Comparative Study of Welding Transformers Based on Nanocrystalline and Ferrite Cores

Georgi Todorov Nikolov

Abstract - **The purpose of the paper is to present a practical comparison between ferrite and nanocrystalline magnetic materials used in power electronics. As an example a welding transformer is designed. Optimization of the windings is carried out to decrease the copper losses to meet the allowed limit. The obtained final results show that using nanocrystalline cores provides significant reduction in the size (volume) and weight of the core and of the component itself.**

Keywords – **Magnetic component design, Magnetic materials, Nanocrystalline magnetic materials.**

I. INTRODUCTION

Nanocrystalline alloys are firstly developed to obtain great permeability. The outcome of nanocrystalline manufacturing processes suggests an alternative about the use of other materials in power electronics applications. In nowadays power electronics applications, the nanocrystalline materials are concurrent to power ferrites and amorphous materials at high frequency devices [1]. Diagrams, presenting the typical properties of some Soft Magnetic Materials in use in Power Electronics is shown in Fig. 1 [2] and Fig. 2 [5,7].

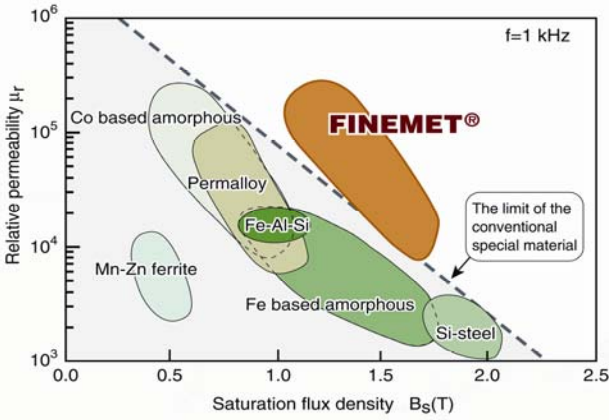

Fig. 1 Typical initial permeabilities and saturation inductions for soft magnetic materials [2]

Combined with low magnetic losses, the great permeability (20 000 to 600 000 vs. 10 000 for ferrites) and high saturation induction (1.2T vs. 0.4T for ferrites) – the new nanocrystalline alloys prove to be a first-rate material for power electronics [3].

The purpose of the paper is to give a practical comparison of the application of ferrite and nanocrystalline materials for a welding transformer. Thus, the obtained design results can be used to compare the advantages and the disadvantages of the two different materials for cores in power electronics.

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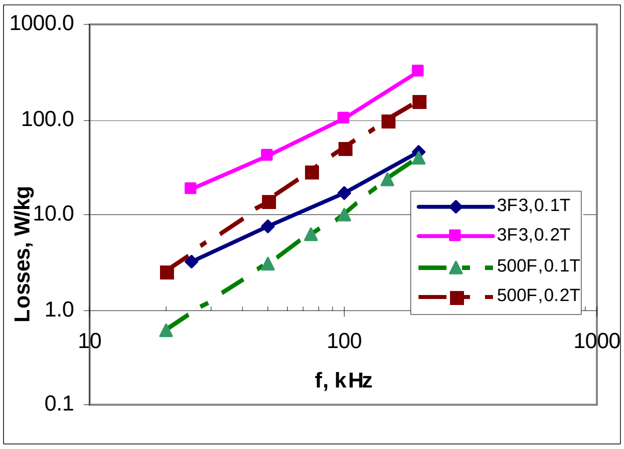

Fig. 2. Loss comparison for ferrites 3F3 and nanocrystalline Vitroperm 500F, under square voltage, for variable duty ratio, from 50 % to 5 % with a 5 % step, f=100kHz, Bpeak=0.1T; 0.2T [5,7].

II. FERRITE CORE TRANSFORMER CALCULATIONS

The calculations in this paper are based on the fast design approach, described in [4]. A welding transformer is calculated based on ferrite cores and on nanocrystalline cores.

In the calculations natural air cooling is assumed. The welding transformer has the following input data:

TABLE 1. INPUT DATA FOR THE TRANSFORMERS

Primary voltage	300V
Secondary voltage (no load)	60V
Secondary voltage (during welding)	26V
Secondary current (continuous)	150A
Working frequency	100kHz

According to the design methodology step 1 is choosing core material and size. This is done with the following two equations where the input data is substituted and the obtained results are:

$$S_{tot} = \sum_{all\ windings} V_{rms} I_{rms} = 9kVA \qquad (1)$$

$$a_{ch} = \left(\frac{S_{tot}}{A} \right)^{1/\gamma} = 8,434cm \qquad (2)$$

where:

A is a coefficient. For ferrites, $A = (5\text{–}25)\times 10^6$ if a_{ch} is in [m]; (A is in the range $A=5\text{–}25$ if a_{ch} is in [cm]);

a_{ch} is the largest dimension of the component (the core);

γ is an exponent, characterizing the material and shape of the core, $\gamma = 3$.

S_{tot} is the total volt-amp rating of the component.

The found parameter a_{ch} is used to select a core size. Using the data sheets, a core with a largest dimension higher then a_{ch} is selected. The core EE100/60/28 (2 pieces per set) is selected for the calculated example and the chosen material is ferrite grade 3F3 [5].

The second design step is finding the heat dissipation capability P_h of the selected core:

$$P_h = k_A\, a\, b = 30W \tag{3}$$

where:

k_A is a coefficient; typical value is 2500 W/m^2; for natural air convection.

a and b are the two largest dimensions of the component, [m].

We assume a high frequency so that the core will not be saturated. In a well optimized design, the losses in the transformer are equally divided into copper $P_{h,cu}$ and core losses $P_{h,fe}$:

$$P_{h,fe} = P_{h,cu} = 15W \tag{4}$$

This simple assumption is true when the magnetic material is not saturated and the core losses are proportional to the square of the induction and eddy current losses in the copper are low.

Having found how much losses can be dissipated with the selected core, the peak induction $B_{p,g}$ corresponding to the specific core losses in the given core grade is found from datasheets:

$$P_{fe,sp,v} = \frac{P_{fe}}{V_c} = 74,3\frac{kW}{m^3} \quad B_{p,g} = 0,12T \tag{5}$$

where V_c is the volume of the chosen core.

Then a simple check is done to prove that the found peak induction is lower than the saturation induction.

Next step in the design is to find the number of turns for each winding:

$$N_1 = \frac{\psi_{pp}}{\Phi_{pp}} = \frac{\psi_{pp}}{A_e\, B_{pp}} = \frac{\psi_{pp}}{2}\frac{1}{A_e\, B_{p,g}}; \; N_i = N_1\frac{V_i}{V_1} \tag{6}$$

$$N_1 = 9,03\,turns; \;\; N_2 = 1,81\,turns$$

where:

$\psi_{pp}$is the peak-to-peak magnetic flux linkage, [Wb];

A_e is the effective cross sectional area of the core.

N_i are the number of turns of the i $^{-th}$ winding;

V_i is the RMS value of the voltage across the i^{-th} winding.

As a result of the rounding up the secondary number of turns ($N_1=9$ for the primary, $N_2=2$ for the secondary), the secondary voltage is increased by about 11% to 67V, which is still acceptable.

Finding the diameter of the wires is the next step. The copper losses are distributed the equally among the windings:

$$d_i \geq \frac{2}{\sqrt{\pi}} I_{rms,i}\sqrt{\frac{\rho_c\, l_{Ti}\, N_i}{P_{cu,i}}}; \tag{7}$$

$$d_1 = 1,25mm, \quad d_2 = 5,97mm$$

where:

$R_{0,i}$ is the DC resistance of the i $^{-th}$ winding;

$I_{rms,i}$ is the RMS current of the i $^{-th}$ winding;

ρ_c is the electrical resistivity of the wire (resistivity of copper);

l_{Ti} is the mean-length-per-turn of the i $^{-th}$ winding.

A practical wire diameter $d_{p,i}$ is selected, which is higher than the calculated by the previous expression value d_i and is the next available wire diameter. The fact, that $d_{p,i}>d_i$, results in reduced ohmic losses, allowing some eddy current losses, without exceeding the total allowed copper losses:

$$d_1 = 1,40mm; \;\; d_2 = 6,30mm$$

Next step is calculating the actual ohmic copper losses:

$$P_{cu,ohm} = \sum_{i=1}^{all\ windings} R_{0,i}\, I_{rms,i}^2 = 6,127 + 6,723 = 12,850W \tag{8}$$

where:

$I_{rms,i}$ is the RMS current of the i $^{-th}$ winding;

N_i is number of turns of the i $^{-th}$ winding;

p_i is the number of wires in parallel (or the number of strands in a litz wire)

$\rho_c=23\times10^{-9}\ \Omega m$ at 100° C; $\rho_c=17,24\times10^{-9}\ \Omega m$ at 25° C.

The last two steps in calculation of losses is finding eddy current losses and summing them all:

$$P_{cu,eddy1} = 0,438W \;;\; P_{cu,eddy2} = 2,166W$$

$$P_{cu} = \sum_i P_{cu,i} = 15,454W \tag{9}$$

A check is done whether the total copper losses are lower than the thermally allowed copper dissipation:

$$P_{cu} \leq P_{h,cu} \tag{10}$$

The check fails, so the design should be optimized. The choice of wire diameters and winding arrangements can be used as optimization parameters.

Possible improvements are:

1. If the design results in a **single layer** winding, the diameter of the wire can be increased in order to fill the layer completely, as far as it is tolerated by the creeping distance. If this trick is not sufficient, one can think of interleaving, where the secondary winding wound with thick wires (typically 2 times the penetration depth or more) is sandwiched by two primary windings of a lower diameter.
2. If the design results in **two or more layers**, then it is useful to use pi wires in parallel to reduce the eddy current losses. In this way, the diameter of the wires can be diminished with a factor $\sqrt{p_i}$ and thus eddy current losses reduced.

   Special care should be taken to make sure that the current in the wires is almost equal. This is usually obtained by symmetry.
3. A special case of paralleling wires is Litz wire [6]. In this case pi becomes the number of strands.

A check is done in the last step to prove that the core window area W_a is large enough to fit all the windings. We assume a copper filling factor $k_{cu}=0,4$ for round conductors and $k_{cu}=0,2$ for Litz wire and check the inequality:

$$\sum_{i=1}^{n} p_i N_i \frac{\pi d_{i,p}^2}{4} \le k_{cu} W_a ; \quad 76,199 \le 768.345 \qquad (11)$$

In this case the window is large enough to accommodate both windings easily.

Choosing a smaller core (E80/38/20) and using the best of the above optimizations results in 25% more losses than allowed. Thus, such a design is not possible because of the thermal problems.

The results from the carried out optimizations of the windings with the core EE100/60/28 are presented in the Table III in Section IV. In the same section, the comparison with the results obtained for the nanocrystalline-based transformer is made.

III. NANOCRYSTALLINE CORE TRANSFORMER CALCULATIONS

The same calculations as in the ferrite core section are repeated for the transformer based on a nanocrystalline core.

Using the first step calculations the core FINEMET® F3CC0016A (4 pieces per one set) is selected [7].
The heat dissipation capability Ph of the selected core is:

$$P_h = k_A \, a \, b = 10,85W \qquad (12)$$

Again, losses in the transformer are equally divided into copper and core losses:

$$P_{h,fe} = P_{h,cu} = 5,425W \qquad (13)$$

Choosing material with lower losses at the given frequency results in affording a higher magnetic induction:

$$P_{fe,sp,v} = \frac{P_{fe}}{V_c} = 75,04 \frac{kW}{m^3} \ , \ B_{p,g} = 0,20T \qquad (14)$$

Using higher magnetic induction leads to decreasing the number of turns:

$$N_1 = 6,818; \quad N_2 = 1,364 \, turns$$

So, 6 turns for the primary and 1 for the secondary are chosen. Having found the number of turns, the diameter of the wires can be calculated:

$$d_1 = 1,558mm \Rightarrow d_1 = 1,6mm$$

$$d_2 = 5,890mm \Rightarrow d_2 = 6,3mm$$

Determining the copper losses is the next step:

$$P_{cu,ohm} = 4,944W$$

$$P_{cu,eddy} = 1,975W$$

$$P_{cu} = 6,919W$$

The check fails again, so optimization is necessary.

The problem to be solved is the total copper losses which should be lower that the allowed. The optimization is based on the same approaches like for ferrite cores. The results from the optimizations are presented in the tables in section

IV. DESIGN RESULTS AND SPECIFICATIONS FOR FERRITE AND NANOCRYSTALLINE BASED TRANSFORMERS

The final design is carried out for: 1. ferrite core EE100/60/28 and 2. for nanocrystalline core F3CC0016A, using the following winding arrangements (cases):

Case 1:
All parameters are according to the calculations given in the sections II. and III.

Case 2:
The calculations are carried out with increased diameter the wires and few wires in parallel.

Case 3:
The calculations are carried out using Litz wires.

TABLE II
WINDING ARRANGEMENTS CALCULATED FOR THE DESIGNED WELDING TRANSFORMER.

	Ferrite				Nanocrystalline			
	d_1	d_2	p_1	p_2	d_1	d_2	p_1	p_2
Case1	1,4	6,3	1	1	1,60	6,30	1	1
Case2	4,0	6,3	1	2	2,80	6,30	1	2
Case3	0,10	0,10	2625	10500	0,071	0,071	2835	10500

TABLE III
LOSSES IN THE COPPER FOR THE DIFFERENT WINDING ARRANGEMENTS CALCULATED FOR THE DESIGNED WELDING TRANSFORMER, BASED ON FERRITE CORE EE100/60/28.

	Ferrite				
	$P_{ohm,1}$	$P_{ohm,2}$	$P_{eddy,1}$	$P_{eddy,2}$	P_{total}
Case1	6,127	6,723	0,438	2,166	15,454
Case2	0,751	3,362	1,253	4,332	9,698
Case3	0,534	0,991	2,343	4,885	5,876

TABLE IV
LOSSES IN THE COPPER FOR THE DIFFERENT WINDING ARRANGEMENTS CALCULATED FOR THE DESIGNED WELDING TRANSFORMER, BASED ON NANOCRYSTALLINE CORE F3CC0016A.

	Nanocrystalline				
	$P_{ohm,1}$	$P_{ohm,2}$	$P_{eddy,1}$	$P_{eddy,2}$	P_{total}
Case1	2,573	2,371	0,919	1,056	6,919
Case2	0,840	1,186	1,410	2,012	5,447
Case3	0,461	1,778	0,269	0,29	2,798

The comparison of the size and weight of the two components is done using the following dimensions and parameters:

TABLE V
COMPARISON BETWEEN THE DESIGNS

	Volume	Area	Core weight	Copper weight	Total weight
	cm^3	cm^2	kg	kg	kg
Nanocrystalline	67,5	43,4	0,492	0,119	0,611
Ferrite	202,0	120	0,986	0,406	1,392
Improvement by using nanocrystalline core	66,6%	63,8%	50,1%	70,6%	56,1%

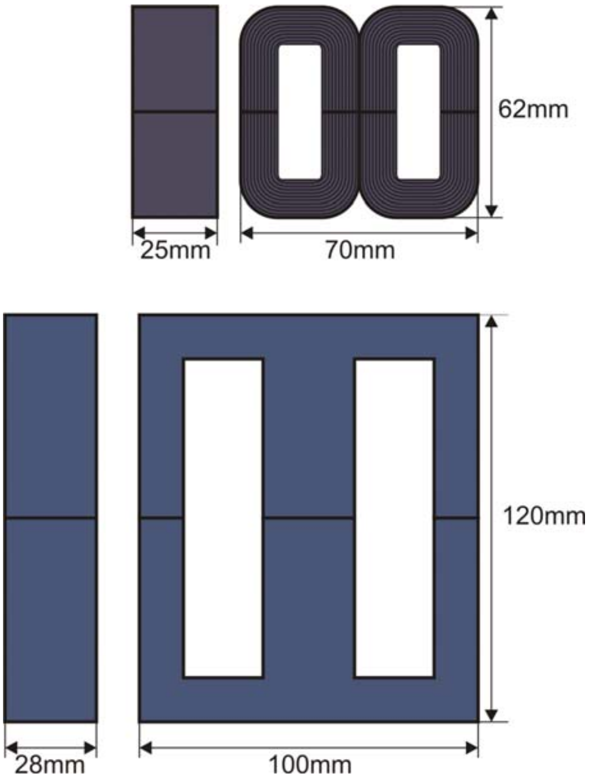

Fig. 3. Dimensions for the used cores.
Above F3CC0016A, bellow EE100/60/28

V. CONCLUSION

This paper presents a practical comparison between ferrite and nanocrystalline magnetic materials used in power electronics. The carried out calculations in the design of the welding transformer based on ferrite cores and on nanocrystalline cores show that using a nanocrystalline core leads to a much lower component size (volume) and weight.

The thermal calculations show that optimization of the winding diameters is necessary to decrease the copper losses and to meet the allowed limit. The three different winding arrangements are calculated and the obtained results are discussed.

For the calculated welding transformer the improvement in size is above 60% and the improvement in weight is above 55%. The advantage of the nanocrystalline core transformer is obtained because of the higher induction level of the material, up to 1.2 T in general.

Although using such a thick wire for the secondary winding 6mm, having only one/two turns makes it possible for realization. Using Litz wires results in lower loss, but it leads to the higher price and worse thermal conditions (possible hot spot at the middle). Thus, Litz wire design is not appreciated in the considered power. Another case, which is not covered in this paper, is using foil conductors. Calculating losses in such conductors is done by a different methodology and is not in the scope of the paper, but for the next research of the authors.

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