19ENG06 HEFMAG

Publishable Summary for 19ENG06 HEFMAG
Metrology of magnetic losses in electrical steel sheets for high-efficiency energy conversion

Overview

Magnetic steel is used for electric motors/generators and transformers, and in both cases the energy losses occurring in the cyclic magnetising of the material are significant. Due to the drive to increase energy efficiency, improved methods were required to assess these energy losses. This project aimed to develop and validate methods and experimental setups for traceable magnetic loss measurements in thin magnetic steel sheets extending the induction, frequency and temperature ranges beyond the current IEC 60404 standards, and to study and model power losses under real operating conditions. The outputs achieved in this project will improve the design and performance of magnetic and power electronics devices in support of the Ecodesign Directive 2009/125/EC and the goals of the United Nations 2030 Agenda for Sustainable Development. The project was able to successfully deliver all of its objectives.
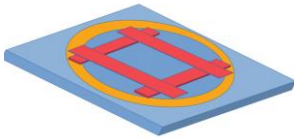
Need

The drive to improve energy efficiency, reduce consumption and curb CO_2 emissions has led to the introduction of increasingly stringent EU and national legislation related to energy efficiency and emissions reduction. Magnetic steel sheets are the core of electric motors, generators, and transformers, which produce and convert virtually all the energy obtained from conventional and renewable sources. Due to the cyclic magnetising of the steel sheets the energy losses that occur are very significant and can easily reach up to 10 %. The ongoing drive for miniaturisation of devices and high-speed rotating machines require increased working frequencies, and steel producers have therefore been striving to develop thinner and highly energy-efficient grain-oriented (GO) and non-oriented (NO) magnetic steels, with enhanced permeability, suitable for kHz frequencies. Novel products based on electrical steel required magnetic loss measurements and modelling under extreme operating conditions, with high temperature, 2D excitation, distorted flux with high harmonic content, skin effects and dc currents.

Objectives

The overall objective of the project was to support the development and characterisation of high efficiency electromagnetic machines (e.g. electric motors and transformers), which operate close to saturation induction and at high temperatures and frequencies, through (i) the development and validation of methods and experimental setups for traceable magnetic loss measurements in thin magnetic steel sheets extending the induction, frequency and temperature ranges beyond the current IEC 60404 standards and (ii) the study and modelling of power losses under real operating conditions, thus facilitating improvements in the design and performance of magnetic and power electronics devices as required by the Ecodesign Directive 2009/125/EC.

The specific objectives of the project were:

1. To build and validate an improved metrological infrastructure for the determination of power losses with relative standard deviation (σ) down to 1 %, using Single Sheet and Epstein frame magnetic circuits in electrical steel laminations at induction values close to saturation and at frequencies ranging from DC to 10 kHz with flux waveforms of different harmonic content. The dynamic magnetic characterisation will target novel thin laminations with thickness as low as 0.20 mm for non-oriented steels and 0.18 mm for grain-oriented materials.

2. To build and validate a new metrological infrastructure for Epstein frame measurements up to 155 °C, corresponding to the "F class" insulation (IEC 60085 and IEC 60034-1), to match the typical operating

temperatures of electric motors, with a direct impact on loss and efficiency evaluation, since the current standard measurement temperature is 23 °C ± 5 °C.

3. To study and model power losses in thin sheets within a DC-MHz frequency regime, with the help of fluxmetric, magneto-optical characterisation techniques as well as scanning probe techniques for the sub-μm regime.

4. To use one-dimensional and two-dimensional measurements and physical models, taking into account the non-uniform flux profiles due to the skin effect, in order to bridge the gap between standard loss characterisation under ideal conditions and real operating condition of state-of-the-art magnetic devices. To also emulate the two-dimensional flux loci arising in the non-oriented steel laminations in the stator core of a rotating machine.

5. To facilitate take up of the results by industry, NMIs and standardisation bodies (IEC TC 68 and ISO/TC201/SC 9) by providing updates on magnetic imaging techniques and good practice guides for improved traceable magnetic loss measurements at higher frequency and induction, allowing for an evolution of the current IEC 60404 standards for loss measurement reflecting up-to-date industrial needs.

Progress beyond the state of the art

Prior to this project, intercomparisons on measurements of magnetic loss measurements involving NMIs and stakeholders had been performed only at 50 Hz, yet modern electrical machines are excited at higher induction and higher frequencies. This project extended the frequency and induction range of traceable and validated loss measurements by performing a round robin test between an Epstein frame and a single sheet tester (SST) at 50 Hz and 100 Hz as well as a new Epstein frame round robin test up to 10 kHz.

Before, all magnetic loss calibration measurements at European NMIs and stakeholders were only carried out at 23 °C ± 5 °C, although electrical machines may operate at temperatures exceeding 100 °C at which saturation magnetisation, anisotropy and electrical conductivity are reduced. This project developed and validated a new metrological infrastructure for Epstein frame measurements at temperatures up to 155 °C, to match the typical operating temperatures of electric motors.

Alternating power losses could be accurately measured and modelled only under sinusoidal flux conditions, but in many modern electrical machines a very high harmonic content and skin effects are both present. This project provided and applied a comprehensive approach to physically based wideband loss modelling in the presence of skin effects. This enabled improved loss prediction under arbitrary flux waveforms and up to the MHz range based on data measured under sinusoidal flux conditions.
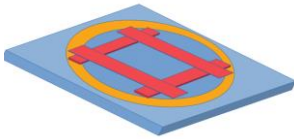
Although several experimental techniques were available at selected NMIs and stakeholders for the determination of 2D losses, no measurement standard had been established. To bridge the gap between standard loss characterisation under ideal conditions versus real operating conditions of state-of-the-art magnetic devices, this project used a comprehensive experimental and modelling approach which compared one- and two-dimensional measurements with physical models taking into account the non-uniform flux profiles due to the skin effect.

The data collected according to the current IEC standards and from additional interdisciplinary experimental techniques were the key ingredients in the study of the energy losses in soft magnetic materials. However, the results obtained during this project went beyond the current state-of-the-art by providing a necessary update to the standard loss measurement techniques at the European NMIs and stakeholder laboratories, reducing the expanded uncertainty, increasing the temperature and frequency ranges and the peak induction, and by enabling the analysis of losses in the presence of eddy currents and complex harmonic content.

Results

Power losses with standard measurement setups:

A set of FeSi NO, GO and FeCo reference samples were obtained through Stakeholder Committee members. The round-robin protocol draft was written also as a foundation for a good practice measurement guide. The partners performed the round-robin activities using Epstein frame samples and equipment at room temperature

19ENG06 HEFMAG

in a frequency range from 50 Hz up to 10 kHz, as well as Single Sheet Tester (SST) samples and equipment at room temperature from 50 Hz to 100 Hz.

Loss measurements performed on NO and GO FeSi laminations achieved the project objective 1 of a relative standard deviation of 1 %, while on FeCo Epstein laminations (with dimensions of 300 mm x 30 mm x 0.2 mm), a standard deviation below 1.5 % was achieved in a majority of measurements; the higher uncertainty was also connected to the magnetostrictive properties which cause vibrations during the tests. On conventional FeSi SST samples (with dimensions of 500 mm x 500 mm x 0.18-0.2-0.3 mm), a standard deviation below 1 % was achieved in almost all measurements. Detailed reports of the round robin measurements and a good practice guide on the measurement of power losses in non-oriented and grain-oriented steel sheets at frequencies ranging from DC up to 10 kHz using standard measurement setups at room temperature have been made publicly available on Zenodo and the project website.

Power losses under operating temperature conditions:

The validation of the new metrological infrastructure as set out in **objective 2 was achieved** through measurements at temperatures of 23°C, 50°C, 100°C, and 155°C performed on one NO sample and on one FeCo sample. The results of the validation showed that on the Epstein FeSi NO 0.2 mm sample, a relative standard deviation $\sigma < 1$ % was achievable in most cases, while on FeCo $\sigma < 2$ % was generally achieved . A measurement report and a good practice guide on the measurement of power losses in non-oriented and grain-oriented steel sheets at frequencies ranging from DC up to 10 kHz using standard measurement setups with variable temperature were made publicly available on Zenodo and the project website.

Alternating power losses in thin sheets up to the MHz range:

Objective 3 was achieved by a combination of different activities, with all results publicly available: 1) The high frequency power loss was studied by Epstein frame magnetic loss measurements up to 10 kHz on NO materials. These results were used to analyse losses in the presence of eddy currents as defined by the joint analysis of the average volume magnetization and the surface magnetization (measured using the Kerr effect and microscopy). 2) Key meteorological results were obtained on toroids of thin nanocrystalline ribbons (10-20 um) and on sintered ferrite powder rings, measured and modelled up to 1 MHz. A technical report was produced by INRIM and NPL containing the results of the high frequency loss comparison which showed that an uncertainty of 3-4 % was obtained up to 1 MHz. 3) Additionally, a report on distorted waveform measurements was completed with reference to IEC TC-68 activities.
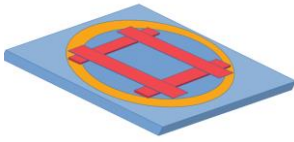
Two-dimensional magnetisation and power losses:

Objective 4 of the project was achieved though the following: 1) A totally new comparison of loss data between three different vector magnetisers and unidirectional Epstein setup was performed and a good agreement was observed across the different experimental setups with 5% uncertainties. 2) A study was completed on the role of sample geometry on the magnetisation curve and losses in high permeability FeSi GO transformer laminations cut along different directions from rolling to transverse, at frequencies from DC to 400 Hz. A phenomenological loss prediction method was devised, based on the behaviour of hysteresis loops and energy losses independently measured under sinusoidal induction in the RD- and TD-cut Epstein strips.

Impact

The HEFMAG website was created at https://hefmag.inrim.it/, and a collaborative platform was made available at https://github.com/HEFMAG with an open access area. Additionally, a community under the title "Metrology of magnetic losses in electrical steel sheets for high-efficiency energy conversion" was started on Zenodo, where all documentation on project results and datasets have been made available. Seven open access papers were already published on international scientific journals with reviewers, which are also accessible through the project and EURAMET websites.

Consortium members presented 34 contributions related to the project at 16 different international conferences, including SMM 2023-2022, INTERMAG 2021-2023 Sendai, IEEE Eurocon 2023, HMM 2023 Wien, WMM'20, AIM 2020, Intermag 2021 and 1&2DM 2020-2022, and at a seminar organised by the UK Magnetic Society 2023. Eight training activities were held, four on loss measurements with Epstein and SST equipment or magneto-optics with more than 25 attendees from academia and industry, three related to new

personnel at NMIs, one at a project partner, and one for PhD students on magnetism in materials and measurements.

A stakeholder committee with 19 members was formed and a first meeting was organised in October 2020. Samples for Epstein and SST measurements were kindly made available by selected stakeholders and a wide number of stakeholders declared interest in participating in activities related to the round robin. A second off-line meeting was held in December 2021 to better identify stakeholder needs and interests and useful feedback was collected though a questionnaire. Reference samples were made available and used by stakeholders in 2023 and a joint data analysis of round robin results was carried out. The Stakeholders were kept informed of the final project reports and publications and follow-up activities will continue after the end of the project.

The project partners provided several inputs towards updates of existing documentary standards on measurements performed on magnetic materials through engagement with BSI, the standardisation body of the United Kingdom, through activities of CEI, the Italian equivalent of IEC, and through IEC TC 68 and IEC TC 113. Furthermore, a report on project outputs was presented at IEC TC 68 Working Group 2 Meeting at ASTM International in October 2023 on the determination of AC loss (Epstein/SST/Rings) at high frequency and at temperatures up to 155 °C. Additional activities were defined to support current IEC TC-68 initiatives.

All publications, including comparison and technical reports, good practice guides and open-access publications, are publicly accessible via the project webpage.

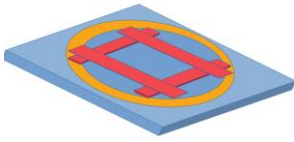*Impact on industrial and other user communities*

The outcomes of this project will benefit the power generation and supply industry; the transport sector; the machinery and metal products industries, leading to an increased energy conversion efficiency in utility transformers, high performance generators (i.e. wind and hydroelectric) and motors including aerospace, electric cars, scooters and bicycles where high efficiency is required. Novel smart-grid power distribution networks driven by renewable sources (wind, solar) as well as high power railway and aircraft/drone engines will require small size solid-state transformers operating at frequencies for which no validated measurement standards yet exist. To date, electrical machine designers have relied on inadequate magnetic hysteresis and loss data obtained under conditions that do not match real world conditions. New calibration and measurement services have been established and offered to relevant European industries, stakeholders and end users. Project results that have been disseminated through updated and new standards, publications, and good practice guides will lead to increased confidence in the use of experimental data for modelling of hysteresis and loss with noticeable improvements in electrical machine design.

Impact on the metrology and scientific communities

Extended magnetic loss measurement procedures developed in the project have been made available to the metrology and scientific communities through the project website and data repository, through reports to EURAMET TC-EM, CIPM CCEM, and the relevant IEC committees, and through good practice guides and open-access scientific publications. Reference samples produced as a result of the round robin comparisons are now available for calibrations and thus will immediately support improved magnetic loss metrology research and development. New and extended metrology infrastructure for loss measurements at high temperatures developed and established at the NMIs participating in the project is now available to the metrological and scientific community. The project also addressed magneto optical surface characterisation under dynamic and elevated temperature conditions that have not been performed on electrical steel to date, as well as studies of the AC magnetic field penetration affected by the skin effect and by local structural defects in a wide frequency range from 50 Hz-10 kHz. The results obtained provided parameters such as domain width and domain densities and additional information about flux penetration depths that will be used within the metrology and R&D communities as input parameters for extended magnetic modelling to improve the reliability and effectiveness of the loss and hysteresis models.

Impact on relevant standards

This project supported the implementation of the Ecodesign Directive 2009/125/EC, which provides consistent EU-wide rules for improving the environmental performance of products by setting out minimum mandatory requirements for energy efficiency, through the development and dissemination of state-of-the-art loss measurement and hysteresis modelling techniques. The consortium has promoted the uptake of the project's results within the standardisation community through the publication of good practice guides directed to end users. This project has directly provided input to the IEC TC 68 *Magnetic alloys and steels* for discussion and

evolution of the current standards as well as to the mirror committees of standardisation bodies of the United Kingdom, Italy and Germany.

Longer-term economic, social and environmental impacts

Europe, with 500 production sites spread across 23 EU countries, is the second largest producer of steel in the world after China. Steel-making is the third largest EU industry, and closely linked to many downstream industries such as construction, automotive, electronics, mechanical and electrical engineering, where magnetic grade steel is used for the production and transformation of almost all of the distributed electric power, for industrial and household motors and now increasingly for the transport sector. The current global magnetic steel market has a value exceeding 20 billion Euros per year and most soft magnetic steel production is in the EU and Asia. Magnetic steel is used in Europe by more than 2500 transformer and electric motor manufacturers and producers. The state-of-the-art and metrologically validated measurement techniques and associated guidance developed in the project will support the characterisation of novel and more energy-efficient industrial steel products, helping Europe to maintain and expand its expertise and leadership in the production of special steel.

People's health can be affected by (local) emissions from power plants, district heating and local residential heating systems, transport and industry. Electricity and heat generated by these facilities lead to increased air pollution such as NOx, SO_2, small particulate matters (PM2.5) and CO_2. The European Environmental Agency estimated that there were 403,000 deaths related to PM2.5 and 72,000 deaths related to Nox in 2012. By reducing energy consumption and implementing energy efficiency policies targeting industrial processes, some of this air pollution can be avoided including emissions of PM2.5.

The cumulative energy savings associated with the implementation of the Ecodesign directive to be achieved between 2009 and 2020 were estimated to reach 2035 TWh, with additional energy savings of 100 TWh per year by 2030. The outcomes of this project, which promotes more accurate and efficient magnetic steel testing measurement methods, are expected to be used in the power generation and supply industry; the transport and aerospace sector; and the machinery and metal products industries, leading to an overall improved energy conversion efficiency. Additional energy savings connected to the design and construction of higher efficiency electric motors, transformers and power electronics devices, will also contribute to reaching the EU 32.5 % efficiency target for 2030, defined by the EC Energy Efficiency Directive 2012/27/EU (amended 2018/2002).

List of publications

Appino, C. (2023) 'Exact formulation for hysteresis loops and energy loss in Stoner–Wohlfarth systems'*, AIP Advances*, 13. Available at https://doi.org/10.1063/5.0143905
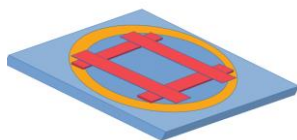
Banu, Nicoleta et al (2023) 'Temperature and Frequency Dependence of Magnetic Losses in Fe-Co'*, IEEE Access*, 11 p. 111422-111432. Available at https://doi.org/10.1109/ACCESS.2023.3322941

de la Barrière, O. et al (2023) 'Wideband magnetic losses and their interpretation in HGO steel sheets'*, Journal of Magnetism and Magnetic Materials*, 565 p. 170214. Available at https://doi.org/10.1016/j.jmmm.2022.170214

de la Barrière, O. et al (2,023) 'Skin effect and losses in soft magnetic sheets: from low inductions to magnetic saturation'*, IEEE Transactions on Magnetics* p. 01/01/23. Available at https://doi.org/10.1109/TMAG.2023.3284421

Dobák, Samuel et al (2022) 'Magnetic Losses in Soft Ferrites'*, Magnetochemistry*, 8 p. 60. Available at https://doi.org/10.3390/magnetochemistry8060060

Ragusa, C. et al (2021) 'Anisotropy of losses in grain-oriented Fe–Si'*, AIP Advances*, 11 p. 115208. Available at https://doi.org/10.1063/5.0066131

19ENG06 HEFMAG

Ulvr, Michal (2023) 'An Experimental Setup for Power Loss Measurement up to 1 kHz using an Epstein Frame at CMI', *Measurement Science Review*, 23(6), p. 275. Available at https://doi.org/10.2478/msr-2023-0035

This list is also available here:

https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 September 2021, 36 months	
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Internal Funded Partners:	External Funded Partners:	Unfunded Partners:
1. INRIM, Italy	6. CNRS, France	-
2. CMI, Czech Republic	7. IFW Dresden, Germany	
3. NPL, United Kingdom	8. INNOVENT, Germany	
4. PTB, Germany	9. POLITO, Italy	
5. TUBITAK, Turkey	10. UNOTT, United Kingdom	
RMG: -		