

Measurement and Simulation of Non-Oriented Electrical Steel Sheets Used in PMSM for Higher Frequency

Nijan Yagal¹, Christian Lehrmann¹, Markus Henke², Christian Heister², Hao Zheng²

¹*Explosion-protected Electrical Drive Systems, Physikalisch-Technische Bundesanstalt, Germany, nijan.yagal@ptb.de*

²*Institute for Electrical Machines, Traction and Drives, Technische Universität Braunschweig, Germany*

Abstract

Permanent magnet synchronous machines (PMSMs) are extensively used because of their superior advantages in industrial applications and electrical vehicles (automotive industry). The losses present in these machines are however of major concern in their application. To precisely determine the core losses in the electrical steels used to manufacture rotors and stators of PMSMs, a better understanding and measurement of the *B-H curve* and iron losses of the materials is required. In this paper, different kinds of non-orientated electrical sheets are measured using a ring core measurement test setup and simulated in Opera 2D software using sinusoidal waveforms with varying frequencies.

Keywords: finite element calculation, materials, material handling, permanent magnet motor, synchronous.

1. Introduction

A PMSM is driven by a frequency converter with modulated voltage which causes additional current harmonics with varying switching frequencies of the inverter, resulting in higher harmonics and iron losses. The accurate or precise measurement and understanding of the iron losses of the electrical sheets is important before calculating the iron losses of the PMSM using any finite element method (FEM) software that is available on the market. The characteristics of the materials are directly dependent on the operating frequency. Nevertheless, most of the proposed methods are performed in the standard 25 cm Epstein frame measurement system (Standard IEC 60404-2) [1-5] which has a fixed frame size and could cause high temperatures in the winding due to high frequencies. The ring test method (Standard IEC 60404-6) [6] is used to determine the iron loss of non-oriented (NO) electrical steel sheets. It provides a continuous magnetic flux path without any air gaps which helps in the accurate calculation of the length of the uniform distributed magnetic field strength *H*. The ring iron core measurement system is cheaper and the test is simple to prepare as it does not require any special measurement system as for the Epstein frame [7].

In this paper, iron loss measurements at higher frequencies for semi-finished materials (M450P-50K) and fully-finished materials (M400-50AP) are presented. Semi-finished NO electrical steels sheets do not have guaranteed magnetic properties when they are supplied by the steels manufacturer. The motor manufacturer punched the semi-finished electrical sheets to the desired shaped and they are further processed to heat-treatment to develop desired magnetic properties. This final annealing treatment reduces losses and improves permeability and polarisation of the NO electrical steels sheets. Whereas Fully-finished NO electrical steels sheets are fabricated with careful selection of alloying content (particularly silicon, Si) in combination with

the most suitable thermo-mechanical (annealing) manufacturing process. At the end of this paper, iron loss measurements in a ring core of different NO electrical steel sheets are presented at higher frequencies as well. In the Opera 2D finite element calculation software, the ring core measurement system is built and it is used to compute a B - H curve and compare them to the measured B - H curves and the data sheet provided by the manufacturer.

2. General measurement principle of the magnetic losses of NO electrical sheets

The iron loss measurement test setup for continuous measurement is shown in Fig. 1. The signal frequencies generator is used to supply varying frequencies (50 Hz - 12 kHz) in the inputs of the ring core measuring system. The measured current of the primary coil and measured voltage of the secondary coil are displayed on an oscilloscope and imported into Matlab for further calculation. With the current of the primary coil, the magnetic field strength H and the voltage of the secondary coil, the magnetic flux density B is calculated. With these two values, the B - H curve is determined and plotted in Matlab. The losses are also calculated using the B - H curve for varying frequencies.

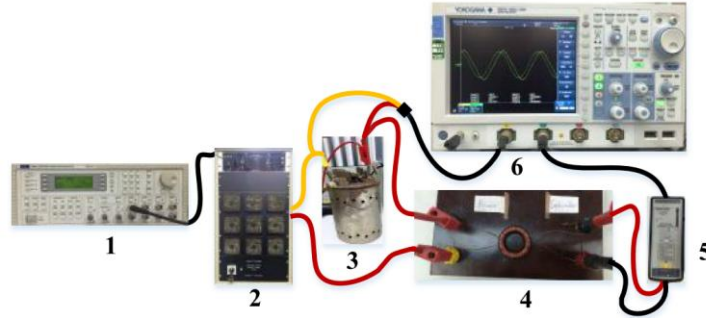


Figure 1: Measurement setup of iron loss of the ring core (1: signal generator, 2: signal amplifier, 3: shunt resistor, 4: ring core of NO electrical sheets, 5: differential probes, 6: oscilloscope)

2.1. Magnetic field strength (H)

According to Ampere's law, the magnetic field intensity in the core is calculated with the primary current I_1 in the core and the number of turns in the primary side N_1 .

$$\oint \vec{H} d\vec{s} = N_1 I_1 = \Theta \quad (1)$$

A simplified form of Eq. 1 is

$$H(r_e) = \frac{N_1 I_1}{2\pi r_e} \quad (2)$$

where r_e is the mean radius of the ring iron sheets which is calculated according to the standard IEC 60205 [8] as follows:

$$C_1 = \frac{2\pi}{h_e \ln\left(\frac{r_1}{r_2}\right)} \quad (3)$$

$$C_2 = \frac{2\pi \left(\frac{1}{r_2} - \frac{1}{r_1}\right)}{h_e^2 \ln^3\left(\frac{r_1}{r_2}\right)} \quad (4)$$

$$r_e = \frac{C_1^2}{2\pi C_2} = \frac{\ln\left(\frac{r_1}{r_2}\right)}{\frac{1}{r_2} - \frac{1}{r_1}} \quad (5)$$

$$A_e = \frac{C_1}{C_2} = h_e \frac{\ln^2\left(\frac{r_1}{r_2}\right)}{\frac{1}{r_2} - \frac{1}{r_1}} \quad (6)$$

where r_1 is the inner radius of the ring core, r_2 the outer radius of the ring core, r_e the effective radius, and A_e the effective area of the core.

The magnetic properties and losses of non-oriented electrical steel strips vary with different cutting technologies [9]. Therefore, in this paper a water jet cutter is used to cut the ring core to the dimensions shown in Table 1. The water jet cutter is used to cut semi-processed and fully processed steel sheets. The semi-processed NO electrical sheets are then annealed at high temperatures to obtain thin insulation layers. This way of mechanical cutting (water jet cutter) and then annealing prevents the NO electrical sheets from undergoing mechanical deformations (local plastic strains and internal stresses) and their magnetic properties do not vary.

Table 1: NO electrical ring specimens with dimensions

Type of NO ring sheets	M450P-50K	M400-50AP
Inner radius, r_1 (mm)	10	10
Outer radius, r_2 (mm)	13	13
No. of sheets	12	12
Processed type	semi-finished	fully finished

2.2. Magnetic flux density (B)

The magnetic flux density $B(t)$ measured using the magnetic flux $\Phi(t)$ inside the core and time variation of flux results in induced voltage V_2 in the secondary coil having N_2 turns according to Faraday's law,

$$\int_{t_0}^t V_2 dt = \Psi = N_2 \phi(t) \quad (7)$$

$$B(t) = \frac{\phi(t)}{A_e} \quad (8)$$

Using Eqs. 7 and 8 gives

$$B(t) = \frac{\int_{t_0}^t V_2 dt}{N_2 A_e} \quad (9)$$

2.3. Magnetic power losses (p_{Fe})

The effective iron losses of the iron core are calculated as follows [6, 10]:

$$p_{Fe} = \frac{1}{\rho_{Fe} V_e T} \frac{N_1}{N_2} \int_{t=0}^T I_1(t) V_2(t) dt \quad (10)$$

where $V_e = A_e 2\pi r_e$ is the effective volume and ρ_{Fe} is the specific mass density of the test iron core.

3. Measurement and simulation results

3.1. Measurement results

To verify the ring core measurement system, the M450P-50K ring core was initially tested at a 50 Hz frequency and compared with the data sheet and the measurement done with the Epstein frame measurement system as shown in Fig. 2. For a better understanding of the influence of fully finished materials over semi-finished NO materials, the M400-50AP ring core was tested and its comparison with the data sheet is also shown in Fig. 3. The influence of the number of primary and secondary windings is also studied. The optimal number should be determined for fast measurement but one also needs to be careful about power supply capability generating the magnetizing current [11]. The effect of the winding numbers is not presented in this paper. The simulation results are also included in this study, the magnetic flux lines are shown in Fig. 4. The final simulation results are also shown in the simulation section.

Figure 2 shows that there is a perfect match of the measured $B-H$ curve with the data sheet and the Epstein frame measurement system, whereas Fig. 3 shows there is some variation of the measured values and the data sheet in the lower value of the magnetic field intensity. One of the variations may be because of the insulation material that is present in the materials. In the fully finished materials (M400-50AP), the material is directly obtained from the manufacturer and it is cut into the desired shape of the ring. The measurement is then performed. The water jet cutter is used to cut the fully processed steel sheets (annealed by the manufacturer). Their magnetic properties may vary during water jet cutting methods. A detailed study of the insulation material after cutting it into ring shapes found that the NO electrical sheet material is poorly insulated.

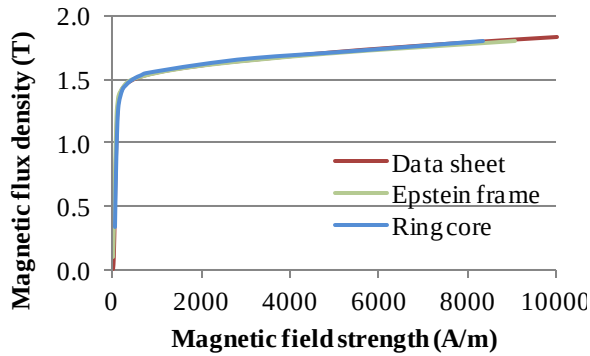


Figure 2: Comparison of the $B-H$ curve of the semi-finished M450P-50k with data sheet, Epstein frame and ring core measurement at 50 Hz

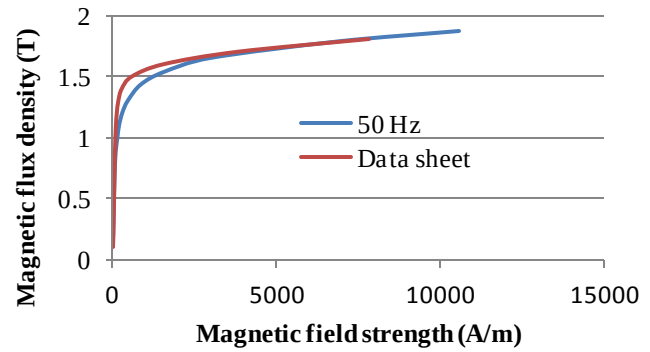


Figure 3: Comparison of the $B-P$ curve of the fully finished M400-50AP with data sheet and ring core measurement setup at 50 Hz

3.2. $B-H$ curve and power losses of ring core at higher frequencies

This section presents the comparison of the measurement of the $B-H$ curves and power losses of the ring cores M450P-50K and M400-50AP with varying frequencies. The results obtained are as expected, with higher frequency yields in higher iron losses as shown in Figs. 5 and 6.

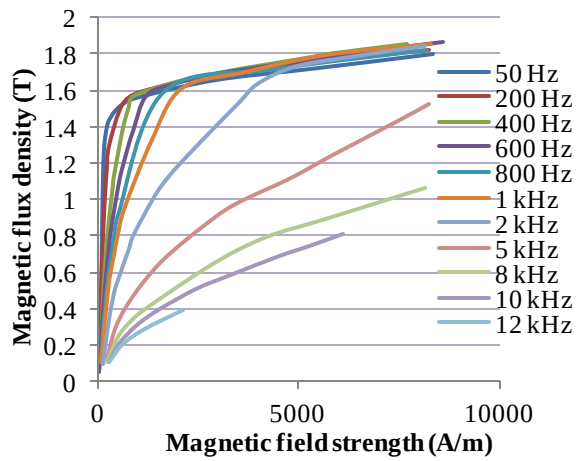


Figure 4a: B - H curve of the M450P-50K with varying frequencies

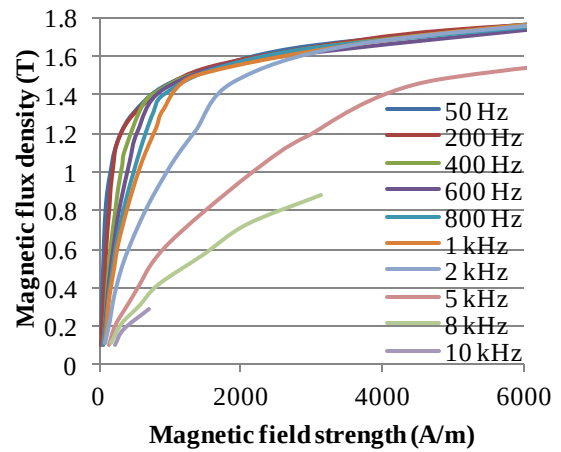


Figure 4b: B - H curve of the M400-50AP with varying frequencies

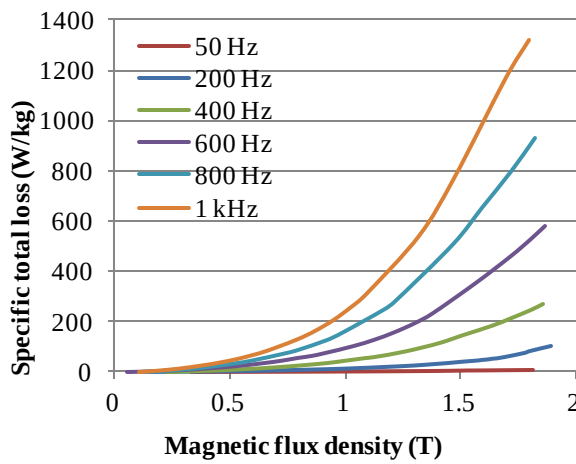


Figure 5a: Iron losses of M450P-50K using ring core measurement system from 50 Hz to 1 kHz

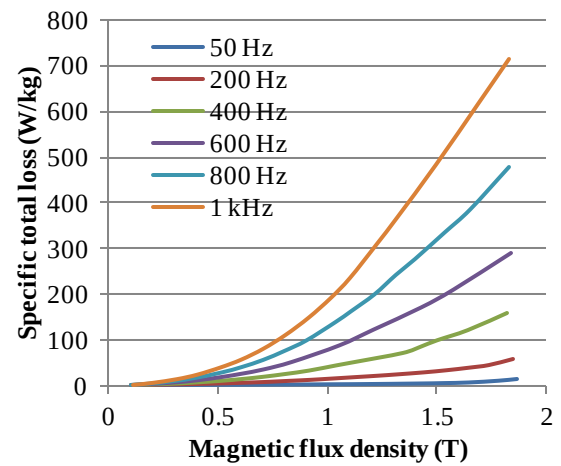


Figure 5b: Comparison of losses of M400-50AP using ring core measurement system from 50 Hz to 1 kHz

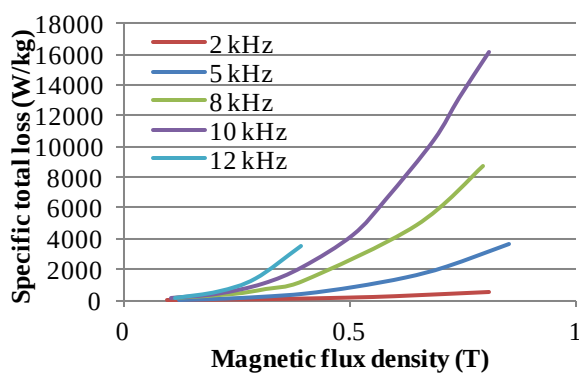


Figure 6a: Iron losses of M450P-50K using ring core measurement system 2 kHz to 12 kHz

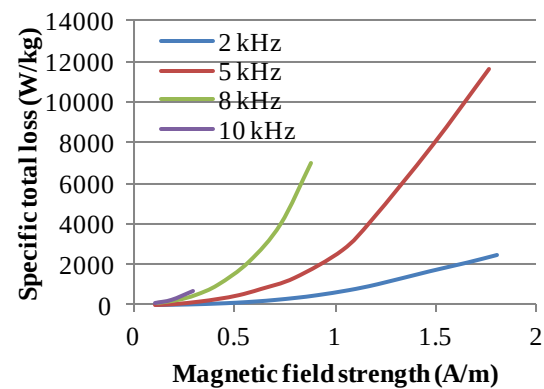


Figure 6b: Comparison of losses of M450P-50K using ring core measurement system 2 kHz to 10 kHz

3.3. Simulation results

The finite element method is used to validate how close the measured B - H curves are to the data sheet and the simulation results. Figure 4 shows the cross section of the NO ring core model in Opera 2D. The NO magnetic material iron core is marked as the blue ring area. The B - H data from the data sheet is adopted as the B - H curve for NO iron core in Opera 2D. The four red layers refer to the cross section of the primary and secondary windings. The secondary winding is wound directly onto the core. The primary winding is wound onto the secondary winding. A power source is connected directly to the primary winding. From the source a 50 Hz sinusoidal current signal is fed into the primary winding. A large resistance is used in the secondary winding as the idling resistance. The primary current i_p and the secondary voltage u_s are obtained after completing the simulation.

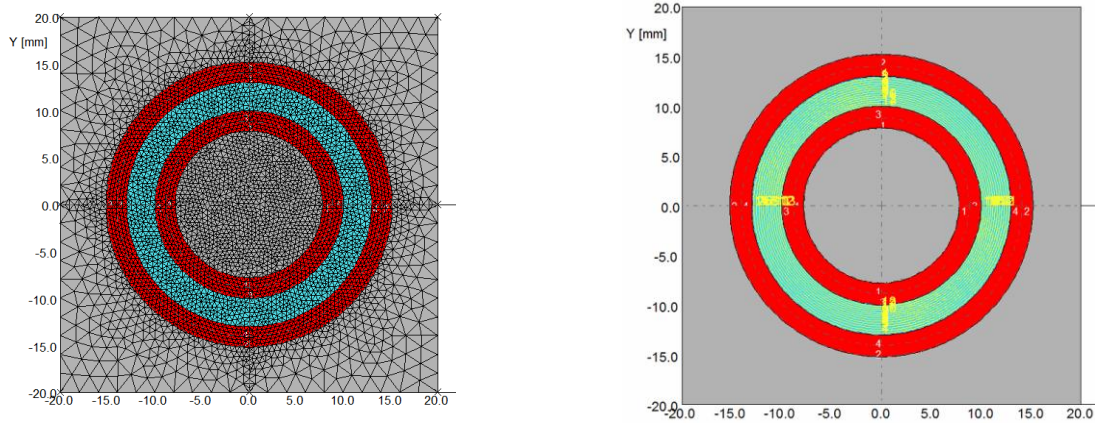


Figure 7: Magnetic flux lines plotted in 2D Opera FEM (red: primary and secondary windings, blue: ring iron core, yellow: magnetic flux lines)

From the simulation, the primary winding current i_p and the secondary winding voltage u_s are obtained. With the help of Eq. (11) and Eq. (12) using Matlab / Simulink, the magnetic field intensity (H) and the magnetic flux density (B) are calculated. After the simulation, the simulation result is evaluated using Eqs. 11 and 12. Figure 8 shows the B - H curve comparison between the simulation result, the data from the data sheet and from the measured B - H curve. The red line is the B - H curve of the simulation result. In comparison, the blue line shows the B - H curve of the data sheet. It can be seen that the two curves are almost identical.

$$H(r_e) = \frac{N_p i_p}{2\pi r_e} \quad (11)$$

$$B(t) = \frac{\int_{t_0}^t u_s dt}{N_s A_e} \quad (12)$$

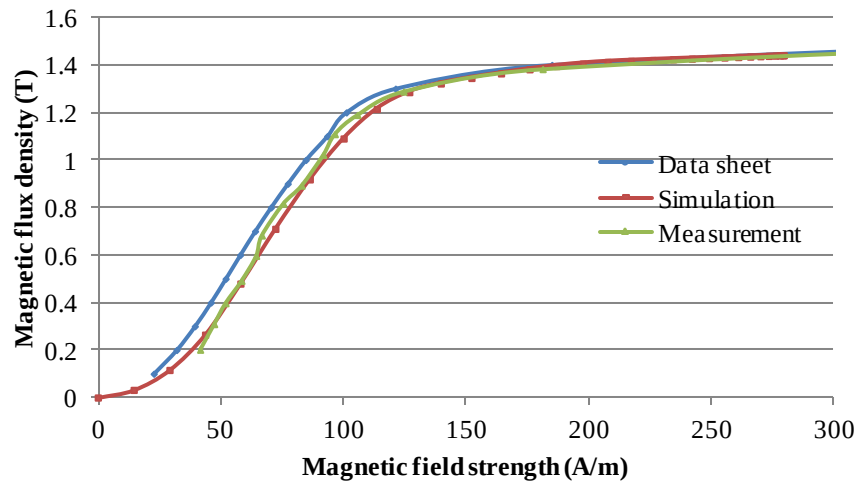


Figure 8: B - H curve from simulation, measurement and data sheet for 50 Hz

4. Conclusion

In this paper the successful measurement of the NO electrical sheets using the ring core measurement system at normal room temperature up to a frequency of 12 kHz is presented. The measured B - H curve (Figs. 2, 3 and 4) and the power losses curve (Figs. 5 and 6) are then compared with those provided by the manufacturer of the sheet material to validate the ring core measurement system. Using the proposed measurement system as shown in Fig. 1, the measurement is successfully achieved without any heating problem in the iron sheets at normal room temperature. It can be seen that the measurements obtained from the ring core measurement system agree well with the Epstein frame measurement system and the data sheet that is provided by the manufacturer and also with the article [12].

This paper provides a detailed discussion of the measurement of fully processed and semi-processed material with varying frequencies as well as losses of the iron core resulting from changing temperature. Simulation results compare the measured B - H curves with the data sheet of the NO electrical sheets. The simulated B - H curve, measured B - H curves and data sheet provided by the manufacturer are close to each other. The results of ring core measurements are perfect for semi-processed NO materials in relation to the fully processed material in this study. The deterioration effect of the magnetic properties of fully processed materials might result from the cutting process on steel edges as the electrical steel in this area might have become too saturated. Alternatively, the insulation that is present in the fully processed material might have deteriorated.

Acknowledgments

The authors would like to express sincere gratitude to Working Group 5.1 (Scientific Instrumentation) of the Physikalisch-Technische Bundesanstalt (PTB) for cutting NO electrical sheets into ring core using water jet cutter tools. Much appreciation goes to Dr Elke Panzer and Mr. Dirk Seehase from VEM motors GmbH for providing us non-oriented electrical steel sheets which we used in our test bench for measurement in this paper. Special thanks also go to Mr. Manfred Glander, Working Group 3.52 (Explosion-protected electrical Drive Systems) of PTB for giving us valuable advice and information about measurement instruments and their accuracy, which are the major challenges of this paper.

References

- [1] L. D'Alessandro and A. Ferrero, "A method for the determination of the parameters of the hysteresis model of magnetic materials," *IEEE Trans. Instrum. Meas.*, vol. 43, pp. 599–605, Aug. 1994.
- [2] E. Carminati and A. Ferrero, "A virtual instrument for the measurement of the characteristics of magnetic materials," *IEEE Trans. Instrum. Meas.*, vol. 41, pp. 1005–1009, Dec. 1992.
- [3] S. Zurek, P. Mareketos, T. Meydan, A.J. Moses, "Use of novel adaptive digital feedback for magnetic measurements under controlled magnetizing conditions", *IEEE Trans. Mag.*, Vol. 41, No. 11, Nov. 2005.
- [4] G. Bertotti, "General properties of power losses in soft ferromagnetic materials," *IEEE Trans. Magn.*, vol. 24, pp. 621–630, Jan. 1988.
- [5] *Magnetic Materials - Part 2: Methods of measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame*, IEC 60404-2, Geneva, Switzerland, 2007.
- [6] *Magnetic Materials - Part 6: Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to 200 kHz by the use of ring specimens*, IEC/EN 60404-6, Geneva, Switzerland, 2006.
- [7] S. Tumanski, *Handbook of Magnetic Measurements*, 1st ed. CRC Press, 2011, ISBN: 1439829519.
- [8] *Calculation of the effective parameters of magnetic piece parts*, IEC 60205, Geneva, Switzerland, 2006.
- [9] V. Manescu et al. "The Influence of Punching and Laser Cutting Technologies on the Magnetic Properties of Non-oriented Silicon Iron Steels" *2014 International Symposium on Fundamentals of Electrical Engineering, University Politecnica of Bucharest, Romania*, Nov. 2014.
- [10] F. Fiorillo, "Measurement and Characterization of Magnetic Materials", Elsevier Academic Press, Amsterdam, 2004.
- [11] M. Petkovesk "Soft-Magnetic Ring Core Measuring System With a Decreased Number of Primary and Secondary Winding Turns," *IEEE Trans. Instrum. & Meas.*, vol. 53, pp. 444–447, April. 2004.
- [12] N. Yogal et al. "Loss comparison of non-oriented electrical steel materials to be used in PMSM under explosion protection aspects" *Power Electronics and Applications*, pp.1-7, Sept. 2015.

Authors



Mr. Nijan Yagal was born in Dhulikhel, Nepal, in 1985. He completed his MSc in Electrical Power Engineering at the Technical University of Darmstadt, Germany.

He worked at Bombardier Transportation, Mannheim, Germany while doing his Master's thesis where he was employed in the field of power electronics focusing on new semiconductor devices such as SiC MOSFET and PinFin IGBT module Si-SiC IGBT for motor converters for locomotive applications.

Mr. Yagal previously worked in the field of electrical machines at the TU Darmstadt concentrating on the simulation of PMSM. His special fields of interest are power electronics, electrical machines and electric drives. Since 2013 he has been carrying out research work on PMSM under the aspects of explosion protection as part of his PhD at the Physikalisch-Technische Bundesanstalt (PTB).



Dr.-Ing. Christian Lehrmann was born in Wolfenbüttel, Germany, in 1972. He received his Dipl.-Ing. in Electrical Engineering from the Technical University of Braunschweig in 1999.

Also in 1999 he joined Working Group 3.72 (Explosion-proof Electrical Drive Systems) at PTB, Braunschweig as a research assistant and gained his PhD in 2006. His thesis was on the type-approval procedures for explosion-protected converter-fed squirrel-cage rotors with the type of protection "increased safety". He has worked as the Assistant Head of the Explosion-protected Electrical Drive Systems Working Group since 2006 where he undertakes research into electric motors and electric drives in the field of explosion protection with high safety. Dr. Lehrmann is a member of the working group on drives technology at the VIK (German Federation of Industrial Energy Consumers) as well of IEC TC 31 Working Group 27 focusing on electric machines (motors and generators).

In 2008 he was awarded the Adolf Martens Prize for a new explosion protection concept for converter-fed drives with the type of protection "increased safety".



Prof. Dr.-Ing. Markus Henke was born in Oelde, Westfalia, Germany, in 1968. Prof. Dr.-Ing. Markus Henke received the Dipl.-Ing. degree in electrical engineering from the University of Paderborn. In 1996 he became a research assistant at the University of Paderborn designing linear electrical machines in mechatronic railway applications. In 2002 he received his Dr.-Ing. in the field of electrical machine design and control.

In 2003, he joined Volkswagen AG Wolfsburg, Germany, where in 2007 he became head of the research department for electrical drives. Since 2012, he is University Professor for electrical drive systems at the Technical University of Braunschweig, and there he is the head of the Institute for Electrical Machines, Traction and Drives (IMAB).



Mr. Christian Heister was born in Hamburg, Germany in 1986. He received his Bsc. of electrical engineering and business administration in 2011 and Msc. in 2013 at the Technische Universität Braunschweig. The main focus of his Msc studies was Electric machines (design and calculation), Automatic Control systems, power electronics, Finance, production and logistics.

Since 2013 he has been working as scientific research assistant at the Institute for Electrical Machines, Traction and Drives (IMAB) at the Technical University Braunschweig. His current field of application includes the design of electrical machines and armature windings.



Mr. Hao Zheng was born in Urumqi, Xinjiang, China, in 1991. He completed his BE in Mechatronics Engineering at Tongji University (Shanghai, China) in 2013. In 2012 he came to Germany as an exchange student and studied at the Hochschule Zittau/Görlitz – University of Applied Sciences.

Since 2013 he has been studying Electrical Engineering at the Technical University of Braunschweig. In 2015 he began his Master's thesis at the Technical University of Braunschweig and started working as a member of the Explosion-protected Electrical Drive Systems Working Group at PTB. His work in this field focuses on the study and measurement of magnetic properties of different non-oriented electrical steel sheets that are used in explosion-proof electrical machines and building the automatic measuring test bench for ring core measurements. His thesis will mainly focus on the measurement and simulation of NO electrical sheets.