IMPROVING THE POWER DENSITY OF TRANSFORMERS WITH NANOCRYSTALLINE CUT CORES

New production process reduces the iron losses of VITROPERM 500 cut cores even further. They are an excellent choice for high performance medium-frequency transformers (MFTs).

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INTRODUCTION

Continuous improvements in conventional Si-based semiconductors and new wide bandgap materials like silicon carbide (SiC) and gallium nitride (GaN) are regarded as the key drivers for future high power applications like medium-frequency solid-state transformers. Their typical fields of applications are railway, smart power grids and DC fast charging for electric vehicles.

Despite the rapid development of active switches, especially the inductive components are critical for size and weight of the system and its performance. Switching frequencies between 1 kHz and 100 kHz for power levels beyond 100 kVA allow for an effective reduction in the size of all magnetic components; however, high switching frequencies usually go along with higher switching losses in the core material. A reduction of the effective magnetic flux density partly compensates this, leading to larger core dimensions.

High power designs usually require the application of cut cores – mainly for a more convenient winding design – at the cost of higher losses and larger magnetic stray fields.

SOFT MAGNETIC MATERIALS

The world of soft magnetic materials for these applications consists of four relevant material groups with their own strengths and weaknesses:

Soft ceramic ferrites, mostly manganese-zinc (MnZn) and nickel-zinc (NiZn) ferrites. For medium-frequency applications, MnZn is usually preferred due to the lower losses, its higher initial permeability and higher saturation induction at frequencies below 3 MHz. MnZn ferrites offer a much better loss behavior compared to SiFe between 25 kHz and 200 kHz. High frequency ferrites can be used up to 500 kHz.

Due to the rather broad portfolio of material grades, the material characteristics can be optimized for the specific operating conditions. As the production process is based on sintering, various core shapes can be realized. The main drawback of MnZn ferrites is their comparably low saturation induction of typically 0.35 – 0.55 T. Moreover, the magnetic characteristics are highly temperature-dependent, typically further limiting the achievable magnetization under operating conditions.

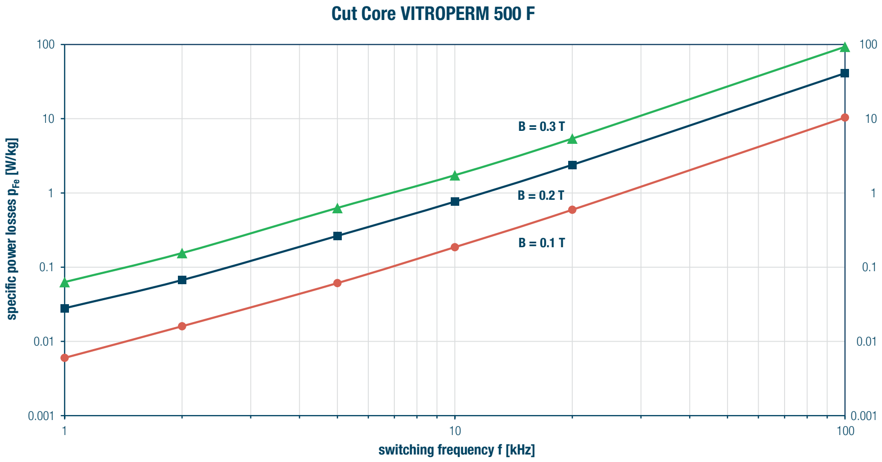

Figure 1: Specific power losses versus switching frequency for peak flux densities between 0.1 and 0.3 T.

Practically, there are two ways to mitigate these constraints: increasing the switching frequency or raising the effective iron cross section. The first approach results in higher switching losses, while the second reduces the power density of the design.

Grain Oriented Electrical Steel (GOES), based on silicon iron (SiFe) with 3wt% silicon, is the most widely used material in the manufacture of energy efficient transformers, especially for 50 Hz power applications. The main advantages are the high saturation induction of 2.0 T, the relatively easy mechanical processing and the high availability of this material. The main disadvantage is the high total loss with respect to frequency. Usually the application of grain oriented electrical steel is limited to applications with switching frequencies below 1,000 Hz.

The third relevant material group includes **amorphous iron-based alloys** produced by melt spinning where metalloids such as boron (B) and silicon (Si) are intentionally added to stabilize the amorphous state. The main advantage of these materials is the combination of relatively low losses and high saturation induction of around 1.5 – 1.6 T. The good performance in comparison to SiFe makes this material very attractive for distribution transformers.

The main disadvantage is the relatively high magnetostriction of about 25 – 30 ppm. This intrinsic material property describes the coupling between the internal magnetization of the material and the change in its dimensions. The consequence is the development of disturbing noise during magnetization and its high sensitivity to mechanical stress. This causes handling problems and limits the possibilities for further improvements in the magnetic performance.

The fourth group consists of **nanocrystalline iron-based alloys**. Similar to the amorphous alloys, these materials are produced in a rapid quenching process with a subsequent heat treatment for formation of the nanocrystalline grains inside the material. Due to the production process, the material comes as a thin strip with a thickness of below 20 µm and variable width. This is the main reason why amorphous and nanocrystalline cores are limited to toroidal, oval and rectangular shapes. Compared to the iron-based amorphous material, with nanocrystalline material the magnetostriction can be tuned to practically zero. Consequently, it offers the smallest power losses for a wide frequency range up to 200 kHz at a considerably high saturation of 1.2 T. Moreover, practically no temperature-dependence is visible under typical operating conditions. Usually, the main disadvantage of nanocrystalline cores for high power applications has been the significant increase in core losses after cutting.

NEW PRODUCTION PROCESS FOR NANOCRYSTALLINE CUT CORES

To overcome this disadvantage, VACUUMSCHMELZE has conducted a broad R&D initiative with external partners in order to optimize the complete production chain of cut cores. The magnetic performance of cut cores does not solely depend on the quality of the cut, but also on the shape of the core as well as the involved elementary magnetization processes. The latter is additionally influenced by technological parameters.

Starting with a new winding technology that is capable of applying much higher winding forces without compromising the magnetic quality, nominal core filling factors of around 80 % become achievable. This directly increases the effective iron cross section of the core, subsequently allowing for a reduction of the core volume. After winding, the heat treatment takes place, turning the amorphous material into its nanocrystalline state.

Afterwards, the core is prepared for cutting by applying a suitable resin. This material needs to exhibit a low viscosity in order to completely fill the core. For optimal cutting results, a good adhesion on the nanocrystalline VITROPERM® strip and high peel strengths are also required. At the same time, low residual stress is mandatory to minimize the influence on the magnetic performance of the core. Finally, a high glass transition temperature is necessary to meet customers' requirements of operating temperatures in the range of 130 °C.

In its nanocrystalline state, the material is very brittle, increasing the risk of massive destruction of VITROPERM layers if the wrong cutting technique is used. In cooperation with external partners, VACUUMSCHMELZE has conducted an extensive analysis of the different possibilities of cutting and their effects on the magnetic quality. In the end, the optimal cutting technique was selected, combining superior magnetic quality with cost-efficient production times.

This is followed by the final treatment of the raw cut surfaces, significantly improving the loss level at higher frequencies.

LOWER LOSSES AND COMPACT DESIGNS

These improvements along the production chain involve a number of benefits: The increased filling factor allows for compact designs, reducing the footprint and volume of the end application. The continuous operating temperature of 130 °C directly supplements this freedom in design.

The key advantage is clearly the reduction of the specific power losses: Figures 1-3 show the specific power losses versus the switching frequency in the range 1 to 100 kHz for fixed peak flux density between 0.1 to 0.3 T. Additionally, the specific power losses against the peak flux density in the range 0.1 to 1 T for fixed switching frequencies between 1 kHz and 100 kHz.

The figures clearly show the usability for high peak flux densities up to 1 T and the very low power losses. The new cut cores are practically comparable to uncut cores of the same size in terms of their loss level. Accordingly, the new VITROPERM 500 cut cores exhibit the lowest specific power losses of all materials discussed in this article.

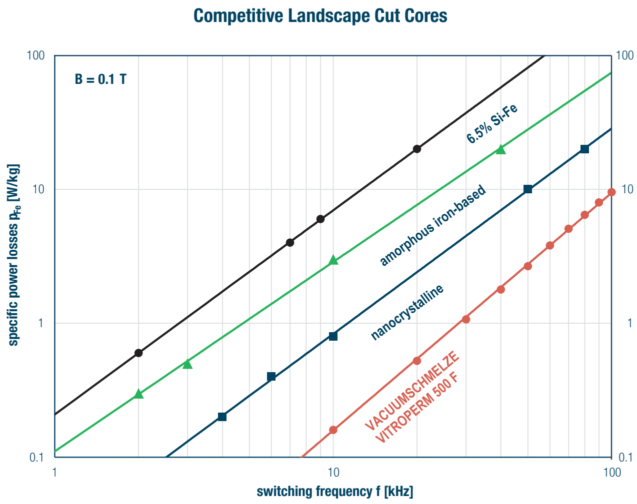

Figure 3: Specific power losses versus switching frequency at 0.1 T for cut cores made of various magnetic materials.

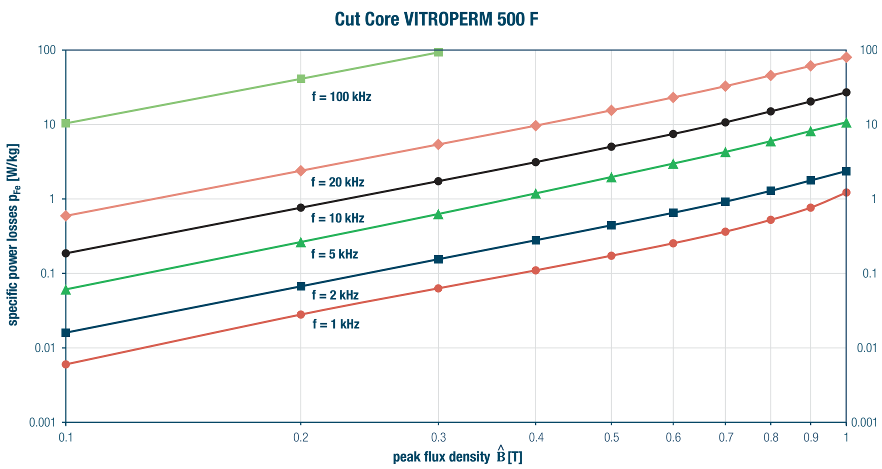

Figure 2: Specific power losses versus peak flux density for switching frequencies between 1 and 100 kHz.

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