

# High Frequency Transformer Design Report

## Work Package 4

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### Abstract

This report presents the material options for the core of the medium frequency transformer that is being investigated within the Work Package 4 of the “Next Generation HVDC Network for the Offshore Renewable Energy Industry” project.

*Keywords:* medium frequency transformer, HVDC transmission, core losses, HV transformer

## 1 Introduction

A literature review is presented by Robert Fox within WP 2, in which different medium-frequency transformers were compared and the components of medium-frequency transformers are listed. This report will focus on the core materials and the main losses in a transformer.

Increasing frequency of a transformer reduces its volume and cost. In [1], it is stated that the weight and size of a 3 MW 1.2 kHz transformer is less than 8% of an equivalent 50 Hz line transformer. In Fig. 1, volume variation with operating frequency for a 1 MW transformer is presented.

However, as the frequency is increased, skin effect, proximity effect, hysteresis losses and dielectric losses are significantly increased. Furthermore, the reduction in size usually implies same power loss in much smaller area, which demands forced cooling. Important design factors in conventional line transformers and high frequency transformers are tabulated in Table 1. Challenges of medium-high frequency transformers can be listed as [2]:

- Loss reduction for higher frequency range.

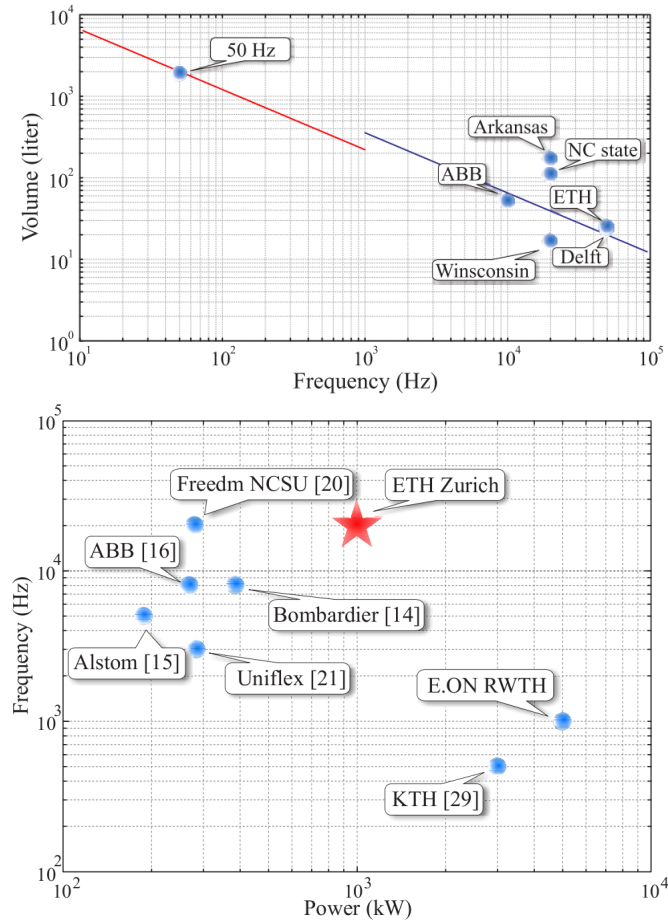


Figure 1: Volumes of high frequency transformers(normalized to 1 MW) and rated power and operating frequencies of existing DC-DC converter prototypes [3, 4].

- Efficient thermal management, higher power levels are contained in equal volumes.
- High-dielectric stress generated by rapidly changing rectangular voltage waveforms.
- High-isolation levels are required (due to multi-level inverter structure).
- Generation of acoustic noise, which reaches the most sensitive range of the human ear.

Line Transformer (50 Hz)	High Frequency Transformer
Core Mass	Skin Effect
Copper Losses	Core Losses
Volume	Parasitic Capacitance
	Cooling
	Resonance

Table 1: Important factors in the design of line frequency and high-frequency transformers.

## 2 Core Materials

Although, various types of electrical steel laminations are commonly used in power transformers. As the operating frequency is increased, there are more options available:

### Amorphous Materials

Amorphous cores are typically made of Metglas (metallic glass alloy), which is a thin non-crystalline amorphous metal alloy of iron, boron, silicon and phosphorus. The material has a much higher resistivity in electrical steel which results in a low eddy losses. Furthermore, the hysteresis losses of amorphous cores are lower, which reduces the no-load losses compared to one with electrical steel. However, amorphous materials usually have lower saturation flux density compared to conventional iron-silicon electrical steel.

Some manufacturers of amorphous transformer cores can be listed as:

- Hitachi Metals (Powerlite)
- Vacuumschmelze (Vitrovac)
- Metglas
- Vijai Electricals

Although, amorphous materials are superior to electrical steel laminations, nano-crystalline materials are superior to amorphous materials with their lower cost and higher flux densities [5]. Nano-crystalline materials will be discussed in the next section. The specifications of amorphous and nano-crystalline materials are compared in Table 2. The only application that a amorphous material can be more advantageous is high-frequency single-ended forward converter topologies. For all other topologies, nano-crystalline materials are considered to be more suitable.

	Amorphous (Vitrovac)	Nano-crystalline (VitroPerm)
Saturation Flux Density	0.8 T	1.2 T
Losses (f= 20 kHz, B=0.2 T)	2 W/kg	1.4 W/kg
Max. Operating temperature	110 °C	120 °C
Curie temperature	365 °C	600 °C

Table 2: Comparison of amorphous (Vitrovac) and nano-crystalline (VitroPerm) materials [5].

### Nano-crystalline

Nano-crystalline is a fairly new material that consists of approximately 80% of iron with the remaining is mixture of silicon, boron, carbon, nickel and other materials. This is a special type of amorphous material, which has superior magnetic characteristics, such as lower core loss and high permeability. Other specifications can be listed as [6]:

- Up to 50 % permeability than 80% nickel material (e.g. Supermalloy).
- High saturation flux density (1.2-1.5 T).
- High operating temperature up to 130 °C.
- Minimal change of magnetic characteristics with temperature.
- 17 % lighter than Nickel with a density of 7.3 g/cm<sup>3</sup>.
- Stacking density up to 90 % can be achieved.

Some main manufacturers of nano-crystalline materials can be listed as:

- MK Magnetics
- Vacuumschmelze
- Hill-Tech

In this section, different types of nano-crystalline materials will be compared. Vacuumschmelze manufactures various soft magnetic nano-crystalline materials under the brand of VitroPerm.

### VitroPerm

Nanocrystalline VitroPerm alloys are based on Fe with Si and B with Nb and Cu additives [7]. VitroPerm nano-crystalline alloys are optimized to combine highest permeability and lowest coercive field strength. The combination of

very thin tapes and the relatively high electrical resistance ( $1.1\text{-}1.2\ \mu\Omega\text{m}$ ) to ensure minimal eddy current losses and an outstanding frequency vs. permeability behaviour. Along with saturation flux density of 1.2 T and wide operational temperature range, these features combine to make VitroPerm superior in many aspects to commonly used ferrite and amorphous materials. Magnetization curves and B-H characteristics of VitroPerm materials are presented in Fig. 2.

VitroPerm has a wide range material options with different permeability scale as shown in Fig. 3. The permeability of VitroPerm 500F is significantly higher than ferrite as shown in Fig. 4.

VitroPerm has also a high operating temperature compared to ferrite. The Curie temperature of VitroPerm alloys are  $600\ ^\circ\text{C}$ . Furthermore, the saturation flux density only reduces by 10% at  $120\ ^\circ\text{C}$ , which allows the core can be overloaded for short-amount of periods up to  $180\text{--}200\ ^\circ\text{C}$ . The variation of permeability with temperature for VitroPerm is presented in Fig. 5.

## **Silicon-Steel**

Silicon-steel is a popular choice in line frequency power transformers for its low cost and high-saturation magnetic induction. However, core losses of silicon-steel is high compared to other materials, which makes them unsuitable for medium frequency transformers. The core losses of material will be compared in the next section.

## **Ferrites**

Ferrites have a low-loss density in very high-frequencies, which makes them a suitable material for high-frequency applications such as RF-filters and chokes. However, they have saturation flux density around 0.5 T, which increases the core volume and mass in high power applications.

## **Core Material Comparison**

Different core materials and manufacturers are presented in Table 3. In Fig. 6, prototypes with common core materials are presented. It can be seen from the table that nano-crystalline and amorphous materials are the most suggested materials for medium frequency transformers that work between 1 kHz and 25 kHz.

The hysteresis losses and the core loss of different materials are compared in Fig. 7. Core losses are presented in Fig. 8. It can be seen that between 1 kHz and 10 kHz, the core loss of 0.3 mm silicon-steel laminations are 25

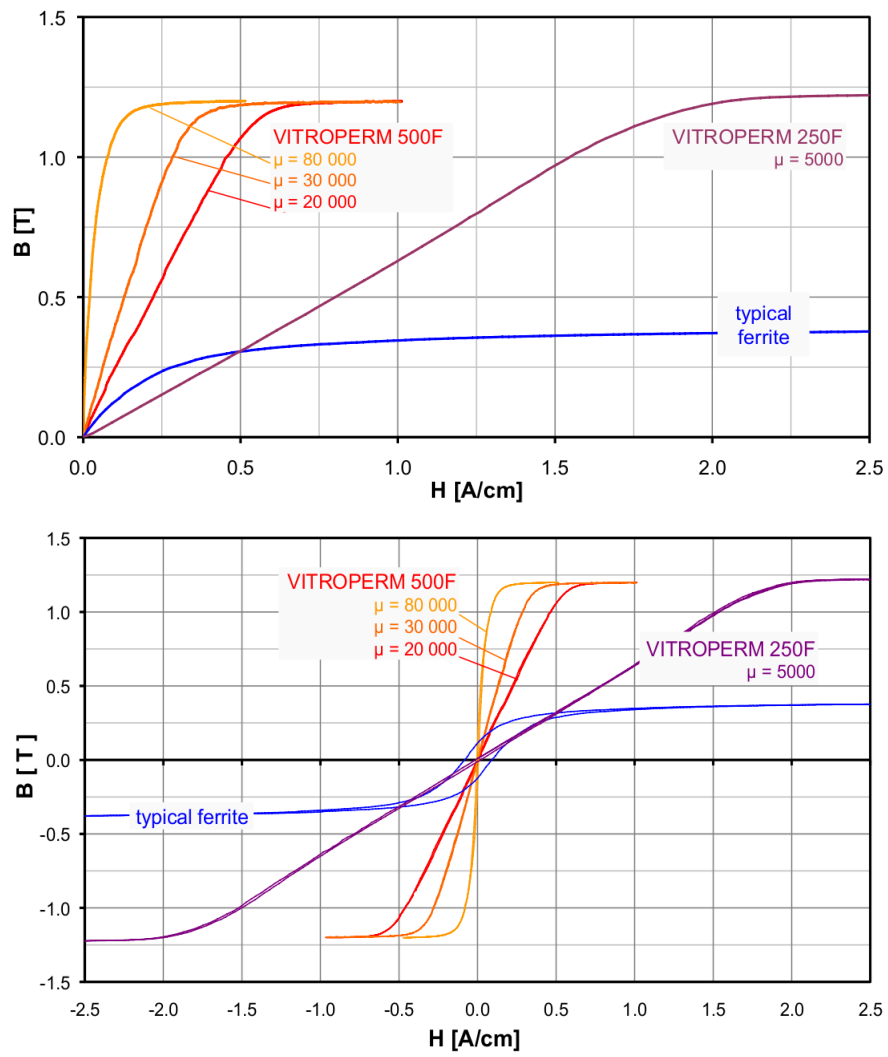


Figure 2: Magnetisation curve and B-H characteristics of VitroPerm [7].

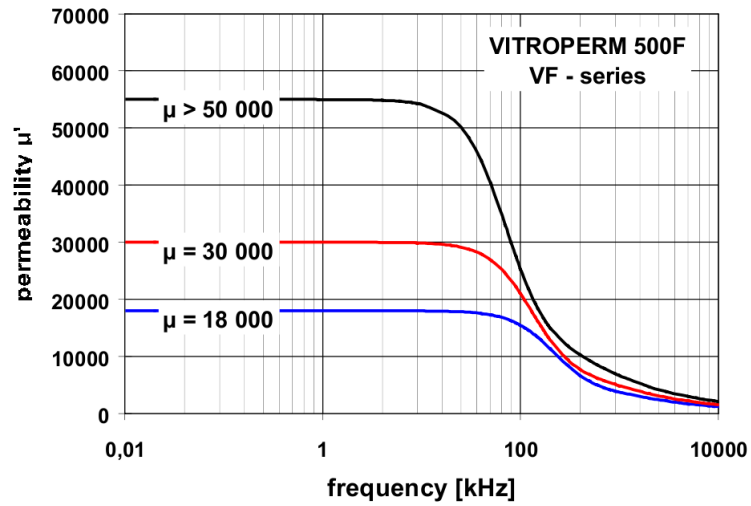


Figure 3: Permeability change of different VitroPerm materials with frequency [?].

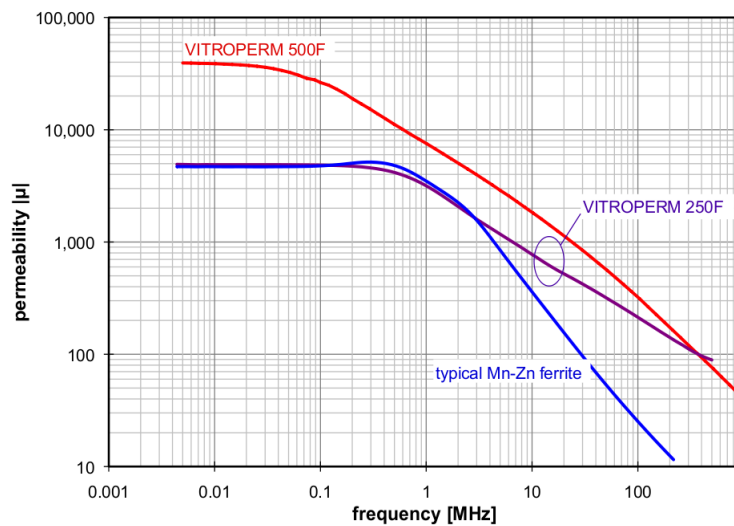


Figure 4: Permeability change of VitroPerm 250F( $\mu = 5000$ ), VitroPerm 500F( $\mu = 40000$ ) and ferrite( $\mu = 5000$ ) with frequency. [7].

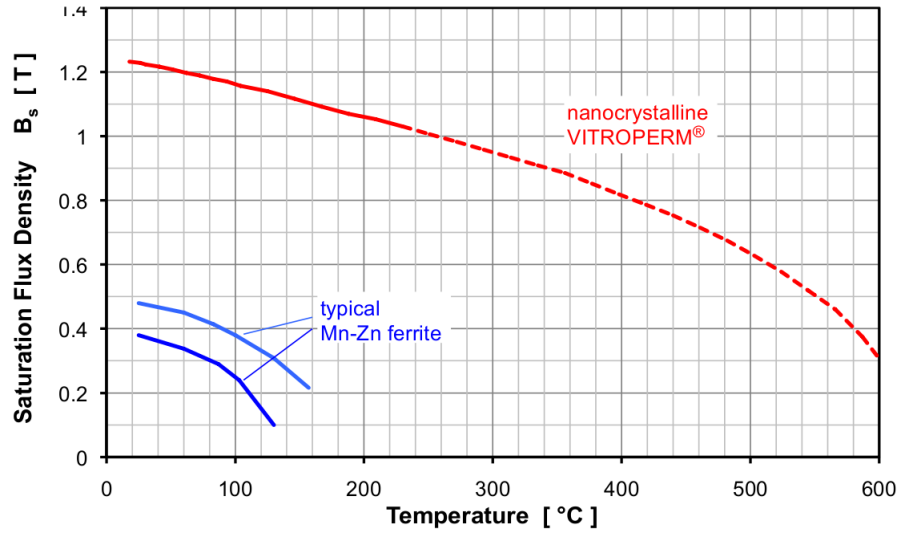


Figure 5: Saturation flux density variation of VitroPerm with temperature.

Material	Brand	Saturation Flux	Core Loss	Manufacturer
Amorphous	Microlite	1.56 T	1.5 kW/kg	Metglas
	Powerlite	1.56 T	0.6 kW/kg	Metglas
	Namglass	1.59 T	0.34 kW/kg	Magmet
	Vitrovac	0.82 T	0.19 kW/kg	VAC
Nano-crystalline	Finemet	1.23 T	0.14 kW/kg	Hitachi
	VitroPerm	1.2 T	0.07 kW/kg	VAC
	Nanoperm	1.2 T	0.04 kW/kg	Magnetec
	Namglass 4	1.23 T	0.04 kW/kg	Magmet
Silicon Steel	Arnon 7	1.53 T	1.6 kW/kg	Arnold
	Arnon 5	1.48 T	1.06 kW/kg	Arnold

Table 3: Core materials and manufacturers for high-frequency transormers (specific losses at  $B = 1$  T,  $f = 20$  kHz) [4].



Frequency	Magnetic Material	Low-Leakage Inductance Resonant Converter	High-Leakage Inductance Non-Resonant Converter
< 1 kHz	Silicon-Steel (FeSi)		<b>Traction, 75 kVA</b> 400 Hz, Bare 340 $\mu$ H, Oil [Hugo et al., 2007]
1 kHz to 25 kHz	Nanocrystalline	<b>Traction, 350 kVA</b> 10 kHz, Coaxial < 50 kg, 3 $\mu$ H, Water [Heinemann, 2002]	<b>General, 10 kVA</b> 20 kHz, Litz wire 1.6 $\mu$ H + $L_{ext}$ 21 $\mu$ H [Akagi and Inoue, 2006]
		<b>Traction, 500 kW</b> 8 kHz, Coaxial 2.3 $\mu$ H, Water, 18 kg [Steiner and Reinold, 2007]	<b>Traction, 1 MVA</b> 4 kHz, Litz wire 215 $\mu$ H, 148 kg, Cyclo [Kjellqvist et al., 2004]
	Amorphous	<b>General, 50 kW</b> 25 kHz, Interleaved Foils 3 $\mu$ H + $L_{ext}$ 37 $\mu$ H [Pavlovsky et al., 2005]	<b>Wind, 280 kVA</b> 1.2 kHz, Coaxial 251 nH, Passive Rectifier [Prasai et al., 2008]
			<b>Wind, 1 MW</b> 10 kHz, HV Litz wire 50 $\mu$ H, Passive Rectifier [Morren et al., 2001]
> 25 kHz	Ferrite		<b>Wind, 3.6 kW</b> 50 kHz, Litz wire 14 $\mu$ H, Passive Rectifier [Morren et al., 2001]
			<b>General, 50 kW</b> 50 kHz, Coaxial 1.6 $\mu$ H [Kheraluwala et al., 1992]
			<b>Drives, 25 kW</b> 50 kHz, Litz wire 2.2 mH, Forced Air [Aggeler et al., 2008]

Figure 6: Common materials used in medium frequency transformers and previous prototypes (Heinemann, 2002:[8], Steiner,2007:[9], Pavlovsky,2005:[10], Morren,2002:[11], Prasai,2007:[1]) [2].

times higher than nano-crystalline material. A 50 kV, high frequency (20 kHz), 150 kW transformer that uses nano-crystalline material is presented in [12], in which the core losses are estimated as 60W/kg at an operating flux density of 1 T.

### 3 Losses in a Transformer

#### 3.1 AC Winding Losses

The high frequency excitation in a medium frequency transformer has two main effects in the transformer windings:

- Skin Effect: In AC excitation the current itself generates an opposing magnetic field and current, which reduce the net current density inside the conductor. The total current will stay same, but the distribution will be higher across the circumference of the conductor.
- Proximity Effect is the interaction between two adjacent conductors that alters the current distribution in the conductor. Same principles(e.g. proximity, frequency) apply in the proximity affect.

##### 3.1.1 Skin Effect

Skin effect is an important factor in AC resistance and eddy current losses in a transformer. Skin effect is effected by the skin depth, which can be expressed as:

$$\sigma = \sqrt{\frac{2\rho}{\mu\omega}} \quad (1)$$

where  $\rho$  is the resistivity of the conductor,  $\mu$  is permeability, and  $\omega$  is the frequency in rad/s. Skin depth of copper for different operating frequencies are presented in Table 4. For reasonable AC resistance characteristics, the rule of thumb is to choose the conductor diameter smaller than 1.6 times of the skin depth. Thus, for a 1-2 kHz transformer application, the conductor shouldn't be thicker than 2-3 mm.

In a step-up transformer the cross-section area of the primary conductor will be larger. However, the limit due to skin-depth limits the thickness of the conductor. Therefore, the most feasible way is to use foil conductors in the primary windings. Dowell calculated eddy losses in foil type transformer windings in [13]. A detailed explanation of these one dimensional Maxwell equations can be found in [2] and a summary will be presented in this section.

The DC resistance of a foil winding can be expressed as:

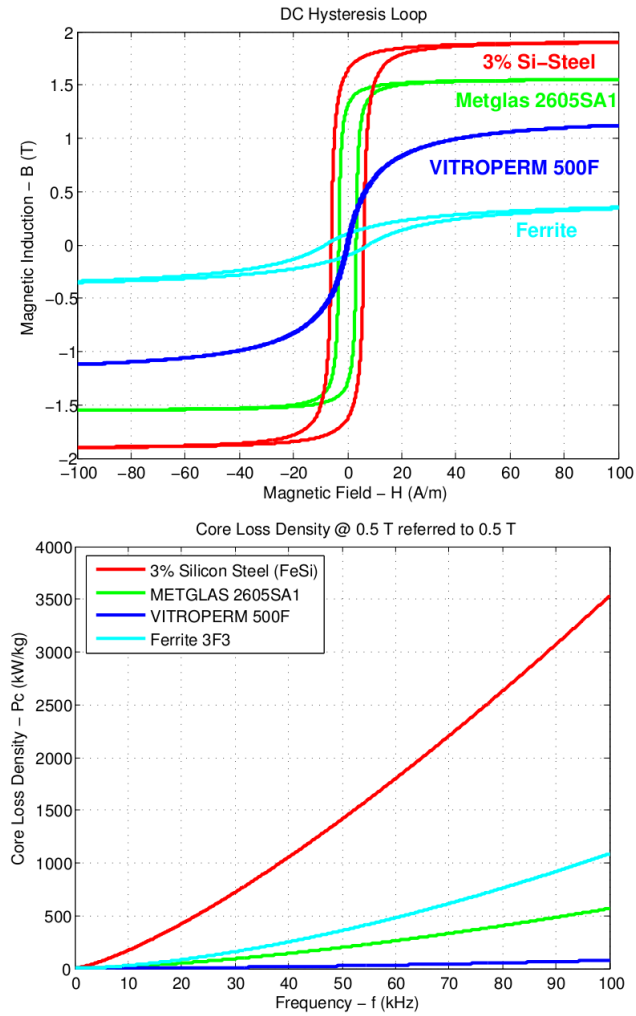


Figure 7: Loss comparison of silicon-steel, amorphous, nano-crystalline and ferrite materials [2]. a) Hysteresis loss, b) Core loss.

Frequency	Skin Depth
50 Hz	9.2 mm
1 kHz	2.06 mm
2 kHz	1.49 mm
5 kHz	0.94 mm
10 kHz	0.65 mm
50 kHz	0.29 mm

Table 4: Skin depth in a copper conductor.

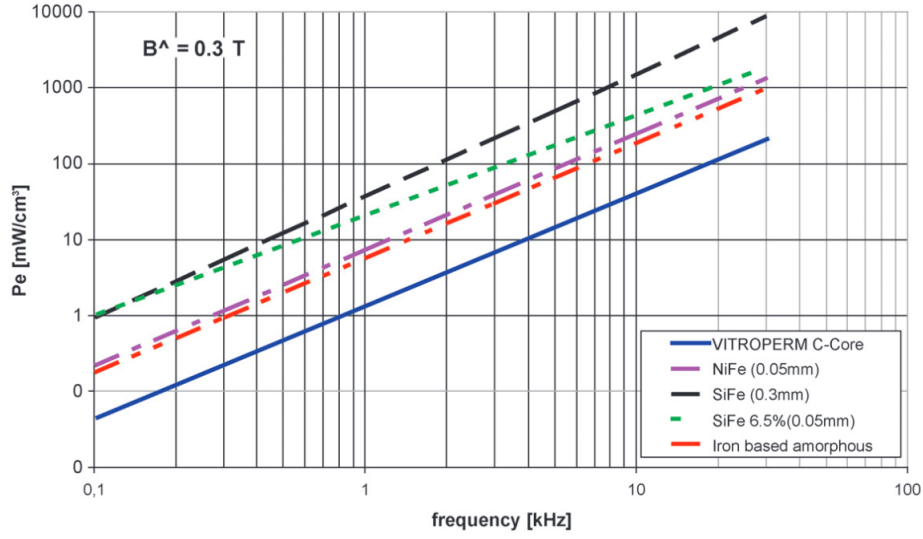


Figure 8: Core loss comparison of nano-crystalline (VitrePerm) with electrical steel and amorphous material [7].

$$R_{dc} = \rho \frac{L_{mean}}{t_w h_w} N_{turns} \quad (2)$$

where  $L_{mean}$  is the mean turn length of the coil,  $t_w$  is the thickness,  $h_w$  is the height,  $\rho$  is the resistivity of copper.

The AC resistance is more complicated to calculate and depends on the ratio of the wire thickness to skin depth ( $\delta$ ) and can be expressed as:

$$R_{ac} = \rho \frac{L_{mean}}{h_w \delta} N_{turns} \left[ \zeta_1 + \frac{2}{3} (N_{turns}^2 - 1) \zeta_2 \right] \quad (3)$$

where:

$$\zeta_1 = \frac{\sinh(2\Delta) + \sin(2\Delta)}{\cosh(2\Delta) - \cos(2\Delta)} \quad \zeta_2 = \frac{\sinh(\Delta) - \sin(\Delta)}{\cosh(\Delta) + \cos(\Delta)} \quad \Delta = \frac{t_w}{\delta} \quad (4)$$

as can be seen from the equation above, the important factor is the penetration factor (i.e the ratio of conductor thickness to skin depth,  $\Delta$ ). The ratio of AC resistance to DC resistance is called Dowell's resistance factor ( $F_r$ ). The resistance factor as a function of penetration ratio for a 2 mm thick foil wire is presented in Fig. 9. For example, at 1 kHz the skin depth is 2.1 mm (the penetration ratio is approximately 1), the resistance factor is 2.7 for a layer number of 4. Thus the resistive losses will be 2.7 times more compared to DC conduction.

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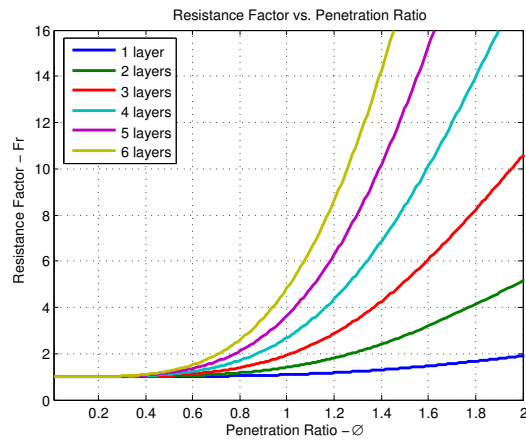


Figure 9: Resistance factor for a function of penetration ratio (for 2 mm thick foil conductor) [2].

## 4 Secondary-Winding

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Assumptions from WP2 Document

Winding

Low voltage side: Foil topology (reduces the size and weight). High voltage side: Circular strands (mechanical strength and increased dielectric strength).

Insulation

Dry transformer is chosen for increased reliability. Epoxy material is used for insulation.

Water cooling system to reduce the size.

## 5 All Graphs

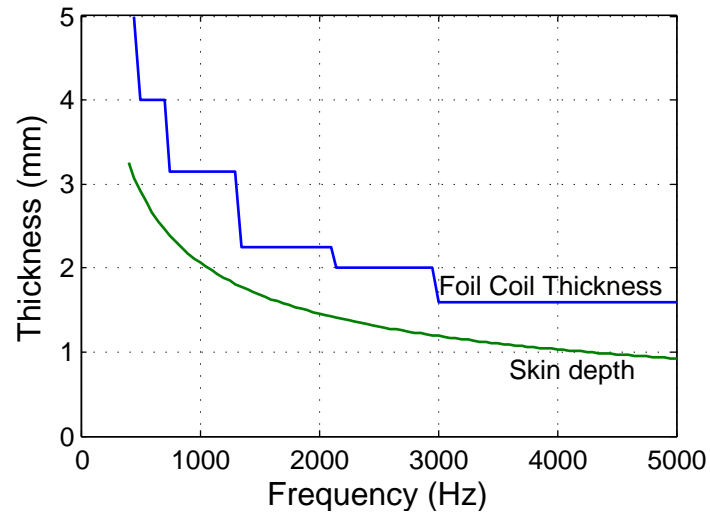


Figure 10: Skin depth and primary foil winding size variation (Standard foil conductor sizes are used).

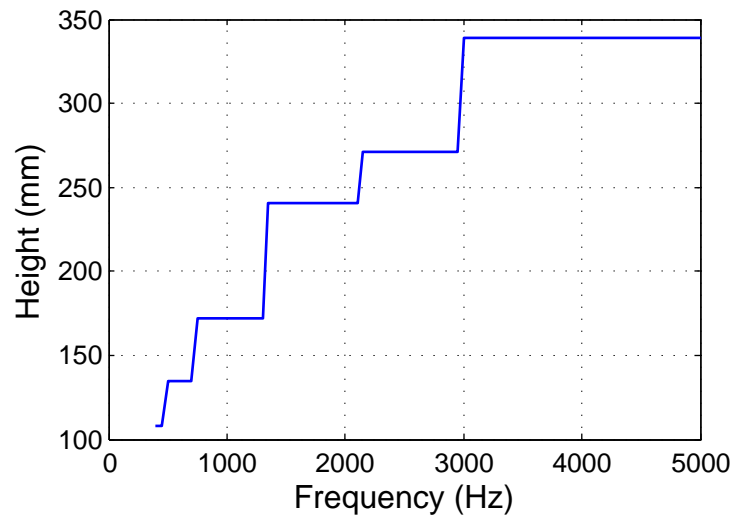


Figure 11: Tum grafikler

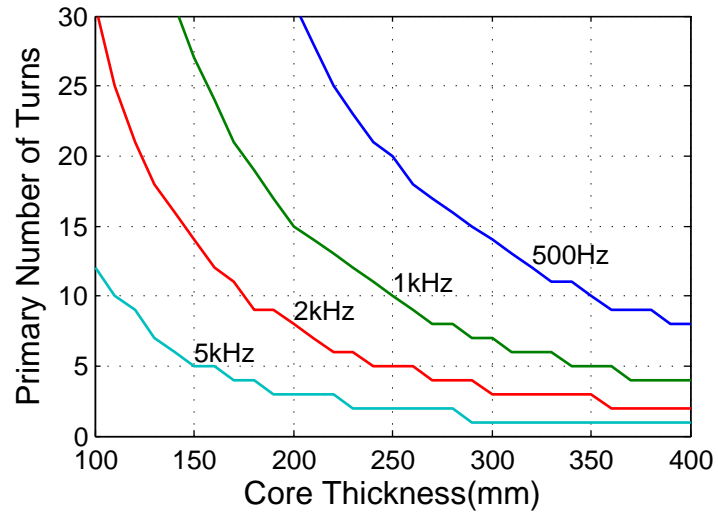
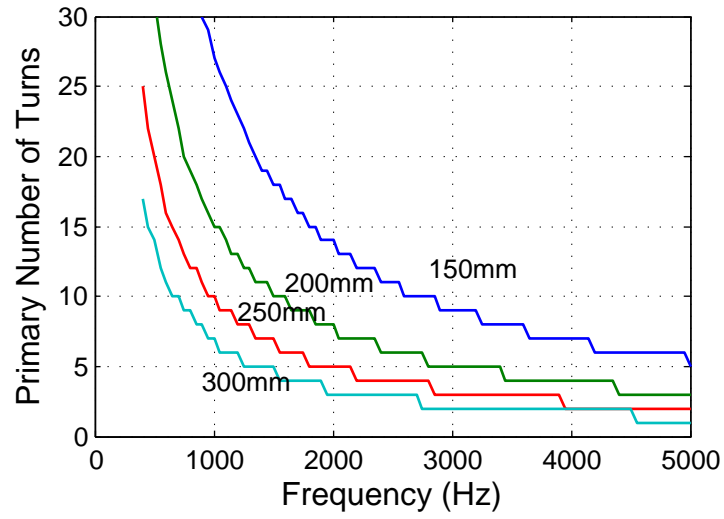


Figure 12: Tum grafikler

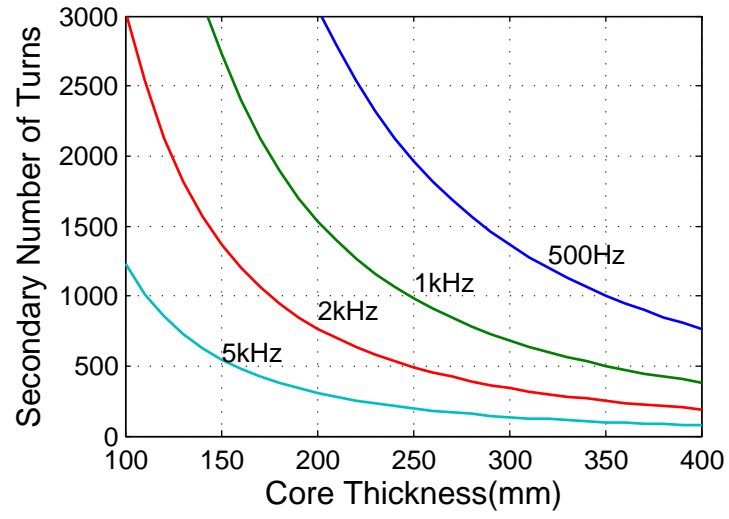
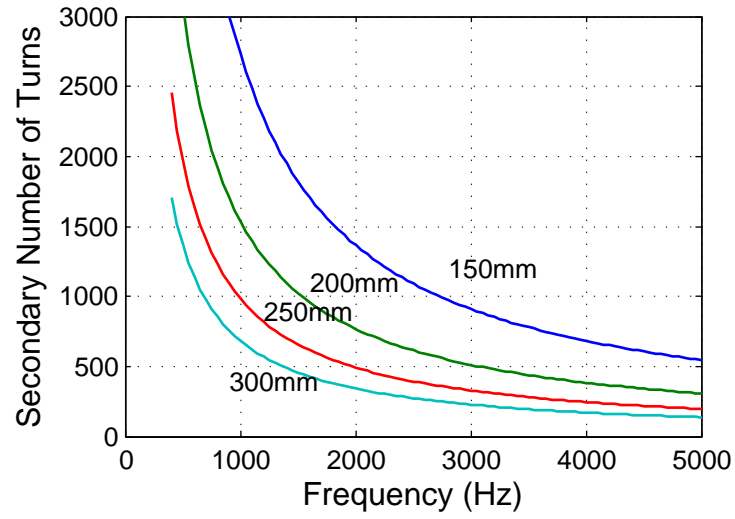


Figure 13: Tum grafikler



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