CBMM | Niobium Nb

innolectric

Whitepaper

Availability and Economical Feasibility Application of Soft Magnetic Materials in Power Electronics

Nanocrystalline soft magnetic cores can offer higher efficiencies and power densities in applications in power electronics. Until recently, they seldomly seemed to be available for trials and economically feasible mass applications. An example of power electronics in commercial vehicle applications now shows a different picture. A research study in coorperation with CBMM.

Córrego da Mata, s/n
Araxá, Brazil 38183-903

+55 34 3669 3000
+55 11 3371 9222

cbmm.com
niobium.tech

Table of content

Introduction

Nanocrystalline soft magnetic materials enable further miniaturization and highly efficient operation of magnetic components for power electronics such as EV charging applications. This is because nanocrystalline materials offer high permeability, low coercivity, low magnetostriction, high Curie temperature up to 570 °C[1] and high saturation flux density under a wide range of frequencies, environmental and mechanical conditions. Compared to ferrites, their much higher saturation points of induced magnetic fields can lead to an improvement in power density, besides that, its high permeability simplifies wiring and allows greater flexibility in the design of cooling systems.

Niobium is a key element in the production of nanocrystalline soft magnetic materials and the global leader in the production and commercialization of this element, CBMM, has joined innoelectric AG in this international research project. The main aim was to analyse the bennefits of using nanocrystalline soft magnetic materials on a serial product manufactured by innolectric: an On-Board Charger system (OBC) with a common power factor correction (PFC) and an inductor-inductor capacitor (LLC) topology. The components studied were requested from various manufacturers and engineering service providers worldwide. The set goal was to create an overview of the variance in performance, lead time and costs to demonstrate that parts with nanocrystalline material are suitable for use in current or planned development projects in the field of power electronics. In this paper, the results specifically for the filter elements AC and DC common mode choke are presented and evaluated across various aspects.

Background of the research project

Supply of electronic components to the automotive industry holds many challenges, being cost sensitivity, strict limitations in installation space and the need to decrease weight and boost efficiency some of them.

Yet, there is also an advantage that is specific to innolectric's customer sector. Purchase decisions can be made based on the total cost of ownership, opening the possibility to use new magnetic materials that can result in an optimised solution for the final application.

Figure 1 Standard components used in OBC applications as: AC Common Mode Choke (left), AC Grid Filte (center), DC Common Mode Choker (right)

[1] 01/2023 Proterial Ltd. – "Nanocrystalline soft magnetic material FINEMET®": https://www.proterial.com/products/catalog/sm/PR-EM07_FINEMET_Ribbon_PR-EM07.pdf?

As part of the joint research work, the innovative nanocrystalline soft magnetic core material is being tested in direct application in the On-Board Charger from innolectric. To allow a comprehensive functional test and analysis of potential benefits, the electrical and thermal behavior as well as electromagnetic interference are tested directly in the existing product.

Usually, a standard OBC power electronics design consists of a PFC and LLC stage.

The initial power-factor-correction "PFC" stage regulates and filters the three phase AC input and generates a rectified DC output for the LLC stage.

The second stage, with two inductances (L) and one capacitor (C) "LLC" and DC output stage enables current and voltage regulations for the eventual electric vehicle battery charging process.

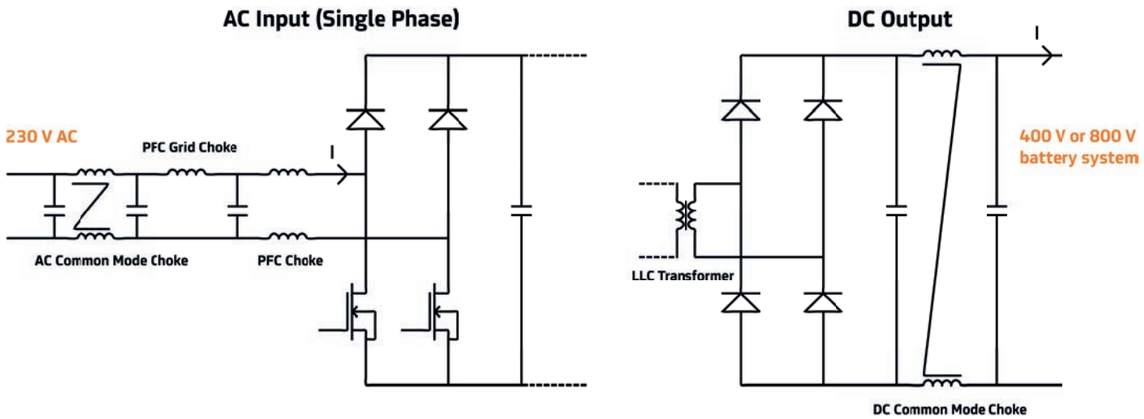


Figure 2 Simplified Schematic of a single phase OBC

PFC Stage

A standard PFC stage contains three major inductances: an AC common mode choke, a secondary grid filter (PFC grid choke - Figure 2) and an individual choke (PFC Choke - Figure 2), that minimizes the common mode noise and the injection of harmonics back into the grid.

The AC current is then rectified with inclusion of the main PFC inductor. All three components are essential to the design and functionality and have a significant impact on the OBC volume, cost and efficiency. Therefore, all three components were chosen for analysis, tetsing and optimisation.

LLC and DC Output Stage

The LLC and DC Output stage comprises two main components. The LLC main transformer's major function is the isolation of the input and output of the OBC as required by High Voltage automotive safety standards. Another main function is the voltage transformation for different battery voltage levels. The frequencies applied to this transformer are in the range of several hundred kilohertz. Substantial improvements with nanocrystalline materials were not expected due to these high frequencies. This is why the component was not prioritized for further analysis. However for other projects and products this might be different when weight and volume play greater rolls than efficiency and electromagnetic emissions. Nevertheless, the DC common mode choke was selected. Its major function is that of a filter for compliance with electromagnet compatibility.

Soft Magnetic Materials

Common Understanding

In today‘s market many different types of soft magnetic materials are available such as Grain oriented silicon steel (GO), Non grain oriented silicon steel (NGO), Ferrites (Mn-Zn and Ni-Zn), Iron powder (Fe), Iron alloy powders (Fe-Si-Al, Fe-Si, Fe-Ni-MO, others), Nanocrystalline ribbon (Fe-Si-B-Cu-Nb), Amorphous ribbon (Fe-Si-B, Co-Fe, etc.). Nanocrystalline soft magnetic materials (NSMM) are a type of advanced soft magnetic materials developed to help emerging power electronic systems to achieve high power density and efficiency for designing high frequency magnetic components.

In the production, these materials are rapidly solidified and formed to thin tapes or ribbons (e.g, 14- 30 µm thick). Such a process can be so called “melt spinning”, where melt is pushed the form of a jet onto a cooled rotating wheel or drum and ejected from that wheel already in form of the ribbon or tape. A subsequent heat treatment at around 500-600 °C induces the final magnetic properties into the material that form an initial amorphous microstructure into the final nanocrystalline state.

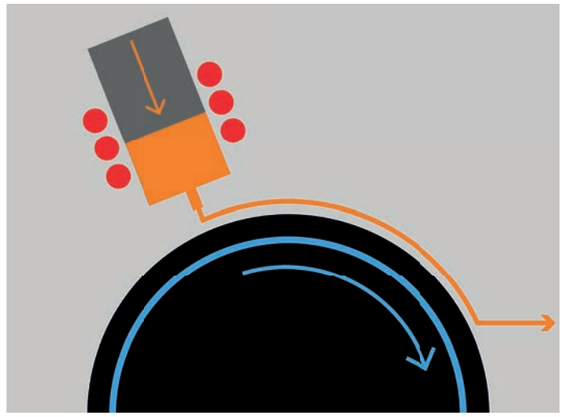


Figure 3 Melt Spinning Process

Nanocristalline Material Development Value Chain

Next to Common Mode Chokes, PFC Inductors and Transformers which are of interest for this project, other applications of NSMM ribbons and cores are DC-DC inductors, Current transformers, Current Detectors, Magnetic Amplifiers, Electric Motor Stators, Magnetic Shielding and Wireless Charging.

The market scenario has changed rapidly in the last ten years, previously NSMM was expensive and very hard to source.

Now, CBMM can enumerate more than 100 companies around the globe who are involved in production of nanocrystalline soft magnetic materials and subsequent design of components based thereon. Among the countries involved are China, South Korea, Japan, India, Germany and the United States. Therefore the competitiveness and accessibility have greatly improved.

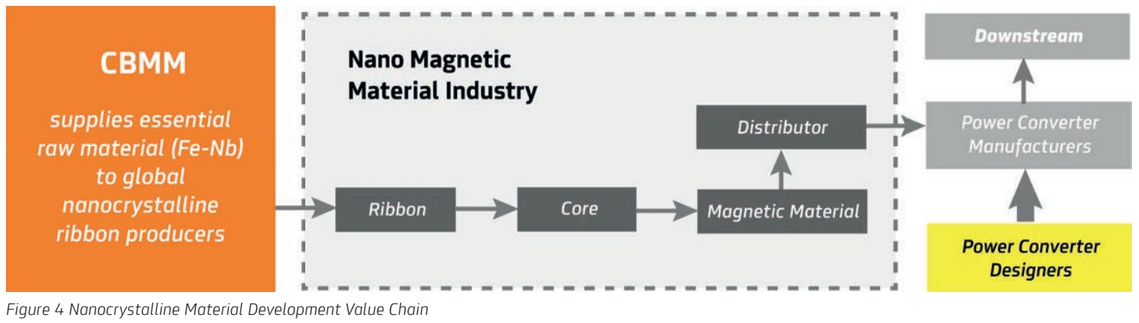


Figure 4 Nanocrystalline Material Development Value Chain

Technical Challenges

In many cases, the On-Board Charger is the component in the vehicle through which the total energy for the drive and auxiliary consumers is supplied. The efficiency of the OBC strongly influences not only in the operating costs of a vehicle, but also the evaluation of the vehicle before buying it. The charging process, for example, is part of the Worldwide Harmonised Light Vehicle Test Procedure (WLTP), which is used to measure energy consumption and provide a strong evaluation criterion for purchases. If an OBC has high thermal losses, these must be dissipated via a correspondingly larger vehicle cooling system. The available installation space is severely limited, especially in smaller passenger transport vehicles. In modern vehicles, this space should be available for comfort functions and extras for which additional peripherals such as actuators are required. In vehicles for transporting goods, every additional weight of power electronics directly reduces the possible payload. This is where most designs have particularly great potential for optimization. Components with magnetic cores and windings can easily account up to over 15 % of the total weight of power electronics in the electric vehicle, including the On-Board Charger.

They should occupy smaller areas and installation spaces, have higher efficiencies or better electromagnetic filter properties. Moreover the existing installations space in the On-Board Charger must not be exceeded and temperature limitations of the PCBs must be observed. The power density must be maintained.

Especially in the DC output, high voltages of up to 1000 volt, the accompanying insulation and high charging currents are requirements which are hard to fulfill.

Optimizing a component under the different requirements thus represents a multi-criteria problem. This challenge was passed on to the possible suppliers of alternative components. They were only informed of the minimum necessary requirements of the respective application and if available the data sheets of an existing component.

Motivational Background

- Better efficiency reduces operating costs
- Smaller size reserves space for premium passenger car features
- Weight reduction increases possible payload of delivery vehicles
- The exploitable potential of the On-Board Charger is great
- Still meeting the technical requirements of the current product pose a challenge

Development & Procurement

To conduct the challenge only companies that openly advertise their know-how in the field of nanocrystalline materials on the internet were approached.

With the objective that only limited specifications get handed to possible suppliers of alternative components, the following information was given and requirements specified:

Request For Quote Parameters
Application (Common Mode Choke)
Number of phases (2 / 4)
Base frequency
Nominal voltage and current levels
Inductances over frequency
Temperature rating
Installation orientation and footprint (for PCB parts)
Specific requirements like insulation or max. dimensions

Companies that asked for production quantities, were given numbers in the four-digit range. However, requests for samples could be made for test purposes. This was the case, for example, with companies on the North American continent that belong more to service providers or also support research projects on their own initiative.

It was interesting that in the majority of inquiries the request for nanocrystalline magnetic materials had to be repeated. When the application market was mentioned, a strict focus on cost efficiency was expected and the decision on soft magnetic materials therefore questioned.

In all cases, samples were obtainable within a timeframe between 4 and 8 weeks after placing the order. They were either free of charge or, in the case of a development service provider, within a cost range in the low three-digit Euro range per piece.

Lineup

In many designs, a part with iron based nanocrystalline material is used for the common mode choke at the AC Input. The part is a series product and freely available on the supplier market. This component is compared with a variant based on a classical ferrite core. This should enable an assessment of the saving potential already exploited by the components used with nanocrystalline cores. The results show clear differences in both the height and the diameters of the magnetic core consisting of two rings.

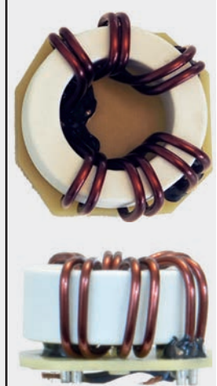
Comparison of AC Common Mode Chokes

	AC CMC: Widely used version with nanocrystalline core	AC CMC: Ferrite based solution
Realistic size comparison		
Core material	Nanocrystalline	Ferrite
Supplier	Europe; off the shelf product	North America; Prototyping to Series Production; Custom built
Dimensions	50 mm * 18 mm **	62 mm * 26 mm **
Weight	165 g	430 g

** outer core diameter* *** height*

Like the AC common mode choke, a standard component at the DC output is freely available from a European company as well as through distributors, the core is a classic ferrite core. The design of an alternative was initially entrusted to the same manufacturer that developed the ferrite-based comparison for the AC Common Mode Choke. As the picture below indicates this Alternative 1 already makes a clear difference. After it was presented to other vendors as an additional reference. The results can be seen in Alternative 2. The dimensions of the core and the number of windings is almost identical. An optical difference makes only the baseplate which adapts the component to the existing PCB. Alternative 3 forms a center span with regard to dimensions. As Alternative 1, comes from a manufacturer that is only specialized in producing engineering samples and smaller series, it will not be analyzed for its economic aspects as its pricing is not comparable to those of the mass producers of Alternative 2 and 3.

Comparison of DC Common Mode Chokes

	DC CMC: Widely used version	DC CMC: Alternative 1	DC CMC: Alternative 2	DC CMC: Alternative 3
Realistic size comparison				
Core material	Ferrite	Nanocrystalline		
Supplier	Europe; off the shelf product	North America; Prototyping to Series Production; Custom built	Asia; Mass producer; Custom built	
Dimensions	45 mm * 20 mm **	34 mm * 13 mm **	34 mm * 13 mm **	45 mm * 18 mm **
Weight	182 g	50 g	60 g	102 g

** outer core diameter* *** height*

Testing

The functionality testing of compared components consisted of three stages: (1) the determination of the electrical characteristics (Resistance, capacitance, inductance - RLC) without load, (2) the functionality, power dissipation and thermal behavior under full load and (3) the wired electromagnetic interference behavior according to standards. An initial baseline measurement was taken for an example OBC topology regarding power losses and electromagnetic interference.

Components were first checked individually without load for their electromagnetic parameters that included the determination of the resonance frequency. Then they were individually and successively exchanged in the exemplary OBC topology so that their behavior could be assessed as isolated as possible. Two different operating points were run to analyze both the highest possible loads in terms of flowing currents (lowest output voltage) and high switching frequencies (highest output voltage) at full system output power. The power losses were determined electrically with high frequency sampling rates on voltage and current. The temperatures of the cores and windings were monitored as they were cooled under the same conditions with constant air ventilation. For the analysis of Electromagnetic Compatibility (EMC), common measurement methods for automotive power electronics development were included which are based on the widely used UNECE R10 standards. The setup focused on cable bound interferences on the input and output connections which could be recorded in a regular electronics laboratory in consideration of CISPR 16-2-1 („conducted disturbances on AC or DC power lines from vehicles“), CISPR 25, and IEC 61000-3-12.

Technical Analysis

Testing Results

General findings

- Already in the initial analysis of the RLC values, the nanocrystalline soft magnetic cores stand out clearly. The analysis of the resonance frequency shows that these cover a much wider frequency range of about 20 to 30 times more than ferrite cores reaching values of e.g. 16 MHz instead of just 0.5 MHz before reaching resonance.

- As several fixed points for (minimum) inductance at different frequencies were given to the suppliers, the different attenuations of the magnetic materials showed significant differences. The alternative DC common mode chokes achieved values that were between 20 % (Alternative 1) and 90 % (Alternative 3) higher.

- The capability of nanocrystalline material made it possible to reach the desired value of inductance with a smaller number of windings which has the profit of lower parasitic capacitances, e.g. for DC Common Mode Chokes by a factor of ten (Alternative 1) to a thousand (Alternatives 2 and 3).

AC Common Mode Choke - Ferrite Comparison

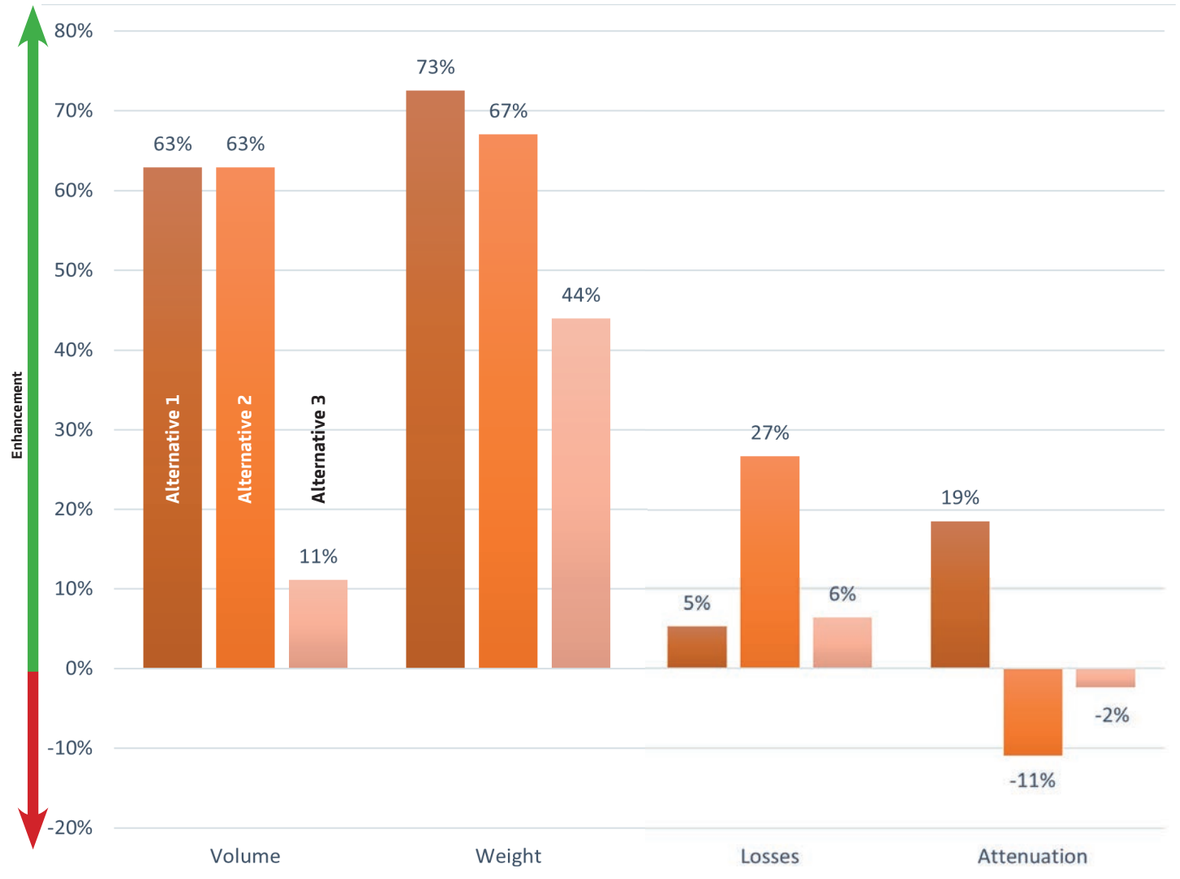
When we look at the AC Input Common Mode Choke, nanocrystalline material shows a much better performance. Comparing the core size the potential savings are around 34 % area on the PCBAs. The volume of the core is around 54 % smaller and the weight of the choke is reduced by 62 %. Meanwhile the efficiency is very similar. The determined thermal losses differ in the two load points in a range from +10 % to -10 %. The ferrite variant is slightly better in the higher current load range. The currently used variant with NSMM performs better at high output voltages for which the power electronics must use higher clock rates for the transistors. The achieved temperatures of core and windings also differed only by a maximum of 6 °C. In the case of the highest output voltage of 53 °C to 59 °C in favor of the nanocrystalline variant.

In this respect, the advantages in the size of the core come without disadvantages in efficiency. As the choke with ferrite material is bigger than the widely used component, it could not be fitted in the regular test setup. Therefore, reliable EMI measurements for comparison were not possible.

DC Common Mode Choke - Alternatives

Comparing the Common Mode chokes at the DC output, the alternatives with nanocrystalline materials show significant benefits in their mechanical properties. The weight can be reduced to a third with the alternatives, as do the volumes of the cores. Only Alternative 3 has fewer advantages here, although the higher inner diameter suggests that it should still be possible to optimize the same material through tighter geometries. For thermal losses and electromagnetic behavior, the picture is more diversed. As Figure 5 shows, there are quite different qualities of the components when losses and attenuations are included. But Alternative 1 alone can still show significant advantages over the existing component with ferrite core in both areas.

The losses show the differences for the operating point with highest possible output current at which the components partially heated up to temperatures around 90 °C, but in all cases lower than the ferrite component. Smaller differences resulted at higher output voltages and thus higher LLC frequencies. Alternative 2 and 3 show weaker filtering characteristics. Still, there is no linearity between the attenuation and the losses and other quantities. Thus, for Alternative 3, the magnitude and efficiency advantages appear to have a degradation in the filtering effect. For Alternatives 1 and 2, however, no direct correlation was found.



- ***Volume:*** *Volume the magnetic core*
- ***Weight:*** *Combined weight of the magnetic core and winding*
- ***Losses:*** *Losses at most challenging operating pint of highest output current of 65 A*
- ***Attenuation:*** *Attenuation in dB at the most challenging point of LLC frequency compared to that of the currently applied component with maximum output current*

Figure 5 DC Common Mode Choke - Improvement Over Existing Component

Economic Analysis

A financial consideration in place of the AC common mode choke is not meaningful due to the only comparison with a single component of a manufacturer for prototypes.

For the DC common choke, on the other hand, a very interesting comparison can be made. Only Alternative 1 will be excluded from the comparison as an economically feasible mass production was not offered by the supplier.

A rather subjective assessment is that components with nanocrystalline cores from the same manufacturer are two times more expensive than ferrite cores. The DC common mode chokes offered by mass producers, Alternative 2 and Alternative 3, could be obtained for a low single-digit euro amount per piece. As shown in Figure 6, in this case, this is however only one-third to a quarter the price of the currently applied component. The currently installed, freely available component has to be procured in a high single-digit euro range.

This single brand product is therefore much more expensive than the alternative requested from other companies for the same quantity. Even if components based on nanocrystalline soft magnetic cores can be more expensive than those with a simple ferrite core, the development and production can be the much more important factor. Even the price difference between the different materials that still exists after selecting the best supplier can be amortized in the operation of the product. For this purpose, we make the following consideration by way of example.

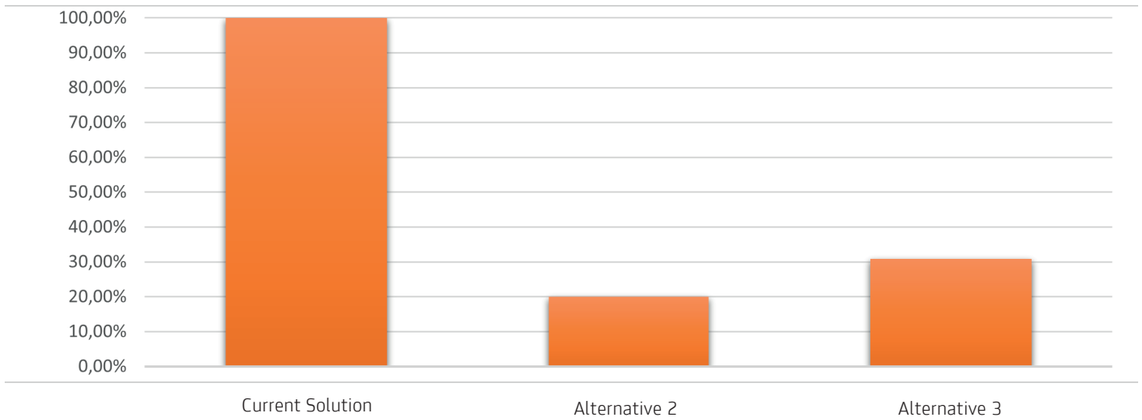


Figure 6 Relative Pricing of Alternatives 2 and 3 compared to Currently Applied Component

Considering advantages of NSMM in total cost of ownership

How can the argument now be made that the technical advantages of the alternatives shown here can compensate even the higher purchasing costs compared to those with Ferrite cores? For this purpose, a simple example for the usage of the On-Bard Charger will be given: The influence of the AC charging process on the total cost of ownership with regard to the system's energy efficiency and energy costs for the end customer.

To this end, the following highly simplified assumptions are made:

- An alternative DC Common Mode choke is 2 € more expensive than the ferrite-based component.
- A commercial vehicle, e.g. delivery van uses 50 kWh daily for a driving distance of 250 km.
- 300 recharges are performed annually with the electrical cost of 30 cents per kWh.
- A DC common mode choke causes 50 W losses in the system, 0.23 % of the total power of 22 kW and thus 113.6 Wh per charge and thus 34 kWh per year.
- The alternative component with nanocrystalline core would mean an additional cost of 2 € in the purchase price.

With the assumptions made that the applied component alone results in costs of ownership of about 10 € per year. An improvement in efficiency such as shown by the components here in a range of 5 % to 27 % would lead to a payback within one to a maximum of four years of operation. Like other power electronics, an OBC is designed for the lifespan of a commercial vehicle.

If for example this is 16 years, a brake-even point is already reached after 6.5 % to 25 % of the operating lifetime.

Other parameters such as size, weight and electromagnetic compatibility can also be factored in, but this is more specific to the device in question.

Summary & Outlook

The assumption that soft magnetic, nanocrystalline soft magnetic cores enable strong optimisations in the application field of On-Board Chargers could be confirmed. They offer easy leverage to achieve the reductions in size and weight demanded by the market without sacrificing existing high efficiencies and electromagnetic compatibility.

Alternatives could be requested from various suppliers around the globe without having to provide detailed requirements and expertise. They were delivered with respectable speed and always demonstrated high quality. In addition to the technical aspects, they are also commercially convincing. Manageable cost disadvantages are more than compensated by unique selling points and advantages for the customer in the total cost of ownership.

An important experience made within this project is also that the comparison of different offers and the detailed testing in the overall system is worthwhile. The technical added values and financial expenses differ greatly. Alternatives 2 and 3 are both economically feasible, but the electromagnetic behavior could make the difference in the selection process. Especially if this is the greater challenge in a project.

In the future, innolectric AG will preferentially use nanocrystalline soft magnetic materials in its innovative products and in the field of electric drive systems and is available as a partner for development projects.

CBMM will continue to showcase EV applications and revolutions, both in electromagnetic components and EV batteries, in which niobium is also a key component. All potential partners are invited to join a network representing the entire supply chain for niobium and soft magnetic materials all the way to the end user. Developers can be provided with in-depth scientific knowledge and application notes, as well as support in sourcing components.

Bharadwaj Reddy

Technical Market Development - Nanomaterials

“CBMM supplies FeNb to NSMM ribbon producers and we would like to help in accelerating the market growth for this material. Therefore, our strategy is to work with all the stakeholders in the value chain from upstream to downstream.“

About innolectric

innolectric AG combines innovation with in-depth knowledge in a stable base. The company develops and tests charging communication and power electronics for commercial electromobility. From the first prototype to the series device, the components are developed in-house at the Bochum headquarters.

The product portfolio includes the innolectric On-Board Charger in 400 V and 800 V versions as a system solution for flexible AC and DC charging; the DC Charging Controller and the On-Board Charger Grid, which was developed for applications with direct grid connection. Beyond the finished products ready for series production, the innolectric team offers engineering services.

In this way, products can be individually designed for customer projects. innolectric also carries out continuous research work, for example in the form of joint research projects such as this one together with CBMM.

About CBMM

CBMM is the world leader in the production and commercialization of Niobium products and has been in the market for over 60 years. CBMM is headquartered in Brazil, with regional offices in China, the Netherlands, Singapore, Switzerland, and The United States. CBMM manufactures and supplies Niobium products and develops technology related to Niobium product applications for the infrastructure, mobility, aerospace, health, and energy sectors. CBMM historically has a production capacity that exceeds the global demand for Niobium products. The company counts on robust logistics infrastructure on all continents, serving more than 400 clients in 50 countries.
Its business model is guided by solid corporate governance and is based on guaranteed supply, innovation, and the development of new technologies in partnership with the most renowned research centers worldwide.

Córrego da Mata, s/n
Araxá, Brazil 38183-903

+55 34 3669 3000
+55 11 3371 9222

cbmm.com
niobium.tech

What are the advantages of nanocrystalline soft magnetic materials in power electronics?

What are the challenges and potentials in the application in On-Board Chargers for commercial and industrial vehicles?

How well is the material available on the growing global market today and how important are comparison and testing?

Can components with soft magnetic cores already be economically advantageous in the short term compared to standard materials?

CBMM | Niobium Nb

innolectric

If you have any questions about this whitepaper or specific content of our research study, please do not hesitate to contact us at ***info@innolectric.ag****. Learn more about our work at* ***innolectric.ag****!*