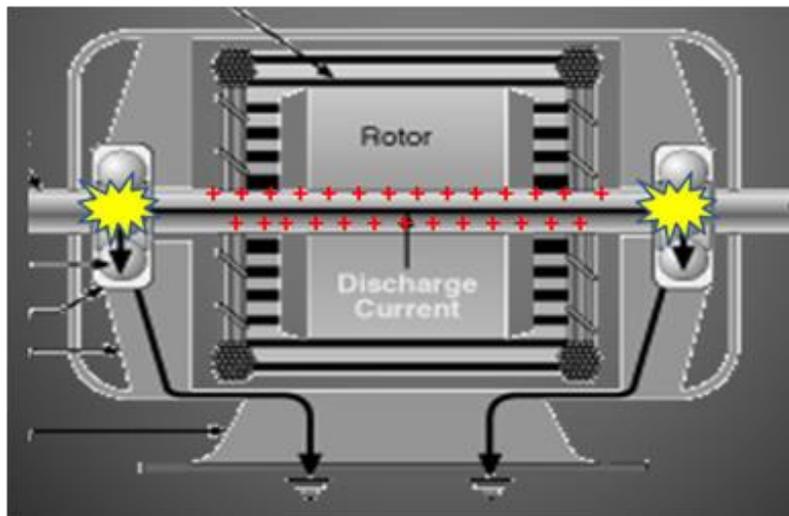


Shaft Grounding and Sliding Electrical Contacts



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Introduction

A sliding electrical contact is a component that conducts electrical power between surfaces that are in relative motion. The most common applications have been the many types of motors and generators that require power to the rotating part. The electrical and magnetic circuits in these machines inherently create a high potential for static and induced voltages. As the power capacities of these machines increased over the years the tendency for accumulation of electric charges on the shaft became ever more prevalent. These, like any electric charges, always seek the lowest resistance path to ground. **As a rotating conductor the shaft can only make an electrical connection to a stationary part through a sliding electrical contact.** Many electrical machines have had premature failure due to the flow of these electrical charges through relatively high resistance electrical contacts, i.e. the bearings. Components specifically designed to be sliding electrical contacts, such as carbon brushes, have been used very successfully for conducting the main power current to the rotor in these electrical machines. They have also been used extensively for decades to facilitate a safe, low resistance path to ground for the accumulating electrical charges on the shaft. The purpose of this document is to review various types of sliding electrical contacts and to analyze their use for shaft grounding.

History of Sliding Electrical Contacts in Electrical Machines

The invention of rotating electric motors and generators followed a long process of development spanning many decades during the mid-1800s. Electric motors finally became commercially viable in the 1880s as the drive power for transit vehicles. The need for electric power in the rotating part of the motor required the development of sliding electrical contacts. The first sliding electrical contacts were made of metal since these materials were highly conductive and were successful for stationary electric circuits. Copper leafs and copper bristles were among the first products for successful sliding contact with the rotating part and its rotor circuit. It is from these designs that the component became known as a “brush”.



Copper Leaf Brushes



Copper Bristle Brushes

As these machines increased in use the regular maintenance of the brushes became an unacceptable burden. The frequent trimming of the metal contact surface and the replacement of these metal contact brushes became a negative factor for the continued use of electric motors in drive systems. Although the metal to metal contact was very functional electrically, the high frictional wear from the sliding abrasion became a frequent interruption of service. Applications throughout our mechanical world have taught us well that metal to metal contact is high in friction and wear. Then in 1885 experimentation began with carbon as an alternative sliding contact material. Carbon proved to be a significant advantage with lower friction for improved life of the sliding contact and the contact

surface, yet the material was still conductive enough to perform electrically. Brush maintenance time was reduced to an acceptable level temporarily.

As motors and generators advanced the frictional and current-carrying capacity characteristics of the carbon material were no longer adequate. The desire for longer brush life and better performance became ongoing and led to continuous development of carbon brush technology.



Electric Motor Carbon Brushes 1885

The century that followed included continuous research on improving the carbon-based materials for sliding electrical contacts on a wider range of increasingly demanding high speed, high amp, and long life sliding electrical contact applications. Just like metal before it, the high maintenance associated with carbon as sliding contact material became excessive for most applications. Black amorphous carbon is in fact relatively high in resistance and friction compared to the semi-crystalline form of carbon called graphite. One of the most important developments for sliding electrical contact material was the introduction of graphite in its several forms that met the needs for lower friction, lower resistance, higher amp capacity, and slower wear rates. Today there is a wide range of very sophisticated **graphite**-based materials available for any sliding contact application.

Throughout the 20th century the development of electric motors demanded improvements in carbon brush technology. The result was innovations including improvements in wire connections to the carbons, split carbons, shock absorbing pads, quick connect terminals, and higher contact forces to keep pace with the ever increasing

power demands of electrical machines. The increased performance and life of carbon brushes were the key to continued use of rotating electrical machines as a major power source for the world's many drive systems. For almost a century now the product has really not been made of "carbon" and has not been shaped like a "brush". The many years of development of the so-called carbon brush has allowed the sliding electrical contact to reach a very high level of sophistication. Nevertheless the demand for no maintenance fueled the development of brushless electrical machines which have gained popularity in many markets.

Electrical Machines and Shaft Grounding

Throughout the history of rotating electrical machines there has been a continual demand for more power in smaller frames. This goal led to increased volts, amps, and speed in the designs. It is well known that turbo generators with surface speeds over 125 MPH or 200 Km/Hr., for example, need sliding electrical contact grounding systems as a standard part in the equipment design for bearing protection. The higher speeds cause higher friction and more potential for build-up of static electrical charges on the shaft.

The constant trend to higher voltage in electrical machines increased the potential for induced voltages on the shaft and other rotating conductors. In particular the recent development of brushless motors with high frequency voltage switching and common mode voltages has resulted in more concerning levels of accumulation of electric charges on the shaft. These factors have resulted in the need for shaft grounding of electrical charges that has never been greater.

Input Power to Electrical Machines

The electric power systems in many of today's rotating electrical machines include AC-DC conversions, electronic switching, and electrical imbalances. All of these involve high frequency voltage changes (dv/dt) which exaggerates the problem of electric charges developing on the shaft. These factors can be minimized on the front end at the electrical source with the use of high quality drive systems. Also some add-on products have been

developed to improve the quality of the electric power to electrical machines. These involve the use of toroidal inductors surrounding the input cables to the motor which effectively dampens the rate of change in voltage and proportionately decreases the rate of accumulation of electric charges on the shaft. The use of inductors then reduces the frequency of discharges to ground and thereby slows the rate of damage to a bearing over a given period of time. Toroid manufacturers have typically suggested a 60-75% effectiveness in extending the life of the bearing. There may be cases where this alone is sufficient improvement for satisfactory bearing life. This method does have clear benefits but does not directly or completely protect the bearings or other components from discharges to ground.

Although the frequency of the discharges is decreased with the use of inductors, the results show that the peak voltage on the shaft is not significantly reduced. It is in fact the breakdown resistance in the sliding electrical contact path from the shaft to ground that determines the peak volts on the shaft and the amount of energy and damage from each discharge to ground. If the path is through the bearing, it is a high resistance sliding electrical contact. The result is high peak shaft voltage and more damage from each discharge to ground. Most often then a lower resistance path to ground is still recommended in addition to an inductor as a more complete solution with much greater assurance of long term bearing protection.

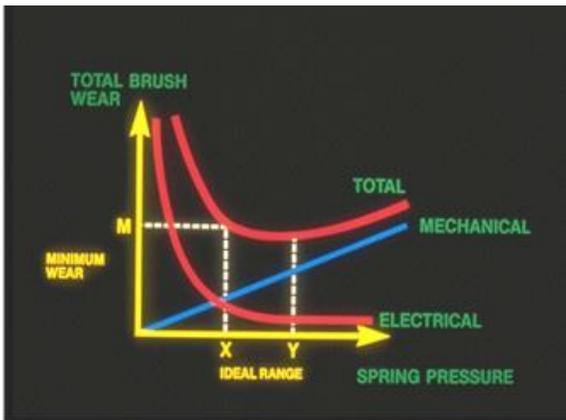
The root causes for charges to build up on the shaft of rotating electrical machines have been very well documented in technical papers. Given the fact that this is a common problem, the balance of this document is intended to discuss the merits of the various sliding electrical contact concepts. The goal is to determine the most effective practical path from the shaft to ground for these unwanted electric charges.

SLIDING ELECTRICAL CONTACTS

There are several inherent challenges with sliding electrical contacts compared to the very reliable realm of solid electrical contacts. The physical contact during the sliding action naturally creates friction, abrasion of particles, and mechanical wear

considerations. At the same time a sliding electrical contact involves the passage of electrical charges across a resistance layer. This dynamic connection interface with continuously changing contact points then results in electrical erosion of the contact surfaces.

In the application of sliding electrical contacts there is always a compromise between these mechanical and electrical factors. This includes the force applied to the sliding contact on the moving surface more generally expressed as a spring pressure. The contact force must be adequately low to avoid excess abrasive wear but must be adequately high for proper electrical contact. The following graph showing the ideal range for spring pressure applies to all sliding electrical contacts including shaft grounding:



The goal is to address these mechanical and electrical challenges to provide a contact interface with minimal friction and minimal resistance.

The continuous progress for more than a century in carbon brush technology has allowed the product to attain a very high level of performance. Today sliding electrical contacts remain an efficient and effective method for the transfer of electrical power between moving surfaces. This knowledge base from the history of carbon brushes should be very valuable now for the best choice of shaft grounding solutions.

Electrical Charges from the Shaft to Ground

Electrical charges will always seek the path of least resistance to ground. A moving shaft as a rotating part can only have a path to ground through a slid-

ing electrical contact. Some machine designs include insulated bearings or coated shafts to raise the resistance or in other words insulate these areas of contact from being a path for electrical charges to ground. This method attempts to inhibit the flow of electric charges to ground. The accumulation of electric charges on the shaft remains and the constant voltage pressure that can lead to insulation breakdown or damaging current flow through other components.

With the motion of sliding electrical contact there is effectively a resistance barrier at the sliding contact interface. There must be enough build-up of electrical charges or in other words high enough voltage to force the current to flow across this resistance layer. The higher the resistance of this sliding contact barrier, the higher will be the voltage necessary to force discharge from a rotating shaft to the stationary ground circuit. The objective then must be to provide the lowest resistance path to ground for the most efficient flow of the electric charges with the least damage.

ANALYSIS OF SHAFT GROUNDING METHODS

Metal bristles, carbon fibers, and carbon brushes have become the most popular choices for shaft grounding. These sliding electrical contacts are designed to carry electric charges across the sliding interface between the contact surfaces. Helwig Carbon, having all of these materials available, has done extensive testing to analyze these options through measurement of shaft voltages and discharges. These factors are the best indicators of the amount of electric charges (amps) and the damage from the discharges to ground.

The peak voltage on the rotating shaft is easily measured and is an excellent indicator of the resistance to ground. As electric charges accumulate there is increasing voltage until the breakdown voltage for the lowest resistance sliding contact path is reached. There will then be a discharge and a return to near zero volts followed by another accumulation of charges on the shaft and discharge in a high frequency repetitive process. The energy and electrical damage from one discharge is dependent on the voltage (electrical pressure) and amps (electrical volume). The total damage will depend on the frequency of these discharges over time. The goal is to determine the effectiveness of the various contact options in providing the lowest resistance parallel path to ground.

Test Data

Laboratory tests were conducted with the installation of the various grounding devices on the drive end of the same shaft of a VFD motor for easy comparison of the data. The motor ratings were 7.5 kW 480 VAC 3Ø 60 Hz and the motor drive was adjusted for a carrier frequency of 16 KHz. The generator pictured below on the left provided an adjustable load on the motor. Measurements were made on the motor shaft on the right with no grounding device installed as a base line reference.



The results oscilloscope traces for shaft voltage discharge with the various grounding devices are shown as follows.

Without Grounding Device



Scales: Vertical 2V/Div Horizontal 50 msec/Div

With no grounding device there was peak shaft voltage of 5.36V. The high frequency peaks show the repetitive discharging through the bearings which over time would certainly threaten the life of the motor. It is common for VFD motors without grounding protection to have much higher values for shaft voltage.

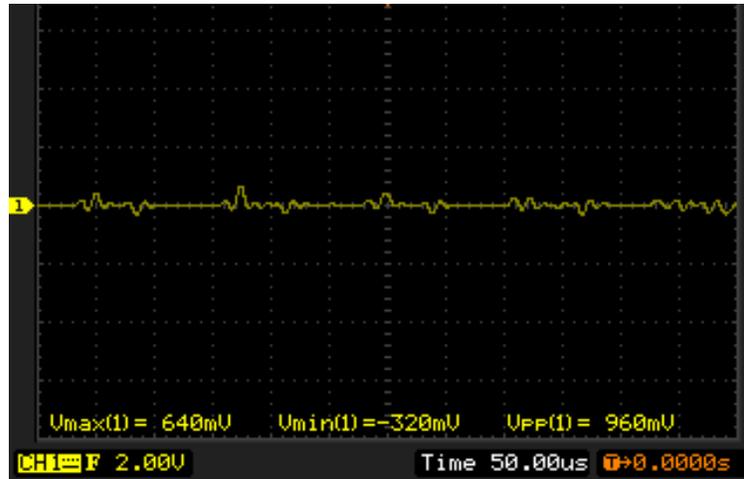
Metal bristle or wire mesh contact in various brush-like forms has been used for grounding applications. Sliding contact history shows this is a “step back in time” as the concept mirrors the origins of brushes on the oldest rotating electrical machines.



Metal Fiber Grounding Examples

The test was set up with sufficient bending of the metal fibers to attain a moderately high contact force for the voltage measurements. There was significant variation in results depending on the amount of deflection of the fibers.

Metal Fiber



Scales: Vertical 2V/Div Horizontal 50 msec/Div

The metal fiber with significant deflection for contact force resulted in a dramatic improvement in reducing the peak voltage to 0.64V. The good electrical performance follows the early success of metal to metal contact in the first electric motors. During many hours of testing however, there was an accumulation of metal filings under the grounding device. This relatively high frictional wear of the metal fibers results in a reduced deflection of the bristles, lower contact force, and increasing contact resistance and voltage. The high coefficient of friction and the high rate of mechanical abrasion between the metals remains an inherent disadvantage as a sliding contact material just as it was in the 1800s.

Some have attempted to reduce the friction with the use of a minimal contact force however this significantly increases the contact resistance and negates the advantage of using metal in the first place. Others have attempted lubrication of the metal to metal interface in a similar way as in so many mechanical devices in our world. The regular application of grease or oil however adds to the maintenance costs and detracts from the low resistance advantage of the metal contact.

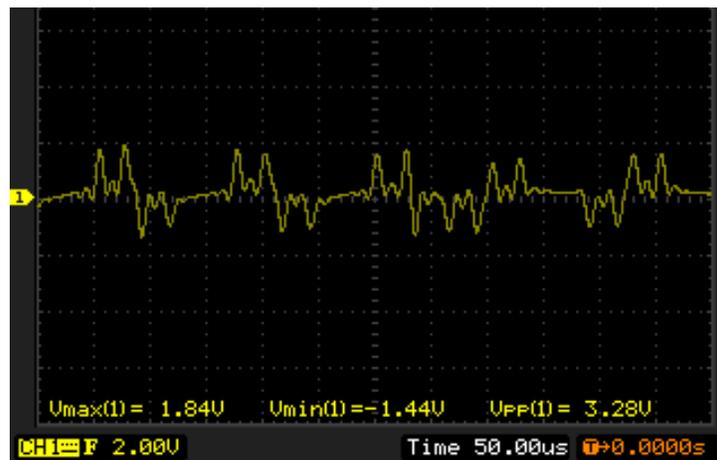
Carbon fibers have become a popular material for a wide range of products in recent decades taking advantage of the material's high strength to weight ratio and its chemical resistance. With carbon being a conductor there also have then been attempts to once again use carbon in a fiber form for electrical contacts.



Carbon Fiber Contact Examples

The fibers can provide many points of contact on a sliding interface to reduce the effective contact resistance. This test set up was optimized with adjustment of the interference fit of the shaft and the carbon fibers. This was necessary to attain deflection of the fibers and the needed contact force for the lowest voltage reading.

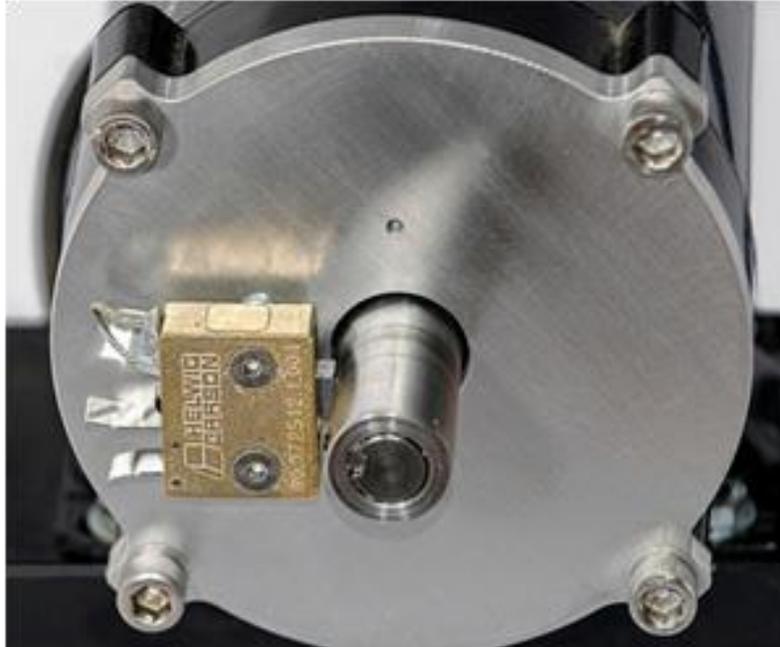
Carbon Fiber



Scales: Vertical 2V/Div Horizontal 50 msec/Div

The peak voltage with the optimized setting of the carbon fiber was 1.84V. As expected based on the characteristics of carbon, this result was higher than for metal fiber. The measurements do confirm however that the many carbon fibers can still provide a lower resistance path from the shaft to ground than through the bearings. Just as with metal fibers, the added force from deflection of the fiber on the contact surface will result in more wear due to the relatively high friction of carbon. The wear of the short fibers also results in decreasing deflection, decreasing contact force, and increasing peak voltage. With less force the resistance then increases with greater risk of discharge through the bearing. Later tests with less deflection of the fibers resulted in shaft voltages 2-3 times higher than these results. In addition, just as with the historic development of conventional carbon brushes, the inherent high resistance and high friction of carbon are disadvantages.

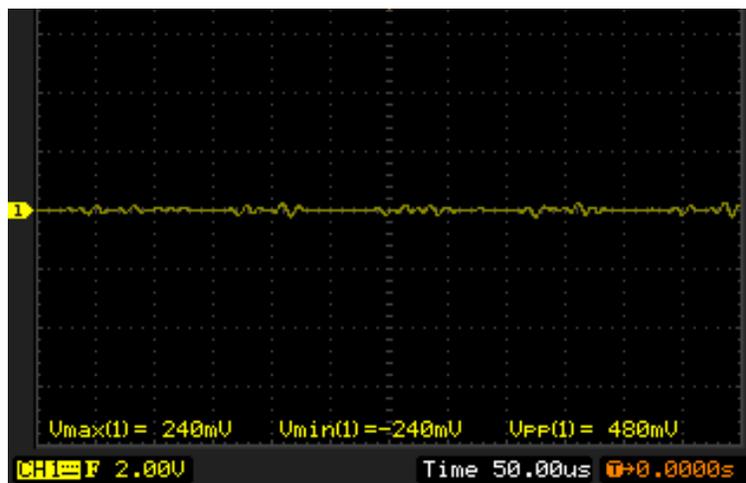
The material carbon in its amorphous or non-crystalline form had historically been sufficiently conductive for some sliding contact applications. The development of brush materials for motors throughout the 1900s however dramatically improved grades to provide very low friction and very high conductivity for the increasingly demanding applications. Graphite is the semi-crystalline form of carbon with very different characteristics. Graphite is about ten times lower in resistance, about 2 times higher in current carrying capacity, and about 3 times lower in friction than carbon. Helwig Carbon has developed a graphite material with the addition of silver for significant further reduction in resistance and with a low friction additive to optimize the material for very long life.



Silver Graphite Brush & Constant Force Holder System

The following test used a more conventional style brush installed in a constant force brushholder as employed today on most high quality sliding electrical contact systems.

Silver Graphite Brush



Scales: Vertical 2V/Div Horizontal 50 msec/Div

The peak shaft voltage was 0.24V. This result was the best among all sliding contact methods for low resistance to ground due to the inherent characteristics of silver and graphite and the definite contact force. The friction was also extremely low due to the special graphite which resulted in extremely low wear rate.

SLIDING CONTACT RESISTANCE

The results with metal and carbon confirmed what the history of carbon brushes had already taught us. The natural high friction and resistance characteristics of metal and carbon require the unavoidable compromise between the electrical performance and mechanical abrasion. The fibers must be deflected significantly to attain a low resistance contact yet this deflection dramatically increases the frictional wear.

It is then very challenging with metal bristles or carbon fibers to design a device having sufficient and consistent contact force to attain the desired long-term low resistance contact. The bristles and fibers must be deflected at some angle to create a good electrical contact against the shaft. This force however, cannot be excessive because the mechanical wear factor increases significantly with metal or carbon. Then with wear of the bristle or fiber the deflection is reduced and there is a corresponding decrease in the amount of force and increase in the contact resistance. Satisfactory performance can be attained as evidenced by the above test results, however the installation needs to be very precise and the results are not sustainable in the long run. In addition bristles and fibers are not effective on reversing applications.

The many highly developed contact systems including a brush and brushholder allow the application of an appropriate constant contact force to maintain consistently reliable low resistance performance. Silver graphite materials yield the lowest contact resistance for the most reliable grounding connection. Performance testing has proved that the brush and holder contact system provides the best solution for effectively conducting electrical charges from the shaft of rotating electrical machines to ground.

SLIDING CONTACT LIFE

Following the electrical analysis of the various methods for shaft grounding function, testing continued for life of carbon brush type contacts. Many typical carbon brush applications are very high amps and high speed resulting in high electrical and mechanical wear. A shaft grounding brush contact however conducts extremely low amp levels so the electrical wear factor is negligible. The shaft has a lower peripheral speed than the corresponding commutator or ring surface in the same machines which reduces the mechanical wear. With the use of ultra-low friction graphite-based contact materials there was significant further reduction in the mechanical wear factor. The result is dramatically longer life of the shaft grounding brush compared to the more typical demanding high power motor and generator applications on rings and commutators. This was consistently confirmed in lab testing with less than 1.0mm of wear per 250,000 kilometers of sliding distance (0.040 inches of wear per 150,000 miles). Extremely low wear rates with the advanced brush and holder systems are very attainable for the shaft grounding function.

Summary

The continuous improvement in carbon brushes has been an important element in the dramatic progress of electric drive systems. The data and analysis presented above confirms that the same historic development of sliding electrical contact materials and concepts is equally important today for the selection of shaft grounding products. The history of carbon brushes and the above data confirm that the inherent material characteristics of silver graphite are a clear advantage over copper and carbon for sliding electrical contacts. In addition to the material advantage, a brush and holder system has a definite contact force for the most reliable low resistance contact. This system also offers an opportunity for adjustment of contact materials and contact force in special situations according to different application conditions such as contaminated environments. It can be concluded that grounding of the shaft is a very easy sliding electrical contact application compared to the more typical function of conducting very high amps at high speeds to the rotor in motors and generators.

The conventional “carbon brush” type of sliding contact system with optimal contact material and proper constant force contact have all the advantages for shaft grounding performance and long life. This proven flexible economical readily available product is the best solution for grounding of electrical charges on the rotating shaft of electrical machines.



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