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MINIMUM LOSS DESIGN OF A 100 kHz INDUCTOR WITH FOIL WINDINGS

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Abstract. In high current, high frequency inductors and transformers foil windings will be competitive with other types like litz wire if they are properly designed. Effective loss calculation tools presented by Dowell [2], Jongsma [3] and Carsten [4] gives good control of the losses in foil windings used in transformers. In an inductor, problems arises due to the needed air gaps.

A minimum loss design of a 100 kHz inductor with foil windings using a multi air gap approach is presented. In the design process finite element eddy current computations have been used extensively. A prototype has been constructed and tested.

The inductor is supposed to be used in a 20 kVA Dual-Active-Bridge Inverter. The required inductance is 5 μH. In the final design, a multi air gap solution with 16 air gaps is used keeping the winding losses as low as 35 W at 75 A rated current. The additional losses rising from the fringe field near the air gaps is only 7 W at rated current.

Our tests on the inductor verifies that all sources of high frequency winding losses are well under control.

Keywords. High frequency inductor, eddy current losses, foil windings, multi air gap

1 INTRODUCTION

In high frequency transformers and inductors winding losses are normally kept under control by using foil conductors or multistrand litz wire. When such conductors are properly designed, additional losses defined as skin effect and proximity effect can be kept at very low values. This is especially true for high frequency transformers, where primary and secondary ampere turns are ideally equal in magnitude and oppose each other, giving a characteristic one dimensional leakage field parallel to the winding sections. Very useful analytic tools for optimizing foil windings and calculation off losses are well described in [2], [3] and [4]. When it comes to ac-inductors and coupled inductors (e.g. a flyback transformer) where energy are stored in air gaps, the field distribution and loss mechanisms become more complicated and unpredictable. Additional eddy current losses in windings due to non-axial magnetic fields from air gaps have a two dimensional character. Established analytic tools are not applicable for analysis of these types of losses. Therefore numerical tools as the finite element method have to be used.

This paper describes the effect from the fringe field on the foil windings of a multi air gap ac-inductor, and optimization of a prototype by using finite element computations. The paper also reports design and test of the prototype. This prototype was designed to be the high frequency link inductor on the 20 kVA Dual-Active-Bridge Inverter, reported in [8].

2 WINDING AND CORE DESIGN. ANALYTIC APPROACH

Both foil conductors and litz wire have their advantages and drawbacks. Litz wire is fairly easy to wind up and to terminate and is adaptable to various window geometries. On the other hand litz wire is expensive and gives poor fill factor. Foil conductors are fairly easy to produce in a variety of heights and widths, and if optimum foil height for a given number of turns is used, the winding becomes compact and has a potential for low losses. On the other hand the optimal foil winding tends to become very wide where high current, high frequency and a large number of turns are present at the same time. Wide foil windings entails termination problems and represents potential risks for other types og high frequency losses.

One reason for selecting foil windings in the present construction was our previous experience from finite element analysis and practical design and test experience of such foil constructions, which implied that additional losses as skin effect, proximity effect and end effect was remarkable low in the optimized constructions. End effects represent a significant local loss density, but appears only in small fractions of a wide foil. The local heat may well become intense, but is effectively spread to the rest of the foil surface.

Finite element analysis also implied that thermal losses are easily kept under control if the height of the conductor used to terminate the winding is of the same magnitude as the foil winding itself.

When it comes to selection of core materials, 3F3 or 3C80 would probably have been the correct choice at 100 kHz. But cores of these new materials are still limited in size. Therefore our prototype design was based on the use of available big U- and I-cores of 3C8 martial. The penalty for using a non-optimal core material is a bigger construction, or significantly higher losses.

Another problem when selecting core material was the unstandard shapes of the core disks between the air gaps. These are expensive in small quantities, even though the disks are small and have simple shape. Therefore we built our prototype by cutting disks from ordinary 3C8 I-cores with the same core area as the U-cores selected for the yokes.

Table 1 Specification for the ac-inductor

Inductance	5 μH
Frequency	100 kHz
Current - dimensioning core losses	172 A peak
Current - dimensioning winding losses	75 A rms sinusoidal

Results from the first analytic design approach is given in Table 2. Data for core losses are taken from the manufacturers catalogue. Winding losses are calculated by applying the analytic tools described in [2], i.e. additional losses due to end effects, core gap effects and termination effects are not taken into account. It should also be mentioned that the calculation of winding losses are done with sinusoidal current, while the actual wave shape is trapezial or triangular [8]. However, the harmonic content of the real current is very small, so the sinusoidal approach gives a very good estimate.

Optimal foil height at 100 kHz sinusoidal current and 14 turns is 0.074 mm, giving winding losses of 19.3 W. As can be seen, using a foil height of 0.1 mm, giving 23 W is not far from that optimum. 0.1 mm is selected for practical reasons.

Table 2 Results from the first analytic design approach in figure 1

Core material and shape	3C8, 4xI93/28/30
Effective core area	840 mm^2
Peak induction at rated current	73 mT
Total air gap length in each leg	20 mm
Core losses @ 70 mT, 100 kHz	100 mW/cm^3
Estimated core losses (310 cm^3)	31 W
Number of turns	14 on each leg, coupled in parallel
Dimensions of copper foil	0.1mm x 90 mm
Calculated ratio R_{ac}/R_{dc}	2.09
Analytically calculated winding losses	23 W

3 FINITE ELMENT ANALYSIS OF THE ANALYTIC DESIGN

Introduction

The magnetic field in the inductor is a 3 dimensional field. Performing a full 3 dimensional field calculation on this inductor is complicated and laborious, specially the modelling.

The skin effect and the proximity effect responsible for the additional losses can be computed with high accuracy using 2 dimensional cross sections. Using a 2 dimensional approach, the effects due to the winding termination of the foil windings are neglected. Special care must be taken to minimize the additional losses in the termination, but it is not necessary to take the effect of the termination in to account when computing the fringing field from the air gaps.

The finite element model

The selected cross section used in the finite element fields analysis is shown in Fig. 1. Because of the symmetry, only one quarter of the leakage window need to be modelled.

The materials used in the bobbin and in the insulation between the foil turns are nonmagnetic with very low conductance. They are therefore modelled as air.

The magnetic permeability of the core material is high compared to the air (or other materials used in the inductor). The flux will therefore enter the core almost perpendicularly. The core (leg and yoke) can then be omitted in the model. Instead, a boundary condition are set on the surface of the core in order to ensure that the field enters the core perpendicularly.

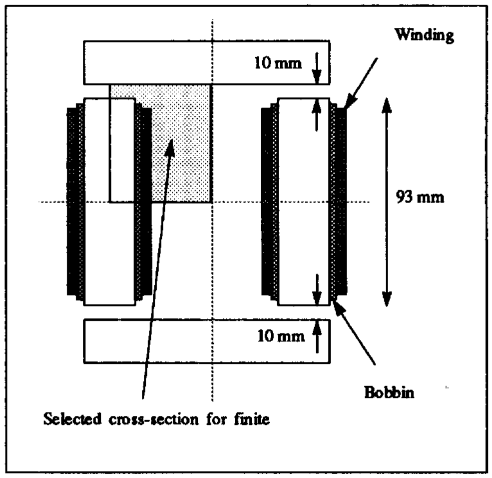

Fig. 1 Initial design, analytical approach

The Finite Element program

The numeric field calculations presented in this paper was carried out using a 2 dimensional eddy current program called INDUS2D which is a part of the finite element program package ELMADE [1]. The programs have been under development at the Department of Electrical Engineering since 1988.

The program has the possibility to enforce a total current in each foil conductor. This simplifies the analysis of the inductor and makes it possible to compute the induced voltage in each conductor and thereby the inductance. The program also compute the losses in each turn and total losses in the winding.

We decided to use higher order finite elements. This makes it possible to trace the fast changes in current density inside each foil conductor accurately without using to many finite elements.

Numerical results

To illustrate how bad the design presented in Fig. 1 is, the winding losses was computed by INDUS2D [5]. The losses are presented in Table 3. They clearly shows that this is an unrealistic design for high frequencies. In some parts, the copper in the winding will probably be melting. A first and simple attempt to reduce the losses, is to cut the core leg in two parts and have one air gap in the middle of the leg. This reduce the additional losses approximately to one half, but the losses are still far too high.

Table 3 Computed winding losses, initial design

Description	Losses num.	Losses ana.
Two air gaps, 10 mm each (top and bottom)	643 W	23 W
One air gap, 20 mm (in the middle)	351 W	23 W

The formulas used to compute the winding losses analytically only takes into account the skin and proximity effect due to axial flux [2], [3]. The impact of discrete air gaps is therefore tremendous, as presented in the above table.

4 STRATEGY FOR REDUSING THE LOSSES

The loss mechanism

The additional winding losses are induced by the fringing flux near air gaps.

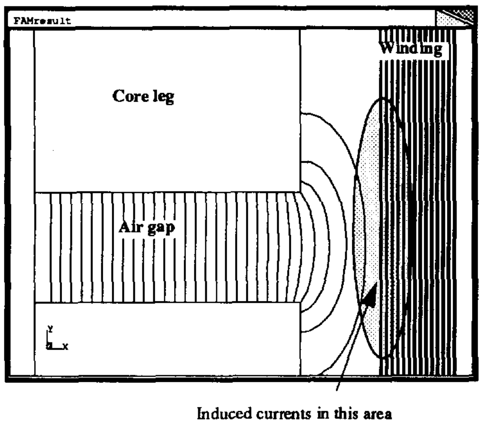

Fig. 2 Loss mechanism

Almost all ampere-turns generated are used to overcome the magnetic reluctance in the air gap. It will therefore also be a magnetic field outside the core as shown in Fig. 2 because the magnetic field intensity (H) will be high in this part of the inductor. The radial component of the field outside the core near air gaps causes eddy currents in the foil windings when trying to penetrate the winding.

Changing the design

To obtain a useful design, it was quite obvious that the radial flux components had to be reduced. To obtain this we where working along two strategies:

1. 'Consume the ampere-turns where they are generated'. This is achieved by using many small air gaps.
2. Reduce the impact of the radial flux component. This is accomplished by increasing the distance between the core leg and the windings, i.e. increase the thickness of the bobbin.

The ideal solution to reduce radial flux components is to use a material in the core legs with an adjustable permeability. The needed air gap would then have been 'distributed' perfectly and the radial flux component removed completely.

Our next proposed design based on the above guidelines is presented in Fig. 3. The inductor has 4 air gaps, each 5 mm long in each leg. The distance between the winding and the core leg (b_w) is 2.4 mm (as before).

The design in Fig. 3 was further modified until the losses were acceptable. This was done by successively increasing the number of air gaps and the distance between core leg and winding. It is important that there are a certain distance between the air gaps when there are many air gaps in one leg. Otherwise, the air gaps will be 'short circuited', see Fig. 4. It is not necessary to use a field calculation program to find out that the losses will decrease when increasing the number of air gaps or the distance between core leg and winding. But it is necessary to use a field calculation program to find out *how* many air gaps are needed. To many air gaps will increase the manufacturing costs.

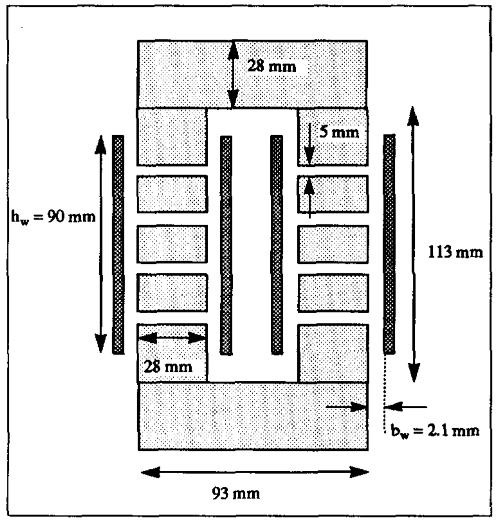

Fig. 3 New inductor with 8 air gaps

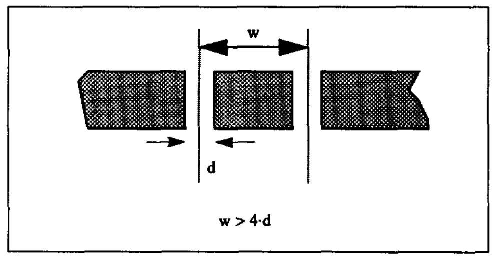

Fig. 4 Minimum distance between air gaps

5 RESULTS FROM THE FINITE ELEMENT ANALYSIS

The computed losses for different designs are presented in Table 5. The results clearly shows that the additional losses are dramatically reduced when the number of air gaps are increased form 4 to 8, and the distance between core leg and windings from 2.1 mm to 4.2 mm (compare model no 1 and 4).

The additional losses are, as expected, highest in the foil turn closest to the core leg (turn no. 1). The effect is dramatic. Even for our 'optimum' design, 26% of total winding losses are in the inner turn.

The difference between model no. 4 and 5 is that the width of the foils, h_w, are reduced from 90 mm to 80 mm. The reduction in losses is quite interesting and can be explained by inspecting Fig. 5. By reducing the width (h_w) the additional losses at the top (and bottom) of the winding are reduced.

Fig. 6 displays the magnetic field in the final designed inductor (model no 5). The leakage field flows in the 'channel' between the core and the windings.

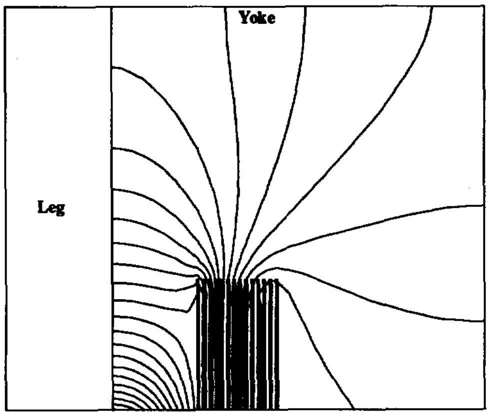

Fig. 5 *Magnetic field at the top of the winding (l_w= 90mm)*

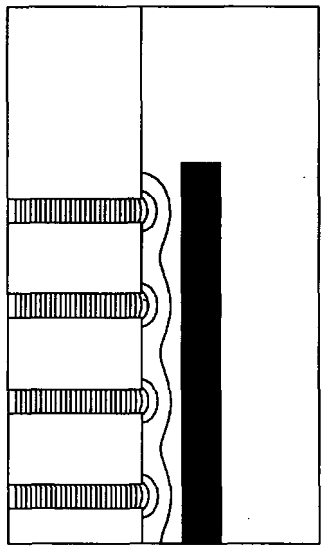

Fig. 6 *Magnetic field in the final design*

6 PROTOTYPE DESCRIPTION

A prototype was build, on the basis of the core and winding selection described in chapter 2, and on distributed air gap details as for model no 5 in Table 5. For practical reasons, some small modifications had to be made on the prototype:

Table 4 *Prototype modifications*

	Model	Prototype
Distance foil end to yoke	13 mm	24 mm
Distance leg to winding	4.2 mm	5.0 mm

These small modifications are assumed to be of little or no significance. If any, the prototype additional losses are slightly less than for model no 5.

A cross section of the core and one winding part, with physical dimensions and materials, is shown in Fig. 7.

The prototype inductor seen from one side, with support brackets and foil terminals is shown in Fig. 8.

Recalculated losses for the prototype, when adjustments on the length of each turn and increased core volume are taken into account, are as follows:

Table 6 *Prototype recalculated losses*

Winding losses	38W
Core losses	37 W
Total prototype losses	75 W
Analytic one dimensional losses	31 W

7 TEST MEASUREMENTS

The simple test circuit described in Fig. 9 was set up for running the inductor prototype continuously at rated current (75 A) and for short

Table 5 *Computed winding losses*

MODEL DATA					WINDING LOSSES				
					Analytic	Numeric (Finite element calculation)			
Model #	# air gaps	Length of air gaps	Dist. leg-wind b_w	Foil width h_w	Total	Turn # 1		Total	Additional losses
1	4	5.0 mm	2.1 mm	90.0 mm	23 W	134.1 W	73 %	183.7 W	699 %
2	4	5.0 mm	4.2 mm	90.0 mm	25 W	60.6 W	63 %	95.6 W	282 %
3	8	2.5 mm	2.1 mm	90.0 mm	23 W	52.9 W	63 %	84.2 W	266 %
4	8	2.5 mm	4.2 mm	90.0 mm	25 W	18.9 W	42 %	44.5 W	78 %
5	8	2.5 mm	4.2 mm	80.0 mm	28 W	8.9 W	26 %	34.8 W	24 %

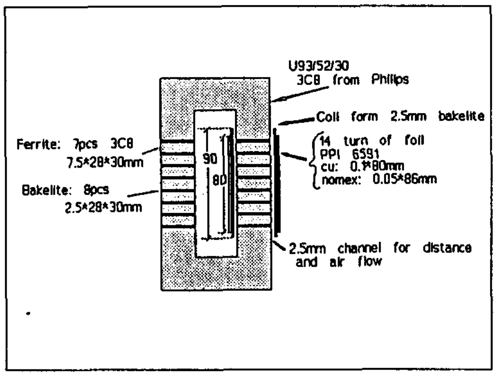

Fig. 7 *Cross section of the inductor prototype*

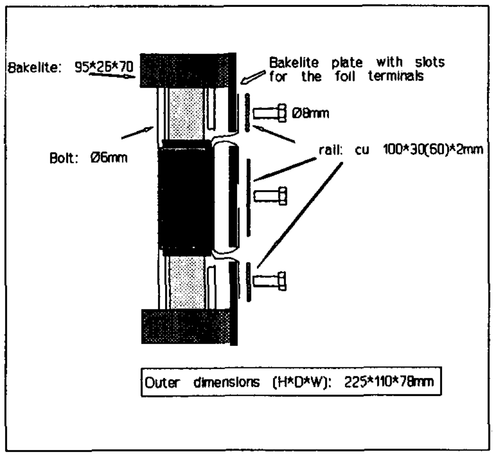

Fig. 8 *The prototype inductor seen from one side*

time at a higher current (100 A). The value of the series resonant capacitor was selected to give resonance with the inductor under test at about 100 kHz. When running the circuit exactly at the resonance frequency (92.5 kHz), and carefully tuning the dc-link to give only a few volts, just to cover the circuit losses, both current and voltage waveforms of the inductor are close to sinusoidal. Waveforms were recorded by oscilloscope. Current and voltage at 100 A rms is shown in Fig. 10.

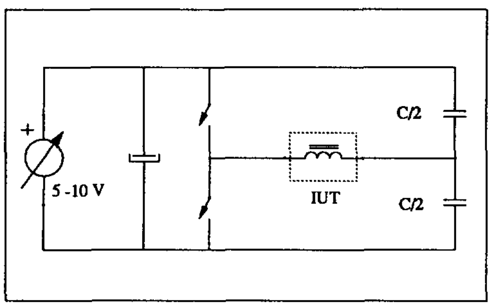

Fig. 9 *Test circuit for the ac-inductor*

Temperature sensors of the type AD590 were positioned on three locations, which were assumed to be critical:

No 1:	On the winding nearest to the core, and close to the foil edge.
No 2:	On one terminal foil nearest to the core where it enters the winding.
No. 3:	On the centre ferrite disk on one leg (no 4 from top or bottom in Fig. 7).

Table 7 *Results from load test*

The highest temperature was measured at location no 1. Location no 3 had the lowest temperature increase. The temperature difference between location no 1 and 3 was less than 10°C.	
75 A rms continuously	$T_{no1} \approx 75°C$ @ $T_{amb} \approx 25°C$. Stabilized after 10 min.
100 A rms in 5 min.	$T_{no1} \approx 100°C$ @ $T_{amb} \approx 25°C$.

The inductor was naturally cooled (no fan) under the test. Up-down position of the test object was as it appears in Fig. 7 and Fig. 8.

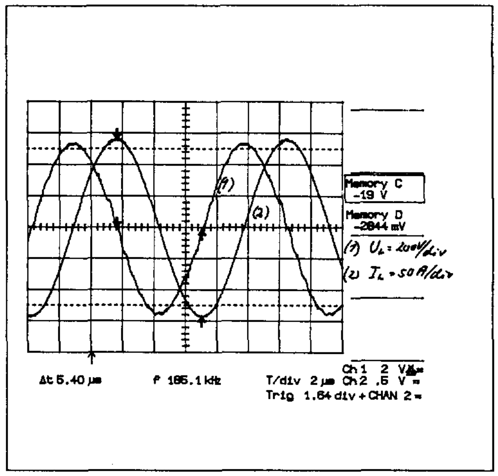

Fig. 10 *Inductor voltage and current waveforms at 100 A rms*

8 CONCLUSION

The paper has presented a way to optimize air gap ac-inductors by using numeric finite element analysis tools. A 2D eddy current program is sufficient for comparative analysis of different multi air gap configurations. It is shown that losses from the fringe field near the air gaps are reduced from hopeless 643 W in 4-air gap design to 34.8 W for the 16-air gap design. For the latter the fringe field losses represents only 7 W.

A prototype inductor was composed of standard U-cores and special, but simple square disks. The disks represent a problem for prototypes, but have a potential to become cheap in mass-production because of small and simple shape. It is therefore believed that multi air gap, multi disk ac-inductors will become a competitive way of design in the future, especially where high power and high frequency both are present.

The 3C8 core material in the prototype is not optimal, but was selected because more suitable materials as 3F3 is not available in big enough dimensions at the moment. The 3F3 core material would have given a significant reduction in both overall size and losses.

Test results verify that all sources of high frequency winding losses are well under control.

The distance between core and winding gives a double benefit. It reduces the fringe field in winding area, and it gives a cooling channel between winding and core leg. This cooling effect has been verified by numerical heat flow analysis, but is not documented in this paper.

9 ACKNOWLEDGEMENT

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10 REFERENCES

[1] Robert K. Nilssen, "Numerical Computations of Electric and Magnetic Fields - program development based on commercially available software",Dr.Ing. Theses, NTH,Trondheim 1988.

[2] P. I. Dowell, "Effects of Eddy Currents in Transformer Windings", Proc. IEEE Vol. 113, No 8, August 1966.

[3] J. Jongsma, "High-frequency power transformer and choke design, Part 3: Transformer winding design", N. V. Philips' Gloeilampenfabrieken, September 1982.

[4] B. Carsten, "High frequency Conductor losses in Switchmode Magnetics", Proc. HFPC, pp. 155-176, May 1986.

[5] S. Rosenvinge, "Tap i høyfrekvens transformatorer og spoler", Diploma Thesis, NTH, Trondheim, June 1991 (in norwegian).

[6] M. Hernes, A. Nysveen, "Induktanser for høyfrekvens resonansomformere", Memo, EFI AN 91.40.45, Oct. 1991 (in norwegian).

[7] M. Hernes, "Ac-drossel prototyp med 16x2.5 mm luftgap, konstruert med utgangspunkt i modell nr 5 i EFI AN 91.40.45",Meno, EFI AN 92.40.16, May 1992 (in norwegian).

[8] K. Vangen, T. Melaa, A.K. Adnanes, "Soft - switched High-Frequency, High-Power DC/AC Converter with IGBT", Proc. PESC'92, June 1992, Toledo, Spain.