Application overview of nanocrystalline inductive components in today’s power electronic systems

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In the last 20 years, the nanocrystalline alloy Fe73.5Cu1Nb3Si15.5B7 (known as FINEMET®) gained increasingly importance in numerous applications. The combination of excellent soft magnetic properties namely a high saturation induction of 1.2 Tesla and advantageous high frequency properties is still unique. This material family contributes to the optimization of todays and tomorrows advanced power electronic systems in terms of weight and size reduction as well as energy efficiency. In many ‘old’ applications, existing Ferrite or Permalloy or even Cobalt amorphous solutions have successfully been replaced by improved nanocrystalline versions. In many cases it was achieved to combine the technological progress with lower cost at the same time. In even more new applications, the advanced material has become the first choice: electrical energy generation, -distribution, -conversion and finally energy monitoring and -management will become more efficient, more reliable, lighter, smaller and smarter at the same time.

This paper briefly describes several application examples of realized or actually projected schemes over the last 20 years - but it raises no claim to completeness. Outdated former applications for nanocrystalline cores like e.g. ISDN interface components (1998) as well as magnetic amplifiers (2001) are considered here not anymore.

Index Terms— bearing current, EMC filtering, Fe-based nanocrystalline soft magnetic alloys, inverter technology

I. INTRODUCTION

HITACHI Metals rolled out nanocrystalline FINEMET® cores to the market around 1992. About at the same time, VACUUMSCHMELZE started the production of their equivalent named VITROPERM®. At that time prices were very high. This was partly due the dominating role of two monopolists. Thus, only a limited amount of IGBT driven industrial applications was able to justify the high cost for the advanced inductive components made of nanocrystalline cores. In the last 10 years, due to increased production quantity and the vibrant arising competition by several highly capable manufacturers in China, prices came down significantly. The estimated total global nanocrystalline strip production currently is ~7.000t/a whereof ~70% is supposed to be made in China - mostly low grade. Meanwhile, trends like increasing electricity cost on one hand but also the global CO2 reduction hype are pushing the needs of high performance soft magnetic materials. Apparently, from that point of view, the time for a nanocrystalline ‘boom’ has come.

Recently, the initial standard alloy Fe73.5Cu1Nb3Si15.5B7 was complemented by new variants with additions of Nickel and Cobalt for permeability levels < 10.000 [1]. The gap between 10.000–15.000 may be closed in future by a new alloy version.

<table>
<thead>
<tr>
<th>VACUUMSCHMELZE branded alloy composition</th>
<th>Bmax</th>
<th>Hmax</th>
<th>nmax</th>
<th>magnetization</th>
<th>typical application</th>
<th>suitable use</th>
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<tr>
<td>Fe73.5Cu1Nb3Si15.5B7</td>
<td></td>
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<tr>
<td>VP 500/600</td>
<td>1.20</td>
<td>~35,000 – 700,000</td>
<td>66</td>
<td>~0.3</td>
<td>ELCB, CT, EMI cores &amp; chokes, power trx.</td>
<td>1992</td>
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<td>1.20</td>
<td>~101</td>
<td>70</td>
<td>~0.5</td>
<td>universal use, replacement of ferrites</td>
<td>2008</td>
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<tr>
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<td></td>
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<tr>
<td>VP 270</td>
<td>1.32</td>
<td>6,000 – 5,000</td>
<td>82</td>
<td>~7</td>
<td>EMI chokes and CTs with DC tolerance</td>
<td>2011</td>
</tr>
<tr>
<td>Fe73.5Cu1Nb3Si15.5B7</td>
<td>1.24</td>
<td>3,000 – 7,000</td>
<td>84</td>
<td>~8</td>
<td>EMI chokes and CTs with DC tolerance</td>
<td>2010</td>
</tr>
<tr>
<td>VP 250</td>
<td>1.24</td>
<td>1,800 – 3,000</td>
<td>86</td>
<td>~14</td>
<td>EMI chokes and CTs with extended DC tolerance</td>
<td>2010</td>
</tr>
</tbody>
</table>

Fig. 1. Properties of soft magnetic nanocrystalline alloy grades - cores are available in a very wide range of permeability from ~100 < μr < 700,000.

II. EARTH LEAKAGE CIRCUIT BREAKERS ELCB, RCCB

20 years ago, electromechanical earth leakage circuit breakers for the European market were solely equipped with Permalloy cores (e.g. Ni80Fe20). In the recent years, those cores were almost completely replaced by nanocrystalline versions. The result was a size and core mass reduction of typically 25-50% for AC types at significantly lower cost. The worldwide annual production is approx. 50 Mio pcs. of cores with a typical mass of 10g (household version with tripping current of 30mA) which results in an estimated annual consumption of up to 500t tons in Europe and China’s Export. In the Chinese local market, about another 50 Mio. of simple nanocrystalline cores are used in electronical ELCB/RCCB because of the low price provided by several Chinese mainland manufacturers.

Fig. 2. Core permeability as a function of H field applied. The optimum working point is ~10mA/cm. Nanocrystalline cores provide double the permeability compared to Permalloy versions and thus reduce size and cost significantly. [2]
III. EMC FILTER COMPONENTS FOR INVERTER DRIVES

For long years common mode chokes in the EMI/EMC filters of variable speed drives were almost solely made with ferrite cores in a wide range of industrial applications. Due to their higher permeability and three times higher $B_{sat}$ nanocrystalline cores can reduce weight, size and - more and more important - power loss of the copper winding by typically 50-70% compared to ferrites. [3] It is basically possible to replace existing two-stage filters based on ferrite chokes by a single stage solution made with a nano crystalline core as several projects have proven.

![Fig. 3a. Significant size, weight, volume and copper loss reduction of common mode EMC filter chokes when replacing Ferrite by nanocrystalline cores - with the same performance.](image)

![Fig. 3b. 1 - or 3-phase chokes depending on the rated power of inverter drive systems (example: Siemens Sinamics G120)](image)

IV. POWER TRANSFORMERS FOR KILO WATT SMPS

With the coming of IGBT technology in the early 90s of the last century, switch mode power supplies (SMPS) in the KW range were increasingly designed with a single transformer using full bridge topologies. Higher power density, i.e. lower weight and volume, as well as improved efficiency compared to solutions based on Ferrite cores were the most convincing incitements for designing in the newly available cores from the 1990s until now. Typical applications are battery chargers and on-board converters in planes and trains as well as many industrial power supplies in the KW range using IGBTs like welding equipment, inductive heating and many others.

![Fig. 4. Power transformer for plasma welding rated 32kW, $f = 20$kHz with stacked nanocrystalline toroidal cores having significantly lower losses ($dB = 100$mT) and reduced weight (~ 30%, $m = 9$kg, $\phi = 200$mm) compared to conventional materials. [4],[5]](image)

V. MOTOR/GENERATOR BEARING PROTECTION

In power applications with inverter drives up to the Mega Watt (MW) range, high frequency generator/motor bearing surfaces tend to wear out more or less rapidly by electrical discharge machining effects. The root cause are unwanted RF bearing ground currents which are created by IGBTs of the actual generation. Big nanocrystalline core stacks, operated as single-turn inductors, solve the problem efficiently whereas Ferrite cores would require too much space (approx. 300%) and suffer temperature problems. Typical applications are: wind energy turbines and large (ship) drives up to several MW power rating as well as industrial scale air conditioning systems (chillers), huge paper production lines as well as many other high power applications incl. container cranes.

![Fig. 5a. Working principle of nanocrystalline cores operated as single-turn inductors in order to mitigate destructive RF-common mode currents $I_{CM}$ for motor/generator bearing protection in the power range from ~ 20kW – 3 MW. [6]](image)

![Fig. 5b. Measured 75% mitigation of high frequency common mode ground current $I_{CM}$ from 45A (left) to 10A (right) by 6 stacked nanocrystalline single turn inductors ($\phi : 160$mm, $\mu_r \sim 30.000$)](image)

VI. ON-SHAFT MOTOR BEARING PROTECTION

AC cage induction machines, fed by PWM voltage inverters, face significant bearing lifetime limitations due to erosive high frequency ground currents. By placing suitable nanocrystalline toroidal cores ($\mu_r \sim 30.000$) concentrically onto the shaft of the motor, the rotor impedance can be increased significantly and thus, the circulating destructive bearing currents reduce significantly [8]. This solution is considerably cheaper, more durable and smarter compared to expensive hybrid bearings.

![Fig. 6. Measured 90% amplitude mitigation of destructive circulating bearing ground currents by on-shaft mounting of a nanocrystalline core in a 110kW AC cage motor. A long service life is ensured at low cost compared to expensive ceramic hybrid bearings which generate more audible noise, too.](image)
VII. HIGH VOLTAGE DC POWER TRANSMISSION LINES

HVDC is preferred for energy transmission lines with distances > 80 km because of the loss and cost advantages compared to conventional 50 Hz HVAC lines. Self-commutated HVDC PLUS® inverters are equipped with trigger transformers based on nanocrystalline cores. In case of an IGBT failure, the transformers ignite a mechanical bypass in order to continue the IGBT cascade’s operation. Besides the existing Trans Bay cable Link in San Francisco, there are four new offshore wind park projects in the north sea currently under construction with a power in total of about 3 GW. [13]

Fig. 7. HVDC power transmission for long ranges > 80km with nanocrystalline trigger transformers for failure protection.

VIII. HIGH VOLTAGE GAS INSULATED SWITCHGEAR - GIS

Gas insulated switchgears (GIS) are very reliable components of electrical power transmission networks. During the last years, the system voltages reached up to 1.2 kV. Switching operation in GIS may cause dangerous transient over voltages (VFTO). Those destructive high frequency (~15 MHz) over voltages can effectively be attenuated by nanocrystalline cores when operated as a single turn reactor mounted concentrically around the inner conductor. Other core materials like Ferrite cannot solve the problem.

Fig. 8. Measured damping effect of very fast, high frequency transient over voltages (VFTO) by 20 nanocrystalline cores (\(\mu_r = 30,000\), \(\varnothing = 200\text{mm}\)) in 200kV GIS (gas insulated switchgear) [7]

IX. SMART WATT HOUR METERS

Smart Meters are inevitable elements of the upcoming Smart Grid. Due to a unique linearity, very low power losses and recently also a suitable DC capability due to a new low permeability option, nanocrystalline cores are the preferred solution for Current Transformers (CT) for residential meters.

A typical smart meter requires one CT for each of the three phases. As a part of the establishment of the smart grid, the anticipated worldwide replacement of several 100 Mio. pcs. installed old fashioned Ferraris meters bears as huge potential. Former CT solutions based on Co-amorphous or Fe-amorphous cores are gradually replaced by low permeability (\(\mu_r = 1.500\)) nanocrystalline versions, partly due to more stringent standards. In China, probably more than 2.000 tons/a of nanocrystalline high \(\mu\) but low grade (i.e. not complying IEC standards) material is consumed by metering CTs.

Fig. 9. For metering CTs, nanocrystalline cores offer extreme linearity and very small amplitude and phase errors and DC capability. Permeability range from \(1.500 < \mu_r < 80.000\). [9],[16]

X. AC/DC SENSITIVE RESIDUAL CURRENT MONITOR RCM

For electrical safety as well as for preventive maintenance purposes, industrial assembly lines with frequency converters or welding inverters are increasingly equipped with active AC/DC sensitive residual current monitors. A fault current resolution of only less than 2 mA is provided by specially designed active current transformers equipped with a nanocrystalline core (\(\mu_r \sim 80,000\)). Other related application are eCar charging stations or photovoltaic DC/AC inverters.

Fig. 10. AC/DC sensitive magnetically shielded current transformers in active RCM equipped with highly sensitive nanocrystalline cores used for example in automotive welding lines. [14]

XI. DRIVE TRANSFORMERS FOR POWER SEMICONDUCTORS

Modern MOSFET and IGBT require reliable and undistorted trigger signals. Most important for a suitable transformer are a low leakage inductance \(L_c\) and a low coupling capacity \(C_k\) which is achieved by a low number of turns. With their high permeability and high \(B_{sat}\), nanocrystalline cores provide best the required magnetic properties for almost ideal transformers.

Fig. 11. Trigger transformers with high permeability nanocrystalline cores offer low leakage inductance and provide small designs, signal fidelity and high insulation voltage at the same time. [15],[17]
Inverter technology increasingly finds a use in modern fully electrical and hybrid cars. Nanocrystalline cores secure safe and long-life operation due to their capability to reliably work even at a temperature of up to 180°C. Ferrites are not taken into account because of their temperature limit of ~ 100°C.

Soft magnetic nanocrystalline inductive components have conquered a wide range of old and new power electronic applications. This growth trend will certainly continue because of the requirements of the ‘new electricity age’ of our days are perfectly met. This is because they provide:

- reduced size
- reduced weight
- lower losses at high frequency
- wide range of permeability from ~100 … 700.000
- increased operational temperature range up to 180°C
- excellent aging stability, highly durable
- highly linear properties with all respects
- various shapes of hysteresis loop (from Z to flat)
- advanced level of safety and reliability
- (almost) no Nickel, Cobalt or rare earth ingredients.

Another driving force for the nanocrystalline core option certainly will be the anticipated next generations of power semi-conductors like SiC or GaN based MOSFET’s or IGBT’s. Here the target is to even further reduce switching losses with the consequence of even more critical emissions of unwanted high frequency noise which needs to be kept under control.

Due to a continuously growing global demand accompanied by a steadily growing vendor basis, prices for nanocrystalline materials are predicted to further drop. This will broaden the market for soft magnetic nanocrystalline cores even further. The same with the recently introduced new low permeability alloy variants [1] as well as the new cut cores which provide from now on low and very low permeability options for inductive component functions with energy storage character.

REFERENCES

[16] HAGER www.hager.de, eHZ EDL

Fig.12b. 32 kW inverter with integrated DC/DC converter for example in Audi’s hybrid versions of Q-series are equipped with specially designed oval shaped nanocrystalline cores for on-board EMI compliance. Inverter mass: 8kg, volume: 5 liters [11]. Similar solutions will be used at Volkswagen’s and BMW’s eCars.

Fig.13. Heavy Ion Synchrotron SIS 18 upgrade will be equipped with nanocrystalline core loaded cavities operating at 300kHz < f < 5 MHz as a part of the FAIR project which is currently under construction at GSI Darmstadt. A typical core mass for a cavity core is ~ 15-20kg, typical Ø : 500-660 mm, about 10-20 cores per cavity [12]