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Design of a Naturally Cooled High Frequency Integrated Magnetic Component

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Abstract—A methodology for designing naturally cooled high frequency integrated magnetic component is presented. Windings losses are analytically estimated, and then improved using Finite Elements calculation.

The component geometry determines the maximal temperature on the surface of component by taking account the natural air convection and radiation effects. During its thermal stability, a magnetic component (windings, core, and isolation) could have a homogenous temperature in all its parts because of the good thermal conductivity of copper and ferrites.

A prototype of 500 W, 48V half bridge integrated current-doubler rectifier is implemented. Component temperature was simply detected using infrared camera.

This methodology could easily be integrated in computer aided design tools recently developed for designing magnetic component.

I. INTRODUCTION

Automated conception for high frequency discrete magnetic components [1], [2], transformers and inductors, reduces time, effort, human errors and also it is more compatible with optimization lines.

For an integrated magnetic component, more difficulties will be introduced like the neighboring of inductor and transformer windings with different current waveforms in the window area and the air gapped effects. So more simplifications will be required to achieve a design methodology which can be integrated in such computer tools.

In this paper, we present a methodology for designing naturally cooled high frequency integrated magnetic structure. An application for 500 W, 48V half-bridge integrated current-doubler rectifier is implemented.

II. STRUCTURE OPERATION

The current-doubler rectifier, shown in Fig. 1, has been integrated into a single magnetic core [3], [4]. The overall efficiency treated in [3], [4], was simply studied using DC winding losses as a comparative point, so losses due to air gap effect and classical eddy currents (proximity and skin effects), were ignored.

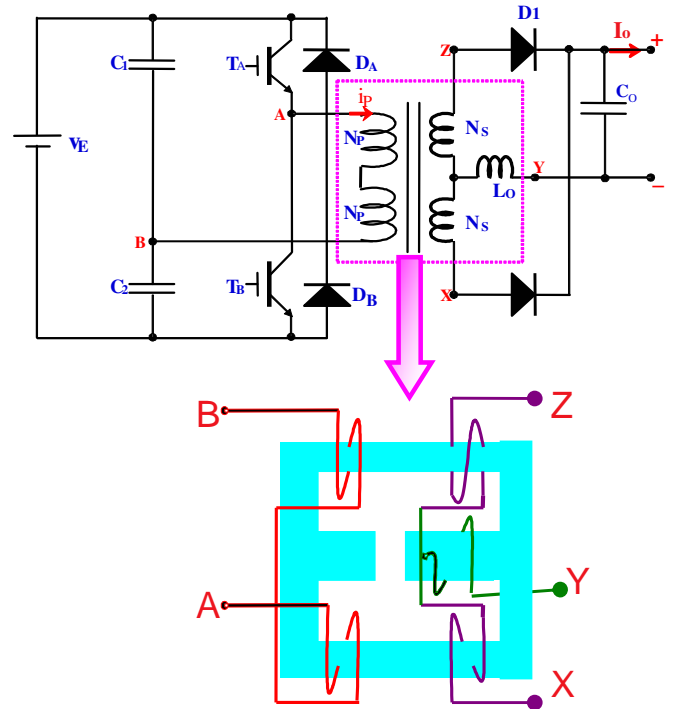


Figure 1: Half-bridge converter using current doubler rectifier with the integrated magnetic component.

III. DESIGN CONSIDERATIONS

A. Core specifications

1. Core material

A core material determines power losses as a function of magnetic inductions with frequency and temperature as parameters.

2. Core shape

Cores shapes influence directly on the electromagnetic emissivity and on the thermal dissipation through the outer surface to ambience.

B. Windings losses

To maintain the one dimensional solution of the magnetic field in the core window, we suppose the following:

1) Air gap effects could be neglected using the techniques proposed in [5],[6] where fringing flux can be modified and still very close to the air gap, hence the presence of one-dimensional magnetic field in the core window becomes evident.

2) The presence of one-dimensional magnetic field allows the primary and secondary winding losses to be estimated using Dowell [7] or Ferreira method.

3) For the center leg windings, conduction losses will only be considered because of the reduced output current ripple.

So for primary and secondary windings, losses could be estimated using the following expressions:

$$P_{cu} = \frac{\gamma}{2} \left[\left(\frac{\sinh \gamma + \sin \gamma}{\cosh \gamma - \cos \gamma} \right) + \left(\frac{\sinh \gamma - \sin \gamma}{\cosh \gamma + \cos \gamma} \right) \cdot (2m-1)^2 \right] \cdot R_c \quad (1)$$

Where $(\gamma = \Delta / \delta)$: Δ is the thickness of the foil and, δ is the skin depth, R_{dc} is the DC resistance of the foil layer and P_{cu} is the dissipated power from the m'th foil layer. For windings constructed using Litz wire, losses could be estimated using the expressions indicated in [8].

For the center leg windings:

$$P_{cuc} = R_{dc.c} I_o^2 \quad (2)$$

Where $R_{dc.c}$ is the total DC resistance of the center leg windings.

C. Heat transfer

Heat can be transferred through the component surface to the ambient by two ways: radiation and convection. Radiated heat could be estimated using Stefan – Boltzmann law defined as:

$$P_{rad} = 5.710^{-8} E \cdot A \cdot \eta \cdot (T_{max}^4 - T_{amb}^4) \quad (3)$$

Where E is the emissivity of the component surface, η presents the blockage effect of the desk, A is the total surface of the component in $[m^2]$ and T_{max} , T_{amb} are the maximal and ambient temperature respectively in Kelvin.

Thermal simulation of cubic objects using Flotherm shows that $\eta = 1$ for the upper horizontal surface, and $\eta = 0.5 \sim 0.7$ for low profile structures.

Free convection is expressed using Newton's law as:

$$P_{conv} = \theta A (T_{max} - T_{amb}) \quad (4)$$

Where θ is the average convection coefficient defined for horizontal and vertical positions [9], A is the vertical or horizontal surface area in (m^2) .

Power dissipated through the upper horizontal surface A_{up} is given as:

$$P_{con,h} = \theta_{up} A_{up} (T_{max} - T_{amb}) \quad (5)$$

The average convection heat transfer coefficient θ_{up} of the upper horizontal surface is given by:

$$\begin{aligned} \theta_{up} &= 0.55 \frac{(T_{max} - T_{amb})^{0.25}}{L_{cr}^{0.25}} \quad \text{for } Ra_L \leq 10^4 \\ \theta_{up} &= 0.61 \frac{(T_{max} - T_{amb})^{0.25}}{L_{cr}^{0.25}} \quad \text{for } 10^4 < Ra_L < 10^5 \\ \theta_{up} &= 0.68 \frac{(T_{max} - T_{amb})^{0.25}}{L_{cr}^{0.25}} \quad \text{for } 10^5 < Ra_L \end{aligned} \quad (6)$$

Where L_{cr} is the characteristic length of the horizontal surface, it is defined as:

$$L_{cr} = \frac{A_{up}}{P_{er}}$$

P_{er} is the perimeter of the surface in (m) and Ra_L is Rayleigh number.

These values of θ_{up} were empirically extracted using a thermal simulation tool (Flotherm) from 45 cubic objects with heights, lengths and widths varied from 5 (mm) to 150 (mm).

While A_{up} can be calculated as:

$$A_{up} = (w + 2\lambda)(2\lambda + l)$$

While l and w are the length and the width of the core in (m), λ is the width of transformer windings (primary and secondary) in (m), and can be calculated as:

$$\frac{S_{tr}}{S_w} = \frac{\lambda \cdot h}{b \cdot h} = \frac{k_{cu} (N_p S_p + N_s S_s)}{k_{cu} (N_p S_p + N_s S_s + N_c S_c)} \quad (7)$$

Where S_p , S_s and S_c are the wire sections of the primary, secondary and central winding respectively, S_{tr} and S_w are the surface area of transformer (primary and secondary) windings and window area respectively and h is height of windings area.

Recognizing that [10]:

The output voltage V_o is given as:

$$V_o = 2\alpha \cdot m V_{ab} \quad (8)$$

And secondary windings are calculated by:

$$N_s = 2mN_p \quad (9)$$

Central leg windings are given such:

$$N_c = \frac{L \cdot I_{o \max}}{B_{c \max} A_c} - \frac{N_s}{2} \quad (10)$$

Where m is the transformer ratio, L is the output filtering inductor and B_{cmax} is the magnetic induction in the centre leg.

Supposing that in all windings we have the same current density J , then:

$$S_p = I_{prms} / J, S_s = I_{srms} / J \text{ and } S_c = I_o / J.$$

Where J is the current density (A/mm²).

The *rms* values of primary secondary and central currents are:

$$I_{prms} = \sqrt{2\alpha} m I_o \quad (11)$$

$$I_{srms} = \sqrt{2\alpha + 1} \frac{I_o}{2} \quad (12)$$

$$I_{crms} = I_o \quad (13)$$

Where I_o is the out put current, and α is the duty cycle.

$$A_o = \frac{V_{ab}}{4 N_p B_{\mu \max}} \alpha T \quad (14)$$

$$A_c = 2 A_o \quad (15)$$

Where $B_{\mu \max}$ is the alternative magnetic induction in (T), A_o and A_c are the cross-sectional area of the outer and central leg in (m²).

Introducing the following factors:

$$k_{\mu} = \frac{B_{c \max}}{B_{\mu \max}} \quad (16)$$

$$k_{rip} = \frac{\Delta I_o}{I_o} \quad (16)$$

Where ΔI_o is peak to peak output current ripple.

Substituting (7, 15) in (6) and Multiplying by (A_c / A_c), we obtain:

$$\lambda = \frac{K_{\mu} K_{rip} (\sqrt{2\alpha} + \sqrt{2\alpha + 1}) b}{K_{\mu} K_{rip} (\sqrt{2\alpha} + \sqrt{2\alpha + 1} - 1) + 2(1 - 2\alpha)(1 + 0.5 K_{rip})} \quad (18)$$

Therefore, λ can be expressed in equation (16) as a fraction of the windings area width b , Fig. 2.

Then the power dissipated through the vertical surface A_v could be expressed as:

$$P_{con,v} = \theta_v A_v (T_{\max} - T_{amb}) \quad (19)$$

The convection heat transfer coefficient θ_v of the vertical surface is given by:

$$\theta_v = 1.42 \frac{\Delta T^{0.25}}{h^{0.25}} \quad (20)$$

Overall vertical surfaces can be determined as:

$$A_v = 2h(4\lambda + l + w) \quad (21)$$

Therefore, equation (17) can be rewritten as:

$$P_{con,v} = 2.84 h^{0.75} (4\lambda + l + w) (T_{\max} - T_{amb})^{1.25} \quad (22)$$

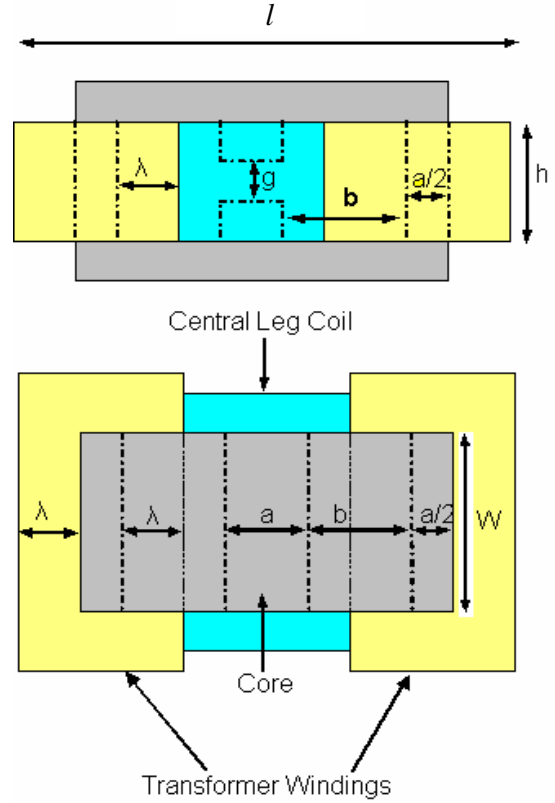


Fig.2. Perspective view of the integrated magnetic component with both core and windings.

IV. DESIGN PROCEDURE

A. Inputs Specifications

The input specifications required to begin the design are:

V_{ab} : Input voltage (V)

V_o : Output voltage (V)

P_o : Output Power (W)

f : Frequency in Hertz (Hz)

α : Duty cycle

K_{rip} : Output ripple factor ($K_{rip} = \Delta I_o / I_o$).

K_{μ} : Factor expressed as ($k_{\mu} = B_{cmax} / B_{\mu max}$).

T_{\max} , T_{amb} : Maximal and ambient temperature respectively.

B. Filtering Inductance L

The output inductance required to keep the output current ripple at the desired value is given by:

$$L = \alpha \frac{(mV_{ab} - V_o)}{f \Delta I_o} \quad (23)$$

C. Initial selection of core size

Product area A_p (window area $W_a \times$ core section A_c) is defined [10] as:

$$A_p = \frac{k_{cu}}{4J \cdot f B_{\mu\max}} (\sqrt{2\alpha} + \sqrt{2\alpha + 1} - 1) P_o + \frac{k_{cu} L I_{o\max} I_o}{B_{C\max} J} \quad (24)$$

Where arbitrary values of $B_{\mu\max}$, J and K_μ are determined to make an initial selection of core size. Core material was selected using the performance factor: $Pf = f \cdot B$

D. Turns

Transformer ratio m using (8)

Primary windings $2N_p$ using (14)

Secondary windings N_s using (9)

Central leg windings N_c using (10)

E. Air gap length:

$$g = \mu_0 \frac{(N_c + N_s / 2) I_{o\max}}{B_{C\max}} \quad (25)$$

F. Core losses

Core losses can be expressed as:

$$P_f = \gamma_f k_f f^{K_1} \left((B_{\mu\max} + \frac{\Delta B_c}{2})^{K_2} V_{outer} + 2^{K_1} (\frac{\Delta B_c}{2})^{K_2} V_{cent} \right) \quad (26)$$

Where K_1 , K_2 and K_f are constants supplied by manufacturers, γ_f is the mass density of the core material, V_{outer} and V_{cent} are the outer and central part of core volume respectively in (m^3).

G. Winding losses

Defining the turns, wires sizes and layers, then windings losses P_{cu} could be estimated using (1) and (2).

H. Maximal Heat Dissipation

Once the core is selected and all windings are calculated, then the maximal power dissipated P_{dis} can be calculated as:

$$P_{dis} = P_{conv} + P_{rad}$$

Where:

$$P_{conv} = P_{conv.v} + P_{conv.h}$$

$$P_{rad} = P_{rad.v} + P_{rad.h}$$

Thermal balancing at the desired maximal temperature T_{max} occurs when:

$$P_{dis} = P_{cu} + P_f \quad (27)$$

Note that we suppose that the maximal temperature is uniformly distributed on the component surface.

V. EXPERIMENTAL APPLICATION

The previous procedure was applied to design a half bridge integrated current-doubler rectifier with the following input specifications:

V_E (V)	V_o (V)	P_o [kW]	f (kHz)	K_{rip}	K_μ	T_{max} (°C)	α
380	48	0.5	150	20 %	65 %	85	43 %

The selected core is E43/10/28 planar, with $2N_p = 20$, $N_s = 7$ and $N_c = 3$. Primary windings (20 turns) are constructed using a foil of (7 mm x 0,2 mm) dimensions, secondary windings (7 turns) are constructed using a foil of (2// : 9 mm x 0,2 mm) and central windings (3 turns) with a foil of (2// : 4 mm x 0,3 mm). The converter is experimentally tested and also simulated using 2D finite elements tool.

Winding losses are obtained by using finite elements simulation and are equal to 10 W. Simulation results are presented in Table. I.

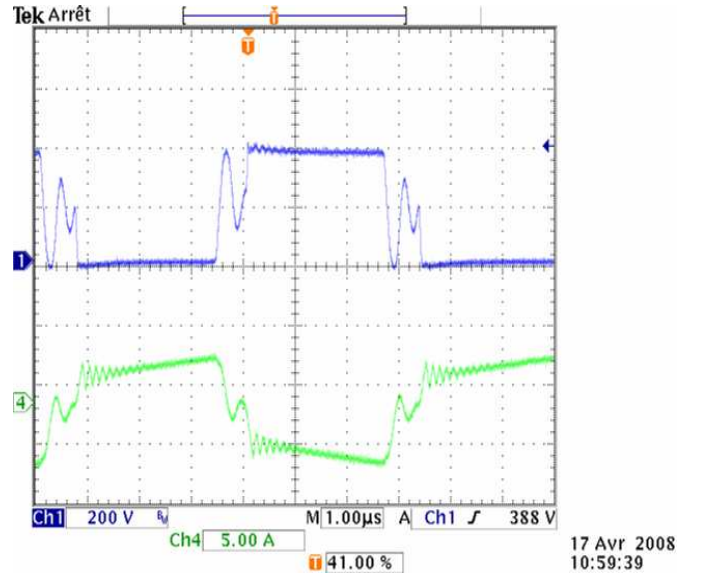


Fig. 3: Transistor voltage waveform in blue and primary current waveform in green.

TABLE I
ESTIMATED LOSSES IN THE 2D PLAN

	Primary losses (W)	Secondary losses (W)	Central leg winding (W)
2D Numerical estimation (single air gap)	4.23	5.6	0.178
Analytical estimation	3.5	3.86	0.091

Note that analytical estimation of the central leg winding in neglecting air gap effects equals 50% of the numerical estimation, but this difference equals 0.8% of global losses. The difference between the two proposed estimations could be explained, on the one hand, by the edge effect not taken into account in the analytical method and, on the other hand, by the difference between primary and secondary windings.

Magnetic losses are also calculated using (26):

$$P_f = 1.48 \text{ W}$$

Then total losses are:

$$P = P_{cu} + P_{cuc} + P_f$$

$$P = 11.48 \text{ W}$$

Core specifications are listed in Table II.

TABLE II
CORE SPECIFICATIONS

Core material	K_1	K_2	V_{outer} (m ³)	K_f	γ_f (kg/m ³)
3F3	1.24	2.6	10.8×10^{-6}	1.9×10^{-3}	4800

The heat dissipated through the natural convection and radiation is calculated using with an emissivity factor $E = 0.9$. Thermal specifications are listed in Table III.

TABLE II
THERMAL SPECIFICATIONS

T_{amb} (°C)	T_{max} (°C)	$P_{conv,v}$ (W)	$P_{conv,h}$ (W)	P_{rad} (W)
20	85	1.84	0.923	11

Then, the total dissipated power capability is 13.76 W.

Note that dissipated power is higher than total losses, but these losses are computed using 2D model.

The following image Fig. 4 presents the temperature distribution of the integrated magnetic component at the nominal power captured using infra-red camera. The maximal temperature is 87°C on the surface of transformer windings.

Thermal measurements show that there is no significant difference between windings temperature 88 °C and core temperature 82°C.

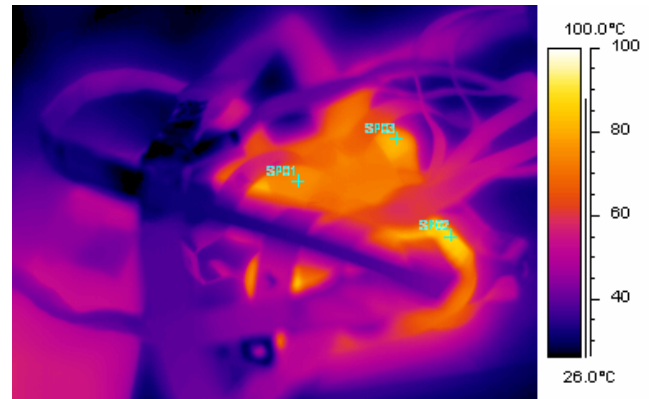


Fig. 4: Thermal image of the integrated component with its nominal power.

VI. CONCLUSION

A simple methodology of integrated magnetic component designing is presented. High frequency windings losses were analytically treated in adapting the one dimensional solution of magnetic field to the integrated structure, and the losses were also computed using a FE tool. Thermal dissipation by natural convection and radiation was exploited to achieve a thermal balancing at the desired maximal temperature. This methodology was applied to design a half-bridge converter with an integrated magnetic component. The operating temperature of the integrated structure was simply captured using an infra-red camera. This methodology can be integrated in a computer aided design developed recently for classical components.

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