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THE EFFECT OF THE COAXIAL TRANSFORMER DESIGN ON THE WINDING CURRENTS DISTRIBUTION AND FLUX DENSITY

Summary. The novel construction of the modular concentric transformer for power electronics is described and analyzed in the paper. Proposed design of the transformer is dedicated for high frequency (the best results are in the range of 500 kHz to 3 MHz). The transformer has two windings made of concentrically arranged, thin-walled pipes, formed as a multi-turn spiral and put into magnetic core. The primary (inner) turns are connected in series and secondary (outer) ones are connected in parallel. The transformer described in the paper has turn-to-turn ratio 2:1, but in general the turn ratio can be different. The transformer is of high efficiency (above 98%) and very high ratio of windings coupling (about 0,998). High power density (above 100 kW/kg) for output power about 5 kW is its additional advantage. The paper is focused on influence of the shape and arrangement of the windings and magnetic core on the transformer properties. The results of analysis (efficiency, output power and power density) determine optimal design of transformer with respect of relevant transformer parameters. The analysis is based on FEM and is carried out using ANSYS software. The selected results of FEM analysis (in particular parameters of the equivalent circuit of the transformer) are compared with the results of the laboratory measurements.

WPŁYW SPOSOBU KONSTRUKCJI NA ROZKŁAD PRĄDU ORAZ GĘSTOŚĆ STRUMIENIA TRANSFORMATORA WSPÓŁOSIOWEGO

Streszczenie. W artykule przedstawiono sposób budowy i analizę nowej współosiowej konstrukcji transformatora modularnego. Konstrukcja ta przeznaczona jest do pracy przy wysokiej częstotliwości (najlepsze właściwości w zakresie 500 kHz do 3 MHz). Uzwojenia transformatora wykonane z cienkościennych współosiowych rur, uformowane w kształcie spirali, umieszczone są wewnątrz rdzenia magnetycznego. Zwoje pierwotne (wewnętrzne) połączone są szeregowo, natomiast zwoje wtórne (zewnętrzne) równolegle. Opisywany transformator posiada przekładnię zwojową 2:1. Charakteryzuje się wysoką sprawnością (około 98%), bardzo wysokim współczynnikiem sprzężenia uzwojeń (powyżej 0,99) oraz bardzo dużą gęstością mocy (powyżej 100 kW/kg) przy mocy wyjściowej około 5 kW. Artykuł skupia się na analizie wpływu rozmieszczenia i kształtu uzwojeń na właściwości transformatora. Analiza przeprowadzona została w oparciu o metodę elementów skończonych. Wybrane elementy analizy porównano z wynikami eksperymentu laboratoryjnego.

1. INTRODUCTION

The transformers are often used in high frequency power electronic conversion. In order to obtain the best possible efficiency and power density in the transformers power electronics is looking for new designs [3, 4, 5]. The different designs are known, for example, planar, PCB, flat and coaxial ones [3]. The concentric spiral transformer, described in details in [1, 2], is the example of this type of design. This design is characterized by modular structure and very high ratio of windings coupling, the higher in comparison with above mentioned solutions [3, 4, 5]. Although preliminary investigations of the coaxial transformer have already been carried out [1, 2] the further analysis of this solution is still required.

The first paper [1] describes in details basic coaxial design of the concentric transformer and shows its particular advantages. The second paper [2] reports the results of analysis where the influence of two parameters diameters D and d_{io} (fig. 2) on the transformer properties. The certain optimum was obtained there as the result. This optimum is the starting point the analysis presented in this paper.

This paper focuses on two main problems. The first one is related to current density in the windings and its influence on power losses, while the second problem concerns the distribution of flux density in the magnetic core and its influence on power losses of the transformer.

Aforementioned features in turn are function of the shape and dimensions of the windings and magnetic core. The analysis results in an optimal shape that ensures the highest efficiency and the highest power density. The analysis was carried out using ANSYS software [7] (based on Finite Element Method (FEM)). Results obtained by means of computation are compared with the results of measurements.

2. DEFINITIONS

The following definitions have been formulated for the purposes of this work:

a) *Concentric arrangement* (C): Arrangement of windings, made of circular pipes, in which cross section of the windings is concentric (and where the outer pipe is secondary and inner one is primary) Also cross section of the magnetic core is concentric with cross section of windings. This arrangement is called also as *basic arrangement* (B); cf fig. 2.
b) *Oval concentric arrangement* (OC): Arrangement of windings, made of oval (noncircular) pipes, in which cross section of the windings and magnetic core is concentric; cf fig. 9a.
c) *Non-concentric arrangemen*t (NC): Arrangement of windings, made of pipes of circular cross section, where cross section of primary (inner) is non concentric in relation to the secondary (outer), while cross section of magnetic core is concentric to the cross section of the secondary (outer winding); cf fig. 9b.

* *transformer* (*T) : Transformer that is characterized by * relevant arrangement. For instance, transformer with oval concentric arrangement is called *oval concentric transformer* (OCT). The transformer with basic arrangement of the windings will be called as *basic transformer* (BT) for given magnetic core selected in [6].

3. DESCRIPTION OF THE BASIC TRANSFORMER (BT)

The basic transformer (BT) is a kind of reference in this work. Fig. 1 and fig. 2 depict it in details. The transformer is made of two concentrically arranged pipes put into ferrite core. It forms spiral. Thickness of the windings is calculated from skin depth at optimal frequency (1 MHz). This frequency was calculated in previous analysis [1].

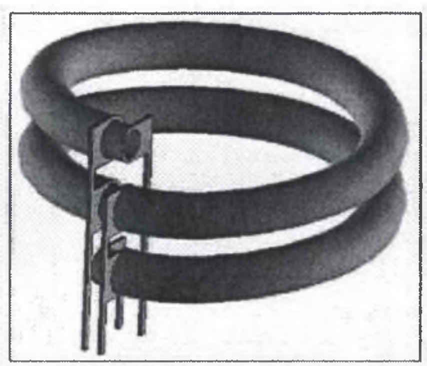


Fig. 1. Windings of the basic transformer (BT) (without magnetic core)
Rys. 1. Uzwojenia konstrukcji bazowej transformatora (bez rdzenia)

The windings are separated by thin layer of insulation. The primary winding (inner) is a one piece spiral. The secondary winding (outer) is also a spiral being divided into two parts. One can observe that the transformer looks like two transformers of 1:1 turn-to-turn ratio. Their primary windings are connected in series while secondary ones in parallel.

The windings are made of copper and the magnetic core is the Philips ferrite 3F4. The insulation is made from silicon dioxide SiO_2. The constructional data of the basic transformer is as follows (cf fig. 2): number of primary turns: $n=2$, height $H=20\ mm$, outer diameter $D_o=40\ mm$, (average) diameter of windings $D=30\ mm$, outer diameter of cross-selection of outer winding $d_{oo}=5\ mm$, outer diameter of cross-selection of magnetic core $d_c=10\ mm$, thickness of windings $\delta=0.15\ mm$ and thickness of insulation $\delta_i=0.1\ mm$. The thickness δ is equal $\delta=d_{oo}-d_{oi}=d_{io}-d_{ii}$ and the thickness of insulation δ_i is defined as $\delta_i=d_{oi}-d_{io}$.

In order to use 2D ANSYS model the simplification of the construction was needed where axial symmetry is assumed.

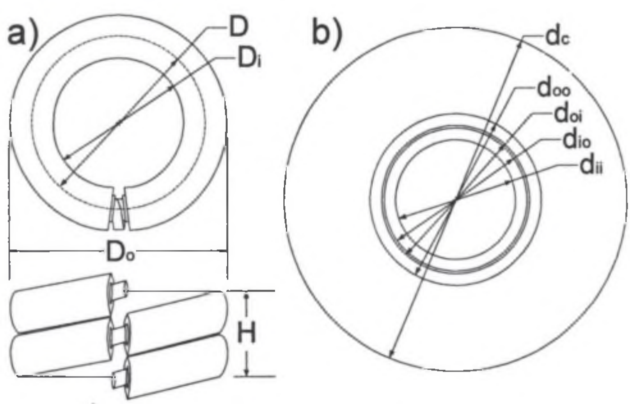


Fig. 2. Dimensions of the basic transformer (BT): a) top and front view; b) cross section of the windings and magnetic core

Rys. 2. Wymiary konstrukcji podstawowej transformatora (BT): a) widok z góry i z boku, b) przekrój przez uzwojenia i rdzeń

4. ANALYSIS OF BASIC TRANSFORMER (BT)

Analysis of basic transformer (BT) is the reference for the other constructional variants, oval (OT) and non-concentric (NCT). Described here, in this section analysis is also description of the applied method of analysis. The whole analysis is based on Ansys software.

The most essential quantities which describe properties of transformer are efficiency and power density. These quantities are mutually related and defined by admissible power losses. Total power losses of the transformer are generated in two places: in the windings and in the magnetic core. Admissible power losses are determined by the performance of given cooling system. The results of calculations in this chapter are carried out for 1 MHz.

4.1. Power losses in the windings

Calculations of the power losses in the windings are based on the equivalent circuit of the transformer described as two-port network by formula (1).

$$\begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ -I_2 \end{bmatrix}. \qquad (1)$$

The parameters of matrix Z are calculated from values of voltages and currents of the transformer for the idle and short circuit states using ANSYS. The lossless magnetic core was assumed at this stage of analysis. The subsequent calculations were done basing on circuit model of two-port network. Then the efficiency was determined as function of the output current (or load resistance) for the constant input voltage. After that, winding losses vs input voltage were calculated for chosen load resistance producing maximal efficiency.

4.2. Power losses in the magnetic core

The power losses in the magnetic core depend on peak value of flux density and that in turn is the function of amplitude and frequency of input voltage. The peak of flux density in magnetic core in the basic transformer at input voltage of 210 V of amplitude and 1 MHz and at 1 Ω of load is depicted in fig. 3b.

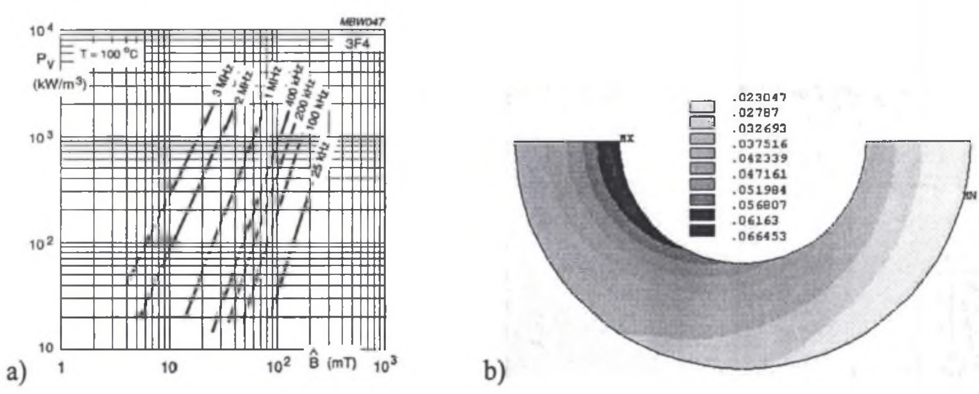


Fig. 3. The specific power losses (a) and distribution of flux density (b) in the magnetic core
Rys. 3. Jednostkowe straty mocy (a) oraz rozkład indukcji magnetycznej (b) w rdzeniu

The specific power losses in the core are given by (2), where k is a coefficient for unit conversion (fig. 3a).

$$P_V = k\, f^{1.3}\, B_{max}^{2.5}\,. \tag{2}$$

The actual specific losses versus peak of flux density for given frequency is take from data shit given in [6] - fig. 3a. The core losses are calculated by ANSYS using on formula (2).

4.3. The total power losses in the transformer

The total power losses are obtained by summation of both components of the power losses, i.e. in windings and in magnetic core. They depend on input voltage (fig. 4). The maximum input voltage that is the rated value is determined from this characteristic for total power losses equal to admissible losses.

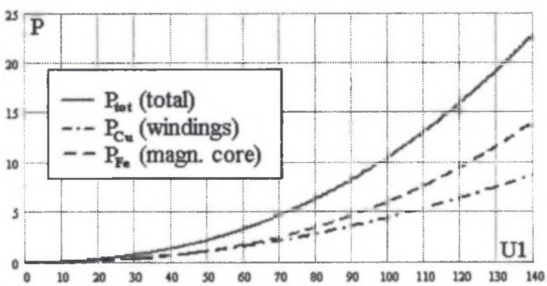


Fig. 4. The power losses in the basic transformer (BT) versus input voltage (rms value)
Rys. 4. Zależność strat mocy w transformatorze (BT) od napięcia zasilającego (rms)

4.4. Efficiency and output power of the transformer

The efficiency of the transformer was calculated using formula (3). The input power P_1 was obtained from calculations based on the two-port network model of the transformer. It was performed for rated input voltage and the load resistance for which efficiency is maximal.

$$\eta = \frac{P_1 - P_{tot}}{P_1} \cdot 100\%\,. \tag{3}$$

The efficiency versus output power is depicted in fig. 5. The point A represents efficiency at rated output power of the transformer. It is the highest value of efficiency (99,65% for ~75 A).

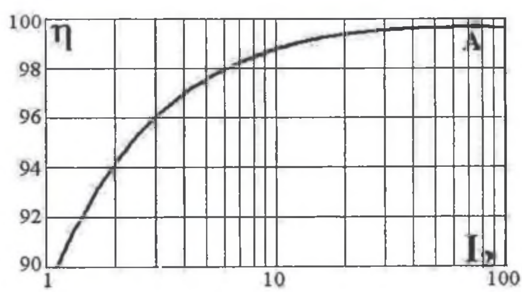


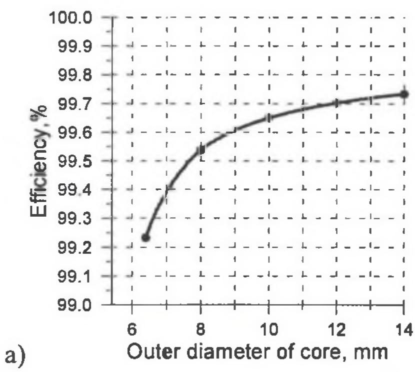
Fig. 5. The efficiency versus output current (BT)
Rys. 5. Sprawność transformatora (BT) w funkcji prądu wyjściowego

The output power is calculated as difference between input power and power losses. The output power is proportional to output current squared. The power density is calculated as output power related to the mass of the transformer (kW/kg).

5. ANALYSIS OF MODIFIED BASIC TRANSFORMER (BT)

The chapter is devoted to analysis of the influence of magnetic core volume on the features of the basic transformer. Modification means that only outer diameter d_c of the core is changed in basic transformer (5,6 mm – 14 mm).

The lower value of outer diameter d_c is limited by admissible flux density in the magnetic core - 0,1 T (below saturation) and it is equal to 6,4 mm. Such diameter corresponds to thickness of the magnetic core 0,5 mm. The upper limit of outer diameter was chosen arbitrary 14 mm. It may result for instance from constrain imposed on symmetry of secondary windings.



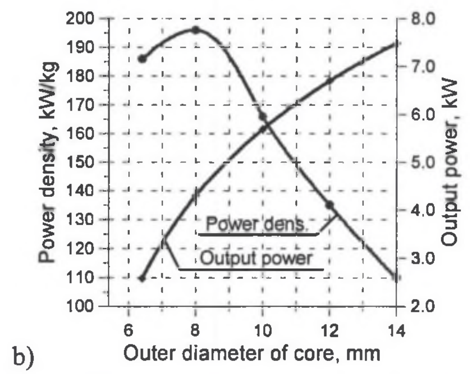


Fig. 6. The efficiency (a) and power (b) of the transformer vs outer diam. d_c of magnetic core
Rys. 6. Sprawność (a) i moc transformatora (b) jako funkcja średnicy d_c rdzenia

Table 1

Calculation parameters for characteristics in fig. 6

Diameter d_c[mm]	Input voltage (rms) [V]	Load resistance [Ω]
6,4	94,3	0,43
8	110,9	0,71
10	146,4	0,94
12	171,6	1,10
14	192,2	1,23

The results of the analysis are depicted in fig. 6. The first characteristic (fig. 6a) shows efficiency vs outer diameter of magnetic core. The efficiency slightly arises with diameter of core. The second one (fig. 6b) depicts output power and power density in the transformer vs outer diameter of the core. The output power increases with diameter d_c and with the volume of core. Simultaneously the power density increases for d_c<8 mm and decreases above this value of d_c. Analysis of fig. 6b reveals that there is no simple answer which value of outer diameter is the best solution. If someone searches for higher power density the best solution is in the range of small value of d_c. In case the objective is to obtain highest possible power, for given windings, the best solution is in the region of high d_c. What is more for higher diameters of the core give very low values of flux density, about 1/10 of admissible. The calculations of characteristics in fig. 6 were carried out as follows. The input voltage and load resistance were adjusted to obtain total losses equal to admissible value. The table 1 contains these values. It is necessary to remind that d_c for basic transformer is 10 mm.

6. ANALYSIS OF OTHER CONSTRUCTIONAL VARIANTS OF THE TRANSFORMER

The analysis includes influence of windings shape (circular and oval windings) and windings arrangement (concentric and non-concentric arrangement) on transformer characteristics. Two mentioned constructional variants are analyzed: oval concentric and circular non-concentric

6.1. Oval concentric transformer (OCT)

The power losses locally depend on current density distribution. The shape of the windings changes the current density distribution in the windings. The distribution of losses in the windings of basic transformer is non-uniform. Change of winding shape such as in fig. 7a may lead to more uniform distribution of the current and lower losses.

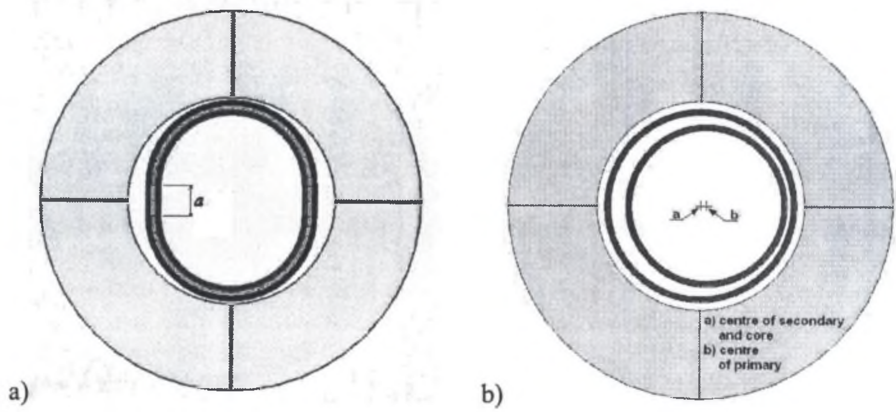


Fig. 7. The cross section of transformer (a) oval concentric (OCT); (b) non-concentric (NCT)
Rys. 7. Przekrój transformatora a) koncentrycznego owalnego oraz b) niekoncentrycznego

The changes of windings shape in oval transformer consist in "flatting" lateral parts of windings. It produces windings in the shape described by "a" parameter - fig. 7a. The a is called oval rate. It ranges from 0 to 1 mm. The windings circumference and volume is the same in all cases of analysis and equal to these parameters of the basic transformer.

The result of the analysis, output power, is depicted in fig. 8. It slightly changes with oval rate. It has maximum around oval rate equal to 0,7 to 0,8 mm. The oval rate a=0 means the basic transformer. Possibility of increasing of output power in comparison with basic transformer can be exploiting in engineering practice.

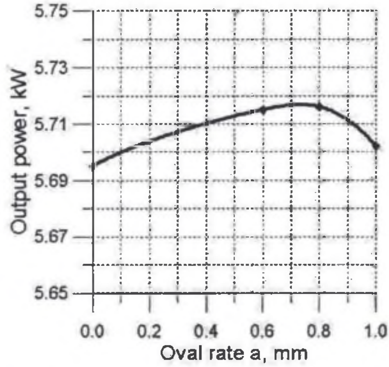


Fig. 8. Output power versus oval rate in OCT transformer
Rys. 8. Moc wyjściowa transformatora jako funkcja współczynnika owalności *a*

6.2. Circular non-concentric transformer (NCT)

The another way to obtain uniform current distribution in the windings of the transformer is non-concentric windings arrangement (NCT) - fig 7. It is described by the distance between centers of primary "a" and secondary "b" cross-sections. The sample of current distribution in the windings for centers' distance 0,0125 mm is given in fig. 9b.

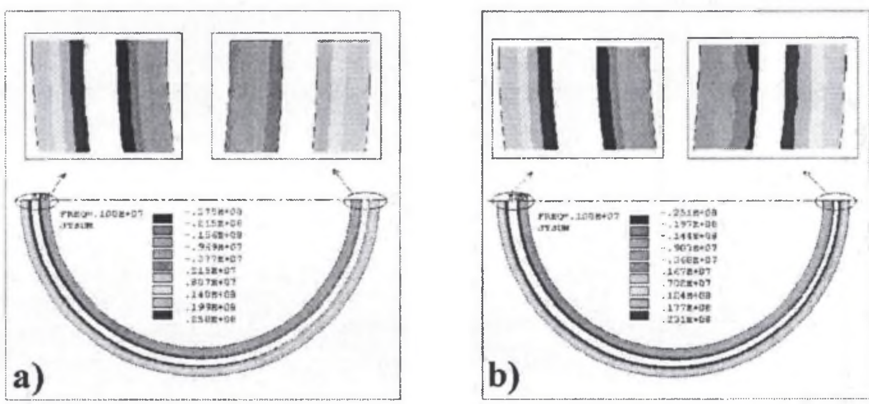


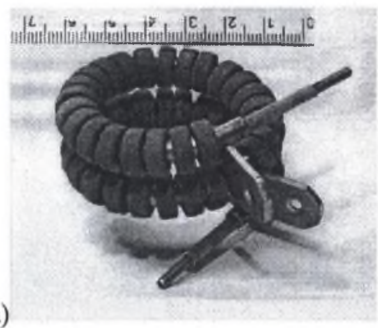
Fig. 9. The distribution of the current in the windings of (a) BT and (b) NCT arrangement
Rys. 9. Rozkład prądu w uzwojeniach transformatora o konstrukcji (a) BT (b) NCT

The analysis reveals that non-concentric arrangement is not the way of improving properties of the transformer, i.e. efficiency and power density. The uniform of current distribution for given centers' distance can be obtained only for particular load.

7. SELECTED RESULTS OF THE MEASUREMENT

In order to verify the computational results the prototype transformer has been designed and built - fig. 10a. Then measurement of the parameters of equivalent circuit as two-port network has been carried out. The results of the measurement are compared with the results from computational analysis.

This transformer is made from copper pipes insulated by glass fiber insulation. Thickness of inner pipe is 0,5 mm and thickness of outer one is 1 mm. The dimensions are considerably greater than those of the basic transformer. The corresponding ANSYS model was created and analyzed.

a) 

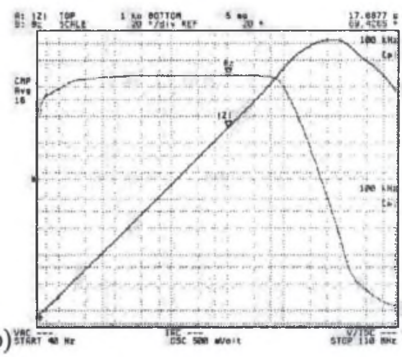
b) 

Fig. 10. The prototype transformer (a) and its |Z| and θ characteristics vs frequency (b)
Rys. 10. Prototyp transformatora (a) i jego charakterystyki częstotliwościowe |Z| i θ (b)

The measurement was done using Impedance Analyzer HP4294A in the range of 40 Hz to 110 MHz. Sample result, the impedance |Z| and phase angle θ, as a function of frequency, measured on the primary with secondary open is depicted in fig. 10b. In this case the transformer is described by R, L connected in series.

Fig. 10b indicates resonance at ~10 MHz. It is due to parallel resonance phenomena in the transformer (with parasitic capacitances). At very high frequencies capacitances of transformer considerably influence on the transformer properties.

Table 2 contains the results of ANSYS analysis and measurement. For 100 Hz resistance R_1 and inductance L_1 of the primary winding, ratio of the windings coupling *k* and secondary-to-primary voltage ratio of the transformer ϑ are given there. Basically the results are in good agreement except of resistance of R_1. The differences in R1 are result from additional resistance of clamp connections that were not included in the computational analysis. Besides, the differences are caused by non-regular of the construction in the area the clamps are connected to the pipes.

Table 2

Selected parameters of transformer

Frequency	**Parameter**	**ANSYS**	**Experiment**
DC	R_{1DC}	1,72 mΩ (calculated from geometry)	
100 Hz	R_1	1,84 mΩ	2,96 mΩ
	L_1	27,86 μH	28,05 μH
	K	0,9969	0,9959
	ϑ	2,00	1,941
100 kHz	$\lvert Z_{11}\rvert$	17,49 Ω	18,47 Ω
	$\lvert Z_{22}\rvert$	4,37 Ω	4,97 Ω
500 kHz	$\lvert Z_{11}\rvert$	85,5 Ω	90,4 Ω
	$\lvert Z_{22}\rvert$	21,46 Ω	24,7 Ω

Additionally DC resistance R_{1DC} of windings is calculated from geometry. Its value is considerably close to the R_1 at 100 Hz.

8. CONCLUSIONS

The following conclusions are the results of the analysis:

1. The coaxial transformer characterizes very high efficiency (above 98% in broad range of loads), high output power (around 5 kW at 1MHz of frequency) and very high power density (above 100 kW/kg - it is the highest value in comparison with the density of known constructions, see [3])
2. The volume of magnetic core strongly influence on the transformer properties. The output power increases and power density decreases with increasing of volume of core.
3. The windings shape influence on properties of the transformer. The oval shape of windings improves slightly (around 0,3%) rated output power and it has maximum at 5,72 kW.
4. The non-concentric arrangement of the windings causes uniform current density in the windings at particular value of load resistance and not improves radically output power of the transformer.
5. Results of the experimental measurement confirm results of numerical computation. Slight differences result from simplification of computational model to 2D.

Very good properties of transformer are an encouragement for further investigations that should embrace fabrication of experimental model with very thin layer of isolation between primary and secondary and its measurement at full predicted output power.

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Recenzent: Prof. dr hab. inż. Sławomir Wiak

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