Project Title:

Electrical Machine Magnetic Properties Characterization Setup for Aerospace Application - **EMMPC**

Final

Publishable Summary

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Contents

1. Executive summary 1
2. Summary of the project context and the main objectives. 2
3. The main S&T results 4
4. Potential impact and the main dissemination activities 14
5. Contact details 16

1. Executive summary

The purpose of this project was to develop a test setup able to characterise magnetic materials when excited with pulsating or rotational fields at high frequency and high flux density under various mechanical conditions. This development will help the European aeronautic partners to have better knowledge on the design criteria of aerospace electrical machines and have a reliable test method to guarantee that the materials will behave as expected in the application at hand.

The main objectives of the project, defined as work packages, were to review, design and manufacture test-setup prototypes with the final aim of developing a test systems for both soft and hard magnetic materials, controlled by a central measurement unit.

Following proper system calibration and results verification the commissioned setup met the required specification by fulfilling the five main measurement sequences mentioned below:

a. Measurement of 1D iron losses using both sinusoidal and non-sinusoidal flux excitation in soft magnetic materials subjected to simultaneous strain (compressive or tensile) and temperature variations:
    - High frequency sinusoidal up to 20 kHz; Amplifier bandwidth up to 100 kHz for PWM
    - Up to 500 MPa in tension
    - From -40°C to 300°C
b. Measurement of magnetostriction under 1D excitation, stress and ambient temperature
c. Measurement of 1D iron losses for annular samples compressed radially and axially
d. Measurement of 2D iron losses at rotational power loss tester using both sinusoidal and non-sinusoidal flux excitation in soft magnetic materials
e. Measurement of iron losses in hard magnetic materials exposed to high frequency counter fields and subjected to compressive strain and temperature variation
f. Full characterisation of hard magnetic materials using a hysterograph

2. Summary of the project context and the main objectives.

The deviation in performance and efficiency of electrical machines from the expected design values is very much a function of the deviation (from datasheet values) in magnetic properties experienced by the constitutive materials of the machine. Such variations have been the subject of research for many years, with the main concern being permeability and power loss variation upon application of non-ideal mechanical conditions on the electrical steel sheet or under non-sinusoidal (harmonic rich) induction distributions. To date, material is specified and traded against data supplied under the standard measuring techniques as described in international standards (such as IEC 60404) for sinusoidal field magnetization. The growing demand for new, high power density electrical machines is primarily addressed by increasing both current loading and the operating fundamental frequencies of such machines. This will result in a drastic increase in power losses (due to the applied high frequency and high induction fields experienced by the soft and hard magnetic materials), coupled with a drastic increase in the experienced mechanical stresses of both rotating and stationary components (due to higher centrifugal forces in case of the rotor and experienced differential expansions (housing to core) under high thermal gradients for the stator). The conditions experienced by both soft and hard magnetic materials under such operating conditions are therefore far from ideal, rending the most common available data ineffective. A high fidelity system is thus required to be capable of reproducing as far as possible both the electromagnetic and mechanical conditions experienced by the materials used in current, high-power density electrical motor designs for the aerospace application. In summary the developed equipment will thus be able to characterize magnetic materials in terms of B-H characteristics and losses for both soft and hard materials used within the electrical machines developed for the future aerospace needs by fulfilling the following aims:

1. Reproducibility:
   a. Samples of standard geometry
   b. Capable to perform all standard tests according to IEC 60404
   c. Evaluated similar IEC 60404 certified equipment

2. High fidelity:
   a. Measurement of 1D iron losses using both sinusoidal and non-sinusoidal flux excitation in soft magnetic materials subjected to simultaneous stress (compressive or tensile) and temperature variations:
      - High frequency sinusoidal up to 20 kHz; Amplifier bandwidth up to 100 kHz for PWM
      - Up to 500 MPa in tension
      - From -40°C to 300°C
   b. Measurement of magnetostriction under 1D excitation, stress and ambient temperature
   c. Measurement of 1D iron losses for annular samples compressed radially and axially
   d. Measurement of 2D iron losses at RTP using both sinusoidal and non-sinusoidal flux excitation in soft magnetic materials
   e. Measurement of iron losses in hard magnetic materials exposed to high frequency counter fields and subjected to compressive strain and temperature variation

To achieve the above mentioned goals the project was subdivided into 5 main tasks as described below:

- Review the existing measuring setups and define the final most relevant parameters and measuring ranges to be covered by the new setups
- Improve the signal waveform regulation for magnetisation process
- Design and build a combined one and two dimensional measuring setup
- Design and build sensors for magnetic characterisation of materials at DC and AC at various frequencies and waveform shapes measurements under applied stress and temperature,
- Write an operating software for the measuring setup with various sensors

3. The main S&T results

Brockhaus Measurements as a world-wide leading manufacturer of measuring systems developed a test setup able to characterise magnetic materials when excited with alternating or rotating fields at high frequency and high flux density. This development was divided in to the main work packages (WP). The foregrounds of the work done in the various work packages are presented in following sections.

- ***WP1: Review of test setups and methodologies***

All measurement methods of magnetic samples testing with existing test setups were reviewed. Based on this review, measurement parameters and conditions were established.

- ***WP2: Real time digital wave-form control***

A digital feedback control algorithm for a various user defined output voltage waveforms was developed such that the output voltage and therefore imposed flux density could be actually controlled to reproduce the following waveforms:

- Pure sinusoidal up to 20 kHz
- Pulse width modulated (PWM) up to 100 kHz of switching frequency
- Free waveform (user designed waveform) and high harmonics

The block diagram of the control loop of the signal waveform feedback is shown in Fig.1 and Fig.2.

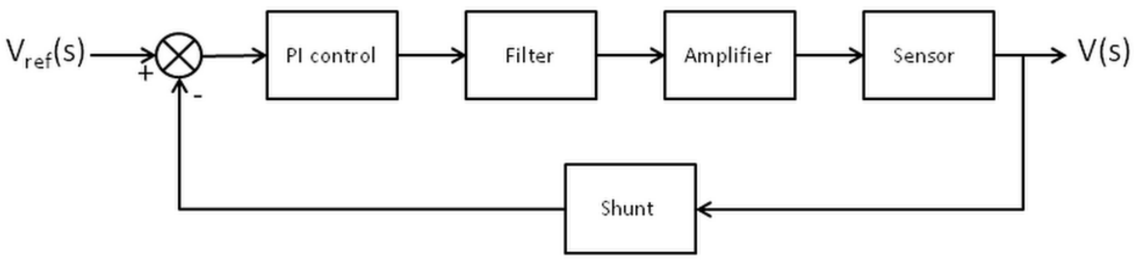


Fig 1. Schematic diagram of signal waveform control loop

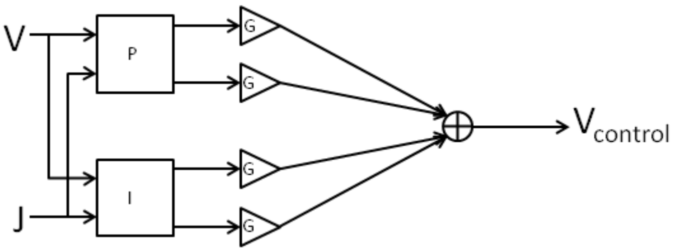
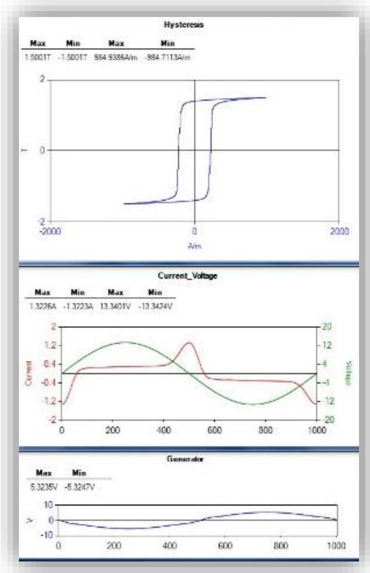
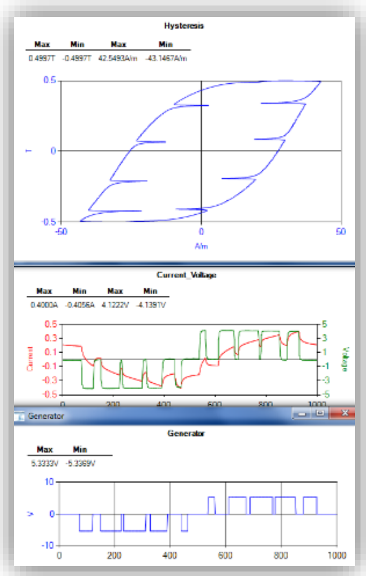
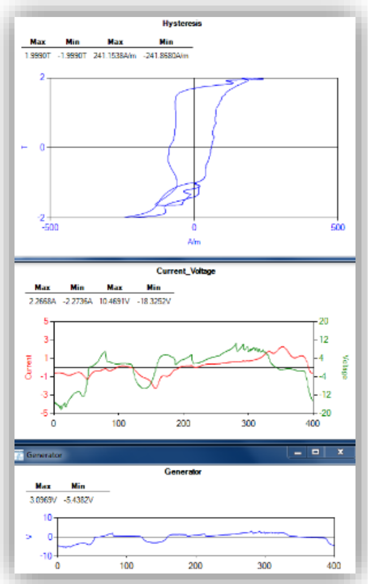


Fig 2. Schematic diagram of PI control

The filter inside the loop is used to limit the output signal bandwidth in order to reduce the incurred noise of the signal supplied to the input of the amplifier. The three main control modes and output signal waveforms are shown in Table 1.

Table 1. Signal waveform control

		
B and H mode	*PWM*	*Free Curve*

- ***WP3: Design of the combined one and two dimensional measuring setup***

The central measurement unit as shown in Fig.3 combining one and two dimensional test setup for soft and hard magnetic materials was built. All measurement sensor systems presented in WP4 were connected to this unit to generate, control and measure all the required signals.

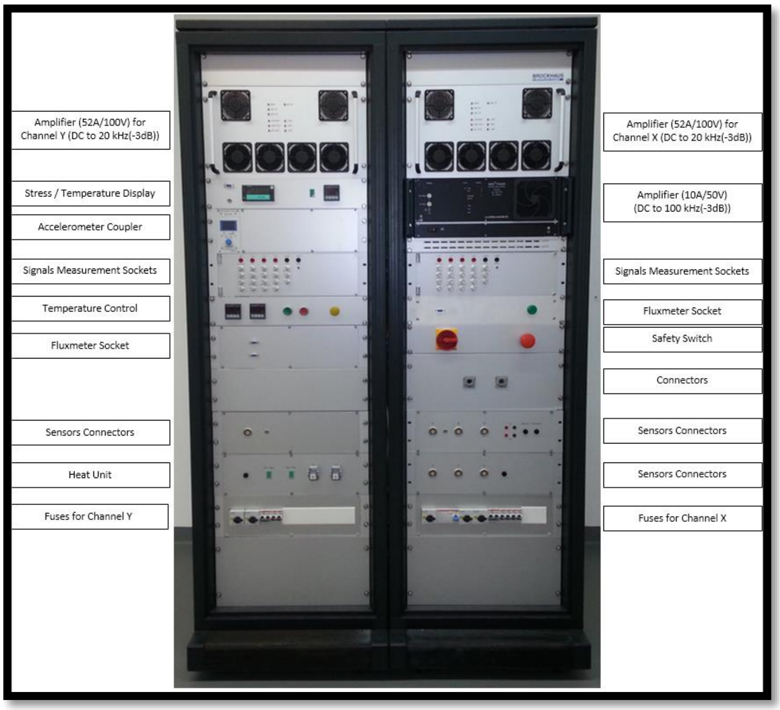


Fig 3. Central measurement unit

- ***WP4: Design of new sensor systems***

The nine sensor systems were manufactured and developed for soft and hard magnetic materials measurements. The successfully tested sensors are described in the following sections:

- ***Epstein Frame***

Two Epstein frames (shown in Fig.4) with 100 turns ,to be used for high frequency measurement, and 700 turns for the low frequency measurements were produced to magnetise a stack of Epstein laminations at DC and AC (wide range of frequencies also including DC-bias) magnetic field. Samples will be measured in accordance to the international standard - IEC 60404-2.

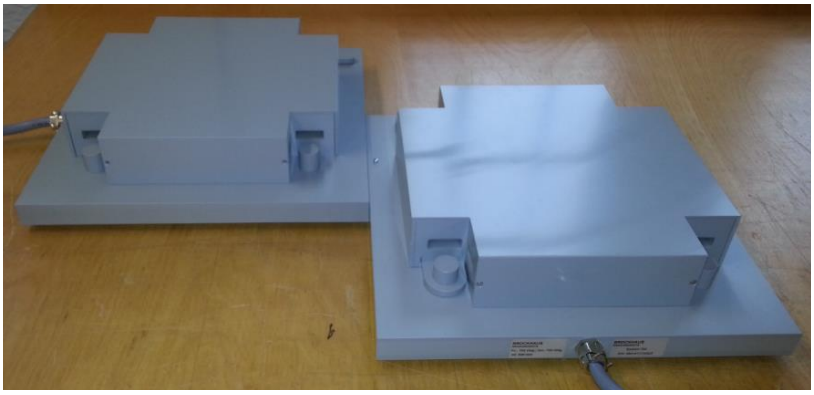


Fig 4. Epstein frames for low and high frequencies

- ***Magnetostriction and iron loss measurement system***

A system for magnetostriction and loss measurements under stress on Epstein strips (305 mm x 30 mm) was built. Two accelerometers were employed to measure the required differential acceleration (with one fixed to the sample clamp and other to the system's base). The acquired acceleration thus measured is then integrated twice to arrive to a displacement and thus magnetostriction.

The sample's power loss when subjected to the same existing-field conditions was simultaneously measured via a wattmeter / Epstein approach. The magnetic field (H) generated by primary windings was known through the performed current measurement and magnetic flux density estimated via integration of the induced voltage in secondary windings. Both windings were around packet system into which the sample was placed. Two yokes were then used to close the magnetic flux path during the magnetisation process. A load cell with maximum load of 5 kN connected to a pneumatic cylinder is used to control and measure the applied stress to the sample in the range of +500 MPa (tension) to -250 MPa (compression).

- ***SST under stress and temperature system***

A single strip tester (SST) was also built to measure loss of an Epstein strip under tensile and compressive stress when subjected to a wide range of temperatures from -40ºC to +300ºC. The whole system (apart from the sample and two yokes) was made out of non-magnetic stainless steel and ceramic parts. Moreover a copper cable with ceramic insulation, withstanding high temperatures up to 300ºC was used for both primary and secondary turns which are wound around the sample pocket. Iron loss measurement is performed in the same way as in the magnetostriction setup. An environmental chamber with a temperature control loop is used to supply and control the wide range of temperatures in the sample during magnetisation.

A simple stressing system in the form of a screw and a clamp is used to apply stress to the tested sample. A torque meter was used to measure a force applied by the screw. To convert such applied torque (in Nm) to an applied stress (in MPa) in the sample, a single strain gauge fixed to an initial test sample surface (of the same material as that to be tested under the conditions mentioned earlier) was used. The measured values of strain and hence stress (via the material's Young's modulus) were then correlated to the applied Nm on the screw.

- ***Radial compression rig***

A stressing rig was manufactured to apply radial compression to a stack of ring samples. A set of primary and secondary windings were wound on the stack and used to introduce the required magnetic field and measure flux. To protect rings from bending a number of G-clamps with two supporting rings placed on the top and bottom surface of the stack were used. The rig applies compressive stress by tightening of a set of screws placed between aluminium parts. Also between the top surface of the stack and the top protection ring, a set of strain gauges can be placed to measure radial stress in the top ring.

- ***Surface compression rig***

Two rings with slots for windings (Fig.5) were manufactured to apply the uniform stress to the surface of ring samples. A bench press with a load of maximum 50 tons was used to apply stress to the setup. The primary winding will be wound around the 14 big slots and the secondary in 4 small drilled holes are to be wound for field generation and loss measurement.

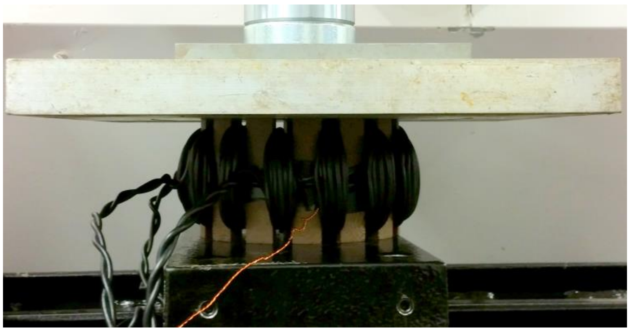


Fig 5. Surface compression system

➢ ***System for two dimensional measurement***

A rotational power loss tester (RPT) with a set of 4 yokes with primary windings as shown in Fig.6 was built to magnetise 60 mm x 60 mm samples at two dimensional AC field. A magnetising yoke system is used to generate a magnetic field in any needed direction. By changing the phase shift between two magnetising axes the system induces a rotating flux density vector *B* within the sample. This flux is measured by two crossing secondary coils wound between the drilled holes in the sample.

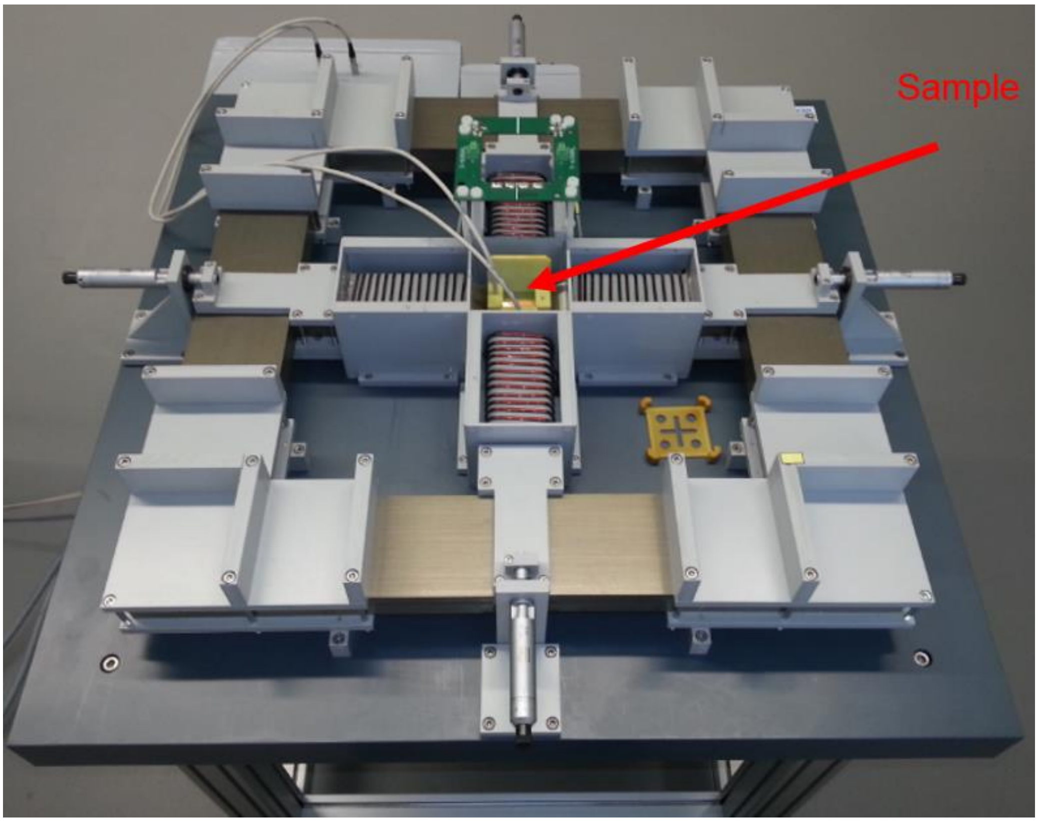


Fig 6. Rotational power loss tester

➢ ***Electromagnet***

An electromagnet as shown in Fig.7 with integrated cooling (up to -40ºC), heating (up to +300ºC) and compression (up to 500 MPa) systems was built for testing permanent magnets at various environments. In the electromagnet a load is applied by a top pole and a force is measured by a load cell fixed below a bottom pole. Two heating pads fixed between the each pole and pole cap with attached thermocouple are used to heat the magnet to a certain temperature. A jet-freezer™ jacket, was used and along with the supplied CO_2 to cool the sample to value well below -40˚C. The cooling temperature was controlled by a thermocouple place inside the jacket.

Fig 7. Electromagnet with integrated temperature and stress systems

- ***Eddy current-induced-loss measurement system for permanent magnets***

The setup shown in Fig.8 was built to generate an AC magnetic field and measure eddy currents in permanent magnets with various dimensions. The system includes 3 different yoke blocks to adjust the height of the air gap dependent on the thickness of the magnet. Also an increase of a temperature in the magnet due to induced eddy currents is monitored by a thermocouple.

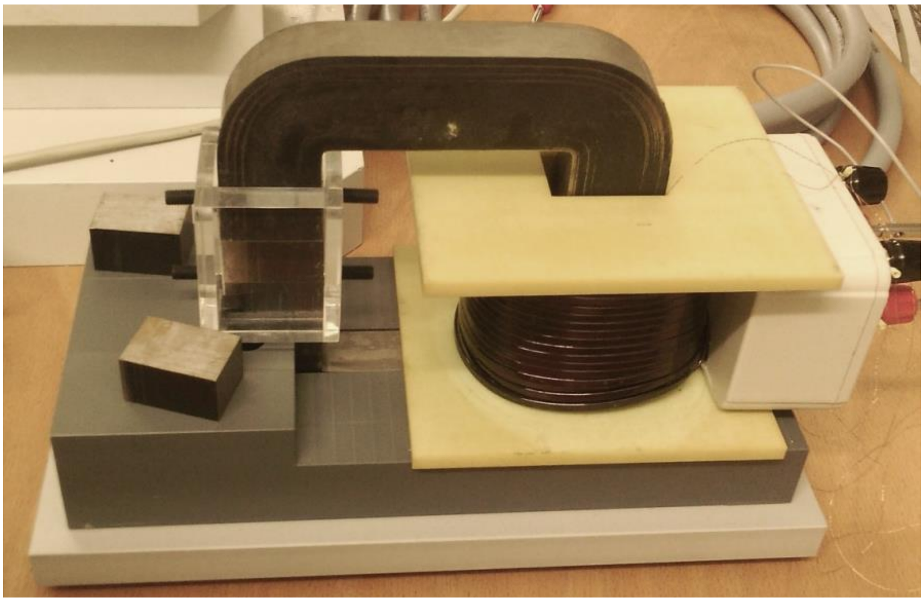


Fig 8. Eddy current-induced-loss measurement system for permanent magnets

- ***WP5: Software design***

The software suits for testing soft magnetic materials in one and two dimensions as well as hard magnetic materials was written, some screen shots of which are shown in Fig.8(a-e). Algorithms for one and two (rotational) dimensional magnetisation were developed to control several types of waveforms up to 20 kHz and 5 kHz, respectively.

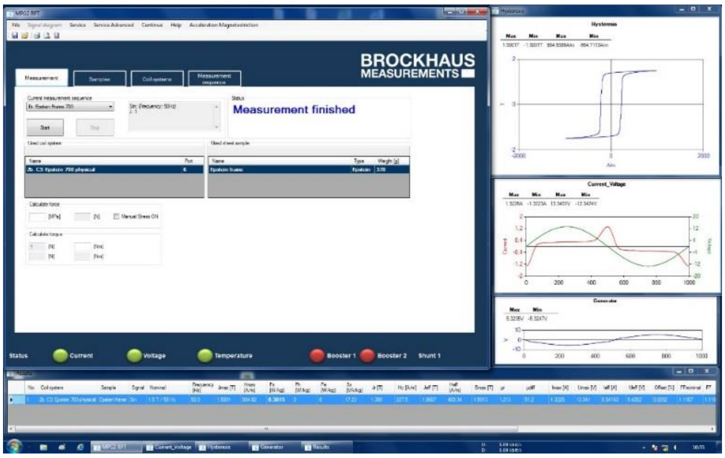


Fig 8a. Software set to sinusoidal waveform control for soft magnetic materials

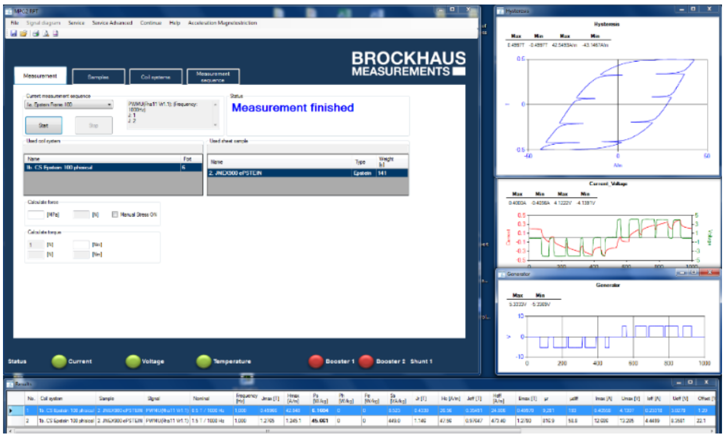


Fig 8b. Software set to PWM waveform magnetisation for soft magnetic materials

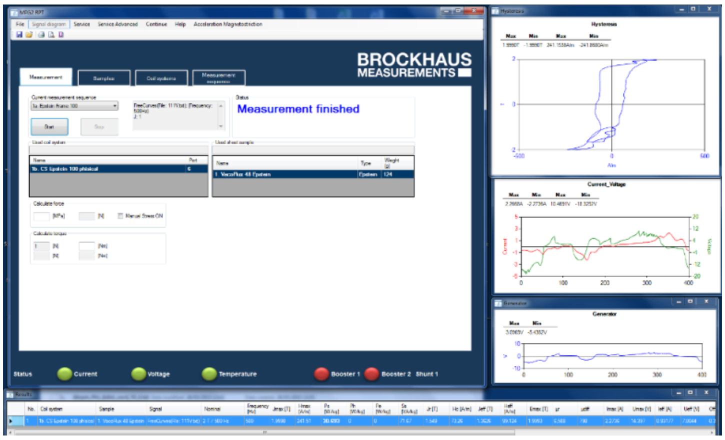


Fig 8c. Software set to free curve waveform magnetisation for soft magnetic materials

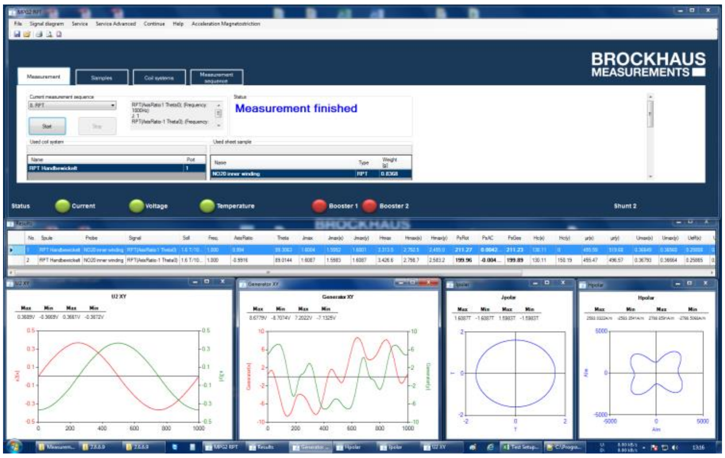


Fig 8d. Software set to rotational magnetisation for soft magnetic materials

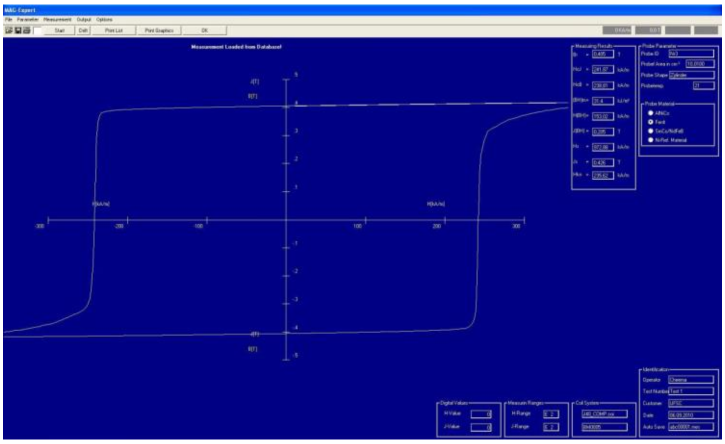


Fig 8e. Hysterograph software for hard magnetic materials

4. Potential impact and the main dissemination activities

The results of the measurements undertaken by the equipment delivered as part of this project will help the partners in the JTI to gain a deeper understanding into the behaviour and limiting for the materials making up the new generation high performance electrical machines. The commissioned setup, integrating all the required measurements to be performed on such materials is a European first and as such allows the partners access to all of the required material knowledge to improve the power density and reliability of future electrical machines for the demanding aerospace sector and beyond.

This set up allows for the magnetic characterisation of a wide range of material grades and types. These can now be tested for magnetostriction, B-H data, and power loss under various stress, temperature and electro-magnetic excitation conditions. The measured data will have a large impact in the estimation of future electrical motor performance, in that the underlying magnetic properties measured in conditions which closely emulate those expected during actual operation can now be inputted in the design models used. This will allow for:

- Better loss estimation leading to better thermal models and overall system design
- Selection of materials with lower magnetostriction when exposed to compressive stress. This will potentially reduce noise emissions from such devices
- Selection of materials with lower loss even under externally applied stress and/or various temperature
- Further understanding and the possibility of loss data inclusion for materials under rotational magnetisation (such data is very relevant for inclusion in iron loss models for machines in which cooling comes at a high premium)
- Characterisation of losses due to eddy currents in permanent magnets and selection of the best grades and types of materials. This would also potentially increase the efficiency of such electric motors, and reduce the power loss especially at the higher frequency operation.

Results obtained from this setup already started being published as part of the initial dissemination strategy ("*An Investigation into the Geometric Parameters Affecting Field Uniformity in Four Pole Magnetisers*" to be published in the International Journal of Applied

Electromagnetics and Mechanics (IJAEM) and also presented in the 13th 1&2DM International Workshop) and results being integrated in new motor designs.

The setup, located at the Topic Manager's institution is available to all JTI partners who wish to test and evaluate the electromagnetic properties of the constituent materials of their machine designs. This unhindered availability renders the commissioned setup an important tool in the hands of all the JTI partners and as such provides service at no extra cost which previously did not exist. Such a service, and therefore knowledge-gained allows the JTI partners to remain at the forefront of high performance electrical machine design.

5. Contact details

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