White Paper

High Reliability Slip Ring Design for Wind Turbines

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Key Messages

- The transmission of electrical power and signals from the turbine's stationary structure to the rotating blades is most efficiently accomplished with a slip ring.
- Electrical energy is transmitted across the rotating interface in a slip ring assembly by sliding contacts.
- The optimal contact system is the recognition that the contacts must be integrated into a reliable overall system design, as well as proper inspection and maintenance schedules.

Introduction

Most modern wind turbines require electrical power and signals to be delivered to the blades for blade pitch actuation. A number of sensors can also be resident on the rotor that require delivery of electrical power to the sensors and signal transision from the sensors to the controller. This transmission of electrical power and signals from the stationary structure to the rotating blades is most efficiently accomplished with a slip ring. It is important to understand the design and construction of slip ring assemblies in order to properly specify and evaluate their reliability and maintenance requirements. A high reliability, maintenance-free slip ring is possible with careful consideration of proper specifications and design.

There are five very important characteristics of wind turbines that require specialized slip ring design considerations: (1) operational life, (2) environment, (3) electrical requirements (4) maintainability goals, and (5) and reliability requirements. These five operational parameters are critical in the selection of sliding contact materials used in wind turbine slip ring assemblies as well as the housing that protects these electrical contacts from the environment. Table 1 presents a matrix of the performance parameters and their effect on slip ring contact selection.

Life	Continuous rotation at 30 RPM for 100 million cycles or more requires contact materials with an exceptionally good wear rate.
Environment	Contacts must be robust to survive nacelle environments. The materials must tolerate the humidity, temperature, and contamination environments that can be present, and the assembly must be appropriately sealed.
Electrical Requirements	Typical slip rings have power requirements as well as signal transfer requirements. The contact material must have good power (current) capacity as well as low contact resistance for good signal transmission.
Maintainability	Contacts should not degrade significantly with time or be subject to sudden catastrophic failure as long as specified inspection or maintenance procedures are followed.
Reliability	Contacts should require little or no maintenance. Any wear debris must be carefully managed to avoid arcing or short circuits.

Table 1: Wind turbine environment and slip ring performance

Sliding Contact Design for Wind Turbines

Electrical energy is transmitted across the rotating interface in a slip ring assembly by sliding contacts. A brush, or wiper, slides on a rotating ring and maintains continual electrical contact during rotation (Figure 1 shows one such ring and brush configuration).

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change in voltage at a constant current will typically register less than 50 mohm, which in the case of 100 mA results in only 5 mV of noise. Properly designed signal contacts will minimize any increase of this signal variation during the entire life of the slip ring. Noble metals (chemically unreactive, e.g., gold) are typically used to avoid formation of insulating films in the contact zone.

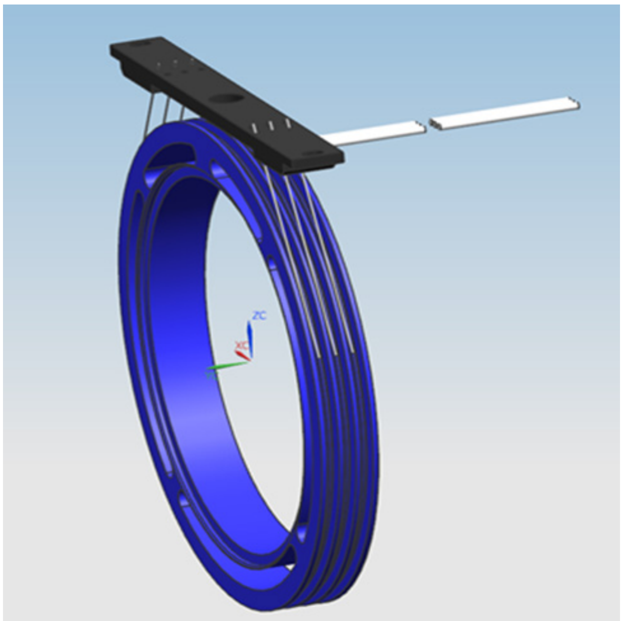

Figure 1: Noble metal sliding contact system for signals

Most rotating systems strive to avoid metal to metal contact between surfaces in relative movement by the use of a lubricating film, for example in the case of bearings. However in the case of sliding electrical contacts, intimate contact is required between the stationary brush and the rotating ring for error-free electrical and arc-free power transmission. Appropriate materials and design criteria must be selected to reduce the wear of these materials in contact during sliding.

It is important to consider the contacts as a conductor of electrical power and signals. In the case of power transmission, the contact material must have sufficiently high conductivity to transmit electrical currents without overheating. The voltage of the transmitted power is not particularly significant for the contacts themselves, but the dielectric separation between the contacts must be sufficient to avoid arcing on power circuits. The ability of contacts to maintain voltage isolation during operation can be critical in the case of contacts that generate conductive wear debris during operation. Without proper insulation this wear debris can cause arcing and ultimate failure. The generation of some wear particles cannot be avoided during slip ring operation, and success depends on the proper "management" of the resultant debris.

In the case of signal transmission through slip rings it is important to maintain signal integrity throughout the life of the slip ring. There is some small variation in contact resistance during the rotation of a slip ring. Under normal conditions this variation is quite low and insignificant. This variation in contact resistance when measured with an oscilloscope as a peak-to-peak change in voltage at a constant current will typically register less than 50 mohm, which in the case of 100 mA results in only 5 mV of noise.

Moog highlights three commonly used contact systems for solving these requirements for wind turbine power and signal transfer (see Figure 2). The first is a brush formed from a carbon/metal matrix that slides on a metal ring; the second is a bundle of noble metal wires in a brush-like configuration sliding on a noble metal ring; and the third is a single noble metal wiper sliding on a noble metal ring. We will first describe the three technologies and then address the appropriate selection criteria that Moog uses in choosing the right technology for a specific application.

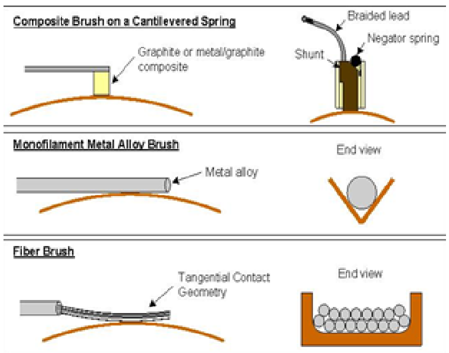

Figure 2: Three types of contact systems use in wind turbine slip rings

As is often the case in any engineering solution, proper contact selection always involves weighing trade-offs. As we discuss Moog's contact solutions, relative advantages and disadvantages are mentioned. It is important to consider all aspects of the application when evaluating the "best" contact solution. The advantage that Moog brings to the wind turbine market is years of research and experience with three different contact systems so that the best solutions can be applied.

Carbon Brushes

Contact materials made from carbon-based composites have been quite common in industrial slip ring applications since the very first days of electrical machinery development. Electric motor commutation is performed almost exclusively by carbon-based brush materials, and large high power industrial slip rings commonly use carbon-based contact material. Slip rings normally utilize a metal-graphite matrix material since the metal content increases current capacity and decreases contact voltage drop (contact resistance). These sintered metal graphite brushes are typically around 60-80% graphite and 20-40% metal (silver and copper are the most common metals), although for specific applications the graphite content can be as little as 5% and as much as 100%. The brushes typically are mated with a silver or copper alloy ring (see Figure 3 which shows a silver ring and silver graphite brushes) and sometimes a noble metal contact material is plated onto a copper alloy substrate. These composite brushes operate on the principle that the graphite provides lubricity for the system during rotation and the metal in the brushes provides the conductivity.

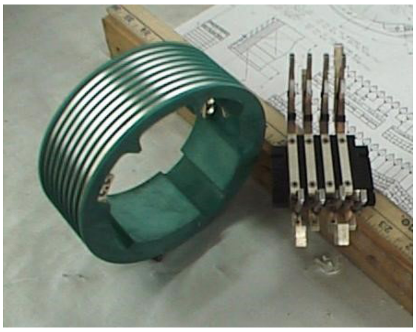

Figure 3: Silver graphite cantilever-style brush block with silver-plated copper ring module

There are hundreds of carbon/metal brush formulations available, and it takes careful selection to choose the best one for different applications. The brush processing techniques as well as the exact composition is extremely critical for successful operation. There are a variety of additives that can be added to the brush to improve wear in specific environments.

The carbon/metal brush contact systems that Moog has integrated into wind turbine slip rings was designed in conjunction with one of the largest carbon brush manufacturers in the world. A brush material with low contact resistance, low wear debris generation, and a wide temperature and humidity range was selected along with a metal ring material to match. This material is capable of operating at high power levels in wind turbine environments for 100+ million revolutions. Extensive life testing was conducted to verify all performance characteristics. This is a very important point since performance characteristics change dramatically over the range of carbon/metal brushes depending on %metal, processing parameters, and design characteristics (brush force, for example), so design verification is a critical step.

Figure 4 shows life test results for the Moog wind turbine graphite metal design. Typically life tests are conducted using "noise" (variation in contact resistance with rotation) as the end of life criteria. At the end of life, the build up of wear debris causes a sharp increase in noise to the point where intermittent open circuits are detected. The actual value of the noise levels is not critical in power circuits as long as there are no channels that approach open circuits. Noise values of less 250 milliohms as shown in Figure 4 are well within acceptable levels for power channels. Noise values are more critical in signals channels. The noise values of less than 100 milliohms on the signal channels is quite acceptable for most discrete and control ciruits, although data channels with data speeds greater than 500 kbps are typically handled with brushes of alternative materials.

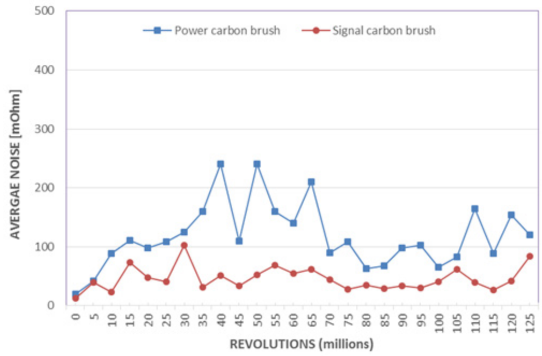

Figure 4: Life test for carbon/metal brushes

Carbon/metal brushes shed wear debris during operation by design. Proper material design and selection reduces the amount of wear debris, but there is always some debris. Properly designed slip rings manage this wear debris in order to avoid arcing or shorts between circuits. For example, raised barriers between rings can significantly increase the length of the creep path beweeen rings thereby decreasing the probability of a short circuit (see Figure 5). Or in some cases an air dielectric as shown in Figure 6 can be used to increase the creep distance. It is important to follow guidelines for inspection and cleaning of carbon/metal slip rings to avoid excessive build-up of wear debris. A properly maintained Moog carbon brush slip ring where debris is vacuumed every 2 years has a 200+ million revolution life. No maintenance at all is required for the first 50 million revolutions or 5 years.

Figure 5: Rings with raised barriers

Figure 6: Carbon brush on ring set with air dielectric

Fiber Brushes

The fiber brush has evolved from research conducted by Dr. Kuhlmann-Wilsdorf in the mid-1970's to improve the efficiency and reliability of high performance motor and generator commutator contacts (Ref.1). Subsequent development work by Moog engineers led to an alternative approach for fiber brush contacts using tangential fibers of noble or precious metal (see Figure 5). This tangential fiber brush design has been proven in a multitude of long life, extreme environment slip ring applications. Three notable applications have been helicopter rotor de-icing slip rings, radar pedestal slip rings, and wind turbine slip rings. Each of these applications requires long life, high conductivity for high power transfer, and operation in very difficult environments.

The fiber brush design involves the bundling of multiple metal filaments into a compact multi-fiber "brush" as shown in Figure 7. Typically these fibers are noble metal and the ring on which the brush operates is noble metal plated. The use of noble metals prevents oxides and coatings from forming on the contacts and allows very light contact forces. Very low contact forces achieved by the fiber brush technology result in very low wear rate without the use of contact lubricant. The multiple metal fibers provide very good conductivity and very high current density, so the fiber brush can be used for both power and signal. And as a final benefit the fiber brush produces negligible wear debris.

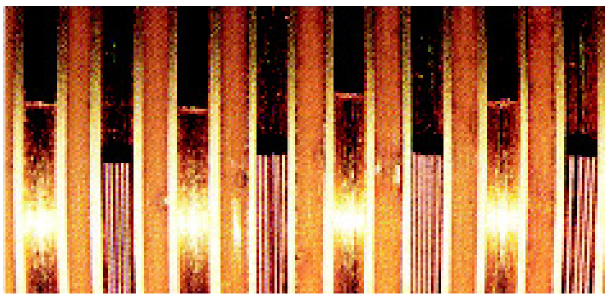

Figure 7: Fiber brushes installed in grooved ring

The theory of the fiber brush as a sliding contact is based on multiple contact points with very light contact forces per contact point. The multiple contacts allow even sharing of both the electrical and mechanical loads. These light contact forces result in a very low wear rate. Results from numerous life tests demonstrate that fiber brushes can be operated in excess of 100 million revolutions with low contact noise, little debris generation, and low wear. Typical data in Figure 8 shows "contact noise" (in milliohms) over a 124-million-revolution life test. The results demonstrate an average of 24 channels with each channel operating at its rated current level (5-10 amps in this case). The data shows after a brief run-in period, the contact noise levels out and stays below 20 milliohms for the life of the test. This test was stopped at 124 million revolutions with no indication that the contacts were at the "end of life."

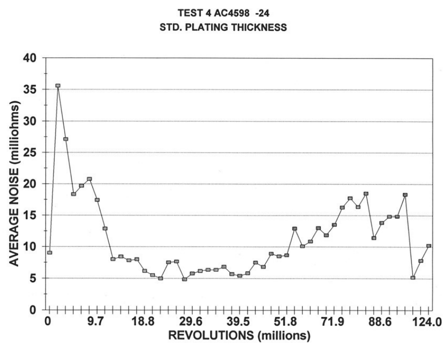

Figure 8: Fiber brush slip ring life test data

All of the contact noise values in this typical test are well below acceptable values in terms of electrical performance of the contacts. The significant point about the contact noise data is that the values are not rising sharply at the end of the test. Contacts near the end of their life typically exhibit a dramatic rise in contact resistance. Contact noise is monitored during life testing since this is the most reliable indicator of slip ring health. Figure 9 illustrates how little wear debris was created during a typical life test, in this case 136 million revolutions.

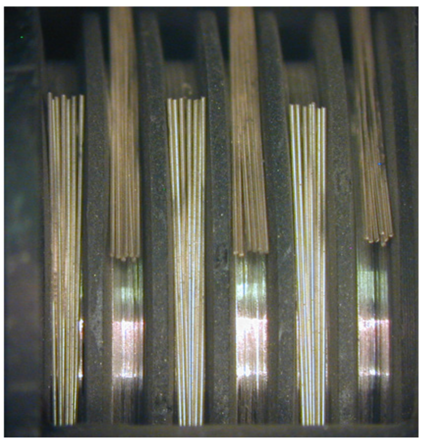

Figure 9: Fiber brush contacts after 136 million revolutions

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One of the advantages of the fiber brush design is that multiple brushes can be "ganged" to provide high current levels, but a single pair of brushes can also provide low noise signal channels. So a wind turbine slip ring can be provided with a single contact material that will handle high power as well as data communication channels. The primary advantage of the fiber brush design is that 100 million revolutions can be achieved in wind turbine blade pitch applications with no maintenance.

Monofilament Metal Brushes

Another design that is used in wind turbine slip ring designs is the monofilament (single) metal brush contacting a metal ring (see Figure 10). These brushes are normally alloys of gold, silver, or other noble metal. The brushes are usually used in pairs to reduce contact resistance variation with rotation, and the ring material is normally noble metal as well, with hard gold or hard silver being the most common. This technology has been in use since about 1950 and was pioneered by Moog for use in instrumentation slip rings. Nobel metals are used to avoid insulating films thereby allowing low brush force. This low brush force results in very low wear and the lack of insulating films produces low contact resistance variation with rotation.

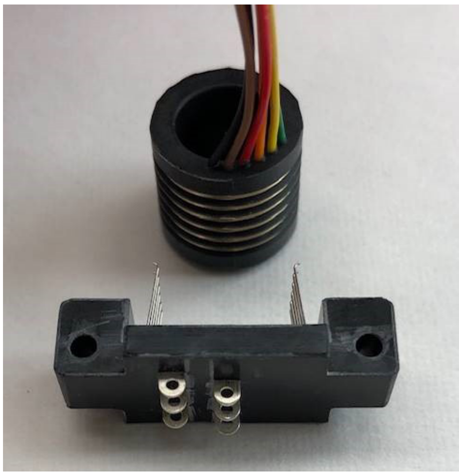

Figure 10: Monofilament brushes and mating rings

Each of these brushes can typically carry up to about one amp, so in order to carry high current loads it is necessary to parallel many brushes on a ring. For this reason it is common the incorporate monofilament brushes in hydrid slip ring designs where graphite metal brushes carry power and monofilament brushes carry data and/or signals. In these cases it is important to isolate the noble metal brushes from the wear debris generated by the graphite metal brushes.

Moog monofilament wire solutions have an expected life of greater than 100 million revolutions with ring cleaning maintenance after the first 5 years (50 million revolutions) and then every 2 years thereafter. The life test data shown in Figure 11 was performed without the 50 million revolution clearning maintenance. Maintenance returns the noise levels to close to "as new" condition.

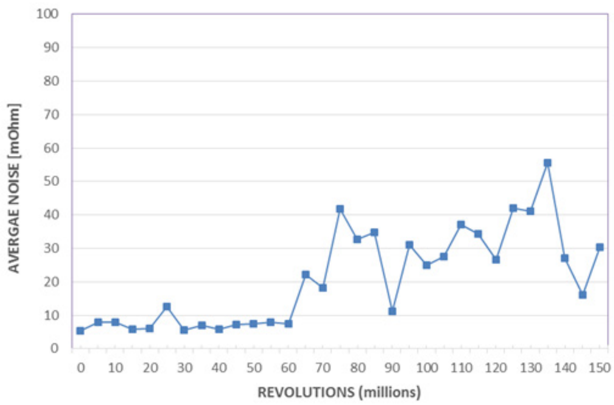

Figure 11: Life test data for monofilament brushes

The Optimal Contact System for Wind Turbine Slip Rings

Wind turbine applications present several challenges for optimal slip ring performance as outlined in Table 1. Historically wind turbine slip rings have been constructed with carbon-based brushes using standard industrial grade materials, and wear debris generation has been a problem causing arcing or short circuits in the power section and high contact noise in the signal section. The carbon brush material developed by Moog is optimized for wind turbine operation and achieves long life and low debris generation and is especially appropriate for high current applications.

Fiber brushes are an ideal solution for low to mid-power as well as signal and data channels. Debris generation is quite low and these brushes can be operated for 100 million revolutions without maintenance. Monofilament brushes can be used in hybrid systems to carry signals and data, but this monofilament design is not very effective with power.

The "optimal" solutions depends on the unique set of requirements for the specific wind turbine—environment, power and data requirements and maintenance schedules to name just a few. The key point to the optimal contact system is the recognition that the contacts must be integrated into a reliable overall system design with proper ring spacing, barrier design, creep paths, structure and bearing design as well as proper inspection and maintenance schedules and procedures. No sliding contact system is inherently more reliable than another — reliability must be designed into the entire slip ring assembly.

Summary

Wind turbine environments present a significant challenge for slip rings. The combination of continuous rotation, long life, and difficult and harsh environments require material and design considerations and selections tailored to these unique requirements.

References

1. The reader is referred to Chapter 22, Sliding Contacts by Dorsey and Glossbrenner and Chapter 23, Metal Fiber Brushes by Dorsey and Kuhlmann-Wilsdorf. An excellent reference book on Electrical Contacts (Paul G. Slade (ed), Electrical Contacts: Principles and Applications. Marcel Dekker AG, Gasel, Switzerland, 2013). These chapters give an excellent introduction to sliding contacts in general.

Figure 1	Slip ring and brush set CAD image provided by Moog.
Figure 2	Contact systems use in wind turbine slip rings provided by Moog.
Figure 3	Legacy Electro-Tec brush and slip ring; photo provided by Moog.
Figure 4	Test data provided by Moog Rekofa.
Figure 5	Photo courtesy Moog Rekofa.
Figure 6	Photo courtesy Moog Rekofa.
Figure 7	Fiber brush photo provided by Moog.
Figure 8	Commercial fiber brush slip ring test data provided by Moog.
Figure 9	Fiber brush photo provided by Moog.
Figure 10	Slip ring and brush set photo provided by Moog.
Figure 11	Life test data provided by Moog Rekofa.

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