

Analysis of a Three-Phase Transformer using COMSOL Multiphysics and a Virtual Reality Environment

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Abstract: The simulation software COMSOL Multiphysics is applied to the numerical computation of the magnetic fields of a three-phase transformer. A three-dimensional model of the geometrical configuration is created with the help of the CAD tools of COMSOL Multiphysics. There, all dimensions of the transformer are defined by parameters. The creation of an optimal finite element mesh is improved by some modifications of the geometrical model. The magnetic field formulation of the AC/DC module of COMSOL Multiphysics is chosen for a static analysis of the transformer. Eddy currents in the iron core are neglected. Nevertheless, a complete period of the time-harmonic currents in the coils is taken into account by a parameter sweep. Finally, the finite element model along with the computed magnetic fields is exported via LiveLink for MATLAB to the visualization software HLRS COVISE for a vivid post-processing within a virtual reality environment.

Keywords: magnetostatics, MATLAB, parameterized model, virtual reality

1. Introduction

The simulation software COMSOL Multiphysics is a very flexible and powerful implementation of the finite element method (FEM). A variety of modules with predefined physical models is available. Hence, most typical field problems are well supported by the clear user interface of COMSOL Multiphysics. Numerical routines and solvers are robust and efficiently implemented to solve large field problems on a multi-core computer or a computer cluster. Furthermore, all equations and numerical formulations are visible. Strength of COMSOL Multiphysics is that its functionality is expandable by additional functions and even own code. This important feature is implemented via LiveLink for MATLAB. The software MATLAB supports many established programming interfaces like component object model (COM), native C, Java, or .NET. Moreover, all functions of COMSOL Multiphysics are accessible in MATLAB. Hence, COMSOL Multiphysics is

a very interesting tool for scientific applications and teaching at a university.

The examined three-phase transformer has been designed for educational applications and is for that reason separable (Fig. 1). A consequence is that all dimensions of the transformer are easily measurable. Furthermore, the transformer is well suited for the visualization techniques augmented reality (AR) and virtual reality (VR) [1].

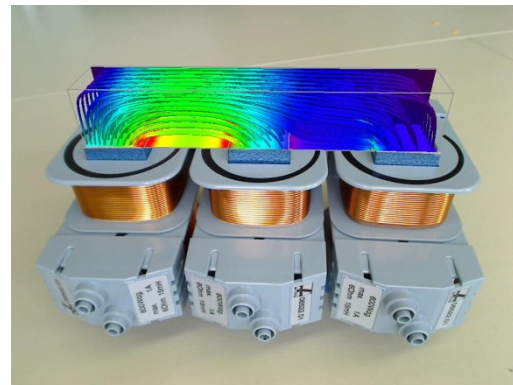


Figure 1. Educational model of a three-phase transformer; magnetic flux density inside the iron core is visualized using augmented reality technique

The AR technique combines the real studied object with computed fields [2, 3]. The virtual objects are added to a live video stream of the real object. The resulting images are very impressive and easy to interpret.

If the studied object is not available or computed values inside the object are visualized, an application of the VR technique is advantageous. Figures, which are created in a VR environment, are particularly impressive, if a CAVE is used [4]. Fortunately, even current consumer displays are able to show three-dimensional content. Hence, VR is a tool, which can be used for everyday work.

The aim of this paper is to present a method, which interactively combines COMSOL Multiphysics and a VR environment. First, the three-phase transformer and its numerical model in COMSOL Multiphysics are de-

scribed in detail. Then, the VR environment based on the visualization software HLRS COVISE is introduced. A focus is on the interactive coupling of COMSOL Multiphysics and HLRS COVISE based on the COM interface of MATLAB.

2. Numerical Model

The numerical model of the studied transformer is introduced in this section. The numerical formulation is presented in the first sub-section. Then the creation of a parameterized CAD model along with the discretization into finite elements with COMSOL Multiphysics is shown. Some details to the physical model are given, too. Finally, the solution of the problem including computational costs is discussed.

2.1 Numerical Formulation

A numerical formulation has to be chosen to enable the computation of the magnetic flux density of the three-phase transformer in dependency of the coil currents. The results should be accurate and suitable for visualization in a VR environment.

The visualization in a VR environment requires three-dimensional data. Hence, a real three-dimensional model is necessary. Furthermore, a three-dimensional computation is more accurate than a two-dimensional computation. Here, a two-dimensional model is only suitable for fundamental studies and tests of the model.

The AC/DC module of COMSOL Multiphysics provides a predefined physical model for magnetic fields with electric currents. Then, a FEM formulation based on the magnetic vector potential \mathbf{A} is applied.

Here, two time dependencies are possible. A static solver along with a parameter sweep or a time-harmonic solver can be chosen. The pro and cons of both solvers are shortly discussed in the following.

The currents in the coils are time-harmonic and the phase difference between the currents is $\frac{2}{3}\pi$. Then, a time-harmonic solution is obvious. However, we decided to apply a parameter sweep along with a static solver. An advantage of this approach is that the static solver

is more robust than the time-harmonic one. Furthermore, a time-harmonic solver is predestined for the solution of eddy current problems. Here, the iron core of the transformer consists of multiple thin iron sheets. Since each iron sheet is electrical insulated, resulting eddy currents are very small. Modeling of the thin insulated iron sheets is very difficult and expensive, too. Hence, we decided to completely neglect eddy currents. Another advantage of the parameter sweep along with a static solver is that also distorted or noisy coil currents, which are not exactly time-harmonic, can be studied.

2.2 CAD Model and Discretization

The complete model of the transformer is defined by parameters. This simplifies the creation of the geometrical model and enables changes of the dimensions, which can be used for a parameter study or an optimization of the transformer.

The surrounding air domain and the iron core are created with the help of blocks. The coils are assembled with blocks and cylinder segments. To improve the quality of the finite element mesh the small air gap between the coils and the iron core is created as a separated geometrical object. The resulting geometrical model is shown in Fig. 2.

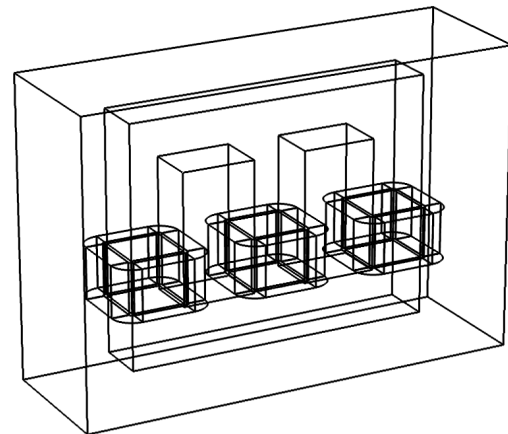


Figure 2. Geometrical model of the transformer including the surrounding air domain

The finite element mesh is created in COMSOL Multiphysics based on this parameterized geometrical model. The size of the elements must be carefully adjusted to obtain accurate results along with acceptable computational costs.

COMSOL Multiphysics supports automatic mesh generation with a given level of element size. Alternatively, the size of the elements and further parameters can be manually defined for domains and edges.

Here, successive automatic mesh generation leads to a mesh of high quality and a relatively small number of elements. First, the iron core, which is the most significant part of this device, has been meshed with extra fine size of elements. Then a normal size of the elements has been chosen for the small air gap between the iron core and the coils. The coils are also meshed with a normal element size. Finally, the surrounding air has been meshed with coarse elements.

The resulting mesh is of good quality, especially inside the iron core (Fig. 3). 41784 tetrahedrons suffice for this three-dimensional problem.

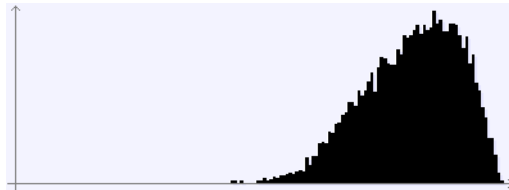


Figure 3. Quality of the finite element mesh inside the iron core

2.3 Physical Model

The predefined model for the three-dimensional solution of magnetic fields with electric currents of the AC/DC module has been chosen. Then, a linear system of equations for the magnetic vector potential \mathbf{A} is obtained. The material properties of the air domain and of the coils are $\epsilon_r = 1$, $\mu_r = 1$, and $\kappa = 0$. ϵ_r is the relative electric permittivity, μ_r the relative magnetic permeability, and κ the electric conductivity. The predefined material soft iron (without losses) is chosen for the iron core.

The boundary condition at the surface of the air domain is $\mathbf{n} \times \mathbf{A} = \mathbf{0}$.

The constitutive relation in the iron core is set to $|\mathbf{H}| = f(|\mathbf{B}|)$. Then the HB -curve of soft iron is used.

The definition of the coil currents is more laborious. The coils are modeled with a constant cross section. Hence, the absolute value

of the volume current density \mathbf{J} is constant, too. The current density in the upright parts of the coils is parallel to an axis of the coordinate system. However, a curved current density must be defined in the cylindrical parts of the coils. Here, a function for the current flow in a cylinder has been set and used in these parts of the coils.

2.4 Solution

A system of linear equations with 266334 unknowns is obtained in total. It is solved iteratively with flexible generalized minimum residual method (FGMRES) along with a geometric multigrid preconditioner.

Since the currents of the three coils are defined in dependency of an initial phase value, this parameter is changed within a parameter sweep to obtain the magnetic fields for a complete period of the time-harmonic currents. A total number of 33 values of the initial phase are used. Then, a visualization of the results over the parameter sweep is of good quality.

The problem has been solved on an Intel Core 2 processor with two cores and a clock frequency of 3.06 GHz. The total computation time has been 130 minutes and the memory requirements have been 1.2 GB.

Here, the solution of a parameter step has been used as starting values for the next parameter step. This reduces the number of non-linear iteration steps from seven iteration steps for the first parameter to 3-4 non-linear iteration steps for the following parameter steps.

3. Post-processing

A meaningful post-processing is very important for a correct interpretation of the computed results and a better understanding of the studied model. Here, COMSOL Multiphysics and HLRS COVISE have been applied to create three-dimensional plots of the magnetic fields of the transformer.

The post-processing tools of the current version of COMSOL Multiphysics are very flexible. They enable a relatively easy computation of integral values, for instance the magnetic flux through the cross section of the iron core. Furthermore, vivid three-dimensional plots of scalar and vector values are possible.

A vector plot of the magnetic flux density and the electric current density is shown in Fig. 4 along with the finite element mesh of the iron core and the coils. The edges of the surrounding air domain are displayed, too.

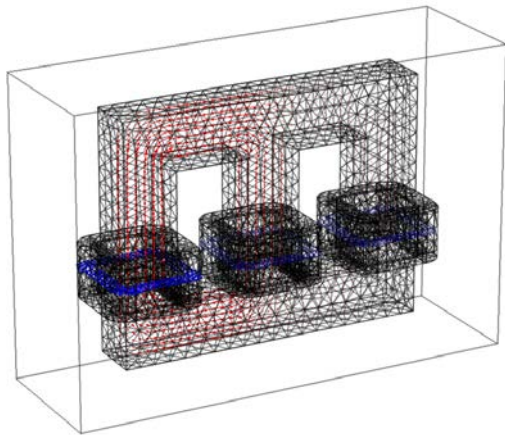


Figure 4. Finite element mesh of the iron core and the coils; edges of the surrounding air domain; magnetic flux density inside the iron core; electric current density inside the coils

A second way to evaluate a model using COMSOL Multiphysics is the module Live-Link for MATLAB. MATLAB is started in combination with COMSOL Multiphysics and all functions of COMSOL Multiphysics including data structures of the model are accessible from the MATLAB console. Frequently used functions are supported by user-friendly interfaces. Strength of this post-processing method of COMSOL Multiphysics is that the functionality of MATLAB is available, too. Hence, this interface supports connections and data exchange with external post-processing tools, for instance the visualization software HLRS COVISE.

3.1 Virtual Reality Environment

Virtual reality is a vivid technique for the presentation of numerically computed three-dimensional fields. Here, the geometrical model along with the magnetic fields is visualized similar to Fig. 4. The difference to the presented post-processing of COMSOL Multiphysics is that a true three-dimensional image is displayed.

A VR environment consists of two main components. One component is software, which renders the three-dimensional images.

The other component is a device, which is able to display three-dimensional content.

Here, the visualization software COVISE, which is developed at the High Performance Computing Center Stuttgart (HLRS) at the University of Stuttgart, is used. It visualizes three-dimensional data, which is for instance given in the nodes of a finite element mesh.

The post-processing features of HLRS COVISE are similar to the tools of COMSOL Multiphysics. Scalar data is displayed with surface or isosurface plots. Vector data is typically visualized with the help of arrows or streamlines. Furthermore, geometrical models can be added. They are extracted from the finite element mesh or additional CAD models, for instance files in virtual reality modeling language (VRML), are used. A video live stream of the real object simplifies the viewing of the computed virtual objects in the so-called augmented reality technique.

The created graphical objects are rendered on a graphic card using the OpenGL standard. Professional graphic cards, for instance the NVIDIA Quadro FX 3800, support quad-buffer stereo. Then, a stereo signal is available at the output port of the graphic card. Here, a signal for both eyes with full resolution is created alternately.

Nowadays, a variety of hardware exists to display three-dimensional content. Professional or consumer monitors and projectors are available. Here, a so-called powerwall, which consists of a consumer 3D projector in combination with a rear-projection screen and NVIDIA 3D Vision Pro shutter glasses, is used. The glasses are synchronized with the graphic card via a proprietary data port. A wireless computer mouse with an accelerometer is applied for navigation.

The above-described VR environment is used to visualize the computed magnetic fields of the transformer (Fig. 5). The magnetic flux density is shown by arrows in a cutting plane inside the iron core of the transformer. Its absolute value is visualized by a color plot at the surface of the iron core. There, half of the surface has been removed for visualization purposes. The electric current density in the coils is displayed to improve the evaluation of the results. All geometrical edges are shown to enhance the visual impression.

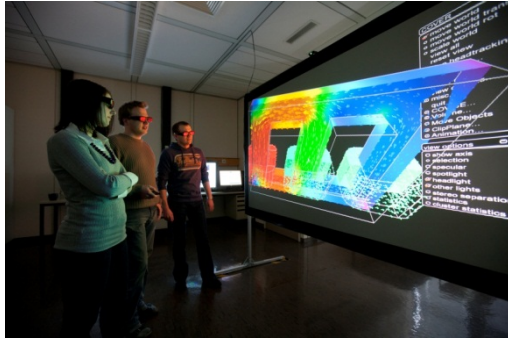


Figure 5. Three-dimensional projection of the virtual model of the transformer on a powerwall; magnetic flux density inside the iron core of the transformer and current density inside the coils

3.2 Data Export

The visualization software HLRS COVISE falls back on data, which is computed with COMSOL Multiphysics. A classical approach to implement such a data exchange is to use files. Then, all data, which should be available in the VR environment, is computed in COMSOL Multiphysics in advance and stored into files. These files are imported into HLRS COVISE. An advantage of this approach is that it is relatively easy to implement. However, a significant disadvantage is that data, which is not necessarily used, is computed, too. Furthermore, interactions between the visualization environment and COMSOL Multiphysics are rarely possible.

Here, a software module, which directly couples HLRS COVISE with COMSOL Multiphysics, has been developed. The main advantage of this approach is that data is only computed on demand and is immediately used for the post-processing. Storage of data, which could be costly in the case of three-dimensional problems, is not necessary.

The software module is implemented as a plug-in for HLRS COVISE. A graphical user interface enables an easy definition of the name of the COMSOL Multiphysics file and of the values, which have to be computed. The software module uses the component object model (COM) interface of MATLAB for the communication with COMSOL Multiphysics. COMSOL Multiphysics is started with MATLAB. Then, the complete functionality of COMSOL Multiphysics is available in MATLAB. Most frequently used functions have a user-friendly function call. If MATLAB runs as automation server, other processes, for

instance the above mentioned software module, are able to connect to this running process of MATLAB. MATLAB and HLRS COVISE must run on the same computer. COMSOL Multiphysics server can run on the same computer or on a computer cluster.

First, the file of the model is read and the model is stored as an object in MATLAB. Then, the finite element mesh of the model is exported in all cases. The nodes, the elements, and the domain number of the elements are extracted from the class of the model. Finally, this data is sent via the COM interface to HLRS COVISE.

The current version of COMSOL Multiphysics supports only linear finite elements. This degree of interpolation of the geometrical model suffices, since linear elements are much more efficient for visualization than higher order elements. Visualization tools and graphic cards are usually optimized for linear triangles and tetrahedrons.

The field values are computed using the function 'mpheval' of COMSOL Multiphysics. It computes the chosen field values, for instance the magnetic flux density, in all nodes of the finite element mesh for each step of the parameter sweep with only a single function call. Hence, multicore computers or computer clusters are efficiently used. Furthermore, field values are evaluated for each domain separately. Then, field values are correctly calculated even at material boundaries.

The quality of the post-processing functions of COMSOL Multiphysics in MATLAB is the same as the one of the stand-alone version. Hence, techniques like mesh refinement or polynomial-preserving recovery can be used. Note, visualization tools perform only a linear interpolation on the elements. Therefore, derived data or interpolated data between the element nodes, for instance during a streamline computation, may have less accuracy than inside COMSOL Multiphysics.

Another interesting feature of the presented approach for the data exchange between the visualization software HLRS COVISE and COMSOL Multiphysics is that an interactive post-processing is possible. Parameters of the model can be changed and the solution of the problem is updated. Here, the model is too large for a real interaction, even if a computer

cluster is used. However, some modifications are possible for future work. A simple two-dimensional model suffices for many fundamental studies. Then, the magnetic fields are computed with the help of a two-dimensional model and the results are mixed with a three-dimensional geometrical model. An advantage is that real interactions are possible and three-dimensional figures are generated. Physical properties are easily visible and can be experienced with the help of virtual reality.

4. Conclusions

The simulation software COMSOL Multiphysics has been applied to the solution of a parametric model of a three-phase transformer. The solution has been efficiently computed using the built-in tools and solvers of COMSOL Multiphysics. Furthermore, a vivid visualization of the results in a virtual reality environment based on the software HLRS COVISE has been presented.

A focus has been on the interactive coupling of COMSOL Multiphysics with HLRS COVISE via MATLAB and LiveLink for MATLAB. The data exchange is implemented with the help of the component object model interface of MATLAB. Powerful functions of COMSOL Multiphysics enable an efficient post-processing of complex three-dimensional and parameterized models.

In summary, COMSOL Multiphysics is a very flexible and efficient tool for numerical field computations. Add-ons and integration into other tools are supported. Hence, COMSOL Multiphysics is well suited for scientific applications, research projects, and teaching at universities.

5. References

- [1] Lang, U. and Wössner, U., "Virtual and augmented reality developments for engineering applications", Proceedings of ECCOMAS 2004, Jyväskylä, July 24-28, pp. 24-8, 2004
- [2] Buchau, A., Rucker, W. M., Wössner, U., and Becker, M., "Augmented reality in teaching of electrodynamics", COMPEL, vol. 28, no. 4, pp. 948-963, 2009
- [3] Buchau, A. and Rucker, W., "Computation of Three-Dimensional Electromagnetic Fields for an Augmented Reality Environment", COMSOL Conference, Hannover, 2008
- [4] Cruz-Neira, C., Sandin, D.J. and DeFanti, T.A., "Surround-screen projection-based virtual reality: the design and implementation of the CAVE", Computer Graphics Proceedings, Annual Conference Series, 1993