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FO-11. Performance factor comparison of nanocrystalline, amorphous and crystalline soft magnetic materials for medium frequency applications.

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Abstract The efficiency of electromagnetic devices, such as e.g. transformers, is influenced by the losses of the applied soft magnetic material. Different structured materials are available but choosing the appropriate material is not instinctive. A performance factor is evaluated in this paper for frequencies up to 10 kHz. The studied application is a medium frequency transformer. A semi-physical iron loss model is used to describe the measured losses. These results are used to determine the performance factor for various boundary conditions. **Introduction** The iron losses of soft magnetic materials are frequency dependent. Different loss components such as hysteresis losses and eddy current losses and their individual dependency on frequency and flux density determine the total losses of each material. The introduction of amorphous and nanocrystalline materials enabled new possibilities to design electromagnetic circuits. When compared to standard silicon iron, which can be grain and non-grain oriented electrical steel, amorphous and nanocrystalline materials benefit from reduced eddy current and excess losses due to thin material layers and the absence of grain structures with considerable grain sizes [1]. However, choosing for the most appropriate material grade is difficult and needs to be examined for each design and application. One way to compare different ferromagnetic materials is to evaluate a *Performance Factor* [2]: $\mathbf{F} = B*f$ (1.1) The multiplication of the peak flux density and the sinusoidal frequency is also present in Faraday's law and can describe the compactness of a magnetic circuit. Under the presence of sinusoidal excitation, the cross sectional area of a magnetic circuit can be calculated by $A = V_{rms}/(2\pi/\sqrt{2}*B*f*N) = V_{rms}/(2\pi/\sqrt{2}*\mathbf{F}*N)$. (1.2) **Measurements** The measurements are performed with standardized Epstein frames or a ring coil testing module according to DIN EN 60404-2 [3] and DIN EN 60404-6 [4]. All measurement instruments are limited to a maximum flux density of B = 2.0 T and a maximum frequency of f = 10 kHz. The studied specimens are nanocrystalline, amorphous and silicon steel based alloys. Quasistatic measurements and sinusoidal measurements with frequencies up to 10 kHz are performed to identify the required loss parameters for the IEM-5-Parameter model [5]. $P_{IEM,5} = a_1*B^{\alpha}*f + a_2*B^2*f^2 + a_2*a_3*B^{a4+2}*f^2 + a_5*B^{1.5}*f^{1.5}$ (1.3) **Performance Factor** A high performance factor implies that either a high flux density, a high frequency or both can be applied to the material under the limitation of a maximum allowed loss dissipation. The geometric size, the material mass respectively used volume can be decreased by choosing a material grade with a high performance factor. Typically, the performance factor is calculated over a wide frequency range per material but is often only valid for one fixed maximum iron loss dissipation because of a two dimensional consideration (Fig. 1) [6]. This paper evaluates the performance factor of each studied material in a third dimension. The IEM-5-Parameter model is used to extract the required information. The boundary of one fixed maximum loss dissipation per plot (Fig. 1) is discarded by the introduction of a third dimension respectively axis, which describes different loss limits (Fig. 2). The full paper will present a detailed overview with all mentioned material grades. **Results** In this digest the results for two different material grades are discussed. The performance factor is evaluated for a non-grain oriented silicon steel and an amorphous material grade. In high frequency applications above f = 1 kHz, the amorphous material performs better in this comparison. The critical frequency is loss dependent (Fig. 2). In case of lower loss limitations, the cutoff frequency decreases and the application of the amorphous material becomes worthwhile for lower frequencies as well. **Conclusions** In the full paper, further materials will fulfill the comparison. The different materials will be introduced and discussed based on material properties and the IEM-5-Parameter model. A frequency based recommendation for each material can be expected in the full paper. In addition, the material prices €/kg can be included into the comparison for an economic based solution regarding the inset of volume. This may be done because of the direct link between performance factor and required material weight. In this digest is shown, that in case of low frequencies below f = 500 Hz, amorphous materials can perform better than SiFe material. **Acknowledgement** Funded by Bundesministerium für Bildung und Forschung, Forschungscampus Elektrische Netze der Zukunft (FKZ03SF0489).

[1] T. Kauder und K. Hameyer, *Iron loss comparison of standard SiFe and nanocrystalline materials for power transformers in a dual active bridge converter*, 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe): IEEE, 2016. [2] A. J. Hanson, J. A. Belk, S. Lim, C. R. Sullivan und D. J. Perreault, *Measurements and Performance Factor Comparisons of Magnetic Materials at High Frequency*, IEEE Trans. Power Electron, Bd. 31, Nr. 11, S. 7909–7925, 2016. [3] Magnetic materials - Part 2: *Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of an Epstein frame*, DIN EN 60404-2. [4] Magnetic materials - Part 6: *Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range of 20 Hz to 200 kHz by the use of ring specimens*, DIN EN 60404-6. [5] D. Eggers, S. Steentjes und K. Hameyer, *Advanced Iron-Loss Estimation for Nonlinear Material Behavior*, IEEE Transactions on Magnetics, Bd. 48, Nr. 11, S. 3021–3024, 2012. [6] I. Villar, A. Garcia-Bediaga, U. Viscarret, I. Etxeberria-Otadui und A. Rufer, *Proposal and validation of medium-frequency power transformer design methodology*, IEEE Energy Conversion Congress and Exposition (ECCE): IEEE, 2011.

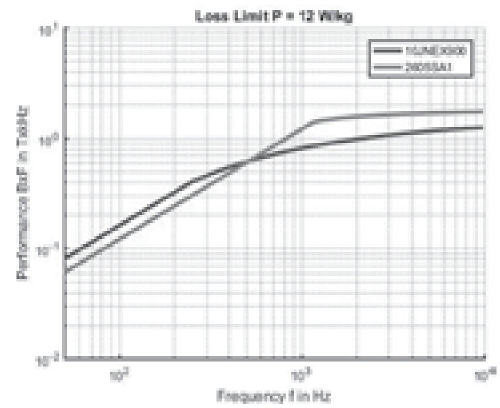

Fig. 1: Performance Factor evaluated for one fixed loss limit P =12 W/kg.

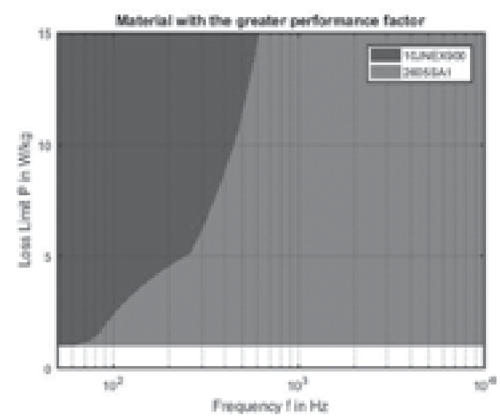

Fig. 2: Top view of a three-dimensional evaluation.