CAGEN: A MODERN, PC BASED COMPUTER MODELING TOOL FOR EXPLOSIVE MCG GENERATORS AND ATTACHED LOADS

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Abstract

We will describe the PC based computer program CAGEN in its current state of development. It models the performance of many varieties of Magneto-Cumulative-Generators (MCG) which are energized with High Explosive (HE). CAGEN models helical or coaxial types (in the same generator, if desired) which have HE on the interior. Any materials and any HE types may be used. The cylindrical radius of the windings (or outer conductor) and the radius of the armature may vary with axial position. Variable winding width, thickness, shape, and pitch can be represented, and divided windings are allowed. The MHD equations are used to advance the magnetic field into and through the conductors in order to compute resistance, melting, flux loss, pressure and contact effects. The MCG model is treated as part of a lumped circuit, which includes the priming circuit, several different opening fuse switches, transformers, peaking circuit, and loads. Several calculations of benchmark published experiments are shown. A typical problem will complete in a few minutes. Graphical input, run control, and results-analysis, is provided by MathGraf, a CARE'N CO. application.

I. INTRODUCTION

For decades HE driven MCG's have been used for experiments which required enormous delivered electrical energy (Megajoules) at modestly high electrical power (Terawatts) or at least high energy/power for the size/weight allowed for the source. There is a very large literature base[1] on such applications and the device technology associated with them. The simulation and modeling of these interesting devices and the circuits to which they have been attached is not nearly so advanced as the technology itself. Large axi-symmetric (2D) hydro-codes have had the MHD approximations to Maxwell's equations incorporated and have been applied to the truly axi-symmetric devices called co-axial MCG's. The simulation results have been, at times, remarkably good[2]. Most interesting applications of MCG's utilize the helical wound MCG because of the high gain offered. These devices are not axi-symmetric, although they have some characteristics which are axi-symmetric. At this writing, there are no simulations in 3D of this device, although several organizations are actively pursuing this goal. (There can be no simulations in 2D of these 3D constructions, only models). However, 2D models of these "almost" symmetric helical wound MCG's have appeared in several publications[3]. CAGEN is such a code.

II. DESCRIPTION OF CAGEN

The evolution through time of the parameters determining the dynamic state of the generator and the other components of the circuit is computed by integrating the simple difference equation representing each, starting from their initial values. The difference equations are the voltage loop equations. Although some components are not dynamic, most change with their temperature and configuration. Each component is represented in Fortran by an individual sub-routine. Consequently, model changes are quite modular. All time scales are supported by sub-cycling each activity at a rate needed to resolve the fastest time scale. For example, the loop equations are cycled fast enough to resolve the shortest resonance available. Shown below are two of the available circuits.

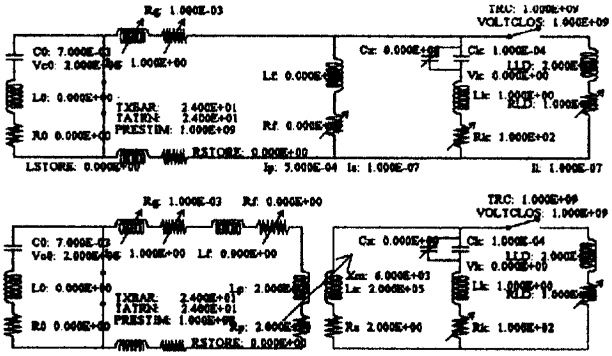

Figure 1. The two complete circuits allowed in CAGEN. Any element can be removed.

The generator is conceptually sliced into variable thickness disks perpendicular to the pseudo-symmetry axis. All hydrodynamics parallel to the axis are ignored. However, all important dynamics are included. The HE region is assumed to be surrounded by a metal, electrically conductive layer, and both are assumed to be exactly axi-symmetric. The HE expands the metal armature according to a tabulated acceleration profile obtained in various convenient fashions including the Gurney relation. The outer winding region, the stator, is encountered by the outward moving armature forming a first contact point which moves smoothly from left to right. "Turns splitting" is allowed, and windings may have circular or rectangular cross section. The diameters of the armature and stator may vary with position along the axis.

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14. ABSTRACT

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The inductance of the generator is evaluated at every moment from tables and analytic fits from Grover[4]. The resistance is much more complicated. Our solution is one of the unique features in CAGEN. Within each axial zone (the disks), the armature and the stator are sub-zoned from their surfaces into their interior. The MHD equations are solved over these sub-zones to determine the fully dynamic configuration of the penetrating magnetic field and the current distribution. The circuit resistance is determined from the field distribution. Heating of each sub-zone is computed, and the conductivity is adjusted appropriately. Figure 2 shows the progression of the diffusion wave into a metal of 3 different resitivities in scaled distance. Shown is the leakage into the interior of the armature.

The shape of the conductors and the proximity of the nearby conductors are accounted for. A "contact" resistance is computed from the loss of magnetic flux contained within the conductors as the contact point moves along.

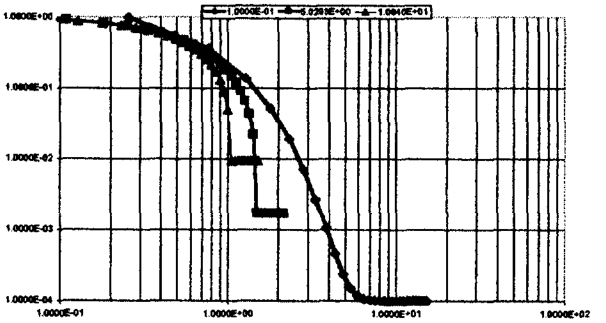

Figure 2. Magnetic diffusion into and through the armature for different constant resistivities and scaled distances.

There are three opening switch systems available: a Bulk Electrically Exploded Fuse (BEEF), a Bulk Explosively Formed Fuse (BEFF), A MHD modeled Electrically Exploded Fuse (MHDEEF). The BEEF incorporates no hydrodynamics but includes such effects directly in the "EOS" for the resistivity table which is a function of Joule heating specific energy. The EOS can be provided from an experiment. The BEFF uses a resistance versus time-table for its function, while the MHDEEF computes the explosion of the foil in 1-D dynamical detail.

The transformers modeled are an air core, tape wound, auto-transformer and a wire wound air-core type. The inductances are computed from Grover tables or are specified by the user.

The closing switch operates discontinuously when one of two conditions are met: the voltage across the switch exceeds the breakdown value provided, or the time exceeds that provided. The rise time of the current through the load is determined by the explicit components specified.

The load models available include an unvarying resistance and inductance, a Bulk Electrically Exploded Fuse (BEEF), a Bulk Explosively Formed Fuse (BEFF), a resistance derived from an electrically exploding foil modeled with a 1-D MHD solver (MHDEEF), and a resistance computed from the Child-Langmiur equation.

III. BENCHMARK CALCULATIONS

Very few adjustable parameters are available in CAGEN for the MCG model. The most prominent is a multiplier on the contact resistance where the exact physics is dubious. Other less obvious parameters are associated with the material specifications such as the resistivity and heat capacity. The inductance is quite accurate except where either strong 3D effects are at play, or when structures exist not currently modeled in the code. Sometimes the inductance must be modified to compensate. However, the purpose of a model code is to initially guess at the performance of an MCG and then to be benchmarked against some appropriate experiment. Here, several benchmark comparisons are given.

The mini-generator[5] was approximately 2 inches in diameter. It had no turns splitting and was wound with constant diameter copper wire at a constant pitch. This example represents a system of quite high flux which displays very high internal resistive flux loss. Figure 3 shows the current comparison between model and experiment. The contact resistance factor was set to 0.5. The peak values of the calculations can be varied adequately by selecting approximations to the copper resistivity. The model has insufficient early gain.

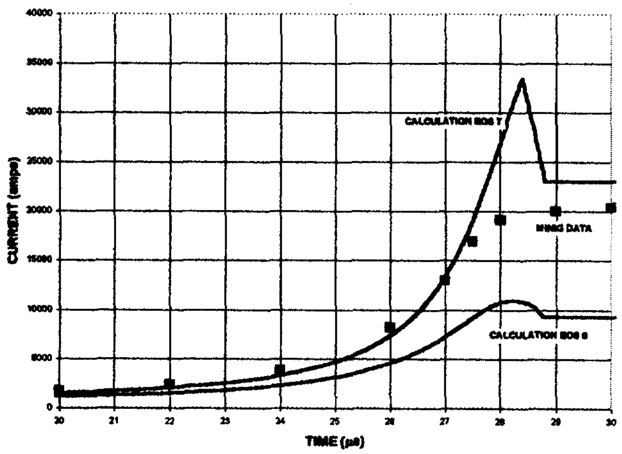

Figure 3. CAGEN calculation with two resistive equations of state (7, 8) compared to the mini-generator (dots).

This experiment was particularly interesting because of the careful measurement of the terminal voltage as shown in Figure 4.

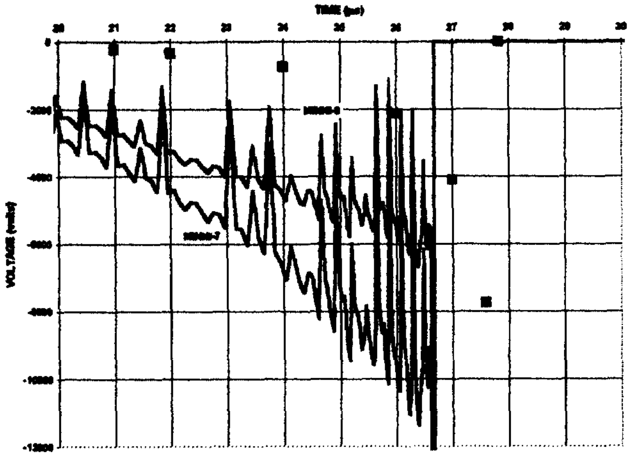

Figure 4. CAGEN calculation of the terminal voltage compared to the mini-generator (dots).

A different small, constant pitch generator is the UKMINI[6] generator. It has many fewer, large diameter wire windings. Figure 5 shows the current comparison. The model seems to fit the data here better than the fit to the US MINI-Generator of figure 3, even though the model parameters are essentially the same as figure 3. The different ending slope means the load inductance is not quite right. The resistivity model number 7 fits best.

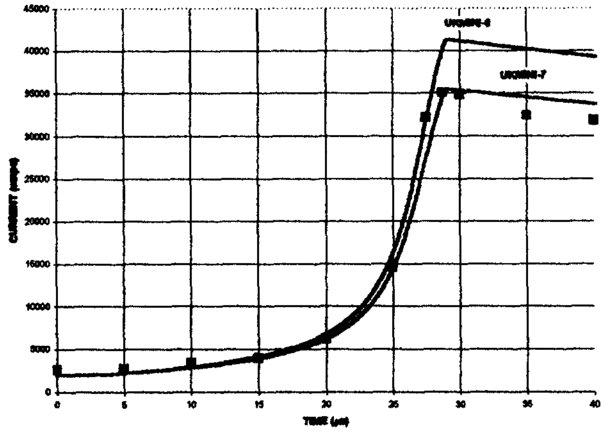

Figure 5. CAGEN calculation of the UK mini-generator compared to the measured data (dots).

Figure 6 is a comparison of the CAGEN result with the measured current[7] for a small, high gain, turns-split helical generator. The model used is the same as the previous comparisons with slightly different values for the contact resistance multiplier. This calculation is typical to all split-turn generators in that the model predicts higher I-dot than the experiment but much lower early gain. Apparently, there is some physics which produces more gain early and more loss late. The different calculations have differing contact resitance factors (R0.0 and R0.5) and the two copper resistivity models (ETA7 and 8).

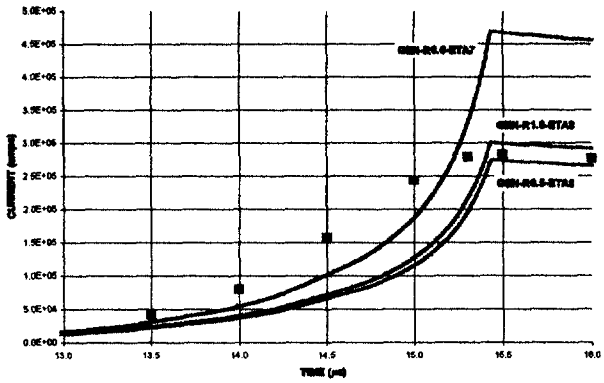

Figure 6. CAGEN calculation of a high gain split-turn generator compared to the data (dots).

IV. THE FULL CIRCUIT

When the generator model is being solved in concert with the full circuit, an integrated, tightly coupled, self-consistent solution is obtained. As an example, figures 7 and 8 show some of the dynamic parameters for an MCG driving the primary loop of a tape wound transformer in series with an electrically exploded fuse. In figure 7, the heavy line is the decreasing inductance of the generator, and the small dashed line is the generator resistance. The resistance curve clearly shows the collision of the armature with the stator windings at the point when the inductance is at about half value. That is the place where the contact resistance begins to take effect, since only then can flux be lost behind the contact point. Later, the generator resistance falls with decreasing generator length and at each winding splitting point. The thin solid line is the current flowing in the primary loop, while the heavy dashed line is the resistance of the fuse. The fuse is sized to transition to a vapor at the point where the inductance of the generator is near zero. In that way the full voltage generated across the fuse is seen by the primary of the transformer. The voltage across the self-closing break-down switch becomes very high before it shorts, placing the load onto the transformer and shorting out the fuse. That is why the fuse does not re-strike. Figure 8 shows the two other currents: the peaking circuit current and the load current. Before the closing switch closes, current is flowing into and out of the peaking capacitor, producing a net residual charge.

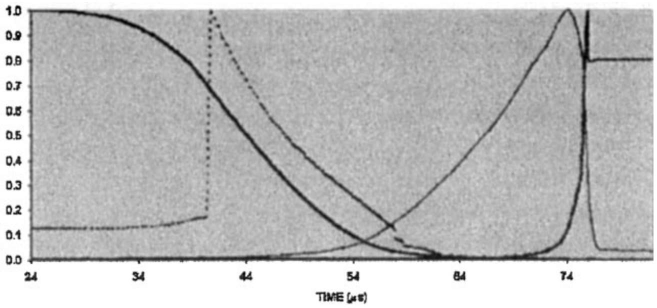

Figure 7. CAGEN circuit values showing generator inductance (heavy line), generator resistance (small dashes), generator and primary current (thin line), and the fuse resistance (heavy fuzzy line).

When the switch closes, the initial rapid rise in the current through the load is because of energy flowing from the capacitor, while the second peak is due to the magnetic energy stored in the transformer.

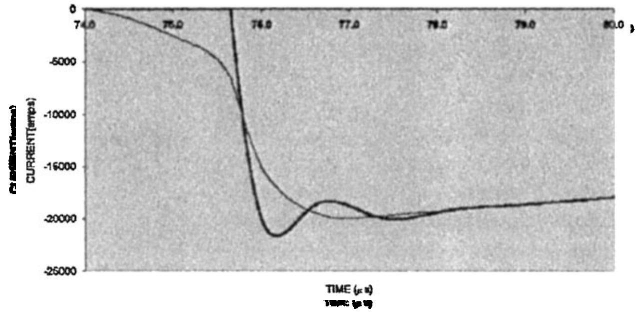

Figure 8. CAGEN secondary currents for the same circuit showing the peaking loop current (thin line) and the load current (heavy line).

V. THE INPUT TO CAGEN

Input is via a graphically assisted menu system. It is intended to be very nearly self-documented. As development continues, features will enhance and perfect the ease of building a new problem and repeating an existing problem while exploring the effects of some parameter. When all the pages used to determine all of the parameters have been entered, the problem can be run by typing "crun". Progress is reported via a separate window. When the problem is done, in a few seconds to minutes, CAGEN stops in the analysis state, waiting for instructions for plotting.

VI. CONCLUSIONS

CAGEN is a very competent model code which can be used to design MCG's and the attached application circuit. The code is still under development with improvements driven by current applications. Future work will include a "flux trap" generator model and an air shock model for the interior of the generator. Written in Fortran, CAGEN is very portable, and currently operates on the PC-Pentium platform. The graphical input engine is provided by MathGraf. The output phase depends upon MathGraf's forte: very fast interactive Math-Graphics .

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