DESIGN OF POWER TRANSFORMER WITH FREQUENCY 1 kHz

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Resume

This paper deals with the noise level of power transformers operating at a middle frequency from 800 Hz to 2000 Hz. The factors that influence the noise produced by power transformers are size, design and operating conditions. The research shows that the noise level of power transformers can vary widely depending on these factors. The paper discusses an overview of different types of power transformers core and their impact on the transformer's noise performance. 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 2000 Hz, with a capacity of 200 kVA, air-cooled, to be fed from a suitable frequency converter, characterized by reduced noise. The proposed solution allows implementation of galvanically isolated DC-DC converters for auxiliary traction drives and other DC-DC converters.

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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 1 kHz, 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.

The immediate component of galvanically isolated DC-DC converters of higher voltage and power are isolation transformers. Due to the required size and weight of the converters, these are switched at higher frequencies, while the isolation transformer in question must also operate at a higher frequency than the middle-frequency power transformer (MfT). If for most converters of smaller power ratings, the switching frequencies are from 5 to 20 kHz, but in the case of converters with a power rating of hundreds of kVA the switching frequencies with regard to losses in the semiconductor switches are up to about 1 kHz. For these switching frequencies the magnetic circuit material, the winding and its insulation system must be designed.

Among the available materials, magnetically soft amorphous metal materials (AMMs), nanocrystalline materials (NCMs) or ferrites can be used for the MfTs in question. The use of ferrite cores for this power class of MfTs is not relevant due to, among other things, the size and weight of such MfTs. Depending on what is commercially available on the market, depending on the shape of the cores, toroidal or split (cut, "2U" shaped and glued on the side edges) cores of both AMM and NCM can be used. Toroidal cores of AMM or NCM are available in a much wider range, but their use is technologically almost impossible for MfTs of hundreds of kVA, due to the manufacturability of the windings. Only the split cores can be considered, of which the

NCM ones are preferable, but they are only available in a narrower range, of limited dimensions and their main drawback is their considerably high price, which predisposes them only for higher frequencies. The AMM cores are already available in larger sizes and weights, at an acceptable price, but their main drawback is the splitting section, which is a source of excessive noise resulting from electromagnetic forces generated in the core and manifested by mechanical vibrations with consequent significant noise. The source of the noise is the magnetostrictive forces originating in the large magnetostriction coefficient, which is characteristic for the AMM tapes. In specific tests, it has been shown that the use of these cores in MfTs has resulted in noise levels such that their use has proved to be unacceptable, despite the fact that the manufacturer declares their use also in the middle frequency transformers.

EVPU 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 [1-5].

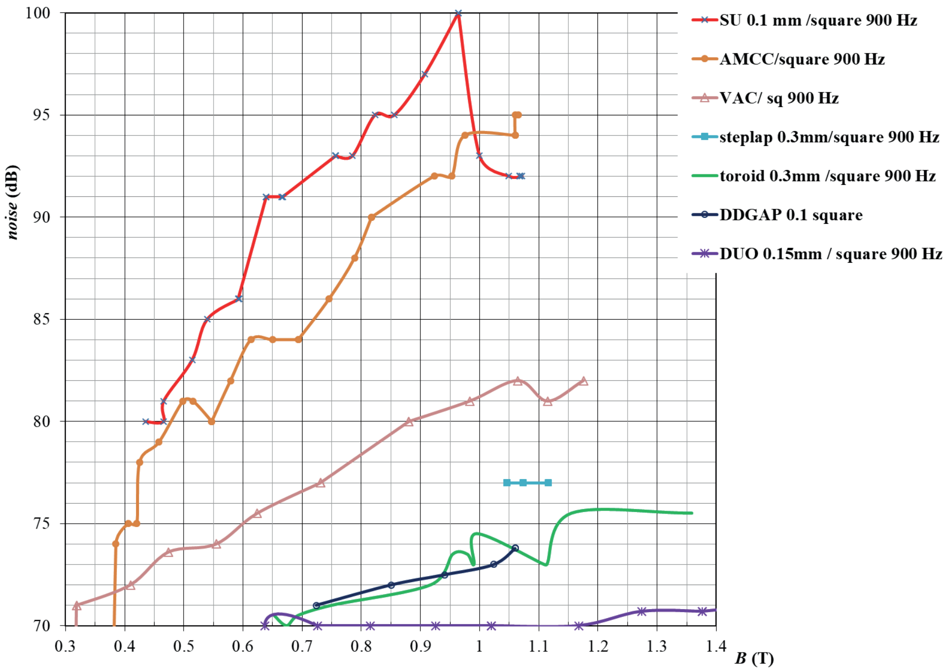
In the design of a power isolating traction converter for supplying vehicle's auxiliary drives with a power 200 kVA, the care must be taken on several design issues. Considering the high power, application, losses of power semiconductor elements, a switching frequency of 900 Hz was selected for this purpose, it was necessary to design a power middle-frequency isolation transformer. During the tests of the prototype isolation transformer, a high level of noise was observed at this operating frequency. Therefore, the source of noise and possible solution was investigated, which is described in this paper.

2 Design of power transformer with frequency 900 Hz

The objective was to design a transformer with a target power of up to 200 kVA, with an operating frequency of 900 (1000 Hz), with a voltage ratio of 2000 V/890 V, with forced air cooling. According to the design and the elaborated design documentation, a prototype transformer type T1O-200-2000/893 was manufactured with the following parameters:

- Rated power 200 kVA
- Primary voltage (rms value) 2000 V (4000 V_{max})
- Secondary voltage (rms value) 893 V
- Frequency 900 Hz
- Test voltage (N1 ↔ N2) 9.5kV; 50 Hz; 60 s

The basis of the prototype transformer was a core



Key: ***SU*** *standardized split tape core, sheet thickness 0.1 mm (material: C5 korno)*
AMCC *AMM cut core (material: Metglas Alloy 2605SA1)*
VAC *NCM cut core (material: Vitroperm 500)*
Steplap *stacked core, transformer sheet thickness 0.3 mm*
Toroid *toroid core, transformer sheet thickness 0.3 mm*
DDGAP *bent core, transformer sheet thickness 0.1 mm*
DUO *bent core, transformer sheet thickness 0.15 mm*

Figure 1 *Comparison of measured noise vs. flux density for different types of magnetic circuit at an operating frequency of 900 Hz*

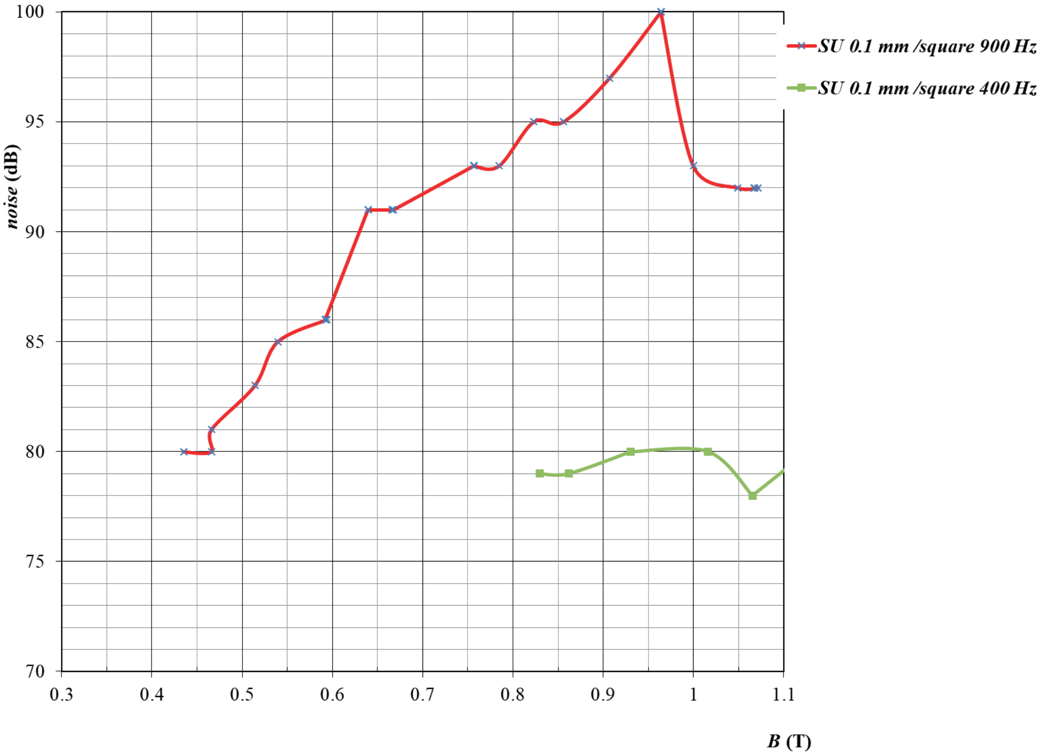


Figure 2 *Comparison of measured noise for standard split core at frequencies 400 and 900 Hz*

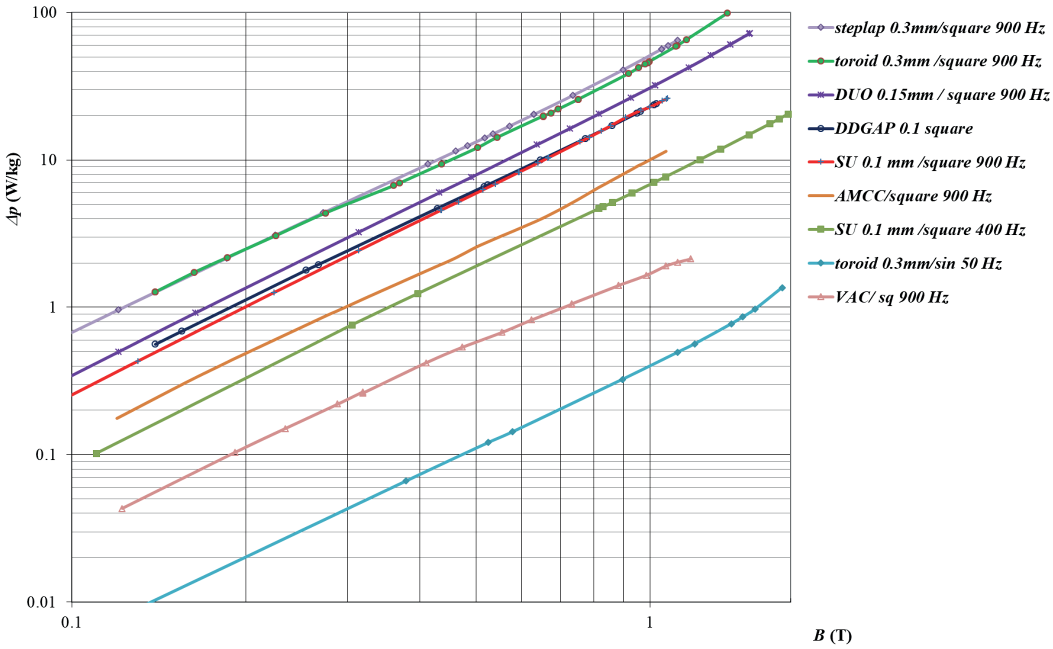


Figure 3 *Comparison of measured specific iron losses from flux density for different types of cores (core design and material)*

made from the amorphous metal materials type UMCCC-2553. The transformer design is a shell type with 6 pieces (2xC) of core. During measurements on the prototype transformer, a very negative phenomenon was found - noise, the level of which exceeded the limit of 80 dB (limit value of traction equipment) already at an induction of approx. 0.45 T, at the nominal operating point it was approx. 100÷104 dB.

A number of measurements and experiments have been devoted to identifying the reasons for existence and elimination of noise [6-8]. In Figure 1, a comparison of the noise of the selected magnetic circuits can be seen as a function of the flux density at a frequency of 900 Hz and when supplied with a voltage with a square-shaped waveform. It should be noted here that this was not an exact noise measurement in a noiseless chamber, but in

a) b)

Figure 4 *Photography of isolation transformer T1O-200-2000/893: a) a prototype of the transformer with a built core made from AMM; b) a new design with a bent core made of 0.1 mm thick transformer sheet*

laboratory conditions with possible noise overlap from the external environment. The measured characteristics is further complemented by a remark, the conclusion that the measured noise was about 3÷5 dB lower when supplied with a sinusoidal voltage waveform. For full information, Figure 2 shows the measured noise for a cut core composed of 0.1 mm thick transformer sheet at 900 and 400 Hz, for a frequency of 5 Hz the noise was unmeasurable under the given conditions with respect to the background i.e. less than 60 dB.

From these measurements it was concluded that the main cause of the noise is the operating frequency of 900 Hz, which is not only clearly audible to the human ear, but the oscillation, the banging of the sheet metal in the air gap, is of such a magnitude that it results in a significant noise.

In addition to noise measurements, these measurements also identified specific core losses in the magnetic circuits, see Figure 3, where it can be seen why an AMM (type UMCCC) was chosen for the prototype implementation (Figure 4), which at this frequency of 900 Hz is the second best after the NCM cores (VAC), but the VAC cores are not produced in the required size.

As mentioned above, different variants were analysed, either in shape, core design (2xC core, toroid, DDGAP) or material used (amorphous AMCC, UMCCC, nanocrystalline VITROPERM 500, VITROPERM 500F, 0.3; 0.15; 0.1 mm sheet metal). Considering the noise, the chosen application, the losses, the manufacturing possibilities, etc., the folded core "step lap" design became the basis for the final design of the transformer and the material chosen was GT 100, i.e. sheet metal with a thickness of 0.1 mm.

The above shortcomings were eliminated by a new way of designing the magnetic circuit and windings of the MfT based on the requirement to suppress magnetostriction in the core sheet metal bundle of the magnetic circuit and thus minimize the noise caused by this phenomenon, as much as possible. The essence of the solution is that for the cores of the MfT magnetic circuit, an electrical sheet of 0.1 thickness, or thinner, with a smaller coefficient of magnetostriction, is used. This sheet is cut in the longitudinal direction and bent by AEMcore technology into an "O" shape, with the individual sheets in contact to form a distributed air gap, with the individual sheets in the bundle having the ability to dilate and thus compensate for the effect of the magnetostriction phenomenon. The actual joining of the plates may be in the coupling or in the column, whichever is more convenient from the point of view of assembly. The number of individual cores of the magnetic circuit also depends on the power of the transformer. The method and design of the individual cores and their assembly into a complete magnetic circuit and the requirement to design at least one winding as a high-voltage winding make it necessary to design the transformer as a core transformer, with two concentric coils of individual windings. Losses arising in the individual cores of the magnetic circuit are dissipated by forced air cooling, the cooling channels being formed by insulating spacers between the individual cores. Likewise, losses arising in the windings are dissipated from the surfaces of the individual windings, by means of channels formed therein by insulating wedges, also

***Table 1** Parameters of the designed transformer*

Parameter	Value
Rated power	200 kVA
Primary voltage (rms value)	2000 V (4000 V_{max})
Secondary voltage (rms value)	893 V
Frequency	900 Hz
Test voltage (N1 ↔ N2)	9.5kV; 50 Hz; 60 s
Insulation temperature class	F
Cooling AF	forced air, >5 m/s
Cooling AF	forced air, >5 m/s
Load type	S1 (permanent)
Operating ambient temperature	-40 °C ÷ +60 °C
Vibration and shock according to	EN 60373
primary winding resistance	0.01945 Ω
secondary winding resistance	0.00232 Ω
short-circuit voltage	9%
The weight of the transformer	118kg

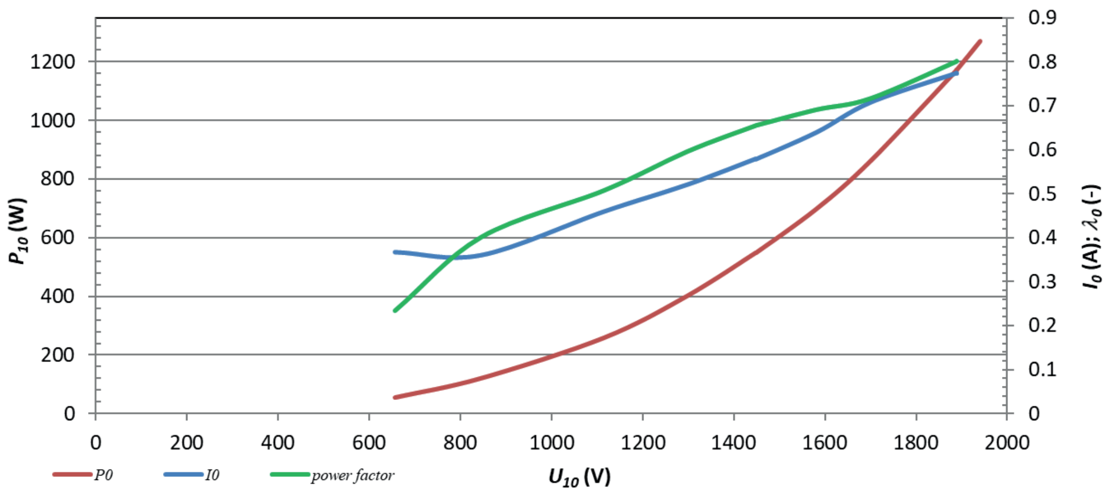


***Figure 5** Measured no load characteristics*

filling the insulating barrier between the windings by means of cooling air. The nominal parameters of designed transformer are listed in Table 1, while the initial experimental verification of the operational properties is shown in Figure 5.

The title of the article states a frequency of 1 kHz, whereas the actual operating frequency of the tuned power circuit was 900 Hz in the final. The conclusions stated are also valid for a frequency of 1000 Hz. The design of the transformer was done analytically based on the experience of the author's team in the development of the Mf transformer series.

3 Conclusion

This paper deals with the noise level of power transformers operating at 900 Hz, 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 900 Hz, with a power 200 kVA, cooled by air, to be fed from a suitable frequency converter characterised by reduced noise, are described. Considering the noise, the chosen application, the losses, the manufacturing possibilities, etc., the folded core "step lap" design, became the basis for the final design of the transformer and the material chosen was GT 100, i.e. sheet metal with a thickness of 0.1 mm. The proposed solution allows implementation of the 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's noise on the surrounding environment.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] KUCHTA, J., FRANKO, M. The concept of the traction circuits for modernizing electric locomotives on two traction feed systems. In: 18th International Conference Current Problems in Rail Vehicles PRORAIL 2007: proceedings (in Slovak). 2007. ISBN 978-80-89276-06-6, p. 377-385.

[2] KUCHTA, J., KUCERA, R., FRANKO, M., FULIER, M. Modernization of locomotive r.361 from the perspective of development of new components of traction equipment. In: 20th International Conference Contemporary Issues in Rolling Stock PRORAIL 2011: proceedings (in Slovak). Vol. II. 2011. ISBN 978-80-89276-31-8, p. 193-202.

[3] KUCHTA, J., FRANKO, M., ILONCIAK, J. Concept of traction and auxiliary converters for diesel-electric locomotives. In: 22nd International Conference Contemporary Problems in Rolling Stock PRORAIL 2015: proceedings (in Slovak). 2015. ISBN 978-80-89276-48-6.

[4] FRANKO, M., KUCERA, R., BUDAY, J. Modernization of locomotive s.365 with regard of new components of traction equipment. In: 24th International Conference Contemporary Issues in Rolling Stock PRORAIL 2019: proceedings (in Slovak). 2019. ISBN 978-80-89276-58-5, p. 127-134.

[5] KUCERA, R., FRANKO, M., BUDAY, J., KOVAC, M. Assessment of interoperability subsystems "railway vehicle" of series 365 related to the required parameters and tests of traction converter and auxiliary converter. In: 24th International Conference Contemporary Issues in Rolling Stock PRORAIL 2019: proceedings (in Slovak). 2019. ISBN 978-80-89276-58-5, p. 381-387.

[6] RAJNAK, M., TIMKO, M., KOPCANSKY, P., PAULOVICOVA, K., KUCHTA, J., FRANKO, M., KURIMSKY, J., DOLNIK, B., CIMBALA, R. Transformer oil-based magnetic nanofluid with high dielectric losses tested for cooling of a model transformer. *IEEE Transactions on Dielectrics and Electrical Insulation* [online]. 2019, **26**(4), p. 1343-1349. ISSN 1070-9878, eISSN 1558-4135. Available from: https://doi.org/10.1109/TDEI.2019.008047

[7] KANG, M., ENJETI, P. N., PITEL, I. J. Analysis and design of electronic transformers for electric power distribution system. *IEEE Transactions on Power Electronics* [online]. 1999, **14**(6), p. 1133-1141. ISSN 0885-8993, eISSN 1941-0107. Available from: https://doi.org/10.1109/63.803407

[8] HUANG, P., MAO, CH., WANG, D., WANG, L., DUAN, Y., QIU, J., XU, G., CAI, H. Optimal design and implementation of high-voltage high-power silicon steel core medium-frequency transformer. IEEE Transactions on Industrial Electronics [online]. 2017, **64**(6), p. 4391-4401. ISSN 0278-0046, eISSN 1557-9948. Available from: https://doi.org/10.1109/TIE.2017.2674591