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High power – high frequency transformer design constrains

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Abstract This paper describes the design of a middle-frequency power transformer, its material composition and the design of the magnetic circuit and windings, operating in the frequency range 800 to 2000Hz, with a capacity of 200kVA, air-cooled, to be fed from a suitable frequency converter, characterized by reduced noise. The proposed solution allows the implementation of galvanically isolated DC-DC converters for auxiliary traction drives and other DC-DC converters.

Keywords power electronic system, electric machine, high power, high frequency

JEL Q4, L62, L69

1. Introduction

Power transformers can produce several types of noise, including magnetostriction noise, stray magnetic field noise, and electrical noise. The level of noise produced by a transformer depends on several factors, such as the design of the transformer, the quality of the materials used, and the operating conditions.

At a frequency of 1kHz, the noise level of a power transformer can vary widely depending on its size and design. In general, larger transformers tend to produce more noise than smaller ones due to their greater physical size and the larger magnetic fields they generate.

The noise level of a power transformer is typically expressed in decibels (dB) or in terms of sound pressure level (SPL) measured in decibels relative to a reference sound pressure level. The noise level of a typical power transformer ranges from around 20 dB SPL to 70 dB SPL, depending on the transformer's size, design, and operating conditions.

In summary, the noise level of a power transformer operating at a frequency of 1kHz can vary widely depending on its design and operating conditions. However, a typical range of noise level for such transformers is from around 20 dB SPL to 70 dB SPL.

EVPÚ a.s. has been developing and manufacturing static semiconductor traction converters for more than a decade, and part of the equipment of traction vehicles is also the need to design and develop smoothing chokes for traction motors or traction intermediate circuit. Several types of middle frequency power transformer and chokes been designed for traction converters.

2. Design of the high-frequency power transformer

Before the actual design of a power transformer, it is necessary to determine or establish the key parameters that this transformer should possess. These parameters are illustrated in Table 1. Based on these parameters, it is possible to mathematically calculate the required characteristics of the transformer, which can then be used to design and construct the power transformer.

Table 1. Input parameters for design of the high-frequency power transformer

Power [kW]	12
Input voltage [V]	452
Output voltage [V]	30
Conversion [-]	14
Magnetizing inductance [mH]	0.8
Primary series inductance [µH]	25
Secondary series inductance [nH]	127.5
Switching frequency [kHz]	125

An example design of a power transformer is shown in Figure 1. As can be seen in this figure, the transformer has multiple parallel windings made of high-frequency wires, which are terminated with ring eye terminals and connected in parallel on a PCB or power bus of the device.

The series resonant circuit for the transformer requires a resonant inductance and a resonant capacitance. The resonant inductance can be implemented as a separate inductor connected in series with the winding, or alternatively, the total leakage inductance of the transformer can be used as the resonant inductance.

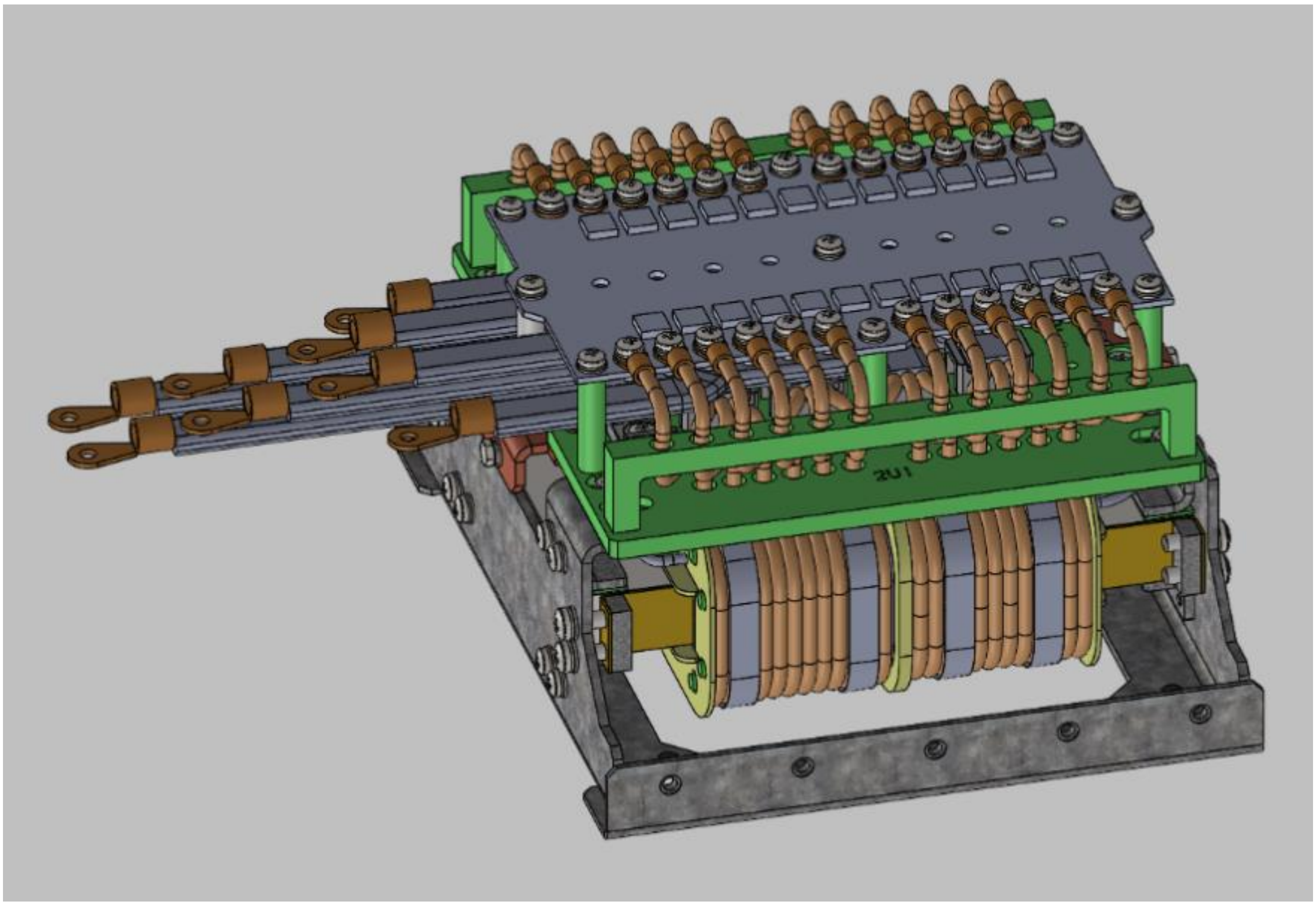

Figure 1. An example of the 3D design of power transformer with resonance capacitors board.

The selected type of inductance scenario has significant impact on the transformer design. Each method has its advantages and disadvantages. These are the two methods:

a) External inductor

- Requires an additional magnetic component.
- The desired inductance can be more precisely tuned during the inductor production.
- A transformer with tight coupling has low leakage inductance and lower losses.

b) Integrated inductance

- No need for an external inductor.
- Achieving the desired value may be challenging.
- Reproducibility may be poorer, and worse manufacturing tolerances can be expected.
- A deliberately poorly coupled transformer will have higher losses.

For this application the resonant capacitor will be created from multiple SMD capacitors connected in parallel. The series-connected resonant capacitors with the secondary winding will be located on the PCB above the transformer. The construction of the transformer includes the mounting of this board. If the actual resonant inductance deviates significantly from the planned value, it may be necessary to fine-tune the value of the resonant capacitance or adjust the switching frequency of the charger.

During the process of the design of the transformer with given parameters and specification, several approaches were considered. The approaches were to optimize the dimension parameters with the inductor with high inductance but lower operating current on the primary side or the inductor with low value of the inductance but with operating current at value of 400 A. For both different solutions of the main magnetic circuit, designs were created, processed, and evaluated. However, the approach was taken to use a transformer topology with defined leakage inductance. Construction documentation was prepared for this topology, based on which a prototype was manufactured. This prototype design was named T1N-12-452/30. The 3D design of this prototype design can be seen in Figure 1.

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3. Measurements of the designed transformer

The measurements of the designed transformer were conducted on a laboratory-created prototype, the T1N-12-452/30, whose results were compared with a professionally constructed transformer from the German company STS Trafo. STS Trafo is actively involved in this field and was approached with a request to construct this transformer design. They received the same assignment and focused on designing solutions for a "good" transformer and an additional inductor with defined inductance, both of which are integrated into a single module. STS Trafo's transformer can be seen in Figure 5 and prototype of the Chopra inductor is shown in Figure 6.

3.1. Experimental measurements of the laboratory-created prototype transformer

Experimental measurements on the prototype transformer were conducted with the aim of adjusting the leakage reactance of the transformer by changing the windings position.

The measured data of the laboratory-created transformer prototype is graphically represented in Figures 2, 3, and 4. Figure 2 shows the open-circuit characteristic of the transformer at switching frequency of 120 kHz. The short-circuit characteristic of the transformer prototype obtained at a switching frequency of 30 kHz is shown in Figure 4. The magnetizing inductance of the transformer (Lm = *f*(U)) at a switching frequency of 120 kHz is presented in Figure 3.

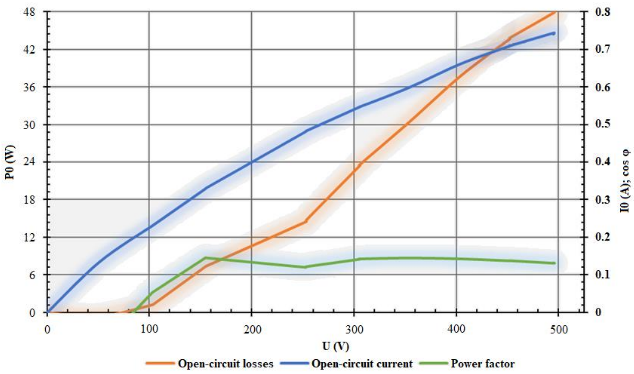

Figure 2. Open-circuit characteristic of the lab-created transformer.

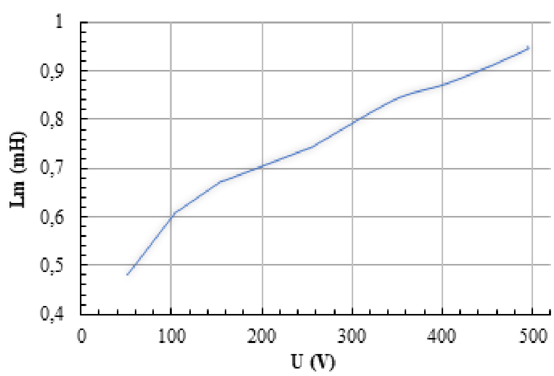

Figure 3. Magnetizing inductance of the lab-created transformer.

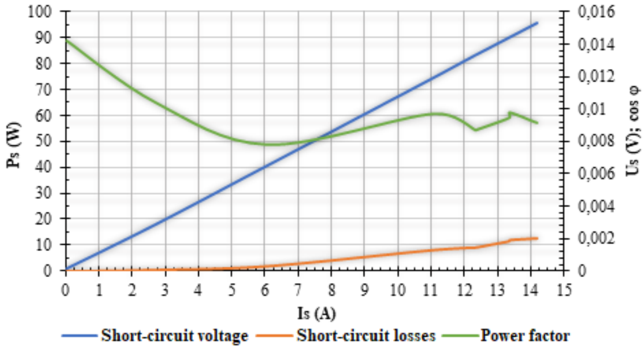

Figure 4. Short-circuit characteristic of the lab-created transformer.

Through measurements on the designed laboratory-created transformer, it was found out that the limiting value of the leakage inductance is 38 µH. Further increasing the gap between the windings of the transformer resulted in a stable value, indicating that further increases of the gap does not increase the value of leakage inductance.

3.2. Experimental measurements of the STS Trafo's prototype transformer

Since the company STS Trafo got the same specification for their prototype of the same named transformer, the measured output parameters should be very similar. The STS Trafo prototype with Chopra inductor configuration is shown in Figure 5 and 6.

Figure 5. Designed transformer prototype constructed by STS Trafo.

Figure 6. Prototype of the external Chopra inductor by STS Trafo.

Just like in the case of the laboratory-created prototype transformer, the open-circuit and short-circuit characteristics of this transformer were also measured. They are depicted in Figure 7 (open-circuit characteristic) and Figure 8 (short-circuit characteristic).

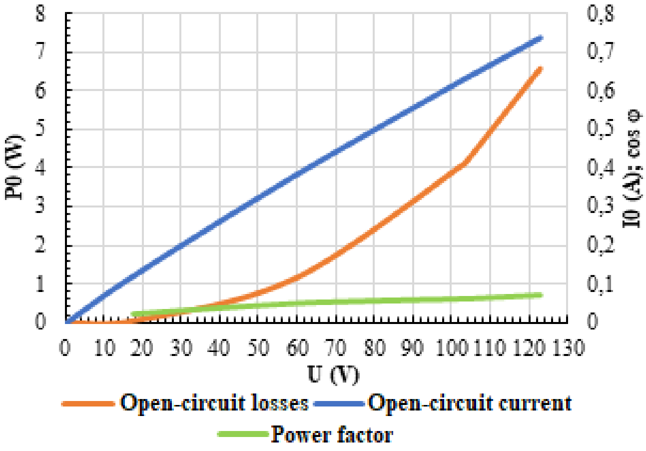

Figure 7. Open-circuit characteristic of the STS Trafo transformer.

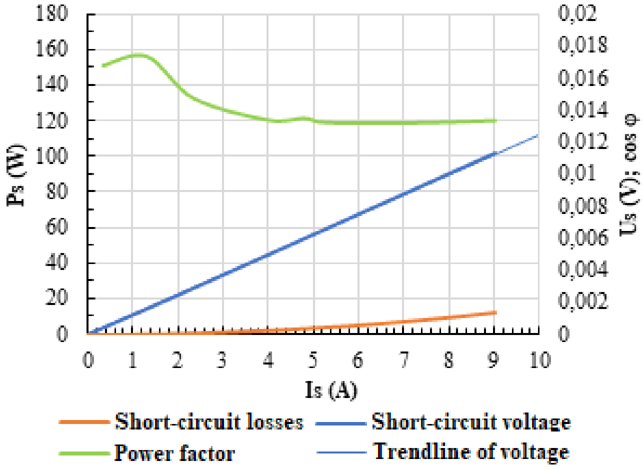

Figure 8. Short-circuit characteristic of the STS Trafo transformer.

Both measured characteristics on the prototype assembled by STS Trafo were obtained at a switching frequency of 30 kHz. The measured value of the limit leakage inductance for this prototype is 58 μH.

4. Conclusions

This paper investigates the noise level of power transformers operating at 900Hz, the source of which is the transformer core. The study examines the factors that influence the noise produced by the core of a power transformer, and consequently the selection of a suitable core type and manufacturing technology. The design of a middle-frequency power transformer, its material composition and the design of the magnetic circuit and winding, operating in the frequency 900Hz, with a power 200kVA, cooled by air, to be fed from a suitable frequency converter characterised by reduced noise, are described. The proposed solution allows the implementation of galvanically isolated DC-DC converters for auxiliary traction drives and other DC-DC converters. The findings of this paper can be used in the design and operation of power transformers and help mitigate the impact of transformer noise on the surrounding environment.

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