ZESZYTY NAUKOWE POLITECHNIKI ŚLĄSKIEJ 2005
Seria: ELEKTRYKA z. 198 Nr kol. 1709

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# COAXIAL TRANSFORMER FOR POWER ELECTRONICS – TECHNOLOGY OF PROTOTYPE AND ITS CHARACTERISTICS

**Summary.** The coaxial transformer for high power conversion is the aim of this work. The paper contains an idea of the transformer, its novel technology and characteristics. The coaxial transformer is a system of coaxially arranged pipes divided by a thin layer of electrical insulation. The transformer has high efficiency of 98% within the broad range of load, high power density, approx. 75 kW/kg, good coupling and small leakage inductances (FEM). The experimental transformer is a practical verification of this idea. The novel method of manufacturing technology is developed for the presented transformer. The characteristics of the prototype transformer presented in this paper are primarily efficiency and power density. The transformer properties are determined on the basis of FEM simulations and measurements. The experimental results are compared with those obtained from FEM analysis.

# WSPÓŁOSIOWY TRANSFORMATOR ENERGOELEKTRONICZNY – TECHNOLOGIA WYKONANIA I JEGO CHARAKTERYSTYKI

**Streszczenie.** Przedmiotem pracy jest transformator energoelektroniczny dużej mocy. W pracy opisano ideę transformatora, zaproponowano nowoczesną technologię jego wykonania oraz opisano podstawowe właściwości. Transformator współosiowy jest układem współosiowych rur przedzielonych warstwą izolacji. Taki układ zapewnia dobre sprzężenie między uzwojeniami oraz minimalizuje straty mocy w uzwojeniach. Opisywany w pracy transformator charakteryzował się sprawnością powyżej 98% w szerokim zakresie obciążeń oraz gęstością mocy około 75 kW/kg (FEM). W celu potwierdzenia korzystnych właściwości transformatora zbudowano jego prototyp. W pracy zaproponowano nowoczesną technologię wykonania transformatora, polegającą na odpowiednim nanoszeniu cienkich warstw. Podstawowe charakterstyki transformatora opisywane w pracy to sprawność i gęstość mocy. Wyniki pomiarów porównane zostały z wynikami symulacji komputerowych MES.

## 1. INTRODUCTION

The high frequency power conversion requires that the transformers should have better performances than the standard ones. The following parameters: power/mass [kW/kg], power/volume [W/cm$^3$], efficiency, coefficient of coupling and frequency dependent voltage ratio allow estimating these performances. A coaxial transformer has been examined many times, e.g. [2] to [6]. It has been proved that transformers proposed in [4, 5] and [6] exhibit better properties than multiturn solutions described in [2] and [3]. In previous works the authors of this paper were mainly concentrated on the systematic computational analysis of the coaxial transformer of their design [4, 6]. It is based on a primitive transformer where primary and secondary are of one turn and both are made of tube. Primary pipe is inside the secondary. The paper is devoted to experimental examination of this transformer (with magnetic core). The spiral and linear forms of the transformer are discussed at the beginning. Then technology of its fabrication is presented. After that, an experimental linear transformer is specified. The results of FEM analysis of the experimental linear transformer are given in the subsequent section. Next step delivers the description of the experimental set up (HF inverter, calorimeter, etc.). One before last section contains measurements results. Conclusions are the last part of the paper.

## 2. OVERVIEW OF THE SUBJECT

The coaxial transformers reported in literature are designed for high frequency, but predominantly for low power applications, i.e. in telecommunications [1]. The coaxial transformers are known also for higher power applications, [2, 3, 5] but they operate within a low frequency range (10 to 100 kHz). The transformer presented in [2] dedicated to contactless energy transfer was experimentally verified at 10 kW. Its properties are presented in Table I under the name "Universal". The transformer presented in [3] - "Actively cooled" is of similar construction. Because of water cooling it has relatively high output power, 120 kV·A. A third coaxial transformer reported in literature [5] is a product of ABB Corporation designed for multilevel converters. Its properties are better in comparison with such properties of a conventional transformer [9] operating at 50 Hz. Besides, properties of other high frequency transformer are presented in Table 1.

Table 1

Properties of power transformers reported in literature

| **Transformer type** | **Frequency** | **Efficiency** | **Output power** | **Power/mass density** | **Power/volume density** |
|---|---|---|---|---|---|
| | kHz | % | kW | kW/kg | W/cm$^3$ |
| Universal [2] | 77 | 99.0 | 10 | 5.8 | - |
| Actively cooled [3] | 20 | 99.6 | 120 | 24.8 | 59.5 |
| ABB [5] | 10 | 99.3 | 350 | 7 | - |
| Payton Group [8] | 50 – 1000 | ≈98 | 0.01 – 20 | 6.67 | - |
| Product Center [7] | high | ≈98 | - | - | 36.6 |
| Tabtronics [9] | 0.05 | 92.7 | 0.3 | 0.11 | 0.42 |
| Tabtronics [9] | 0.05 | 96.3 | 1.9 | 0.16 | 0.68 |

The transformers presented in Table 1 can be treated as a representative sample for this class. This overview allows stating that such a coaxial transformer has not been analyzed in such a way as is proposed in this work.

## 3. IDEA OF THE COAXIAL TRANSFORMER

The concept of an ideal coaxial transformer is given in Fig. 1, where windings are in the form of straight tubes. The inner tube is the primary winding, the middle one is the secondary and the outer forms a ferromagnetic core. A thin layer of insulation is placed between the primary and secondary windings. The transformer is supplied by AC voltage and loaded. The flux and current density along the circumference of the cross-section of the windings and the core are uniformly distributed. It is illustrated in Fig. 2.

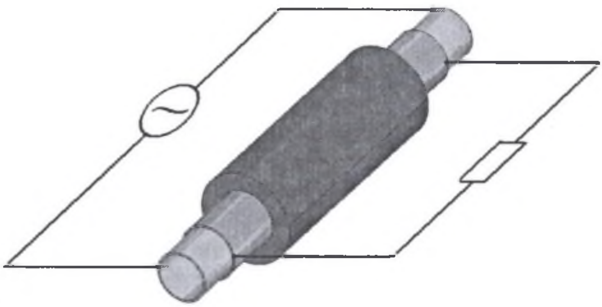

Fig. 1. Idea of coaxial transformer
Rys. 1. Idea transformatora współosiowego

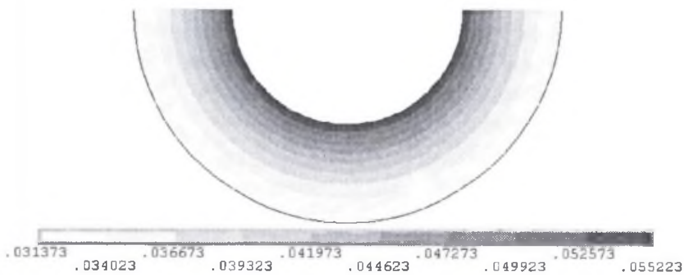


Fig. 2. Magnetic flux distribution in the magnetic core of ideal coaxial transformer
Rys. 2. Rozkład strumienia magnetycznego w rdzeniu idealnego transformatora współosiowego

In order to have the series inductance of the transformer as small as possible it is necessary to bind the tubular coaxial windings to get the form depicted in Fig 3a. This is the spiral transformer. Another approach results in the linear transformer - Fig. 3b. The series inductance is composed of the inductance of relatively long connecting wires and leakage inductances of the transformer.

When the frequency range is relatively low (up to a few MHz), the ferromagnetic core for a transformer is needed. At a frequency above this limit coreless solution could be more reasonable. Tubular windings make it possible to use water cooling.

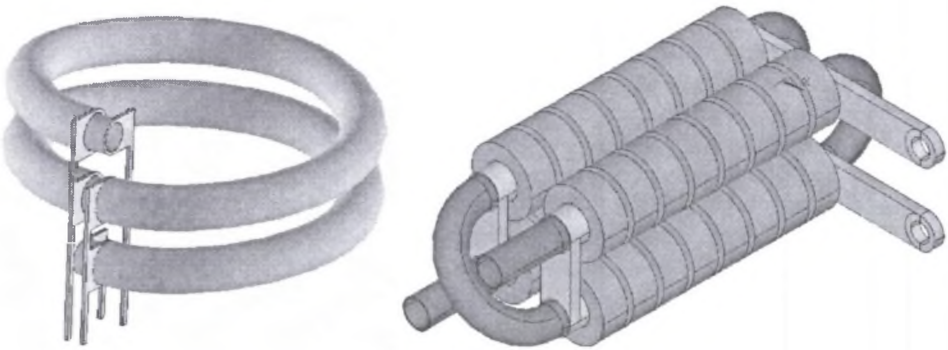

Fig. 3. Two solutions of the coaxial transformer - spiral (a) and linear (b), turn-to-turn ratio 2:1
Rys. 3. Dwa rozwiązania transformatora współosiowego – spiralny (a) i liniowy (b), przekładnia zwojowa 2:1

## 4. TECHNOLOGY OF MANUFACTURING

The technology of manufacturing was elaborated to obtain the smallest possible leakage inductances and the highest possible coefficient of coupling, and also minimized losses. First two requirements can be obtained when the insulation layer thickness is as small as possible. In order to minimize winding losses one has to assume the thickness of winding tubes equal to double skin depth [3].

For the assumed frequency of 1 MHz the skin depth for copper is 67 μm. It produces very small thickness of transformer windings (around 0.15 mm). Such a thin inner tube without any additional former is too delicate to be the transformer support. Therefore much thicker than double depth of penetration inner tube was assumed (0.5 mm). In order to obtain very small insulation layer and small thickness of windings special technological process was used.

The transformer insulation is made of PTFE (Polytetrafluoroethylene). Many different materials of insulation layers were tested i.e. $Al_2O_3$, $TiO_2$, $CeO_2$, $MgF_2$ and $SiO_2$. The PTFE properties were the most advantageous from electrical and mechanical point of view. The thickness 100 μm of this layer was chosen to have insulation withstanding 500 V DC. It would be slightly thinner but it is not mechanically acceptable. Because of low adhesivity between copper deposited on PTFE the additional layer of Titanium was deposited. Its thickness was 100 to 400 nm. Next layer was outer windings of copper. The thickness of this layer is around 140 μm. For protection of mechanical defects and oxidation of outer copper layer, the additional most outer layer of PTFE was placed. Forming inner tube as a spiral was the first step in the manufacturing, next thin layers were placed. The dimensions of such design are shown in Fig. 4. The transformer windings prepared for 2:1 of turn-to-turn ratio and transformer dimensions are depicted in Fig. 5. The diameters are as follows: D = 50 mm, H = 10 mm, $d_c$ = 10 mm, $d_{oo}$ = 5 mm, $d_{ii}$ = 4.2 mm.

The construction of clamps and interwinding connections is the serious problem. It is because the clamps and interwinding connections have to be robust and attached to a delicate outer winding. The solution is given is Fig. 6 where clamps and interwinding connections are connected electrolytically. Because the construction of clamps and interwinding connections is not ready for manufacturing only the thick variant of the linear transformer is laboratory tested.

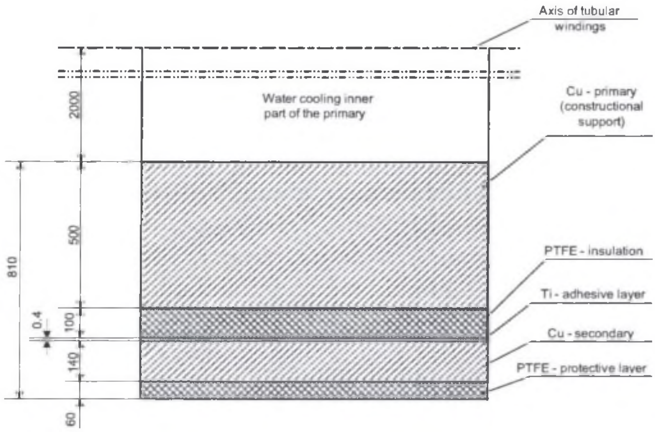


Fig. 4. Dimensions of layers of thin construction of spiral and linear transformer (given in μm)
Rys. 4. Wymiary cienkościennej konstrukcji transformatora współosiowego (dane w μm)

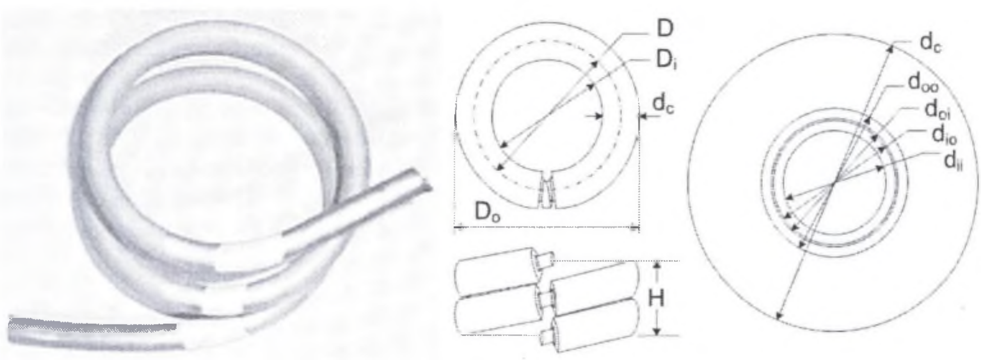


Fig. 5. Windings of the spiral transformer (clamps excluded) and dimensions of the transformer with ferromagnetic core
Rys. 5.Uzwojenia transformatora spiralnego (wyprowadzenia zdemontowane) i jego wymiary wraz z rdzeniem ferromagnetycznym

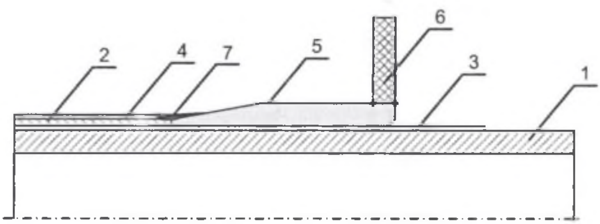


Fig. 6. Cross-section of the clamps and interwinding connections, 1, 2 - copper tubes, 3, 4 - PTFE layer, 5 - copper connecting muff, 6 - clamp welded to muff, 7 - electrolytically deposited copper
Rys. 6. Przekrój przez uzwojenia wraz z wyprowadzeniami, 1, 2 – rurki miedziane, 3, 4 – warstwy PTFE, 5 – miedziany pierścień łączący, 6 wyprowadzenie, 7 – elektrolitycznie naniesione połączenie miedziane

## 5. SPECIFICATION OF PROTOTYPE LINEAR TRANSFORMER

The prototype coaxial linear transformer was manufactured for laboratory tests. It is linear thick type described additionally later in the section "Results of FEM analysis". The dimensions of the transformer are shown in Fig. 7. It is composed of four sections that are indicated on the left hand side in Fig. 7. Each section, beginning from the center, is made of inner copper tube, insulation, outer tube and the tube made of magnetic core.

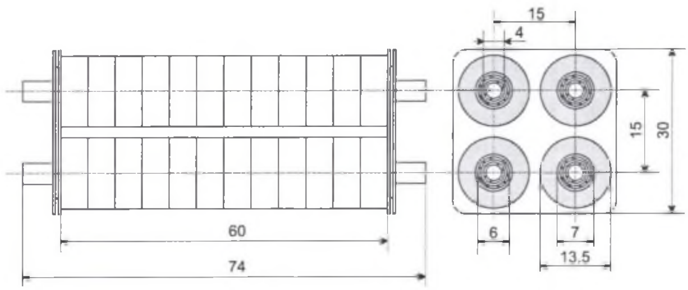


Fig. 7. Dimensions of the prototype coaxial linear transformer
Rys. 7. Wymiary prototypowego transformatora liniowego

The insulation made of glass fibre has thickness of 0.5 mm. The total number of core rings, TN13.5/7/5-3F3 - each 5 mm width, is 48. It produces the transformer length of 60 mm that is one half of the circumference of one turn of the spiral transformer. It is so because it gives certain equivalency between the spiral and linear construction. The photograph of the experimental transformer is shown in Fig. 8. The interwinding copper connections are soldered with tin but it is planned to bond them with laser in future

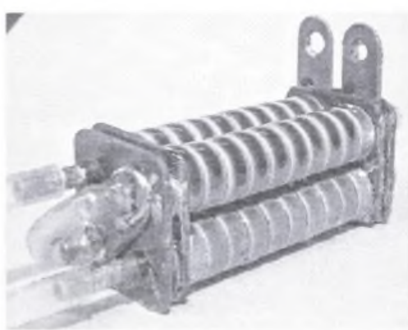

Fig. 8. The prototype coaxial linear transformer (turn-to-turn ratio 2:1)
Rys. 8. Prototypowy transformator liniowy (przekładnia zwojowa 2:1)

## 6. RESULTS OF FEM ANALYSIS

Four variants of the coaxial transformer were analyzed. Two of them are spiral while two other are linear ones. The first variant of the spiral transformer is called "thin" because the walls of winding outer tube and the insulation between windings are thin (around 100 μm). The second variant of the spiral transformer is named "thick" since the wall of the outer tube and the insulation between windings are thick (around 500 μm). Similar description can be given for two linear variants of the transformer.

The coaxial transformer described in the previous section – "Technology of manufacturing" - was analyzed basing on FEM (ANSYS software [10]). The energy parameters are the results of this analysis. The selected characteristics of the coaxial transformer obtained by FEM (ANSYS software) are presented below. The transformer energy parameters defined, are: efficiency, output power and power density (power/mass and power/volume ratio). These parameters are calculated at the assumed power losses (20 W) that can be extracted by cooling system. The results for 1 MHz are presented in Table 2.

Table 2

Power properties of the coaxial transformer (FEM) at 1MHz (at maximum efficiency)

| Transformer type | η | $U_{1N}$ | $P_{2N}$ | $I_{2N}$ | $\Delta P_{tot}$ | $R_{load}$ |
|---|---|---|---|---|---|---|
| | [%] | [V] | [kW] | [A] | [W] | [Ω] |
| Spiral thin | 99.5 | 109.8 | 4.28 | 78.2 | 20 | 0.7 |
| Spiral thick | 99.2 | 108.5 | 4.16 | 77.5 | 20 | 0.7 |
| Linear thin | 99.5 | 112.1 | 4.36 | 80.0 | 20 | 0.73 |
| Linear thick | 99.3 | 110.8 | 4.21 | 79.2 | 20 | 0.72 |

The first important energy parameter is the efficiency. One can observe that the efficiency is near the same for all four variants of the transformer. The characteristic of the efficiency vs. secondary current for the spiral thin-walled transformer at 1 MHz is depicted in Fig 9. The maximum value of the efficiency is reached in the region of 100 A.

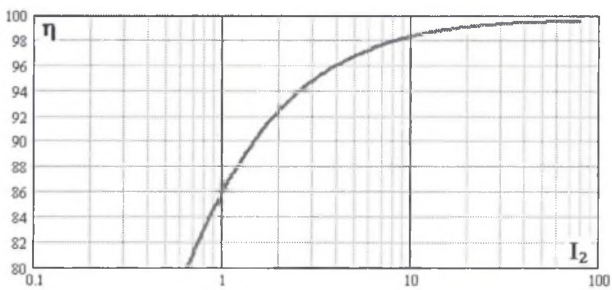


Fig. 9. Efficiency vs. load current [A] of spiral thin-walled transformer at 1 MHz

Rys. 9. Sprawność transformatora cienkościennego jako funkcja prądu przy 1 MHz

For 1 MHz the ratings of the spiral thin-walled transformer are: $P_{out}$ =4.28 kW, $U_1$ =110V, η = 99.5%. The total power losses in the transformer are a sum of the power losses in windings and in the magnetic core. At the maximum efficiency the power losses in windings are 11.1 W, while in the magnetic core they are of 8.9 W. Very high power density is also important advantage of the coaxial transformer. The power/mass ratio of the analyzed transformer (volume permitted by diameter 40 mm and height 20 mm) is 75 kW/kg, while the power/volume ratio is around 200 W/cm$^3$. It is necessary to emphasize that the more intensive cooling causes the higher power/mass ratio. In the examined case the intensity of cooling is rather low. It means that it is possible to increase the power/mass ratio by improving the cooling system.

## 7. EXPERIMENTAL SET-UP

A laboratory unit was built specially for this work. It is composed of a Class E inverter, examined transformer, load and water cooling system - Fig. 10. The Class E inverter (Fig. 11) operates at 1 MHz with maximum output power of 1 kW being supplied from DC source of 110 V (E). The output power is controlled by an adjustable voltage source E. The load is 1 Ω with the small parasitic inductance of 500 nH and it is compensated with the series $C_O$ capacitance in order to limit the voltage across the primary winding. The efficiency of the transformer is measured using a calorimeter since it is the most accurate method. Water is a cooling agent in the transformer and the load. Measurements were carried out in the steady state. The temperature of the inlet and outlet water was measured with a mercury thermometer. For the transformer the thermometer is of (16 – 25)°C range with resolution of 0.01°C. The thermometer for the load temperature has the (0 – 50)°C range and its resolution is 0.1°C. The resolution of flow measurement is 0.1 $cm^3$/min.

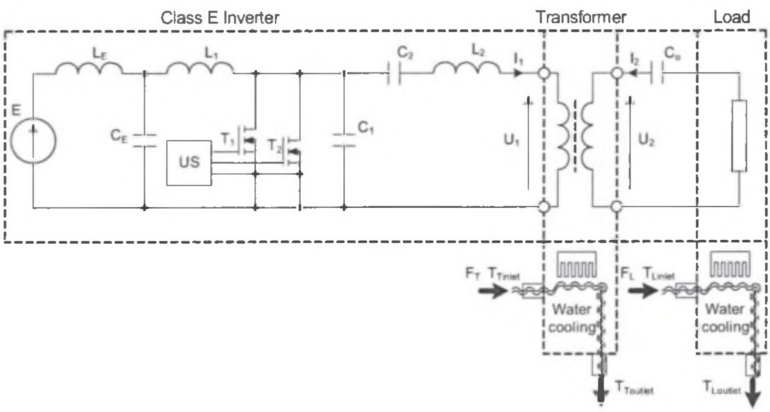


Fig. 10. Schematic diagram of the set-up for measurements
Rys. 10. Schemat ideowy stanowiska pomiarowego

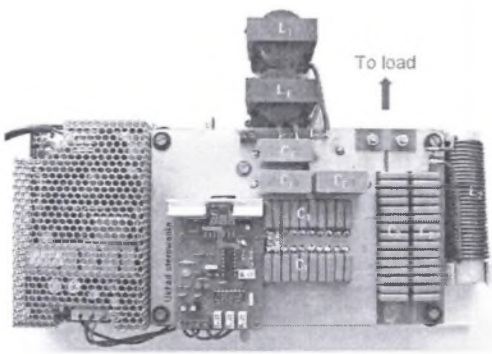


Fig. 11. Photograph of the Class E Inverter 1kW, 1 MHz, DC source of 110 V (E)
Rys. 11. Zdjęcie falownika klasy E 1 kW, 1 MHz zasilającego transformator, wejście 110 V DC

## 8. MEASUREMENTS

Only the linear transformer of thick type was measured. The output power and power losses were measured and efficiency was calculated. These measurements were carried out for the output power up to about 500 W due to the limited performance of the Class E inverter that was at the disposal. The measurements were taken at frequency 1 MHz. The measured efficiency is higher than 98% and is in good agreement with theoretical ones calculated for this range of output power. The results are gathered in Table 3.

Table 3

Energy measurements using calorimeter (1 MHz)

| **Power losses in transformer** | | | | **Output power** | | | | **Efficiency** | |
|---|---|---|---|---|---|---|---|---|---|
| **Flow** | $\vartheta_{inl}$ | $\vartheta_{outl}$ | $\Delta P_{tot}$ | **Flow** | $\vartheta_{inl}$ | $\vartheta_{outl}$ | $P_{odb}$ | $\eta$ | |
| $cm^3/min$ | °C | °C | W | $cm^3/min$ | °C | °C | W | % | |
| Measurements (calorimetric method) | | | | | | | | | FEM |
| 17.4 | 19.72 | 20.39 | 0.80 | 113 | 16.8 | 31.3 | 112.75 | 99.29 | 99.38 |
| 17.2 | 19.82 | 21.42 | 1.89 | 188 | 16.8 | 32.8 | 206.08 | 99.09 | 99.31 |
| 16.6 | 19.93 | 22.61 | 3.05 | 245 | 16.6 | 33.6 | 285.35 | 98.93 | 99.26 |
| 16.2 | 20.12 | 23.96 | 4.26 | 323 | 16.6 | 33.8 | 380.62 | 98.88 | 99.22 |
| 23.0 | 19.40 | 23.58 | 6.59 | 330 | 16.6 | 38.0 | 483.82 | 98.64 | 99.18 |
| 23.0 | 19.56 | 24.47 | 7.74 | 412 | 16.6 | 36.6 | 564.53 | 98.63 | 99.16 |

The transformer efficiency curves versus the output power obtained by FEM computation and by measurements under the same operation conditions are displayed in Fig. 12. Because the load resistance ($R_{load} = 1\ \Omega$) is higher than the optimum value the efficiency decreases slightly whereas the output power increases. The higher power losses obtained from the measurements are due to the resistance of the interwinding connections (neglected in numerical analysis).

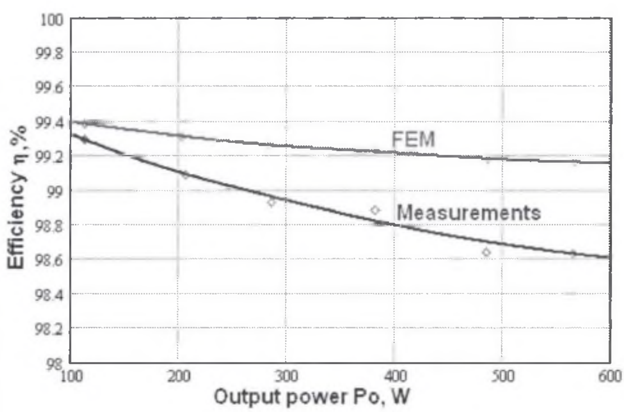


Fig. 12. Efficiency of coaxial transformer vs. output power obtained from FEM analysis and measurements ($R_{load} = 1\ \Omega$)

Rys. 12. Charakterystyka sprawności transformatora współosiowego jako funkcja mocy wyjściowej otrzymana na drodze symulacyjnej MES oraz na drodze eksperymentu laboratoryjnego ($R_{load} = 1\ \Omega$)

## 9. CONCLUSIONS

1. The following parameters of the linear coaxial transformer have been obtained from FEM analysis at 1 MHz: efficiency 99.5%, output power 4.28 kW, power/mass density 75 kW/kg.
2. These parameters are more advantageous than those reported in literature.
3. The measured linear thick transformer has the efficiency of over 98% at about 500 W of output power. This transformer has almost the same power/mass density as the theoretical power/mass density of 75 kW/kg but in this case the intensity of cooling is rather low. It means that this performance could be improved by creating the better cooling.
4. The proposed technology of the transformer manufacturing is expected to be improved because a very thin layer of the secondary winding is difficult for manufacturing more robust clamps.
5. The linear transformer is much easier for manufacturing and cheaper than the spiral one.
6. Further research should be focused on the improvement of manufacturing technology and analysis of its costs in comparison with costs of low frequency transformers.
7. Further experiment should be aimed at development of Class E inverter of 6 kW output power.

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*This work was presented in particular part in 11th European Conference on Power Electronics and Applications, 11 -14 September 2005, Dresden, Germany*

Wpłynęło do Redakcji dnia 13 sierpnia 2005 r.

Recenzent: Prof. zw. dr hab. inż. Sławomir Wiak