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AUTHOR(S) M. L. HODGDON
A. R. MARTINEZ
S. SALON
P. WENDLING
L. KRAHENBUHL
A. NICOLAS
L. NICOLAS

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APPLICATIONS OF THE COMPUTER CODES FLUX2D AND PHI3D FOR THE ELECTROMAGNETIC ANALYSIS OF COMPRESSED MAGNETIC FIELD GENERATORS AND POWER FLOW CHANNELS*

M. L. Hodgdon, H. Oona, and A. R. Martinez

Los Alamos National Laboratory, Los Alamos, New Mexico, USA 87545

S. Salon

Rensselaer Polytechnic Institute, Troy, New York, USA

P. Wendling

MagSoft Corporation, Troy, NY, USA

L. Krahenbuhl, A. Nicolas, and L. Nicolas

Department Electrotechnique, Ecole Centrale de Lyon, France

ABSTRACT

We present herein the results of three electromagnetic field problems for compressed magnetic field generators and their associated power flow channels. The first problem is the computation of the transient magnetic field in a two-dimensional model of a helical generator during loading. The second problem is the three-dimensional eddy current patterns in a section of an armature beneath a bifurcation point of a helical winding. Our third problem is the calculation of the three-dimensional electrostatic fields in a region known as the post-hole convolute in which a rod connects the inner and outer walls of a system of three concentric cylinders through a hole in the middle cylinder. While analytic solutions exist for many electromagnetic field problems in cases of special and ideal geometries, the solutions of these and similar problems for the proper analysis and design of compressed magnetic field generators and their related hardware require computer simulations. In earlier studies, computer models have been proposed, several based on research oriented hydrocodes to which uncoupled or partially coupled Maxwell's equations solvers are added.[1] Although the hydrocode models address the problem of moving, deformable conductors, they are not useful for electromagnetic analysis, nor can they be considered design tools. For our studies, we take advantage of the commercial, electromagnetic computer-aided design software packages FLUX2D and PHI3D that were developed for motor manufacturers and utilities industries. The solutions to the problems discussed here satisfy the need in the pulsed power community for the computation of electromagnetic fields in the

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intricate geometries of generators and power flow channels. In addition, they establish the usefulness of FLUX2D and PHI3D for electromagnetic analysis and design of pulsed power hardware.

FLUX2D and PHI3D

FLUX2D was developed at the Laboratoire D'Electrotechnique de Grenoble by Jean-Claude Sabonnadiére, Jean-Louis Coulomb, Bernard Morel and other researchers and software engineers of the group Modelisation et CAO.[2] It is a CAD package consisting of several modules of computer codes that perform electromagnetic and thermal analysis in planar and axisymmetric geometries. The geometry of the device to be analyzed is entered in the preprocessor module in a conversational mode at the terminal. This module includes the option of assigning names to the design dimensions so that the critical dimensions may be studied parametrically. Linear and nonlinear material properties, the problem definition, and the boundary conditions are assigned in a second module. The types of problems that can be studied with FLUX2D are electrostatic, magnetostatic, electrodynamic, magnetodynamic, transient magnetic, electroconductive, steady state and transient thermic, coupled magnetothermic and electrothermic. In our work, we have used the electrostatic, magnetostatic, electroconductive and transient magnetic options. In future work, we will use the coupled magnetothermic and electrothermic options so that the temperature dependence of the electrical conductives is included. The third and fourth modules of FLUX2D are the finite element solver and the postprocessor. There are also auxiliary modules for the creation and maintenance of a material properties data base and for parametric studies.

FLUX2D obtains solutions for the above problems using the finite element method.[2] For planar, static fields, the two dimensional Poisson equation

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial\phi}{\partial y}\right)+f=0$$

is solved with the boundary conditions appropriate to the problem. In this code, the available boundary conditions are Dirichlet, Neumann, cyclic, anticyclic, translation, and floating potential. In electric field problems, the solution variable ϕ is the electric scalar potential, λ is the electric permittivity, and f is the charge density. In magnetic field problems, the solution variable ϕ is the z-directed component of the vector potential, λ is the inverse of the magnetic permeability, and f is the z component of the current density. Here, f and λ may depend on the spatial variables x and y, and λ may also vary with ϕ, the gradient of ϕ, or the curl of ϕ. Similar formulations are used for axisymmetric, transient, and dynamic problems.

PHI3D solves Maxwell's equations for electrostatic, magnetostatic, and high frequency magnetodynamic problems in three dimensions by the boundary element method.[3,4] For the scalar potential ϕ, it solves Laplace's equation,

$$\Delta\phi \quad 0 \quad ,$$

throughout a region by the integration of ϕ and its normal derivative ϕ' over surfaces of objects where either ϕ or ϕ' is known, and over interfaces between electric or magnetic materials where the different material properties have been specified For magnetic problems, ϕ has contributions from current carrying conductors and from magnetizable bodies. Unlike the finite element method, the boundary element method is limited to linear materials. However, it has a advantage in that discretization is required only over surfaces and interfaces. PHI3D is a CAD package similar to that of FLUX2D. It was developed at the Laboratiore d'Electrotechnique de Lyon.

Two Dimensional Transient Magnetic Field Problem

An axisymmetric, two-dimensional model of a helical compressed magnetic field generator was studied with FLUX2D. This generator consists of a stator of four winding sections, each with a different pitch and wire size, copper end rings, and an aluminum armature. The applied signal ramped from 0 to 1 volt/meter in 136×10^{-6} seconds. We show, in Fig. 1, lines of equal flux and, in Fig. 2, the magnetic field vectors for sections of the generator at the 20×10^{-6} seconds.

An Eddy Current Problem

In several helical generator designs, the stator coil consists of turns of parallel wires. At the beginning of each winding section, the number of parallel wires is doubled. In this problem, we computed the eddy currents in the section of the armature beneath this bifurcation point. The results in Fig. 3 show the expected increase in width of the eddy current region when the number of parallel wires is increased from one to two.

The Three-Dimensional Electrostatic Problem

In an explosively formed fuse switching system designed for current diversion in a power flow channel, six conductive posts connect the inner and outer cylinders of a three cylinder power flow channel through holes in the middle cylinder. For this system, we computed with PHI3D the electrostatic fields in the region of one of the posts. By utilizing the six-fold symmetry, we needed to model only one sixth of the system. The problem geometry and the potentials of the post and the inner channel walls are shown in Fig. 4. Figures 5 and 6 are cross sectional views of the potential and electric field within the power flow channel. The results of these calculations are used to determine regions of probable electric breakdown.

CONCLUSIONS

The three problems presented here are examples of the application of FLUX2D and PHI3D to electric and magnetic field problems of compressed magnetic field generators and power flow channels. They form a foundation from which specific generators and channels may be studied through the modification of dimensions and the inclusion of detailed current histories and applied potentials. The ease of use and the detail of the results establish FLUX2D and PHI3D to be of great utility in the design and analysis of such generators and power flow channels.

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FIGURE CAPTIONS

Fig. 1. Lines of equal flux in a helical generator for a signal that increases linearly from 0 to 1 V/m in 136 μsecs. This problem simulates the effect of the loading current and is useful is specifying the state of the generator before detonation.

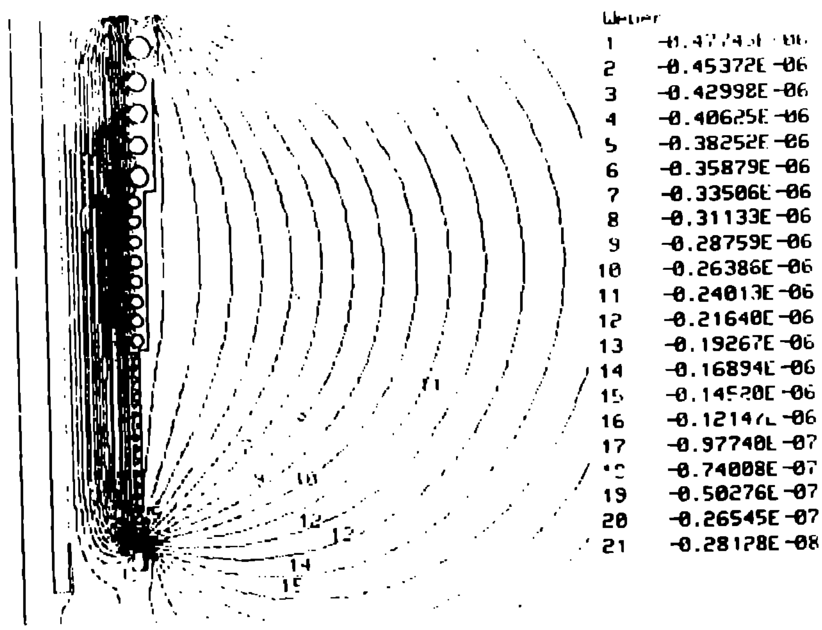
Fig. 2. Magnetic field vectors in each finite element in a section of the generator shown in Fig. 1. The magnitude and orientation of the field is given by the size and direction of the vectors. The presence of vectors inside the armature and the coil wires show the diffusion of the field and current into these regions.

Fig. 3. Eddy currents in an armature section beneath a wire bifurcation point from a PHI3D calculation. This three dimensional problem is part of a complete study of the field and currents in helical generators.

Fig. 4. The potentials inside the post-hole convolute of an explosively formed fuse switching system for a PHI3D calculation. To obtain this cut away view, several outside surfaces were specified as transparent, and only the outline of the transparent surfaces are shown. In this calculation, the proper curvatures of the hole in the middle cylinder, of the connection between the post and the cylinder walls, and of the lower flanges are included.

Fig. 5. The electric potential between the post and the cylinder walls of the post hole convolute from a PHI3D calculation of an approximation of the system shown in the Fig. 4. In this cross sectional view, the center line lies to the left of the plot. The cylinder walls are vertical. The post is horizontal. To decrease the computer time necessary to complete this problem, the curvatures of the hole and the post connections were approximated, so that the hole in this view is bounded by the V-shaped lines. The potential outside of the system is also shown.

Fig. 6 The electric field between the post and the cylinder walls in an enlargement of the cross section shown in Fig. 5. Here the plot is reversed with the center line to the right of the figure. The magnitude and the orientation of the field is specified by the shading and the direction of the cones.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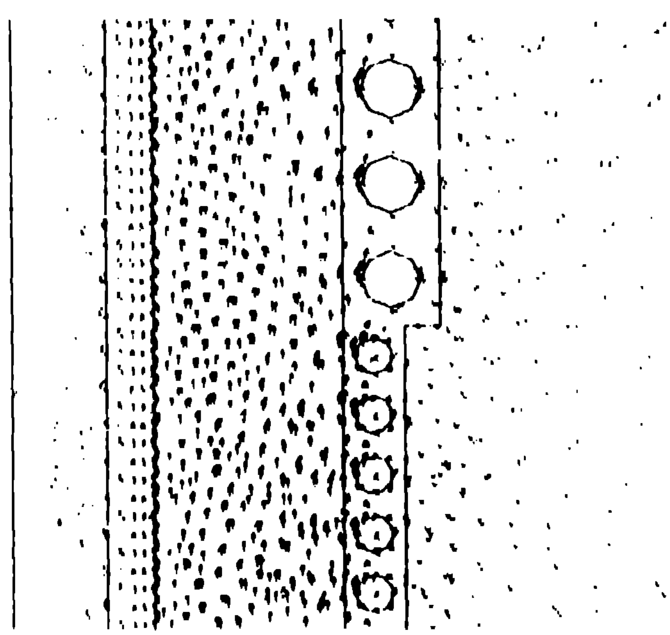
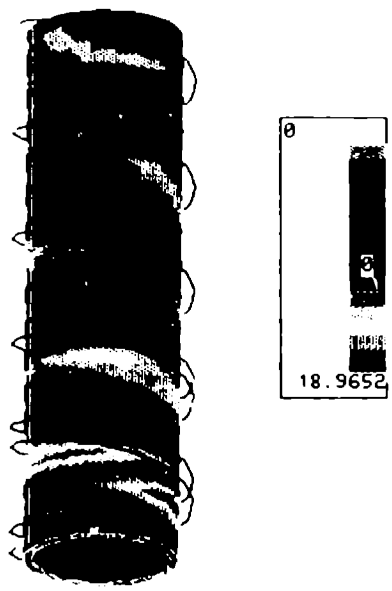
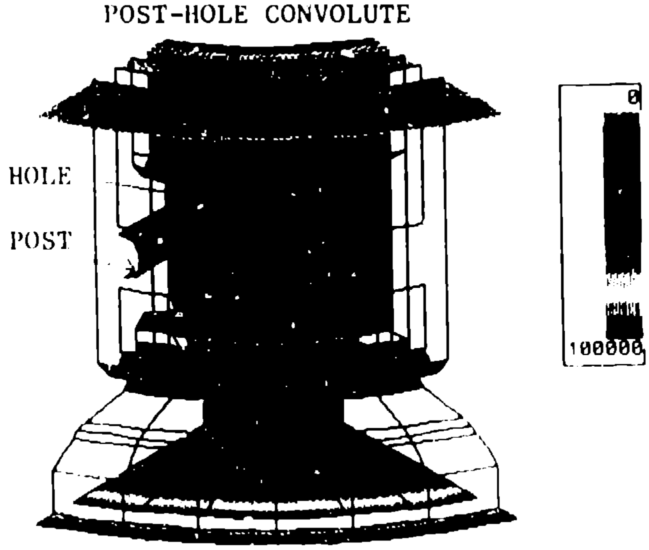
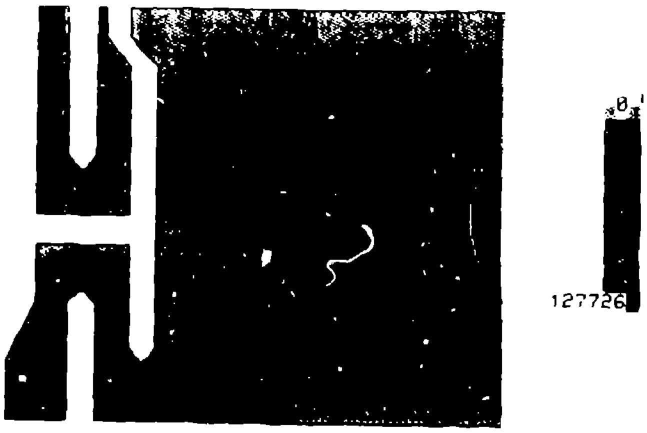




POST-HOLE CONVOLUTE

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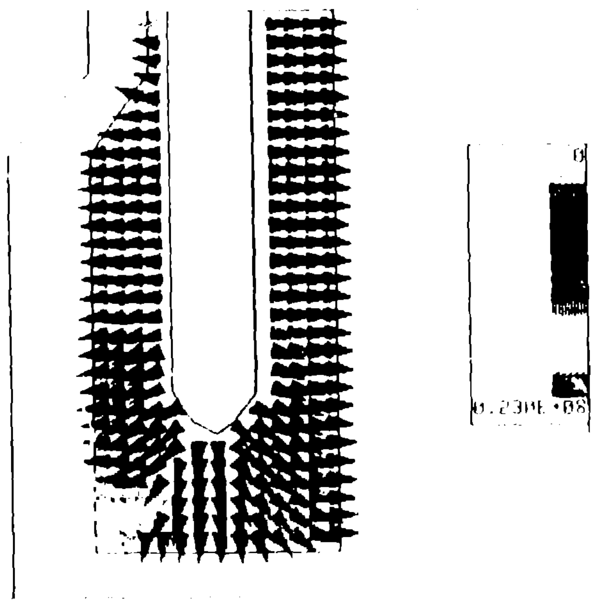
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