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Optimal Inductor Design and Material Selection for High Power Density Inverters Used in Aircraft Applications

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Abstract—This paper presents the design and optimization of power inductors for three-phase high-power-density inverters to be used in aircraft applications. The inductor's geometric parameters, magnetic properties, core material selection, core and copper losses in addition to temperature calculations are taken into account to meet the low losses and high frequency specifications of the considered high power density inverter. A multi-objective optimization algorithm was developed to calculate weight, volume, and losses of the inductor for different current ripples, different switching frequencies and different inductor core materials. The results of a weight-objective optimization are presented showing the optimal efficiency and power density of the inverter for five chosen core materials, namely the silicon steel, ferrite, iron powder, amorphous and nanocrystalline.

Keywords— High power density inverters, inductor design, magnetic components, aircraft applications

I. INTRODUCTION

High power density has become one of the key topics in the development of power electronics converters [1]. Accordingly, power converters are designed not only to meet input and output power quality requirements but also to achieve low volume or lightweight as needed. The demand for reducing converter's volume and/or weight is usually driven by application-specific constraints. In aircraft applications, a low converter weight is important since weight has a dramatic impact on speed, CO₂ emissions, operational costs and overall operational capabilities [2]. Weight saving may be achieved by increasing the switching frequency of the system, which is nowadays possible with the development of new Wide Bandgap semiconductor technologies (such as SiC and GaN devices), since they offer faster switching speeds, lower losses, and the ability to operate at high temperatures [3][4].

In order to meet low losses and high frequency specifications of a high power density converter, more constraints are applied to the converter's filter design, especially concerning the inductor design. The inductor often appears as the converter's largest component, thus a compact and efficient magnetic design results in converter size and weight minimization. Material selection is one of the main issues facing the inductor designer. There is a wide variety of magnetic materials available and the optimum choice of magnetic core for a design is not straightforward. The choice is influenced by different design parameters associated to the converter topology as well as core material properties, such as frequency, current, current ripple, saturation flux density, flux swing, DC bias, operating temperature etc. Furthermore, the use of WBG semiconductors complicates the inductor design due to their operation at higher switching frequencies and the

use of high current ripples in order to decrease their switching losses [5]. Thus, magnetic materials must be deeply studied, reevaluated and compared to match the new semiconductor technologies. Magnetic materials available for power converters applications include silicon steel, ferrite, iron powder, and tape wound amorphous/nanocrystalline materials.

For each of these materials, inductor losses, volume and weight variations with current ripple and frequency are studied and compared in order to find the optimal design for a high power density inverter specifically designed for aircraft applications.

II. HIGH POWER DENSITY INVERTERS

A. Three phase inverters trade-offs

Inverters are used in aircraft systems to convert a portion of the aircraft's DC power into AC. This AC power is used mainly for instruments, radio, radar, lighting, air conditioning, actuation systems and other accessories. The converter topology most commonly used in these systems is a basic three-phase inverter, which is shown in Fig. 1a, representing the DC bus capacitor, the three inverter legs (composed of 2 switches each which are commonly IGBTs or MOSFETs) and the output filter. Fig. 1b shows the current waveform in the inductors of the output filter which is used for the inductor and inverter design.

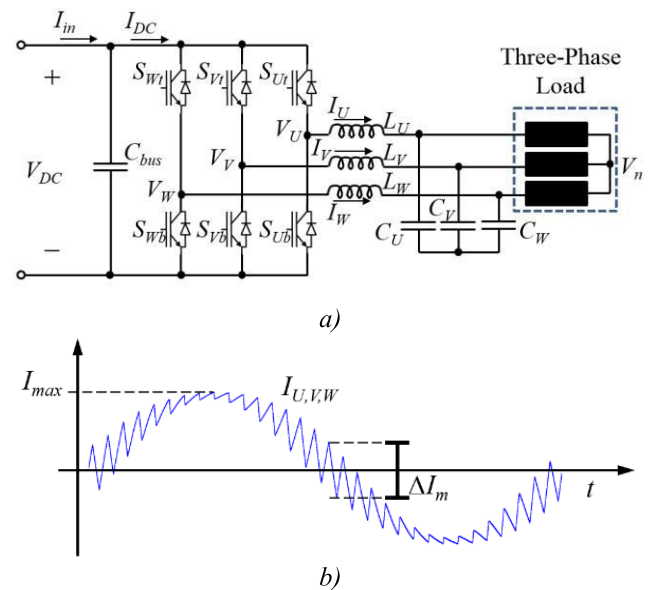


Fig. 1. a) Basic three phase inverter and associated filter; b) Current waveform in each inductor, used to calculate core and copper losses in the inductor optimization and in the inverter design.

One of the main difficulties in an inverter design is having many parameters impacting all aspects of the design. Higher switching frequency reduces the volume of passive elements, but at the same time increases losses, dropping the efficiency. Moreover, it can lead to high junction temperature in the semiconductors. Higher current ripple at the output of a switching cell may reduce switching losses, but at the same time increases conduction and copper losses. Considering the impact of all parameters together is mandatory to achieve an optimal design. There is a trade-off between the system's efficiency, power density and cost. The best efficiency can be obtained using oversized components or high-quality materials but at prohibitive cost. On the other hand, low-cost designs are rarely efficient.

High power density of the inverter implies a very constrained design of the output filter. Furthermore, all losses in the power conversion are to be reduced, in order to increase efficiency. On the other hand, the cost must obviously be maintained at a reasonable level. Thus, when starting to design the inverter many design stages are to be considered:

- Power ratings, modulation strategy, and switching frequency.
- Power stage: semiconductor material choice, switching capabilities, voltage and current limitations
- Inductor: choice of material, number of turns, magnetic circuit size, and geometry.
- Capacitor and heat sink: their main impact on the inverter design is volume and weight.

B. High current ripple for power density improvements

Authors in [5] have shown that a SiC-based buck converter must have high current ripple in the output filter inductor in order to decrease transistor switching losses for a given load and frequency. This is due to fact that with such a high current ripple, transistors of the commutation cell only turn-off current (turning-on always happens at zero voltage). However, high current ripple increases conduction losses, which can be negligible when compared to the reduction of switching losses at high frequencies.

Concerning the filter, in order to increase the current ripple in the output of an inverter leg, the output filter inductance must be reduced. However, the output filter capacitance must be increased with the purpose of maintaining the same filter cutoff frequency. Since the inductor is usually the most expensive, bulkiest and heaviest component of a filter, decreasing the inductance value is usually a good way to reduce the inductor's volume and weight, hence decrease the power density of the inverter. Nevertheless, higher current ripples increase copper and iron losses in the inductor. For this reason, it is important to optimize the whole system in order to reduce total losses in the converter and increase the inverter

power density. The magnetic materials used for the inductor optimization are presented in the next section.

Core losses, volume and weight variations with current ripple and frequency are studied in order to find the optimal design for a high power density inverter. However, before that, the available magnetic materials and the ones of interest are presented in the next section in addition to core losses calculations and materials comparisons.

III. MAGNETIC MATERIALS COMPARISON

A. Available Materials Characteristics and Selected Cores

The optimum magnetic material selection for an inductor design is not straightforward. Material selection depends on the inductor operating conditions such as maximum power, efficiency, input and output voltage, inductance and operating frequency. The ideal material would have high saturation, linear permeability and low power loss. However there is no ideal material and there is a wide variety of possible materials choices for a power inverter. In this study the materials are chosen to cover most material types used in power electronics. A core of each type is selected as shown in Table I based on their relatively low losses in the desired frequency range. The table represents five material types: silicon steel, ferrite, iron powder, amorphous and nanocrystalline. Selected cores are: 10JNHF600 Silicon-steel from JFE, 3C93 ferrite from Ferroxcube, MPP60 iron-powder from Magnetics, 2605SA1 amorphous from Hitachi, and Vitroperm 500F nanocrystalline from VAC.

Silicon steel is a Si-Fe alloy manufactured in the form of strips less than 2 mm thick stacked together to form a magnetic core. They are coated to increase electrical resistance between laminations, reducing eddy currents. Silicon steel has high losses compared to the other magnetic materials but it provides higher saturation flux density and lower cost.

Ferrites are chemically inert ceramic materials, having a magnetic cubic structure. They have low saturation induction but high resistivity providing low losses at very high frequencies. The common types of ferrites are Mn-Zn ferrites used for medium frequencies applications up to several kHz and Ni-Zn ferrites used for higher frequencies applications up to few MHz.

A powder core consists of small particles of pure iron and/or metal alloys, coated with a thin insulating layer and pressed at high pressure. There are many different mixes of the powdered-iron cores, having different permeabilities and power losses. The permeability of the powdered cores can be adjusted during the manufacturing process as the air-gap is distributed in the material. Powder cores have a lower value of permeability but a higher saturation flux density, than ferrites.

TABLE I
MAGNETIC MATERIALS

Material type	Manufacturer	Name	μ_r	$B_s(T)$	ρ (g/cm ³)	Filling Factor
Silicon-steel	JFE	10JNHF600	800	1.87	7.53	0.9
Amorphous	Hitachi	2605SA1	1200	1.56	7.18	0.83
Iron-powder	Magnetics	MPP60	60	0.75	8.2	1
Nanocrystalline	VAC	Vetroperm500F	15500	1.2	7.3	0.7
Ferrite	Ferroxcube	3C93	1800	0.5	4.8	1

The amorphous and nanocrystalline are tape wound materials resulting from high-tech production process of low cost raw materials like silicon and iron. They combine the high flux of Fe-Si with improved high frequency performance of ferrites. Magnetic nanocrystalline materials are formed by an assembly of regions of coherent crystalline structure, while amorphous metals do not have a crystalline structure, all the atoms are randomly arranged, thus giving it a higher resistivity value than that for crystalline counterparts. Ribbons of nanocrystalline and amorphous alloys are made by rapid solidification, deposition techniques and solid state reactions. The produced ribbons are then used to form fragile tape wound toroidal cores.

Silicon steel has the highest saturation flux density (1.87 T) followed by amorphous metal (1.56 T), nanocrystalline (1.2 T), MPP iron powder (0.75 T), and ferrite (0.5 T). These materials permeability depends on many factors, including the chemical composition, particle size, bonding material, stress and heat annealing, etc.

B. Core Loss Calculation

Power loss curves given in units per mass or volume are usually found in magnetic materials datasheets. Manufacturers generally use simple core loss measurements, under a sinusoidal flux density, to trace these losses as function of maximum flux density level (B_{max}) and frequency (f).

These loss curves can be fitted to a simple formula proposed by C. P. Steinmetz called Steinmetz equation (SE) to predict core losses at a given flux density level and frequency. This equation is applicable to sinusoidal waveforms only and is shown in (1)

$$P_{core} = K \cdot f^\alpha \cdot B_{max}^\beta \quad (1)$$

where k , α , and β are called the Steinmetz coefficients and are specific for each magnetic material. These coefficients are usually provided by the manufacturer to calculate core losses. However, both loss curves and Steinmetz coefficients provide losses for a sinusoidal flux density waveforms only, which is not the case of most power electronic applications. Normally flux waveforms applied to the inductor in power converters are triangular, trapezoidal or more complicated ones, such as a mix of triangular and sinusoidal which is the case of the magnetic flux in a filter inductor in the output of an inverter. For that reason, various efforts have been made to improve SE to take into account different flux density waveforms. These modified versions of the SE include MSE [7], GSE [8], iGSE [9], and i2GSE [10].

A good approximation of core losses for non-sinusoidal flux density can be obtained using iGSE presented by (2):

$$P_{core} = \frac{1}{T} \int_0^T k_i \left| \frac{dB}{dt} \right|^\alpha (\Delta B)^{\beta-\alpha} dt \quad (2)$$

where k_i can be calculated from k , α , and β using:

$$k_i = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos \zeta|^\alpha 2^{\beta-\alpha} d\zeta} \quad (3)$$

Equation (2) is used in this paper to calculate core losses for different flux densities amplitudes, frequencies and waveforms. Example of flux waveform in a core of an output filter inductor of a three-phase inverter is shown in Fig. 1 since current and magnetic flux are mostly proportional to each other when core operates in its linear region.

C. Materials Comparison

Power loss curves are a common comparison method used to compare materials performances for different frequencies and flux densities. Volumetric power losses versus sinusoidal and triangular flux densities at 100 kHz for the considered materials are shown in Fig. 2. These losses are traced based on datasheets and Steinmetz coefficients for sinusoidal flux density and on iGSE for triangular flux density.

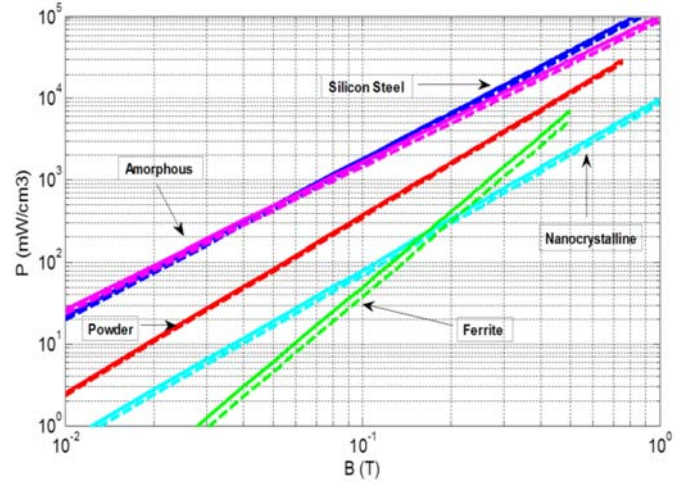


Fig. 2. Core losses comparison: sinusoidal (complete lines) and triangular (dashed lines) waveforms.

At this given frequency some materials perform better at lower flux density while other materials are better at higher flux density. However, this performance may not be the same for different frequencies. The flux waveform also has a non-negligible effect on losses as shown in Fig. 2. The difference between losses under sinusoidal flux waveform (complete lines) and triangular flux waveform (dashed lines) may exceed 20%.

If we focus on the results presented in Fig. 2, the highest core loss is observed in the iron-silicon and amorphous materials. Power loss in the powder core is significantly lower than iron-silicon and amorphous, especially since the selected MPP core may have the lowest losses among powder materials. The selected nanocrystalline and ferrite cores have the lowest loss curves, crossing just above 0.1 T with the ferrite having higher losses at higher flux densities as expected.

The choice of core material has a great impact on the inductor's losses and weight, thus an impact on the inverter's efficiency and power density. For this reason, material choice alongside with other core and copper physical and geometric parameters are taken into account in the inductor design. An inverter connected to a 540 V DC bus used in aircraft applications is considered. Then the inductor for this specific application is designed and optimized in order to find the optimal inverter concerning efficiency and power density

2) *Thermal Calculations:* After calculating copper and core losses, the inductor temperature must be estimated. A simple model considering a unique temperature for the whole magnetic component is used. The total heat exchange area (S_{exc}) of the magnetic component is calculated considering all copper and core surfaces which are in direct contact with air. This is used to calculate the overall temperature rise (T_c) of the magnetic component according to:

$$T_c = \frac{P_t}{S_{exc} \cdot H_{exc}} \quad (5)$$

where P_t is the total losses dissipated by the inductor and H_{exc} is a thermal exchange coefficient which takes into account natural convection and radiation effects at high temperatures.

A. Results of inductor optimization and inverter design

A MATLAB algorithm was developed to calculate weight, volume, and losses of the inductor, using the optimization strategy shown in Fig. 3. An inverter having an input DC voltage of 540 V and peak load current in each phase of 8 A is considered. The inverter was partially designed calculating also losses in the semiconductors of the three phases in order to calculate the weight of heatsinks attached to the switches. Switches used in the optimization are SiC MOSFET CMF20120D from Cree. The output filter was designed using MKP film capacitors from EPCOS (300V rated voltage), and their values were calculated so the output filter has a cutoff frequency one decade below the switching frequency. Heatsink volume and weight were calculated using a Cooling System Performance Index related to weight ($CSPI_m$, as defined in [12]) of 0.37W/K.kg, which is an average value for performant natural convection aluminum heatsinks.

The design algorithm was run for different current ripples, different switching frequencies and different inductor core materials. The following constraints are considered in the optimization routine: maximum inductor temperature rise ($T_{m_inductor}=40^\circ\text{C}$), maximum junction temperature rise ($T_{m_junction}=40^\circ\text{C}$), maximum flux density ($B_{max}=B_s$ of each material) and $H_{exc}=12\text{W/m}^2/^\circ\text{C}$. Calculation was made considering ambient temperature of 25°C . Some results of a weight-objective optimization are presented in Fig. 5, Fig 6 and Fig. 7.

Fig. 5 compares the inductor weight for the different considered core materials. The weight is traced for a maximum current ripple (ΔI_m in Fig. 1b) varying from 10% to 200% of the load's peak current and for two given switching frequencies, 20 kHz and 40 kHz. Considering the curves at 20 kHz and at high current ripple, the amorphous inductor has the highest weight followed by the FeSi inductor given their high core losses which can only be dissipated with a large surface. Iron powder, nanocrystalline and ferrite inductors have a similar weight of less than 0.3 kg at high current ripples. However, at low current ripple, since all materials have low core losses, iron powder and ferrite inductors have the highest weight given their low saturation flux density, followed by the amorphous and nanocrystalline and then the FeSi. The higher the switching frequency, the lower the inductor weight given its lower inductance value. This weight difference is reduced for high current ripple given higher core losses at higher frequencies.

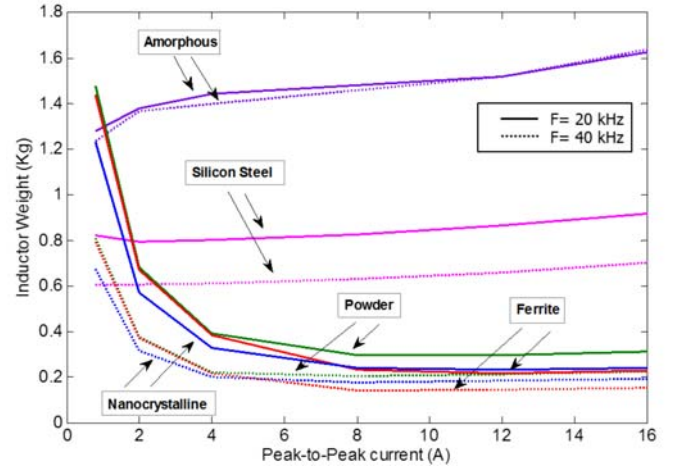


Fig. 5. Inductor weight versus current ripple for different core materials at 20 kHz (complete lines) and 40 kHz (dashed lines).

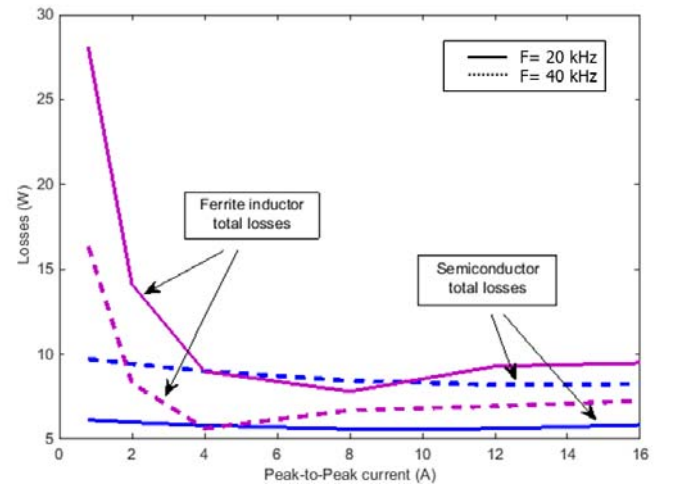


Fig. 6. Inductor and semiconductors total losses versus current ripple at 20 kHz (complete lines) and 40 kHz (dashed lines).

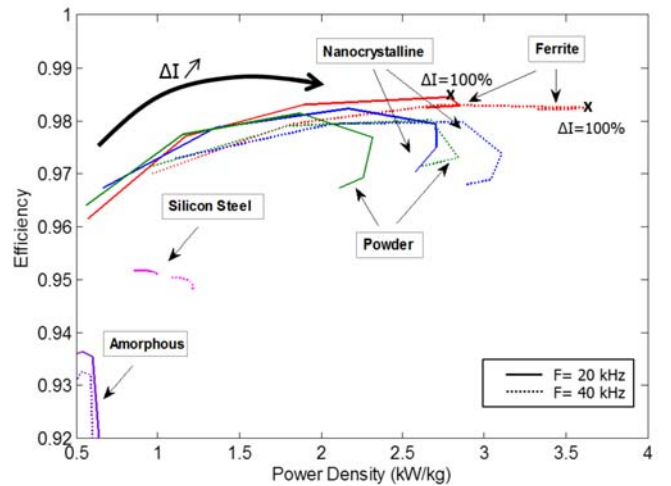


Fig. 7. Inverter efficiency versus power density for different core materials at 20 kHz (complete lines) and 40 kHz (dashed lines).

Fig. 6 shows the total losses in two major components of the inverter, semiconductors and inductor (ferrite core was chosen to be shown in this figure). These losses are traced versus current ripple at two given frequencies, 20 kHz and 40 kHz. Inductor total losses decrease rapidly with current ripple to reach a minimum value at a certain current ripple value, then

they increase slowly. For low current ripple values, as the current ripple increases, the inductance value decreases leading to a smaller core and lower core and copper losses until the current ripple is high enough to generate high core and high frequency copper losses. Also as the frequency increases, a smaller inductor is needed and thus leading to lower inductor losses. Concerning semiconductor total losses, they clearly increase with frequency but they mostly decrease with current ripple, up to a certain point where the ripple is to high generating high conduction losses in the semiconductors. Thus there is a trade-off between frequency and current ripple to obtain minimum losses, as can be seen in Fig. 7.

Fig. 7 shows the inverter's efficiency versus the power density (per mass unit) for the different considered core materials at two given frequencies, 20 kHz and 40 kHz. Each point of each curve is calculated for a different current ripple (from 10% to 200% of the load's peak current), and the direction of current ripple increase is shown in the figure. Inverter's efficiency is calculated using rated power (at resistive load having peak current of 8 A and voltage of 540V with modulation index of 0.8) and semiconductor and inductor losses. Power density is calculated using rated power and weight of heatsink and output capacitor and inductor. As the frequency increases, the efficiency decreases due to higher losses and the power density increases due to lower weight. Ferrite, powder and nanocrystalline curves are in the top of the graph having up to 98.5 % efficiency and up to 3.5 kW/kg power density, FeSi in the middle with 95 % and 1 kW/kg while amorphous in the bottom with 93 % and 0.5 kW/kg. For the two given frequencies, the ferrite core is the best choice having the highest efficiency and power density at $\Delta I=100\%$. This may not be the case for different frequencies and low current ripples. Notably at low current ripple, iron powder and nanocrystalline cores present higher performance then ferrite.

V. CONCLUSION

In the aim of designing a compact and efficient inductor, different magnetic materials were investigated in this paper to minimize the weight of a three-phase inverter designed for aircraft applications. Material selection is one of the main issues in the inductor design depending on the system requirements and the trade-offs between the efficiency, specific power loss, weight, and operating temperature. The selected materials for this study were silicon steel, amorphous, powder, nanocrystalline, and ferrite. Power loss curves of these materials were compared for different frequencies and flux densities.

The inductor application was a 540VDC inverter of variable current ripple (10% to 200%) and frequency (10 kHz to 100 kHz). An inductor design algorithm is employed to show the materials performance over the frequency and current ripple range. The optimization algorithm takes into account the inductor's geometric parameters, magnetic properties, core material selection, losses and temperature. A weight-optimization was run to achieve the minimum inductor

weight, thus higher power density, for a reasonably high efficiency. Results showed that highest inverter's power densities and efficiency are achieved using Ferrite material for inductor cores. The highest power density is achieved for current ripple of 100%. Since the switching frequency must be high in order to decrease the filter size and the current ripple high to decrease switching losses, only the use of low loss materials result on high efficiency and power density of this inverter. Although amorphous, nanocrystalline, FeSi, and iron powder materials have high saturation flux densities, high current ripple induces high magnetic losses in these cores and consequently prevents these cores to operate at high flux densities. These materials result then in cores having greater cross sections than ferrite. Nanocrystalline material present reasonable poorer performance than ferrite, however it is allows higher efficiency and power density than the other materials

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