THE TESTING OF SLIDING ELECTRICAL CONTACTS FOR HOMOPOLAR GENERATORS

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ABSTRACT

Due to the recent interest in homopolar generators as pulsed power supplies, the need has arisen for pulsed brush data on slip rings at high current levels and high surface velocities. Tests were conducted to examine the effect that varying the apparent area of contact has on the coefficient of friction, voltage drop and wear rate. Brush areas from 0.806 cm² to 3.23 cm² were individually tested at current levels from 0.0 A to 2800 A per brush. Experimental data is presented for a high copper grade of commercially available sintered copper graphite material. The data corroborates the "thermal mounding" phenomenon described by R. A. Marshall.¹

INTRODUCTION

Homopolar machines are being developed as pulsed current generators for various applications including resistance welding of large steel sections and energy storage and conversion for tokamak poloidal field systems. In a pulsed duty mode of operation, sintered metal graphite brushes are run at surface velocities and current densities one to two orders of magnitude greater than nominal steady-state conditions recommended by brush manufacturers. Due to the lack of data and general lack of understanding of brushes operating under these severe conditions, the Center for Electromechanics (CEM) at The University of Texas at Austin is conducting a brush testing program as an integral part of its homopolar generator development program.

The tests presented here were conducted to examine the effect that varying the apparent area of contact has on the coefficient of friction, voltage drop and wear rate. Not only do the results have a direct bearing on brush mechanism designs and brush maintenance economics, but they help us to better understand the mechanism of current transfer in high current brushes.

The test results show that, for a fixed current level of at least 1120 A per brush, the coefficient of friction, voltage drop and total weight loss per brush remains essentially constant with changing brush area. The test results also show that as the current level is increased above 560 A per brush, the wear and voltage drop increases while the coefficient of friction decreases. These results verify the "thermal mounding" phenomenon described by R. A. Marshall¹ from tests run at 1200 A on a brush 1 cm x 1 cm.

BRUSH TESTING FACILITY

The controlled atmosphere brush testing facility shown in Figure 1 has a 34.9 cm diameter, AISI 4340 steel rotor which has been tested at surface velocities up to 300 m/sec. The rotor

and shaft assembly is removeable, allowing for different slip ring materials to be tested. The front of the chamber can be covered with a clear, polycarbonate plastic cover (not shown in Figure 1), sealing the chamber for reduced or elevated pressure tests and allowing control of gas composition, temperature, and humidity content.

FIGURE 1. Controlled Atmosphere Brush Tester

The brush interface voltage drop measured between the brush and rotor is obtained with a lead soldered in the brush. The normal force applied by a pneumatic cylinder is measured by a strain gaged proof ring. The friction force is measured by the strain gaged cantilever beam seen on the right hand side of Figure 1. These force measuring systems are virtually uncoupled,

allowing for an accurate determination of the coefficient of friction. The brush wear is determined by removing the brush from the holder and weighing it before and after the test sequence.

In order to get a measureable weight difference, it is necessary to cycle the brush many times for any given test. A cycle consists of lowering the brush on the rotor, passing a current pulse through the brush/rotor interface, lifting the brush off the rotor, waiting for a predetermined amount of time and then repeating the cycle. Except for the initial lowering of the brush, which is initiated by the operator, the remainder of the sequence is controlled automatically by an electronic controller.

The power supply used for these tests is four banks of Exide nickel-iron batteries connected in parallel. The length of the current pulse is controlled by a signal from the controller to a large Westinghouse magnetic contactor, type M-910. The level of current is controlled by the number of batteries connected to the circuit. The batteries deliver a pulse which steps up to a peak current and then decays exponentially to a value of 60 to 75% of the peak current, depending on the pulse length and charge on the batteries. The average current level per pulse also decreases with the number of pulses due to the batteries losing their charge. Therefore, wear data is obtained over a range of current.

Except for wear, all data is permanently recorded by a light beam oscillographic recorder. This allows records of the tests to be kept for future reference and study.

TESTS

The procedure used for these tests was to take a 2.54 cm x 1.27 cm sample of brush material and perform a series of four tests: 1) no current, 2) low current, 3) medium current, and 4) high current. The same test brush was then cut down to 1.90 cm x 1.27 cm and the identical four tests were run. This procedure was repeated, reducing the size to 0.95 cm x 1.27 cm and finally to 0.475 cm x 1.27 cm. The surface velocity was in the direction of the 1.27 cm dimension for all tests. By using the same brush sample, the possibility of variations in the brush material composition influencing the data was eliminated.

The brush material used was a high copper grade of sintered copper graphite (Morganite CMLS) presently used on the 5 MJ homopolar generator in operation at the CEM.

All tests were run in air at a surface velocity of 81 m/sec. The atmospheric dew point determined by a wet bulb, dry bulb thermometer, varied from 0 to 8°C. The brush was lowered onto the AISI 4340 steel rotor with 56 to 60 N down force. Except for the noncurrent test on the 2.54 cm x 1.27 cm brush, all tests were con-

ducted on the same brush track on the rotor with no alteration between tests.

The following timing sequence was used for all tests: 1) The operator initiated a cycle by a push button, causing the brush to lower onto the rotor. 2) Approximately 0.33 sec after brush contact was established, the contactor closed, beginning the current pulse. 3) About 1.64 sec later, the contactor is opened, ending the current pulse. 4) About 0.26 sec after the end of the current pulse, the brush is lifted. This cycle was repeated every 30 sec for 25 cycles per test.

As previously explained, the current level during a test decreases with the number of pulses. The current ranges used for the tests were: 1) low current, 980 to 254 A, 2) medium current, 1750 to 700 A, 3) high current, 2765 to 1155 A. The maximum current corresponds to the peak current on the first pulse and the minimum current corresponds to the current at the end of the twenty-fifth pulse. The current direction is from rotor to brush for all tests.

RESULTS

The symbols used in Figures 2 to 4 represent different current levels and are identified in Table 1.

TABLE 1
LEGEND FOR LEVELS OF CURRENT

○	- no current
□	- low current (980 - 245 A)
△	- medium current (1750 - 700 A)
●	- high current (2765 - 1155 A)

Total Wear

The total mass lost by the brush during a test is shown in Figure 2. Arcing occurred on the high current test for the 0.806 cm² brush, making it an invalid data point. Scatter in wear data is well documented and, therefore, the total wear is assumed to be constant with varying brush areas for a constant current level. Note that the scatter at a constant current level is around four distinct mean values of total wear. Therefore, it can be stated that, for a given brush area, the total wear increases with increasing current level.

Wear Rate

Figure 3 is a plot of a nondimensionalized wear rate versus brush area, where the nondimensionalized wear rate is defined as the linear wear divided by the distance traveled. The values have been multiplied by 10¹⁰ to allow the curves to be plotted on a linear scale. They are calculated from the data in Figure 2 and the other testing parameters.

FIGURE 2. Total Wear vs Brush Area

FIGURE 3. Wear Rate vs Brush Area

$$\text{Wear Rate} = \frac{\text{linear wear}}{\text{distance traveled}} = \frac{\text{Total Wear}}{N A \rho t V}$$

where: N = number of cycles
A = brush area
 ρ = brush material density
t = length of time brush is in contact with rotor per cycle
V = surface velocity

Although this is the same data as in Figure 2, normalizing the values allows one to see the effect that reducing the brush area has on the linear wear.

Since the total wear is assumed to be constant for a given current level, one would expect the wear rate curves to be inversely proportional to the brush area. Therefore, as expected, the curves have the general shape of a hyperbola. This is difficult to see on the high current level tests. The data point at 0.806 cm² is not shown because arcing occurred; and the remainder of the data only shows a small portion of the overall hyperbola, making it appear linear.

Coefficient of Friction

The coefficient of friction, μ , is shown in Figure 4. Due to the varying current levels and varying brush temperatures during the test, the scatter in μ through the whole test is even larger than shown in Figure 4. For this reason,

FIGURE 4. Coefficient of Friction vs Brush Area
it was decided to use the last pulse to determine μ . At this time, the brush temperature has stabilized and the pulse to pulse decrease in current is minimal. Therefore, the values of μ shown are only during the current pulse and

correspond to the lower end of the current levels listed in Table 1.

The value of μ is determined by dividing the friction force by the normal force. At maximum sensitivity on the strain gage amplifier, the friction force can only be determined in increments of 0.5 N. Also, due to the oscillation of the signal caused by the first natural frequency of the cantilever beam being excited, sometimes the accuracy of the friction force is further reduced by ± 0.5 N. Therefore, since the normal force is five to 10 times larger than the friction force, variations in the friction force of only 0.5 N can change the value of μ by 0.01. This, along with the fact that μ actually varies during the pulse, accounts for the scatter of the data shown in Figure 4.

Considering the method of determining μ for Figure 4 and the factors mentioned above, it is difficult to place any significance in the slight variations in μ that occur at the noncurrent level and medium and high current levels. The only definite trend visible is the increase in μ with decreasing brush area at the low current levels.

Generally speaking, for a given brush area, the mean value of μ decreases with increasing current. The only two exceptions to that statement are: 1) at the medium and high current levels for the 2.42 cm² brush where μ is the same, and 2) at the low current level for the 0.806 cm² brush where μ is higher than at the noncurrent level.

Voltage Drop

The interface voltage drop versus brush area is shown in Figure 5. These data points were plotted for a particular value of current. The scatter is due to the voltage drop varying from pulse to pulse and the noisiness of the recorded signal. The voltage drop remains essentially constant with varying brush area at the three upper current levels. Only at the lowest current (560 A) is there a noticeable decrease in voltage drop with decreasing brush area. At a given brush area, the voltage drop increases with increasing current.

DISCUSSION

During the tests, it was noted that small dark spots would appear on the surface of the brush each time the medium or high current level tests were run. It was also noted that these spots would disappear on the noncurrent run, remain gone during the low current test, reappear on the medium current test and remain through the high current test. For example, after the first noncurrent test with the 2.42 cm² brush, it was noticed that there were a few faint dark spots left from the many that existed prior to the test. The spots had originally formed during the high current test on the 3.23 cm² brush. The noncurrent test was rerun and the spots completely disappeared, apparently worn away.

FIGURE 5. Voltage Drop vs Brush Area

The appearance of such small (~2 mm in diameter) dark spots led Marshall to his investigation of the phenomenon which he terms "thermal mounding."¹

Thermal Mounding

As explained by Marshall, when the net rate of heat input into the brush is sufficient to cause the brush material to expand at a rate greater than the material is worn away, a "thermal mound" is formed. If the brush is free to move in the direction normal to the contact surface and cannot tilt to realign itself, the remainder of the brush will be lifted clear of the slip ring and thus force the mound to be the sole conducting spot. At the moment the mound has worn away and ceased to conduct current, the brush material cools and shrinks up into the body, forming a shallow, concave surface. This surface does not immediately make contact with the slip ring and discolors due to oxides forming from the heat. This discoloration is the dark spot visible at the end of the experiment. As one mound is worn away, another forms on a different part of the brush where the cycle is repeated; hence the multiple dark spots at the end of many pulses.

Discussion of Test Results

Not only does the appearance of the dark spots after the medium and high current tests indicate the occurrence of the thermal mounds, the data verifies it.

Once a thermal mound is formed, the brush is forced to make contact with the rotor at only one spot at any time. Assuming the diameter of the

mound is smaller than the brush width, the volume of the mound will be determined by the power input to the mound. This is determined by the electrical and mechanical energy deposited at the interface due to current and friction, respectively. Therefore, for a given current, the mound, and hence the interface characteristics of the mound (real area of contact and localized shear strength of the material), would not be expected to be dependent on brush size, but instead, the current level. Since the coefficient of friction, voltage drop and total wear are determined by the interface characteristics, they would also be expected to be independent of brush size but dependent on current. In fact, for the medium and high current data shown in Figures 2, 4 and 5, all three parameters remain essentially constant with varying brush size.

As the current level is increased for a given brush size, the power input to the mound is increased and hence its interface characteristics are expected to change. The localized temperature would increase and thus decrease the localized shear strength. This would correspond to a decrease in μ but an increase in total wear. At the medium and high current levels, the data also verify this trend.

The voltage drop is expected to be determined by a rotor/brush interface voltage drop plus a mound voltage drop determined by multiplying the current by some effective resistance of the mound, R_{mound} .

$$R_{\text{mound}} = \frac{\rho l}{A}$$

where ρ is the resistivity of the localized material (which varies with temperature), l is some effective length, and A is the real area of contact. How these terms vary with current will determine the voltage variation. As seen in Figure 5, at current levels of 1120 A or above, R_{mound} remains constant for different brush sizes. This is in agreement with the wear and μ results which also remained constant for different brush sizes. This, once again, shows that at high current levels, the brush characteristics are determined by the thermal mounds which are independent of brush size. However, the voltage drop is not linear with current, indicating that R_{mound} varies with increasing current.

Apparently, the mechanism of current transfer is different for low current levels. Not only were the dark spots not visible, but the voltage drop tends to decrease and μ increases as the brush area is reduced. This agrees more with the conventional theory of brushes operating at normal commercial ratings, which states that at any instant there are many (5-20) small areas carrying current.² Holm indicates the possibility that, as the localized heating is increased, the area of the conducting spots would increase.³ In these tests, as the brush size is reduced, the total area in which the 5 to 20 conducting spots can migrate is reduced, thus increasing the localized temperature. With increased

conducting area, the voltage drop should decrease, although the coefficient of friction should increase since it is proportional to the real area of contact. This is in agreement with the data obtained. The increase in real area should also correspond with an increase in total wear. However, any difference in the wear is too small to be detected in these tests.

For the noncurrent test, the total wear agrees with the adhesion theory of friction for two metals sliding in contact with each other. It states that the volume of material lost is independent of the apparent surface area, but dependent only on load and hardness.³ The coefficient of friction also remains constant with varying brush size indicating the real area of contact remains the same. This appears reasonable since the wear is also proportional to the real area of contact, and, as shown, is independent of brush size.

CONCLUSIONS

Above current levels of at least 1120 A per brush, the voltage drop, coefficient of friction, and total wear do not vary with the brush size. As the current level is increased, the total wear and voltage drop increase and the coefficient of friction decreases. Therefore, when designing with high current brushes, it is necessary to refer to amps per brush and not amps per cm^2 , since it is the current level which determines the brush characteristics and not the brush size. These results verify the "thermal mounding" theory described by R. A. Marshall.¹

When considering how often the brushes will need replacing, it is more beneficial to consider the nondimensionalized wear rate, defined as the linear wear per distance traveled. These results indicate that, as the current per brush is increased, the brush size needs to be increased accordingly to give the same brush life.

The test results also indicate that there is a limitation to how small a brush can be for a given current level. Arcing occurred at the high current level with the 0.806 cm^2 brush while no arcing occurred with the larger brushes at the same current. This was probably due to the fact that the mound has less area in which to migrate, thus increasing localized heating to a point of melting of the material.

Due to the formation of the thermal mound, there exists a limitation to the total energy that can be deposited through the interface of any size brush before catastrophic failure occurs, resulting in arcing. This will be determined by the length and level of the current pulse and the speed of the sliding interface.

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