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Specialised CMCs (Common Mode Chokes) from Nanocrystalline Soft Magnetic Cores provide High Performance EMC Solutions in Automotive Power Electronics

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Abstract - Automotive power electronics such as electric power steering, electric drives and high power DC/DC converters require Common Mode Choke (CMC) solutions which combine effective broadband noise suppression at high operating currents with small size, high temperature capability and flexible electro-mechanical design. Recently developed products using special conductor techniques offer evidence of the superior properties of nanocrystalline soft magnetic VITROPERM® in this application field.

1. Introduction

Excellent attenuation properties combined with small volumes and a low number of turns make common mode chokes based on nano-crystalline magnetic cores ideal for use in EMC critical automotive applications such as Electronic Power Steering (EPS) systems as shown in figure 1. This system employs an electric motor to reduce effort by providing steering assistance to the driver. Sensors detect the motion and torque input to the steering column and an electronic control unit applies assistive torque via an electric motor coupled directly to either the steering gear or the steering column. Electric systems provide an advantage in fuel efficiency (0,3-0,4l/ 100km) as they remove the need for a constantly running belt driven hydraulic pump. This is a major reason for their worldwide introduction over the last 5 years across all platforms, from compact to luxury car class.

Another major advantage is the elimination of a belt-driven engine accessory and several high-pressure hydraulic hoses between the hydraulic pump, mounted on the engine, and the steering gear, which is mounted on the vehicle chassis. This greatly simplifies manufacturing and maintenance and leads to an overall system cost reduction of the steering system.

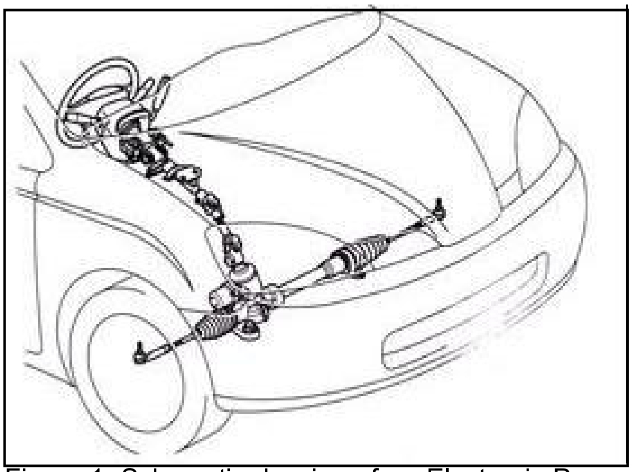

Figure 1: Schematic drawing of an Electronic Power Steering system (pinion gear version). Further information about the diversity of EPS-systems is given in [1].

EPS systems require high current motors to provide adequate torque to the steering systems, especially at standstill and during parking. The high power inverters used to control the asynchronous (ASM) or synchronous (PSM) motors commonly generate a wideband noise spectrum starting at the switching frequency (<100kHz) with harmonics extending up to 30-50MHz. The required attenuation properties can be effectively fulfilled using chokes based on the nanocrystalline material VITROPERM®.

The primary function of a Common Mode Choke (CMC) is to reduce the magnitude of the disruptive, high frequency common mode currents that cause electromagnetic interference radiation (EMI) without influencing the lower frequency differential mode working currents. A CMC generally uses a special winding topology (see figure 2). The positive phase current I+ is compensated by an equal current I- flowing to the negative pole. Since both windings have equal, but opposite amp-turns, only a small leakage inductance, and hence a small impedance is seen by the working current flow. On the other hand the CMC represents a high impedance to the flow of unwanted common mode currents. The CMC is thus an important part of an EMI filter acting to suppress outgoing noise from the EPS device to the powernet of the vehicle (see figure 3).

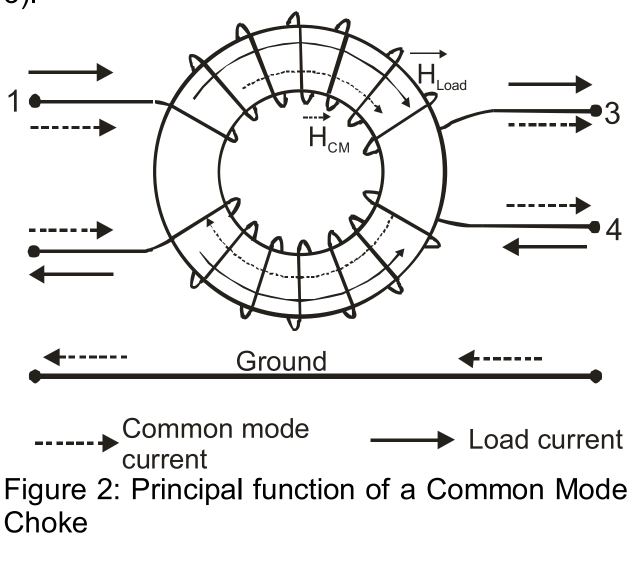

Figure 2: Principal function of a Common Mode Choke

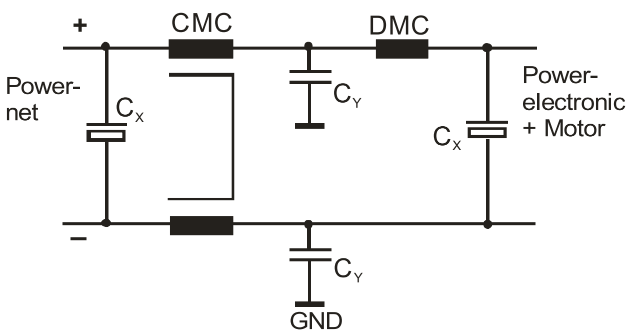

Figure 3: Typical EMI-filter for EPS-systems

The EMI filter structure can be divided in two different sections:

1.) Common Mode: CMC in combination with Cy
2.) Differential Mode: DMC with Cx.

The Differential Mode Choke (DMC) must provide proper inductance across the complete differential mode current range, whereby the symmetrical noise appears typical in the frequency range below 1MHz. The effect of the Y-Capacitors and the CMC leakage inductance can be ignored in this respect. The X-Capacitors have to withstand the maximum switching voltage of the inverters. The Common Mode current (asymmetric) will be effectively blocked by the high impedance of the Common Mode Choke and the Y-Capacitors will short circuit the typical high frequency current to ground. In this case, the effect of the DMC and X-Capacitors can be ignored. Both interferences (asymmetric and symmetric) have to be reduced independently.

2. VITROPERM® Common mode choke

A. Automotive requirements

Automotive applications demand components with a high level of resistance against electrical, mechanical and thermal stress during the vehicle lifetime. The automotive industry has implemented a special methodology to ensure the specific requirements for passive components are met [5] this includes a range of functional and environmental tests. The first and most important requirement such components have to fulfil is to meet the target properties in the final condition. (low and high frequency attenuation, rated current, maximum over-current and component size). Table 1 shows an overview of the major requirements for the Common-mode chokes for EPS-systems and specific tests associated for each requirement.

Requirements Description	Value	Robustness validation test acc. [5] and special further test strategies
Specific attenuation characteristics IZI [Ω]	>200 for T=-40 to 165°C and f=1 to 100MHz	Attenuation curve analysis with Impedance Analyzer
Temperature T [°C]	-40 to +165 (+180)	Temperature storage at T_{MIN} and T_{MAX} and rapid change of temperature between T_{MIN} and T_{MAX}
Current I [A]	25A-100A with an overcurrent capability up to 200 for 2-5s at T_{MAX}=165°C	Lifetime simulation with current – time profiles including special overcurrent testing (“parking test”)

Moisture resistance		Humidity cycling and constant
Low voltage drop/ copper resistance	Typically $\Delta U<500mV \rightarrow R<1m\Omega$	Standard electrical inspection
Tight pin tolerances (fully automated welding process)	0.2 to 0.5mm	Standard mechanical inspection
Technical cleanliness (avoidance of metallic particles)	Metallic particles <100..200 µm	Test method acc. to VDA Band 19
Vibration a [g]	a>10	Vibration and bump tests

Table 1: Major technical requirements for common mode chokes

B. Design

The material specific characteristics for VITROPERM® shown in table 2 give us the opportunity to manufacture common mode chokes (see figs. 4 and 5) with high attenuation in comparison to ferrite chokes with a significantly lower number of turns, here N=3. These materials enable the reduction of copper losses and smaller winding capacitances which is reflected in an excellent high frequency behaviour. Important in this respect is that the core material enhances the high frequency attenuation characteristics indirectly by the reduced winding capacitance due to the low number of turns.

The VITROPERM® core material for the described common mode chokes is produced as an amorphous ribbon using the rapid solidification process. This process is well established for large scale production and currently the worldwide production quantity of cast FeCuNbSiB alloys has grown to approximately 1000 tons/year.

The surface of the amorphous ribbon is typically coated with MgO to reduce the eddy current losses and then wound into toroidal cores which are stabilized using a spot welding process at the ribbons end. The required flat hysteresis loop with an initial permeability of around 100,000 is achieved by a two step annealing process [4]. In the first annealing process at a temperature of around 550°C the material is converted to the nanocrystalline stage, whereby the round hysteresis loop appears with a remanence to saturation ratio of around 50% and a maximum permeability of several hundred thousand.

The required flat hysteresis loop is then achieved by applying a strong magnetic field at the annealing temperature, whereby the anisotropy is aligned perpendicular to the ribbon axes. The initial permeability can be adjusted in a wide range about 15,000 to 100,000 by variation of the magnetic field / annealing parameters. Depending on application requirements the core will be finally protected against damage and corrosion using either a plastic housing or an epoxy coating. The typical characteristics of VITROPERM® (VP) are given in table 2 in comparison to standard ferrites:

Material	Nanocrystalline VITROPERM®	Typical Mn-Zn Ferrite
Initial permeability μ_i	<4 000..150 000	10..10 000 (20 000)
Max. operating temperature T_{MAX} [°C]	165 (180)	<120
Saturation flux density B_S [T]	1.2	0.5
Losses [W/kg] for f=100kHz, B=300mT, T=100°C	80	140
Coercitive field strength H_C [A/m]	<3	5..60 (2000)
Saturation magnetostriction λ_S	10^{-8} … 10^{-6} (µ>10,000)	10^{-6} ..2˙10^{-5}
Curie temperature	>600	150…200

Table 2: Material properties for VITROPERM® in comparison to a standard Mg-Zn-ferrite

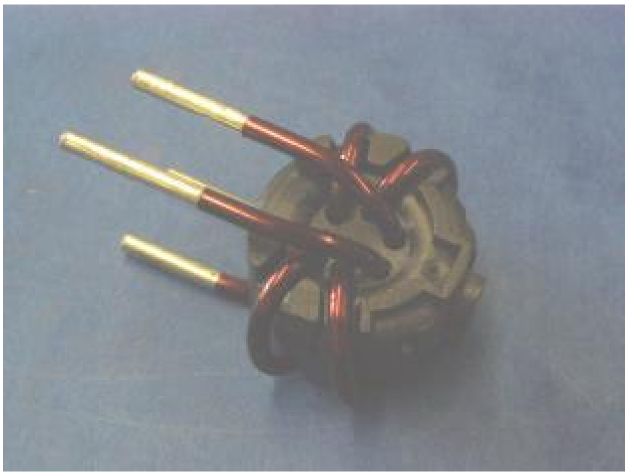

Figure 4: Common Mode Choke for EPS-systems (Type A; Version with thick wire d=2,24mm), I=25A, Imax=120A for t=2sec.

Figure 5: Common Mode Choke for EPS-systems as a semi finished component for a fully automatic welding process (Type B).

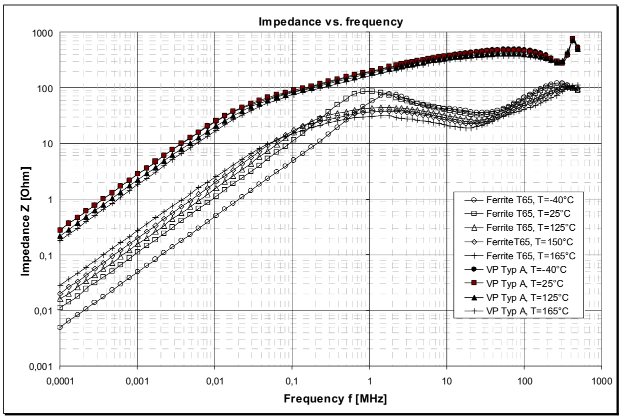

Figure 6: Typical impedance versus frequency behaviour for Type A (wound version, see figure 4) in comparison to a standard EMI-ferrite with a similar component size. Temperature range T=-40°C to +165°C.

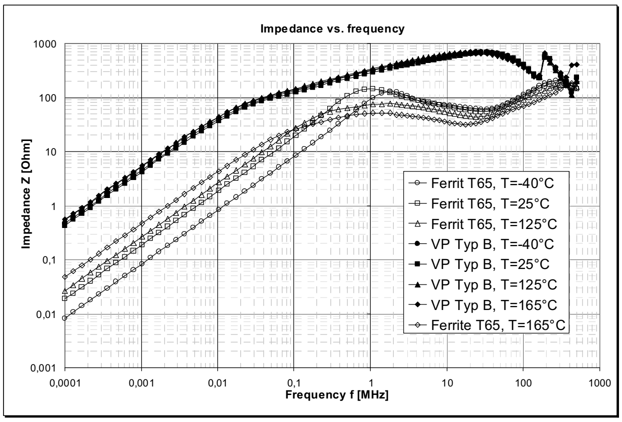

Figure 7: Typical impedance versus frequency behaviour for Type B (see figure 3) in comparison to a standard high temperature EMI-ferrite of the same component size. Temperature range T=-40°C to 165°C.

The higher impedance at lower frequencies (f<500kHz) is the consequence of the significantly higher initial permeability of VITROPERM® (see table 2 and Figure 8). The attenuation characteristic above 1MHz is also higher because of the reduced winding capacitance which results from the lower number of turns. In this application, where the unbalanced current is minimal, the advantages of VITROPERM® could be used to reduce the component size considerably. The use of VITROPERM® high permeability cores in the range of 100,000 is optimum for CMC use. By comparison, even the most expensive power ferrite cores have an upper limit in the range of 15,000 with higher magnetostriction and inferior high frequency performance.

The attenuation characteristics (permeability and quality factor) remain almost constant across the required automotive temperature range (-40 to 165°C) due to the high (>600°C) Curie temperature of VITROPERM® (see figs. 6 and 7).

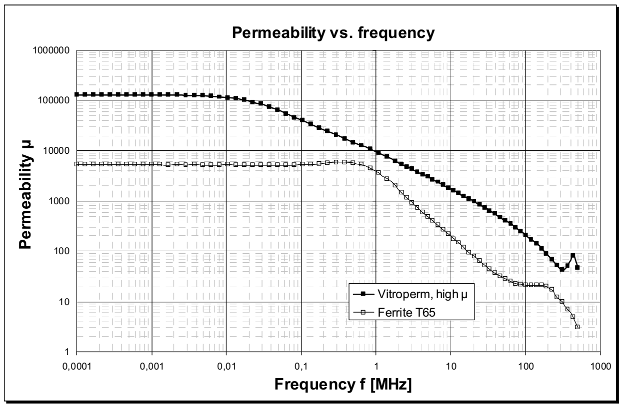

Figure 8: Permeability µ versus frequency f

Furthermore, the quality factor for VITROPERM® at f=100kHz remains the range of 1 or lower. The magnetic core is thus able to absorb noise energy in the form of heat which would otherwise circulate in the filter stage.

Altogether VITROPERM® common mode chokes provide better performance than ferrite chokes due to the improved µ versus frequency function (see figure 8). This is characterized by the eddy current losses (f>fg) and the gyromagnetic losses for f>10MHz. Due to the low hysteresis losses, the permeability-frequency-function μ'_S, which is constitutive for the absolute permeability value for lower frequencies (f<5MHz), can be described by the classical eddy-current-theory:

$$\mu_S^{'} = \mu_i \cdot \frac{1}{x} \cdot \frac{\sinh x + \sin x}{\cosh x + \cos x}$$

with

$$x = \sqrt{\frac{f}{f_g}}$$

and

$$fg = \frac{4 \cdot \rho}{\pi \cdot \mu_0 \cdot \mu_i \cdot d^2}$$

Figure 8 shows that the permeability starts to decrease above fg≈30kHz and drops down with a 1/√f-characteristic for the selected high permeabilitly material (μ_i=110,000). Starting from 5MHz the permeability falls at a slightly higher rate than the 1/√f function because of the upcoming gyromagnetic losses (~1/f) in the magnetic core. The deviance from the 1/√f-characteristics from gyromagnetic effects is usually low because of the dominance of the eddy current losses at higher frequencies. Ferrites exhibit a different behaviour because of their own gyromagnetic loss characteristic (~1/f). In the range of 1 MHz the permeability for both materials are nearly the same, but for higher frequencies the nanocrystalline core is superior to ferrites due to the flatter 1/√f-performance.

Table 2 summarizes the design advantages [2] of nanocrystalline magnetic cores for common mode chokes over standard ferrite material and give some hints according the benefits of a common mode choke for EPS-systems.

Material properties	Design advantages	Benefits for EPS-systems
High initial permeability μ_i	Small component size	No packaging problems, Robust ag. vibration, cost reduction
	High attenuation for the low frequency range	Effective noise reduction for f>150kHz
	Small number of turns (lower copper losses)	Low voltage drop ->High current capability
	Low winding capacitances	Effective noise reduction f>10MHz
Slow decrease of the permeability vs frequency	High attenuation for $f>f_G$	Excellent broadband noise suppression
Curie temperature T>600°C	High operating temperature	Robust against overload
	Mounting position uncritical	Compact design without additional heatsinks
Minimal temperature dependence of μ and B_S	Attenuation characteristics independent of temperature	Effective noise reduction for T>125°C (parking)
High saturation	Small component size	No packaging problems
	Robust against unbalanced currents	High attenuation under bias conditions

Table 3: Design advantages of nanocrystalline magnetic cores in comparison to standard Mg-Zn-ferrites and hints about benefits EPS common mode chokes.

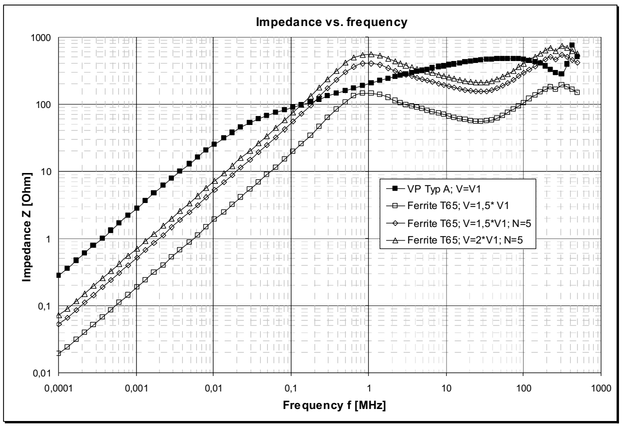

Figure 9: Design studies

The results from comprehensive design studies (figure 9) shows that a ferrite must be at least a factor of 2 bigger and the number of turns has to be increase to N=5 instead of N=3 to reach the same attenuation in the frequency range up to around 1MHz. The wideband attenuation of VITROPERM® offers unmatched performance.

A major design challenge for the CMC Type A is that a thick wire (d=2,24mm) has to be wound around a small magnetic core with tight tolerances for the lead outs suitable for use in the customers automated production process. To achieve this, we have developed a special semi-automated winding process and housing design. The major function of the plastic housing is to shield the magnetic core against external winding stresses in addition to effectively ensuring that any metallic particles from the magnetic core are contained. This requirement has a growing importance for the automotive industry, whereby the no metallic particles philosophy will support the zero error strategy of the vehicle manufacturer.

The mechanical design of the CMC Type B is based on the requirement for high working currents (requires increased copper cross section) and high broadband attenuation (compare figs 6 and 7). The semi-finished part is based on a similar magnetic core to Type A although in this case, a standard plastic housing is used because of the reduced mechanical stress on the core compared to Type A. The winding $N_1=N_2=3$ consists of 6 copper bows which will be welded together at the powerframe of the EPS system. This configuration minimises mechanical stress to the magnetic core and provides a robust 12 spot welded connection to the powerframe for increased shock and vibration behaviour in comparison to 2 or 4 pin components.

C. Validation results

One of the major targets of the design and product validation is the technical evaluation if a component is to withstand the lifetime requirements in automobile applications. The described components are tested according AECQ200 [5] test methodology and additional tests which are specific for the EPS-systems.

The following results shows the stable characteristic of VITROPERM® for these tests. Note: To highlight the marginal changes of the impedance over frequency, the impedance axis scale is shown linear instead of logarithmic as in the other diagrams :

a.) Temperature storage at T=180°C, t=500h with a DC-bias slightly below saturation (B~1T) Fig 10.
b.) Current-time profile (lifetime testing) for different application temperatures. Fig 11.

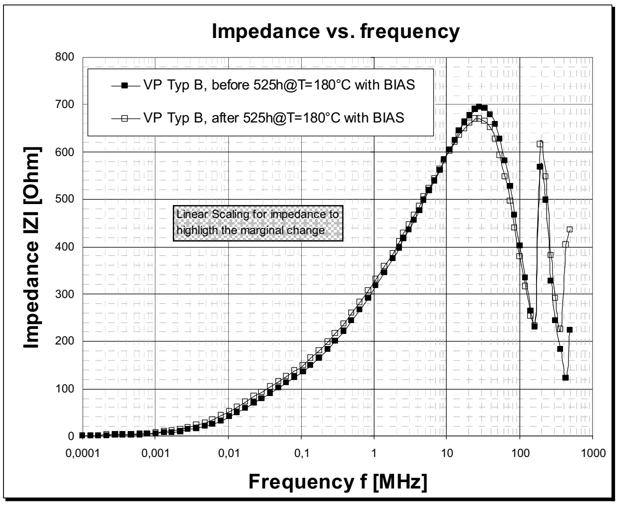

Figure 10: Impedance versus frequency for the Common Mode Choke (Typ B; semi- finished version) welded in the final powerframe before and after temperature storage test at T=180°C for t=525h under unbalanced conditions.

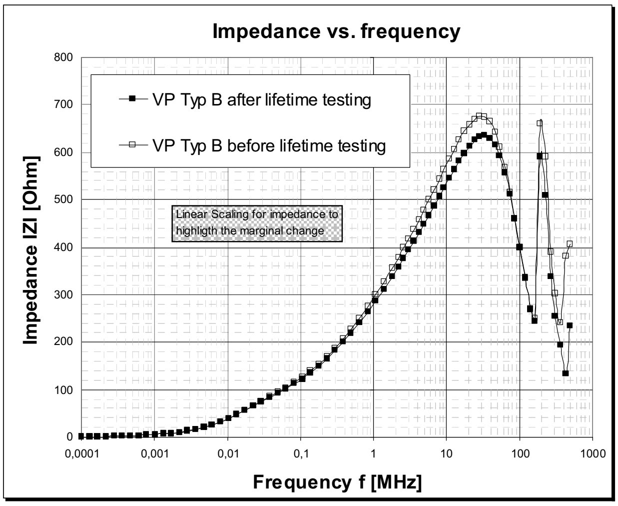

Figure 11: Impedance versus frequency for the Common Mode Choke (Typ B; semi- finished version) welded in the final powerframe before and after lifetime test.

3. Conclusions

Excellent attenuation properties combined with small component size and a low number of turns make common mode chokes based on VITROPERM® nanocrystalline magnetic cores ideal for the use in EMC critical automotive applications such as Electronic Power Steering systems (EPS-systems). The CMCs presented in this paper have been designed to reduce the broadband noise of high power electronics effectively at high temperature and very demanding environmental conditions as are typical for the automotive applications. The two different designs for the same application as outlined therein show superior performance in comparison to high temperature ferrites.

Acknowledgements

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4. Literature

[1] www.zf-lenksysteme.com
www.continental.com

[2] Designvorteile durch nanokristalline Kerne: SKD´s mit breitbandiger Dämpf-ung; E&E- Kompendium 2005/ 2006, Johannes Beichler

[3] Nanocrystalline materials in common-mode-chokes; PCIM Europe 2003, J. Petzold, R. Klinger

[4] Advantages of soft magnetic nano-crystalline materials for modern electronic applications, Journal of Magnetism and Magnetic Materials, 242-245 (2002), J. Petzold

[5] AECQ200-Rev C, June 17, 2005: Stress Test qualification for passive comp-onents