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Research articles

Examination of magnetic properties of the multi – Gap amorphous $Fe_{78}Si_{13}B_9$ block cores intended for harmonic filters used in electric power systems

R. Kolano [a], A. Kolano–Burian [a,*], M. Haltof [b], J. Czornik [b], M. Hreczka [a], P. Zackiewicz [a], M. Polak [a]

[a] ŁUKASIEWICZ Research Network - Institute of Non-Ferrous Metals, Gliwice, Poland
[b] ELHAND Transformatory Sp. z o.o., Lubliniec, Poland

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ABSTRACT

There is a permanent demand worldwide for the advanced low-losses soft magnetic materials intended for application in power electronics, including power electronic converters used to process various forms of the electrical energy into such that is best suited for the specific user loads or applications. This paper shows result of investigation of magnetic properties of amorphous multi-gap cores which were used to manufacture a prototype 27-multi-gaps core for the three-phase harmonic filter with a common yoke, with a rated power of 7.5 kW, operating voltage of 400 V and electric power frequency of 50 Hz. The main attention was focused on studying the effect of the chemical composition and core structure on the level of power losses in the core and temperature increase during operation for amorphous material in relation to the polycrystalline Fe-Si steel with 3 wt% Si core despite the low operating frequency of 50 Hz.

1. Introduction

Intensive research works are permanently carried out worldwide on the advanced soft magnetic materials intended for application in power electronics [1]. As it is commonly known, considerable portion of the electric energy generated frequently requires some form of conversion. The power electronic converters are used to process various forms of the electrical energy into such that is best suited for the specific user loads or applications, such as an electric machine, induction, resistance or dielectric heating system, electric drive or power electric network. It should be noted that most of the modern power plants based on renewable energy sources utilizes power electronic conversion systems [2]. Their primary task is to process and control the main flow of electrical energy, and to store and improve quality of that energy. Except for power electronic switches, they almost always contain passive electric components such as inductors and capacitors. The chokes working in power electronic circuits characterized by a wide spectrum of current/voltage harmonics are the components causing high power losses, hard to eliminate. Because the whole energy transmitted to the load flows through these chokes, reduction of power losses taking place in them, and the reduction of their size and mass at the preserved high performance, is the question of great importance. The chokes for harmonic filters are produced nowadays in Poland and elsewhere with the use of soft magnetic cores made from electric steel, 0.3, 0.35 and 0.5 mm in thickness. Research works conducted for these materials through various modifications of the production process, additives or grain orientation modification lead to the improvement of properties and reduction of power losses in the core up to 5% during operation at the frequency of 50 Hz [3,4,5]. The soft magnetic cuboid-shaped block cores made from the amorphous $Fe_{78}Si_{13}B_9$ strips, characterized by high saturation induction $B_s = 1.56$ T, satisfactory mechanical strength and relatively low power losses, might successfully replace conventional Fe-Si steel with 3 wt% Si steel in the production of harmonic filters. These filters are used in electric networks during transmission of the electric energy from the source to the object of its application (i.e. load). Their task is to suppress harmonic currents flowing in the power system from the source by reducing harmful current distortion caused by nonlinear loads. Up to the present, there are not many publications on application of the amorphous and nanocrystalline soft magnetic materials in the chokes of harmonic filters [6–12]. The main part of a filter is the choke

* Corresponding author.
E-mail address: aleksandra.kolano-burian@imn.gliwice.pl (A. Kolano–Burian).

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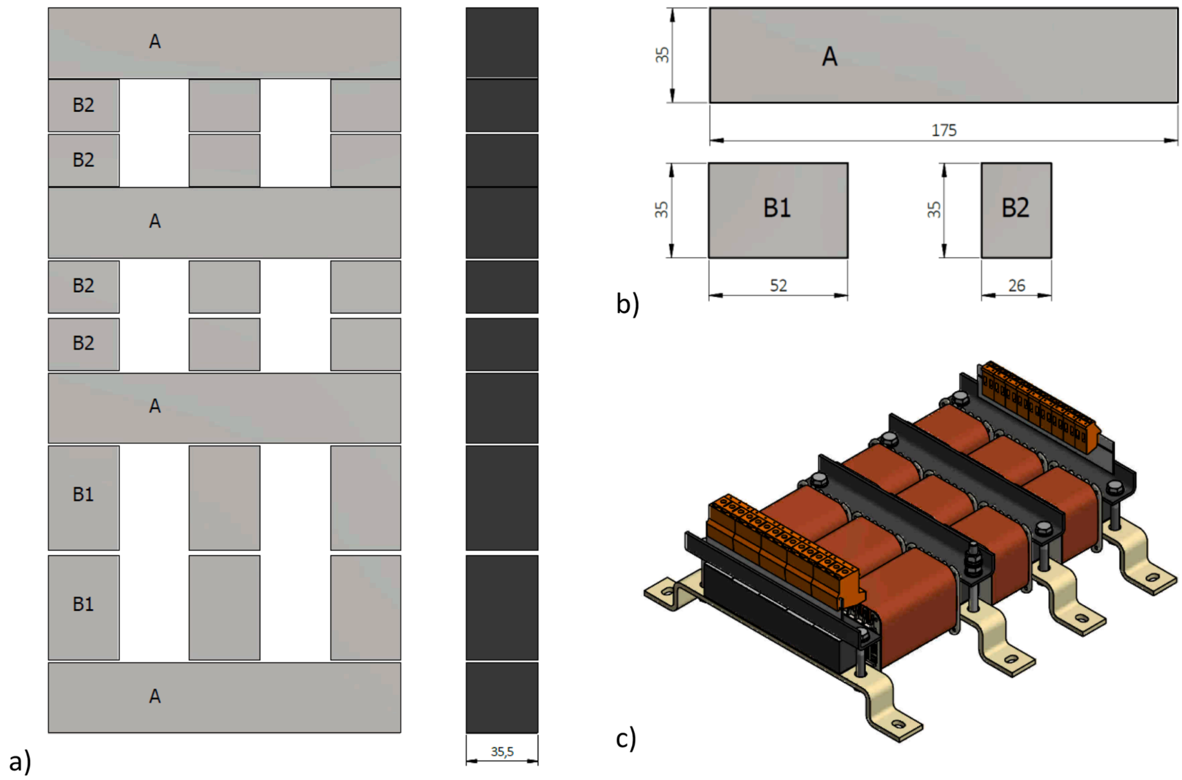


Fig. 1. Structure of the amorphous multi-gap $Fe_{78}Si_{13}B_9$ core used in the 7.5 kW/400 V/50 Hz harmonic filter, a) arrangement of particular blocks, b) dimensions of the A, B1 and B2 blocks c) isometric view of a core of the harmonic filter with wound chokes.

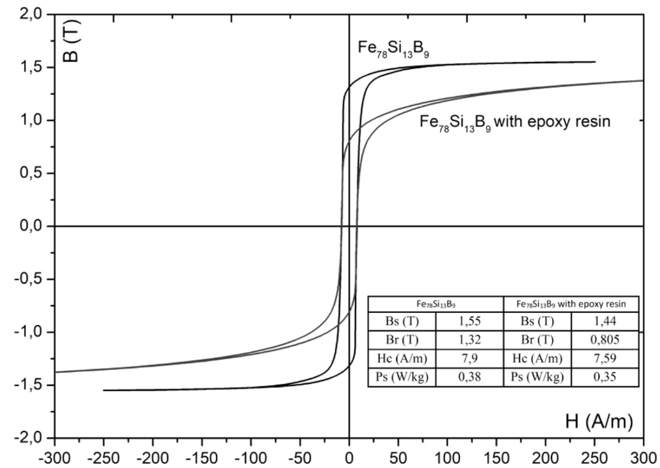
assembly which consist of specific inductors L and capacitors C ensuring the required higher harmonics suppression. An effect of the material type (Fe-Si steel with 3 wt% Si ; $Fe_{78}Si_{13}B_9$) on power losses in a choke's core was investigated by L. Wang *et al.* [6], showing that at the magnetizing field frequency of 350 Hz these losses in a Fe-Si steel with 3 wt% Si core, 18.5 kg in mass, were 7.7 W/kg at B = 0.8 T, whereas in case of the $Fe_{78}Si_{13}B_9$ core of the same mass they decreased to 0.96 W/kg. General trends in magnetic materials selection for the chokes of output filters used in high-frequency inverters (up to 150 kHz) powered from renewable energy sources have been presented by M. Handzel *et al.* [7]. Magnetic characteristics of the block cores made from the rapidly-quenched ribbons cast from newly developed soft magnetic nanocrystalline alloy with composition $Fe_{80,8}Cu_1Mo_{0.2}Si_4B_{14}$ have been shown by A. Yao *et al.* [8]. They compared soft magnetic properties of the nanocrystalline $Fe_{80,8}Cu_1Mo_{0.2}Si_4B_{14}$ block cores with those of the amorphous $Fe_{78}Si_{13}B_9$ block cores, and have found that power losses measured at $B = 1.5$ T and $f = 600$ Hz in the nanocrystalline and the amorphous cores were 11 W/kg and 7 W/kg, respectively. This proves that at such working conditions, particularly in reference to the magnetic field frequency, the nanocrystalline materials are not significantly better than the amorphous ones. In another study [9], results of application of nanocrystalline block cores produced from the FeCuNbSiB ribbons in high-frequency chokes (10 kHz) are presented. The core produced from nanocrystalline $Fe_{56}Co_{24}Nb_4B_{13}Si_2Cu_1$ ribbon for application in the 25 kW DC-DC converter, rated for operations in discontinuous conduction mode at a peak current of 300 A and a switching frequency of up to 20 kHz, has been described elsewhere [10].

The aim of the research was to develop a technology for the production of amorphous multi-gap cores and to design and manufacture a prototype 27-multi-gaps core for the three-phase harmonic filter with a common yoke, with a rated power of 7.5 kW, operating voltage of 400 V and electric power frequency of 50 Hz. The research was aimed at examining the influence of the chemical composition and core structure on the level of power losses in the core and temperature increase during operation for amorphous material in relation to the polycrystallineFe-Si steel with 3 wt% Si core despite the low operating frequency of 50 Hz.

2. Experimental

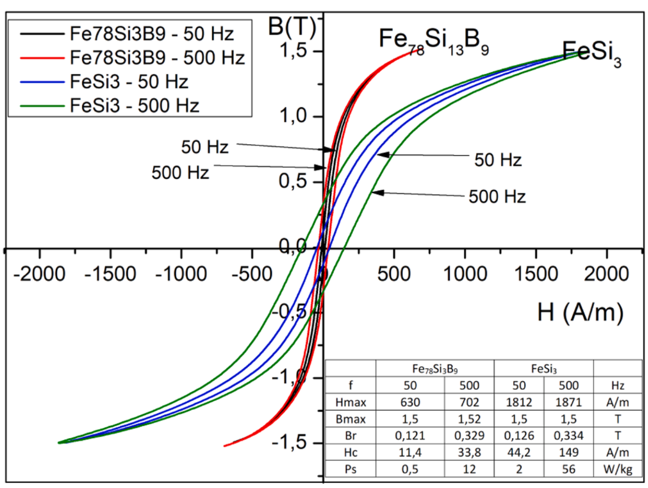
The structure of a core for chokes intended for application in the 7.5 kW/400 V/50 Hz harmonic filter is shown in Fig. 1a. The $Fe_{78}Si_{13}B_9$ amorphous ribbon, 35 mm wide and 20 μm thickness, was used to wind the rectangular core, which was subjected to thermo-magnetic treatment at the temperature of 623 K for 1 h in Ar protective atmosphere. The second stage of work was the consolidation process carried out by using impregnation plant for magnetic cores. After completion of that process, blocks A, B1 and B2 were cut out from the cores (see Fig. 1b) by means of the MAGNUTOM-500 (STRUERS) automatic high-capacity cutting machine and were subjected to the final surface treatment before using them to produce the multi-gap core. The core of the filter consists of 22 stably mounted cuboid blocks (A, B1 B2 in type), at the preserved required gaps between them. During mounting of the core, it is important to ensure the possibility of precise adjustment of a width of a gap between surfaces of particular rectangular blocks.

The harmonic filters presented in this paper have been built of a number of chokes mounted onto a common core. The filters with Fe-Si steel with 3 wt% Si core and the $Fe_{78}Si_{13}B_9$ core incorporate three three-phase chokes: an input choke (linear, L_{IN} in inductance), resonance choke (parallel, L_R , in a circuit limb containing capacitors of the capacity $C_\Delta = 8\mu F$, connected in a triangle), and an output choke (L_{OUT}, linear). In the case of both cores it was intended to apply the common-yoke T-type active filter configuration for economic results so as to reduce mass of necessary ferromagnetic material and dimensions of the device. However, the passive harmonic filters are mostly composed of the inductors built on separate magnetic cores because of simpler design solutions in such cases. In case of the common yoke core, there is a danger of power loss increase resulting from the flow of double magnetic fluxes associated with inductor windings mounted on the neighboring



$Fe_{78}Si_{13}B_9$		$Fe_{78}Si_{13}B_9$ with epoxy resin	
Bs (T)	1,55	Bs (T)	1,44
Br (T)	1,32	Br (T)	0,805
Hc (A/m)	7,9	Hc (A/m)	7,59
Ps (W/kg)	0,38	Ps (W/kg)	0,35

Fig. 2. Hysteresis loops (f = 50 Hz) measured for the rectangular $Fe_{78}Si_{13}B_9$ core after thermo-magnetic treatment conducted at 638 K/1h before impregnation with the Ultimeg 2004LN resin and after impregnation.



	$Fe_{78}Si_3B_9$		$FeSi_3$		
f	50	500	50	500	Hz
Hmax	630	702	1812	1871	A/m
Bmax	1,5	1,52	1,5	1,5	T
Br	0,121	0,329	0,126	0,334	T
Hc	11,4	33,8	44,2	149	A/m
Ps	0,5	12	2	56	W/kg

Fig. 3. Hysteresis loops measured for rectangular cores with two gaps, made from the amorphous $Fe_{78}Si_{13}B_9$ ribbon and from 0.25 mm thick polycrystalline Fe-Si steel with 3 wt% Si strip.

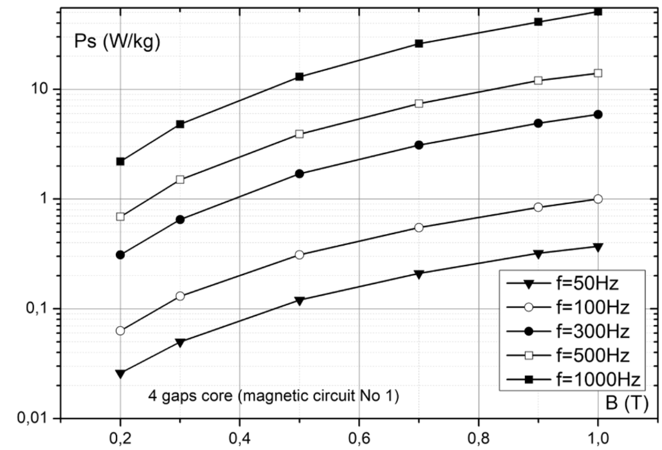


Fig. 5. The $P_s = f(B)$ dependence measured for the circuit no 1 at various frequencies of the magnetizing field.

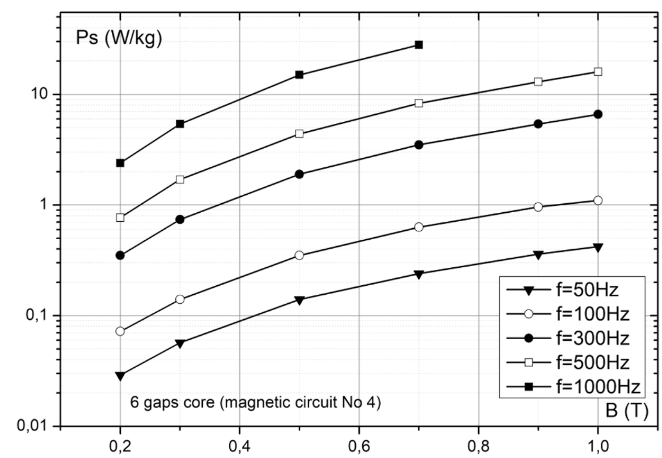


Fig. 6. The $P_s = f(B)$ dependence measured for the circuit no 4 at various frequencies of the magnetizing field.

columns. Each of nine windings have been mounted on multi-gap columns. The gaps had a determined width and were filled with paramagnetic material so as to obtain suitable magnetic reluctance of the circuit. The required suppression characteristics were obtained by calibration of the core gaps so as to obtain the following choke inductances: $L_{IN} = 8.3mH$, $L_R = 17mH$, $L_{OUT} = 1.7mH$, with ± 2% tolerance.

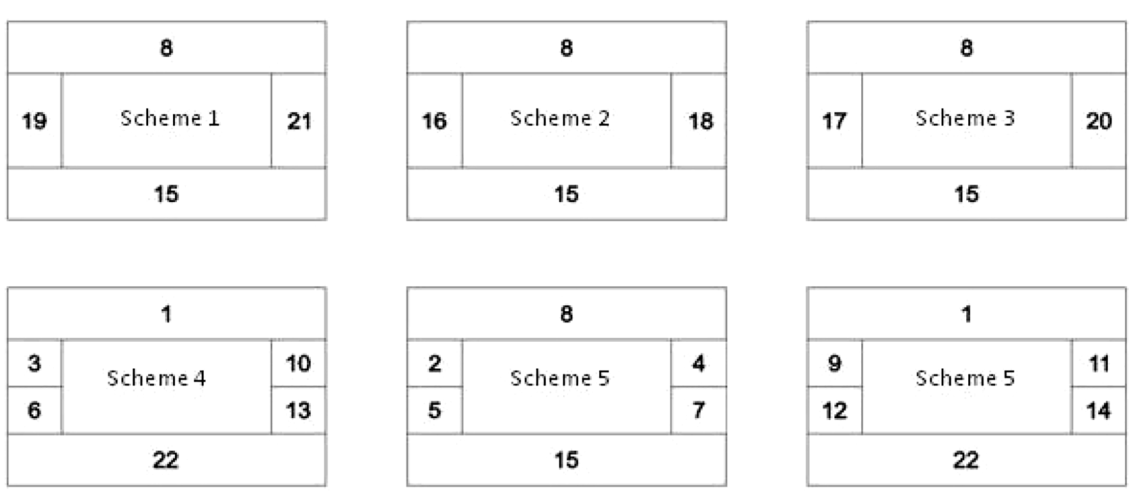


Fig. 4. Partial circuits built from the amorphous A, B1 and B2 blocks.

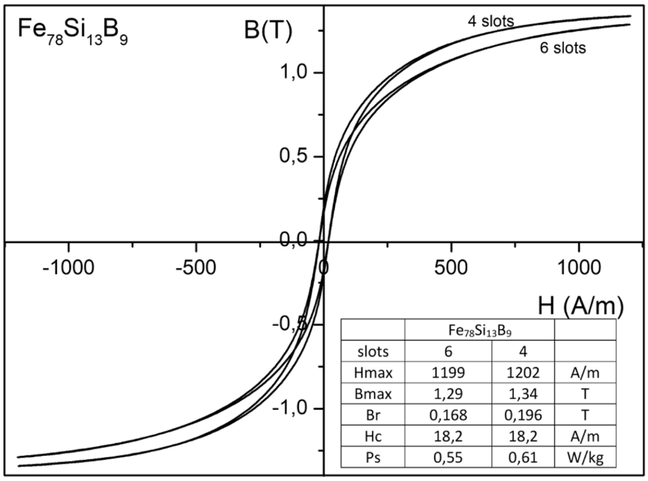


Fig. 7. Hysteresis loops of a circuit No 1 with four gaps and the circuit No 5 with six gaps.

Table 1
Results of the noise level measurements carried out for the partial circuits (Fig. 4) during their re-magnetization with the frequency of 300 Hz, for two values of magnetic induction: B = 0.7 T and B = 0.9 T.

Circuit No	Number of gaps	Noise level (dB) at B = 0,7 T	Noise level (dB) at B = 0,9 T
1	4	67,0	70,0
2	4	62,4	66,2
3	4	68,5	69,5
4	6	76,0	82,0
5	6	77,8	80,5
6	6	79,5	82,4

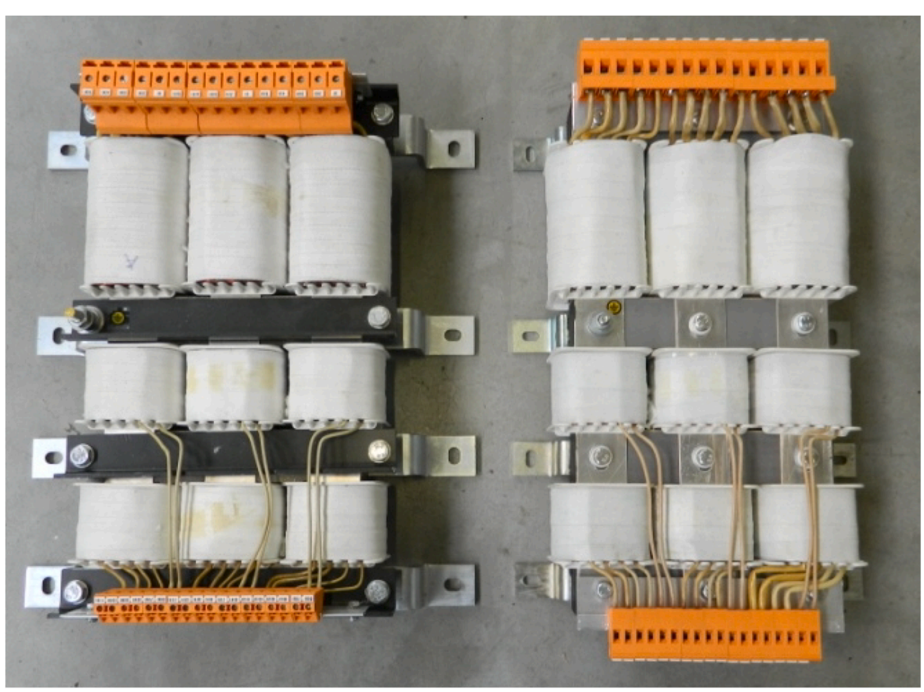
Parameters of the filter have been designed at the assumption that its application will reduce the THDi (Total Harmonic Distortion of current) index to the level of below 8% in a circuit with resistive-inductive loadbank. The total harmonic distortion in a circuit under test without filter was THDi = 86.94%. The harmonic filters were tested in the conditions of the rated load.

Measurements of the magnetic properties of the multi-gap amorphous core were made by using a Remacomp C-1200 system (Magnet-Physics GmbH). The noise level measurements for the multi-gaps cores were made by using the Digital Sound Level Meter AZ8921.

3. Results and discussion

Fig. 2 shows comparison of the magnetic properties of the $Fe_{78}Si_{13}B_9$ core after optimal thermo-magnetic treatment and after its impregnation with an epoxy resin. It is seen that introduction of resin to the core, results in the decrease of its magnetic induction B within the examined range of magnetic field intensities. No clear effect of the resin on coercivity H_c of the core has been observed. Based on the obtained magnetic properties of the "starting" core it could be expected that the blocks of required geometrical dimensions, cut out from this core, should also be characterized by suitable magnetic properties and mechanical strength after using them in the assembly of closed magnetic circuits. Such circuits should be capable to work at the magnetic induction up to 1.3 T, at the several times lower losses than in the case of the Fe-Si steel with 3 wt % Si cores.

The hysteresis loops obtained for rectangular cores with two gaps, made from the $Fe_{78}Si_{13}B_9$ and Fe-Si steel with 3 wt% Si ribbon, are presented in Fig. 3. The cores were impregnated with an epoxy resin. It is seen that the loops themselves and the respective magnetic parameters specified in the table are very advantageous from the point of view of potential applications of the soft magnetic $Fe_{78}Si_{13}B_9$ cores. At the frequency $f = 500$ Hz they reach the induction $B = 1.5$ T at the magnetic field $H = 702$ A/m, whereas core losses are 12 W/kg. In case of the Fe-Si steel with 3 wt% Si core, however, the core losses P_s at $f = 500$ Hz and $B = 1.5$ T are 56 W/kg. It should be emphasized that the induction $B = 1.5$



a) b)

Fig. 8. The $Fe_{78}Si_{13}B_9$ amorphous core(a) and the Fe-Si steel with 3 wt% Si core (b), applied in the three-phase harmonic filters 7,5kW/400 V/50 Hz.

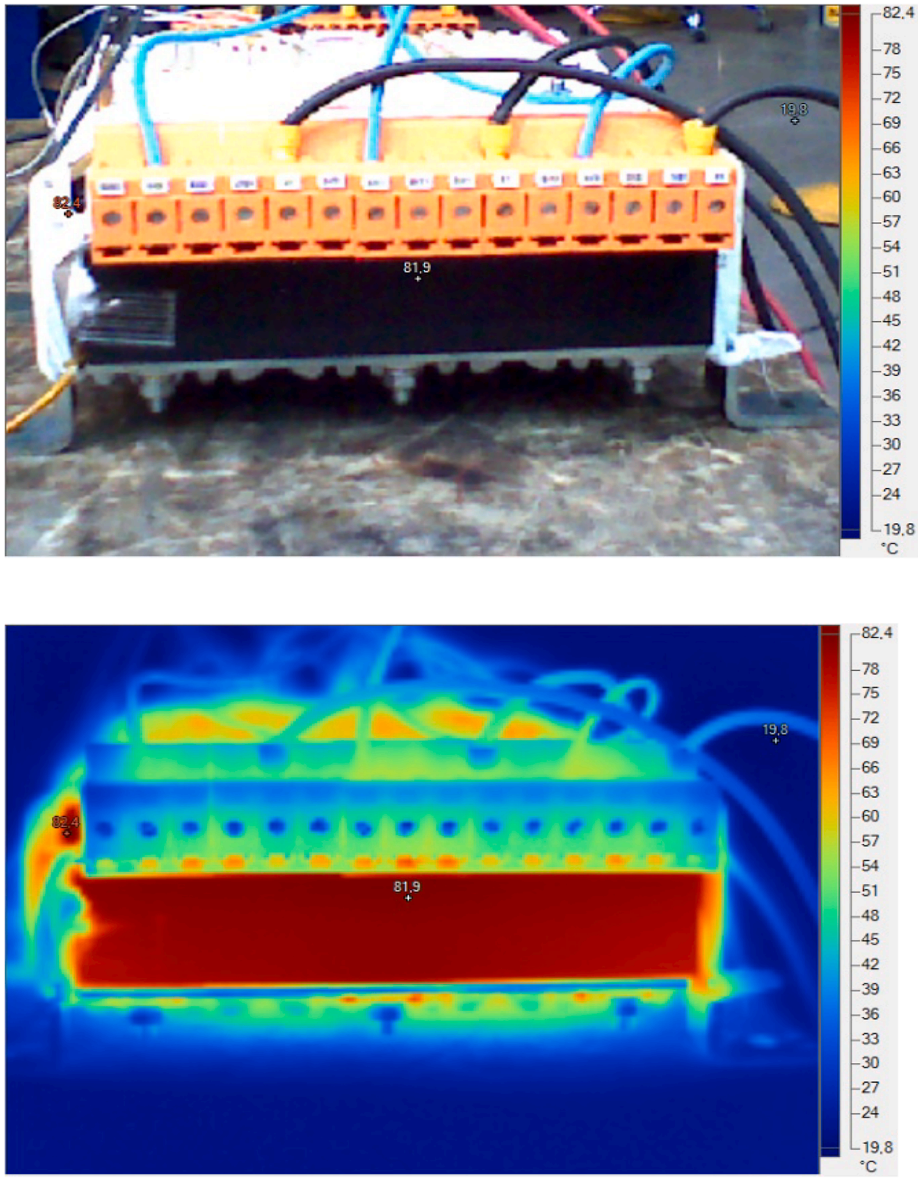


Fig. 9. A filter with Fe-Si steel with 3 wt% Si core: (a) idle (top) and (b) during operation (bottom).

T is achieved in the Fe-Si steel with 3 wt% Si core at H = 1871 A/m, whereas in case of the amorphous core – already at H = 702 A/m.

Some disadvantage of the amorphous $Fe_{78}Si_{13}B_9$ cores is their relatively high magnetostriction (27 ppm), causing a noise during core remagnetization at the induction *B* exceeding 1 T. However, this noise can be to great extent eliminated by filling micro-gaps inside the core with the Ultimeg 2004LN resin; the process is being carried out at the reduced pressure.

3.1. Determination of the magnetic properties of the amorphous blocks

In order to obtain necessary information about magnetic properties of the particular blocks used to build the multi-gap core of a choke, i.e. A; B1 and B2, six partial circuits with no gap have been assembled (Fig. 4). Next, the P_s = f(B) characteristics have been determined for each of these magnetic circuits at the frequencies of 50; 100; 300; 500 and 1000 Hz. Moreover, the level of noise arising during operation of these circuits at two different magnetization levels has been measured. The P_s = f(B) curves are presented below only for the circuits No 1 (Fig. 5) and No 4 (Fig. 6), because they are similar to those obtained for other partial circuits, i.e. with four and six gaps. Mass of the each of magnetic circuit is about 3500 g.

The main factors influencing the shape of the hysteresis loop and magnetic parameters of the rectangular multi-gap cores is the number of gaps and magnetizing field frequency.

Comparison of the characteristics P_s = f(B) obtained for the circuits No 1 and 4 shows that there is only slight difference between them. For instance, power losses P_s at f = 500 Hz and B = 1 T are 14 W/kg in the circuit No 1 (Fig. 5) and 17 W/kg in the circuit No 4 (Fig. 6).

Fig. 7 shows hysteresis loops for the circuit No 1 with four gaps and for the circuit No 4 with six gaps. Both loops have been measured at the sinusoidal magnetizing field, 50 Hz in frequency. Induction B in a circuit with six gaps is lower than the one in a circuit with four gaps because the loss of a core mass, caused by cutting out two additional gaps, has not been taken into account in the respective calculations. However, other magnetic parameters of both cores, such as coercivity H_c, remanence B_r and power losses P_s are almost the same.

The partial magnetic circuits were also subjected to the measurements of a noise level. The measurements were made for each magnetic circuit at two values of magnetic induction B: 0.7 and 0.9 T. The

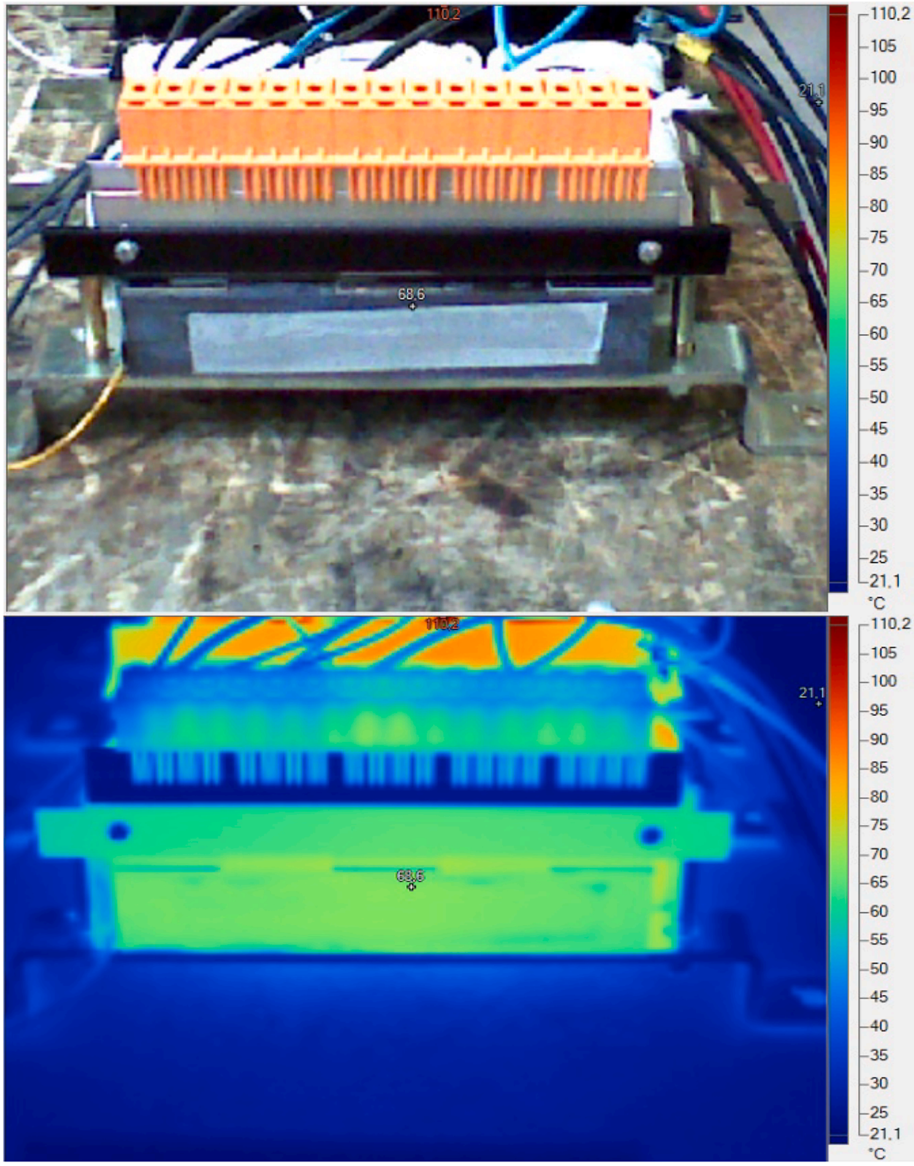


Fig. 10. A filter with $Fe_{78}Si_{13}B_9$ core: (a) idle (top) and (b) during operation (bottom).

experimental data given in Table 1 indicate that at the frequency of a magnetizing field set at the value of 300 Hz and the noise level during operation of a multi-gap core depends on magnetic induction *B* and on a number of gaps in the core.

The examined amorphous blocks were used to build a three-phase harmonic filter (7,5kW/400 V/50 Hz).

3.2. *Evaluation of the properties of the harmonic filter incorporating the amorphous $Fe_{78}Si_{13}B_9$ core.*

The harmonic filter built with the use of the amorphous core (Fig. 8a) was subjected to the comparative performance tests together with the filter incorporating the Fe-Si steel with 3 wt% Si polycrystalline core of the same electric specifications (7.5 kW/400 V/50 Hz) (Fig. 8b).

The harmonic filter comprising the Fe-Si steel with 3 wt% Si core made from the 0.3 mm-thick strip and then installed in a power electronic converter made it possible to reduce the content of the input current harmonics from the level THDi = 86.94% to the level THDi = 5.19%, at the filter rated current I_N = 11.5A. The filter with an amorphous soft magnetic core also decreased the harmonics content in the input current to the similar level of THDi = 6.68%. The difference in the obtained values of THDi results from the assumed tolerance of the constituent inductances and the production process. The overload tests were carried out within a range of 130–160 % of a value of the rated current of a filter with an amorphous core, confirming its full capacity of harmonics suppression – the amorphous core did not saturate and reached the induction B = 1.4 T. The main benefit from application of the amorphous $Fe_{78}Si_{13}B_9$ cores in the harmonic filters instead of the Fe-Si steel with 3 wt% Si cores results in significant reduction of power losses. This positive effect is related to much smaller thickness of the $Fe_{78}Si_{13}B_9$ ribbons (0.025 to 0.25 mm) and their over 2.5-times higher resistivity (130 do 47μΩ.cm) in comparison to the Fe-Si steel with 3 wt% Si strips. This fact is presented in Fig. 9a, b and Fig. 10 a, b which show thermograms of the filters containing the Fe-Si steel with 3 wt% Si and $Fe_{78}Si_{13}B_9$ cores, working under rated operational conditions at the current fundamental frequency of 50 Hz (the current spectrum contains also higher harmonics – 5 h, 7 h, 11 h, 13 h, etc.).

Temperature of the amorphous $Fe_{78}Si_{13}B_9$ core, characterized by considerably lower power losses than the Fe-Si steel with 3 wt% Si core, increased by ΔT = 49 °C, whereas in case of the Fe-Si steel with 3 wt% Si core this increase was higher (ΔT = 62 °C). Much higher temperature differences between the cores of both filters were observed in case of higher frequencies, because the overall core losses consist of hysteresis losses, which are proportional to frequency f, and eddy currents – proportional to f^2 [12].

4. Conclusion

The advantage of $Fe_{78}Si_{13}B_9$ amorphous material over polycrystalline Fe-Si steel with 3 wt% Si core in terms of power losses in the core is clearly visible when the operating frequency is at 10–20 kHz. In this case power losses in the amorphous core are up to 80% lower than for the polycrystalline Fe-Si steel with 3 wt% Si core. However, the conducted research showed that in the case of the designed three-phase harmonic filter (7.5 kW/400 V/50 Hz) the advantage is also visible at 50 Hz. Under this work, a three-phase harmonic filter has been designed and fabricated using the 27-multi-gaps amorphous block cores The tests showed that the filter with an amorphous core exhibits similar harmonics filtration capability as that with the Fe-Si steel with 3 wt% Si core but power losses in the amorphous core are about 20% lower than those in filter with polycrystalline Fe-Si steel with 3 wt% Si core. In addition, the temperature rise after 1 h is lower about 13 °C.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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