Constructional Design, Manufacturing and Evaluation of High Power Density Medium Frequency Transformer Prototypes

Master of Science Thesis

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Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014
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Manufactured High Power Medium Frequency Transformer Prototypes

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Abstract

- The aim of this project is to manufacture and test two 60 kW, 1.2/3.6 kV, 6 kHz 46/28
  µH prototype transformers.
- Based on the prepared high power medium frequency transformers’ design data, the
  constructional design of two prototype transformers is performed. During the
  constructional design, determination of the type, shape and volume of the suitable
  magnetic, thermally conductive and dielectric materials available in the market was
  done. The materials were bought and processed, and two prototype transformers were
  manufactured. The important technical data regarding the insulation characteristics of
  insulation materials was examined at nominal wave shape and frequency considered
  for the transformer application and the insulation coordination of the transformers was
  updated accordingly. At the same time, to prepare for the design validation tests,
  evaluation of the available high voltage, high current and medium frequency square
  wave shape supplies and the voltage and current measuring equipment was performed.
  The transformers were subjected to a set of design validation tests and the results were
  recorded, analysed and compared with the calculated values.
- Key Words: Solid state transformer, Medium frequency Power transformer, DC-DC
  converter, DC grid collection, Transformer testing and design validation

Index Terms:
HV, High Voltage
LV, Low Voltage
PT, Voltage measurement Transformer
CT, Current measurement Transformer
LCP, Liquid Crystalline Polymer
HPMF, High Power Medium Frequency
DAB, Dual Active Bridge
ZVS Zero Voltage Switching
PWM, Pulse Width Modulator
Acknowledgements

This work has been carried out at the SP Technical Research Institute of Sweden and the Department of Energy and Environment at Chalmers University of Technology. The financial support was given by SP Wise measurements for smart grids platform.

First, I express my sincere thanks to Amin Bahmani, Jan Johansson and Valter Tarasso without their help the initiation and realization of this project would be impossible. While conducting this project, I had the warm and unconditional support of Amin Bahmani, Torbjörn Thiringer and Johan Söderbom. I thank them wholeheartedly. I need also to thank all my colleagues in SP whose warm technical help was invaluable; among them, Henrik Petersen and Mikael Björnram stand out in my memory. Special thanks go to Vacuumschmelze and Lars Kvarnsjö for providing the Nanocrystalline cores for free and Energimyndigheten for sponsoring the rest of the materials needed in the thesis work.

Eventually, my heartfelt gratitude goes to my family for all their support and love.

Mohammad Kharezy
Gothenburg, Sweden, 2014
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1 Introduction

1.1 Background

Using high power density medium frequency transformers in DC/DC converters results in a considerable reduction in weight and volume of the transformer’s magnetic part and consequently on the cost of the converter [1].

DC/DC converters are used for DC collection, transportation and distribution systems which have a huge potential in the future wind farms. They give a potential for reduced technical complexity and accordingly reduced cost in the future distribution systems (see Figure 1-1).

Renewable energy production using offshore wind farms and integration of it into existing power grids is significantly increasing. The latter can, for locations far out in the sea, be made cheaper by avoiding using conventional low frequency AC collection systems [2].

However, in order to make this development possible, a key component is missing, the dc transformer (smart transformer). To be more specific it is not a “dc transformer”; it is a dc/dc converter with a high power medium frequency (HPMF) transformer as the key component, as it is demonstrated in Figure 1-2. The rated power of such components can be from a few kVA to 1 MVA [2].

It is a well-known fact that, increasing the operation frequency reduces the magnetic device volume, this is something already put into practice in the low-power applications due to the availability of fast and efficient semiconductor devices. Nowadays, this is also becoming a reality in high power applications [3-7].

![Figure 1-1: Potential application of SST in the future distribution systems [8].](image)

Despite the advantages and additional functionalities introduced by these new conversion systems, the main motivation for their application lays today in the possibility for volume, material and weight reductions in the restricted areas, such as ships, traction solutions and wind power. There is an obvious interest in developing such systems, clearly demonstrated by the effort made by several industrial companies, mainly related to the traction applications, which have proven the technical feasibility and advantages of the medium-frequency conversion systems. There are also similar initiatives in the wind power field, related to the offshore applications where spatial and weight restrictions are the driving factors [1].
1.2 Previous work

Many research activities devoted to overcome the challenges regarding design and manufacturing of the medium frequency high power transformers which is mostly because of additional losses in the core and windings and originates from a high switching frequency [1].

At sinusoidal excitation, the core losses can easily be calculated using the supplied core datasheets [9]. However, considering the nonlinear magnetic characteristics of the core materials and non-sinusoidal waveforms, it is a challenge to estimate the losses of a so called a DC-DC high power high frequency transformer. Determination of losses is vital for designing a proper transformer cooling system [2]. The main elements of the losses are the core losses and the winding losses.

At high frequencies, the losses in the copper conductors will drastically rise because of the skin effect in the conductors and the proximity effect to the adjacent conductors. Having access to a set of precise formulas, the calculation of winding losses can be performed with an acceptable accuracy [9]. References [10] and [11] propose formulas to accurately calculate the AC resistance of the conductors under high frequency switching conditions. The formulas can be used for the windings of any combination arrangements of the number of the layers and turns [11].

Because of complexity of the supplying voltage and current wave shapes, it is difficult to estimate the core losses of so called DC-DC high power high frequency transformer without actual measurements on the prototype samples. This is true, especially considering nonlinear magnetic characteristics of the core materials [1]. References [2] and [9] present an overview of the selection procedures of the shell type and the loss calculations for transformers that will be implemented for high frequency non-sinusoidal wave shape applications. A shell type transformer is the best selection in the case of this application [2, 9].

1.3 Purpose

According to the highlights presented in previous section, to overcome the complexity of the core loss evaluation of an HPMF transformer, it is vital to manufacture a prototype transformer to be used for conducting the proper measurements and evaluation of the methods and theories applied for the designing of the transformer.

The main purpose of this master thesis is to construct and evaluate two high power medium frequency prototype transformers and verify the design. The transformers are designed for the Division of electric power engineering for studies on the losses and behaviour of these kinds of transformers.

Having the prototypes and using the available supplying equipment and measuring instrument, a set of preliminary measurements will be done to verify the design methodology of the transformers.

1.4 Contribution

Among the others, the results of this work are presented in a paper titled “Design Methodology and Optimization of a Medium Frequency Transformer for High Power DC-DC Applications” which has been accepted for presentation at the “30th Annual IEEE Applied Power Electronics Conference (APEC) & Exposition” to be held in Charlotte, North Carolina in March, 2015.
The transformer design

2.1 Calculations of dimensions based on defined leakage inductance and required insulation withstand voltage

A dual active bridge (DAB) converter for high power applications can benefit from a transformer leakage inductance ($L_{\sigma}$) to transfer the power between the input and output bridges and this will result in higher power density (see Figure 2-1). By controlling the switching on the two sides, the square wave voltage from the primary and the secondary converters will be adjusted to have a defined phase shift relative to each other. Such a transformer serves as an inductance, in addition to its natural duty of voltage adoption between the primary and secondary bridges. In other words, the design of the transformer should fulfil the criteria of having a determined leakage inductance in addition to keeping the specified insulation, efficiency and the thermal requirements [12].

Figure 2-2: Expected voltage and current wave shapes and switching cycles of the transformer used in a DAB converter [1].

Figure 2-2 shows the voltage and current wave forms applied to the HPMF transformer in a DAB converter. It is notable that, unlike a conventional low frequency transformer, the wave shapes are not sinusoidal for this case.
The core loss is highly dependent to the duty cycle and the rise time of the wave shapes [9]. The lowest loss is achieved at the zero voltage switching (ZVS) which occurs at the minimum phase shift, $\varphi_{\text{min}}$ between the primary and secondary bridges. Therefore, in case of this type of transformer, the leakage inductance and its related phase shift is under consideration and the transformer leakage inductance, $L_{\sigma}$ corresponds to the value calculated from (2.1) [12].

$$L_{\sigma} = V_{\text{DC}1}V_{\text{DC}2}\varphi_{\text{min}}(\pi - \varphi_{\text{min}})/(2P_{\text{out}}\pi^2 f n)$$  \hspace{1cm} (2.1)

where

- $P_{\text{out}}$ is the output power of the DAB converter
- $V_{\text{DC}1}$ is the DC voltage of the LV side of the DAB converter
- $V_{\text{DC}2}$ is the DC voltage of the HV side of the DAB converter
- $n$ is the turns ratio of the transformer
- $f$ is switching frequency

An optimization flowchart is proposed which takes the rated power, the input and output voltages and their ratio, the frequency and the defined leakage inductance as input requirements and based on these, defines the fixed parameters like the core material, distances between the windings and between them and the ground in addition to the insulation materials properties. To optimize the design regarding the efficiency, size and the heat dissipation, a set of free parameters are chosen based on a set of iterative calculations. These include the core cross section, number of the turns per layer and number of layers, the thickness of rectangular wires and finally the maximum allowed current density [1]. The most important parameters to be decided about are the number of turns of the primary winding and the distance between the primary and the secondary windings [2]. Figure 2-3 demonstrates a typical 2D schematic of all the defined transformer dimensions.

![Figure 2-3](image-url)
The following formulas are used for calculation of the geometrical and isolation distances in the transformers [1].

\[ A_c = \frac{V_{\text{rms}1}}{(k_f k_c N_1 B_m f)} \]  
(2.2)

and

\[ A_c = 2 n_c A B \]

where

- \( A_c \) is the cross section area of the core
- \( n_c \) is the number of stacks of the core (Each stack includes 4 pieces of the U shaped core pieces.)
- \( A \) is the length of the frontal side of the core
- \( B \) is the length of the lateral side of the core
- \( V_{\text{rms}1} \) is the RMS of the primary voltage
- \( N_1 \) is the number of turns of the primary winding
- \( B_m \) is 80% of the saturation level of the selected magnetic core (0.52T for Ferrite & 1.2T for Nano)
- \( k_c \) is the filing factor of the core (the ratio of effective cross section of the core to its physical cross section: 1 for Ferrite cores and 0.75 for Nano cores)

\[ k_f = 2 \sqrt{2D - \frac{8R}{3}}/(D - R) \]  
(2.3)

where

- \( D \) is the duty cycle (0.5 for phase shift modulation in the DAB converter)
- \( R \) is the relative rise time of the rectangular waveform (0 for phase shift modulation in the DAB converter)

\[ d_{cf} = \frac{V_{\text{DC}1}}{(k_{saf} E_{\text{ins}})} \]  
(2.4)

where

- \( d_{cf} \) is the clearance of the inner winding to the core
- \( K_{saf} \) is the safety factor (30%)
- \( E_{\text{ins}} \) is the dielectric strength of the isolating material (29 kV/mm for CoolPoly-D5108)

\[ d_{c1,2} = \frac{V_{\text{DC}2}}{(k_{saf} E_{\text{ins}})} \]  
(2.5)

where

\[ d_{c1,2} \] is the horizontal or vertical clearance of the outer winding to the core

\[ d_{\text{iso-min}} = \frac{V_{\text{iso}}}{(k_{saf} E_{\text{ins}})} \]  
(2.6)

where

- \( d_{\text{iso-min}} \) is the minimum allowed isolation distance between the windings (which should also fulfill the requirement regarding the desired leakage inductance)
- \( V_{\text{iso}} \) is the isolation level between primary and secondary bridges (60 kV)

\[ J_{\text{max}} = \frac{I_{T1}/[(h_{b1} - 2d_{\text{ins1}}) d_{f1}]} \]  
(2.7)

where

- \( J_{\text{max}} \) is the maximum allowable RMS value of the current density in the conductor
- \( I_{T1} \) is the LV side current
- \( h_{b1} \) is the height of the insulated LV wire
- \( d_{\text{ins1}} \) is the insulation thickness of the LV winding
- \( d_{f1} \) is the width (thickness) of the wire conductor

\[ J_{\text{max}} = \frac{I_{T1}/[n(h_{b2} - 2d_{\text{ins2}}) d_{f2}]} \]  
(2.8)

where

- \( J_{\text{max}} \) is the maximum allowable RMS value of the current density in the conductor
- \( I_{T2} \) is the HV side current
- \( h_{b2} \) is the height of the insulated HV wire
- \( d_{\text{ins2}} \) is the insulation thickness of the HV winding
- \( d_{f2} \) is the width (thickness) of the HV wire conductor
\[ I_{T1}(\text{rms}) = \left[ \frac{n_{\text{PC1}} + V_{\text{PC2}}}{n_{\text{PC2}}} \right] \sqrt{(4t_1^2t_\phi + T_s t_1^2 + 4t_1^2t_1 - T_s t_1 t_\phi + T_s t_\phi^2)/(3T_s)} \]  

(2.9)

where \( T_s, t_1 \) and \( t_\phi \) are demonstrated in Figure 2-2.

\( I_{T1} \) is the LV side current and has an inverse relation with the targeted leakage inductance. It is also a function of phase shift. (At \( \phi_{\text{min}} \), there is a zero voltage switching in the DAB converter.)

\[ h_w = (N_{t1} + 1)h_{b1} + N_{t1}d_{t1} \]  

(2.10)

where \( h_w \) is the winding height

\( N_{t1} \) is number of turns per layer of LV winding

\( d_{t1} \) is vertical distance between the wires

\[ W_1 = m_1(d_{f1} + 2d_{\text{inst}})(m_1 - 1)d_{\text{inst}} \]  

(2.11)

where

\( W_1 \) is the total thickness of the LV winding

\( m_1 \) is the number of layers of the LV winding

\[ H = h_w + 2d_{ct1} \]  

(2.12)

where

\( H \) is the core window height

\( N_{t2} \) and \( W_2 \) can be calculated similarly. The core window width, \( G \) and maximum dimension of the transformer are calculated having the \( d_{\text{iso}} \) which is the permitted isolation distance between the windings which also fulfills the requirement regarding the desired leakage inductance. The calculation of \( d_{\text{iso}} \) is presented in details in Reference [1].

2.2 The designed transformer

In this project the following information is used as the input for designing two 60 kW, 1.2/3.6 kV, 6 kHz 46/28 \( \mu \)H prototype transformers.

According to explained method, considering Coolpoly–D5108 as main insulation material and Ferrite and Nanocrystalline as the core materials, the dimensional parameters displayed in Figure 2-3 were calculated during the design process. The calculated results used for starting the manufacturing process are presented in the Table 2-1 [1].

| Table 2-1: Optimized parameters for the prototype transformers [1]. |
|-------------------|-------------------|-------------------|-------------------|
| **Parameters/Dimensions** | **Values** | **Parameters/Dimensions** | **Values** |
| \( n_{t1} \) | 5 | \( n_{t2} \) | 2 |
| \( A \) | 28 mm | \( A \) | 38 mm |
| \( B \) | 10.3 mm > 30 mm | \( B \) | 27.4 mm > 31 mm |
| \( G \) | 25.9 mm > 34 mm | \( G \) | 31 mm > 40 mm |
| \( h_{w1} \) | 85.5 mm | \( h_w \) | 117.6 mm |
| \( H \) | 87.5 mm > 56 mm | \( H \) | 115.6 mm > 120 mm |
| \( d_{w1} \) | 9.2 mm | \( d_{w2} \) | 19.2 mm |
| \( N_{l1}/N_{l2} \) | 21 / 63 | \( N_{l1}/N_{l2} \) | 20 / 10 |
| \( n_{l1}/N_{l1} \) | 540 / 150 | \( n_{l1}/n_{l2} \) | 540 / 150 |
| \( m_1 \times N_{t1} \) | 3 \( \times \) 7 | \( m_1 \times N_{t2} \) | 3 \( \times \) 10 |
| \( m_1 \times N_{t2} \) | 2 \( \times \) 22 \( \times \) 1 \( \times \) 19 | \( m_1 \times N_{t1} \) | 2 \( \times \) 30 |
| \( d_{w1}/h_{w1} \) | 2.4 mm > 16.6 mm | \( d_{w1}/h_{w1} \) | 3.5 mm > 10.6 mm |
| \( d_{w2}/h_{w2} \) | 2.9 mm > 3.6 mm | \( d_{w2}/h_{w2} \) | 2.6 mm > 6.6 mm |
| \( d_{s1}, d_{s2} \) | 3 mm, 3 mm | \( d_{s1}, d_{s2} \) | 1 mm, 1 mm |
| \( d_{f1} \) | 1 mm | \( d_{f2} \) | 1 mm |
| \( d_{s1}, d_{s2} \) | 1 mm, 1 mm | \( d_{s1}, d_{s2} \) | 1 mm, 1 mm |
| \( M_{l1} \) | 48 mm | \( M_{l1} \) | 284 mm |
| \( M_{l2} \) | 615 mm | \( M_{l2} \) | 486 mm |
| \( d_{s1}, d_{s2} \) | 0.1 mm, 0.1 mm | \( d_{s1}, d_{s2} \) | 0.1 mm, 0.1 mm |

Interlayer distances min 0.1 mm, max 0.4 mm | Interlayer distances min 0.1 mm, max 0.4 mm |
In the Table 2-1:
nc is the number of stacks of the core
A is the length of the frontal side of the core
B is the length of the lateral side of the core
G is the width of the core window
ha is the height of the winding
H is the height of the core window
diso is the isolation distance between two windings
N_{1,2} is number of the turns
ns_{1,2} is number of the strands
m_{1,2} is number of the winding layers
N_{tl,2} is number of the turns per layer
d_{wl,2} is the width of the litz wire
h_{wl,2} is the height of the insulated litz wire
d_{c1,2} is the distance between the cores
d_{cfr} is the clearance of the inner winding to the core
d_{col,2} is the clearance of the outer winding to the core
MLT_{1,2} is the mean length of the winding turns
D_{ins1,2} is the horizontal distance between the wires
Based on the above mentioned dimension data of two transformers, the calculation of the resistance of the winding and magnetising inductance of the cores are performed and presented here. Later in the Table 5-1, the calculated results are compared with the measured results.

2.3 Calculation of resistance of the windings
The winding resistance is calculated from the formula

\[ R = \frac{\rho}{A} = \rho \frac{MLT \times N}{\pi r^2 n_s} \]  

(2.13)

where
R is the resistance of the winding
\( \rho \) is the resistivity of the copper wire
MLT is the mean length of the winding turns
N is the number of the turns of the measurement side
r is the radius of the each wire strand
n_s is the number of the strands

The calculated magnetising inductances for both transformers are presented in Table 2-2 and these are compared with the measured results in Table 5-1.

<table>
<thead>
<tr>
<th></th>
<th>Ferrite</th>
<th>Nano</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HV</td>
<td>LV</td>
</tr>
<tr>
<td></td>
<td>HV</td>
<td>LV</td>
</tr>
<tr>
<td>( \rho ) (\Omega/\text{m})</td>
<td>1.68\times10^{-8}</td>
<td>1.68\times10^{-8}</td>
</tr>
<tr>
<td>( MLT ) (m)</td>
<td>0.615</td>
<td>0.475</td>
</tr>
<tr>
<td>N</td>
<td>54</td>
<td>18</td>
</tr>
<tr>
<td>r (m)</td>
<td>0.1\times10^{-3}</td>
<td>0.1\times10^{-3}</td>
</tr>
<tr>
<td>n_s</td>
<td>181</td>
<td>543</td>
</tr>
<tr>
<td>( R ) (\text{m}\Omega)</td>
<td><strong>98.1</strong></td>
<td><strong>8.4</strong></td>
</tr>
</tbody>
</table>
2.4 Calculation of magnetisation inductance

For the calculation of the magnetising inductances, the initial permeability should be extracted from the cores technical data sheets. Table 2-3 and Table 2-4 present the initial permeability values given by the producers of Ferrite and Nanocrystalline cores respectively.

\[ L_m = \frac{\mu_0 A_c N^2}{\left( \frac{c}{\mu_i} + l_g \right)} \]

where
- \( L_m \) is the magnetising inductance of the transformer
- \( l_c = 2H + 2G + 4A \) is the length of the core
- \( l_g \) is the inevitable air gap length
- \( A_c = 2n_c A.B \) is the cross section area of the core
- \( \mu_0 = 4\pi \times 10^{-7} \) is the absolute permeability
- \( \mu_i \) is the initial permeability of the core
- \( N = N_1 \) is the number of the turns of measurement side
- \( n_c \) is the number of the core stacks

Table 2-3: The technical data of the used Ferrite core material [13].

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred application</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td>N87</td>
</tr>
<tr>
<td>Base material</td>
<td></td>
<td>MnZn</td>
</tr>
<tr>
<td>Initial permeability (T = 25 °C)</td>
<td>( \mu_i )</td>
<td>2200</td>
</tr>
<tr>
<td>Flux density (H = 1200 A/m, f = 10 kHz)</td>
<td>( B_s (25 , ^\circ\text{C}) )</td>
<td>mT</td>
</tr>
<tr>
<td></td>
<td>( B_g (100 , ^\circ\text{C}) )</td>
<td>mT</td>
</tr>
<tr>
<td>Coercive field strength (f = 10 kHz)</td>
<td>( H_c (25 , ^\circ\text{C}) )</td>
<td>A/m</td>
</tr>
<tr>
<td></td>
<td>( H_g (100 , ^\circ\text{C}) )</td>
<td>A/m</td>
</tr>
<tr>
<td>Optimum frequency range</td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>Hysteresis material constant</td>
<td>( \eta_b )</td>
<td>10^{-6}mT</td>
</tr>
<tr>
<td>Curie temperature</td>
<td>( T_c )</td>
<td>°C</td>
</tr>
<tr>
<td>Mean value of ( \sigma_p ) at 25 ... 55 °C</td>
<td></td>
<td>10^{-6}K</td>
</tr>
<tr>
<td>Density (typical values)</td>
<td></td>
<td>kg/m³</td>
</tr>
<tr>
<td>Relative core losses (typical values)</td>
<td>( P_V )</td>
<td>kW/m³</td>
</tr>
<tr>
<td>25 kHz, 200 mT, 100 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 kHz, 200 mT, 100 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 kHz, 100 mT, 100 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 kHz, 50 mT, 100 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>( \rho )</td>
<td>Ωm</td>
</tr>
<tr>
<td>Core shapes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RM, P, PM, ETD, EFD, E,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER, EP, EQ, ELP, U, Toroid</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2-4: The technical data of Nanocrystalline Vitroperm 500 core material [14].

<table>
<thead>
<tr>
<th>Property</th>
<th>Nanocrystalline cores</th>
<th>Permalloy cores</th>
<th>Si-steel cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation induction (T)</td>
<td>1.25</td>
<td>0.76</td>
<td>2.03</td>
</tr>
<tr>
<td>Initial permeability (at 0.8 mA/cm)</td>
<td>40,000 to 80,000</td>
<td>&gt; 50,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Maximum permeability</td>
<td>&gt; 250,000</td>
<td>&gt; 200,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>7.2</td>
<td>8.85</td>
<td>7.65</td>
</tr>
<tr>
<td>Curie temperature (°C)</td>
<td>570</td>
<td>400</td>
<td>740</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.025 ± 0.035</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Stacking factor</td>
<td>≥ 0.75</td>
<td>0.9</td>
<td>0.95</td>
</tr>
</tbody>
</table>
The calculated values of magnetising inductances for both transformers are presented in Table 2-5 and are compared with the measured results in Table 5-1.

**Table 2-5: The calculated magnetising inductances for the transformers.**

<table>
<thead>
<tr>
<th></th>
<th>Ferrite</th>
<th>Nano</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_i$</td>
<td>2200±25%</td>
<td>40000</td>
</tr>
<tr>
<td>$n_e$</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>$A$ (mm)</td>
<td>28</td>
<td>36</td>
</tr>
<tr>
<td>$B$ (mm)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$H$ (mm)</td>
<td>92</td>
<td>120</td>
</tr>
<tr>
<td>$G$ (mm)</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td>$N_f$</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>$l_e$ (mm) (assumption)</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>$L_m$ (mH)</td>
<td><strong>6.0</strong></td>
<td><strong>12.5</strong></td>
</tr>
</tbody>
</table>

Figure 2-4 shows a schematic 3D picture of the transformer that is expected to be manufactured during this project [1].

![Figure 2-4: A schematic of the designed transformer to be manufactured during the project [1].](image)
3 Ferrite transformer

Title photo: The Ferrite transformer without heatsinks.

3.1 Dimensioning the transformer

After having the preliminary design parameters as demonstrated in Chapter 2, the following parameters were considered to finalize the design dimensions of the prototype:

- the dimension of the core based on what is available in the market
- the dimension of the litz copper conductors based on what is available in the market
- The insulation characteristics of the material considered for production of the bobbins, insulation of winding layers and outer insulation of the conductors

3.1.1 Core material and dimension

The transformer under consideration consists of four U cores combined in a way that configure a three column core, in which the middle leg is wound (see Figure 3-1) [2].

Figure 3-1: One Ferrite core stack (left) compared with one Nanocrystalline core stack (right).
For selection of the magnetic material to be used for the medium frequency high power transformer, four parameters shall be considered among the others: lower loss, higher saturation flux density, higher relative permeability and higher operation temperature. Higher power and loss density ask for higher endurance of the core material to the elevated temperature rating. Amorphous material has a higher saturation flux density but the losses in a transformer of the same rating with the Nanocrystalline core is much lower. Amorphous and Nanocrystalline are among the low loss and high saturation level ferromagnetic materials. Nanocrystalline and Ferrite are favoured to be used for manufacturing a medium frequency high power transformer. Ferrite has lower saturation level and this, results in a larger core cross section compared to a Nanocrystalline core used in a transformer with similar electrical ratings [9].

Table 3-1 presents the magnetic characteristics of three different magnetic materials [1].

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Manufacturer brand</th>
<th>$B_{sat}$ (T)</th>
<th>Specific losses (kW/kg) at 0.1T &amp; 100kHz</th>
<th>Operating Temperature ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon Steel</td>
<td>10JNHF600</td>
<td>JFE</td>
<td>1.87</td>
<td>0.24</td>
<td>150</td>
</tr>
<tr>
<td>Ferrite</td>
<td>3C93</td>
<td>Ferroxcube</td>
<td>0.52</td>
<td>0.009</td>
<td>140</td>
</tr>
<tr>
<td>NanoCrys.</td>
<td>Vitroperm500F</td>
<td>VAC</td>
<td>1.2</td>
<td>0.01</td>
<td>120</td>
</tr>
</tbody>
</table>

Although Vitroperm 500F is the best available Nanocrystalline core material that has been used for production of similar transformers during previous research activities [1], a medium frequency Ferrite core material was used for the production of the first prototype. The advantages of using the Ferrite cores includes the lower price, better accessibility of the material in the market and possibility of studying pros and cons of using Ferrite in comparison with a Nanocrystalline core material. The selected core with the highest dimension available is [15]:

- U core N87, B67345B1X87
- Core combination U-U: Material = N87; AL value =5700 nH; $\mu_e =1900$
- Manufacturer: EPCOS

According to the transformer design, the parameter $n_c$ introduces the number of stacks of the core. Each stack includes 4 pieces of the U shaped core pieces, with a UU configuration according to Figure 3-1. In the case of the Ferrite core, the window size will be 34.6×96 mm$^2$ and this is in agreement with the design parameters of a core window height $H$ (87.5-96 mm) and width $G$ (25.9-34 mm).

Some accessible suppliers in Sweden for this material are introduced in Appendix A.
3.1.2 Conductors type and dimensions

Because of the high skin effect at high frequencies it is not economical to use normal wires to produce the windings. Copper foils are suitable alternatives for higher frequencies but they need a great care during the production and termination. With the introduction of litz wires (bunch of individually insulated conductors), higher flexibility in the production and lower losses can be gained.

A high-frequency litz wire consists of a group of enamelled strands (see Figure 3-3). The enamel insulation of the conductor is modified polyurethane. At higher frequencies, increasing the number of strands together with the reduction of the strand’s diameters, counteract the increase in conductor impedance. The alternating current causes eddy currents in the conductor which acts against the flow of current. At higher frequencies, the effect of these eddy currents increases and an AC resistance which is dependent on frequency is added to the DC resistance. The eddy current loss in the middle of the conductor is at its minimum value and increases moving toward the out of the conductor. This causes that the current to flow more close to the surface of the conductors instead of in the centre of it (the skin effect). The skin depth is a representation of the thickness of the conductor which is carrying the current. Because of the proximity effect, the fields of the adjacent conductors increase the eddy losses. The cross-sectional area of the single conductor is reduced to minimize these losses. Several conductors in parallel are used to carry the nominal current of the whole wire. To compensate the effects of the fields on the individual strands, the conductors are twisted together so that, throughout the length of the wire, the position of one conductor changes regularly between the centre and the outside of the bunch. Because of the high capacitance effect of the conductor, litz wires can be used only up to 2 MHz. A typical diameter of each conductor as a function of frequency is 0.4 mm for 50 Hz – 1 kHz, 0.25 mm for 1 kHz – 10 kHz or 0.032 mm for 1.5 MHz – 2.8 MHz [16].

With an effective reduction of skin effect, litz wires have the best performance in high frequency circuits. Commercial production of several types and dimensions of the wire gives a good flexibility for getting the highest benefit in this project. Having a rectangular cross section, the rectangular litz wire is estimated to be one of the best candidates as the high and low voltage conductors of his project. The rectangular cross section helps for higher density and more mechanical strength of the winding. The available constructions from one of the leading litz wires manufacturers are presented in pages 127-165 of the Reference [16].

The wires considered for the prototype were:
- **LV**: 541 strands of 0.2 mm conductors, 7.0×4.0 mm² as total dimension
- **HV**: 181 strands of 0.2 mm conductors, 3.8×2.5 mm² as total dimension

The 541 strands wire was not delivered and instead, a combination of three parallel 181 strands wire was used. According to the design, more than 60-80 meters of LV type (541 strands) and 120-130 meters of HV type (181 strands) were needed.

Some litz wire suppliers accessible in Sweden are introduced in Appendix A.

Table 3-2 was prepared and used to compare the price and the minimum delivery volume of the litz wires from the different manufacturers.
Table 3-2: Comparison table for selection of the best supplier of the litz wires.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type designation</th>
<th>strand diameter (mm)</th>
<th>Fill factor of strands</th>
<th>Length</th>
<th>Price</th>
<th>price</th>
<th>Min. DELIVERY</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dahrentråd</td>
<td>Round copper wire</td>
<td>0.2</td>
<td></td>
<td>2012-2251</td>
<td>3247</td>
<td>500</td>
<td>0.153988</td>
<td>100 g 500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>119 strands</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27.28571</td>
<td>59500 2180.628</td>
</tr>
<tr>
<td>NewE.</td>
<td></td>
<td>(17×7/36)</td>
<td>(3.9×0.81mm²)</td>
<td>0.127</td>
<td>3767.014878</td>
<td>66.22517</td>
<td>5761.649</td>
<td>87.0009</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(17×7/33)</td>
<td>(5.5×1.1mm²)</td>
<td>0.18</td>
<td>1966.942149</td>
<td>33.0033</td>
<td>2422.334</td>
<td>73.39672 305 m 22386</td>
</tr>
<tr>
<td>Vonroll</td>
<td></td>
<td>(541/-)</td>
<td>(7.0×4.0mm²)</td>
<td>0.2</td>
<td>1932.142857</td>
<td></td>
<td></td>
<td>100 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(181/-)</td>
<td>(3.8×2.5mm²)</td>
<td>0.2</td>
<td>1905.263158</td>
<td></td>
<td></td>
<td>50 kg</td>
</tr>
</tbody>
</table>

The wire that was possible to purchase was a 3.80×2.50 mm² rectangular copper HF-litz wire, having 180 strands of 0.2 mm with the product name of Polysol 155 with the properties presented in Table 3-3 from Elektrisola Germany.

Table 3-3: The supplied litz wire properties [18].

<table>
<thead>
<tr>
<th>Property</th>
<th>Polysol155</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown voltage (at 20 °C, 35% humidity)</td>
<td>180 V/µm</td>
</tr>
<tr>
<td>Solder-ability for grade 1 wires</td>
<td>0.7s / 370 °C &amp; 0.5s / 390 °C</td>
</tr>
</tbody>
</table>

According to the technical data the wires have the breakdown voltage of 180 V/µm and based on the information received from the producer, having a wall thickness of 73 µm, the wires can withstand 2.5-3 kV to ground which means the breakdown voltage of maximum 6 kV between the wires (or turns in the case of a winding). However as it is explained in section 5.6, the breakdown voltage is much lower at the practical 6 kHz tests.

3.2 Other elements of the prototype

After determining the material and dimensions of the core and winding materials, the decision was made regarding insulation and cooling material, the parts used for fixing the coils and those for clamping the cores and also regarding holding the whole structure. Considerations for leading out and termination of the high voltage conductors were also made.

3.2.1 Insulation and cooling material

In a normal oil type power transformer, the oil has two main roles:
- to increase insulation level between the energized electrodes (and accordingly reduce the size of transformer) and
- to assist in the removal of produced heat from the heated up elements.

In this project, the transformer is a dry type transformer. For normal dry type power transformers a special mixture hardened with epoxy resin is used as insulation material which has enough thermal conduction to conduct the produced heat inside the windings to the cooling air. The other parameters to be considered are:
- the volumetric mass density of the material which helps with the reduction of the total weight of the transformer and
- the mechanical properties of the material at the transformer normal operation temperature which serves as a fixture for the core and coil assembly.

According to the explanations given under chapter 2, to fulfil the electromagnetic and electrical criteria, the windings should have a defined distance from each other and this distance should withstand the defined high voltage level. On the other hand, the insulation material should help for
conducting out the produced heat inside the windings out to the heat sinks on the outer surfaces of the transformer. A HPMF transformer having lower volume and higher loss density needs much higher thermal conductivity compared with a normal low frequency transformer [2]. These requirements call for a material with high insulation and high thermal conductivity. Searching the available materials in the market led to acquaintance with a new type of polymer, Coolpoly-D5506. The material has 10 W/mK as thermal conductivity and 46 kV/mm as insulation withstand voltage.

The purchasable main insulation and cooling material for this project was Coolpoly-D5108, a thermally conductive liquid crystalline polymer (see Figure 3-4) [19].

![Figure 3-4: The CoolPoly thermally conductive electrically isolative polymer granules (a) and produced sheets (b).](image)

Several parameters led to selection of this material for this purpose:
- Very high thermal conductivity (10 W/mK)
- Very high insulation withstand voltage (29 kV/mm)
- Very high temperature of deflection suitable for manufacturing the bobbins (>240 °C)

The CoolPoly-D5108 supplier is introduced in Appendix A.

A set of insulating adhesive materials were selected to be used in the proper applications as will be described later in the report (see Figure 3-5).

![Figure 3-5: The 3M tape (a), Electrolube paste (b), 3M epoxy (c).](image)
The tape (Figure 3-5a) considered as insulation between layers and as insulation between the winding and the grounded electrodes were selected as follows [20]:

- Tape 3M 8943
- Thermally conductive, 200MMX10M
- Thermal conductivity, 0.9 W/mK
- External length, 10 m
- External width, 200 mm
- Thickness, 0.2 mm
- Breakdown voltage, 55 kV/mm or 11 kV/0.2mm

During the insulation tests which have been performed and presented later in this report, the actual breakdown voltage was proved to be much less than the mentioned level where the frequency was 6 kHz and the test setup was similar to the transformer under consideration in this project.

An accessible supplier of the insulating tape in Sweden is introduced in Appendix A.

The paste material (Figure 3-5b) considered for filling the possible air packets between the windings or the core and the polymer heat sink was [21]:

- Thermal Paste HTSP50T
- Thermal conductivity, 2.5 W/mK
- Dielectric strength, 18 kV/mm
- Resistivity, 1015 Ω/cm
- Density, 2.10 g/cm³@ 20 °C
- Silicon oil, metal oxide powder based
- Operating temperature, -50...+200 °C

To facilitate the possibility of potential improvements or repairs on the transformers, application of this paste was postponed up to the time when the heat run test is going to be performed on the transformer.

An accessible supplier of the thermally conductive paste in Sweden is introduced in Appendix A.

The glue (Figure 3-5c) considered to keep the bobbins’ parts strongly together was [22]:

- Epoxy adhesive DP760
- Non-sag, two-part room temperature curing adhesive
- High temperature resistance
- Work life (minutes), 45-60
- Time to handling strength (minutes), 360-480
- Full cure (days), 7

The epoxy adhesive DP760 supplier accessible in Sweden is introduced in Appendix A.

Two heat sink plates were installed on two upper and lower pressing aluminium plates (see Figure 3-6).

![Figure 3-6: Heat sinks to be installed on the aluminium pressing plates [23].](image-url)
For the Ferrite transformer the suitable width was 200 mm and best selection was the one which helped for more mechanical strength along the longer direction of the pressing plate.

Although the width of the Nano transformer pressing bars were 142 mm, the same concept was applied and the bought heat sink for the Ferrite transformer was used for this transformer too.

The selected heat sink was the model, KS200, width: 200 mm, height: 25 mm and length: 1000 mm.

Two distributors are:
- Elfa (Model: KS200, width: 200 mm, Height: 25mm, Length: 1000 mm [23])
- RS components AB (Model: WA 217.0B, Width: 200 mm, Height: 25 mm, Length: 1000 mm [24])

To investigate more about the existing models, the following catalogues have useful information:
- Online catalogue Fischerelektronik [25]
- Online catalogue Austerlitz-electronic [26]

Some heat sinks suppliers accessible in Sweden are introduced in Appendix A.

To insulate the outgoing wires from adjacent grounded conducting surfaces a set of heat shrink tubing was used (see Figure 3-7).

![Figure 3-7: A heat shrink tube dimensions to be considered during a selection process [27].](image)

Three parameters were considered to select them among the others:
- High withstand voltage (here >30 kV/mm),
- High temperature withstand stability (here >175 °C),
- Proper dimension before and after shrinkage.

For LV side the following material was selected [27]:
- A, 12.7 mm
- B, 6.4 mm
- C, 0.3 mm
- Material, polyvinylidene fluoride (PVDF)
- Dielectric strength, ≥ 30 kV/mm
- Temperature range, -55 to +175 °C

For HV side the following material was selected [28]:
- A, 4.8 mm
- B, 2.4 mm
- C, 0.25 mm
- Material, polyvinylidene fluoride (PVDF)
- Dielectric strength, ≥ 30 kV/mm
- Temperature range, -55 to +175 °C

A heat shrink tubing supplier is introduced in Appendix A.
3.3 Production of the parts and the assembly

3.3.1 Moulding the polymer, producing the sheets, and manufacturing the coil bobbins

Safety cares were taken because of the strict safety precautions given in the MSDS-D5108 data sheet [29] and according to the information sticker on the 5 kg package received.

The required data for moulding was extracted from the product’s processing guideline. The rear, centre and front zone temperatures in the moulding machine should be approximately 285, 310 and 320 °C consequently. The temperature of melt polymer is in the range of 310-330 °C and the mould should have a temperature of 135-180 °C.

For the produced sheet, the temperature of deflection is 276 °C at 0.45 MPa which means that the material is very hard at a low environment temperature. The tensile modulus is 23600 MPa which means that the material is very hard in its nature and the nominal strain at breaking point is 0.16 % which means that there is nearly a zero elongation possibility for the material.

A 280×210 mm² frame of 2 mm thick metal sheet was produced (see Figure 3-8b). This frame was used to keep the mould in itself under pressure and to form the polymer sheets.

The density of the material is 1.82 g/cc according to the data sheet, so to produce sheets for building bobbins for the two LV and HV windings having 2 mm of thickness and 280×210 mm², the amount of material needed to be moulded is approximately 250 g (see Figure 3-8c).

To produce a 2 mm sheet, the granules are preheated for 5 minutes placed at 20mm distance between the upper and lower pressing jaws, after having 300 °C for the upper pressing jaw and 290 °C for the lower one. Then the pressing process was performed at 200 kN for 3 minutes (see Figure 3-8d).
The whole process took 2-3 hours for each sheet considering the time required for heating up and cooling down the machine. If the granules are kept out of the sealed package for a long time, the material should be dried out at 120 °C for 4-6 hours in the heating chamber before starting the moulding process (see Figure 3-8a). According to the technical data, the injection moulding temperature is 310-330 °C which means that the selected 300 °C is suitable for a compression moulding process.

Using the prepared drawings presented in Appendix D, the produced sheets were then cut by a water jet cutting machine to have precise dimensions and 90 degrees edges. The cut parts are glued together using the high temperature epoxy glue (see Figure 3-9).

![Figure 3-9: The glued polymer sheets.](image)

### 3.3.2 Winding the coils

As a rule of thumb, the length of the wire spent for each corner is equal to its thickness in the direction of the bending (here 4 mm). Therefore, having a bobbin of 165×70 mm² and bending thickness of approximately 4 mm and 4 bending edges, each conductor will have the length of 9324 mm.

For the LV winding, three 3.8×2.50 mm² litz conductors were placed on top of each other to form a 11.4×2.50 mm² conductor (see Figure 3-10a). The LV winding was coiled as 3 layers of 6 turns of conductors to have a total number of 18 turns. Based on the explained results of insulation coordination tests, one 0.2 mm layer of the thermally conductive tape was placed between every two winding layers.

![Figure 3-10: Windings on the bobbins.](image)

The HV winding was coiled as 3 layers of 18 turns of 3.8×2.50 mm² litz conductor, having the total 54 number of turns. Based on the explained results of insulation coordination tests, presented in Section 5.6, two 0.2 mm layers of thermally conductive tape were placed between every two winding layers. The completed windings are demonstrated in Figure 3-10b.
3.3.3 Pressing the core and coils assembly using the aluminium plates
The mechanical design of the transformer was performed targeting the usage of a minimum number of mechanical fixing parts. No additional material is used for keeping the distances and the coil and core assembly were fixed using only four nuts.

Two aluminium plates were designed according to the drawing presented in Appendix D and produced by a CNC cutting machine at SP’s work shop. The plates, each 12 mm thick, were screwed together at the points 192 mm apart from each other (see Figure 3-11). This caused to experience bendings in the longitudinal direction of the two pressing rectangular plates. To improve and strengthen the pressing uniformity on the all core stacks, the direction of the heat sinks blades was considered to be in a direction which helps the pressing plates to have a better strength in the longitudinal direction. In this way the construction was improved after fixing the heat sinks to the plates.

3.3.4 Soldering the conductors and terminating the windings
Because of having a film insulated multi strand wire, care must be taken to remove the required amount of insulation of all the individual strands before applying a tin soldering process to the wire.

Figure 3-12 shows the setup used for this purpose and the result of the soldering work. More details regarding the soldering of litz wires can be found in Reference [29].

Figure 3-11: Pressing plates of the core and coil assembly.

Figure 3-12: Soldering the litz wires.
3.4 Extraction of the actual parameters for the transformer

During the construction of the transformer and having access to the real data from purchased materials and manufactured components and typical dimensions, the design parameter values were finalised. The final updated data is presented in Table 3-4.

*Table 3-4*: The mechanical design values updated with the construction of the Ferrite transformer [1].

<table>
<thead>
<tr>
<th>Parameters/Dimensions</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_c$</td>
<td>5</td>
</tr>
<tr>
<td>A</td>
<td>28 mm</td>
</tr>
<tr>
<td>B</td>
<td>30 mm</td>
</tr>
<tr>
<td>G</td>
<td>34 mm</td>
</tr>
<tr>
<td>$h_w$</td>
<td>88 mm</td>
</tr>
<tr>
<td>$H$</td>
<td>92 mm</td>
</tr>
<tr>
<td>$d_{iso}$</td>
<td>9.6 mm</td>
</tr>
<tr>
<td>N1/N2</td>
<td>18 / 54</td>
</tr>
<tr>
<td>$n_{s1} / n_{s2}$</td>
<td>540 / 180</td>
</tr>
<tr>
<td>$m_1 \times N_{il}$</td>
<td>3 × 6</td>
</tr>
<tr>
<td>$m_2 \times N_{i2}$</td>
<td>3 × 18</td>
</tr>
<tr>
<td>$d_{b1} \times h_{b1}$</td>
<td>$2.5 \text{ mm} \times 11.4 \text{ mm}$</td>
</tr>
<tr>
<td>$d_{b2} \times h_{b2}$</td>
<td>$2.5 \text{ mm} \times 3.8 \text{ mm}$</td>
</tr>
<tr>
<td>$d_{c1}$, $d_{c2}$</td>
<td>2 mm, 2 mm</td>
</tr>
<tr>
<td>$d_{cf}$</td>
<td>2 mm</td>
</tr>
<tr>
<td>$d_{cl1}$, $d_{cl2}$</td>
<td>2 mm, 2 mm</td>
</tr>
<tr>
<td>MLT$_1$</td>
<td>475 mm</td>
</tr>
<tr>
<td>MLT$_2$</td>
<td>615 mm</td>
</tr>
<tr>
<td>$d_{ins1}$, $d_{ins2}$</td>
<td>0.2 mm, 0.4 mm</td>
</tr>
</tbody>
</table>
4 Nanocrystalline transformer

4.1 The cores
The second transformer design is based on Vacuumschmelze Vitroperm® 500 Nanocrystalline as the core material [31].

![Figure 4-1: Delivered core and its drawing [32].](image)

The delivered cores have the cross section of $35.6 \times 29.6 \text{ mm}^2$ instead of $37.6 \times 31.6 \text{ mm}^2$ which was given in the technical data (see Figure 4-1). Therefore, the design of the transformer was done based on the actual measurements rather than the dimensional data presented in the datasheets.
4.2 The bobbins

To manufacture the bobbins, the polymer sheets were produced based on the similar concepts as presented in Chapter 3. The total weight of the polymer material used for two prototypes was 4.7 kg.

![Figure 4-2: Corrugated 4 mm polymer sheets and the produced bobbin.](image)

Based on the experience gained during the manufacturing of the first Ferrite sample, as an improvement, a thickness of 4 mm was considered for the sheets. In addition, to improve the fitting of the pieces together, the edges of the plates were cut along a square wave pattern. This gives the possibility for an easier assembly process, a better thermal conductivity between the sheets and a higher mechanical strength to the bobbins (see Figure 4-2).

The drawings were made using the free LibreCad 2007 software which can directly be used as input file for the water jet cutting machine. The requirement for the drawings was to have 5 mm clearance on the sides and 0.8 mm between the cut parts. The drawings for the Nano transformer are presented in Appendix D.

To produce the 4mm sheets, the granules are preheated for 6 minutes placed in the minimum distance between the upper and lower pressing jaws, after having 300 °C for the upper and the lower pressing jaws. The pressing process was performed at 200 kN for 5 minutes.

The cut parts are glued together using the introduced high temperature epoxy glue.

4.3 The windings

Three 3.8×2.50 mm² litz conductors were placed on top of each other to form a 11.4×2.50 mm² conductor. The LV winding is coiled as 2 layers of 8 turns of conductors to have a total number of 16 turns. Based on the explained results of the insulation coordination tests, two 0.2mm layers of thermally conductive tape were placed between the two winding layers.

The HV winding was coiled as 2 layers of 24 turns of 3.8×2.50 mm² litz conductor, having the total 48 number of turns. Based on the explained results of the insulation coordination tests, three 0.2mm layers of the thermally conductive tape is placed between every two winding layers.

All the cavities besides the windings were filled with the cooling polymer pieces. This increases the heat transfer capacity of the winding medium and decreases the vibration of the conductor. Lower vibration gives a longer life to the insulation, decreases the noise and gives more short circuit withstand capability to the winding (see Figure 4-3a).

The windings were covered by the frames of cooling polymer. Using the plates both under and over the copper windings helps to keep the conductors exactly in the required distance from each other. In this way the dimensional requirements are fulfilled and consequently, the electrical parameters of the transformer become near to the targeted design values. In addition, this helps for improvement of the heat conduction from all the surfaces of the windings and also to reduce the sound and vibration of the windings which is produced by the high current they carry. In addition, this increases the electrical insulation to the nearby conducting surfaces (see Figure 4-3b).
4.4 The pressing assembly

According to the drawing presented in Appendix D, two aluminium plates were designed and cut by a CNC cutting machine at SP. The plates were selected to have a 30 mm thickness instead of the 12 mm for the previous design. This was done to improve the undesirable bending condition of the plates and for a better fixation of the curved core edges.

4.5 The conductors high voltage terminations

The transformer terminations were designed considering the three parameters of the mechanical strength, the voltage and the rated current.

To standardize the high voltage terminations, a set of standard supporting insulators were used; a 1000 V insulator for LV and a 3000 V for HV (see Figure 4-4a) [33]. Some accessible suppliers of supporting insulators in the region are introduced in Appendix A.

Considering the cross section of the cables and diameter of the screwing bolt, two types of cable shoes were selected (see Figure 4-4b). The cable ends are soldered in the soldering bath, then they are pressed in the cable shoe and final soldering was performed.
4.6 Extraction of the actual parameters for the transformer

During the construction of the transformer and having access to the real data from purchased materials and manufactured components and typical dimensions, the design parameter values were finalised. The final updated data is presented in Table 4-1.

Table 4-1: The mechanical design values updated with the construction of the Nano transformer [1].

<table>
<thead>
<tr>
<th>Parameters/Dimensions</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_c$</td>
<td>2</td>
</tr>
<tr>
<td>$A$</td>
<td>36 mm</td>
</tr>
<tr>
<td>$B$</td>
<td>30 mm</td>
</tr>
<tr>
<td>$G$</td>
<td>39</td>
</tr>
<tr>
<td>$h_w$</td>
<td>112 mm</td>
</tr>
<tr>
<td>$H$</td>
<td>120 mm</td>
</tr>
<tr>
<td>$d_{iso}$</td>
<td>21.5 mm</td>
</tr>
<tr>
<td>$N_1/N_2$</td>
<td>16 / 48</td>
</tr>
<tr>
<td>$n_{s1}/n_{s2}$</td>
<td>540 / 180</td>
</tr>
<tr>
<td>$m_1 \times N_{l1}$</td>
<td>2 × 8</td>
</tr>
<tr>
<td>$m_2 \times N_{l2}$</td>
<td>2 × 24</td>
</tr>
<tr>
<td>$d_{b1}\times h_{b1}$</td>
<td>2.5 mm × 11.4 mm</td>
</tr>
<tr>
<td>$d_{b2}\times h_{b2}$</td>
<td>2.5 mm × 3.8 mm</td>
</tr>
<tr>
<td>$d_{c1}, d_{c2}$</td>
<td>4 mm, 4 mm</td>
</tr>
<tr>
<td>$d_{cf}$</td>
<td>4 mm</td>
</tr>
<tr>
<td>$d_{cl1}, d_{cl2}$</td>
<td>4 mm, 2 mm</td>
</tr>
<tr>
<td>$MLT_1$</td>
<td>295 mm</td>
</tr>
<tr>
<td>$MLT_2$</td>
<td>510 mm</td>
</tr>
<tr>
<td>$d_{ins1}, d_{ins2}$</td>
<td>0.3 mm, 0.6 mm</td>
</tr>
</tbody>
</table>
5 Test and analysis

The main purpose of the testing is to validate the design parameters. However, additional tests relevant to the low frequency power transformers are defined to help to discover the differences and additional considerations for designing the next prototypes.

5.1 Standard tests for low frequency power transformers

After more than hundred years of production of power transformers, the methods of type and routine tests that should be performed on these types of high voltage equipment are well established and the details are internationally accepted. Although the methods are not directly applicable for the transformer that is under consideration in this project, listing the related tests will help as a guide for applicable tests and selectable methods for this special case. Considering the whole commercial productions of new types of medium frequency power transformers, it is clear that technical standards will be developed and released in this regard in future.

A list of standardized tests on dry type medium sized power transformers is presented in Appendix B [40].

5.2 Test equipment

The list of test equipment which is used during the project is presented in Appendix C for future reference and in case it is needed for possible repetition of the tests. A benefit of having the list is much shorter time to search for the proper equipment during a future work.

5.3 Preliminary tests on a downscaled transformer

As it is explained in Section 2.1, unlike a conventional low frequency transformer, the voltage and current wave forms applied to the HPMF transformer in a DAB converter are not sinusoidal. Therefore, to investigate the possibility of feeding a transformer with a high current, high voltage, and medium frequency source before delivery of the ordered materials, a 1:3 transformer was manufactured using an existing round Ferrite core and pieces of existing litz wires. The transformer was short circuited and supplied with a square wave produced by a signal generator and amplified by an audio power amplifier which was loaded by a set of high power 4 \( \Omega \) resistors. A scope meter was used to register the supply side voltage and current wave shapes. The current was measured using a high precision current shunt (see Figure 5-1).
Figure 5-1: Investigations on a typical short-circuited Ferrite transformer supplied with a 5 kHz square wave voltage; The 1:3 Ferrite transformer (a), the circuit (b), the voltage wave shape (c) and the current wave shape (d).

5.4 Resistance and inductance measurements

5.4.1 DC resistance measurement

DC resistance of HV and LV sides of the transformer were measured using a Fluke 8508A multimeter and the results are presented in Table 5-1 (see Figure 5-2).

Figure 5-2: LV Resistance measurement using a reference multimeter and the 4 wire method.

HV/LV resistance measurements were repeated using the volt-ampere method at 2 A (current measurement using SP’s 0.4 Ω shunt) and the results were the same.

5.4.2 Inductance measurement

The leakage and magnetising inductance values were measured using a precision LCR meter. Measurements were made at 6 kHz from the LV side of the transformers. The results are presented in Table 5-1.
Figure 5-3: A precision LCR meter (a) and a network analyser coupled with a test fixture (b).

Table 5-1: Results of the inductance and resistance measurements.

<table>
<thead>
<tr>
<th></th>
<th>Ferrite transformer</th>
<th></th>
<th>Nanocrystalline transformer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary, open circuit</td>
<td>Ls (mH)</td>
<td>-</td>
<td>6.5</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Rdc (mΩ)</td>
<td>109.8</td>
<td>98.1</td>
<td>10.2</td>
</tr>
<tr>
<td>Secondary, short circuit</td>
<td>Ls (µH)</td>
<td>-</td>
<td>39.3</td>
<td>46</td>
</tr>
</tbody>
</table>

The inductance measured at the open circuit condition is the magnetising inductance of the transformer. An accurate measurement can be done after the demagnetising process. The core can become magnetised after a DC resistance measurement or even during the production process at the production stage. The other deviation source for the measured inductance can be any possible air gap in any of the core stacks which is inevitable. The presented values are calculated with the assumption of an air gap distance over the magnetic circuit.

For the DC resistance measurements, the deviations from the calculated values are in the range of 11-42%. The deviations can originate from using a very low current for the measurements compared with the high rated current of the windings. During the future work, the resistances can be measured on windings without the cores and at a higher current level. Disassembling the cores eliminates the effect of the core magnetisation current on the resistance measurement. The terminating cable shoes can be re-soldered in case of a high deviation from the calculated values.

The inductance measured at the short circuit condition is the leakage inductance of the transformer. There is an acceptable agreement between the measured and the calculated values.

Because of importance of the leakage inductance value, the single frequency measurements which had been performed using a LCR meter were repeated using an Agilent network analyser coupled with a HP16047C test fixture. The leakage inductance measurement has been performed over the range of 1-10 kHz for both the transformers. The instruments used for inductance measurements are presented in Figure 5-3 and the results are presented in Figure 5-4.
5.5 Ratio measurement
Transformer voltage ratio was controlled by applying 6 kHz low voltage to the primary side of the transformers and measuring the secondary side voltage. The results were equal to the specification and no inter-turn short circuit observed.

Any turn to turn short circuit inside any of the windings can cause a circulating current to pass in the winding. This circulating current opposes the flux in the core and causes the voltage on the secondary side to be much less than the expected value calculated from the ratio of the numbers of the turns.

5.6 Insulation coordination tests
Due to the normal application purpose of the insulation materials, the presented data in the insulation material data sheets are normally achieved doing DC or 50Hz insulation tests. As the insulation of the conductors and the isolative coverage of the winding layers and its corners by a layer of insulation are very important for insulation coordination of the transformer, using the actual voltage wave shape and the frequency, a set of simulated insulation tests were performed.

Considering proper safety factors, the number of insulation layers between the winding layers and between the windings and grounded electrodes were examined. The evaluated thickness of required insulating tapes was entered in the construction schemes.

5.6.1 Insulation tests at 50 Hz using a 5 kV insulation tester
According the information achieved from the producer, the litz wires used, having a wall thickness of 73 µm, can withstand 2.5-3 kV to ground. In addition, according the product data sheet, the thermally conductive tape used, having a thickness of 0.2 mm, can withstand 11 kV if it is tested between two high-voltage electrodes of a standard shape. To check the actual limits for the transformer construction geometry, two test specimen were set. In the Figure 5-5, the prepared test objects (a&b), the high voltage supply (c) and the peak voltmeter (d) used is shown.
Figure 5-5: 50 Hz insulation tests; The wire to wire object (a), the wire-insulation-wire object (b), the 5kV HV supply (c) and a pressing log and the peak voltmeter (d).

The withstand tests presented in Table 5-2 showed that the bare lacked wire’s withstand voltage is <900 V and the bare lacked wires insulated by a layer of insulating tape withstand voltage is >5 kV. The test results dictates placing a layer of insulating tape even for the LV side of the transformer where the voltage between the two adjacent wires can reach up to 800 V.

<table>
<thead>
<tr>
<th>Test setup</th>
<th>Failure voltage RMS (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wire-one layer insulation-wire</td>
<td>&gt;5 (No failure accrued)</td>
</tr>
<tr>
<td>wire-wire</td>
<td>0.9</td>
</tr>
</tbody>
</table>

The tests performed on the Ferrite transformer after these insulation tests showed that the insulation level may decrease applying a high frequency voltage. For different insulation materials used in the project, a study was required to investigate the relation of insulation strength and the power frequency. A 6 kHz sinusoidal PWM amplifier was used to do the high frequency tests on one of the prototype transformers and later also on the different insulation systems used in the project.
5.6.2 Insulation test at 6 kHz on the Ferrite transformer

To evaluate the suitability of a 6 kHz sinusoidal PWM source for the insulation tests of the produced transformers, a test setup was arranged according to Figure 5-6.

![Figure 5-6: The circuit for insulation test on the prototype transformer.](image)

At the first stage a 6 kHz 1200 V sinusoidal voltage was successfully applied to the HV side of the Ferrite transformer. At the second stage the supply side was changed to the LV side to supply the transformer with its nominal voltage.

The following equipment, instrument and settings are used for the testing (see Figure 5-7):

- Signal generator (output voltage: 2.2 V_{pp}, 6 kHz)
- PWM amplifier (gain setting: 50)
- DC supply (setting: 250V)
- CT2: 50 A/5 V, Pearson wide band current monitor (measured transformer input current: 100 mA)
- CT1: 400A/4V, Pearson wide band current monitor to measure the step-up transformer primary side current (measured value: 23 A)
- Step-up transformer: 600 V/3 kV, 333 A/(9.1A@22kV)
- PT: 3 kV/100 V, MWB standard voltage transformer
- Resistor: 33 Ω, 9 A
- HP34401A multimeters for measurement of currents and voltages
Figure 5-7: The circuit elements to supply 1200V to the Ferrite transformer from HV side; The test object (a), the voltage transformer (b), the signal generator and multimeters (c), the PWM and DC source (d), the step up transformer (e), the resistance (f), the 400 A Pearson current transformer (g) and finally the 50 A Pearson current transformer (h).
The test was not successful. Investigation presented in next section shows that according to the wave shape presented in Figure 5-12, the applied voltage has had much high frequency content and it reached 3-4 times of the measured RMS voltage. As a result, this source was not a suitable source to be used for testing of the transformer.

5.6.3 Insulation tests at 6 kHz using a PMW amplifier

Figure 5-8, Figure 5-9, Figure 5-10 and Figure 5-11 demonstrate the test setup used for insulation tests at a sinusoidal 6 kHz voltage.

*Figure 5-8:* A 35A fuse (a) is used in the primary side of step-up transformer (b) to protect the test equipment.

*Figure 5-9:* Test circuit arrangement overview (a) and the pressing bakelite plates over two under test electrodes (b).

*Figure 5-10:* Two test object arrangements, wire to grounded plate (a) and wire to wire with an insulating tape layer in between (b).
Figure 5-11: The circuit for insulation test on different conductor-tape combinations.

The applied voltage wave shape was recorded using a Tektronix oscilloscope. The output voltage of the PWM amplifier was 150 V over the test object and $150 \times \frac{600}{9900} = 9$ V at the output of the PWM (see Figure 5-12). It was observed that the noise level remained the same with increased voltage level.

Figure 5-12: The output wave shape of the PWM amplifier.

The withstand tests recorded using a modular data acquisition system named DEWE-50-USB2-8 (see Figure 5-13a). The voltage measurement was done using a compressed gas capacitor in series combination with an AC divider low voltage arm as a 6700V:1V capacitive voltage divider instead of the pre-mentioned standard voltage transformer (see Figure 5-13b). The reason was to protect the very expensive lab equipment from experiencing a failure during the withstand tests and to investigate the possibility of using a capacitive voltage divider for measurement of the 6 kHz voltage. A pre-calibration of the voltage measurement system is performed using the standard voltage transformer at a low voltage level.

Figure 5-13: The DEWE recorder (a) and the capacitive voltage dividing system (b).
Figure 5-14: Samples of recorded breakdown voltage and current values during the 6 kHz sinusoidal insulation tests: wire-insulation-wire (a) and wire-insulation-grounded plate (b).

The step-up transformer primary current, the RMS and the peak value of the applied voltage and the wave shape were recorded during the withstand tests (see Figure 5-14).

The schematic diagram of the test specimen and the results of the tests are presented in Table 5-3.

Table 5-3: Summary of the results of the 6kHz withstand tests.

<table>
<thead>
<tr>
<th>6 kHz voltage applied between</th>
<th>Test setup</th>
<th>Failure voltage RMS (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wire-one layer insulation-wire</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td>3400</td>
</tr>
<tr>
<td>wire-grounded plate</td>
<td><img src="image2.png" alt="Diagram" /></td>
<td>210</td>
</tr>
<tr>
<td>wire-grounded plate</td>
<td>repeat</td>
<td>220</td>
</tr>
<tr>
<td>wire-one layer insulation-</td>
<td><img src="image3.png" alt="Diagram" /></td>
<td>2500</td>
</tr>
<tr>
<td>grounded plate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-15: Breakdown points; the wire-tape-wire composition (a), the wire-plate composition (b), and the wire-tape-plate composition (c) and the effect of discharge on the wire’s lack.

Figure 5-15 presents photos from the traces of electrical discharges on the wires and insulations.

5.6.4 Insulation coordination based on the test results

The Ferrite transformer has three layers for each winding for both high voltage and low voltage sides and the Nano transformer has two. The voltage distribution along the transformers windings are according to Figure 5-16.

Figure 5-16: The schematics of the voltage distribution along the windings.
According to the test data presented in Table 5-3, considering 210V as minimum withstand voltage between two bare wires and 2500 V as minimum withstand voltage between the wire, insulated with one layer of tape to a grounded plate, Table 5-4 can be used as the transformers insulation coordination schemes. The required number of insulation layers to be applied between the winding layers to fulfil the targeted safety factors is presented in the table.

Table 5-4: The transformers insulation coordination scheme based on the results of the 6 kHz insulation tests.

<table>
<thead>
<tr>
<th>Winding</th>
<th>LV</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ferrite</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>1200</td>
<td>3600</td>
</tr>
<tr>
<td>Number of turns</td>
<td>18</td>
<td>54</td>
</tr>
<tr>
<td>Number of layers</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Maximum voltage between adjacent turns</td>
<td>66.7 V</td>
<td>66.7 V</td>
</tr>
<tr>
<td>Maximum voltage between adjacent layers</td>
<td>800 V</td>
<td>2400 V</td>
</tr>
<tr>
<td>Required additional insulation between wires</td>
<td>No (Safety factor 3)</td>
<td>No (Safety factor 3)</td>
</tr>
<tr>
<td>Required additional insulation between layers</td>
<td>1 layer (Safety factor 3) (1 layer was applied.)</td>
<td>1 layer (No Safety factor) (2 Layers were applied.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Winding</th>
<th>LV</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nano</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>1200</td>
<td>3600</td>
</tr>
<tr>
<td>Number of turns</td>
<td>16</td>
<td>48</td>
</tr>
<tr>
<td>Number of layers</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum voltage between adjacent turns</td>
<td>75 V</td>
<td>75 V</td>
</tr>
<tr>
<td>Maximum voltage between adjacent layers</td>
<td>1200 V</td>
<td>3600 V</td>
</tr>
<tr>
<td>Required additional insulation between wires</td>
<td>No (Safety factor 3)</td>
<td>No (Safety factor 3)</td>
</tr>
<tr>
<td>Required additional insulation between layers</td>
<td>1 layer (Safety factor 2) (1.5 layers were applied.)</td>
<td>2 layers (Safety factor 1.5) (3 layers were applied.)</td>
</tr>
</tbody>
</table>

Although the Ferrite transformer that was tested using the PWM amplifier seemed to be failed, after disassembly of the transformer, no sign of breakdown was found inside the transformer. It was decided to remanufacture the Ferrite transformer and produce the Nano transformer based on the insulation test results performed using the 6 kHz PWM amplifier. After production of the transformers, four no-load tests were performed on the transformers using the existing voltage supplies. First a 6 kHz square shaped voltage was applied to the Ferrite transformer and the voltages of the primary and secondary sides together with the primary side current were recorded. Then the test was repeated applying a sinusoidal voltage and finally the same tests were repeated for the Nano transformer. The details are presented in the following section.
5.7 No-load tests

For the complete evaluation of the losses for the manufactured transformer, they should be supplied with nominal current and nominal voltage. It is not possible to simulate the real transformer working condition without having a real load. In order to determine the main elements of losses in the transformer it should be subjected to full voltage and full current. This can be performed in two separate stages, at the no-load condition when the primary winding is supplied with the nominal voltage and the secondary is open and at short circuit condition when the primary winding is supplied with the nominal current and the secondary is short circuited.

Because of a very low phase angle between voltage and current, every small phase shift error in measured voltage or current introduces a notable error to the indicated power. An accurate measurement of losses under short circuit condition needs a high precision power analyser. The high voltage and the high current should be divided to reach a suitable scale to be fed into a power analyser. The wave shapes should not be neither deformed nor shifted over time in a precise loss measurement process. A high frequency voltage divider and a current shunt is required which should be calibrated and have a defined scale factor and phase displacement error values. Reference [33] presents examples of core loss measurement systems on the typical magnetic core materials magnetized with a symmetrical/asymmetrical rectangular voltage. The voltage at the open secondary coil together with the current at the primary coil is measured and (5.1) is used for determination of the core losses [34].

\[
P_I = \frac{1}{w_e} \frac{N_1}{N_2} \frac{k_1}{k_2} \int_0^T v_L i_L dt
\]

where
- \(w_e\) is the mass of the core
- \(T\) is the period
- \(N_1\) is the number of the turns of the primary winding
- \(N_2\) is the number of the turns of the secondary winding
- \(v_L\) is the inevitable air gap length
- \(i_L\) is the inevitable air gap length

The same formula can be used for calculation of the losses based on the voltage and current measurement data which is presented in the following section.

5.7.1 No load test using a signal generator and a power amplifier

To create and apply the nominal voltage, the transformer shall be left open at the secondary side. In this way a high voltage low current source will be strong enough to supply the created losses in the transformer. For a 50 Hz transformer it is easy to use a step-up transformer supplied with a variable voltage source directly connected to the mains voltage. However, a high frequency and a non-sinusoidal wave shape for this project calls for a signal generator and a power amplifier. In this case the available instrument is a Fluke 5205A Precision power amplifier which has a maximum of 1000 V at 200 mA at its output (see Figure 5-17a) [35].

\[\text{Figure 5-17: Fluke 5205A power amplifier (a) and Yokogawa WT3000 power analyser (b).}\]
The voltage, current and the power parameters are registered using an existing Yokogawa, WT3000, precision power analyser which is shown in Figure 5-17b. A Tektronix oscilloscope was used to control the wave shapes (see Figure 5-18a). A 2 A fast fuse was installed in series with the supply side in a fuse holder shown in Figure 5-18b. The maximum applicable voltages available from the amplifier for two types of wave shapes were registered. The results are presented in Table 5-5. The wave shapes of the applied voltages are presented in Figure 5-19.

### Table 5-5: Maximum available supply voltage and measured parameters using the power amplifier.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sinusoidal wave</th>
<th>Square wave</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supplied from HV side</td>
<td>Supplied from LV side</td>
</tr>
<tr>
<td>$U_{rms1}$ (V)</td>
<td>88.2</td>
<td>84.6</td>
</tr>
<tr>
<td>$I_{rms1}$ (mA)</td>
<td>96.6</td>
<td>126.7</td>
</tr>
<tr>
<td>$P1$ (W)</td>
<td>0.02</td>
<td>0.39</td>
</tr>
<tr>
<td>$S1$ (VA)</td>
<td>8.5</td>
<td>10.7</td>
</tr>
<tr>
<td>$Q1$ (var)</td>
<td>8.5</td>
<td>10.7</td>
</tr>
<tr>
<td>$\lambda_1$</td>
<td>0.003</td>
<td>0.04</td>
</tr>
<tr>
<td>$\Phi_1$</td>
<td>89.8</td>
<td>87.9</td>
</tr>
<tr>
<td>$fU_1$ (kHz)</td>
<td>6.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

At the next step, using a Fluke 5700 calibrator, at 6 kHz, 100 and 200 V sinusoidal voltages were applied to the transformers LV sides respectively and 0.132 and 0.238 A were recorded. It was the maximum applicable voltage using this voltage source. The nominal current of Fluke 5700 is 10 mA at 6 kHz. It seems that the calibrator has no protection in the case of inductive loading. Normally these kinds of calibrators are made for supplying a highly resistive or capacitive load of the voltage meters. Controlling the measured current using a wide band resistive shunt showed the same current as it was read by the multimeter.

### Figure 5-19: Sinusoidal and square waves at the maximum applicable voltage by Fluke 5205.
5.7.2 No-load test using a PWM

After application of the additional insulation layers between the windings and adding 1-3 layers of insulation tape on the open corners, between the windings and grounded metallic parts, the no-load tests at 6 kHz were continued using a PWM source designed and manufactured based on a common SP-Chalmers master thesis work [36]. The primary and secondary voltages and the supply side current were recorded using a 4 channel, 25 MHz, 200 MS/s PicoScope oscilloscope, two Lecroy AP032 differential voltage probes and a Pico TA018, AC/DC 60/20 A current clamp (see Figure 5-20).

Figure 5-20: The 6 kHz square wave source (a), test and measurement circuit (b) and the measurement equipment used (c&d).

A rectangular 180 V voltage supplied to the primary side of the Nano transformer, and then the primary current and secondary voltage were recorded using a Pico clamp probe and a Lecroy differential voltage probe connected to a four channel Picoscope. It should be noted that the output of the PWM cannot be grounded at one of the output terminals. Therefore, it is not possible to use a conventional voltage probe to measure the voltage. In addition, the HPMF transformer application which requires having the high pulsed DC voltage on both terminals of each winding dictates a non-grounded supply and measurement circuit.

To investigate the amplitude of the spikes on the voltage at the output of the PWM supplier (the primary side of the transformer) and at the secondary side of the transformer a set of recordings at the 6 kHz were done which are presented in Figure 5-21.

Figure 5-21: The source voltage without connection to the load (a), the source voltage with connection to the HV side of the transformer (b) and the voltage measured at the LV side (c).
Figure 5-21c demonstrates the measured high frequency spikes which are >100% higher than the fundamental voltage level at the secondary side of the transformer and in the range of 25% at the primary side of the transformer. To have a true squared shape voltage signal, some improvements were done on the supply circuit elements.

5.7.3 The final no-load tests with 300 V, 6 kHz rectangular wave

Some possible improvements on the supplying system were performed. A set of capacitors which were connected to the DC link using connecting wires, were disconnected and soldered on the low inductance busses and the gate resistors of the converter were increased.

No-load tests were performed with the maximum available rectangular voltage on both transformers. Voltages from 50 V to 300 V were applied to the HV side of the transformers in steps of 50 volts. The results are summarized using the Matlab software and presented in the Figure 5-22 and Figure 5-23.

Figure 5-22: Voltage and current wave shapes of the Ferrite transformer.
Figure 5-23: Voltage and current wave shapes of the Nano transformer.

Figure 5-24 and Figure 5-25 present the results recorded on the Picoscope dashboard’s display. It is notable that the high frequency spikes cannot be observed directly on the display. In addition, the RMS values of the primary and secondary voltages and the supplied current can be read from the display.
Figure 5-24: Picoscope's on screen recordings for the Ferrite transformer; 100 V at secondary, 300 V at primary and 204 mA supplied current.

Figure 5-25: Picoscope's on screen recordings for the Nano transformer; 100 V at secondary, 300 V at primary and 196 mA supplied current.
5.7.4 The final no-load tests with 300 V, 6 kHz sinusoidal wave

In addition, the transformers were supplied by a Fluke 5500 A Calibrator and the no-load tests were performed with the maximum available sinusoidal voltage which was 300 V (see Figure 5-26). The results were recorded as Matlab files. The displayed voltages and the current are presented in Figure 5-27 and in Figure 5-28.

**Figure 5-26:** No-load test circuit (a) on transformers at 6 kHz with sinusoidal voltage performed using a Fluke 5500 calibrator as a voltage source (b).

**Figure 5-27:** Picoscope’s on screen recordings for the Ferrite transformer; 100V sinusoidal at secondary, 300V at primary and 150 mA supplied current.
5.8 Evaluation of the load loss testing facilities

To create and inject the nominal current, the test object shall be short circuited on the secondary side. In this way a low voltage, high current source will be strong enough to supply the consumed losses in the transformer. For a 50 Hz transformer, it is not hard to use a step-down transformer supplied with a variable voltage supply connected to the mains voltage as a source. Having high frequency and a non-sinusoidal wave shape for this project, calls for a signal generator and a current amplifier. In this case the available instrument was a Clarke-Hess, 8100, Trans-conductance amplifier which can supply 100 A at 100 kHz and at a maximum output voltage of 7 volt (see Figure 5-29) [37].

The maximum voltage and current available at 6 kHz to supply the HV side of the LV short circuited transformer, was 5.7 V & 0.43 A. The maximum voltage and current available at 6 kHz to supply the LV side of the HV short circuited transformer, was 6.4 V & 4.3 A. The maximum applicable voltage and current at minimum frequency (900 Hz) to the transformer at the maximum input voltage of the amplifier and maximum output voltage of the amplifier was 6.2 V & 28.4 A. As a result, this system cannot be used for the winding loss measurements on the transformers.

Figure 5-28: Picoscope’s on screen recordings for the Nano transformer; 100V sinusoidal at secondary, 300V at primary and 70 mA supplied current.

Figure 5-29: The load loss test on transformers using a Clarke-Hess, 8100, Trans-conductance amplifier.
5.9 Evaluation of the temperature measurement facilities

Because of the presence of high voltage, a general propose temperature sensor is not suitable for direct measurement of temperature on high frequency and high voltage coil or winding. Nowadays, optical fibre sensors are used for direct winding hotspot temperature measurements of high voltage transformers. The price of these temperature measuring systems can be high and out of this project’s financial scope. The simplest instrument available on the Swedish market is LumaSense, LUXTRON 812, a single channel industrial temperature monitor which is shown in Figure 5-30 [38].

![Figure 5-30: LumaSense, LUXTRON 812, single channel industrial temperature monitor [38].](image)

Several sensors can be installed and fixed on the targeted points during the manufacturing process of the transformers. In this way, a real validation of calculated temperatures is possible. Using the introduced system, only two online measurements at a time is possible and the terminations can be switched every time it is necessary. Some accessible system suppliers in Sweden are introduced in Appendix A.

The other possibility comes with this consideration that the high temperature only exists during a heat run test which is performed by short circuiting the transformer and applying a very low voltage to it. During the heat run test, the total losses of the transformer under test (which is nearly equal to the sum of the core and windings losses) is fed into the transformer.

In this case, it is possible to use normal PT1000 sensors to measure the temperature of the targeted points. A set of conducting pipes can be installed inside the transformer body, filled with thermally conductive paste to be used for penetration of the sensors during a thermal test and pulling them out during a high voltage test.

![Figure 5-31: Investigation of the effect of high frequency high current on a PT1000 temperature sensor.](image)

To investigate the effect of the high frequency electromagnetic field on the temperature measuring system a test setup was prepared using a prototype 18:3 HF transformer supplied with approximately 10 A, at 5 kHz (see Figure 5-31). The effect was not considerable and the measured temperature was stable inside the accuracy range of 0.1 °C.
6 Conclusion and discussion

6.1 Results from present work

The constructional design of two prototype 60 kW, 1.2/3.6 kV, 6 kHz 46/28 µH shell type transformers was performed.

The required technical data and the quantity of the materials including Ferrite EPCOS N87 and Nanocrystalline Vacuumschmelze Vitroperm cores, Elektrisola’s Polysol155 Litz wire and Coolpoly-D5108, thermally conductive liquid crystalline polymer were determined and the alternatives of the suppliers were introduced and the materials were purchased.

The insulation characteristics of the supplied insulation materials were examined performing typical tests and the insulation coordination of the transformer was strengthened accordingly. It was observed that the breakdown voltage at 6 kHz square wave voltage is much lower than the breakdown voltage at 50 Hz sinusoidal wave shape.

The proper machinery and qualified suppliers of services for production of different parts were identified, and the constructional design drawings were prepared. Having access to SP’s polymer sheet production machine, the bobbins were produced in the form of glued polymer sheets. The polymer sheets were cut by a water jet cutting machine. The pressing aluminium plates were produced by a CNC machine, owned by SP.

Two prototype transformers were manufactured and became ready for the design validation tests.

The evaluation of the available high voltage high current and medium frequency square wave shape supplies as well as the voltage and current measuring equipment were performed. A Fluke 5500 calibrator was used to apply a sinusoidal voltage with the maximum level of 300 V to the HV side of the transformers. In addition, an existing PWM amplifier was used to apply a 300V, 6 kHz voltage to the HV side of the transformers. The existing amplifier needs improvements for the eliminations of square wave’s overshoots, to be qualified for application of the full 1200V to the LV side of the transformers. Regarding evaluation of available equipment for performing a load loss test, in contrary to what was thought, the application of the nominal current at low voltage is not possible using the existing Clarke-Hess, 8100, Transconductance amplifier. A Yokogawa, WT3000, precision power analyser together with the introduced SP’s precision voltage and current dividers can be used for power loss measurements during no-load and load loss conditions. A temperature measurement system based on the fibre optic sensors can be used for measuring the hot spot temperatures of the transformers at the same time with the application of the high voltage.

Using a precision multitier, a precision LCR meter and a network analyser, the transformers were subjected to preliminary design validation tests and the results were recorded, analysed and compared with calculated values. The design parameters of the transformers were validated to be compatible with the practical results within the acceptable tolerances. The measured resistances, magnetising inductances and the leakage inductances are in a good compliance with the calculated values. The most important parameter is the leakage inductance which was measured as 39.3 and 29.2 µH compared with the calculated 46 and 28 µH for the Ferrite and the Nano transformers respectively.
6.2 Future work

The following tests and investigations are proposed to be done and the results to be used for development of the next prototype transformers:

- Investigations regarding the production of a desired square wave shape supply for conducting a full no-load test. (The source should be able to supply at least 1200 V square shaped voltage without spikes at the rise and fall events. The supply power should be more than the power needed to feed the losses of a transformer.)

- Loss measurements using square wave supply including measurement of the no-load losses in the core by applying the nominal voltage to the open circuit transformers and the load losses in the windings by applying the rated current to the short circuited transformers.

- Insulation tests on the simulated conditions on the different conductor-insulation combinations using a high frequency (much higher than 6 kHz which practically exists at the voltage rise time), high voltage source. It is specially proposed to repeat the performed tests until coming to a reliable breakdown voltage and to continue the insulation tests on the two and three layer combinations. The latter is for investigating if the breakdown voltage will be doubled when the number of insulation layers increases to a double layer.

- Insulation evaluation tests on the transformers including insulation resistance measurement, applied power frequency test, induced overvoltage tests and partial discharge measurements. Passing these tests is vital for the purpose of a long term practical application of the transformers.

- Heat run test including temperature measurements on various points of the transformers.

- Verification of the thermal model of the transformer.

- Making a dummy coil and doing measurements to check the true winding losses.

The following should be done as improvements for the reproduction of prototypes:

- The insulation tape layers between the windings and between the windings and the grounded electrodes should be decided in detail before preparing the constructional drawings. These insulation layers should be placed on the corners over the bobbins and covering the windings before starting the winding and after finishing it.

- Mechanical tests should be done on the produced polymer sheets. SP has the 300°C limit for the production of the sheets which is at the minimum range of the production temperature limit of the Coolpoly. It was not possible to investigate the effect of increasing the temperature on the mechanical strength of the plates.

- The 4 pressing bolts are used as supporting legs, they should be changed from M6 to M8.

- The conductors should be insulated using a tape insulator or a heat shrink insulator before leaving the winding and passing through the bobbin’s hole. A suitable space between the winding and the upper polymer sheet should be considered for this.

- The 12 mm cooling and pressing aluminium plates of the Ferrite transformer should be changed to 30 mm thick plates for a more even distribution of the pressing forces on the five core stacks.

- The polymer insulation sheets of the Ferrite transformer should be changed from 2 mm to 4 mm thick sheets with corrugated edges for better mechanical coupling stability, higher thermal conductance and better dimensional positioning of the windings.

- Thin tubes should be installed inside the transformer body on proper positions for penetrating and conducting the PT1000 temperature sensors inside the transformer every time it is needed.

- In case of need for a sealing glue with the high thermal conductivity and relatively high voltage insulation level, the TCOR, a thermally conductive RTV (Oxime) can be used [39].

- The nuts and bolts screwed into the support terminating insulators should be changed from steal to copper to reduce contact resistance where the high current flows through the transformer.
7 References


[23] https://www1.elfa.se/data1/wwwroot/assets/datasheets/ks200_ger_bro.pdf,
Accessed 2014-10-05
Accessed 2014-10-05
[27] https://www.elfa.se/elfa3--se__sv/elfa/init.do?item=55-065-02&toc=19779,
Accessed 2014-10-05
[28] https://www.elfa.se/elfa3--se__sv/elfa/init.do?item=55-064-99&toc=19779,
Accessed 2014-10-05
Appendix A, Addresses and contact details

Addresses and contact specifications for the materials used for the project:

Ferrite cores:
- www.elfa.se/
- www.se.rs-online.com/

Nanocrystalline cores:
- Lars Kvarnsjö
  Vacuumschmelze Sales Office Denmark, Norway, Sweden
  Tel: +46 (0)8 7140835
  Mobile: +46 (0)70 2190835
  Email: lars.kvarnsjoe@vacuumschmelze.com

Insulating polymer:
- Kathleen Rush
  Cool Polymers
  Inside Sales/Customer Support
  51 Circuit Drive
  North Kingstown, RI 02852
  T: (401) 667-7830 / F: (401)667-7831
  kathleen.rush@coolpolymers.com

Litz wires:
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<th>Contact person</th>
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<th>Representing Company</th>
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<tr>
<td>Jerker Andersson</td>
<td><a href="mailto:Jerker.andersson@ljww.se">Jerker.andersson@ljww.se</a></td>
<td>0512300345</td>
<td>Dahrendal, Sweden</td>
<td>LiljedahlWinding Wire, Sweden</td>
<td></td>
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<tr>
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<td>049927197</td>
<td>Bevi AB, Sweden</td>
<td>Elektrisola, Germany</td>
<td></td>
</tr>
<tr>
<td>Dominique Rey</td>
<td><a href="mailto:Dominique.rey@vonroll.com">Dominique.rey@vonroll.com</a></td>
<td>00416 17855370</td>
<td>Vonroll, Switzerland</td>
<td>Vonroll, Switzerland</td>
<td>Min 50 kg</td>
</tr>
<tr>
<td>Lars Lundin</td>
<td><a href="mailto:ll@moreelectronics.dk">ll@moreelectronics.dk</a></td>
<td>0859086590</td>
<td>MoreElectronics, Sweden</td>
<td>NewEnglandWire, USA</td>
<td>Min 305 m</td>
</tr>
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</table>

Insulating tape:
- http://se.farnell.com/

Thermally conductive paste:
- www.elfa.se/

Epoxy adhesive DP760:
- KA OLSSON & GEMS AB,
  Sallarängsgatan 3, 431 37 Mölndal
  Tel 031-74 64900
Aluminium heat sinks
  • www.elfa.se/
  • www.se.rs-online.com/

Heat shrink tubing:
  • www.elfa.se/

Supporting insulators as HV terminals:

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<tr>
<td>Euro Energy Components AB</td>
<td>Tälje Mätinstrument AB</td>
</tr>
<tr>
<td>Varlabergsvägen 25</td>
<td>Wedavägen 24A</td>
</tr>
<tr>
<td>434 39 Kungsbacka</td>
<td>152 42 SÖDERTÄLJE</td>
</tr>
<tr>
<td>Tel: 0300-69 00 40</td>
<td>Tel: 08-550 312 12</td>
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</table>

Fiber optic temperature sensor:
  • Pentronic, Per Bäckström, Tel. 070 543 02 84, http://pentronic.se/start/instrument/ir-pyrometrar.aspx
  • BLInstruments, Agne Bogren, Tel 070516 39 95, http://www.blinstruments.se/index.html
Appendix B, List of standard tests

List of standardized tests on dry type medium sized power transformers [40]:

Routine tests:
- Measurement of winding resistance
- Measurement of voltage ratio and check of phase displacement
- Measurement of short-circuit impedance and load loss
- Measurement of no-load loss and current
- Dielectric routine tests (IEC 60076-3)

Type tests:
- Temperature-rise test
- Dielectric type tests (IEC 60076-3)

Special tests:
- Dielectric special tests (IEC 60076-3)
- Determination of capacitances windings-to-earth, and between windings
- Determination of transient voltage transfer characteristics
- Measurement of zero-sequence impedance(s) on three-phase transformers
- Short-circuit withstand test (IEC 60076-5)
- Determination of sound levels (IEC 60551)
- Measurement of the harmonics of the no-load current (10.6)
- Measurement of insulation resistance to earth of the windings
- Measurement of dissipation factor (tan δ) of the insulation system capacitances
Appendix C, List of equipment used

The list of test equipment which is used during the project:

- Fluke, 5205A, Precision power amplifier
- SP502130, Fluke 5500A Calibrator
- Lab Gruppen, SS 300B, Audio power amplifier
- SP BX31332, Yokogawa WT3000, Precision Power Analyser
- SP503045, HP 33120A, Function/Arbitrary Waveform Generator
- SP501155, HP 34401A, Multimeter
- SP603031, Tektronix TDS 3054B, 500MHz 5GS/s oscilloscope
- SP503042, Fluke 99B series II, 100MHz Scope-meter
- SP900414, Agilent E4980A, 20 Hz-2 MHz, Precision LCR Meter
- SP BX31914, Fluke 5700, High performance Multifunction calibrator
- SP503241, SP, 2A 0.4Ω, High precision current shunt
- SP9xxxx, SP, 20A 0.8Ω, High precision current shunt
- SP900408, Metrix AX 322, 30V 2.5A, DC power supply
- R&B, UH 27, 5kV 50Hz, High voltage insulation tester
- Sensitive research instrument corporation, ESH, Electrostatic voltmeter
- SP603237, Clarke-Hess, Model 8100, Trans-conductance amplifier
- SP900180, Pearson 301X, 400 A/4 V, Wide band current monitor
- Step-up transformer: 600 V/3 kV, 333 A/ (9.1A@22kV)
- SP900180, Pearson 3972, 50A/5V, Wide band current monitor
- SP501235, MWB, 3kV/100V, Standard voltage transformer
- SP901239, DEWE-50-USB2-8, Modular data acquisition system for USB
- SP603268, WSTS CP100, Compressed gas capacitor, 37pF
- SP602798, AC divider low voltage arm 0.25μF
- Chalmers Elteknik inv. Nr. 470, PicoScope, 4 channel, 25 MHz, 200 MS/s Oscilloscope
- Chalmers Elteknik inv. Nr. 578 & 90, Lecroy AP032 Differential probe
- Chalmers Elteknik inv. Nr. 471, Pico TA018, AC/DC Current clamp 60/20A
- SP603223, Fluke 8508A Reference multimeter
- SP902103, Agilent technologies, E5061B, 5 Hz to 3 GHz, ENA series Network analyser coupled with HP16047C HP test fixture
Appendix D, Drawings

Drawings:

- Drawings for production of Ferrite transformer HV and LV bobbins cooling polymers
- Drawings for production of Nano transformer HV and LV bobbins cooling polymers
- Drawings for production of Ferrite transformer Aluminum pressing plates
- Drawings for production of Nano transformer Aluminum pressing plates
Appendix E, Materials technical data

The list of attached technical data sheets of the materials used for the project:

- Polysol155 Enamelled Copper Litz wire
- Vitroperm 500 Nanocrystalline cut core
- U93, N87, Ferrite core
- CoolPoly D5108 Thermally conductive Polyphenylene Sulfide Polymer
- 3M 8943 Thermally conductive adhesive tape
- 3M Scotch-weld, DP760 Epoxy adhesive
- KS200, Fischerelektronik Heat sink
- HTSP50T Silicone Heat transfer compound plus
- GMxxx, Metasistema support insulator