Improved Methodology for Design of Magnetic Components

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Abstract – **In this paper, an improvement to an existing methodology for design of magnetic components is presented. By incorporating the suggested improvements, it is possible to design magnetic components with nanocrystalline and ferrite soft magnetic materials. The component can use either natural or force convection for dissipating the generated by the losses heat.**

Keywords – **Magnetic components, Nanocrystalline, Ferrites.**

I. Introduction

There are lots of design methodologies that are used today ([1], [2]). However, most of them allow a design to be carried out for ferrite soft magnetic materials with natural cooling of the magnetic component. Using one of these methodologies - „Fast Design Approach” [3] as a basis,an improvement is proposed. The chosen methodology combines simple but accurate equations and easy to use graphics. It takes into account the effect of eddy current losses in magnetic component and in the windings. The approach categorizes the design cases into two major cases: saturated thermally limited design and non-saturated thermally limited design. The improvements that we proposed are concentrated in two of allfifteen steps.

II. Calculate the Heat Dissipation Capability P_H(Step 2)

In this step an estimation of the heat dissipation capability of the chosen core (in step 1) is made. The rule of the thumb used is:

$$P_h = k_A a\, b \qquad (1)$$

where

k_A is a coefficient with typical value of 2500 W/m^2;

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

The value for k_A=2500 W/m^2 is selected for a general case of magnetic component design where ferrite materials is used and natural cooling is used. The maximum working temperature is about 85°C, and the maximum ambient temperature as about 60°C. Such temperatures are typical for magnetic components working in confined enclosure.

Our first improvement is more accurate calculation of this coefficient for wider range of temperatures and cooling options. The proposed steps are valid when the following conditions are met:

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- The magnetic component is placed in such way, that the cooling air can easily move around it.
- There are no heat sinks mounted on the component.
- Only magnetic components with EE cores are used, with windings on the centre leg.

The following steps are carried out in order to determine the value of k_A.

- Calculate the surfaces involved in the heat transfer;
- Calculate theParameter L as the total distance of the boundary layer;
- Select the speed of the cooling air – v;
- Calculate the total emissivity of the surface of the component ε_T.
- Calculate the heat transfer
- Determine the value ofk_A.

Equivalent surfaces of an EE transformer - S_{conv} andS_{rad}

As there is no heat sink mounted on the component the heat transfer by conduction is neglected. The heat transfer by convection and radiation have different mechanisms, and as a result, two different surfaces are involved in the heat transfer - S_{conv} andS_{rad}. The surface, which is used in the heat transfer by radiation, is reduced compared to the convection surface, because the efficiency of the radiation is decreased in adjacent areas. The surface for convection takes into account all open areas, that can be cooled down by the incoming fluid. The formulas for calculating S_{conv} andS_{rad} are shown in Eq.2 and Eq.3 corresponding surfaces are shown on Fig.1, and the

$$S_{rad} = 2\left(4S_1 + 2S_2 + S_3 + 2S_4 + 2S_7 + 2S_8\right) \qquad (2)$$

$$S_{conv} = 2\left(2S_5 + 2S_6 + S_3 + 2S_4 + 2S_7 + 2S_8\right) \qquad (3)$$

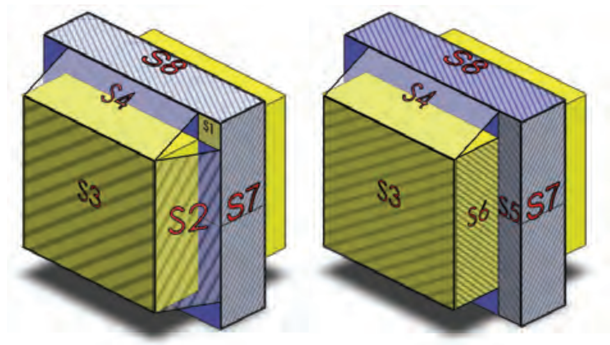

Fig.1Equivalent surfaces of an EE transformer, left for radiation; right for convection

The results for two transformers can be found in Table 1. The first chosen transformer is with core EE80 and ferrite soft magnetic material, while the second one is for nanocrystalline cut core - F3CC0010. As the F3CC0010 is UU type, 2 sets are used to make an EE core.

TABLE.1

EQUIVALENT SURFACES OF AN EE TRANSFORMER

Parameter	Unit	E80/38/20	F3CC0010
S_{rad}	mm^2	23820	16080
S_{conv}	mm^2	25580	17196
L	mm	120	94

One can see that the equivalent surface used in the convective heat transfer is about 7% larger, than the surface used for radiation.

Total distance of the boundary layer - L

This parameter is equal to the distance that the cooling air makes around the component. It is usually half of the shortest air path (in the direction of air) - Fig.2. For the transformer shown on Fig.2c), the total distance of the boundary layer is:

$$L = c + 2b - 2(b - f) + 2\sqrt{(b - f)^2 + \left(\frac{e - d}{2}\right)^2} \quad (4)$$

where:
a, b, c, d, e, f – are the dimensions of the core according to Fig.1

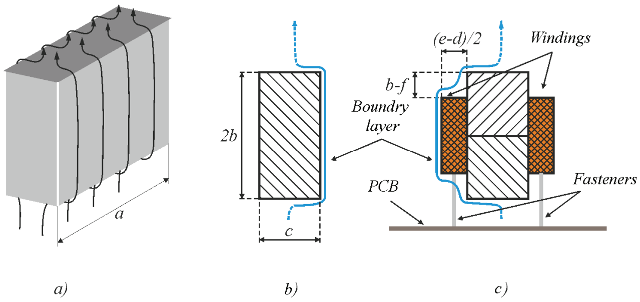

Fig.2 Total distance of the boundary layer

The results for the total distance of the boundary layerof the two cores, with the same orientation as shown on Fig.2c), are shown inTable 1.

Air velocity - v

To calculate the heat transfer, when force cooling is involved, the air velocity is needed. Usually the magnetic component is placed inside the enclosure of the equipment. With a particular fan that generates the airflow, one can calculate the air velocity, from the relationship between pressure rise and volume flow rate. However, it is difficult and time consuming to take into accounts all the variables that can influence the pressure rise. As a result, few experiments were conducted to investigate the air velocity in a real device. An inverter welding unit is chosen – S1700, manufactured by Struna Ltd. For comparison, an air duct with only one entrance and exit for the air is used. Simplified representations of both test setups are shown in Fig.3. The fan that is used to generate the airflow is PMD1212PMB1-A.

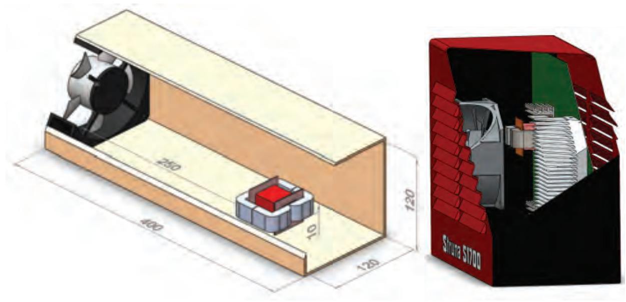

Fig.3Simplified representation of the two test setups

Two different transformers are used for the experiment. One of the transformer have a nanocrystalline core - F3CC0010, and the other a ferrite one - EE80. The winding fills about 60-70% of the window. Both transformers are placed in a way that allows the air to flow all around them. Several experiments are carried out with different rotation and position of the transformers, with or without additional components (PCBs, heat sinks, other large components) that simulates real device. The air velocity is measured at a distance of 1cm in front of the magnetic component with anemometer EA3000 with maximum error ±5%.

Table. 2 shows the results for the air velocity when the voltage of the fan is varied for two typical cases. The experiments are carried out relative humidity of air 65%, temperature 24°C, altitude 91mabove sea level.

TABLE. 2. AIR VELOCITY WHEN THE VOLTAGE OF THE FAN IS VARIED

Voltage of the fan		V	5	7	10	12	14	15
Air velocity	Air duct	m/s	1,9	2,7	4,1	4,7	5,4	5,6
	Welder	m/s	1,8	2,6	3,7	4,2	4,5	4,6

One can see that air velocity in the welding unit is about 10% lower than in the air duct. This important decrease in the velocity should be noted when the power dissipation of the magnetic components is calculated.

Heat transfer with forced cooling

When no cooling heat sink is mounded on the component, the conduction heat transfer can be neglected (only small percentage of the heat is transferred by the pins of coil former). The resulting heat transfer can be calculated by Eq.5.

$$q = q_{rad} + q_{conv} = \varepsilon_T \, \sigma \, S_{env} \left(T_w^4 - T_{amb}^4\right) + \alpha_c \, S_{conv} \left(T_w - T_{amb}\right) \quad (5)$$

where:

q_{rad}, $q_{conv}$is the heat transfer rate for radiation and convection;

ε_T – total emissivity of the material;

σ – Stefan–Boltzmann constant – $5{,}6704.10^{-8}$ [$W.m^{-2}.K^{-4}$];

S_{rad} – the radiating area [m^2];

S_{conv} –area for convection heat transfer [m^2];

T_w–temperature of the surface [K];

T_{amb}–ambient temperature[K];

α_c –convection heat transfer coefficient of the material;

A simplified equation is used to find the convection heat transfer coefficient of the material α_c[4]:

$$\alpha_c = (3,33 + 4,8v^{0.8})L^{-0.288} \qquad (6)$$

where:

L is the e total distance of the boundary layer;

v – velocity of the fluid.

When the total emissivity of the material is unknown, it can be determined by several different ways – with special paint, strips, or specialized tools. In the particular case, we use a specialized wireless non-contact infrared thermometer (PeakTech 5005USB), that can measure the temperature also with a thermocouple. The thermometer automatically calculates ε_T. The experiments shows $\varepsilon_T = 0,82$ for the tested nanocrystalline material and $\varepsilon_T = 0,96$ for the ferrites.

The expression (6)is consistent with the classical reference [5] up to v=12m/s as well with, "case 2" in [6]. The advantage of Eq. (6) is that it combines both natural ($v=0$) and forced convection ($v>0$) processes.

In the next calculations, it is assumed that the copper windings fill the window completely -the worst cooling case. The isolation between the windings is ignored in the calculations.

The areas S_2, S_3, S_4, $S_6$of the transformer shown in Fig.1 have total emissivity 0,80 (copper with enamel –[7]).

For all cut cores manufactured by Hitachi Metals (12 sizes) and all EE cores from Epcos (34 sizes), the corresponding heat dissipating capability is calculated. In the limited space of this paper, the results only for the cut cores of Hitachi Metals are shown in Table 3.

The following conclusions can be made.

- For natural cooling, the generated losses are dissipated effectively by radiation and convection. For transformers smaller than E32/16/9, more heat is dissipated by convection compared to radiation.
- For forced cooling, the losses dissipated by convection are several times more than those dissipated by radiation.
- When all conditions are same, the transformer with ferrite core can dissipate 5-10% more heat, because of the higher total emissivity.Nevertheless, the transformers with nanocrystalline soft magnetic materials have the advantage of higher working temperature.

TABLE 3. CUT CORES HEAT DISSIPATION CAPABILITY

T_w=120°C, ε_T=0,82; v=2,5m/s	T_{amb}=30°C					
	α_c	Q_{rad}	Q_{conv}	P_h	k_A	error
	W/ (m^2.K)	W	W	W	-	%
F3CC06.3	27,3	9,1	33,0	42,1	12809	-0,4%
F3CC0008	27,2	10,1	36,4	46,5	12765	0,0%
F3CC0010	26,3	11,5	40,7	52,3	12042	5,8%
F3CC016A	25,9	12,5	43,2	55,7	12831	-0,3%
F3CC016B	25,2	14,0	47,5	61,5	12209	4,7%
F3CC0020	24,9	15,0	50,1	65,1	12921	-0,8%
F3CC0025	24,5	17,7	58,5	76,2	11337	11,6%
F3CC0032	24,2	18,9	61,4	80,3	11942	7,0%
F3CC0040	23,9	20,1	64,2	84,3	12540	2,4%
F3CC0050	23,2	26,5	83,2	109,7	10342	19,6%
F3CC0063	23,0	28,0	86,6	114,6	10806	16,0%
F3CC0125	21,8	40,4	118,6	158,9	10426	19,2%

To find the value of the coefficient $k_A$the following equation is used:

$$k_A = \frac{P_h}{2ab} \qquad (7)$$

where:

$P_h$is the calculated dissipating capability of the magnetic component;

a, b– are the dimensions of the component according to Fig. 2.

The results presented in Table 3 are analyzed andF3CC0008 is chosen as a reference. In the calculations later, its value of $k_A$is used. Using this coefficient has the advantage of very simple calculatnion of the heat dissipation capability of the core. The error from using one coefficient for all cores is shown in the last column of Table 3. The same analysis is done for the EE cores and E20/14/5 is selected as a reference. On the next graph are presented the results for this error for both cut cores and EE cores.

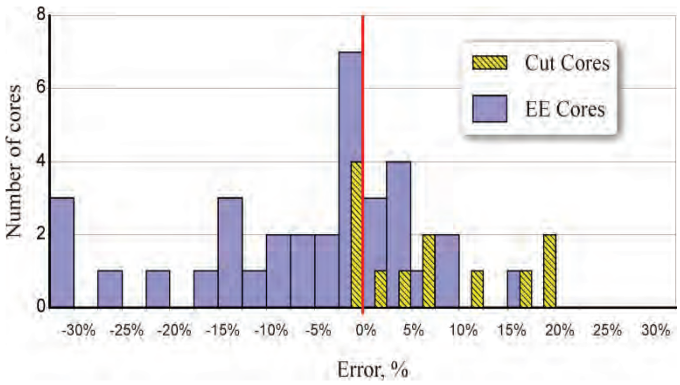

Fig.4 Distribution of the error from using one k_A: T_w=100°C (EE cores), T_w=120°C (cut cores), T_{amb}=30°C, v=0m/s, εT=0,96.

About 30% from the EE cores and approximately 40% from the cut cores have error less than ±2,5%. The largest error is observed when very little or very large cores are used, compared to the reference ones.

In all cases when high accuracy is required, it is best to calculate the results for the particular case. When using k_A some additional errors can influence the result. Sources of such errors are manufacturing tolerances, additional isolation, partial filling of the winding window and others.

Using the results for heat dissipating capability, two tables are built, that allows quick and easy determination of the coefficient k_A. The tables are for maximum ambient temperature of 30°C, but similar graphs can easily be drawn for any ambient temperature.

TABLE4. COEFFICIENTK_AACCORDING TO THE WORKING TEMPERATUREAND AIR VELOCITY, FOR NANOCRYSTALLINE CUT CORES, TAMB= 30°C

Nanocrystalline cut cores		**Air velocity,v[m/s]**					
		0	1	2	3	4	5
Maximal working temperature,Tw, [°C]	70	2080	3680	4860	5930	6930	7880
	80	2660	4660	6140	7480	8720	9910
	90	3260	5670	7450	9050	10540	11970
	100	3900	6700	8780	10650	12390	14050
	110	4560	7770	10140	12280	14270	16170
	120	5270	8860	11530	13940	16180	18320
	130	5990	9990	12960	15630	18130	20500

TABLE5. COEFFICIENT K_AACCORDING TO THE WORKING TEMPERATUREAND AIR VELOCITY, FOR FERRITE EE CORES, TAMB= 30°C

Ferrite EE cores		**Air velocity,v[m/s]**					
		0	1	2	3	4	5
Maximal working temperature,Tw, [°C]	70	2430	4390	5850	7160	8380	9550
	80	3110	5560	7380	9020	10550	12000
	90	3810	6760	8940	10900	12740	14480
	100	4550	7980	10530	12820	14960	17000
	110	5320	9240	12150	14770	17220	19550
	120	6120	10540	13810	16760	19510	22130
	130	6960	11870	15510	18780	21840	24750

III. FINDING THE PEAK INDUCTION $B_{P,DATA}$

In the original design methodology, the peak induction is taken from the datasheet of the material for specific temperature, frequency and core losses. However, this can lead to serious errors. The main reason for this is that the voltage waveform can influence the core losses. Usually the manufacturers' datasheets are for sinusoidal waveforms, while most of the power electronics nowadays work with square waveforms. Articles like [8], [9], [10]discuss this problem. Using the mathematical models for the core losses, proposed by the authors in [8], the peak induction $B_{p,data}$ can be calculated.

Using the core loss model for nanocrystalline and ferrite soft magnetic material is the second improvement to the "Fast design approach".

IV. CONCLUSION

In this paper, an improvement to the existing "Fast design approach" is proposed. Two of all fifteen steps are modified. As a result, the design of magnetic components with ferrite and nanocrystalline soft magnetic materials, with or without forced cooling is possible with the proposed improved methodology.

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