NEW NANOCRYSTALLINE MATERIALS FOR POWER ELECTRONICS APPLICATIONS

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Summary New nanocrystalline materials for the applications in the power electronics systems are developed and tested. These materials are intended to be used in the magnetic circuits of switching-mode power supplies (SMPS). The aim was to achieve extremely low hysteresis and non-linearity in operating region resulting in increased efficiency and decreased weight and size whilst keeping low price of the high-power frequency converters for SMPS.

1. INTRODUCTION

As the magnetic circuits are essential functional parts of SMPS and similar electronic devices, their size, losses and optimal design are of utmost importance. One of the most important features of this kind of circuits is their operation with non-sinusoidal voltages and currents in the frequency range covering tens Hz to tens kHz.

The work done can be divided into several main parts:

- the materials with magnetic properties comparable (or even better) to the commercially available one (VITROPERM 500F, produced by VACUUMSCHMELZE GmbH) were prepared,
- theoretical analysis and experimental verification of proper arrangement of the windings from the point of view of minimizing the error of specific loss measurement of large toroidal samples at high frequencies and exciting fields was carried out, [1],
- the high-power amplifier based on commercially available hybrid power operational amplifier kit was designed, constructed and tested,
- basic static and dynamic magnetisation characteristics and parameters of the cores made of VITROPERM as well as newly developed materials were measured.

2. MATERIALS PREPARATION

The materials tested have the composition based on classical FINEMET ($Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$) as well as with increased silicon content, $Fe_{71.5}Cu_1Nb_3Si_{15.5}B_9$. The aim of research was the development of a new technology allowing controlled change of magnetisation characteristics, mainly their “slope”. The “slope” of hysteresis loop can be controlled by the induced magnetic anisotropy during the nanocrystallisation process. Special preparation technology of the toroidal cores made of nanocrystalline materials with magnetisation characteristics convenient for the application in SMPSs or choke coils requires the annealing of ready-made cores (semi-products) in the magnetic field perpendicular to the ribbon axis. For this purpose a special two-component furnace made of non-magnetic materials providing required heating modes, their stability and radial thermal distribution needed for optimised nanocrystallisation was constructed. The furnace casing was cooled by the water and the sealing allowed annealing in protective atmosphere. The furnace itself has been inserted between vertical pole extensions of the electromagnet. The maximum of magnetic flux density in the air gap was 0.25 T (older set-up) and 0.4 T (new construction of the magnetising coils). The furnace inserted into the electromagnet is shown in Fig. 1. Further optimisation was focused on the exploitation of free space to increase the number of turns aiming at higher annealing fields as well as better insulation allowing higher operating temperatures.

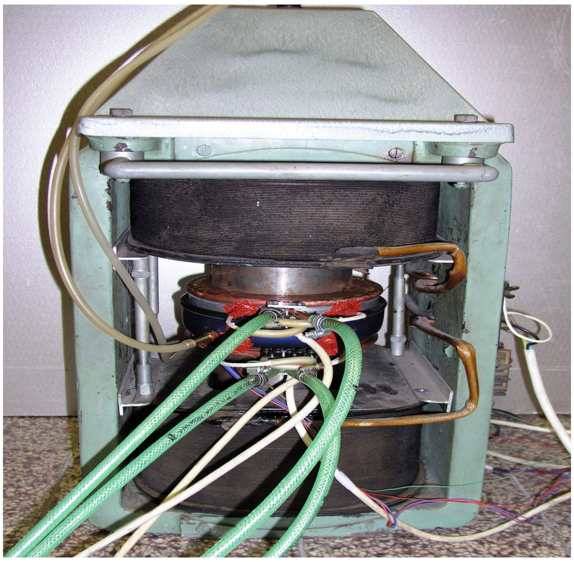

Fig. 1. The arrangement of the furnace and electromagnet, old version.

3. EXPERIMENTAL EQUIPMENT DESIGN

For the required operating frequencies and flux density amplitudes, the limiting factor from the point of view of given maximum allowed output voltage of the magnetising source and given cross-sectional area of the core is the number of turns. The number of turns has to be chosen as a compromise between the homogeneous magnetic field distribution (ideally the winding should be wound around the entire core) and the voltage needed to achieve required magnetic flux density amplitude (the less the number of secondary turns for given amplifier output voltage the higher the flux density). Another way how to increase the output voltage is the usage of the output transformer. In our case this is not possible because of the feedback from the secondary winding providing required sinusoidal flux density waveform described later. This feedback does not work with output transformer because of instabilities leading to oscillations that could damage the push-pull output stage of the amplifier. Thus, for the specified amplifier maximum output voltage the best choice in our case was only a single-turn or double-turn primary and secondary winding.

The results of numerical analysis in 2D approximation as well as their experimental verification for two types of magnetic materials with different permeabilities have confirmed, that if the relative permeability μ_r>1000, the magnetic loss measurement error due to non-uniform arrangement of magnetising as well as sensing winding is comparable to the intrinsic measurement error itself even in the worst case (single turn), [1]. The results obtained are essential for the design of magnetising circuitry, since the increasing of the output voltage significantly increases the cost of the equipment. Moreover, large number of turns increases the parasitic inter-turn and inter-winding capacities resulting in an additional error especially at high frequencies.

From the point of view of intended applications our goal was to design the experimental equipment allowing to measure the magnetisation characteristics at the frequency f=100 kHz and maximum flux density B_m=0.3 T while the sinusoidal flux density waveform is provided. On the basis of these requirements, the high-power amplifier allowing to measure within the frequency range from DC to 300 kHz with maximum output current 10 A and maximum output voltage swing 180 V based on commercially available hybrid power operational amplifier kit was designed, constructed and tested. The basic kit, shown in Fig. 2, along with recommended protection circuitry against the overloading and voltage peaks in the output and supply terminals was supplemented by two external feedbacks; one introduced from the secondary winding provides defined sinusoidal induced voltage (flux density) waveform and the second one acts as so-called DC servo.

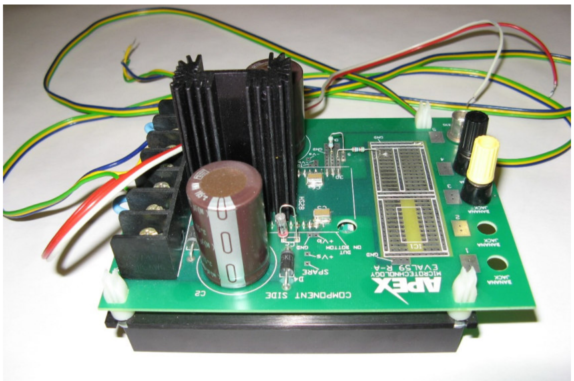

Fig. 2. The power amplifier kit.

This is needed to suppress any DC offsets and low-frequency drifts from the input causing the amplifier abruptly reach the limitation state, since the first feedback loop is open for DC signals.

4. RESULTS AND DISCUSSION

An example of quasi-static hysteresis loop of commercially available nanocrystalline material (VITROPERM 500F) is shown in Fig. 3,

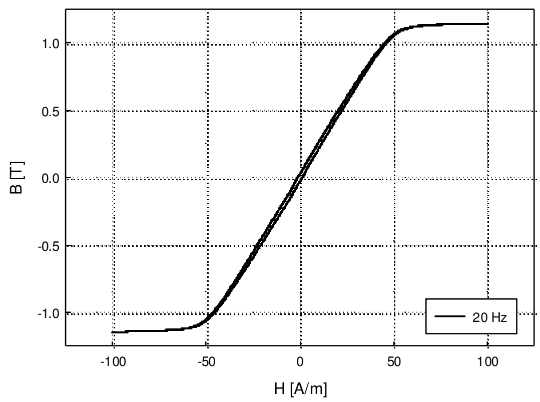

Fig. 3. Quasi-static hysteresis loop of VITROPERM 500F.

As can be seen from the figure, the material exhibits nearly no hysteresis. Moreover, the magnetisation characteristics within the range of applied field ±40 A/m is almost linear with the character of a magnetic circuit with an air gap. Our task in this phase was the testing of various technological variations during annealing (external field, annealing temperature regimes, etc.) and material composition with the aim of the preparation of materials achieving comparable magnetic properties whilst keeping low costs during the whole technological process. Some examples of quasi-static hysteresis loops of the materials prepared at the Institute of Physics of the Slovak Academy of sciences are shown in Figs. 4 and 5. One can see that in the case of sample FA2 the loop is more abrupt than VITROPERM (narrower linearity range), meanwhile in the case of sample FA6 prepared in higher magnetic field during annealing the loop has almost the same shape and anisotropy field.

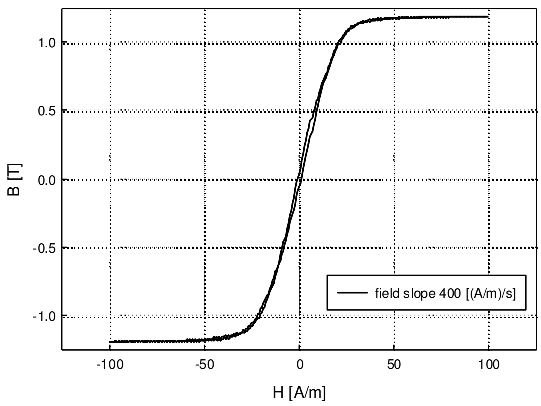

Fig. 4. Quasi-static hysteresis loop of sample FA2.

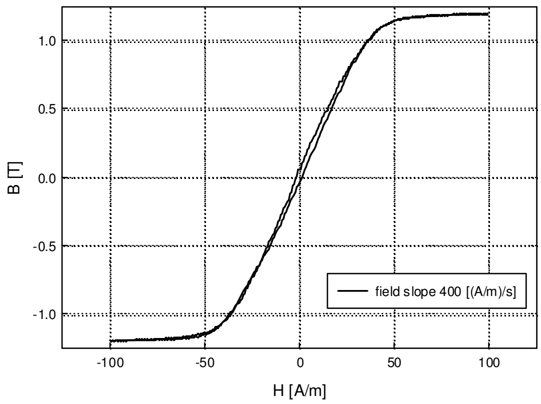

Fig. 5. Quasi-static hysteresis loop of sample FA6.

The main difference between our two samples is the slope of the linear part of magnetisation curves giving different values of the permeability. Thus, we are able to tailor the magnetic properties for any particular application by means of different annealing methods and material mixture. More samples were prepared, but the results obtained on these two samples seem to be the best taking into account the time and energy consumption as well as total costs during preparation procedures.

Dynamic properties of the materials were compared by means of total power losses. The dependence of total power losses on the amplitude of flux density measured at 100 kHz is in Fig. 6. One can see that the measured values are not affected by the number of turns of the primary and secondary winding; thus it is possible to use less number of turns to achieve higher maximum flux density with the same amplifier. The variation of measured values is caused by the core heating during the testing. Our results are comparable to the values provided by the producer of commercially available material. Currently, the losses of VITROPERM 500F measured at f=100 kHz and B_m=0.3 T according to the product datasheet are p=80 W/kg, [2]. Note that in the time when our research started, the losses certified by the producer were p<110 W/kg.

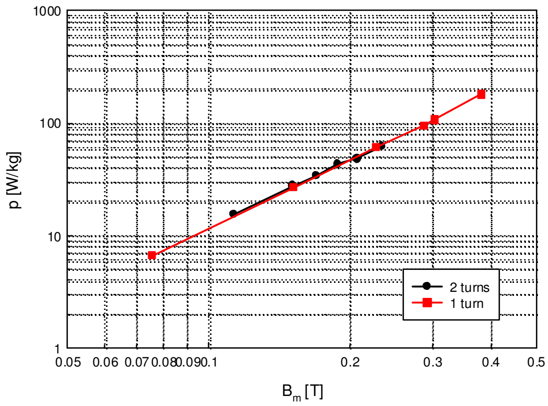

Fig. 6. Total power losses as a function of flux density amplitude, f=100 kHz, sample FA2.

5. CONCLUSION

New nanocrystalline materials based on FINEMET-like composition intended for use in switching-mode power supplies were developed and tested. The work was focused on the proper annealing procedure from the point of view of temperature profile and applied external magnetic field as well as the material composition. To achieve the required magnetic properties the new annealing furnace and magnetising electromagnet were constructed. The magnetic characteristics were evaluated by means of newly designed experimental equipment allowing to measure at high frequencies and amplitudes of magnetic flux density. The results of measurement have shown that we are able to prepare the materials with magnetic properties comparable to commercially available materials with less expense. On the other hand, the technology has to be optimised in order to further decrease the total losses and to achieve better reproducibility.

Acknowledgement

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[2] VACUUMSCHMELZE GmbH & Co. KG VITROPERM 500F datasheet: *http://www.vacuumschmelze.de/dynamic/docroot/medialib/documents/broschueren/kbbrosch/PKB_EMV_E.pdf*