Comparison and design of power electronics transformers in 25 kHz - 400 kHz range

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***Abstract*—The paper presents comparison and design considerations of power electronics transformers in 25 kHz - 400 kHz range. Improved design algorithm consisting of 15 steps is applied. Five designs of power transformers under the same input parameters are realized based on different frequencies: 25kHz, 50kHz, 100kHz, 200kHz and 400kHz. The material used is ferrite (N87). The design is aimed at minimizing losses and volume of the component. A set of parameters is defined to compare the obtained design results including operating and construction parameters. The obtained design results are verified by carried out simulations using FEM. Design conclusions and guidelines are derived based on the comparison of the carried out designs regarding the influence of operating frequency on the total parameters of the power transformers.**

Keywords—power electronics transformers, magnetic materials, power losses

I. INTRODUCTION

Magnetic components are among the most decisive components in power electronics equipment when targeting volume, losses and price of a device. The power electronics transformers have different parameters when varying the operating frequency. The influence of the frequency on the design is in a few directions- possibility to reduce the core size, but in the same time increasing eddy losses in the core and copper. The paper compares and guidelines the design of power electronics transformers in 25 kHz - 400 kHz range based on ferrites.

II. EDDY CURRENT CALCULATIONS

The critical aspect in such a wide frequency range is calculation of eddy current losses in wires. The traditional area-product method discussed by McLyman [1] does not consider enough eddy current losses in windings. Eddy current losses, including skin and proximity effects in transformers are discussed by Dowell [2] and many other papers [3], [4], which are related to some extent to Dowell's interpretation and results. Practical methods to model measure transformer core loss in high-frequency magnetic components are proposed in [5], [6], [7]. Thermographic analysis of power converters including all the components is presented in [8]. The purpose of the paper is to present advanced designs of power transformers for different frequencies and thus, to direct to corresponding conclusions of frequency influence on the main operating parameters. To calculate the eddy current losses in wires a novel approach is applied and further developed. The applied in the paper approach includes a global loss factor k_c, which represents the ratio between the eddy current losses compared to the losses in the ohmic resistance of the winding of a transformer

$$P_{eddy} = (R_0 \cdot I_{ac}^2)k_c \quad (1)$$

where I_{ac} is the AC current component, R_0 is the ohmic resistance of the winding and k_c is the global loss factor.

To facilitate the design procedure a set of graphs are derived presenting dependence of k_c on an aggregate coefficient K_{tf}, where $k_c \approx m_E^2 \cdot K_{tf}$. Fig. 1. and Fig. 2 present K_{tf}.

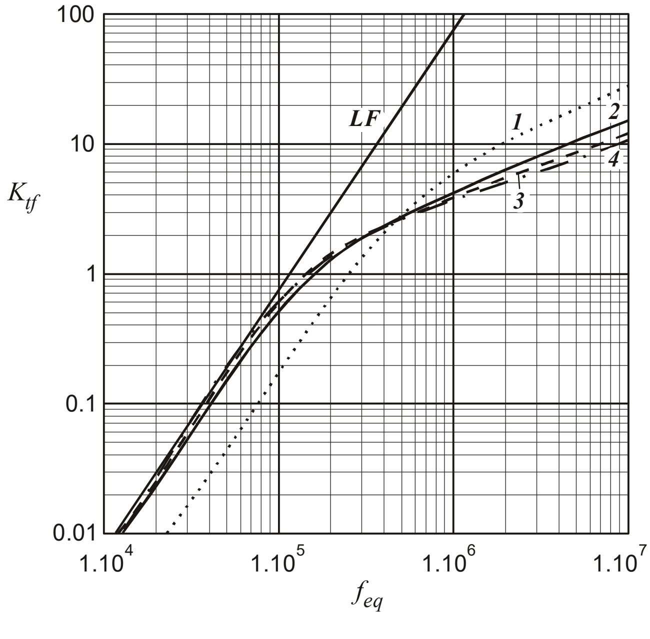

Fig. 1. Typical transformer factor K_{tf} for d = 0.5 mm, $\rho_c = 23 \cdot 10^{-9}$ Ω.m and λ = 0.5 at η = 0.9; 1) dotted line: half layer, m_E = 0.5; 2) solid line: single layer, m_E = 1; 3) dashed: two layers, m_E = 2; 4) dash-dot: three or more layers, m_E > 2. LF– low frequency approximation.

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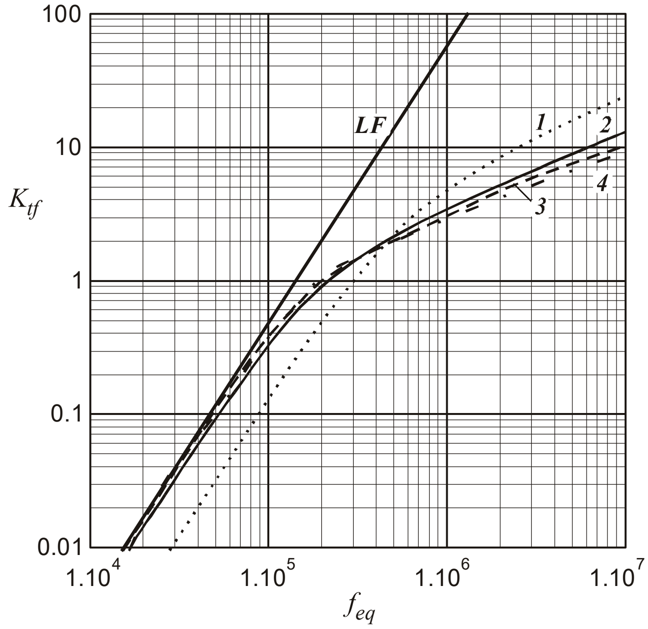

Fig. 2. Typical transformer factor K_{tf} for d = 0.5 mm, $\rho_c = 23 \cdot 10^{-9}$ Ω.m and λ = 0.5 at η = 0.7; 1) dotted line: half layer, m_E = 0.5; 2) solid line: single layer, m_E = 1; 3) dashed: two layers, m_E = 2; 4) dash-dot: three or more layers, m_E > 2. LF– low frequency approximation.

Parameters: p is the number of parallel wires, λ is copper filling factor in the direction perpendicular to the layer, η is copper filling factor in the direction of the layer, m_E (equivalent layer) and LF (low frequency approximation) are introduced and defined [9]. Equivalent frequency f_{eq} calculation is given as

$$f_{eq} \approx f_{op}\left(\frac{d_p}{0.5\,mm}\right)^2\left(\frac{23\times10^{-9}\ \Omega.\mathrm{m}}{\rho_c}\right) \tag{2}$$

where f_{op} is the apparent frequency, d_p is the practical wire diameter and ρ_c is the conductor resistivity.

The loss factor k_c depends on the operating frequency f_{op}, the wire diameter d_p and the distance between the conductors, presented by the parameter η, and the distance between the layers presented by the parameter λ.

III. Design Results and Set of Parameters

Five designs of power transformers under the same input parameters are carried out with ferrite cores (N87). Input design parameters: voltages and currents of the primary and secondary windings: $V_{prim,rms}$ = 300 V, $V_{sec,rms}$ = 100 V, $I_{sec.rms}$ = 12 A, f_{op} = 25 kHz - 400 kHz. A set of parameters of the power transformers is defined to estimate the results of the design and operating quality. The set includes core size and volume, losses, copper filling factor. For the calculations of the transformers an algorithm consisting of 14 steps is applied presented in [9]. The thermal calculations are carried out according presented in [10], [11] and [12] models. The obtained design results are summarized in Table 1. The obtained results of the analytical dimensioning and design five transformers at the frequency range 25 kHz - 400 kHz, P = 1200 W lead to following conclusions:

- increasing the frequency provides possibility for reducing the size, volume and total losses of the component;
- peak induction value $B_{ac,peak}$ is decreased with increasing the frequency, thus decreasing the core losses;
- eddy current losses in the wires are the main problem to be solved with increasing the operating frequency;
- optimization approaches to reduce the power losses in windings (interleaving, half layer) are strongly recommended, otherwise reducing the core size is impossible;
- using Litz wire is advisable for frequencies above 200 kHz to reduced total power losses.

IV. Simulatons and Experimental Validation

The heat transfer and magnetic field distribution in the designed components are modelled using FEM. The main operation parameters, temperature rise and magnetic field distribution are obtained. The results of the simulations of the six transformers (plus one extra at 300 kHz) are presented in Fig. 3. The presented results depict the field distribution in the different cores of the different transformers under the corresponding operating frequency. One of the design transformers is realized and measured. The losses are proved by alternative calorimetric measurements.

TABLE I. Design parameters of five transformers at frequency range 25 kHz - 400 kHz, P=1200 W

Design		Core dimensions [mm]	Component weight (core+copper) [g]	$B_{ac,peak}$ [T]	Turns number P/S	Core losses [W]	Copper losses [W]	Total losses [W]	Copper filling factor
f_{op} [kHz]	Core type								
25	E core	65/32/27	677,746	0,14	32 / 11	5,807	5,462	11,269	0,17
50	E core	55/28/21	335,704	0,122	36 / 12	3,792	3,771	7,563	0,223
100	E core	55/28/21	305,473	0,085	26 / 9	3,792	3,532	7,324	0,134
200	E core	55/28/21	282,013	0,057	19 / 7	3,792	3,707	7,499	0,073
400	E core	47/20/16	142,942	0,04	21 / 7	2,089	2,118	4,207	0,276

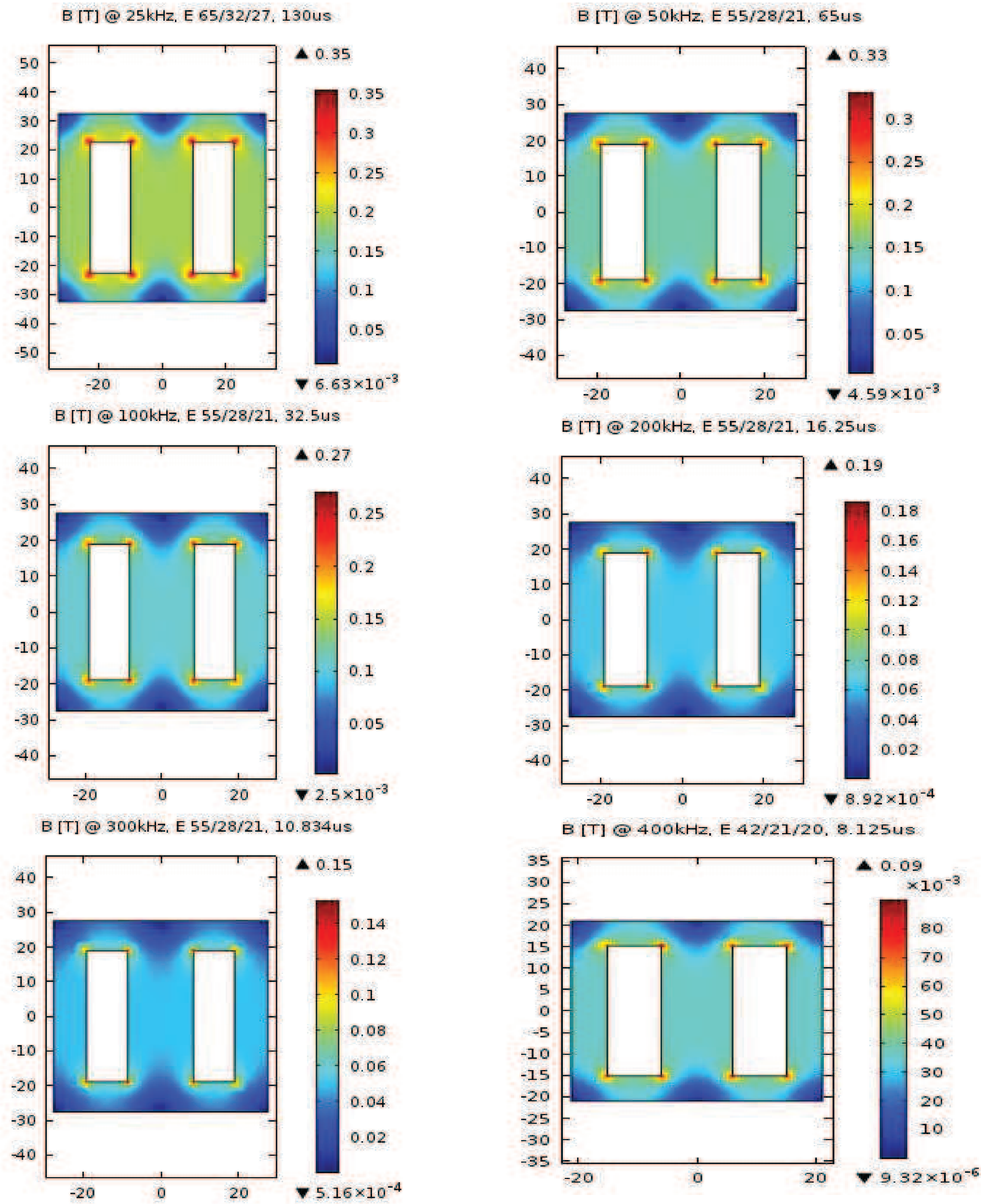

Fig. 3. Magnetic field distribution in the core of the transformer, for different cores and corresponding frequencies:
25kHz; 50kHz; 100kHz; 200kHz;300kHz;400kHz

CONCLUSIONS

The purpose of this paper is the comparison and design guidelines of power electronics transformers in 25 kHz – 400 kHz range. Improved design algorithm consisting of 15 steps is applied including a copper loss factor reflecting eddy current losses in windings. Five designs of power transformers under the same input parameters are calculated on different operating frequencies: 25 kHz, 50 kHz, 100 kHz, 200 kHz and 400 kHz. A set of parameters is defined to compare the obtained design results including operating and construction parameters. The obtained design results are verified by carried out simulations using FEM. Design guidelines are derived based on the influence of operating frequency on the total parameters of the power transformers:

- increasing the frequency, combined with optimization design procedure yields reducing the component weight and size;
- optimization approaches to reduce the power losses in windings (interleaving, half layer) are strongly recommended, otherwise reducing the core size is impossible;
- using Litz wire is advisable for frequencies above 200 kHz to reduced total power losses.

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