HIGH SPEED, HIGH CURRENT COPPER FINGER BRUSHES FOR
PULSED HOMOPOLAR GENERATOR SERVICE

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ORIGINAL
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Presented at the
IEEE Holm Conference on
Electrical Contacts,
September 30 to October 2, 1985

Publication No. PR-29
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PR21

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ABSTRACT

In continuing research into higher energy density, higher current rated pulsed homopolar generators (HPGs), solid copper fingers are explored as sliding electrical contacts to slip speeds of 300 meters per second (m/s) and collector area current densities above 75 megamperes per meter squared (MA/m²). Achieving increased compactness in HPGs is easily accomplished by spinning the inertial energy storage flywheel to higher tip speeds, but generally involves brush operation at higher slip speeds. Sintered copper-graphite brushes presently limit slip velocity to 220 m/s and collector area current densities to 7 to 15 MA/m², if a reasonable brush wear rate is expected.

Development of copper finger brushes began in 1981 by R. A. Marshall who performed low speed (15 millimeter per second (mm/s)) testing at current densities above 450 MA/m². Based on encouraging results obtained by Marshall, the present investigation focused on characterization of copper finger brushes in an actual HPG operating

environment. Experimental data was collected using the Compact HPG System Tester, a working 5-MJ HPG which can deliver current pulses in excess of 1 MA into resistive loads for the evaluation of brush performance. The copper finger brushes tested successfully transferred 1.15 MA at a slip speed of 100 m/s and currents of 600 kA at 180 m/s.

Experimental evaluation of effective contact resistance as functions of slip speed, current transferred, and brush normal force was performed and the results are discussed. Interfacial heat fluxes due to friction and contact voltage drop for the test conditions were also determined, and then extrapolated to operating levels of 300 m/s and 3 MA. These projections were used to determine the feasibility of rejecting the heat flux through direct injection (transpiration) cooling methods. Although problems with coolant delivery and hydrodynamic forces do exist, the approach holds promise in the continuing effort to extend pulsed HPG brush operating limits.

(Key words: Homopolar Generator, High Speed Electrical Contacts,
Actively Cooled Copper Brushes)

1. Introduction

Development of lightweight, compact, pulsed homopolar generators (HPGs) has been underway since 1979 at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) with funding provided by

the U.S. Army Research and Development Command (ARDC) and the Defense Advanced Research Projects Agency (DARPA). Interest in HPG-charged inductors as power supplies for electromagnetic guns has sparked recent efforts to develop portable HPGs which have previously been heavy laboratory-based machines. In May 1982, the first Compact HPG (CHPG), which has a volumetric energy density of 17 megajoules per cubic meter (MJ/m^3) at full speed was assembled and tested.[1] Sintered copper-graphite sliding contacts (brushes) were used in the machine at rotor slip speeds of 220 meters per second (m/s) and collector current densities of 15 megamps per square meter (MA/m^2). These are generally accepted limits of operation for this type of brush in pulsed HPG service. Extending these limits in order to improve HPG performance was the primary motivation for initiation of this ongoing study. Extending brush operation to 300 m/s will effectively double the energy storage density of any homopolar machine because of the capability of higher rotor speeds. Higher collector current density limits are needed for two reasons. First, electromagnetic-launcher performance increases dramatically with current level. More important, from an HPG design standpoint, as smaller and more compact machines are built, the available collector areas generally decrease and higher current densities are necessary to maintain or increase overall current rating.

To facilitate testing of new brushes at higher speeds and current densities, design and fabrication of the CHPG System Tester was initiated in June, 1982.[2] Built to develop component technology required

to build machines with energy densities in excess of 50 MJ/m^3 , the System Tester is a working HPG which stores 2.5 MJ in its 63.50-cm diameter rotor and generates 20 volts (V) at 220 m/s. Originally, the machine was built to operate at 180 m/s and later upgraded for 300 m/s duty because development of a stationary shaft bearing was also an initial goal for the System Tester, and testing in two phases was required due to the complex nature of the bearing. Shown in cross-section in Figure 1, the System Tester performed very well during Phase I while producing a great deal of brush data at speeds to 180 m/s. Presently, Phase II modifications have been implemented and brush testing to 240 m/s has now been accomplished.

In conjunction with the System Tester, a small turbine-driven tester was used for preliminary brush tests up to 300 m/s. This device provided valuable data on friction coefficients (fig. 4) at high speeds for various copper alloys as brush-finger materials. Although these experiments do not subject the brush to the same degree of severity as seen by HPG brushes, they do provide comparative information and allow visual inspection of wear mechanisms under these conditions. From these tests the most promising materials are selected for subsequent System Tester experiments.

2. Copper Finger Brushes

Selection of copper finger brushes (fig. 2) for initial testing on the CHPG System Tester was made for several reasons. The failure

mode of sintered copper-graphite brushes, manifested as very high wear rates, has been observed to be gross melting of the binder material. This phenomenon is caused by high heat fluxes associated with contact volt drop and friction. Melting temperature, thermal conductivity, and thermal capacitance are much higher for solid copper and therefore higher heat fluxes can be absorbed before melting occurs. Use of copper fiber brushes was also considered, but previous studies by Lupton[3] indicate that, although these brushes perform very well at high speeds and low current densities, they are not sufficiently stiff to resist the magnetic forces generated at the current densities of interest. Previous research into copper finger brushes at CEM-UT by R. A. Marshall[4] at low sliding speeds and high current densities provided encouraging results, so high speed testing was therefore considered worthwhile. Also, it was concluded that the copper finger design would lend itself to active cooling better than the fiber brushes because cooling passages could be more easily integrated into the contacts.

3. Pulsed HPG Brush Operation

Collection of current by the brushes at the high peripheral speeds of the rotor represents the single most demanding task of any pulsed HPG component. As background information, a typical HPG discharge is described as follows. The energy storing flywheel is accelerated to high speed, then the external magnetic field is applied via the excita-

tion coil to create a voltage across the spinning rotor. When full field is reached, an external load is connected across the generator terminals through the sliding contacts. As current begins to flow, Lorentz ($J \times B$) forces decelerate the rotor quickly accomplishing the kinetic energy conversion to a single current pulse. Pulse lengths depend upon the characteristics of the external load and are typically from 0.5 to 3.0 s in duration. Overall ratings of machine current and stored energy both affect collector area required to transfer the discharge current because a fraction of the stored energy is necessarily deposited at the brush/rotor interface in the form of heat.

Performance of HPG brushes is also influenced by two external factors: electrical load characteristics, and the method by which the circuit is closed upon discharge. Resistive loads are distinguished by very fast rise times as peak current is often reached in less than 30 milliseconds (ms). Time available for the brush to become seated before carrying full current is therefore extremely limited. Inductive loads, on the other hand, slow the rise time considerably, but also extend the current pulse as the rotor energy is transferred to the inductor. This longer current pulse can significantly increase brush wear rates because the interface flash temperature, the peak temperature reached at the sliding interface, is maintained for extended periods. HPGs are generally switched by two methods. An external closing switch is used, or the load is connected directly to the brushes and switching is performed by actuation of the sliding contacts (brushes). If the latter method is

chosen, an arc is drawn as contact is made, causing pitting and increased wear, thus reducing useful brush life. Experiments in this study were conducted with resistive loads due to the complexity involved in building a suitable load inductor, and the brushes under test actuated onto the slip surface 50 ms before current flow was initiated.

During a discharge current pulse, a sequence of several events is postulated based on experimental observation. When the brush is initially brought into contact with the rotor, the real area of contact (dispersed in many individual contact spots), is relatively small and constriction resistance is therefore high. This effect results in initially high voltage drops across the contacts and correspondingly high power dissipation at the interface. This energy manifests itself as increased temperature which softens the surface of the brush considerably. Contact spot size then increases to support the normal load, and constriction resistance and voltage drop are thereby reduced. Figure 3, a voltage drop trace recorded at 180 m/s and 500-kiloamperes (kA) peak current, clearly demonstrates this phenomenon. Should the heat flux be sufficiently high, or of sufficient duration, melting of the brush fingers occurs and further flash temperature increase is prevented because a great deal of energy is absorbed by the heat of fusion of the melting copper.

4. Experimental Methods and Results

Testing of copper finger sliding contacts on the System Tester was divided into two series, each performed with a new set of contacts. Series I tests included monitoring thermocouple instrumented fingers for temperature rise. A lithium-based grease was applied to the rotor before each Series I test, to provide lubrication. The second series of tests were more comprehensive and included measurement of temperature rise and two other studies conducted to determine the effects of slip speed, current density, and downforce on overall performance. A high temperature silicon grease was used during each of these tests. Use of greases in these experiments was aimed at providing some frictional relief prior to current flow. It was found that the grease was quickly vaporized by the additional heat flux generated when current was introduced. This was determined by performing identical discharges with and without the grease; no change in electrical performance was noted. In actual injection cooled brushes this lubrication would be provided in the coolant itself. In addition, brushes consisting of single rows of six fingers were tested on the turbine-driven brush tester to speeds of 300 m/s. The object of these experiments was to evaluate friction coefficients and wear characteristics that could be expected at speeds which were not yet attainable on the System Tester itself.

Mechanical tests of three copper alloys as brush fingers and three prospective slip surfaces were accomplished on the turbine-driven brush tester. No lubrication was provided and each test involved dropping the six-fingered brush onto the slip ring for 1.5 s at various slip speeds.

ETP copper, silicon bronze, and dispersion-strengthened (DS) copper were tested in various combinations with 4140 steel (R_C40), an electroless nickel coating on steel and Ni-Chrome plating on steel rubbing surfaces. Brush normal force and friction force were monitored by strain gauged members which served to support the brush. Initially, ETP copper was run on steel to generate baseline data for comparison with results from other combinations, and because this was the situation first tested on the System Tester. As shown in Figure 4, DS copper running on Ni-Chrome plating exhibited the best frictional characteristics.

Conventional wear measurement of these contacts is not easily accomplished because wear is generally characterized largely by deformation of the fingers. Although in most cases copper tracks are developed on the slip ring indicating adhesive wear mechanisms, brush life is more determined by brush melting and deformation. Visual inspection of the amount of copper transferred to the slip ring and overall condition of the brush after a defined test sequence were therefore relied upon for wear comparisons. As expected, the best combination from a frictional standpoint was also found to experience the least brush deformation and copper transfer to the slip ring. Based on these findings, tests of DS copper on Ni-Chrome plating are planned for the System Tester at a later date.

For initial experiments on the System Tester, 1,820 ETP-110 copper fingers (Series I tests) were used as outer brushes. Four individual

fingers were instrumented with thermocouples to determine the magnitude of combined electrical and frictional heat loads. Placement of the sensors was 0.076 centimeters (cm) back from the brush tip, but wear incurred during the test program brought the thermocouples progressively closer to the interface on each subsequent test. Because the thermocouples were mounted in four separate fingers, they were brought closer to the sliding interface by brush wear at different rates. In general, the farther the thermocouple was located from the interface, the lower temperature it would record. For example, in Figure 5, the thermocouple which registered an 800 °C rise at the 500-kA level was farther from the interface than other sensors which registered 1,080 °C rises at the 150-to 250-kA level. Finally, on Test #23, at 180 m/s and 12 MA/m² collector current density, one of the thermocouples reached the interface and registered 1,080 °C, the melting point of copper. This data provided proof that interfacial melting was indeed occurring as expected. For several tests, the instrumented fingers were isolated from the discharge circuit so they would not carry current. This was accomplished by simply inserting a 0.051-cm thick sheet of G-10 fiberglass insulation under the copper finger brush. Insulation integrity was checked before each test with a 40-V DC power supply. As shown in Figure 5, these tests also registered high temperature rises. Since frictional and electrical heat inputs were calculated to be roughly equal under these conditions, this pointed out the importance for evaluating both collector current density and brush packing factor.

Because the fingers were spaced very close together (about 40 percent packing factor), heat generated at current carrying interfaces can be carried by the rotor to the non-current-carrying fingers. Later inspection of the rotor showed evidence of the high temperatures in characteristic "blueing" of the steel around the rim.

In order to determine heat fluxes which would be generated at speeds above 180 m/s and collector current densities beyond 75 MA/m² for design of active cooling systems, a series of experiments using control variables was initiated (Series II tests). Slip speed, machine current, and brush downforce, were selected as controlled parameters, and the effective contact resistance, defined as voltage drop at peak current divided by peak current, was monitored to gauge performance. Each control parameter was varied over several tests while holding the other two constant. In this manner, the effects of each parameter could be more easily identified. Figures 6 and 7 indicate that lower slip speeds, higher currents, and heavier downforces all have positive effects on contact resistance. In Figure 7, note that current level has the most profound effect. Almost an order of magnitude drop in contact resistance was documented from 100-kA currents to just over 1 MA. Until higher current data is obtainable, the slope of the projected contact resistance was flattened to allow conservative design of actively cooled brushes for operation at the higher currents.

In addition to contact resistance, brush wear cannot be ignored as a gauge of performance. During the control variable testing, it was

noted that brush degradation seemed most severe at higher normal loads. To further study the relationship, an energy balance was performed on twelve discharges at 180 m/s and 35 MA/m² (about 540 kiloamperes (kA) machine current). Only downforce was varied during this test sequence, so electrical losses elsewhere in the circuit remained essentially constant. Therefore, from the reduction in electrical losses at higher downforces, increases in frictional energy dissipated could be surmized by noting the change in the difference between load energy and electrical brush losses. Figure 8 shows that as a percentage of stored energy, although electrical losses decrease with higher brush downforces, energy delivered to the load resistors remains virtually unchanged. Increased frictional energy at the higher loads therefore offsets the gain in electrical performance at these operating levels. Operation at the minimum load which prevents brush bouncing and arcing was adopted to maximize contact life. It is not clear whether this will be the optimum case at higher current levels and increased speeds, because data suggest that electrical losses will begin to dominate the situation. This becomes an area for further experimental evaluation.

5. Actively Cooled Brushes

Effective cooling of high current, high speed brushes for HPG service must be accomplished at the interface where the heat generation is taking place. If a significant portion of the heat is allowed to

transfer into the brush, melting will most assuredly occur. Cooling passages of forced convection design inside the brush may extend limits somewhat, but will be of little use at the desired operational levels. Transpiration (injection) cooling, or cooling by vaporization of a liquid at the interface, may extract a large fraction of the heat generated. Introduction of the cooling medium into the interface is nontrivial due to windage of the rotor, and will require specially designed brushes. Hydrodynamic forces produced by the liquid before it is vaporized could also lift the brush if not accounted for. Even though this approach appears promising, its application must be investigated.

Removal of peak interface power deposition, defined as

$$P = I_p^2 R_{eff} + \mu N v,$$

where

I_p = peak current

R_{eff} = effective contact resistance at I_p

μ = friction coefficient

N = brush normal force

v = maximum slip velocity,

will be the initial goal of an effective brush interface cooling system.

As shown in Figure 9, an estimated peak power dissipation of 13,200

kilojoules per second (kJ/s) is expected at 300 m/s and a machine current of 3 MA. The basis for the estimated peak interface losses includes the projected effective resistance values shown in Figure 7 and assuming values of 0.25 friction coefficient and a total normal force of 4.4 kN (2.4 N/finger for 1,820 fingers). Peak power levels are considered here over total energy dissipated for several reasons. First, unless a specific HPG application is identified, the total energy to be removed is unknown and depends on the total stored energy of the machine and the ratio of brush contact resistance to overall circuit impedance. Also, if maximum heat input rate can be effectively removed, then lower power levels generated later in the pulse should not pose any problem.

Based on estimated peak power dissipated at 300 m/s and 3 MA, about 6.35 kg of water per second would have to be vaporized in order to fully absorb the losses. Several factors should be pointed out. It is doubtful any coolant delivery scheme will insure that all the cooling fluid is vaporized. Also, if interface temperature is successfully reduced, then contact spot size may remain small, thus increasing voltage drop and subsequent heat load requiring removal. These observations suggest that more coolant than expected would be necessary. However, not all the heat generated must be removed since both the rotor and brushes are capable of conducting away some of the heat, and since peak power dissipation occurs for very short periods of time, greatly reduced flow rates may be sufficient to prevent flash temperatures from reaching the brush melting point. Also, no superheating of the vaporized fluid is counted upon.

Technology for transpiration cooling of re-entry-vehicle nosetips is well established in the aerospace industry and has achieved cooling of heat rates in the vicinity of $2,600 \text{ MJ/m}^2\cdot\text{s}$. Brush interface cooling will present a much different situation and actual cooling rates achievable may differ greatly. Should half the above value be attained, collector areas for 3-MA operation should be of equal or reduced size than those presently used for 1-MA machines. The approach of direct-injection cooling of the interface appears to be a promising and viable solution to increasing the present limits of slip speed and current density.

6. Conclusions and Future Work

The experimental data presented on effective contact resistances and interface heat fluxes provide a solid basis for the design of actively cooled brushes which can extend pulsed HPG brush operational limits by a substantial margin. Effects of slip velocity, current level transferred and brush downforce were successfully documented and it was determined that total current transferred has the most profound influence in reducing effective contact resistance, at least up to 1 MA. Use of lubricating greases was explored and found to have little effect on electrical performance. It is also doubtful that they provided any friction relief beyond the point where current was initiated, which indicates that lubrication should be provided on a continuous basis

during the discharge. This would be done by adding lubricating elements to the cooling medium in the injection cooling technique.

Use of transpiration cooling technology developed in the aerospace industry (for cooling of re-entry vehicle nosetips) combined with experimentally determined heat loads for HPG sliding contacts should allow design of cooling systems capable of extracting much of the power losses. Experiments planned for the remainder of 1985 include testing of several coolant delivery schemes aimed at maximizing vaporization of the fluid. The experiments will also investigate the effects of hydrodynamic forces. Experiments using uncooled brush sets (initially, to obtain baseline data) and eventually cooled brush sets to slip speeds of 280 m/s are also planned.

Design and fabrication of an additional brush testing HPG for rotor tip speeds in excess of 400 m/s will also be initiated in 1985 to continue exploration of brushes for pulsed HPG machines.

It is generally concluded that if electromagnetic accelerators are to be practical, they must be capable of operation in the field. Also, it is desirable that they be portable and easily handled in the harsh environments associated with earth orbits and space. This requires that HPG machines, used as power supplies, must be made as lightweight and compact as possible. In the experience of CEM-UT the crux of this problem lies with the sliding contacts which presently are the limiting factor in HPG performance, as defined by energy density and current

rating. Therefore, this program is judged as extremely important to the overall electromagnetic launch effort.

References

- [1] W. F. Weldon (Principal Investigator), "The Design, Fabrication and Testing of a Compact, Lightweight, Pulsed Homopolar Generator Power Supply," Phase I Final Report, Naval Surface Weapons Center Contract No. N60921-80-C-A033, Center for Electromechanics, The University of Texas at Austin, Austin, TX, September 1981.
- [2] W. A. Walls and M. R. Vaughn, "A System Tester for Compact HPG Component Development," presented at the 2nd Symposium on Electromagnetic Launch Technology, Boston, MA, October 11-14, 1983.
- [3] W. H. Lupton and P. Riechner, "Ultrahigh Speed Fiber Brush Design and Tests," presented at the Advanced Current Collection Conference, Chicago, IL, September 23-25, 1981.
- [4] R. A. Marshall, "High-Current and High-Current-Density Pulse Tests of Brushes and Collectors for Homopolar Energy Stores," IEEE Components, Hybrids and Manufacturing Technology, Vol. 4, CHMT-4, n.1, pp. 127-131, March 1981.
- [5] R. A. Marshall, "Design of Brush Gear for High Current Pulses and High Rubbing Velocities," IEEE Transactions on Power Apparatus and Systems, 85 (1966) pp. 1177-1188.
- [6] I. R. McNab, "Electric Current Transfer Across Sliding Surfaces," Fundamentals of Tribology, Suh and Saka editors, MIT Press 1978.

- [7] I. R. McNab, "Pulsed High Power Brush Research," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, 1 (March 1978) 30.
- [8] R. A. Marshall, "The Mechanisms of Current Transfer in High Current Sliding Contacts," Wear 37 (1976) 233-240.
- [9] M. Brennen, Z. Eleizer, W. F. Weldon, H. G. Rylander and H. H. Woodson, "Testing of Sliding Electrical Contacts for Homopolar Machines," in Proceedings 9th International Conference on Electric Contact Phenomenon, Illinois Institute of Technology, September 1978.
- [10] R. A. Marshall and R. M. Slepian, "Pulsed High Power Brush Research III, Experiments at 15.5 MA/m^2 and 277 m/s ," in Proceedings 9th International Conference on Electric Contact Phenomenon, Illinois Institute of Technology, September 1978.
- [11] A. E. Robson, R. E. Lanham, W. H. Lupton, T. J. O'Connell, P. J. Churchi, and W. L. Warnick, "An Inductive Energy Storage System Based on a Self Excited Homopolar Generator," in Proceedings 6th Symposium of Engineering Problems of Fusion Research, San Diego, CA, November 1975.
- [12] B. Sterlicht and H. Apkarian, "Investigation of Melt Lubrication," in ASLE Transactions, 2 (1960) 248.

- [13] L. Boyer, J. P. Chabrierie, and J. Saint Michel, Low Wear Metallic Fibre Brushes, Wear 78 (1982) 59.
- [14] R. Holm, Electric Contacts Handbook, Springer-Verlag 1958.
- [15] E. Rabinowicz, "The Temperature Rise at Sliding Electrical Contacts," Wear 78 (1982) 171-187.
- [16] P. Reichner, "Metallic Brushes for Extreme High Current Applications," in IEEE Transactions on Components, Hybrids, and Manufacturing Technology, 3 (March 1980) 21.

Figure 1. Compact HPG System Tester - Phase I Configuration

Figure 2. Copper finger brush configuration tested,
(this set includes thermocouples used to
monitor brush finger temperature rise)

Figure 3. Typical copper finger voltage drops at 180 m/s and 500 kA

Figure 4. Mechanical brush test data. Coefficient of friction vs slip speed at 1.34 N/finger downforce.

Figure 5. Copper finger brush temperature rise, (data plotted against machine current)

Figure 6. Effect of brush downforce on contact resistance

Figure 7. Effects of machine current and slip speed on contact resistance, (data collected during Series II tests)

Figure 8. Contact resistance and load resistor energies for various brush downforces (Series II Tests)

Figure 9. Peak interfacial heat fluxes expected at 300 m/s vs total machine current

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