CAD SYSTEMS IN ELECTROMAGNETICS

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Abstract: *The main purpose of the paper is to review some of the most popular CAD systems in electromagnetics, to explain their most common features and to present solved examples with some of these systems. The common features of the CAD systems are considered and the most important among them are outlined and discussed in details. It is shown, that the optimization module is nearly obligatory in the modern CAD systems for electromagnetics. Several solved examples are presented from the fields of electrical machines, transformers, coupled coils, NDT devices, sensors for ECT, busbar systems and electromagnets, using mostly the MagNet, ElecNet and FEMM CAD systems. Conclusions are drawn about the applicability, the teaching and the future of these systems in the engineering work.*

Keywords: *CAD system, electromagnetics, optimization*

1. INTRODUCTION

The field of computational electromagnetics has undergone a big change in the last 20 years. The use of computers in the analysis, design, optimization, testing and production of electromagnetic systems has become a usual practice. The result is a substantial increase in productivity and efficiency of the engineering work. The great impetus for this is the progress being made in the computer hardware. The modern PCs show impressing power with CPU speeds reaching 3.5 GHz, operating memory of 4-8 GB, hard disk storage of 1÷2 TB, and every year these parameters get an increase of 20-30 %. The second stimulating factor is the advances in computational algorithms for electromagnetics, especially for realistic 3D geometric modeling, analyses and visualization. The contemporary CAD (Computer Aided Design) systems unify all these advances and provide a suitable user interface that helps the engineer to enter his design problem in a graphic way and to perform the electromagnetic analysis without having proficiency in numerical and computational methods. From the state of systems for analysis, shown some 15 years ago, the CAD systems have grown to systems for optimization and design with sophisticated intelligence and database management functionality.

The computer simulation of electromagnetic devices is now predominant in the engineering practice, as well as in the scientific computing. Nowadays, very few electromagnetic devices are built without some kind of design on computers. The expensive physical prototyping of these devices in many cases has been replaced by numerical modeling and optimization by using a suitable CAD system. This saves money, time, expensive work, and as a whole, diminishes the development expenses and results in improved characteristics and more competitive production.

A CAD system is a graphically based information system supporting the engineering work in the design and modeling of real world objects. It gives possibilities for building 2D and 3D graphic models, as well as animations – 4D graphic models, analogous to the real objects. As an additional feature, a CAD system gives opportunity for team work over complex models.

Another popular notion is CAE - abbreviation of “Computer-Aided Engineering”. CAE programs analyze the engineering designs, usually by the Finite Element Method (FEM). In electromagnetics, the notion CAD usually embraces the characteristics of CAE systems, as most of the CAD systems here include the finite element method for analysis of electromagnetic field.

The popular CAD systems are usually commercial products. Rarely full-featured CAD systems can be found as freeware, as they require a lot of development efforts and a long history in programming, testing, verifying and improving, that cannot be achieved by a small team of developers.

A typical CAD system for electromagnetics consists of (Fig. 1):

- Geometry definition module – assists the user to create geometric shapes by user specified solid modeling commands;
- Mesh generation module – generates automatically an optimal finite element mesh;
- Finite element analysis module – creates and solves the FEM system of equations;
- Post-processing module – creates field pictures (equipotential lines, color plots of gradients, arrow plots) and computes integral characteristics like energy, inductance, capacitance, force, torque, etc.

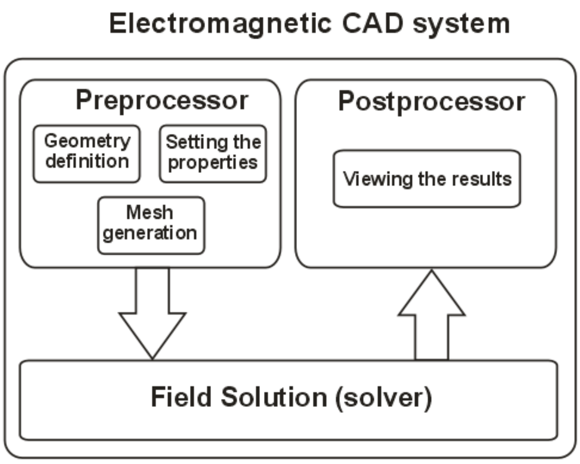

Fig.1. Main structure of a CAD system

The information in the CAD systems must be generated, used and improved for a long time - for the whole life-cycle of the product, and for new generations of software and hardware. Thus, standards are necessary for data exchange among the different CAD systems and their generations in the time. The popular standards for data exchange for CAD systems are DXF, ACIS, SAT, DWF, STEP (ISO 10303), etc.

The main purpose of this paper is to review some of the most popular CAD systems in electromagnetics and to explain their most popular features and possibilities. Next, some critical analysis will be made and the trends and common features in the CAD systems will be emphasized. At the end of the paper some example models will be shown, created by the author.

2. REVIEW OF SOME POPULAR CAD SYSTEMS

2.1. MagNet /ElecNet/ ThermNet/OptiNet (Infolytica Corp.)

Infolytica Corp. [1] has developed a suite of 2D &3D finite element CAD systems for analysis and optimization of magnetic, electric, electromagnetic and thermal fields in electromagnetic devices. The suite consists of:

- MagNet - 2D & 3D Electromagnetic Fields Simulation Software
- ElecNet - 2D & 3D Electric Fields Simulation Software
- ThermNet - 2D & 3D Thermal Simulation Software
- OptiNet – software for continuous and discrete optimization

MagNet can analyze static magnetic fields, time-harmonic electromagnetic fields, and transient fields. The effects of motion for multiple moving components and for arbitrary motion directions can be analyzed also.

ElecNet can analyze static electric fields, static current densities produced by specified DC voltages in conducting material, electric fields produced by specified AC voltages at one frequency in the complex domain, transient electric fields produced by specified voltages that vary arbitrarily in time.

ThermNet can analyze static and transient thermal fields due to conduction, convection & radiation. Both simulation types can be coupled to static or time-harmonic solutions in MagNet.

OptiNet is a tool for optimizing a design based on electromagnetic, electric field and thermal solutions with continuous-valued and discrete-valued variables. OptiNet features evolutionary strategy for finding optimized solutions. Built-in and customizable scripts for the objective functions and constraints are provided. OptiNet works with MagNet, ElecNet, ThermNet & coupled MagNet-ThermNet solutions.

ACIS solid modeler is common for all packages.

Mesh generation can be automatic or user-defined. Automatic mesh adaption tools and higher order elements are available.

All systems have easy importing and exporting of SAT and DXF files; optional modules for CATIA, STEP, IGES, Pro/E and Inventor file Import / export can be obtained.

MagNet also has Circuit modeler for connecting devices to circuit-simulated drives and loads. It is useful for power electronics devices and electric machines.

ElecNet also has modeling of floating conductors, automatic calculation of the resistance and capacitance matrices of electrodes, modeling of thin resistive sheets and surface charges.

Powerful parameterization capabilities are available. Scripting tools (using Visual Basic) help to automate repetitive tasks, customize settings and link all packages.

The Post Processing includes field visualizations - field plots, graphs and animations of time-varying or multi-step problems; data and image exporting. Integral quantities are also computed and exported – inductances, capacitances, impedances, power, power losses, forces and torques.

Drawbacks of the Infolytica packages are: all packages solve low-frequency electromagnetic problems (till several MHz). The packages are not easy to learn, require considerable experience.

2.2. COMSOL

COMSOL [2] is a powerful, interactive environment, developed by COMSOL Corp, for modeling and solving scientific and engineering problems based on partial differential equations.

COMSOL solves a system of partial differential equations (PDE) by the finite element method (FEM) with adaptive meshing and error control. It is possible to set up models as stationary or time-dependent, linear or nonlinear, scalar or multi-component. The package also performs eigenfrequency or eigenmode analyses.

COMSOL has several discipline-specific application modules. These are the Chemical Engineering Module, the Electromagnetics Module, the Structural Mechanics Module, Earth Science, Heat Transfer, and MEMS (Micro ElectroMechanical Systems) Modules.

The Electromagnetics Module covers a broad range of application areas spanning from the static and low-frequency range to very high-frequency phenomena such as optics and photonics.

COMSOL provides powerful CAD tools for creating 1D, 2D, and 3D geometry objects, where Boolean operations (union, subtraction, intersection, etc.) are used for creating composite solid models. Objects created by other modeling software can be imported and used in COMSOL models. The geometry import uses IGES files in 3D and DXF files in 2D.

The triangular- or tetrahedral-shaped unstructured mesh is automatically created by the mesh generator. Adaptive meshing is available.

COMSOL also features a parameterization, which offers a way to examine a parameterized series of models. The varied parameter typically represents a material property or frequency.

COMSOL has equation-based modeling application modes - the PDE Modes. They allow to define own systems of partial differential equations. In the COMSOL GUI, dialogue boxes are provided where equations can be entered in a symbolic way, similar to writing equations by hand. COMSOL can interpret these expressions and arrange the equations so that they can be solved by the FEM.

COMSOL allows to couple physics defined by predefined application modes. The PDE mode can also be used for coupling between systems involving any arbitrary physical description of a phenomenon.

COMSOL is based on MATLAB and allows manipulating model data and the models themselves in the MATLAB environment.

COMSOL features a built-in post-processing tool for direct manipulation and visualization of the results. It provides extensive visualization and post-processing capabilities, including: Interactive plotting of any function of the modeled variables and its derivatives; visualization using slices, isosurfaces, contours, streamlines, vector-field plots, animations, integration along boundaries and sub-domains, cross-sectional plots.

Drawback of COMSOL is the comparatively slow solution of big problems.

2.3. ANSYS Maxwell

ANSYS Maxwell [3] is electromagnetic field simulation software for designing and analyzing 2-D and 3-D electromagnetic and electromechanical devices, including motors, actuators, transformers, sensors and coils. Maxwell uses the finite element method to solve static, frequency-domain, and time-varying electromagnetic and electric fields. Maxwell automatically generates an appropriate and accurate mesh for solving the problem.

A key feature in ANSYS Maxwell is the ability to generate reduced-order models from the finite-element solution for use in ANSYS Simplorer, the multi-domain system simulation software from ANSYS. This capability enables to combine complex circuits with accurate component models from Maxwell to design complete high-performance electromechanical or power electronic systems.

2.4. Flux 2D & Flux 3D / Flux Studio

Flux 2D/3D [4] is a finite element software application used for electromagnetic and thermal physics simulations, both in 2D and 3D.

Flux is featuring a large number of functionalities, including extended multi-parametric analysis, advanced electrical circuit coupling and kinematic coupling. It can analyze:

- Magnetic, electric and thermal fields
- Magnetic/electric/thermal coupling
- Mechanical coupling
- Multi-physics coupling
- Static, harmonic and transient analysis
- Parameterized analysis
- External circuit connections

Flux is suitable for designing, analyzing and optimizing a variety of devices and applications such as rotating machines, linear actuators, transformers, induction heating devices, sensors, HV devices, cables, nondestructive evaluation.

2.5. Integrated Engineering Software (IES)

The software package IES [5] includes AMPERES 3D, COULOMB 3D, FARADAY 3D programmes. It performs analysis of magnetostatic, electrostatic and time-harmonic fields. The main computational method is the Boundary Element Method (BEM). The package has additional possibility for finite element analysis and hybrid BEM-FEM modeling.

2.6. QuickField 5.10

QuickField [6] is a commercial CAD system mainly for 2D FEA. It solves electromagnetic, thermal and mechanical problems. It has simplified interface and is comparatively cheap and suitable for teaching use. Since version 6.0, it supports also 3D electrostatic analysis.

2.7. FEMM 4.2

FEMM 4.2 [7] is a free software package based on finite element method. It performs 2D FEM analysis of magnetostatic, electrostatic, time-harmonic and thermal fields. It has simplified graphical user interface and is very easy to use. It is very easy to learn, very popular in the universities, very suitable for teaching electromagnetics, electrical machines, and electrical apparatus. Its drawbacks are: 1) developed only for 2D FEA; 2) lacks transient analysis.

2.8. CST Studio Suite

CST Studio Suite [8] offers 3D simulations of electromagnetic devices for low-frequency and high-frequency applications. It has intuitive graphical user interface and variety of available solvers. Its strength however is in the high-frequency simulations, where they have long years experience.

The products in the CST STUDIO SUITE® family can carry out electro- and magnetostatic, stationary, low-frequency and high-frequency simulations, as well as calculate the effects of EM fields on magnetic materials, biological tissues and charged particles. Main fields of applications:

- Statics/Low Frequency (CST EM STUDIO)
- Microwave & RF/ Optical (CST MICROWAVE STUDIO)
- EDA/Electronics (CST DESIGN STUDIO)
- Particle Dynamics (CST PARTICLE STUDIO)
- EMS/EMI (CST CABLE STUDIO)

For each field, CST STUDIO SUITE contains tools for designing, simulating and optimizing devices and systems.

The built-in optimizers in all CST STUDIO SUITE modules can be used to optimize any parameter, including the geometry of the model, the properties of the materials and the waveform of the excitation.

CST STUDIO SUITE includes both local and global optimizers. Local optimizers search the parameter space close to the initial values – they offer fast performance for fine tuning a nearly optimal model. Global optimizers on the other hand search the entire parameter space, and are more efficient than local techniques for poorly tuned or complex structures.

2.9. Opera v.16

Opera v. 16 [9] offers 2D and 3D finite element analysis and optimization of electromagnetic devices. It is functionally similar to MagNet/ElecNet, but also has high-frequency module. Opera is a software package for modeling of static and time-varying electromagnetic fields and related multiphysics.

It consists of a powerful 2D/3D modeler for creating design models (or importing from CAD), plus a choice of specialized finite element simulation tools:

- Static electromagnetic fields (‘Tosca’ tool)
- Low-frequency time-varying electromagnetic fields
- High frequency time-varying electromagnetic fields
- Thermal and stress analysis (standalone or coupled)

It is very suitable for:

- Linear and rotating machinery design
- Superconducting magnet quenching
- Particle beams including space charge effects
- Permanent magnet magnetization/demagnetization
- Hysteresis in soft magnetic materials
- Electric field analysis in conducting-dielectric media

After the simulation, a programmable interactive post-processor allows users to view and analyze the simulation results, and performs additional calculations. Model parameters may be changed to rapidly perform ‘what-if?’ investigations. The designs can be automatically improved with the aid of Opera’s Optimizer. Opera is available in 2D or 3D variants.

Main fields of application are:

- Power conversion and electromechanical devices (motors and generators, linear motors, actuators and position sensors, Simulink® co-simulation
- Power systems (losses and interference, insulation and grounding, components)
- Transportation (electromagnetic braking, railways, non-destructive testing)
- Medical physics and science applications (X-ray tubes, electron microscopy/lithography, MRI magnets, superconducting coils)

3. COMMON TRENDS IN THE DEVELOPMENT OF CAD SYSTEMS

The research done about the features of the most popular CAD systems for electromagnetics shows the following trends, which are de-facto standards for the present moment.

3.1. Geometry modeling

Most of the packages use solid modeling for 3D model creation. Parameterization is very common feature, nearly everywhere included. Modeling with geometric primitives and Boolean algebra allows creation of 3D models. Creating 3D models using translation and rotation of 2D cross-sections can be found also. Dimension parameterization is available in most commercial packages.

3.2. Generating the finite element mesh

Mesh generation is automatic, with mostly triangular and tetrahedral finite elements. Adaptively refined meshes, which get more refined in the regions with high gradients are also used in some CAD systems. Higher order elements (till 4-th order) to improve the accuracy, are also used. Bricks, prisms, and other elements, are rarely used. Edge elements are mainly used in 3D. Small number of packages uses BEM.

3.3. Types of analysis

The following types of analysis are mostly used:

- Magnetostatic field analysis
- Time-harmonic field analysis (with sinusoidal quantities)
- Electrostatic field analysis
- Electric fields in conducting media analysis
- Time-dependent (transient) electromagnetic field analysis
- Thermal field analysis – stationary and transient
- Coupled analysis: electromagnetic-thermal or electric-thermal fields.

3.4. Presentation of the results (postprocessing)

The postprocessing is presented usually with separate user interfaces for the different kinds of fields. It includes:

- Plotting of equipotential lines in 2D
- Plotting of color-coded field pictures representing potentials, gradients, errors, etc.
- 2D and 3D graphs of functions (distribution of potentials, magnetic flux density, field intensity, current density)
- Plots of field vectors in 2D and 3D.
- Creation of animation in AVI files

- Computation and output of forces, moments, inductances, capacitances, impedances, induced voltages.

Data output can be in MS Excel, MS Word, text files, etc.

3.5. Links with other CADs

This is done by the use of DXF, DWG, IGES, STEP file standards, for importing drawings, models, and exporting results.

3.6. Boundary conditions

Dirichlet, Neumann and mixed BC are common features; nearly all packages use periodic BC and also infinite elements for open boundary problem, in order to reduce the region analyzed and computational efforts.

3.7. Material libraries

All packages have material libraries containing widespread material data, which can be extended with user defined materials. The material data contain electric, magnetic, thermal, mechanical, etc. properties, including B-H curves. Loss curves of ferromagnetic materials are included also.

3.8. Connecting external circuit connections

Most of the solvers include external circuit coupling feature, together with schematic editor to support arbitrary topology of power-electronic drive circuits and winding connections in electric machines and transformers.

3.9. Solving the system of equations

Mostly iterative PCCG (Preconditioned Conjugate Gradient) solvers are used with sparse matrix storage. Parallel solvers for the FEM systems of equations are already offered for some CADs (ANSYS, CST) which can work on multi-core processors or clusters of computers.

Most of the CAD systems support both 32-bit and 64-bit platforms. The 64-bit versions of the software are used to address bigger memory and obtain higher computation speed.

Using graphic processing units (GPU) is also used to speed-up the computations (e.g., in CST).

3.10. Solving coupled problems

Nearly all electromagnetic CAD systems offer possibilities for solving coupled problems: eddy current+thermal; magnetic+mechanical, etc. - very important feature for solving real-world problems.

3.11. Linear and rotational motion

This feature enables to predict accurately the performance of motors and actuators at different transient conditions, where motion effects are important.

Taking into account of the motion gives better prediction of the characteristics of:

- Linear and rotating electric machines
- Electromagnetic actuators, in which the motion effects in transient analysis are important

3.12. Programming the work of the CAD system

In many CAD systems there exists built-in programming language, which allows a sequence of commands to be created for building and analyzing the model. This feature is useful for:

- Automatic model creation at different input data
- Variant calculations in optimization
- Automatic log of the command sequence at interactive work with the CAD system

Examples of languages used:

MagNet uses Visual Basic Script language;
COMSOL uses MATLAB language;
FEMM uses LUA language;
ANSYS uses APDL, similar to Fortran language.

3.13. Optimization

This capability /Fig. 2/ is included in most of the commercial CAD systems. Very often evolutionary algorithms are used for their ability to find the global optimum and for the lack of derivative computations. The Design of the Experiment (DOE) is also used in some packages /Fig. 3/, to create simplified polynomial models (e.g., in MagNet, in ANSYS). This can decrease considerably the optimization time, especially for 3D models.

The optimization module represents a module included or added in most of the popular CAD systems (e.g., MagNet/ElecNet uses external OptiNet software; COMSOL, ANSYS, OPERA have included optimization module).

3.14. Using parallel computations

The parallel computations can be used effectively in the following cases:

1. Using cluster of computers to solve a problem too big to be solved with one computer.

2. Distributing a large number of independent simulations, that arises in parametric study, to be solved on several computers in parallel.

The independent simulations can come from:

- Optimization problem solved by genetic/evolutionary algorithms
- Computing the variants arising in the DOE application
- Computing the variants for neural network training

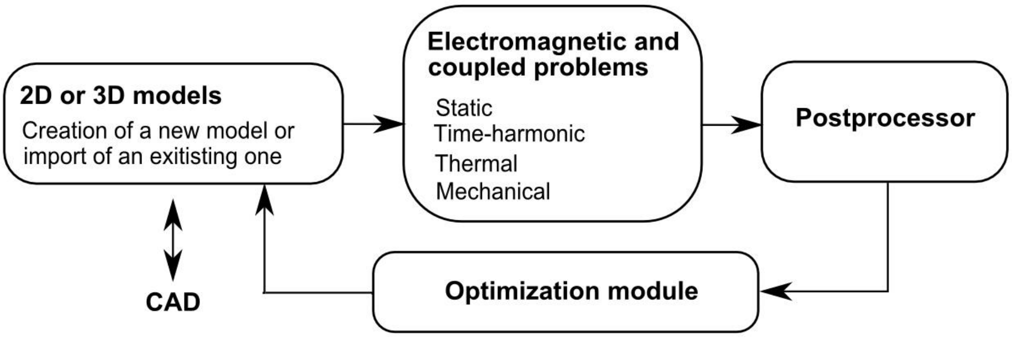

Fig. 2. Flow-chart of CAD system with optimization module

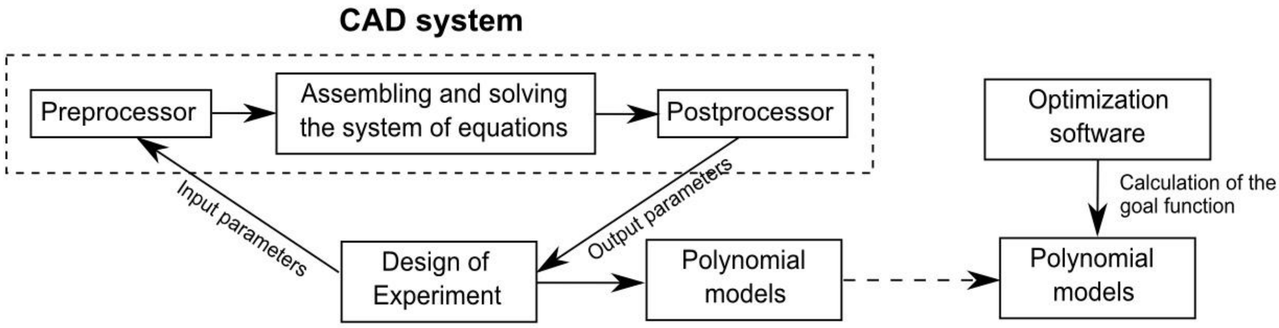

Fig. 3. Flow-chart of DOE in combination with CAD system for optimization

Types of parallel computations used:

- Multithreading - It is used for multi-core processors and multiprocessor systems. It is offered in most of the modern CAD systems...
- Parallel computations using graphic processor units (GPU) – These are used on GPUs like NVIDIA® Tesla, representing additional external modules to the usual workstations. The CST CAD system offers such possibilities.
- Distributed computing - Can be used for independent simulations, which are performed on computer clusters.
- Parallel computations using MPI (Message Passing Interface) - A specialized computer cluster is required, having high computational speed and high-bandwidth connections between the computers. This is the only way to simulate very large models.
- Cloud computing - Offers cluster computing to users that do not own a cluster.

3.15. Availability of simplified free versions

Most of the developers of commercial CAD systems offer also free simplified versions of their software. These are intended mostly for initial acquaintance with the product, mainly intended for 2D magnetostatic and electrostatic simulations.

Some of these simplified free systems have limited number of elements in the created FEM mesh and can be used mainly in the teaching process.

3.16. Price policy and software support

The software prices depend on the desired analysis types, the solvers used, etc.

Usually there is a separate lower price for use in the teaching and in the research at universities. One-month testing period is usually offered for free testing of the full software versions. Usually, there exists one-year free support after the software purchase. Training courses are offered for beginner and advanced users.

Many developers organize dedicated scientific conferences for their users, where they present successful projects with the use of the software.

Availability of Internet site with useful information, examples, help and possibilities to download the software is a common practice.

4. EXAMPLE MODELS

In the following chapter some example models are be presented, developed by the author in the following fields: electric machines; NDT devices; ECT sensors; busbars; dipoles, quadrupoles, etc. The 3D geometrical models, equipotential lines and field vectors of the solution are shown. The MagNet, ElecNet and FEMM CAD systems are used in these examples.

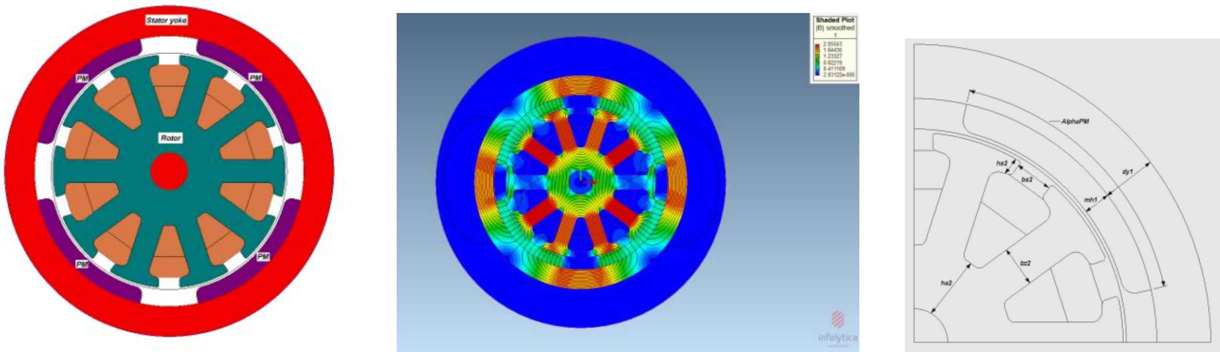

Fig. 4. 4-pole DC machine with permanent magnets

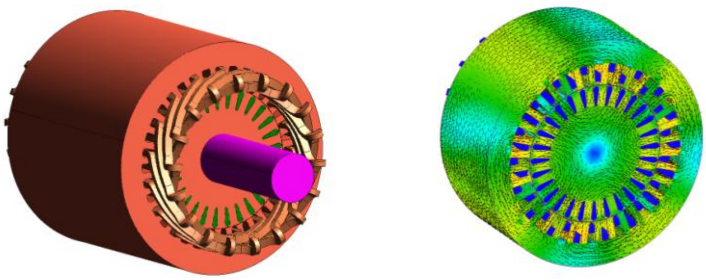

Fig. 5. Induction machine

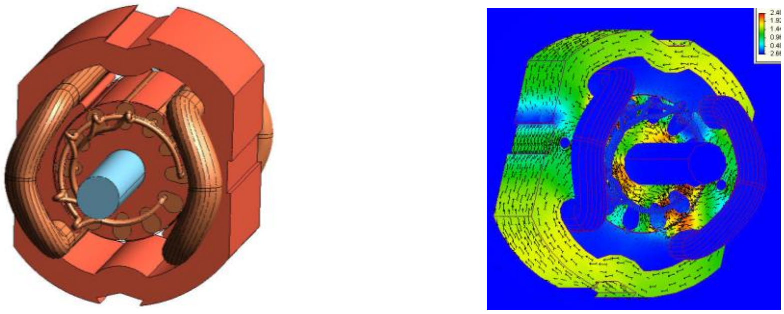

Fig. 6. Universal machine

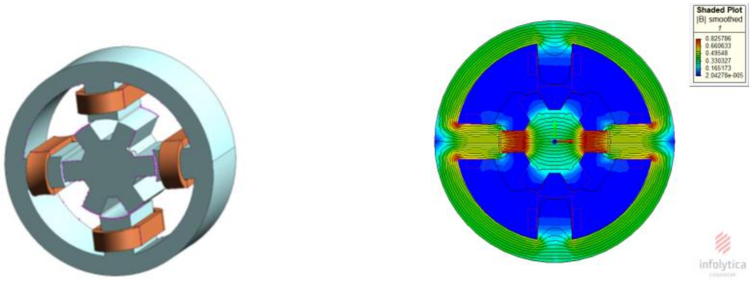

Fig. 7. SRM – Switched Reluctance Machine

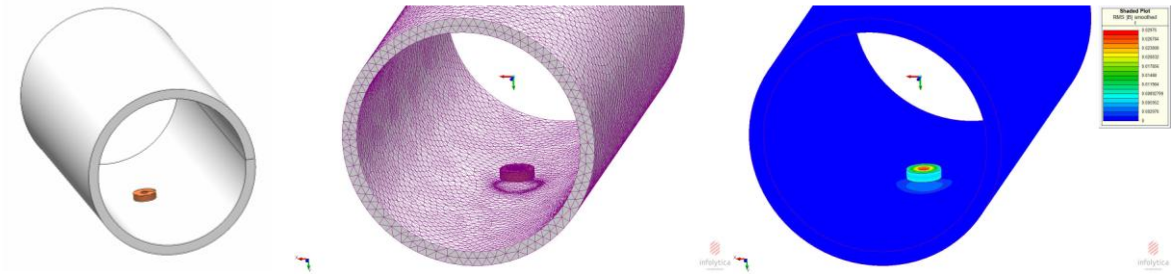

Fig. 8. Pipe and cylindrical NDT sensor

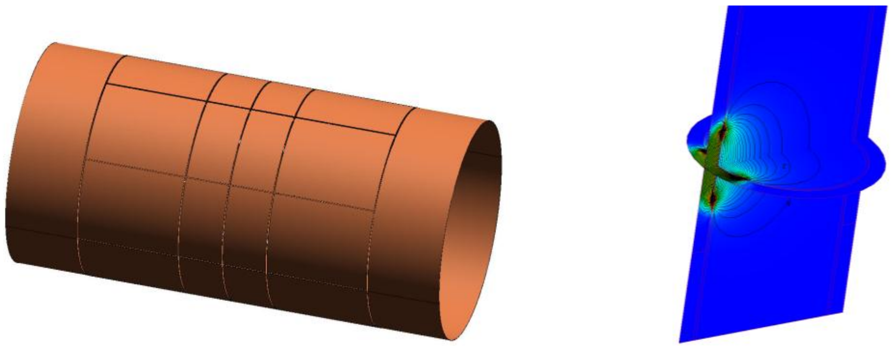

Fig. 9. 32-electrode 4-layer ECT sensor with rectangular electrodes

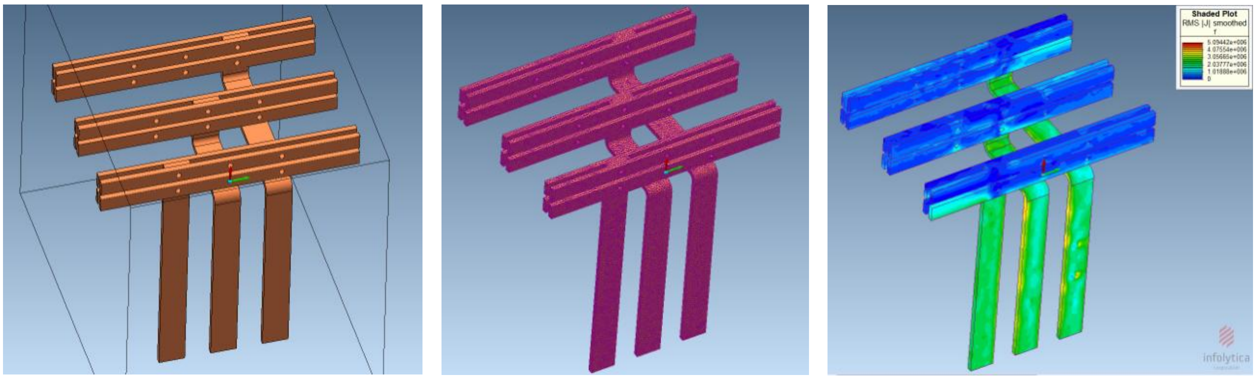

Fig. 10. 3-phase busbar system

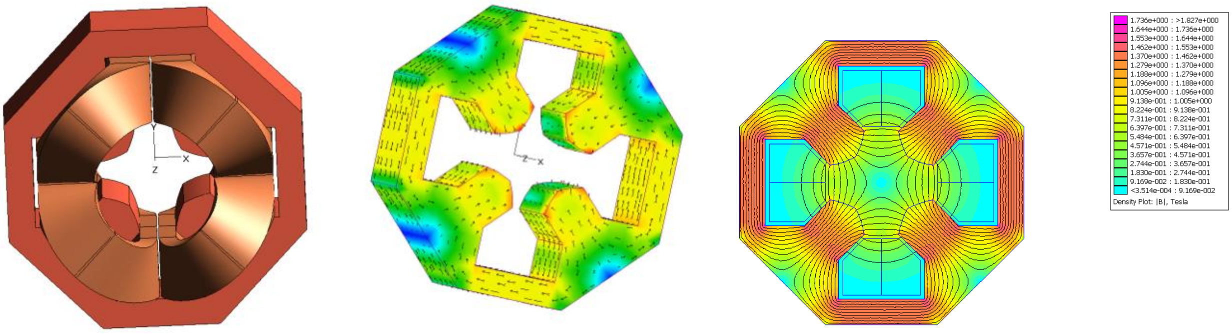

Fig. 11. Quadrupole focusing electromagnet

5. CONCLUSIONS

The CAD systems for electromagnetic calculation are coming in broadly in the engineering work and can be found in every company. So, it is increasingly important for the electrical engineers to get good knowledge of these systems, which makes a necessity their study at the universities. The pedagogical issues of teaching CAD systems in electromagnetics have to be discussed more deeply.

Besides the industrial use, the CAD systems could be used effectively for illustration of topics studied in the courses of Electromagnetics, Electric Machines, Electric apparatus, etc., in most of the universities.

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Reviewer: Prof. DSc R. Stancheva