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Editorial

# Introduction to the special issue *Deep learning for analysis and synthesis in electromagnetics*

In recent years, the integration of deep learning (DL) techniques into various scientific domains has catalyzed transformative advancements. One such domain witnessing a paradigm shift is the research in electromagnetics (EM). Electromagnetic problems in low- and high-frequency have traditionally relied on analytical and numerical methods. However, the complexity of modern EM scenarios often surpasses the capabilities of conventional approaches. This has spurred the exploration and adoption of DL techniques as powerful tools to address challenges in EM applications.

Deep learning, a subset of machine learning inspired by the architecture of the human brain, is characterized by the use of artificial neural networks with multiple layers (deep neural networks). The inherent capacity of DL models to learn complex representations from data has proven invaluable in solving problems that involve vast amounts of information. In electromagnetics, where phenomena are governed by Maxwell's equations and often involve complex geometries, DL offers a promising tool for enhancing efficiency and accuracy.

The aim of this Special Issue, "Deep learning for analysis and synthesis in electromagnetics", is to gather contributions on this topic, showcasing the state of the art in this research field, which is rather new, and many challenges still need to be faced by researchers.

The application of DL techniques in electromagnetic problems encompasses various facets, each contributing to the advancement of EM-related fields. One prominent area is in the design of electromagnetic devices, where optimizing the geometry and material properties is critical to achieve good performances. DL models, used as surrogate field models, can expedite the design process, even in the case of multi-physics problems. These surrogate models allow the reduction of the computational cost when field models must be solved many times, as in an optimization loop. However, the computational burden to train a deep neural network is still heavy, and techniques for reducing it, such as the use of transfer learning or the multi-fidelity approach, deserve investigation. In this Special Issue, several papers deal with the design of electromagnetic devices, optimization of electrical machines, and solution of multi-physics problems using DL techniques.

In the frame of industrial applications, the potential of DL for monitoring and fault detection in electrical machines promises to redefine the landscape of predictive maintenance. In this research field, many papers have been published in the last years, and two papers relevant to this topic are published in this Special Issue, showing two applications for transformers and ultra-high voltage reactors.

Furthermore, at high frequencies, the modeling of electromagnetic wave propagation in complex environments poses a significant challenge. Traditional methods, such as finite-difference time-domain simulations, often require extensive computational resources and are limited in their ability to capture intricate interactions. Deep learning, through its capacity to recognize patterns in vast datasets, enables the development of models that can efficiently predict wave propagation in different scenarios: two papers of the Special Issue utilize DL for the design of antennas and for the estimation of the interaction between electromagnetic waves and the human body, respectively; a third paper applies DL techniques for the evaluation of the electric field produced in a substation during switch operations.

In the context of material characterization, DL techniques exhibit promise in identifying material properties from measured EM fields. This has implications for non-destructive testing, medical imaging, material parameters identification, and the design of metamaterials. In the Special Issue, two papers show how to solve problems of electrical impedance tomography, and two other papers demonstrate how to identify parameters of hysteresis models using DL techniques.

Despite the promise and potential of DL in electromagnetic applications, challenges persist. For instance, identification problems and shape design problems could benefit from DL based techniques. However, nowadays, this is still a challenge because of the ill-posedness of these problems. Regularization techniques can be exploited, and their application to DL-based evaluations is still an open issue. Additionally, the scarcity of labeled data for certain electromagnetic scenarios poses a hurdle, necessitating the exploration of techniques such as transfer learning and data augmentation to mitigate data limitations. Hence, the use of DL for solving forward and inverse problems in electromagnetics represents a breakthrough in this field of research.

In conclusion, the fusion of DL techniques with electromagnetic problems marks a significant leap forward in the quest for efficient, accurate, and innovative solutions. From the design of electrical machines to wave propagation modeling, material characterization, and inverse problems, DL is proving its ability to solve problems in electromagnetics. As researchers continue to explore novel architectures, training strategies, and applications, the synergy between DL and electromagnetic problems is showing new capabilities, offering benefits across a spectrum of industries.

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