Nanocrystalline materials in common-mode chokes

Excellent damping properties achieved by small volumes

Advantages of nanocrystalline materials lie in compact size and covering a wide range of frequency, allowing operating temperatures up to 120°C. Applications are high power transformers for SMPS.

Dr. Jörg Petzold
Dipl.-Ing. Roman Klinger
Vacuumschmelze

Figure 1: *Examples of magnetic cores and components made of Vitroperm*

• With the entry of switched-mode power supplies (SMPS) into almost all areas of industrial and domestic power supplies, as well as in the resulting spatial density of these, there is a significant increase in mutual electromagnetic interference, which can cause failures of electronic devices. Examples are strong electric motors influencing neighbouring telephone installations or personal computers making the simultaneous use of radio or TV sets impossible. For this and similar reasons, modern electronic devices need stipulated standard values both with regard to emission as well as resistance against interference. In practice, radio frequency interference filters (RFI filters) are used, which normally consist of capacitors and inductances. Central components are common-mode chokes (CMC) with soft magnetic cores. The required attenuation properties are fulfilled by the nanocrystalline material Vitroperm. With reference to the different propagation paths through cables (network, data lines...) or through free space (electromagnetic fields) the noise is classified as "conducted" or "radiated". Conducted noise appears typically at frequencies below 30 MHz and radiated noise at frequencies above 30 MHz. Due to the components under discussion this article focuses on conducted noise only.

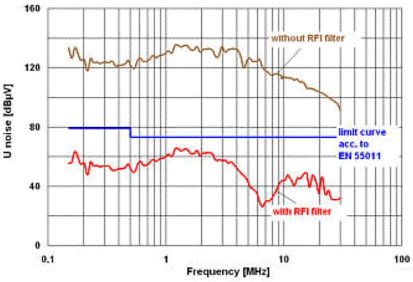

Figure2: *Interference noise voltage of a typical inverter with and without RFI filter*

Switched mode power supplies usually generate a narrow band noise spectrum with discrete frequencies, typically ranging between 20 kHz and 200 kHz, featured by a discrete harmonic spectrum. Examples are PC power supplies, welding sets, kW switched-mode power supplies. Inverters usually raise a wide-band noise spectrum at 10 kHz to 30 MHz. Examples are frequency Converters for motor control systems.

There exists a large number of standards which have arisen historically and often are valid only regionally, e.g. EN 55011 and DIN VDE 0875. In contrast to these, CISPR 11 applies internationally and comprehensively. The maximum permissible noise voltages in the frequency range from 150 kHz to 30 MHz are determined by boundary lines according to EN 55011, whereby a distinction is made between different application sectors (domestic or industrial), between the mode of operation (EMC internal or external) and between the different types of measurement (average or quasi peak). As shown in *figure 2*, the function of the RFI filter is to reduce the noise voltages below the relevant limiting curves in the complete frequency range between 150 kHz and 30 MHz.

The RFI Filters and the mode of operation of a Common Mode Choke (CMC) are shown in the following. According to *figure 3* the operating current I operation of a device flows through the CMC in such a manner that the magnetic fields of both current directions cancel one another. In consequence for equal numbers of windings arranged in opposite directions only a residual stray field remains inducing the slight "differential mode" flux in the core material. Thus, a noise spectrum with a symmetrical course like the operating current will be attenuated only slightly.

If in contrast a high-frequency noise is discharged capacitively through Cy to ground a magnetic field "H $_{I\,com}$" is generated which is not compensated at all and the full impedance Z of the CMC acts against this "common mode" current (I_{com}) causing the desired damping effects.

$$Z(f,H_{I_{com}}) = w \cdot L(f,H_{I_{com}}) =$$

$$2 \cdot p \cdot f \cdot \mu_0 \cdot \mu_r(f,H_{I_{com}}) \cdot \frac{A_{Fe}}{l_{Fe}} \cdot N^2$$

L: inductance, f: frequency of the noise; μ_o: magnetic field constant; μ_r (f, H_{Icom}): relative initial permeability depending on frequency and field strength; A_{Fe}: iron cross section of the core; l_{Fe}: mean iron path length; N: number of turns. The resulting magnetisation B, at which the choke must not be saturated, can be calculated by:

$$B(f,H_{I_{com}}) = \mu_0 \cdot \mu_r(f,H_{I_{com}}) \cdot \frac{I_{com} \cdot N}{l_{Fe}}$$

Best noise damping properties according to eq. (l) and (2) are achieved by core materials with superior softmagnetic properties featured by high permeability and low core losses. In former years crystalline permalloys, Sendust, manganese zinc-ferrites or amorphous cobalt-based alloys have been used. In contrast to other ferromagnets, these alloys exhibit very low magnetocrystalline anisotropies and a low or vanishing magnetostriction. Both features are the most essential conditions to gain excellent soft magnetic properties.

Recently the spectrum of superior soft magnetic materials has been extended by so-called nanocrystalline alloys.

Due to its vanishing magnetostriction and its reliable production process, the composition Fe73.5Cu1Nb3Si15.5B7 is the most prominent representative of this new class of softmagnetic materials. It is produced by VAC in high quantities and is available under the tradename Vitroperm. This material is featured by a two-phase structure consisting of an ultrafine iron-silicon grain with an average diameter of 10 - 20 nm which is embedded in an amorphous residual phase. Due to this structure the magnetocrystalline anisotropy is averaged out and vanishes as well as the saturation magnetostriction does. In consequence these materials can reach highest permeabilities and lowest coercivities. Magnetic tape-wound cores made from this material are signed by linear hysteresis loops with coercivities smaller than 10 mA/cm and a saturation induction of 1.2 Tesla.Moreover, the permeabilities are definitely adjustable between roughly 15 000 and 200 000. These static hysteresis properties combined with a ribbon thickness of 15 - 25 µm and a relative high electrical resistivity of 120 micro-ohmcm yield an excellent dynamic behaviour i.e. lowest core losses and a high initial permeability up to highest frequencies.

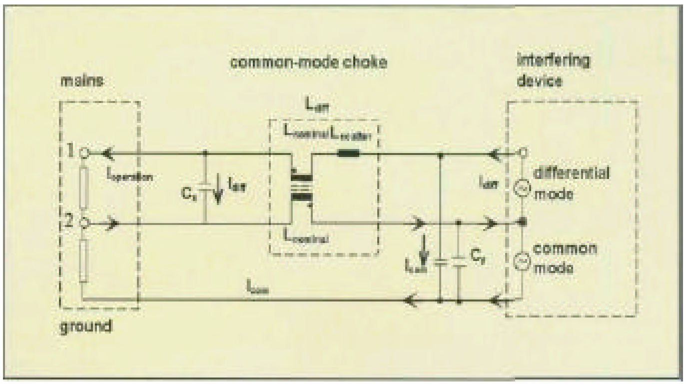

Figure 3: *Schematic circuit of an RFI filter with common-mode choke*

Material Material basis	Co - based amorphous approx. 77 % Co	NiFe Permalloys 60 % Ni	MnZn Ferrite MnZn	Nano-crystalline approx. 73.5 % Fe
Permeability $\mu_{r,max}$ (10 kHz)	>90 000	< 20 000	15000	**15000... > 80 000**
Losses $P_{Fe,\,typ}$ (25 kHz, 200 mT, 100°C)	5 W/kg	14 W/kg	17 W/kg	**3 W/kg**
Saturation Induction B_s	0.6 T	0.8 T	0.48 T	**1.2 T**
Curie Temperature T_c	210°C	400 °C	220°C	**> 600°C**
Upper Cont. Operation Temperature T_{max}	90 °C	120°C	<100°C	**>120°C**

Table 1: *Comparison of softmagnetic core materials for Common-Mode Chokes*

Small component volumes with high nominal choke inductances are according to eq. (l) achieved by core materials with high permeabilities µr. Highest permeabilities are moreover an essential prerequisite for the continuously miniaturisation progress of RFI filters. Medical devices for example require CMCs with highest impedances (highest permeabilities) because the noise current conducted through Cy to ground must be as small as possible. This guarantees sufficient protection if a person comes into an electrical contact with the device.

As *figure 4* shows, the initial permeability of Vitroperm is equivalent to that of the highest permeable amorphous materials and surpasses by far the properties of conventional materials. Due to the small hysteresis losses, the frequency characteristic of the permeability can be given

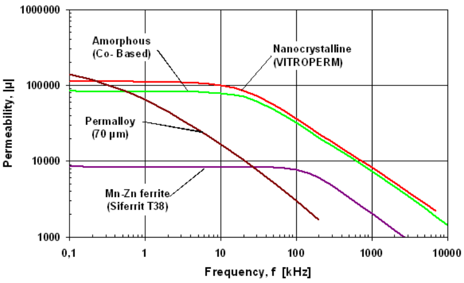

Figure 4: *Comparison of initial permeability vs. frequency curves of soft magnetic materials used for common-mode chokes*

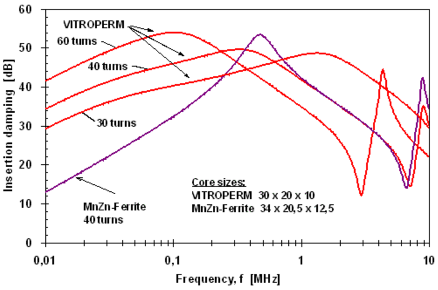

Figure 5: *Insertion loss of common-mode chokes for different numbers of tums and different materials.*

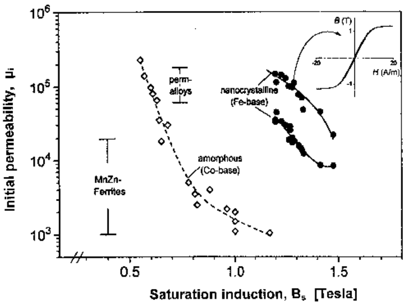

Figure 6: *Initial permeability vs. saturation induction for low magnetostrictive soft-magnetic materials*

by the classical eddy current theory:

$$m'(f) = m_i \cdot \frac{1}{x} \cdot \frac{\sinh x + \sin x}{\cosh x + \cos x}$$

with $x = (f / f_w)^{1/2}$ *and*

$$f_w = \frac{4r}{p m_o m_i d^2}$$

f_w is a critical frequency above which the exciting field cannot penetrate the material any more in full strength and the permeability decreases with increasing frequency. As shown in *figure 4* and following eq. (3) - (4) the favourable frequency characteristic is determined by the magnitude of the initial permeability μ_i, and the high electrical resistance of about 120 microohmcm combined with a low thickness d of the nanocrystalline ribbon of approx. 20 micrometer or less.

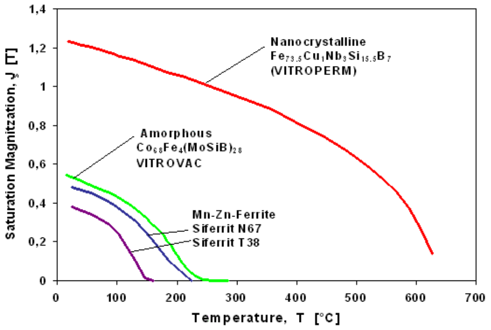

Figure 7: *Influence of temperature on saturation magnetisation J (which is almost equal to saturation induction* B_S *in high permeable materials) of typical CMC core materials*

Due to the high permeability, the insertion loss curve of CMCs with cores ofVitroperm in *figure 5* is much higher than that of CMCs with ferrites mainly at frequencies in the low kHz range. This is advantageous for switched-mode power supplies with discrete noise frequencies because the fundamental waves of the noise sources are attenuated more effectively and thus, the interference effect of the harmonics (which are very often in the relevant frequency band of 150 kHz to 30 MHz) is less pronounced and consequently less filtering is required for attenuation.

Moreover, to achieve the same inductance value of a common-mode choke, the high permeability of Vitroperm allows much lower numbers of turns than would be typical for a comparable CMC made of ferrite. In consequence the parasitic winding capacitances are lowered significantly and the onset frequency of the first resonance and the onset frequency of the deattenuation regime is shifted towards the MHz range where it need not be taken into account in many cases.

In frequency inverters for example, noise voltages with high amplitudes are caused by long motor cables. Consequently the asymmetrical parts of the noise spectrum increase very strongly, so that the core material has to absorb high voltage-time integrals for a short time. However, if the noise signal becomes too high the damping properties of the CMC can disappear almost completely by saturation effects according to eq. (2) if B exceeds the saturation induction of the core material. This can be avoided by using a core material combining high saturation induction with high permeability.

As shown in *figure 6*, in most soft magnetic materials such as MnZn-ferrites, permalloys or amorphous Co-based alloys high saturation inductions exclude high initial permeabilities and vice versa. The iron-based nanocrystalline alloys feature in contrast to these a unique combination of very high saturation induction of 1.2 T with very high initial permeabilities of about 100 000 or even more.

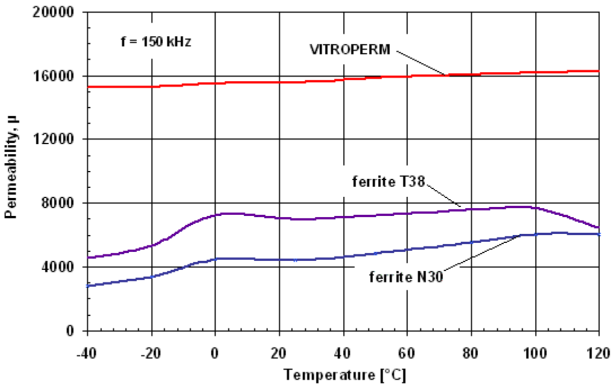

Figure 8: *Temperature dependence of permeability of nanocrystalline alloys and ferrites at 150 kHz*

When considering thermal properties, a basic distinction must be drawn between the upper operation temperatures (for choke design) and the variations of magnetic material characteristics with temperature. The influence of temperature on the saturation induction is shown in *figure 7*. Whereas the Curie temperatures of ferrites and amorphous materials used for CMC are below 300°C, a Curie temperature of more than 600°C can be stated for nanocrystalline Vitroperm.

Ageing effects cause a decrease of permeability and a deterioration of nearly all dynamic properties in the case of ferrites and amorphous materials with high permeability and limit the upper application temperatures below 100°C (typically <80°C). In contrast, nanocrystalline Vitroperm alloys reveal no ageing effects up to 120°C due to the high thermal stability of the microstructure. This allows CMC design either for higher operating currents in the same component volume or with the same damping properties at noticeably smaller volumes. The temperature dependence of the permeability is also closely related to the structural peculiarities described above, whereby some aspects are still under investigation up to now. According to *figure 8*, the initial permeability of Vitroperm behaves at 150 kHz smoothly and almost linearly in the temperature range from -40°C to 120°C. The curves of conventional materials such as ferrites (and also permalloys) show typically a non-linear behaviour, which needs to be considered separately during component design.

The nanocrystalline core material Vitroperm combines the essential requirements for CMCs in a unique manner: highest initial permeabilities, which are further adjustable over a wide range, together with a high saturation induction of 1.2 Tesla, favourable dynamic properties and a high thermal stability. This material will be used in an increasing variety of inductive applications such as fault current transformers, high power transformers for SMPS, high precision current transformers for electronic electricity meters and pulse transformers for communication.

The external dimensions can be varied today from a few mm up to approx. 600 mm, and core heights of a single core between 2 mm and 30 mm. Recently, the standard toroidal core shape range was supplemented by rectangle and oval sized core designs, which can be additionally cut at will. ■

Vacuumschmelze GmbH&Co KG
Grüner Weg 37
63450 Hanau
Phone:+49 6181 38-0
Fax: +49 6181 38-2645
Email: info@vacuumschmelze.com
Home: www.vacuumschmelze.com