Iron Losses in a Medium-Frequency Transformer operated in a High-Power DC-DC Converter

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***Abstract*—The three-phase dual-active bridge is a dc-dc converter, which is highly suitable for high-power application. Amongst others, this is due to the medium frequency transformer in the ac link, which provides galvanic isolation. The transformer is operated with a square-shaped voltage waveform. The flux density in the transformer core is piece-wise linear. But for the sake of simplicity, the magnetic flux is often assumed sinusoidal. Thereby, the actual iron losses generated in the core material are misinterpreted. This paper discusses the difference between the actual piece-wise linear and the sinusoidal course in terms of iron losses. Silicon steel with a thickness of $0.18\,\mathrm{mm}$ is measured at a frequency of $1000\,\mathrm{Hz}$, comparing the sinusoidal excitation with the actual one. The mismatch in the iron losses is quantified finally.**

***Index Terms*—DC-DC power converters, Power transformers, Loss measurement, Magnetic hysteresis, Soft magnetic materials**

I. Introduction

The three-phase dual-active bridge (DAB3), as depicted in Fig. 1, is a dc-dc converter, which is especially suitable for high-power applications [1]. Its inherent soft-switching capability reduces the switching losses drastically. Thereby, the efficiency of the converter is increased. The three-phase transformer in the ac link provides galvanic isolation, which is often essential in high-power applications for safety reasons and to prevent common-mode currents [2]. Additionally, any dc-dc voltage conversion ratio can be set by the winding ratio of the transformer.

The three-phase transformer is operated at elevated frequency, to achieve high power density and to decrease core losses. In this work, the output power of the dc-dc converter is rated for $P = 5\,\mathrm{MW}$. The switching frequency of the semiconductor switches and with it the fundamental frequency of the flux in the transformer is $f = 1\,\mathrm{kHz}$. The primary and secondary side dc voltages are $U_{\mathrm{pDC}} = U_{\mathrm{sDC}} = 5\,\mathrm{kV}$.

In a DAB3, the input and output bridge generate a six-step wave form as depicted in Fig. 2. Power is transferred by inducing a phase shift between the input and output bridge, where the output bridge is lagging by the load angle φ. Due to the voltage difference across the transformer's stray inductance L_σ, a current is built up in the ac link, leading to a power flow through the converter.

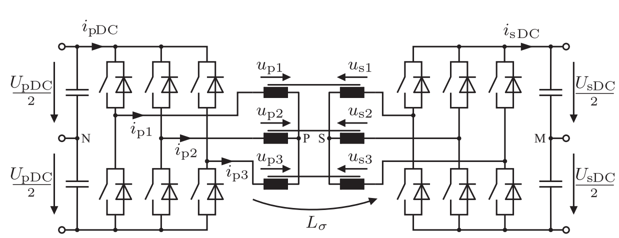


Fig. 1. Topology of a DAB3 dc-dc converter

II. Operation of the Medium-Frequency Transformer

The phase voltage at the transformer is a six-step waveform with the discrete values $\pm\frac{2}{3}U_{\mathrm{DC}}$, $\pm\frac{1}{3}U_{\mathrm{DC}}$ as also depicted in Fig. 2. According to the main inductance of the transformer L_{m}, a magnetization current i_{m} is built up, which generates the magnetic flux ϕ in the transformer core. Correspondent to the integral of the phase voltage, the course of the magnetic flux is piece-wise linear. In the following, silicon steel is measured and the difference between sinusoidal and piece-wise linear excitation is investigated.

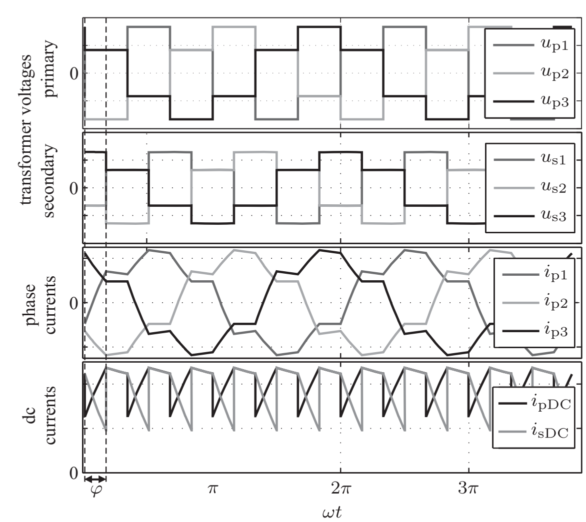
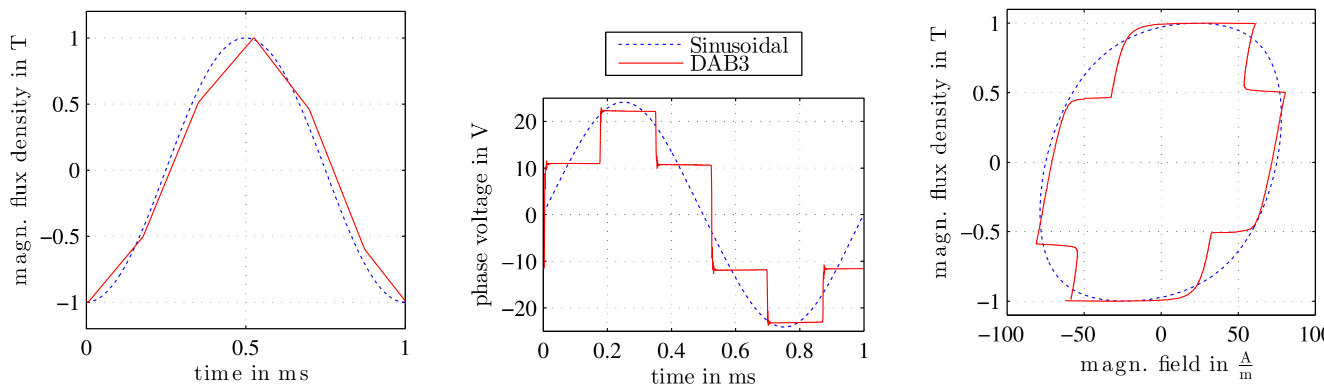


Fig. 2. Characteristic waveforms in a three-phase DAB



(a) Magnetic flux density in the core material
(b) Compared transformer voltages
(c) Magnetic hysteresis loop

Fig. 3. Measuring results

III. Core Losses in a DAB3

To determine the transformer-core losses in a DAB3 application, measurements for frequencies up to $f = 1000\,\mathrm{Hz}$ of the laser-processed grain-orientated steel (thickness $d = 0.18\,\mathrm{mm}$) were performed with an Epstein frame at the Institute of Electrical Machines (IEM) of RWTH Aachen University. The test bench allows to generate any arbitrary form of the flux density. Thereby, a sinusoidal flux density can be compared with the actual flux curve in a DAB3 application. In the following, these cases are referred to as "sinusoidal" and "DAB3". In Fig. 3 and Fig. 4, the red solid graphs represent the DAB3, while the blue dashed graphs represent the sinusoidal excitation. Figure 3 (a) shows the reference magnetic flux density generated in core material, whereat Fig. 3 (b) depicts the voltage set by the test bench to achieve the reference flux. The voltage curve corresponds to the phase voltage in a DAB3. In a first comparison, Fig. 3 (c) shows that the specific iron losses for DAB3 tend to be smaller, as less area is spanned by the hysteresis loop. Figure 4 shows the specific iron losses measured in the core material as a function of the flux density. From that measurement, some data points are given separately in Table I, where B is the magnetic flux density and P_{s} is the specific iron loss in the material. The relative error is given as well. It is evident that the losses in a material for DAB3 are actually lower as for sinusoidal excitation. As for equal peak flux densities the maximum $\frac{\mathrm{d}B}{\mathrm{d}t}$ for DAB3 is smaller when compared to sinusoidal excitation, the specific iron losses are also smaller. The verification based on a state-of-the-art model [3] on the one hand and the IEM-Formula [4], [5] on the other is given in the final paper.

IV. Conclusion

In the future, dc-dc converters play a key role in the electric energy supply. The three-phase dual-active bridge is a perfect candidate for high-power dc-dc conversion. In this type of converter, the actual course of the magnetic flux density in the transformer is often approximated with a sinus. Thereby, the iron losses generated in the transformer are overestimated. Measurements have shown, that the actual power loss density

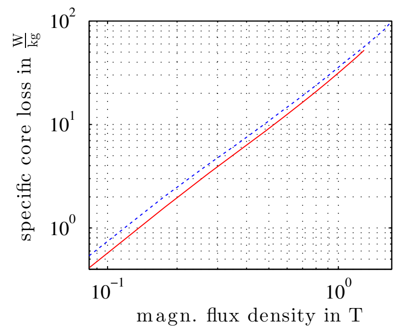


Fig. 4. Specific core loss for sinusoidal and piece-wise linear course

TABLE I
Specific Core Losses

$B_{\max}$ in T	P_{s} in W/kg		$\frac{\Delta P_{\mathrm{s}}}{P_{\mathrm{s}}}$
	Sinus	DAB3	
0.1	0.54	0.41	32 %
0.5	9.61	8.59	12 %
1.0	33.96	31.09	9 %
1.5	73.90	69.73	6 %

is up to more than $30\,\%$ lower than the sinus approximation. The final paper will include the verification using a state-of-art model and the IEM-Formula. Furthermore, a comparison concerning the transformer's iron losses between the single-phase and the three-phase dual-active bridge is given.

References

[1] De Doncker, R.W.; Divan, D.M.; Kheraluwala, M.H., "A three-phase soft-switched high-power-density DC/DC converter for high-power applications," IEEE Transactions on Industry Applications, vol.27, no.1, pp. 63-73, 1991.

[2] Gonzalez, R.; Gubia, E.; Lopez, J.; Marrojo, L., "Transformerless Single-Phase Multilevel-Based Photovoltaic Inverter," IEEE Transactions on Industrial Electronics, vol.55, no.7, pp. 2694-2702, 2008.

[3] Venkatachalam, K.; Sullivan, C.; Abdallah, T.; Tacca, H., "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," IEEE Workshop on Computers in Power Electronics, pp. 36-41, 2002.

[4] Jacobs, S.; Henrotte, F.; Herranz Gracia, M.; Hameyer, K.; Goes, P.; Hectors, D., "Magnetic material optimization for hybrid vehicle PMSM drives," World Electric Vehicle Journal (www.evs24.org/wevajournal), vol. 3, ISSN 2032-6653, 2009.

[5] Eggers, D.; Steentjes, S.; Hameyer, K., "Advanced Iron-Loss Estimation for Nonlinear Material Behavior," IEEE Transactions on Magnetics, vol.48, no.11, pp.3021-3024, Nov. 2012