Shell Structures for the Thermo-Electromagnetic Design of Electrical Machines and Electroheat Applications

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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 problem, 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.**

Index terms **— Finite element methods, induction heating, losses, eddy currents, dielectric losses, electrothermal effects**

I. INTRODUCTION

Material data used to set-up electromagnetic FEM-problems are often strongly 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 caused by the electromagnetic field, 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 are found in every problem. These are identified and programmed in a general-purpose program operating as a shell to co-ordinate the calculation processes.

II. COUPLING ALGORITHMS

The combined problem in the electromagnetic and the thermal domain is generally described by a set of non-linear Helmholtz-like differential equations. The discretisation leads to two or more sets of algebraic equations that have to be coupled numerically: the electric field and/or magnetic field together with the thermal FEM-equations. In principle, 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 inside the magnetic FEM model 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. Therefore, mesh transition operations have to be defined in the shell structure as well.

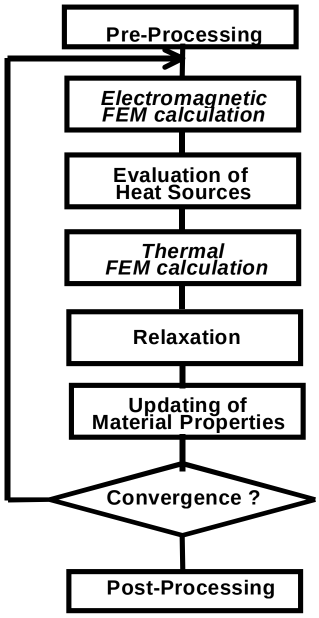

Fig. 1. General flow chart of the cascade algorithm.

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

The most flexible method is the cascade coupled method from which a variant is shown in Fig. 1. Both sets of equations are solved sequentially [2] in an iteration loop. If dedicated solvers developed for a fast solution are used and if appropriate relaxation is applied, the individual physical fields, are solved efficiently. Mesh transitions, material updates and heat source calculations are necessary intermediate steps. It is not necessary to linearise these operations.

An alternative is the generation of a large system of non-linear equations with both types of FEM-equations, together with the linearised coupling terms. However, this large

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linear system may have unfavourable numerical properties due to the different nature of the underlying physical equations, resulting in a difficult to solve problem.

III. Implementation

A. 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 starting solutions are generated.

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 and post-processing.

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.

B. Object oriented implementation of individual operations

The distinguished steps in the process are implemented in "object oriented" code. For every executable script line, a derived 'job'-object is instantiated. The possibility to derive new objects, makes the extension of the program with more advanced heat source calculations possible.

A further feature is the possibility 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 which can be build-in in a user tool to model a typical device, like rod heating, motor simulation, ...

The operations are divided in the following groups:

Updating of material properties [3]: The various temperature dependent material data parameters are updated with knowledge of the relaxed corrections 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.

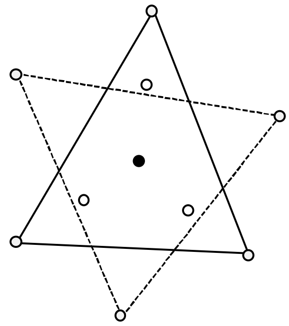


Fig. 2. Projection of element related values by means of Gauss points.

Data transition commands: When different meshes or different types of elements are used, mechanisms are necessary to project the field variables onto another mesh. Basically, this is a per-node interpolation of the solution. The projection of the values associated with the element's surface or volume, e.g. a calculated loss density, is not straightforward. 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 Fig. 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 Fig. 2). One has to take care not to lose accuracy in the projection. This may happen if meshes with elements, covering the same region, but severely differing in size are used. If equally sized elements with different interpolation orders occur, a similar loss in accuracy may occur. However, local problem-specific mesh differences or differences due to mesh quality should not be a problem if the solution fields are of compatible orders.

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 the minimisation of the total or partial (weighted) residual vector [4].

TABLE 1
OVERVIEW OF MAIN HEAT SOURCES IN ELECTROMAGNETIC PROBLEMS.

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	$q_{diel} = \omega\left(\varepsilon_0 \varepsilon_r \tan\delta\right) E^2$	capacitive heating, losses in isolating materials
External heat sources & sinks	Various	look-up table, ...	e.g. ventilation, cooling channels, friction

Heat sources calculation: For the area covered by every meaningful element, a heat source density can be calculated based on the electric or magnetic field solution (Table 1).

IV. Application: Coupled Calculation of a Three-Phase HV Power Cable

A. Construction and loss mechanisms

Three phase power cables exist in many variations and types [5], differing in conductor shape, material choice, conductor arrangement etc. 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.

Insulation layers and filling materials, loaded by an alternating electric field and therefore subject to dielectric losses.

Grounded lead sheath around the primary insulation, 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.

B. Physical fields

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 insulation part loaded by an electric field. Therefore, a mesh covering this region is required to solve the static electric 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 permittivity and the thermal conductivity depend on temperature, but this is an effect of minor influence and not considered here. The largest change is encountered in the conductivity of the

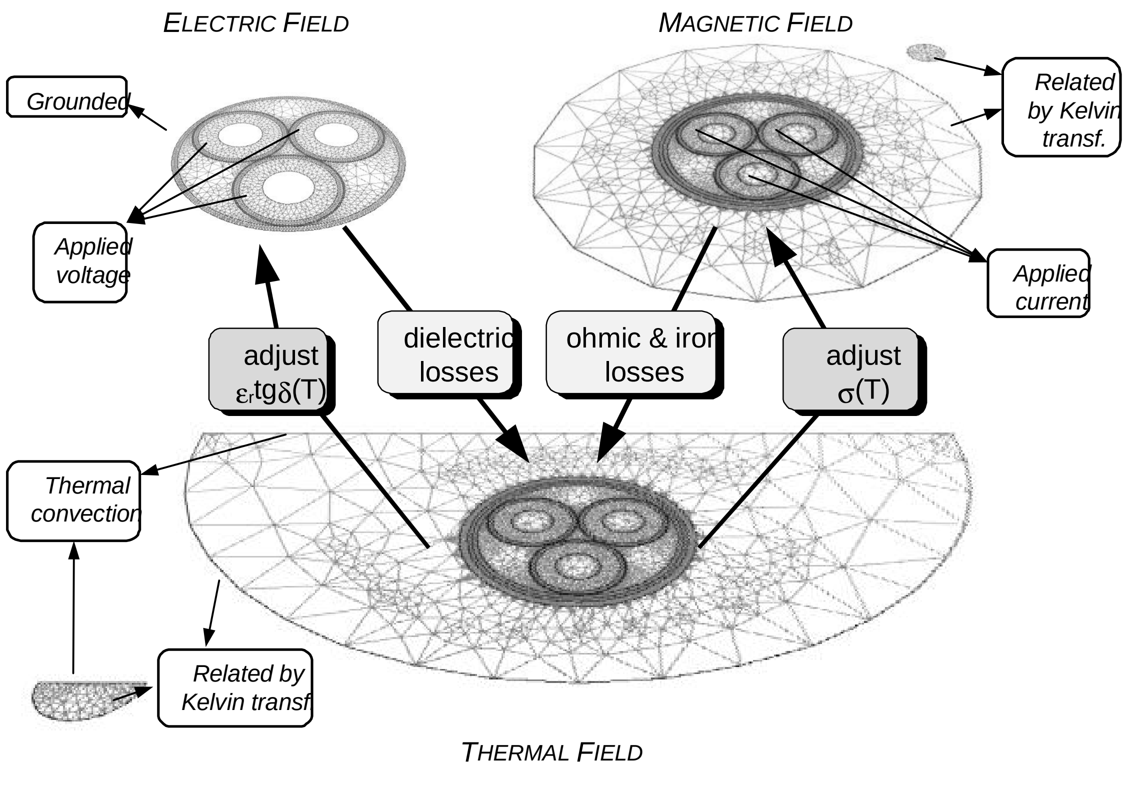
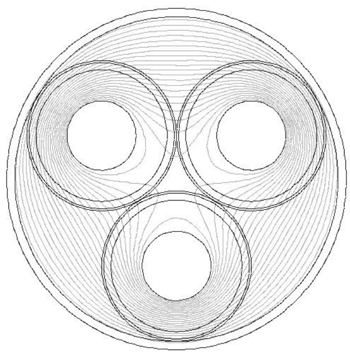


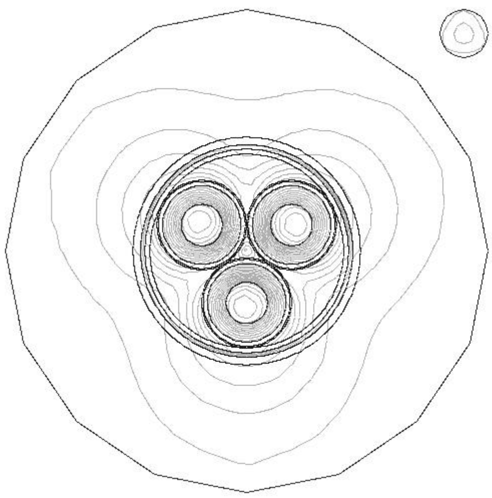
Fig. 3. Finite elements meshes and internal relations.

copper.

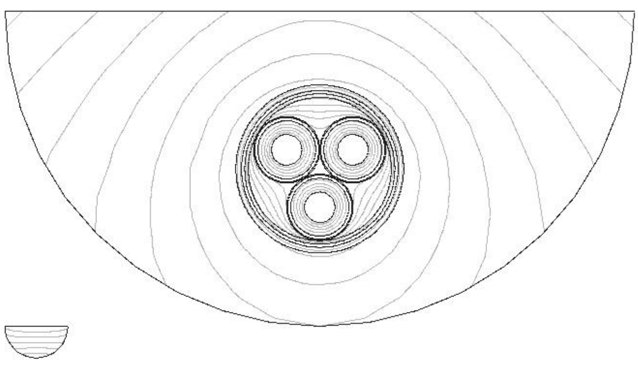
This gives rise to a three-domain mesh, represented in Fig. 4. The mesh for the electric field contains 9943 first triangular order elements, the magnetic field mesh 15378 elements and the thermal field mesh 15560 elements.



(a) Lines of equal rms value of the electric field potential in the insulation.



(b) Lines of equal rms value of the magnetic field in and around the cable.



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

Fig. 4. Solutions of the different physical fields.

C. 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 the overall coupled problem is found in 10 iteration steps without damping and 6 iterations applying 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 of the coupled problem are shown in Fig. 4.

The temperature in the centre of a conductor amounts 84°C, which corresponds to reported measurements. Table 2 shows the value of the heat sources and their location. For full current loading, the copper losses are dominant, but for a minor current loading, the dielectric losses become relatively important.

TABLE 2
RESULTS OF LOSS CALCULATIONS.

Location	*Loss mechanism*	*Value [W/m³]*
Copper conductors	Ohmic	$5{,}97.10^{4}$
Conductor insulation	Dielectric	$1{,}17.10^{2}$
Inter-conductor filling material	Dielectric	$2{,}55.10^{2}$
Mechanical protection	Ohmic + iron	$1{,}23.10^{-3}$

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 electric/magnetic/thermal field calculation of a three phase power cable subject to different loss mechanisms.

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