A GENERAL-PURPOSE ENVIRONMENT FOR THE CALCULATION OF COUPLED THERMO-ELECTROMAGNETIC PROBLEMS

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Abstract

Coupled thermo-electromagnetic problems have to be considered in the simulation of realistic electromechanical devices and electroheat installations. To handle this type of problems, a shell program to co-ordinate the finite element method (FEM) simulations and to perform intermediate calculations, such as heat source evaluation, numerical relaxation and mesh transitions, has been developed. The approach and implementation of this program is presented, together with a representative application of a coupled magnetic/electrostatic/thermal field problem. Here, the results of a three phase power cable simulation are shown.

INTRODUCTION

Material data used to set-up FEM-problems are often heavily depending on the temperature. Since material data parameters occur in many coefficients of the electromagnetic field equations, the calculation of the electrical and/or the magnetic field coupled to the thermal field [1] is necessary. The heat generation of electromagnetic nature results in a coupling of the source term of the right-hand side of the thermal equation.

Independent of the application to be simulated in a coupled way, a number of common calculations and operations is found in every problem. These are identified and programmed in a general purpose program operating as a shell to co-ordinate the calculation processes.

COUPLING ALGORITHMS

The combined problem in the electromagnetic and the thermal domain is generally described by Helmholtz-like differential equations. The discretisation leads to two or more sets of algebraic equations that have to be coupled numerically: electrical field and/or magnetic field together with the thermal FEM-equations. In principal, each of them can be extended with an algebraic set of circuit equations. These include coupling terms as well, e.g. in resistances.

The meshes on which the discretisations for the single field problem are performed, do not have to be identical. Sometimes, only a submesh has a physical meaning: e.g. air carrying a magnetic leakage flux is replaced by a convection constraint in the thermal model; the solid parts can be identical. Even the mesh on areas with more than one continuous degree of freedom can be discretised with different overlapping geometrical meshes and/or element types, so mesh transition operations have to be defined as well.

The groups of algebraic equations can be solved with a fully-coupled or with a cascade-coupled strategy [2].

- The first approach consists of the generation of a large system of non-linear equations with both types of FEM-equations, together with the coupling terms. The mesh transitions and heat source terms have to be written as linearised algebraic functions. This large linear system may have unfavourable numerical properties due to the different nature of the underlying physical equations, resulting in a difficult to solve problem.
- The second method (Fig. 1) sets up an iterative loop in which both sets of equations are solved sequentially [2] by dedicated solvers developed for the fast solution of the single physical field. The mesh transitions and heat source calculations are necessary intermediate steps. These do not necessarily have to be linearised. The relaxation of the non-linear iteration has to be performed by the shell program as well. This approach can be interpreted as a "decomposition" of the different fields of unknowns.

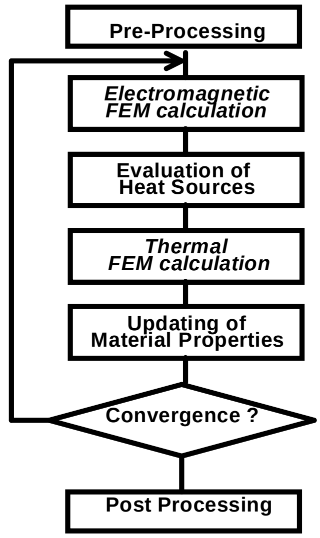


Figure 1: General flow chart of the cascade algorithm.

IMPLEMENTATION

Scripts

The developed shell program, called *Hermes,* is a part of the *Olympos* in-house software package. It controls the coupled calculation according to scripts written by the user. This script describes the mesh-generation, the solvers with their appropriate settings and the intermediate operations. It consists of three parts.

1. *Set-up:* In a first part the initial meshes and initial solutions can be generated, necessary to start up the numerical iteration.
2. *Iteration loop:* The subproblems are iterated towards a solution according to one of the two described strategies, along with intermediate actions and relaxations.
3. *Termination:* Withdrawal of the converged solutions.

For standard type problems, such as induction heating or the coupled calculation of motors, template scripts can be used to set-up a solution procedure.

Object oriented implementation of individual operations

The distinguished steps in the process are implemented in an object oriented way. For every script line action, a derived 'job'-object is executed. The possibility to derive new objects, makes the extension of the program with, for instance, more advanced heat source calculations possible. It is also possible to subtract a group of the objects in order to compile a specialised shell program suited for a certain type of coupled problem, e.g. of the electro-thermal or magneto-thermal type.

The operations are divided in the following groups:

- *Updating of material properties* [3]: The various temperature dependent material data parameters are updated whenever the algorithm requires it. Therefore, various characteristics are implemented. These involve: electrical conductivities, thermal conductivities, permanent magnet material, thermal conductivities and loss coefficients and characteristics.
- *External process handling:* Calls to execute external FEM-solvers and mesh generators.

- *Iteration control:* Process commands to control the flow of the iterative loop and evaluation of stopping criteria. These criteria can be based on absolute or relative residuals or solution differences between two consecutive weighted solutions of the total problem or a subproblem respectively.
- *Data transition commands:* When different meshes are used, mechanisms are necessary to project the field variables onto another mesh. Basically, this is a per-node interpolation of the solution.

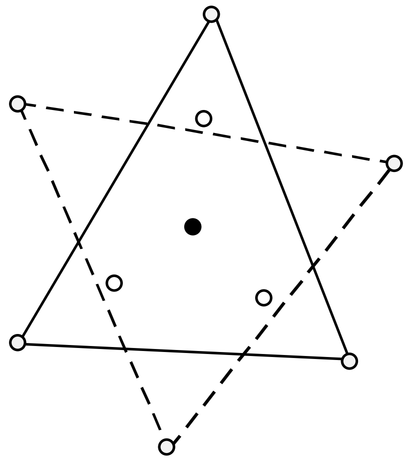


Figure 2: Projection of element related values.

The projection of the values associated with the element's surface or volume, e.g. a calculated loss density, is not straight-forward. If the meshes do not differ very much, the position of the centre of gravity of the element to be filled in, can be located in the other mesh (black dot in figure 2). The corresponding element-related value can then be copied. If the meshes differ much or if a higher order of accuracy is desired, an average can be generated by means of a numerical integration using Gauss points (additional white dots in figure 2).

It can be stated that a large difference between the meshes is not advantageous. It would mean that the related physical domains would not be calculated with a corresponding accuracy. However, mesh differences can arise due to local mesh quality reasons.

- *Adaptive relaxation of the convergence process:* In order to prevent the non-linear iteration process from divergence and to speed up the rate of convergence, an appropriate relaxation method is applied in which the damping factor can be predefined according to a certain function of the iteration number or adaptively, based on a minimisation of the total or partial (weighted) residual vector [4].
- *Heat sources calculation:* For the area covered by every meaningful element, a heat source density can be calculated based on the electromagnetic solution (Table 1).

Heat source	*occurs in*	*formula*	*application*
joule losses	problems with electrical current (perpendicular to or in a plane)	$q_{joule} = \frac{J_{rms}^2}{\sigma}$	conductors in machines, eddy currents in induction heating
iron losses	non-static magnetic field problems	$q_{iron} = \left(c_1 f + c_2 f^2\right) B^{(2)}$	magnetic materials with a hysteresis loop
dielectric losses	non-static electric field problems	$q_{diel} = \omega\left(\varepsilon_r \tan\delta\right) E^2$	capacitive heating, losses in isolating materials
external heat sources & sinks	various	look-up table, ...	e.g. ventilation, cooling channels, friction

Table 1: Overview of main heat sources in electromagnetic problems.

APPLICATION : COUPLED CALCULATION OF A THREE-PHASE HV POWER CABLE

Construction and loss mechanisms

Three phase power cables exist in many variations and types [5], differing in conductor shape, material choice, conductor arrangement etc. (Figs. 3, 4). They consist mainly of the following parts, in which several of the previously mentioned loss mechanisms are found:

- *Conductor*, usually made of copper, suffering from joule losses caused by the high current.
- *Isolation layers and filling materials*, loaded with an electric field and therefore subject to dielectric losses.

- *Grounded lead sheath* around the primary isolation, shielding the electric field; due to its relative low conductance, internal eddy currents can develop.
- *Mechanical protection (armour)*, sometimes made of magnetic steel and therefore subject to hysteresis and eddy current losses.

Figure 3: Photo of the power cable.

The presence of both, electrically related and magnetically related heat sources leads to a combined model consisting of three field types calculated over a complete or a partial cross-section of the cable and its surrounding:

1. *Electrical field*, described by means of the scalar potential V:

This field is only of interest in the isolation part loaded with an electrical field. Therefore, just a mesh covering that region is required to solve the static electrical field equation.

2. *Magnetic field*, calculated by means of a vector potential formulation A:

The time-harmonic magnetic field is calculated on a larger mesh, since it is only partly shielded by the mechanical protection and thus a leakage field can exist outside the model. This leakage flux is considered by the region surrounding the cable geometry; the far field is modelled by a Kelvin transformed mesh. The losses consist of joule losses in the conducting regions, such as the lead, steel and copper and possible iron losses inside the steel.

3. *Thermal field*, represented by the temperature potential T:

The static thermal field consists of the cable with the surrounding soil, in which it is buried. From a certain distance, the ground is modelled by means of a Kelvin transformation and therefore assumed to be infinitely deep. The ground surface is assumed to be cooled by a convection mechanism [6].

The losses calculated per element over the previous meshes are projected onto this thermal mesh. The extracted temperatures are used to update the material properties in the other fields. Basically the dielectric loss factor and the thermal conductivity depend on temperature, but this is an effect of minor influence. The largest change is encountered in the conductivity of the copper.

This gives rise to a three-domain mesh, represented in figure 5. The mesh for the electric field contains 9943 first triangular order elements, the magnetic field mesh 15378 elements and the thermal field mesh 15560 elements.

RESULTS

The coupled calculation is executed for a nominal balanced current and voltage load on the model of an individually lead sheathed three-core cable. Starting the iteration from an initial thermal field of 20°C, a solution for all the fields is found in 10 iterations without damping and 6 iterations with an adaptive damping factor. The stopping criterion is based on the L_2-norm of the difference of the last two consecutive thermal solutions. The different field solutions after convergence are shown in figure 6.

Figure 4: Geometry of a 3-phase power cable.

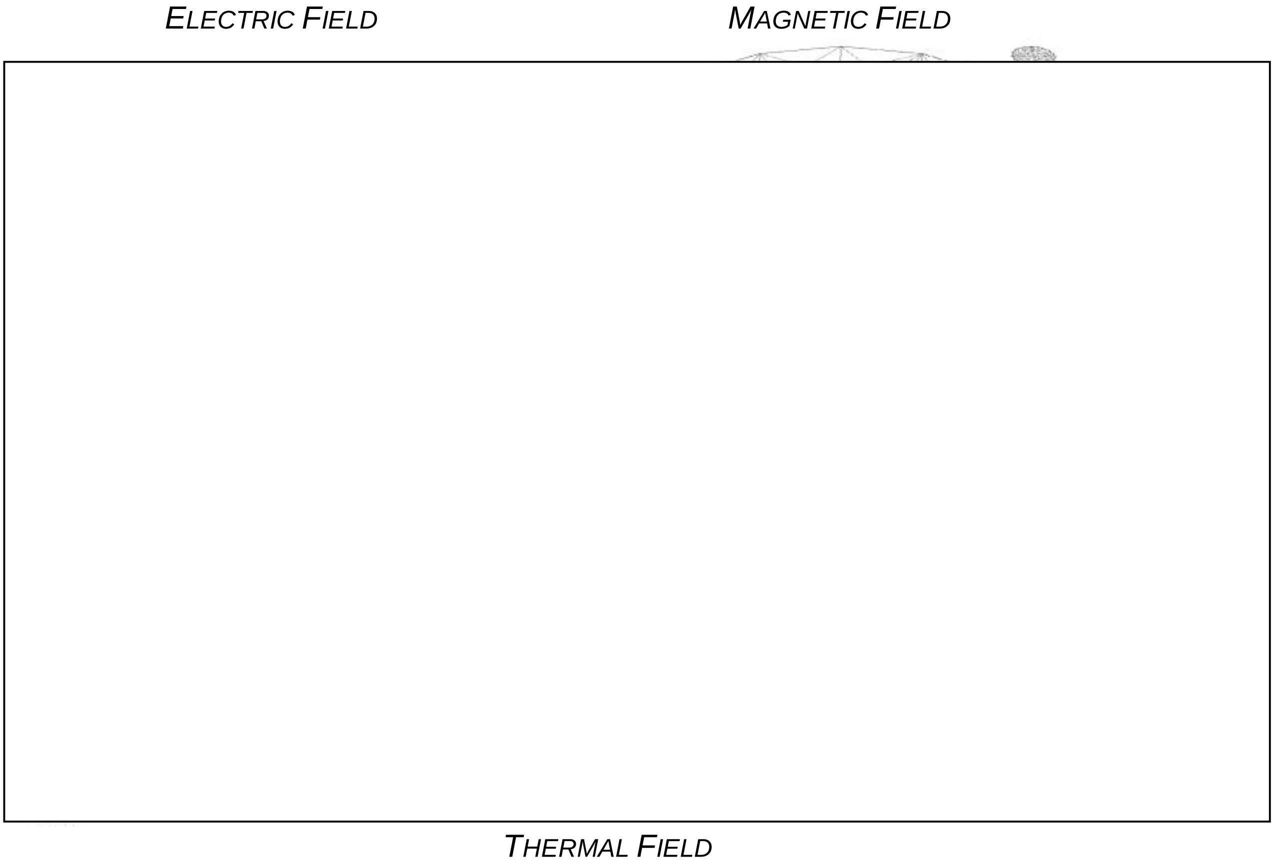
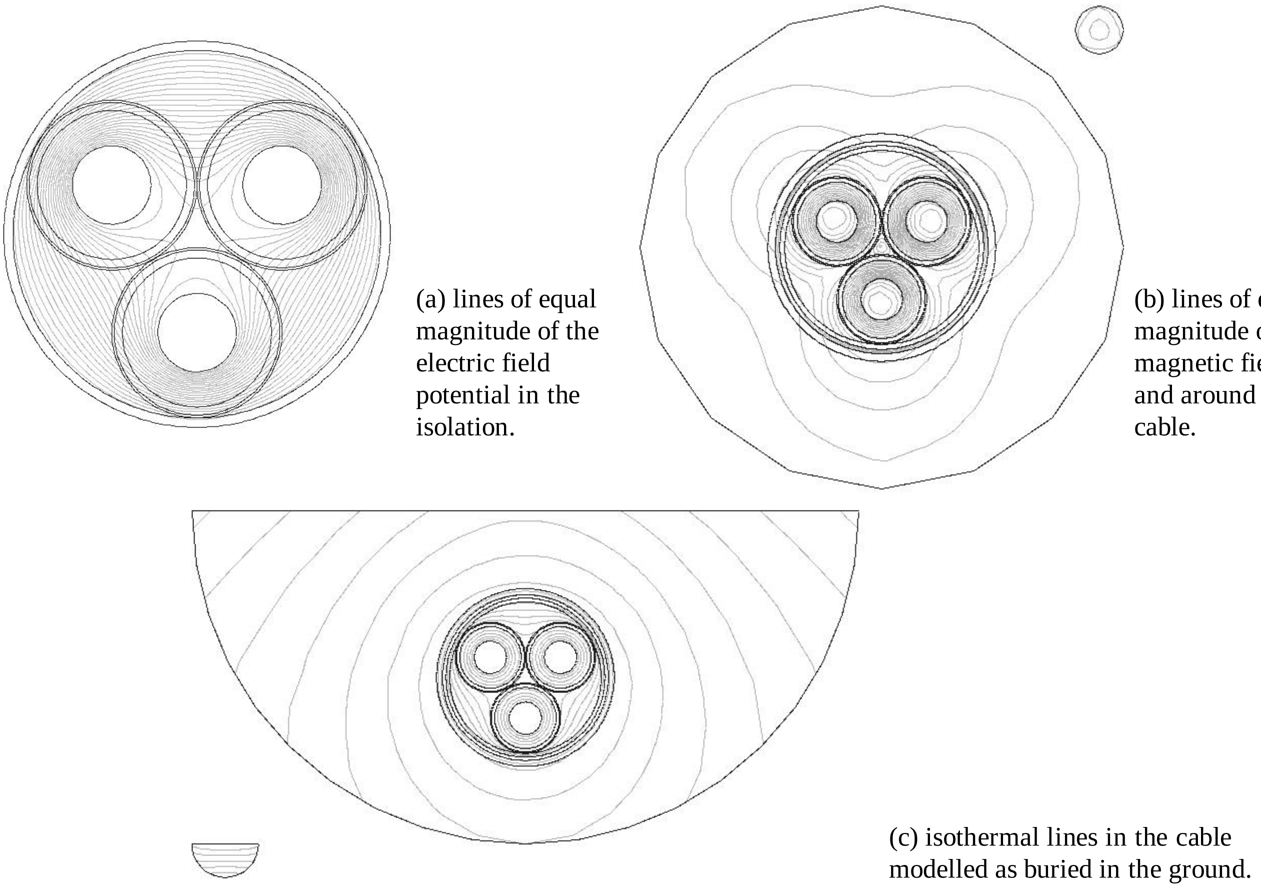


Figure 5: Discretisations used to compute the different physical fields.



(a) lines of equal magnitude of the electric field potential in the isolation.

(b) lines of equal magnitude of the magnetic field in and around the cable.

(c) isothermal lines in the cable modelled as buried in the ground.

Figure 6: Solutions of the different physical fields.

The temperature in the centre of a conductor amounts 84°C, which corresponds to reported measurements. Table 2 shows the value of some heat sources and their location.

Location	*Loss mechanism*	*Value [W/m³]*
copper conductors	ohmic	$5{,}97.10^{4}$
conductor isolation	dielectric	$1{,}17.10^{2}$
inter-conductor filling material	dielectric	$2{,}55.10^{2}$
mechanical protection	ohmic + iron	$1{,}23.10^{-3}$

Table 1: Overview of main heat sources in electromagnetic problems.

CONCLUSION

The basic operations and their object oriented implementation in a shell program developed to solve thermo-electromagnetic coupled problems is presented. The use of template scripts to control the iterative solution process of the multi-field and multi-domain problems is discussed. The various aspects are demonstrated by means of a triple coupled field calculation of a three phase power cable subject to different loss mechanisms.

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