PAPER

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Reduction of idling losses of eighteen-pulse transformer rectifier unit for aerospace application

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Abstract. This paper considers a method of reducing idling losses with the use of amorphous steel for a magnetic core for an eighteen-pulse transformer rectifier unit for the aerospace application. Numerical calculations of transformer rectifier units with various types of amorphous alloys were carried out to determine the mass and overall dimensions and idling losses. To determine the shape, amplitude and harmonic composition of the eighteen-pulse rectifier, an imitation simulation of a three-to-nine-phase rectification system was carried out. In order to determine the maximum temperatures with a nominal mode, a computer simulation of the thermal fields of the transformer rectifier unit was carried out. To verify the numerical calculations, simulation and computer simulations, experimental studies were carried out on the developed demonstration layout.

1. Introduction

Transformer rectifier units (TRU) are static inductive converters related to secondary power supply systems of the aircraft, which serve to convert the voltage value of 115/200 V of a variable frequency of 400 Hz into 27 V rectified voltage.

The developers try to achieve an optimal compromise between such criteria as weight and overall dimensions and the minimum of heat losses (maximum efficiency) when designing TRU for the power supply systems for aircraft [1]. It is possible to achieve a reduction in thermal losses by using amorphous steel [2]-[5] for the TRU magnetic core instead of cold-rolled electrical or precision magnetic-soft steel which has 10-15 times less idling losses [6]-[12]. However, amorphous steel also has a significant disadvantage of the low value of the magnetic flux density of saturation, which leads to an increase in the weight and dimensions of the entire device. Investigations of the expediency of using the magnetic core made from the amorphous steel for the TRU of an aircraft to reduce idling losses while maintaining the weight and overall dimensions are given in the work.

2. Numerical calculations

The object of the study is a three-to-nine-phase transformer with a magnetic core made of three single-phase transformers on the cores in the form of a torus. Transformer have one primary winding with a connection scheme for the high voltage winding "star" and three secondary windings with 1 connection scheme "star" and 2 "zigzag" for the low voltage windings. The rated power of the TRU is 10.5 kVA, primary voltage 115/200 V, secondary voltage 27 V, frequency 360 Hz, load 9 kW.

Numerical calculations of TRU with the following types of amorphous alloys were carried out to determine the weight, dimensions and losses in the magnetic core: 5BDSR, 1SR produced by PJSC "Asha Metallurgical Plant" [13], AMAG321 manufactured by OJSC "Mstator" [14] and Metglas Alloy 2605CO produced by Hitachi Metals [15] with the parameters shown in Table 1.

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Table 1. Properties of various amorphous alloys.

Alloys properties	5BDSR	1SR	AMAG 321	Metglas 2605CO
Flux density, T	1,3	1,5	1,8	1,8
No-load losses W/kg at 1,3 T flux density and frequency of 400 HZ	1,1	3	6	3
Density, g/cm^3	7,6	7,6	7,3	7,18

The results of numerical calculations of TRU with different types of amorphous alloys are shown in Table 2.

Table 2. Results of calculations of TRU with different types of amorphous alloys.

Parameter	5BDSR	1SR	AMAG 321	Metglas 2605CO
Winding weight, kg	2,48			
Magnetic core weight, kg	7,15	6,21	5,17	4,89
Losses in the magnetic core, W	7,87	19,25	31,02	14,67

As can be seen from Table 2, the transformer with a magnetic core made from alloy 5BDSR has the lowest idling losses, but it also has the largest weight, which is an important criterion for an aircraft. The largest idling losses were found in the transformer with a magnetic core made from the AMAG 321 alloy. The transformers with a magnetic core made from the alloy Metglas Alloy 2605CO and 1SP have the lowest weight and sufficiently low idling losses.

The alloy 1SR was chosen for further experimental studies and computer modeling.

3. Simulation modeling

To determine the shape, amplitude and harmonic composition, it is necessary to simulate the electromagnetic processes of the eighteen-pulse rectifier. The schematic diagram of the converter is shown in figure 1. The diagram shows: a three-to-nine-phase (3 → 9) transformer with one primary winding connected to a star and three secondary windings having a star and zigzag connection; three bridges from the diodes VD1-VD6, VD7-VD12, VD13-VD18; load Rd.

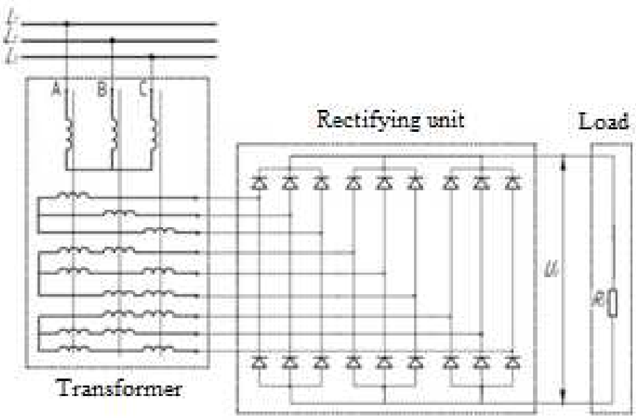

Figure 1. Schematic model of eighteen-pulse rectifier

Figure 2 shows the shape of the primary current of phase A, it is a stepped figure approaching the sinusoid. Figure 3 shows the histogram of the supply current of phase A. The Matlab package produced a harmonic analysis of the current curve consumed by the transformer.

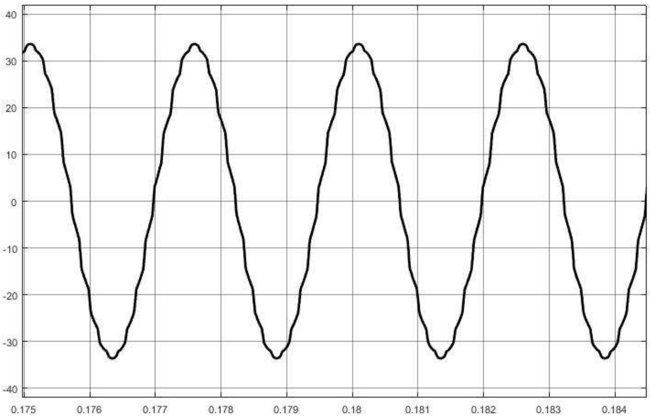

Figure 2. Phase A current shape in the primary winding

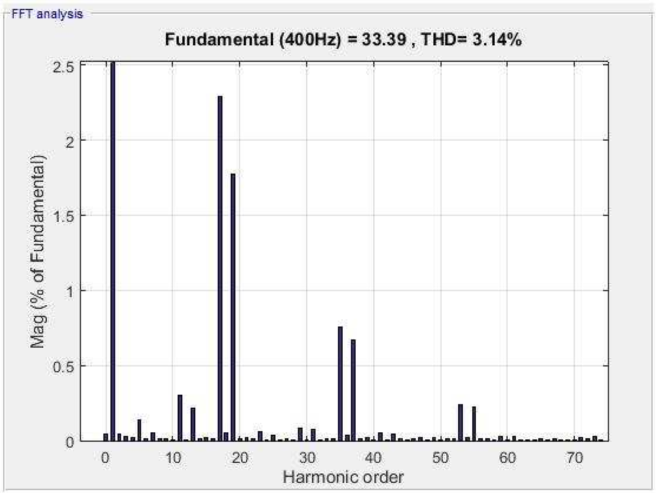

Figure 3. Phase A primary current histogram

The results of modeling the harmonic composition of the primary current of phase A show that the current value of the first harmonic is 33.39 A, the distortion coefficient of the curve is THD = 3.14%. The vertical axis shows the percentage value of the higher harmonics from the fundamental harmonic. The horizontal numbers represent the ordinal numbers of the higher harmonics.

As can be seen from figure 3 in the supply current curve there are higher harmonics multiple to the 17 and 19, in addition to the fundamental harmonic.

4. Computer modeling of thermal processes

The losses of electrical energy during the operation of transformers lead to an increase in temperature. Computer modeling of thermal processes for determining the maximum temperature of the transformer heating during operation was carried out in the software package Ansys IcePack (figure 4).

The magnetic core made from an amorphous alloy 1SR with losses of 14.47 W was used in computer simulation. The winding of the transformer is made of heat-resistant wire PNET-imid with a temperature index of 220 ^{o}C [16]. The transformer does not have forced air cooling.

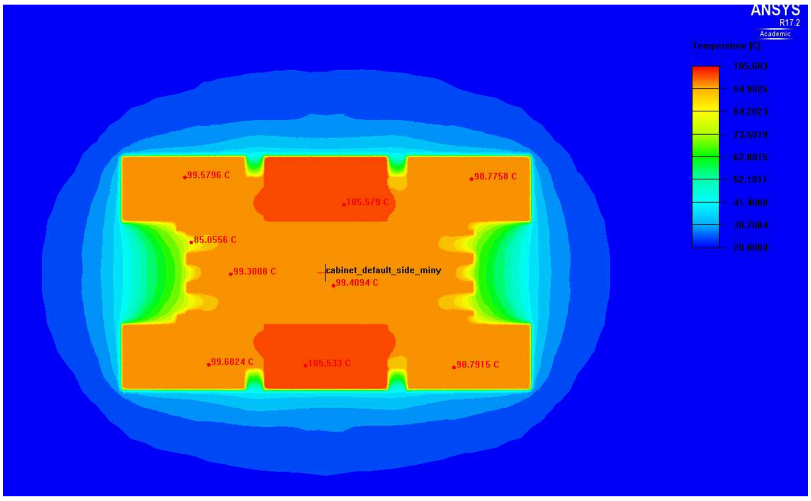

Figure 4. Thermal model of TRU

The results of the computer simulation show that the maximum temperature of the windings in the nominal mode is 105.579 ° C. The temperature index of winding wire PNET-imid is 220 ^{0}C. Therefore, the temperature is admissible. The temperature of the central winding is higher due to its heating by side windings.

5. Experimental study

Based on the results of calculations, a demonstration layout of the transformer (figure 5) with a rectifier unit (figure 6) was developed. The overall dimensions of the demonstration layout are shown in figure 7. The tests were carried out under normal climatic conditions according to [17] on a special test stand.

Requirements for the stand:

– output 3-phase voltage 220 V with variable frequency (360 - 800 Hz) corresponding to section 5.1 of [18].

– load modules with a rated current not less than 1400A.

Figure 5. Demonstration layout of transformer

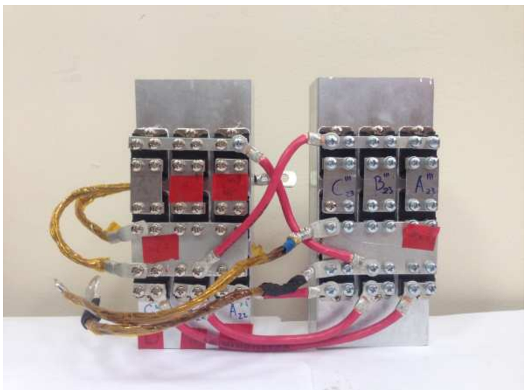

Figure 6. Rectifier unit

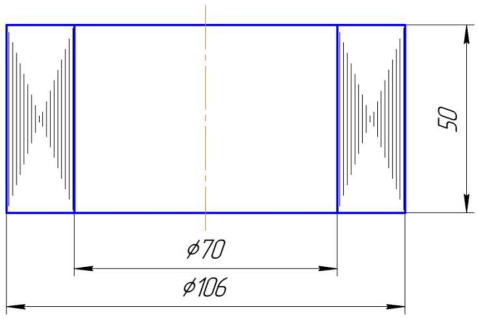

Figure 7. Magnetic core for TRU

Power was applied to 3 phases of high voltage winding U_{1n} = 200V ± 10% with frequency f = 800 ± 10% Hz. The load was connected to the outputs of the rectifier unit, while the current at the rectifier terminals should be in accordance with Table 3. The current was monitored with ampere meter and the voltage was measured with a voltmeter. The temperature of the windings was controlled by the temperature sensors (thermocouples) built into the transformer connected to the multimeter. If the temperature of the windings exceeds 210 ° C, then the test should be stopped.

Table 3. Test results.

Load current, A	Holding time, s	Required rectifier output voltage, V	Voltage at rectifier output, V	The maximum temperature of the windings of the transformer at the end point of time, ^{0}C
50 + 10%	60	27	26,6	27
150 + 10%	60+5	24–30	25	33
330 + 10%	900+20	24–30	24	88
450 + 10%	300+10	Not less than 22,7	20,7	130
600 + 10%	5+2	Not less than 23,1	19,3	134

As can be seen from Table 3, the TRU passed the test successfully. This confirms the correctness of the chosen design methodology and transformer design. It is important to note that the thermal loads detected on the transformer during its tests are insignificant. The maximum temperature threshold for the winding of the product is 220 °C. The maximum temperature found in the most loaded modes was 134 ° C. A slight dips in the rectified voltage (less than 10%) were detected. But this problem is solved by additional laying of one turn in the winding.

6. Conclusion

The test results show that it is possible to create transformers with a magnetic core made from amorphous steel with the weight characteristics slightly exceeding the weight of transformers made of precision soft magnetic alloys or electrical steel.

A further direction of research preceding the implantation of transformers with the magnetic core made from amorphous steel on the aircraft board should be aimed at studying their mechanical properties and the effect of mechanical properties on electromagnetic properties. It is also necessary to study the effect of climate tests on the characteristics of transformers.

Acknowledgments

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References

[1] Konyakhin S F 2009 *Research and development of onboard transformer-rectifying units with a multichannel converting path*, The dissertation author's abstract on competition of a scientific degree of the candidate of engineering science (NIU MPEI, Moscow)
[2] Patent 94049, H01F 27/25 (2006.01), Magnetic core, PJSC "Asha Metallurgical Plant" (RU)
[3] Patent 2190275, H01F 3/04, C22C 19/07, Magnetic core, Scientific-Production Enterprise "Gammamet"
[4] Patent JP2013098351 IPC: H01F27/24, H01F27/26, H01F27/32, Amorphous iron core transformer, HITACHI IND EQUIPMENT SYS.
[5] Patent WO2012173720, IPC: H01F27/25, H01F41/02, Interlaced amorphous material transformer core, ABB TECHNOLOGY AG [CH], OUTTEN SAMUEL S [US]
[6] Da Silva W A, Jorge A M and Ogashawara O 2016 Weight reduction of amorphous alloy core electrical transformers for aircraft applications, 2016 *Int. Conf. on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & Int. Transp. Electrification Conf. (ESARS-ITEC)*, pp. 1–4
[7] Jafari M, Malekjamshidi Z, Lei G, Wang T, Platt G and Zhu J 2017 Design and Implementation of an Amorphous High-Frequency Transformer Coupling Multiple Converters in a Smart Microgrid *IEEE Trans. on Ind. Electronics* **64(2)** 1028–37
[8] Guo J and Li S Study on no-load loss of amorphous alloy control transformer based on the finite element analysis, 2016 *IEEE Int. Conf. of Online Analysis and Comp. Science (ICOACS)*, pp. 16–19
[9] Najafi A and Iskender I Reducing losses in distribution transformer using 2605SA1 amorphous core based on time stepping finite element method, 2015 *Int. Siberian Conf. on Control and Communications (SIBCON)*, pp. 1–4
[10] Liu X, Wang Y, Islam R M, Lei G, Liu Ch and Zhu J 2014 Comparison of electromagnetic performances of amorphous and nanocrystalline core-based high frequency transformers, 2014 *17th Int. Conf. on Electrical Machines and Systems (ICEMS)*, pp. 2028–32
[11] Xin W, Jinlong Zh, Dexu H and Xianjin G 2012 Optimization design and parametric drawing of Amorphous Alloy Transformer, 2012 *2nd Int. Conf. on Consumer Electronics, Communications and Networks (CECNet)*, pp. 422–25
[12] Wang J, Sheng W, Wang L and Yang H Study on technical and economical efficiency of amorphous alloy transformer and on-load capacity regulating transformer in distribution network application, 2014 *China Int. Conf. on Electricity Distribution (CICED)*, pp. 30–34
[13] PJSC "Asha Metallurgical Plant". Electronic source. Link: http://www.amet.ru/ (date of the application 06.04.2017)
[14] JSC «MStator». Electronic source. Link: http://www.mstator.ru/ (date of the application 06.04.2017)
[15] Hitachi Metals America Ltd. Electronic source. Link: http://www.hitachimetals.com/ (date of the application 06.04.2017)
[16] JC «Pscovcabel». Electronic source. Link: http://pskovkabel.ru/ (date of the application 06.04.2017)
[17] GOST 15150-69 Machines, devices and other technical products. Versions for different climatic regions. Categories, conditions of operation, storage and transportation in terms of the impact of climatic factors of the environment
[18] GOST R 54073-2010. Systems of power supply for aircraft and helicopters. General requirements and norms of power quality