

# Computational Electromagnetics in Mexico

**Abstract** — This article presents the historical review of the research activities and teaching in numerical computation of electromagnetic fields in Mexico. It also reports the most relevant publications made by the research groups of four Mexican Universities. It is seen that computational electromagnetic has grown substantially in the last 20 years. Besides, the number of M.Sc. and Ph.D. graduates has increased in our Universities. The growth and future of research in computation electromagnetics are also briefly analyzed.

## I. INTRODUCTION

The paper describes the history of computational electromagnetics in Mexico, as well as the present and future of this area of knowledge. Activities related to the application of electromagnetic theory have been mainly taught at the graduate level in many Mexican universities. Although there were already attempts to introduce the finite element method in two dimensions in some Mexican universities and research centers, the main growth occurred at the end of the 1990s, when some Mexicans went abroad to study for their doctorate and once they finished their studies, they returned to Mexican Universities. Among the universities abroad were: Imperial College of London in the United Kingdom, the University of Bath in the United Kingdom, Grenoble in France, among others. The first papers on electromagnetic computation were published in outstanding scientific journals in the late 1990s.

The teaching of electromagnetic fields has been included in the master's degree programs in Electrical Engineering offered in several Universities. Usually, a course in advanced electromagnetic theory is given, followed by a course on the finite element in electromagnetism. A few years ago, the Metropolitan Autonomous University started a master's program in energy and electromagnetic engineering, and it is expected that the graduates will further strengthen the growth of electromagnetic computation in our country. The development of research activities in this area, as in all parts of the world and areas of knowledge, requires economic funding. In Mexico, funding has been obtained from three main sources: the Ministry of Education, the National Science and Technology Council (CONACYT), and private companies. The funding scheme consists that researchers submit, individually or in groups, their project proposals. Regarding the dissemination of research results within the country, there are three main national conferences: IEEE Power Summer Meeting, IEEE Autumn Meeting on Power Electronics and Computing, and Congress of Electromechanical and Systems Engineering; all of them on Electrical Engineering, where there is a session for the presentation and publication of the advances in electromagnetic fields. Most of the research has been focused on the study of low-frequency electromagnetic fields. Finally, the investigators of the Mexican research groups have been participating in important electromagnetics conferences such as COMPUMAG, CEFC, and ACES.

The future growth of numerical calculation of electromagnetic fields in Mexico looks promising, due to the presence of international companies that increasingly demand more specialists with knowledge of computational electromagnetics. Large companies such as Prolec, General Electric, Mabe,

Weg, Milwaukee, among others, have their internal departments of research and technological development of the electromagnetic and electromechanical devices they manufacture. Additionally, in January 2022 the 23<sup>rd</sup> International COMPUMAG conference will be held in Cancun, Mexico. It is expected that the presence of researchers from all over the world and the Mexican scientific community will allow networking and achieve a greater growth of young Mexican researchers.

In the following sections of this article, we present a detailed description of the research activities carried out by the main research groups in Mexico. The Institutes and Universities are La Laguna Institute of Technology, Metropolitan Autonomous University, Morelia Institute of Technology, and the National Autonomous University of Mexico.

## II. COMPUTATIONAL ELECTROMAGNETICS AT LA LAGUNA INSTITUTE OF TECHNOLOGY

The Laguna Institute of Technology offers a Master of Science in Electrical Engineering since 1979 which is organized in three internal research groups: power engineering, electronic instrumentation, and control systems. In 1992, the doctorate program was offered. In 1999, the Institute started its research activities in computational electromagnetics focused mainly on the analysis of electrical machines. The use and development of finite element code were mainly focused to research new mathematical lumped parameter models in synchronous generators based on electromagnetic theory [1–4]. In the 2000s, the power engineering group began to research the electromagnetic design of electrical power transformers using global optimization with evolutionary algorithms, artificial intelligence, and using finite element models in 2D and 3D using the magnetic vector and magnetic scalar formulations [5–10]. At the same time, the group started to provide technical consultancy in the area of high electrical power transformers and reactors to Mexican and foreign companies. In the same decade, this group began to analyze, develop and incorporate computational fluid dynamics in the analysis of electric power transformers [11–14].

In the last 10 years, the research has been focused on the electromagnetic, mechanical, and thermal design, as well as the fabrication of laboratory prototypes, of permanent magnet synchronous generators for wind energy applications [15–17]. With government funded research projects, it was possible to build the most complete laboratory in Mexico for the electromagnetic design of electrical machines. The laboratory has equipment for the characterization of magnetic materials, commercial software, and in-house developed software. It is well-known that one of the main problems in the validation of an optimal machine design is the manufacture of the prototype. In the manufacture of an electrical machine prototype, an obstacle that all researchers face is the fabrication of the complicated geometry of the magnetic lamination slots. This electrical machine laboratory has a laser cutting machine, which allows the manufacture of a design. Additionally, there is a test bench for electrical machine prototypes. The Laguna Institute research group has finite element software commercial licenses such as SLIM, COMSOL, FLUX, and ANSYS. It also has optimization

programs and expert systems, that were developed in our laboratory.

The research activities in this group have allowed us to graduate 15 M.Sc. and 6 Ph.D. students, specialized in computational electromagnetic and finite element analysis of electrical machines. Our graduates are working in Mexican Universities and the electrical industry such as General Electric, Milwaukee, Prolec, among others. In conclusion, it can be said that there is a huge demand for our graduates specialized in computational electromagnetics.

### III. ELECTROMAGNETICS AT THE METROPOLITAN AUTONOMOUS UNIVERSITY.

One of the main activities performed by UAM in the field of computational electromagnetism is its application to obtain the results that can help improve the transformer design in the industry. Since the mid-2000s, we have been producing research works that are mainly related to transformer design improvement. To extend our services towards solving problems related to the Mexican electric system, there is a need to improve the communications channels between us and the industry by proposing proper coordination and scientific discussions. It will enhance the relationship between academia and industry in Mexico, and ultimately, the trust of working together. However, from an academic point of view, we do not discourage theoretical work, which does not seem to have immediate application in the industry. We believe that such research enriches science and opens doors to solve industry-related problems.

We have been using commercial finite method software (MEGA, Flux, Maxwell, and COMSOL), as well as software that has been developed in other Mexican Universities for solving industrial and academic problems. The community of Mexican researchers involved in computational electromagnetism is small, but growing steadily. The professors of this University have actively participated in the following well-known international conferences: COMPUMAG, CEFC, ICEM, and COMSOL. Apart from contributions in conferences, this research group has also collaborated with several prestigious universities and industries around the world, such as the Indian Institute of Technology, The National Technical University of Athens, University of Vigo, SGB Transformers (Germany), Brandenburg University of Technology Cottbus- Senftenberg (Germany), Arya Transfo Company (Iran), Hellenic Electricity Distribution (Greece), Institute of Electrical Machines and Transformers-Technical University of Lodz (Poland), Transformer Division, Crompton Greaves Ltd. (India), Department of Electrical and Computer Engineering-NYU School of Engineering, and National Center for Scientific Research "Demokritos" (Greece).

Some of the achievements in transformer field calculation to date are significant and can be summarized as follows: our notable works include reducing stray losses in 225 kVA transformers low voltage side using stainless steel inserts around the bushings. The research was done in 3-D finite element method software named ANSYS. The numerical results were experimentally varied to validate its efficiency and efficacy. This is a well-known technique to engineers in the transformer industry; however, no detailed information is available in the literature or internet. It was achieved by measuring the load losses of the transformer with and without stainless steel insert. In this study, we found that the loss savings for the stainless steel insert represent almost 8% of the material cost of the transformer considering a useful life of the

transformer of 30 years. This work helped the engineers and designers in the industry to calculate the optimum inserts and implement them to reduce the losses of the transformer. Full details of this contribution can be found in [18].

In another notable work in 2007, the asymmetry phenomenon experienced during the measurement of the load losses of the three-phase transformer was investigated in depth. In this phenomenon, there is a very noticeable asymmetry in the power readings of the phases. This asymmetry can be explained as a result of two factors: a) asymmetric arrangement of the phases in space with respect to the other phases, which leads to asymmetric mutual impedances, and b) different stray losses produced by the phases. This was verified using 3D finite element simulations of a 31.5 MVA transformer. Details of this research can be found in [19].

In 2014, we helped a Mexican company to investigate the overheating in the bolt that holds the tank and the cover of a 420 MVA transformer, located very close to the high current bushings. The results obtained with the finite element software showed that the heating of the bolts was caused by the loose connection. We performed finite element simulations using Maxwell software and determined that the temperature of the bolts could be reduced by placing copper links from 387 °C to 85 °C. All the interesting details of this failure can be found in [20]. Our group has carried out other research works on field calculation in transformers that can be consulted in the following references [21–26].

### IV. COMPUTATION OF ELECTROMAGNETIC FIELDS AT THE MORELIA INSTITUTE OF TECHNOLOGY.

A group of researchers at the Morelia Institute have been interested in applying electromagnetic field computation, transmission line techniques, and related concepts to problems related to power engineering and the analysis and design of electrical equipment. The impact of switching transients in the dielectric stress developed in machine windings has been reported for one and three-phase windings [27,28]. The propagation of switching impulses requires the modeling of the winding using transmission line techniques; frequency-domain techniques have been successfully applied to this problem. A related subject of research is the transient response of grounding systems, where a multi-phase transmission line models the parallel trajectories in a grounding grid [29].

An effort has been made to develop in-house numerical codes for electromagnetic field computation [30]. Currently, a fairly complete library for finite element modeling of electrical and magnetic field problems has been completed. Also, an interactive computer program based on these developments is available for teaching and research. This effort has culminated in the available tools being used at other institutions for research purposes and in thesis projects [31].

The coupling of field models of electrical equipment and established power system transient simulators has also been of interest [32,33]. This offers the advantage of combining detailed models of power system components, such as transformers, with a more industry-standard lumped parameter model of the remaining electrical grid under study. The time-domain simulation of field models has also been addressed, resulting in generalized methods for field-circuit coupling [8]. Another area of interest has been the development of numerical and analytical methods that can be applied in the design of electrical equipment [34,35].

The participation of the National Autonomous University of Mexico (UNAM) in electromagnetics has been largely led by the Institute of Materials Research as early as the nineteen-eighties [36]. The works, essentially experimental, focused on the magnetic properties of material samples [37–44]. Just in recent years, very few works have been carried out on numerical modeling [45–50]. This new tendency has arisen following the creation of the College of Power System Engineering within the Program of Master and Doctorate degrees in Electrical Engineering of the Engineering Graduate School of our University [31,45,47,48]. A new pool of researchers with some background in computational electromagnetics has infused a new area of interest dealing with the modeling of conventional and superconducting electrical machines. Past and current joint academic projects with the Metropolitan Autonomous University through the doctorate program have allowed sustaining these new interests which show a slight shift from experimental works in material science towards the numerical simulation of electromagnetic systems. Table I provides statistics on the participation of our University in IEEE Transactions on Magnetics since 1983. In a broader context dealing with computational and experimental electromagnetics, researchers have been conducting in the field of wave propagation in open space for antennas and sensors mostly in the Faculty of Engineering [51,52] and the Institute of Applied Sciences and Technology [53,54], with application in theoretical physics in the modeling of the optical and physical properties of materials (superlattice, nanoparticles, superconductivity) in the Institute of Physics [55] and the Faculty of Sciences [56].

TABLE I. STATISTICS ON THE PARTICIPATION OF THE UNAM IN IEEE TRANSACTIONS ON MAGNETICS (TOTAL OF 25 PUBLICATIONS).

	Year span	Percentage (%)
Institute of Engineering	2020 [49,50]	8
Engineering graduate school	2016 – 2019 [31,45,47,48]	6
Institute of Materials Research	1983 – 2017 [36–44]	60
Faculty of dentistry	2016 [57]	4
Center for Nanoscience and Nanotechnology	2015 [58]	4
Institute of Applied Sciences and Technology	2006 [53]	4
Institute of Physics	1997 [55]	4

## V. CONCLUSIONS

In this article, we have presented the history of the Mexican research activities related to computational electromagnetics that were carried out by four groups at Mexican Universities. We have also discussed the future trend and growth of our future young electromagnetic researchers. We have several M.Sc. and Ph.D. graduates in computational electromagnetics and finite element analysis from our Mexican Universities and we expect that this number grows in the next years.

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