FINAL PUBLISHABLE REPORT

Grant Agreement number 19ENG06

Project short name HEFMAG

Project full title Metrology of magnetic losses in electrical steel sheets for high-efficiency energy conversion

Project start date and duration:	01 September 2020, 36 months	
Coordinator: Massimo Pasquale, INRIM	Tel: +39 011 3919820	E-mail: m.pasquale@inrim.it
Project website address: https://hefmag.inrim.it/		
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: -		

TABLE OF CONTENTS

1 Overview 3
2 Need 3
3 Objectives 3
4 Results 4
5 Impact 6
6 List of publications 8
7 Contact details 9

1 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. This was expected to facilitate improved 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 achieve all of its objectives.

2 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.

3 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.

4 Results

Power losses with standard measurement setups:

A set of magnetic steel laminations two FeSi NO of 0.2 mm and 0.3 mm thickness samples, three GO 0.18 mm, 0.2 mm and 0.3 mm thickness samples and one FeCo 0.2 mm thickness samples (Epstein geometry only) for the planned round-robin activities were defined and obtained through Stakeholder Committee members. The round-robin protocol draft was also written as a foundation for a good practice measurement guide. After a preliminary check and improvement of the available experimental setups for loss measurements according to the IEC 60404 set of standards, the partners started the round-robin activities using Epstein frame samples and equipment at room temperature 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 by the relevant partners on NO and GO FeSi laminations achieved a relative standard deviation σ of 1 % or better, thus achieving the objective. More specifically: on conventional Epstein NO and GO FeSi laminations (with dimensions of 300 mm x 30 mm x 0.18-0.2-0.3 mm) σ < 1 % was achieved in 79/87 measurements (91 %), while on special FeCo Epstein laminations (with dimensions of 300 mm x 30 mm x 0.2 mm), σ <1.5 % was achieved in 18/27 cases (66 %), due to the extreme magnetic softness and magnetostriction issues. On conventional FeSi SST samples (with dimensions of 500 mm x 500 mm x 0.18-0.2-0.3 mm), σ< 1% was achieved in 34/41 measurements (9 2%). Technical reports and a good practice guide are available at the following links:

Results of the Epstein Round Robin https://doi.org/10.5281/zenodo.8288792

Results of the SST Round Robin https://doi.org/10.5281/zenodo.8288797

Round Robin including Stakeholder Epstein results https://doi.org/10.5281/zenodo.10032755

Round Robin including Stakeholder SST results https://zenodo.org/doi/10.5281/zenodo.10014600

Loss measurements Good Practice Guide https://doi.org/10.5281/zenodo.8304171

Power losses under operating temperature conditions:

The objective was fully achieved. One 0.2 mm FeSi NO sample and one 0.2 mm FeCo sample were identified for characterisation according to the specific high-temperature round-robin protocol draft agreed by the partners. INRIM, NPL and UNOTT built and positively tested the setups required for the measurements. Tests were made to assess uncertainty contributions against standard measurements at room temperature with a view to optimising the setups when operated at temperatures up to 155 °C. Measurements at the different environment temperatures of 23 °C, 50 °C, 100 °C, and 155 °C were performed on the NO FeSi on the FeCo sample. On the Epstein FeSi NO 0.2 mm sample a relative standard deviation σ <1 % was achieved in 190/200 measurements (95 %), while on FeCo σ < 2 % was achieved in 86 % of the measurements (σ < 2.5 % in the remaining measurements). The increased uncertainty is connected to the details of the measurement procedure and the magnetostrictive properties of the FeCo. The results were summarised in a technical report made available at the links given below and a peer-reviewed paper was published:

Results of the Epstein Round Robin at High Temperature https://doi.org/10.5281/zenodo.8304080

RR Addendum including UNOTT FeSi NO high temperature data https://doi.org/10.5281/zenodo.10039685

Some FeSi GO and NO Epstein strips were extracted from the round robin sets as reference materials for imaging the magnetisation process at elevated temperature and subjected to cutting and polishing in preparation for magneto-optical microscopy as well as scanning probe microscopy. Specific optical equipment was also developed and optimised for operation at high temperature in a controlled atmosphere environment. Magneto optical measurements using the Kerr effect were performed at different temperatures ranging from 25°C to 150°C on GO samples. Final microscopy results are available in the following technical report published in an open access repository:

Magnetic domain observation on (110)[001] Fe-Si steel at elevated temperature
https://doi.org/10.5281/zenodo.8287251

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

Activities in the project were directed to the extension of current declarations of Calibration and Measurement Capabilities (CMCs) and to provide data for the prediction of losses under arbitrary flux waveforms up to the MHz range. FeSi NO, FeCo materials as well nanocrystalline tape samples were provided by stakeholders. The partners performed checks of the equipment devoted to high-frequency loss measurements and measurements were completed. Measurements and analysis up to 1 MHz by project partners and one stakeholder were concluded in the summer of 2023. Project activities provided data on the magnetic domain configuration and its evolution with frequency and temperature. The goal was to obtain an in-depth understanding of the role of magnetic domains and domain wall motion in hysteresis and excess eddy current losses, thus providing the basis for the broadband modelling of losses and eddy currents.

A numerical code implementing a physical model of domain wall dynamics in GO materials from DC to 10 kHz was developed. Such a model takes into account the domain wall dynamics under a sinusoidal polarisation, in particular, the domain wall bowing and non-uniformity of polarisation along the thickness due to the skin effect. The models were compared to experimental results comprising magneto-optical investigations and fluxmetric measurements. A novel broadband power loss and permeability model valid for amorphous/nanocrystalline tapes from DC to 1 GHz was developed using the Maxwell and Landau-Lifshitz equations.

A technical report was produced by INRIM and NPL with the results of the high frequency loss comparison and an assessment of the uncertainty ($\sigma \leq 2.8$ % f <100 kHz, $\sigma \leq 3.9$ % f < 1 MHz):

High Frequency losses technical report https://doi.org/10.5281/zenodo.8304981 .

A report on distorted waveform measurements was completed:

Report on loss measurements in distorted flux conditions https://doi.org/10.5281/zenodo.8296466

A good practice guide for high frequency fluxmetric measurements using a wattmeter/hysteresisgraph circuit was prepared with a detailed description of the setup with explicative pictures of the circuit and measurement details. The information was included in the good practice guide:

Good Practice Guide on Loss Measurements https://doi.org/10.5281/zenodo.8304171

Three open access peer reviewed papers were published, one focused on the high-frequency behavior of materials up to and above the MHz range, one devoted specifically to the topic of skin effects, and the third on FeCo measurements at variable temperature including skin effect.
Additionally, broadband power loss models in FeSi sheets and amorphous/nanocrystalline tapes and related computational models were jointly developed by POLITO, CNRS, INRIM, and UNOTT.

Through the activities detailed above, the objective was fully achieved.

Magnetic domain imaging results

Samples suitable for magneto-optical and scanning probe microscopy were cut, polished, surface treated and transferred to the partners for the planned analysis of magnetic domains. Magnetic domain observation - not requiring polishing or surface treatments – was performed using a sensor based on magneto-optical indicator films with out-of-plane anisotropy. A new sensor, using a magneto-optical indicator film with in-plane anisotropy and a high-speed camera, was developed by INNOVENT and PTB in collaboration with TUBITAK and a report was uploaded on arXiv (https://doi.org/10.48550/arXiv.2308.16344).

IFW performed magneto-optical quasistatic Kerr microscopy on the polished GO and NO disks and also performed surface domain investigations of the GO material at high temperature in a magneto-optical Kerr microscope. A report/draft publication was uploaded on Zenodo:

Magnetic domain observation on (110)[001] Fe-Si steel at elevated temperature
https://doi.org/10.5281/zenodo.8287251

IFW also developed a high spatial resolution technique (down to 60 nm) based on MFM scanning probe for imaging DW dynamics under an in-plane ac-field up to 2mT and a report/draft publication was made publicly available at the following link:

Magnetic force microscopy investigations of domain wall dynamics in grain-oriented Fe-Si samples; V. Neu., B. Singh., S. Deldar, R. Schäfer; https://doi.org/10.5281/zenodo.8283103

Furthermore, two open access peer reviewed papers were published related to the analysis of surface versus volume magnetisation in GO sheets, including skin effects.

The objective was fully achieved.

Two-dimensional magnetisation and power losses:

One goal of the project is to study the magnetisation process in NO materials used in rotating electrical machines under 2D fields, excited using a 3-phase magnetiser up to saturation polarisation, and to develop loss models based on the statistical theory of losses. A three-phase vector magnetiser was used to compare fluxmetric and thermometric measurement methods on NO 0.35 mm thick laminations from 5 Hz to 400 Hz in the polarisation 0.1 T < Jp <1.7 T using the field-metric technique and 1.6 T < Jp <1.9 T using the thermo-metric method. An overlap of the two sets was observed in the 1.6 T < Jp < 1.7 T interval. The measurements have were repeated on an NO 0.3 mm sample under rotational and elliptical flux (with an axes aspect ratio of 0.5) from 5 Hz to 400 Hz in the polarisation range 0.25 T < Jp < 1.5 T using the field-metric technique and 1.4 T < Jp < 1.8 T using the thermo-metric method and an overlap of the two datasets was observed in the 1.4 <Jp < 1.5 T interval. These results were used to better understand and emulate the two-dimensional flux loci in the non-oriented steel laminations in the stator core of a rotating electrical machine. A good agreement was observed across different experimental setups in different configurations with uncertainties between 5-10 % and the results are analyzed in a report made available at the link given below:

2D comparison https://doi.org/10.5281/zenodo.8298626

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 directions from rolling to transverse, from DC up to 400 Hz. In the first part of the project, magnetic hysteresis loop and losses were investigated in GO FeSi 0.3 mm under DC and AC (1 Hz - 200 Hz) regime. The experimental data was collected both using an Epstein frame and a non-standard single sheet/strip tester. 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, which was detailed in a published peer-reviewed paper.

A second paper was written deriving and analytical expression for the hysteresis loss of an ensemble of Stoner-Wohlfarth particles, a step toward the understanding of the 1D and 2D magnetisation process in NO materials which represents a versatile tool for numerical codes simulating the behavior of devices employing magnetic components.

The objective was fully achieved.

5 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).

6 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

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/

7 Contact details

Massimo Pasquale

INRIM, Strada delle Cacce 91, 10135 Torino Italy

email: m.pasquale@inrim.it