**PhD in Electrical, Electronics and Communications Engineering**

**Research Title:** *Advanced experimental and theoretical analysis of magnetic materials and devices for energy: soft magnets for power electronics, e-mobility, and additive manufacturing for power magnetics.*

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<td>Generation, distribution, and conversion of the electrical energy pass through magnetic cores, whose energetic efficiency is crucial to the sustainable exploitation of the natural resources, the containment of CO$_2$ emissions, and their undesirable effects on the world climate. To make an example, more than 50% of all electricity worldwide is converted into mechanical energy by electrical motors [1], giving rise to about $6 \cdot 10^3$ Mt CO$_2$ emissions, a figure predicted to increase at a rate of 100 Mt/year. Progress in design and development of efficient electrical machines and devices relies on <em>improved and better-understood</em> magnetic materials. The physical investigation of the magnetization process is actually the key to the understanding of the response of these materials in applications, besides providing indispensable feedback to the material developers. It goes hand in hand with advances in magnetic measurement methods, the related accuracy and the normative issues, which are the indispensable tools for the industrial development and commercialization of the materials. Although the whole discipline of magnetic characterization of materials and physical modelling is solidly established since many decades, the widening domains of application</td>
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and the development of new materials, devices, and measuring techniques have introduced new phenomenological scenarios and new theoretical and experimental challenges.

**Electrical machines operating at high speed for automotive application** or trends towards miniaturization of devices have imposed increasing working frequencies. In many instances this implies increasingly complex non-sinusoidal flux waveforms (e.g., magnetic cores in switched-mode power supplies and electronically driven motors) bringing about equally complex experimental characterization methods and theoretical models of the core performances. These should efficiently deal with both the phenomenology of the magnetic domain wall dynamics, according to the principle of loss decomposition, and the ubiquitous appearance of skin effect phenomena [2-4]. New problems in the analysis of the material properties have emerged with the growing adoption of Soft Magnetic Composite (SMC) cores in place of the standard Fe-Si and Fe-Co sheets, which require novel solutions. Among the challenges posed by the composite materials is the need for their characterization at high frequencies, for which they have expressly designed, at technically important induction levels (say more than $B_p = 1.0$ T). This should be accomplished both under alternating and two-dimensional fields, as required by their use in rotating machine cores. But, because of the intrinsically low permeability of SMC, pretty high applied fields, beyond a few kA/m, are required for excitation. It is a burdensome condition, attained with great difficulty on approaching the kHz range. The theoretical approach is, on the other hand, similarly demanding, because of the heterogeneous nature of these materials [5].

The classical soft magnets for applications in power electronics are the insulating Mn-Zn and Ni-Zn sintered ferrites, for which the characterization up to the MHz range is usually required. Switch-Mode Power Supply (SMPS) use ferrite core inductors to pump energy from an energy source to a load, with semiconductor devices operating as electronic switches. The resulting steady-state voltages and currents oscillate periodically around a DC value. Appropriate models and methods can allow to analyze saturation in ferrite-core power inductors, and to reliably predict the operation of inductors in SMPS under large inductance drop [6].

Magnetic materials like nanocrystalline and amorphous alloys exhibit a nearly linear magnetization curve, higher saturation threshold, very low power losses, and good stability versus temperature. The resulting inductors have a 10% inductance drop at larger currents. However, these materials are more expensive than ferrites, which are characterized by low losses and low saturation threshold. Composite materials, mixing ferrite and amorphous materials, are a viable alternative to tradeoff costs, size, losses and saturation [7].

**Additive manufacturing** (AM) or three-dimensional (3-D) printing, has the potential to rapidly prototype innovative designs of magnetic components and support the development of soft magnetic parts that
are still not possible to produce now. A few recent studies demonstrated the possibility to develop tall (>4 mm) ferrite cores with relative permeability ranging from 63 to 103 and resonance frequency higher than 30 MHz [8], aimed at improving power density and efficiency of switch-mode power converters. NiZn-ferrite was developed to form the integration of radio-frequency passive components with inkjet printing [9]. Additively manufactured functionally graded FeNi-based high entropy magnetic alloys have been manufactured by laser engineering net shape (LENS) processing, allows near-net shaping of dense metallic objects via introduction of pre-alloyed or blended elemental powders into a melt pool produced by a high-power laser [10]. Synchronous Reluctance Motors have been designed and manufactured using 3-D printing manufacturing technology [11].

References
Objectives

The context of the proposed activity is a collaborative research, involving the Politecnico di Torino – Department of Energy, Torino, Italy, the magnetism laboratory of National Institute for Research in Metrology (INRIM [https://www.inrim.eu](https://www.inrim.eu)), Torino, Italy, and the Laboratory SATIE at Ecole Nationale Superieure–Paris Saclay, France (http://satie.ens-paris-saclay.fr/version-anglaise/), a group that has been established since a few years on the topic of soft magnetic materials for energy applications. The Power Electronics and Renewable Sources LABoratory, Dpt. of Information and Electrical eng. and applied Math. (DIEM), University of Salerno, will also take part in the activities.

The activity planned for the candidate PhD student will be devoted to experimental and theoretical studies on the magnetization process and losses under alternating and rotational fields in Fe-based soft magnetic sheets from DC to the kHz range and broadband (DC-1 GHz) properties of soft sintered ferrites, thin amorphous/nanocrystalline ribbons, and composite materials, mixing ferrite and amorphous materials, for application as magnetic cores of power inductors. For all the types of materials the experiments will cover a broad range of peak polarization values. Particular efforts will be devoted to the experimental characterization under distorted waveforms (e.g. PWM), typical of power electronics devices, and to the elucidation of the concept of loss decomposition in the presence of skin effect.

1) **Measurement techniques** for the experimental characterization and theoretical modelling of commercial and custom saturating power inductors will be developed. In particular, a broadband investigation of saturation and losses of Mn-Zn ferrite, nanocrystalline and composite cores will be pursued. The tests will be carried out by means of a DC-10 MHz calibrated wattmeter-hysteresisgraph endowed with digital control of the induction derivative waveform. The characterization will be performed in sinusoidal induction conditions and under symmetric and asymmetric square-wave voltage, with and without DC bias. The experiments will be performed on core ring samples and on non-toroidal core geometries used in SMPS power inductors (low-medium risk).

2) **Electromagnetic models** for the numerical analysis and optimization of custom power inductors operating in SMPS units will be developed. The physical modelling will chiefly aim at predicting the magnetic losses under asymmetric square voltage regimes, starting from basic knowledge of the material response under sinusoidal centered induction. Such models will be then
extended to magnetic cores with complex geometries, used in custom and commercial power inductors for SMPS units. Suitable numerical models of electromagnetic field phenomena in power inductors will be developed, based on FEM or PEEC methods, taking into account complex geometries, the nonlinear behaviour of the magnetic cores, the windings models, and considering high-frequency large-amplitude non-sinusoidal supply conditions. The physical models of permeability and magnetic losses in magnetic cores will be eventually integrated into a numerical electromagnetic model of the entire inductive component. The obtained procedure will be tested by comparison with experiments made on toroidal and industrial cores, commonly used in custom and commercial power inductors for SMPS units (medium risk).

3) **Additive manufacturing**, design, and related testing technique of new custom power inductors aimed at improving power density and efficiency of switch-mode power converters will be developed. State-of-the-art 3D printing techniques will be exploited to build, as an example, NiZn-ferrite based power inductors and high frequency transformers (high risk).

| Skills and competencies for the development of the activity | Strong interest in electrical sciences, electrical engineering, theoretical modelling and experimental analysis of magnetic materials for electrotechnical application. Excellent mathematical and physical basis, besides a good competence in electrical engineering, are requested. |