International Journal of Energetica (IJECA)
https://www.ijeca.info
ISSN: 2543-3717 Volume 10. Issue 1. 2025
Page 63-69

Magnetic measurements on two Fe Si samples

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Abstract – *This study investigates the magnetic characterization of two silicon-iron materials: Fe Si GO (grain-oriented) and Fe Si NO (non-grain-oriented), using an experimental magnetic measurement bench at the Polytechnic Military School in Algiers. Reproducibility tests performed on Fe Si GO showed highly consistent results, with losses at B = 1.5 T recorded as 1.133 W/kg, 1.132 W/kg, and 1.133 W/kg for the three tests, while Fe Si NO exhibited losses of 5.119 W/kg, 5.119 W/kg, and 5.118 W/kg under identical conditions, indicating maximum deviations of only 0.001 W/kg for each material. Comparison with supplier data revealed slight deviations; for Fe Si GO at B = 1.5 T, the experimental value was 1.133 W/kg compared to the supplier's 1.041 W/kg, while for Fe Si NO it was 5.20 W/kg compared to 5.119 W/kg. Frequency influence tests demonstrated significant increases in losses with frequency. For Fe Si GO at B = 1.5 T, losses rose from 0.063 W/kg at 8 Hz to 7.57 W/kg at 200 Hz, whereas for Fe Si NO at B = 1.5 T, losses increased from 0.39 W/kg at 8 Hz to 14.17 W/kg at 150 Hz. These results confirm the reliability of the measurement setup and provide valuable experimental data to support further modelling and optimisation of electrical machine design.*

***Keywords**: Magnetic characterization, Armature current, Magnetic loss, Magnetic measurements, Magnetic materials.*

Received: 05/02/2025 – Revised: 12/03/2025 – Accepted: 23/04/2025

I. Introduction

The characterization of magnetic materials, particularly through the measurement of their losses and apparent power, plays a vital role in the field of electrical engineering. It is an irreplaceable process in the electrical construction industry, as it directly influences the design, efficiency, and economic viability of electrical machines. With an improved magnetic circuit, machines such as transformers, motors, and generators can achieve higher performance, enhanced reliability, and reduced manufacturing costs for a given operational requirement [1–3]. Therefore, it is in the strategic interest of all electrical equipment manufacturers to study and determine the magnetic parameters of their materials in detail to optimise design choices and operational efficiency.

In this context, our work focuses on performing experimental magnetic measurements on two types of silicon-iron samples, Fe Si GO (grain-oriented) and Fe Si NO (non-grain-oriented), covering as wide a range of characteristics as possible. These measurements aim to establish accurate loss and magnetization curves, which are essential inputs for machine design calculations and simulations. Moreover, while standard characterization is usually limited to the nominal frequency of 50 Hz, we extend our analysis to cover a broader frequency range. This approach enables us to understand the behaviour of magnetic materials under variable frequency conditions, as encountered in modern applications involving inverters and variable speed drives.

The prediction of magnetic losses occupies an important place in electrical engineering design, as losses directly impact energy efficiency and thermal management. Thus, we will study one of the most relevant loss prediction models available in the literature [4–6], and apply it to our experimental measurements to validate its applicability and accuracy. In addition to this modelling approach, the study seeks to provide a deeper physical understanding of the mechanisms involved in the magnetization process, including hysteresis, eddy current, and excess losses [7–9].

The main objective of this work is to experimentally characterize and analyse the magnetic properties of two silicon-iron materials, namely Fe Si GO (grain-oriented) and Fe Si NO (non-grain-oriented), with the aim of assessing the reliability, reproducibility, and accuracy of the magnetic measurement bench available at the Polytechnic Military School in Algiers. This characterization involves measuring magnetic losses under various induction levels and frequencies, comparing the obtained results with supplier data to validate the measurement methodology, and analysing the influence of frequency on total losses. Ultimately, this study provides a validated experimental dataset and practical understanding of material behaviour, serving as a foundation for improving the design and modelling of electrical machines that use such magnetic materials.

II. Methodology

The characterization experiments were carried out at the *Actuators and Electromagnetic Devices Laboratory* of the *Polytechnic Military School in Algiers*. Two types of non-oriented silicon-iron magnetic materials were studied: Fe Si GO (grain-oriented silicon iron) and Fe Si NGO (non-grain-oriented silicon iron). These samples were obtained from certified suppliers, ensuring known reference values to validate the experimental results.

The experimental setup consisted of a magnetic characterization bench equipped with a magnetic circuit assembly that included excitation and measurement windings. A power supply and signal generator provided controlled excitation to the samples, while a digital acquisition system recorded the data for magnetic induction (B) and magnetic field strength (H). Losses were measured using calibrated modules to ensure accuracy and repeatability.

Before each measurement, the samples were prepared to the required standard dimensions for the magnetic bench. Particular attention was given to ensuring flat contact surfaces to minimize any air gaps during testing, which could influence the accuracy of results. Each material underwent a reproducibility test to assess the reliability of the measurements. For this, three repeated tests were performed under identical conditions for each sample, and losses were recorded at different magnetic induction values to analyse the consistency of the data.

To verify the validity of the experimental procedure and equipment, the obtained results were compared with the certified data provided by the suppliers. This comparison aimed to identify and quantify any deviations between the measured and reference values, highlighting the accuracy of the bench and the suitability of the measurement technique.

Finally, to examine the influence of frequency on magnetic losses, measurements were conducted across a frequency range extending from 8 Hz up to 200 Hz for the Fe Si GO sample and up to 150 Hz for the Fe Si NGO sample. The tests were performed at different induction levels, namely 1 Tesla, 1.3 Tesla, and 1.5 Tesla. The collected data were subsequently analysed to establish the relationship between frequency and losses, assess the reproducibility of measurements, and understand deviations in the behaviour of each material under varying conditions.

II.1. Experimental magnetic characterization bench schematic

Figure 1 presents the schematic diagram of the magnetic characterization setup used in this study. The configuration includes a voltage-controlled current generator that supplies the excitation coil, which magnetises the core sample placed at the centre. A sensing coil is positioned to detect the induced magnetic response, and its output is connected to the data acquisition system (DAQ). The DAQ unit integrates an Analog-to-Digital Converter (ADC) for data collection and a Digital-to-Analog Converter (DAC) for controlled output adjustments. All measurements and control commands are interfaced with a computer for processing, visualisation, and storage. This setup enables precise measurement of magnetic induction and losses under different test conditions.

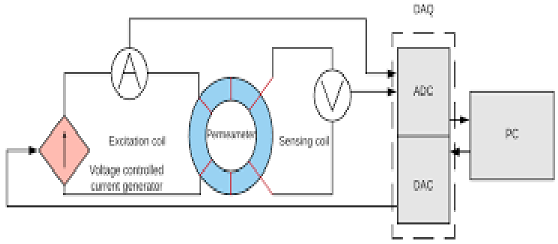

Figure 1. Schematic diagram of the supply system

II.2. Measurement Procedure Flowchart

Figure 2 illustrates the sequential steps followed during the characterization tests. The process begins with the initialization of libraries and programs required for bench operation. Test parameters and sample characteristics are then inputted and stored within the system. Manual calculations and adjustments are performed to set the test conditions appropriately. Following this, data processing algorithms are executed before commencing data acquisition. Finally, the collected data are edited and stored for analysis and reporting. This structured methodology ensures consistency and reliability across all experiments conducted.

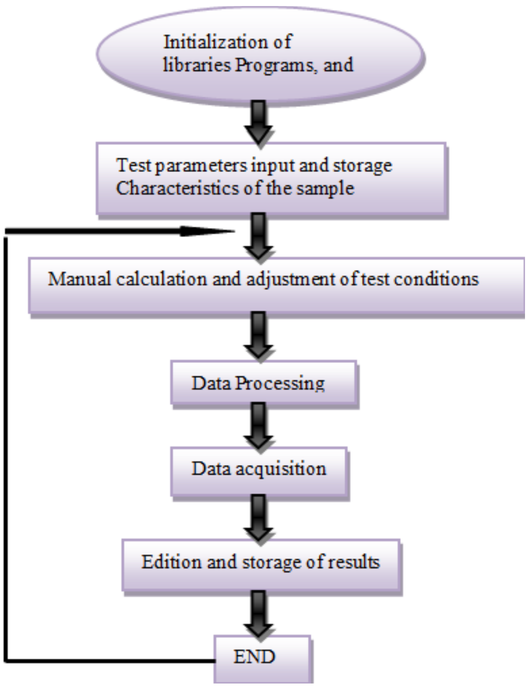

Figure 2. Organizational chart of the measurement bench software

III. Results and discussion

III.1. Fe Si GO – Measurement Reproducibility Test

Figure 3 illustrates the results of the reproducibility test performed on the Fe Si GO sample. Three measurements were conducted under identical test conditions to evaluate the stability and reliability of the magnetic characterization bench. The curves from the three tests almost completely overlap across the entire range of magnetic induction values, from 1 Tesla to 1.7 Tesla. For instance, at B = 1.5 T, the recorded losses were 1.133 W/kg for Test 1, 1.132 W/kg for Test 2, and 1.133 W/kg for Test 3, demonstrating a maximum variation of only 0.001 W/kg. This confirms that the measurement bench provides highly consistent and reliable data for subsequent analyses.

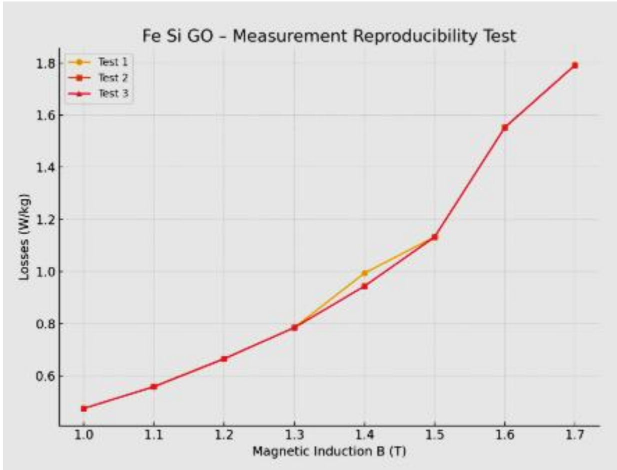

Figure 3. Measurement reproducibility test. (Ref .V97.30 Tissent)

III.2. Fe Si GO – Magnetic Losses vs. Frequency

Figure 4 presents a comparison between the experimental losses obtained and the supplier's certified values for the Fe Si GO sample (first dataset). For example, at B = 1.5 T, the supplier specifies a loss of 1.041 W/kg, whereas the experimental measurement yielded a higher loss of 1.133 W/kg, resulting in a deviation of approximately 0.092 W/kg. Similar trends are observed across all induction values, with experimental losses slightly exceeding supplier values, particularly at higher magnetic inductions. This deviation may be attributed to minor differences in measurement conditions or sample preparation, but overall, the trend remains consistent, confirming the validity of the experimental results within acceptable limits.

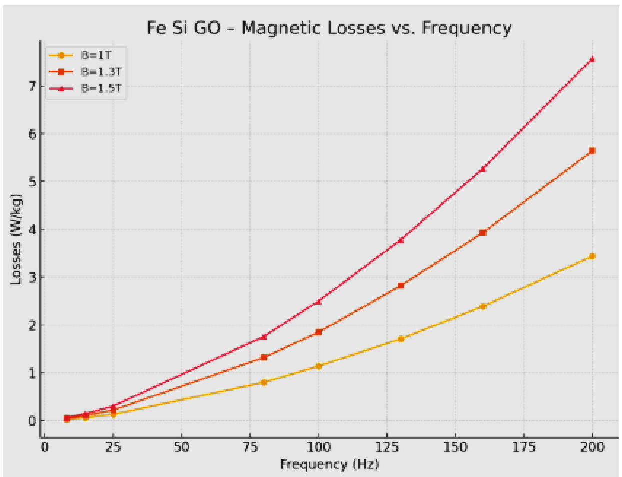

Figure 4. Magnetic Losses vs Frequency

III.3. Fe Si NO – Measurement Reproducibility Test

Figure 5 shows the measurement reproducibility test for the Fe Si NO sample, where three tests were performed under identical experimental conditions to verify the stability and repeatability of the setup. The plotted curves demonstrate near-perfect overlap across all magnetic induction values, confirming excellent reproducibility. For example, at B = 1.5 Tesla, the recorded losses were 5.119 W/kg for both Test 1 and Test 2, and 5.118 W/kg for Test 3, resulting in a maximum deviation of only 0.001 W/kg. Similarly, at B = 1.3 Tesla, the losses were 3.504 W/kg for Tests 1 and 3, and 3.503 W/kg for Test 2. This consistency indicates that the measurement bench provides highly reliable results, suitable for accurate magnetic characterization studies.

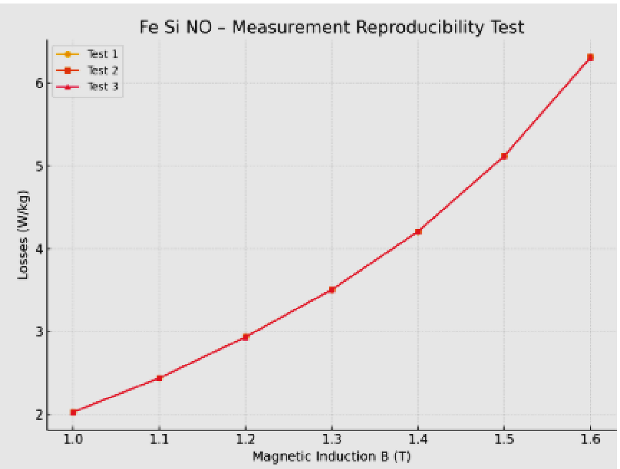

Figure 5. Measurement reproducibility test for the Fe Si NO sample

III.4. Fe Si NO – Magnetic Losses vs. Frequency

Figure 6 illustrates how the magnetic losses of the Fe Si NO sample vary as a function of frequency for three levels of magnetic induction: 1 Tesla, 1.3 Tesla, and 1.5 Tesla. The graph shows that magnetic losses increased markedly with rising frequency at each induction level. For instance, at B = 1 T, losses rise from 0.17 W/kg at 8 Hz to 6.48 W/kg at 150 Hz. At B = 1.3 T, losses grow from 0.28 W/kg at 8 Hz to 10.65 W/kg at 150 Hz. For B = 1.5 T, losses sharply increase from 0.39 W/kg at 8 Hz to a maximum of 14.17 W/kg at 150 Hz. This pattern demonstrates the strong influence of frequency on total magnetic losses, which is mainly due to the combined effects of hysteresis and eddy current losses typical of non-grain-oriented silicon iron materials.

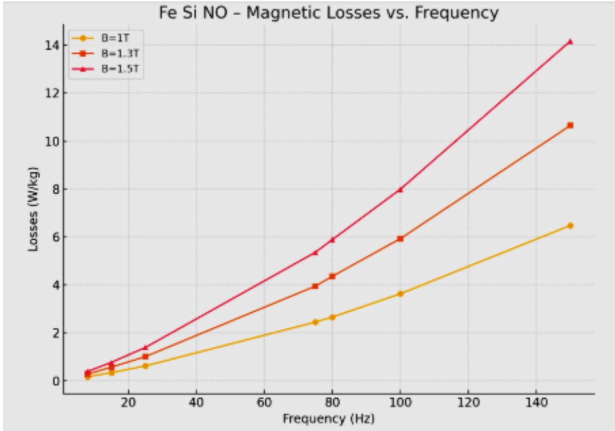

Figure 6. Magnetic losses of the Fe Si NO sample

III.5. (Fe Si GO) – Supplier vs. Obtained Losses

Figure 7 presents a comparison between the experimental losses measured for the Fe Si GO sample and the corresponding supplier's certified values. The graph shows that, across all magnetic induction levels from 1 Tesla to 1.7 Tesla, the experimental losses are consistently slightly higher than the supplier's data. For example, at B = 1.5 T, the supplier specifies a loss of 1.041 W/kg while the experimental value measured was 1.133 W/kg, indicating a difference of 0.092 W/kg. Despite these deviations, the trend remains parallel, confirming that the experimental method is reliable and that discrepancies are within acceptable margins, possibly arising from differences in sample preparation or measurement conditions.

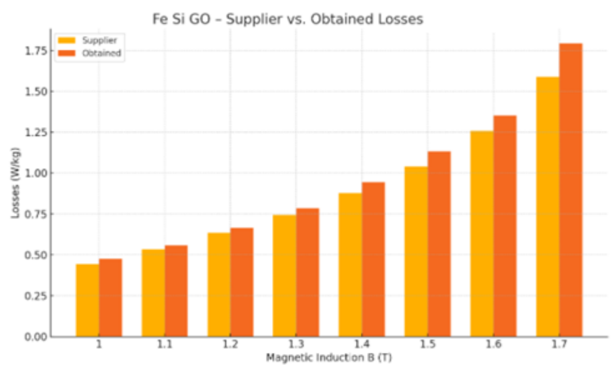

Figure 7. Comparison of Experimental and Supplier Certified Losses for Fe Si GO

III.6. (Fe Si GO) – Supplier vs. Obtained Losses

Figure 8 shows a similar comparison for the Fe Si GO sample. The bar chart indicates that experimental losses are again slightly higher than the supplier's values across the entire induction range. For instance, at B = 1.3 T, the supplier reports 0.743 W/kg while the experimental measurement was 0.775 W/kg, a deviation of 0.032 W/kg. At B = 1.7 T, supplier and experimental values were 1.589 W/kg and 1.730 W/kg respectively, resulting in a difference of 0.141 W/kg. The consistency of the experimental measurements in following the supplier's trend demonstrates the accuracy of the setup despite minor differences.

Figure 8. Comparison Losses for Fe Si GO

III.7. (Fe Si NO) – Supplier vs. Obtained Losses

Figure 9 compares the experimental losses measured for the Fe Si NO sample with the supplier's certified. The results show that the experimental values are slightly higher at all induction levels. For example, at B = 1.5 T, the supplier's value is 5.119 W/kg while the experimental measurement yielded 5.20 W/kg, a deviation of 0.081 W/kg. Similarly, at B = 1.6 T, the supplier's data reports 6.310 W/kg compared to the experimental value of 6.68 W/kg, resulting in a difference of 0.37 W/kg. Despite these small deviations, the experimental results align well with the supplier's data trend, confirming the validity and reliability of the measurement method used in this study.

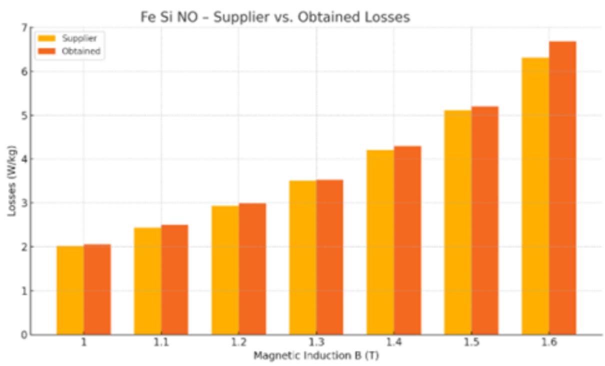

Figure 8. Comparison of Losses for Fe Si NO

III.8. Discussion

The results obtained in this study confirm the well-established behaviour of silicon-iron magnetic materials under varying magnetic induction and frequency conditions. According to Bertotti (1986) [10], magnetic losses in ferromagnetic materials are composed mainly of hysteresis losses, eddy current losses, and excess losses, each exhibiting different dependencies on frequency and induction. The experimental results for Fe Si GO and Fe Si NO samples align with this theoretical framework, as both materials showed significant increases in losses with frequency, particularly at higher induction levels.

Bertotti (1992) [11] further generalised the dynamic loss behaviour by incorporating statistical domain wall dynamics into the Preisach model, highlighting the role of excess losses which increase nonlinearly with frequency. This is consistent with the current results where, for example, Fe Si NO losses at B = 1.5 T rose from 0.39 W/kg at 8 Hz to 14.17 W/kg at 150 Hz, reflecting contributions from both eddy currents and excess losses. The observations also agree with Néel's (1959) [12] analysis of the interaction between elementary ferromagnetic domains, where higher induction levels lead to stronger domain wall movements, thus increasing hysteresis and dynamic losses.

The experimental deviations observed between supplier data and measured values, such as the 0.092 W/kg difference for Fe Si GO at B = 1.5 T, can be partially explained by factors highlighted by Imache (2001) [13], who discussed the impact of sample preparation, residual stress, and material anisotropy on measured magnetic properties. Moreover, Robert (1979) [14] emphasised that even small air gaps or surface irregularities in laminated samples can cause additional localized eddy currents, slightly increasing overall losses.

Finally, Lacroux (1989) [15] discussed the magnetic behaviour of permanent magnets and related materials, noting that non-grain-oriented materials like Fe Si NO typically exhibit higher losses due to their isotropic grain structure compared to grain-oriented silicon steels. This is confirmed in the current study, where Fe Si NO losses at B = 1.5 T and 150 Hz reached 14.17 W/kg, nearly double those observed for Fe Si GO under similar frequency conditions.

Overall, the results align with theoretical models and prior experimental studies, validating the measurement methodology and confirming that the observed behaviour is inherent to the physical properties of these magnetic materials. This experimental data thus provides a reliable basis for further studies involving advanced loss models, such as Bertotti's dynamic generalization and statistical formulations, to improve electrical machine design and efficiency.

IV. Conclusion

In this study, the magnetic properties of Fe Si GO and Fe Si NO samples were characterized experimentally to assess reproducibility, accuracy, and frequency dependence of losses. The reproducibility tests demonstrated excellent consistency, with maximum deviations not exceeding 0.001 W/kg for either sample, confirming the stability and reliability of the magnetic measurement bench. Comparison with supplier data showed minor deviations; for example, Fe Si GO at B = 1.5 T exhibited an experimental loss of 1.133 W/kg versus a supplier value of 1.041 W/kg, while Fe Si NO showed 5.20 W/kg experimentally compared to 5.119 W/kg from the supplier at the same induction. Frequency influence tests revealed a substantial increase in losses with rising frequency; Fe Si GO losses increased by approximately 7.5 W/kg from 8 Hz to 200 Hz at 1.5 T, while Fe Si NO losses rose by 13.78 W/kg from 8 Hz to 150 Hz at 1.5 T. Overall, the results validate the accuracy of the experimental setup and highlight the expected behaviour of both grain-oriented and non-grain-oriented silicon-iron materials under varying operating conditions. This experimental dataset provides a foundation for future studies employing theoretical models such as the Bertotti approach to analyse loss mechanisms and improve electrical machine efficiency.

Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism

Appendix

- Characteristics of the sample used
- Characteristics of the Fe Si GO sheet:
- Total mass: 651g, Specific gravity: 7.65g/cm3, Length: 0.280 m, Losses at 1.7 T: 1.58 (W/Kg).
- Characteristics of the Fe Si NO sheet:
- Total mass: 689g, Specific gravity: 7.85g/cm3, Length: 0.280 m, Losses at 1.4 T: 4,207 (W/Kg).
- A power supply consisting of an arbitrary signal generator and a power amplifier.
- An ammeter for measuring the primary excitation current I, which is directly proportional to the magnetic excitation field.
- The secondary voltage V2 is the image of the magnetic flux, and provides easy access to the magnetic induction.
- A voltmeter is used to measure the secondary voltage

Two qualities of magnetic material were studied:

- Grain-oriented FeSi, 0.30 mm thick.
- Non-oriented FeSi, 0.50 mm thick.

These two samples were characterized under sinusoidal induction.

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