEE Trans. Power Del.* **13** (1998), 532-537.

[4] A.Ilo, H. Pfützner, T. Nakata, Critical induction – a key quantity for the optimisation of transformer core operation, *J. Magn. Magn. Mater.* **215-216** (2000), 637 – 640.

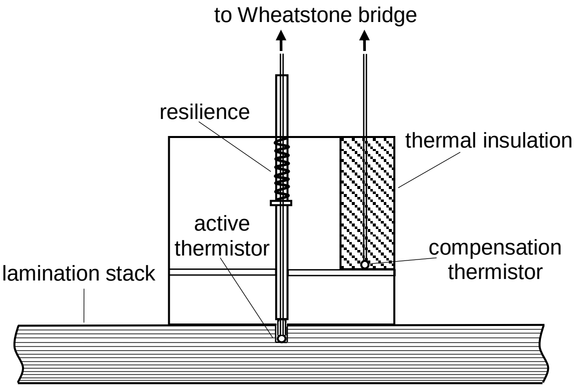
Figure Captions

Fig.1. Design of the thermistor sensor.

Fig.2. (left) Local *BF* for 16 positions on the transformer core at mere AC excitation with B_{NOM} = 1.7 T. **(right)** Mean *BF* values of flux path I – III for B_{NOM} = 1.5 T, B_{NOM} = 1.7 T, B_{NOM} = 1.8 T at mere AC excitation

Fig.3. Fundamental (50 Hz), 3rd and 5th harmonic components of B_{peak} values of flux path I – III at mere AC excitation. Percentage values of higher flux harmonics are related to the fundamental component. **(a)** B_{NOM} = 1.5 T, **(b)** B_{NOM} = 1.7 T, **(c)** B_{NOM} = 1.8 T.

Fig.4. (left) Local *BF* for 16 positions on the transformer core at B_{NOM} = 1.7 T with DC bias (percentage increases in italics). **(right)** Relative increase of the mean ΔBF of flux path I – III for B_{NOM} = 1.5 T, B_{NOM} = 1.7 T, B_{NOM} = 1.8 T with DC bias. **(a)** moderate DC bias (r_{DC} = 1), **(b)** high DC bias (r_{DC} = 5).



to Wheatstone bridge
resilience
thermal insulation
active thermistor
compensation thermistor
lamination stack

Fig.1.

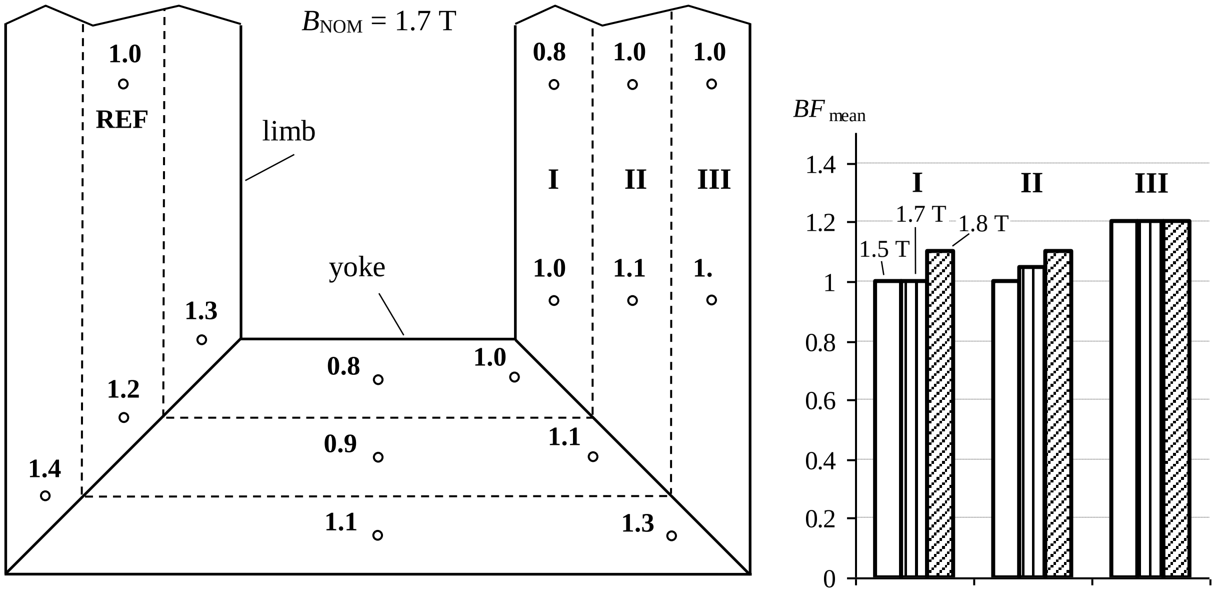

B_{NOM} = 1.7 T
1.0
REF
limb
yoke
1.3
1.2
1.4
0.8
0.9
1.1
1.0
1.1
1.3
0.8
1.0
1.0
I
II
III
1.0
1.1
1.
BF_{mean}
1.4
1.2
1
0.8
0.6
0.4
0.2
0
I
II
III
1.5 T
1.7 T
1.8 T

Fig.2.

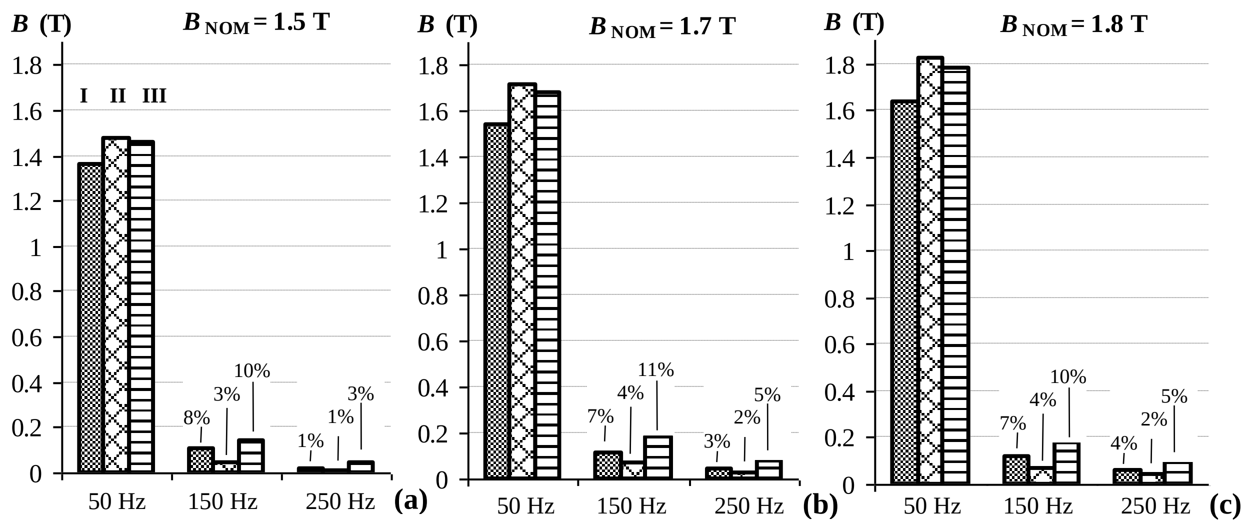
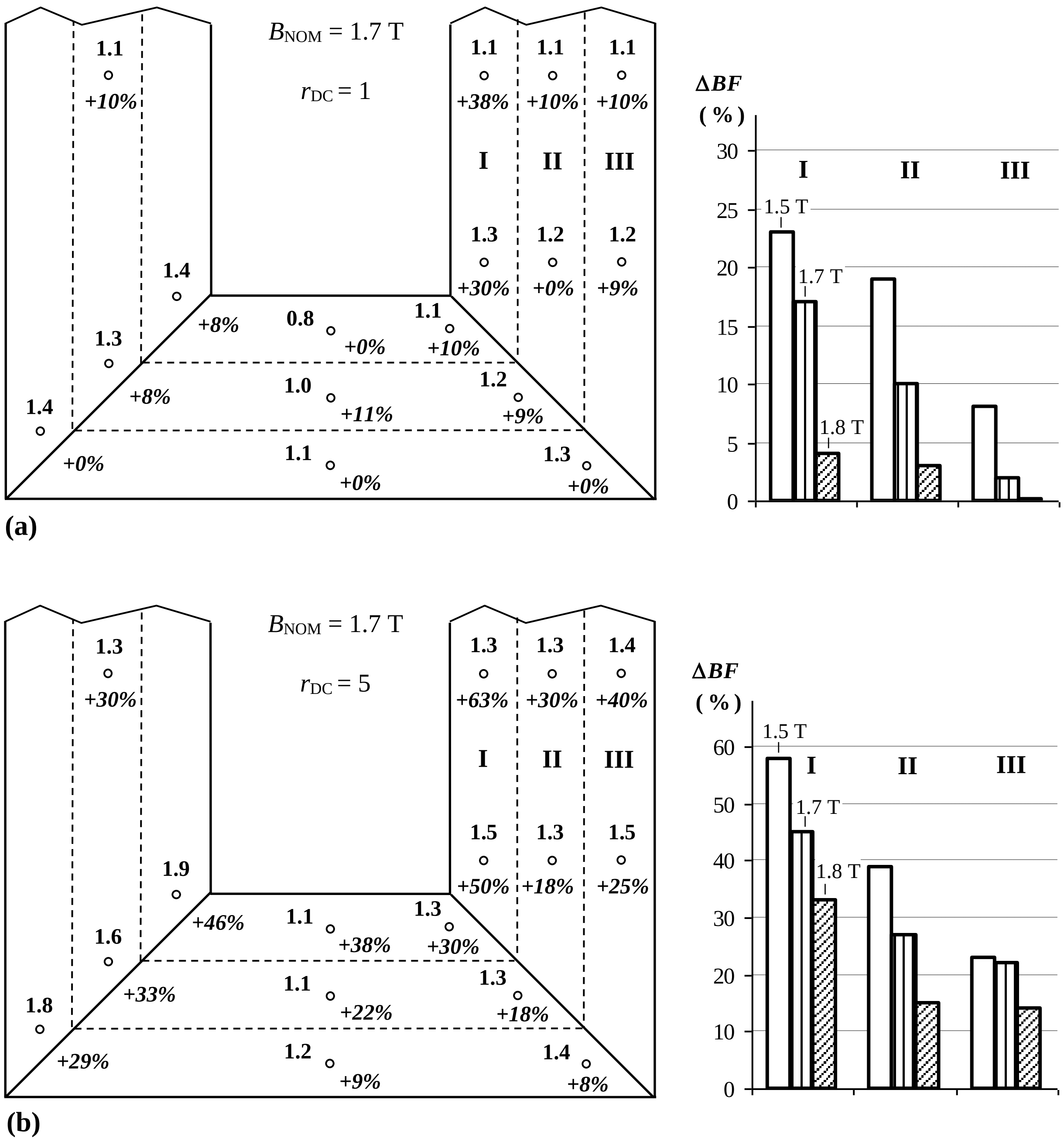

B (T)
B NOM = 1.5 T
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
I II III
8%
3%
10%
1%
1%
3%
50 Hz
150 Hz
250 Hz
(a)
B (T)
B NOM = 1.7 T
7%
4%
11%
3%
2%
5%
(b)
B (T)
B NOM = 1.8 T
7%
4%
10%
4%
2%
5%
(c)

Fig.3.



B_{NOM} = 1.7 T
r_{DC} = 1
1.1
+10%
1.1
+38%
1.1
+10%
1.1
+10%
I
II
III
1.3
+30%
1.2
+0%
1.2
+9%
1.4
+8%
0.8
+0%
1.1
+10%
1.3
+8%
1.0
+11%
1.2
+9%
1.4
+0%
1.1
+0%
1.3
+0%
(a)
ΔBF (%)
30
25
20
15
10
5
0
I
II
III
1.5 T
1.7 T
1.8 T
B_{NOM} = 1.7 T
r_{DC} = 5
1.3
+30%
1.3
+63%
1.3
+30%
1.4
+40%
I
II
III
1.5
+50%
1.3
+18%
1.5
+25%
1.9
+46%
1.1
+38%
1.3
+30%
1.6
+33%
1.1
+22%
1.3
+18%
1.8
+29%
1.2
+9%
1.4
+8%
(b)
ΔBF (%)
60
50
40
30
20
10
0
1.5 T
1.7 T
1.8 T
I
II
III

Fig.4.