Benchmarking the Care'n Co. Flux Compression Generator Code, CAGEN, Implementing the Kiuttu Contact Resistance Model

Jay B. Chase, Gerald F. Kiuttu, Donna M. Chato, and Giles Peterson

Abstract— **The PC-based program CAGEN has been described before and has since continued development. The most recent innovation implemented in CAGEN is the Kiuttu Contact Resistance Model (KCRM). This model is described elsewhere in these proceedings and represents the most important step forward for FCG modeling observed in many years.**

In this paper, the performance of a very large range of helical flux compression generators is computed using CAGEN, with no adjustable tuning factors. These generators span from the small Lawrence Livermore National Laboratory Minigen and the Lobo, each less than 100 cubic centimeters volume, to the quite large Los Alamos National Laboratory Mark IX, which is more than 220 liters in size. The examples range over a factor of 1000 in output current and over a factor of 100,000 in output energy, and represent different construction techniques. The results of eight such benchmark calculations using CAGEN, with the KCRM, are never in error more than 18% with respect to reported experimental current values.

Index Terms— CAGEN, explosive pulsed power, FCG, HEG, KCRM, MCG, modeling.

I. Introduction

The PC-based program CAGEN has been described before [1] and has since continued development. The most recent innovation implemented in CAGEN is the Kiuttu Contact Resistance Model (KCRM). This model is described elsewhere in these proceedings [2] and represents the important step forward for FCG modeling observed in many years.

CAGEN is properly referred to as a MODEL code, in that time is advanced through the integration of the lumped circuit set of equations. The values of the individual "lumps" are obtained by various and separate models. The inductance is computed by a generalization of a technique due to Smythe [3], the resistance by dynamic magnetic diffusion into circular wires and then modified by a proximity factor to account for the nearness of the other windings. The geometry of the generator is changed dynamically using an acceleration table provided by the user. Geometric space is divided in the axial direction into "zones" which are used to provide axial gradients for the resistance and inductance calculations. The zones also allow for the axial definition of the armature expansion. In the past the contact point was imbued with a resistive loss that was "ad hoc" in nature and adjustable to enable CAGEN to be tuned to the region of a particular generator design. This, in turn, allowed quick investigation of trends in the neighborhood of the design.

With the advent of the KCRM, the contact resistive loss is no longer ad hoc. It is nearly impossible to obtain the correct, and almost explosive, loss near the contact point via the MHD diffusion system already in CAGEN. There are two reasons for this: the zones are orders of magnitude too large to resolve this phenomenon, and the proximity correction currently available in CAGEN does not correctly account for the approach of the armature "plane" toward the curved wire surface. Consequently, the KCRM provides the best approach to correcting this CAGEN shortcoming.

In this short paper we present comparisons of CAGEN (with KCRM) calculations to experimental data for a wide range of generator sizes and styles. These span the large non split-turn generators such as MCGJ [4] to the small non split-turn ones such as the MINIG [5], and from the large split-turn generators like Mark IX (MK9) [6] to the small split-turn ones like LOBO [7]. The comparisons are not perfect but are done with no adjustment of any parameters that are not part of a proper physical description of the particular generator. In particular, the KCRM is not adjusted but retains its theoretical value.

II. CAGEN Comparisons

The MCGJ and MCGD [8] generators are wound with two parallel wires (the MCGJ has multiple sizes), while the MK9 generator has four sections of increasing degree of turns splitting. MINIG has a single wire and is dominated by the

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14. ABSTRACT
The PC-based program CAGEN has been described before and has since continued development. The most recent innovation implemented in CAGEN is the Kiuttu Contact Resistance Model (KCRM). This model is described elsewhere in these proceedings and represents the most important step forward for FCG modeling observed in many years. In this paper, the performance of a very large range of helical flux compression generators is computed using CAGEN, with no adjustable tuning factors. These generators span from the small Lawrence Livermore National Laboratory Minigen and the Lobo, each less than 100 cubic centimeters volume, to the quite large Los Alamos National Laboratory Mark IX, which is more than 220 liters in size. The examples range over a factor of 1000 in output current and over a factor of 100,000 in output energy, and represent different construction techniques. The results of eight such benchmark calculations using CAGEN, with the KCRM, are never in error more than 18% with respect to reported experimental current values.

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stator resistance, while the MK9, MCGJ and MCGD are dominated by the KCRM. To illustrate these points, Fig. 1 shows the current comparison of the MCGD to CAGEN and Fig. 2 is the corresponding plot of the CAGEN resistances.

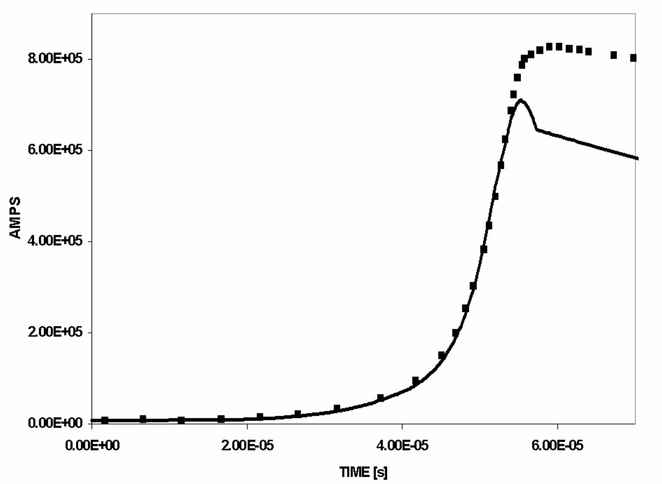

Fig. 1. Comparison of peak current achieved experimentally by MCGD to CAGEN. The experiment is the dotted line.

The total resistance is clearly dominated by the KCRM toward the end of the operation of the generator. The contribution to the resistive loss from both the armature and the stator decreases to zero as the amount of generator left approaches zero. However, since the KCRM is only a function of the local conditions where the stator wire approaches the armature, its value continues to have significant size right until the very end. Indeed, the KCRM's value increases as the current increases.

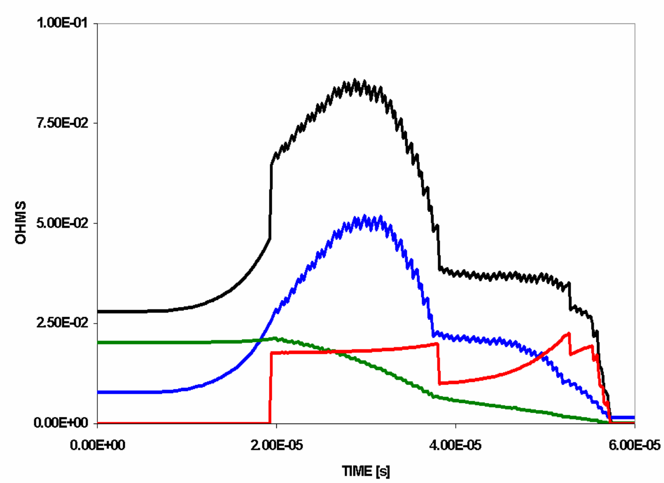

Fig. 2. A CAGEN calculation of MCGD showing the resistance components. The black curve is the total resistance, the blue is that of the armature, the green is the stator and the red is the KCRM resistance.

The MCGJ stator is 266 mm in diameter, the armature is 149.8 mm, the length is 794.5 mm, and the winding wire diameter ranges from 4.114 mm to 9.526 mm. Pitch varies from 4.3 mm to 35 mm. The same numbers for the MCGD are 130.2 mm, 74.6 mm, 328.7 mm, the wire diameter is fixed at 3.26 mm, and the pitch varies from 3.4 mm to 8.81 mm. MCGJ1, 2, 3, and 4 have injection currents of 6, 6, 12, and 12 kA while the corresponding load inductances are 1970, 920, 545, and 240 nH. The MCGD is injected with 8 kA and has a load inductance of 125 nH. Both MCGJ and MCGD use an aluminum armature.

Of the above set of experiments, the current curve comparison of the MK9 and the MINIG are of interest, and are shown in Fig. 3 and Fig. 4, respectively. Whereas the resistance of the MINIG is concentrated in its stator (Fig. 5), the resistance of the MK9 is almost all in the contact (Fig. 6).

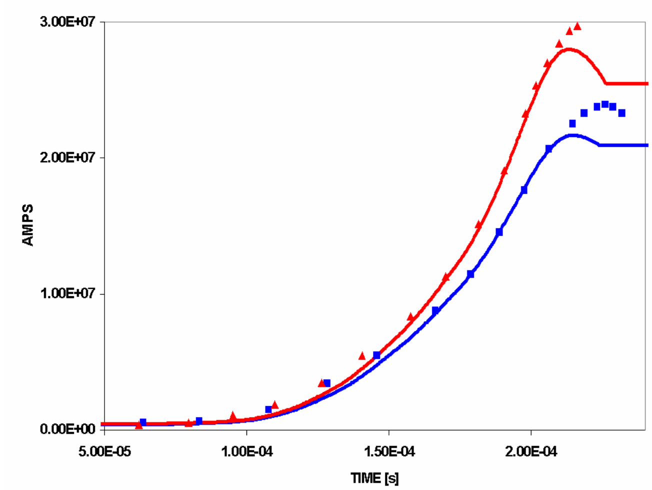

Fig. 3. CAGEN calculated current curve comparisons to MK9a and MK9b. The red curves are MK9b for which the load is 35 nH and the injection current is 460 kA, while the blue set is MK9a which has a load of 56.4nH and the injection current is 413kA. The dots are the data.

There are discrepancies in some of these comparisons. The largest is that of the LOBO. The LOBO has some characteristics that place it at one end of the spectrum of generators. The main one is the very high gain of 230. It shares with the MK9s the split turns winding scheme but the LOBO windings are about half a mm in diameter while the MK9 wires are almost 10 mm in diameter. There is not a current satisfactory explanation for the error.

Another large generator, designated MCGB [4], has been operated at low current. The MCGB stator is 266 mm in diameter, the armature is 149.8 mm, the length is 794.5 mm, and the winding wire diameter is 6.53 mm, and the pitch is 9 mm, and there are no bifurcations. However, there are 16 wires in parallel. The armature and explosive are the same as the MCGJ. A comparison of the CAGEN-calculated current and experimentally measured current is shown in Fig. 7. Like the MK9, the resistance of this generator is almost all in the contact, as shown in Fig. 8.

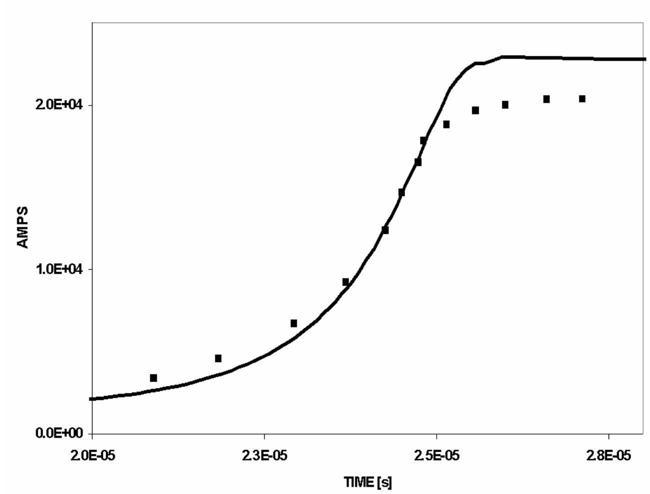

Fig. 4. CAGEN calculated current curve comparison to MINIG. The dots are the experiment.

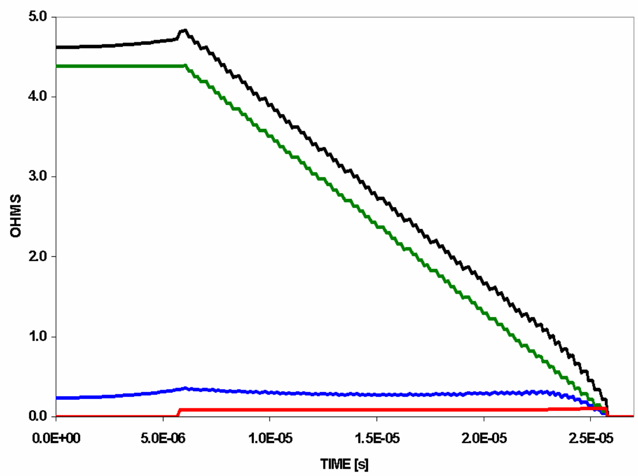

Fig. 5. CAGEN calculated resistances for the MINIG. The black curve is the total resistance while the green curve is the stator resistance. The KCRM, in red, plays almost no role.

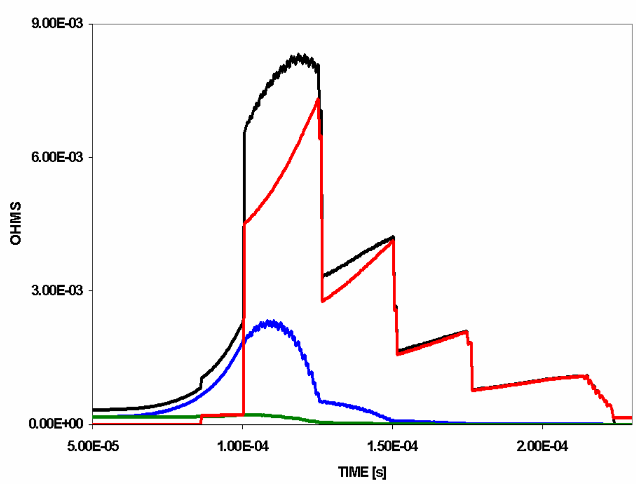

Fig. 6. CAGEN calculated resistances for the MK9a. The black curve is the total resistance while the red curve is the KCRM resistance. The armature and stator resistances, in blue and green, play little role.

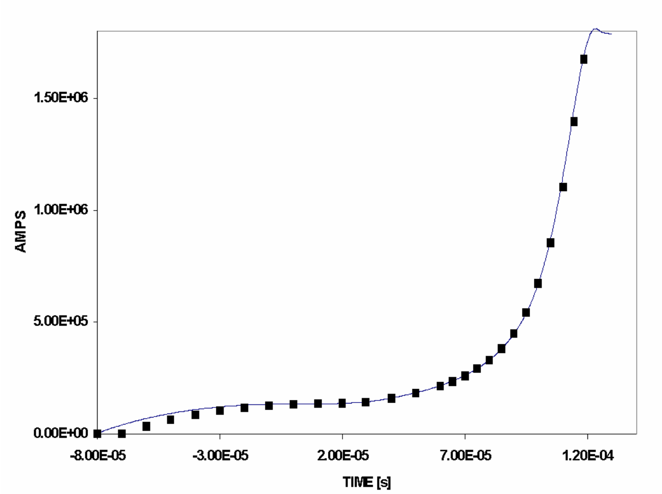

Fig. 7. A comparison of experimental current profile of the AFRL MCGB with that calculated by CAGEN. The dots are the experimental values.

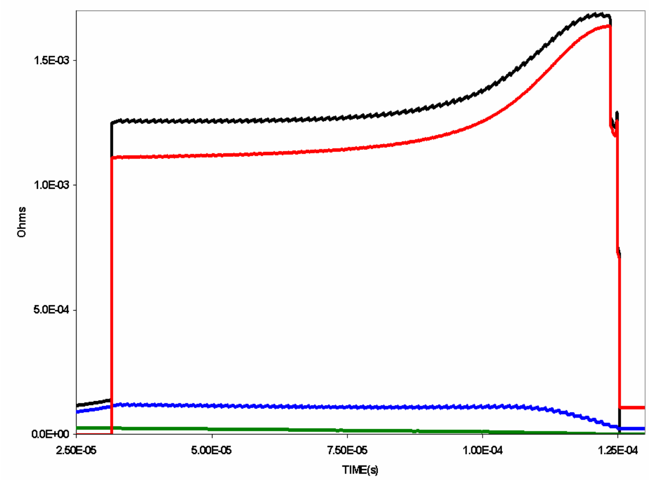

Fig. 8. CAGEN calculated resistances for the AFRL MCGB. The black curve is the total resistance while the red curve is the KCRM resistance. The armature and stator resistances, in blue and green, play little role.

III. CONCLUSIONS

We have shown benchmark calculations with CAGEN for a variety of helical generators. A summary of the degree of agreement between the calculated and measured current for these generators is shown in Fig. 9 and Fig. 10. The agreement, with the KCRM, is very good. However, much work must yet be done toward improving the predictability of the model code CAGEN. Since the core value of CAGEN is in its ability to quickly run many designs, enabling rapid convergence on a chosen goal, models that are so complex as to substantially slow CAGEN are not acceptable. For example, an accurate but quick model for time-dependent generator inductance is needed, and such a model is under development. Still, we have shown that with the development of the Kiuttu Contact Resistance Model, CAGEN can now truly be considered a predictive tool.

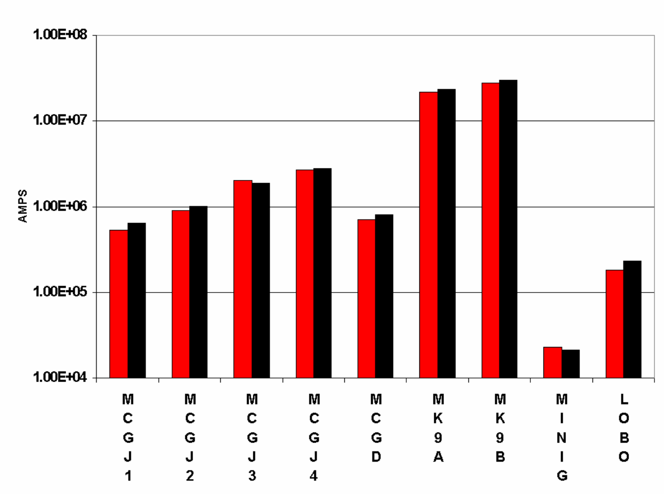

Fig. 9. A comparison of peak current achieved experimentally by a range of generators to the computation with CAGEN (in red). The generators are four MCGJs with different load inductances and injection currents, a MCGD, two MARK 9s, the MINIG and the LOBO. Note the log scale.

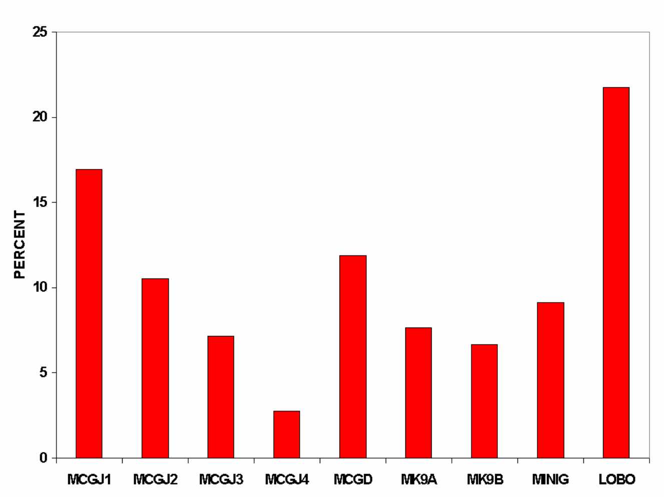

Fig. 10. The comparison shown in Fig. 9, cast in terms of percent error.

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