

# **Maintenance-free alternatives to brush-based electrical transfer systems capable of increased power handling across a rotary interface**

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Dually-fed inductive generators (DFIGs) used in wind turbine applications today continue to rely on brush slip rings for excitation of the rotor. Slip rings have been identified as the “Achilles Heel” in these applications due to reliability and maintenance concerns. High current transfer to the rotor creates heating at the brush contact which exacerbates wear and requires ongoing cleaning and replacement.

Roll-Rings<sup>®</sup> represent the next-generation in rotary contact technology. Invented by Honeywell and installed on the International Space Station, Roll-Rings pass current across the rotary interface using a rolling, instead of slipping contact. Low contact resistance at the rolling interface affords high power handling without heating and wear, resulting in longer life, smaller size, and lower life-cycle costs. Very low wear at the rotary contact means that field maintenance is not required and the high reliability of Roll-Rings allows operators to avoid down time and unscheduled interruptions.

## **Electrical Transfer Considerations**

Traditional slip rings and brush blocks suffer from wear, which results in the generation of debris as a result of the sliding contact between the rotor conductor and the carbon brushes riding on it. As a result of this wear, and subsequent debris, the overall life-cycle costs of having such a component in a system is greatly increased as a result of the required maintenance schedule. This is, in fact the case for high power generators used in wind applications, where maintenance may be required as frequently as twice a year due to debris generation.

Roll-Rings are an alternative to traditional slip rings. Roll-Rings capture a rolling flexure, shaped like a wedding band, between a rotor and a stator. As the rotor turns, the flexure orbits around the stator similar to a planetary gear, maintaining constant contact. Contrary to the sliding contact employed by slip rings, Roll-Rings are based on this rolling interface which extends the functional life of the unit. Conversely, slip rings produce wear debris, which builds up over time and results in degraded electrical performance. As a result slip rings are unable to provide the high reliability needed in harsh environments and critical applications where access may be difficult and downtime for maintenance cannot be tolerated.

## **Brush Technology**

The task of electrically coupling the rotating and the stationary components of a mechanism may be achieved in a variety of ways. Most common is by the use of slip rings in which a sliding interface is established between the two members. This is provided by a spring loaded conductor which is attached to one member with sufficient compliance as to maintain electrical contact with the other.

The slipping brush contact discussion in this section is given only to illustrate how the design of slip rings differs from that of rolling contacts and is driven by application parameters. Slip rings typically have a circular contact surface which is fabricated from conductive materials such as a variety of alloys of silver or gold. A primary function of the brush is to mechanically contact the

mating surface but not cause the wear rate to be excessive. Excessive wear is not desirable since the generated debris can cause circuit shorting if not eliminated over time.

Contact brushes are primarily of two types. Composite brushes are usually pressed combinations of such materials as Molybdenum disulfide, graphite and silver platelets. This type of brush is primarily used in dry or inert gas environments. Another type is a monofilament brush usually made of various gold alloys. This type of single contact brush requires an organic or similar lubrication of some type at the contact sliding interface. The wear rate of contact brushes is usually a function of transfer current level because of the degrading effect of the electrical transfer power loss which is converted to thermal heating at the contact interface. This power loss at the contact point is the product of the square of transfer current and the contact interface resistance. It directly affects the temperature at the contact and limits the brush to a relatively low power capacity.

It is obvious that many disciplines must be understood and controlled to achieve long and predictable life from slip ring transfer mechanisms. Other factors come into play and need to be dealt with during the design of any slip ring system which can influence operating life. These include materials, interface sliding velocity, atmospheric pressure, humidity and type, contact surface, and radial and axial run out magnitude and rate to name a few.

### **Diamond's Roll-Ring Technology**

Roll-Rings are an alternative to sliding contact which uses rolling interfaces to avoid many of the short comings of traditional slip rings. This rolling electrical transfer technology was initially developed by Sperry Flight Systems in 1975, and further refined by Honeywell in the 1980's and 1990's. More recently, Roll-Rings have been utilized for semiconductor ion implanters, radar systems, inertial gyro test tables and helicopter test stands. The Diamond Roll-Ring technology consists, generically, of a pair of concentric nested coplanar conductive rings which are electrically coupled with a suitable "bridge" member which connects the two rings while orbiting in the space between the ring pair during relative rotation of one of the rings.

As testimony toward the significance of this rolling electrical transfer technology, it was selected to receive Design News "Excellence in Design Competition" at the Sixth Annual Engineering Achievement Award Presentation in 1993 when this technology was developed for use on the International Space Station (ISS). The ISS power and data transfer system is comprised of multiple components which electrically interconnect the solar array power sources with the Command and Control Module. The Beta Gimbal Assembly (BGA) consists of a mast canister which houses the solar array and the Bearing, Motor and Roll-Ring Module which is used to rotate the Solar Array Wings (SAW) and transfer and distribute the DC power. The qualified power level is 35kW (200 ampere steady-state, 5000 ampere surge capacities) per BGA. There are two BGA's and two SAW's. In addition to the BGA's there is a Solar Alpha Rotary Joint (SART) which transfers the 200 kW power as well as low level electrical signals between the rotating side of the BGA to the stationary side. The two BGA Roll-Ring systems went to space November, 2000, and have been operational since January, 2001.

Figure 1 is a photograph of the major component of the Roll-Ring Power and Data Transfer System used on the ISS.

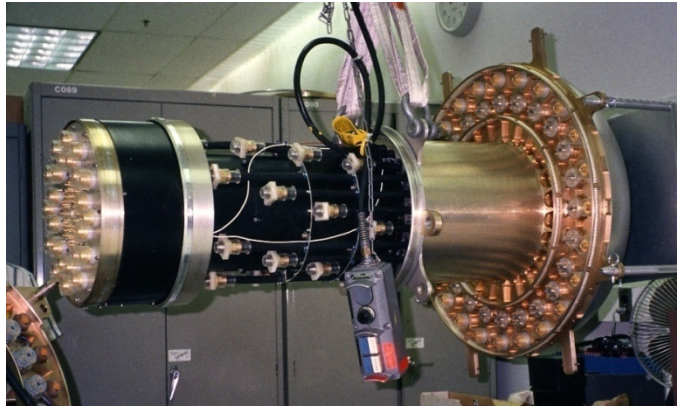


Figure 1: Roll-Ring delivered for use on ISS

Roll-Ring units in various designs have been used to transfer both AC and DC currents from micro-amps to high power, tested to 1 billion revolutions without maintenance and without failure, have handled voltages to 3kV, currents to 200 Amps and rotational speeds to 10,000 RPM. They have application potential for operation in all environments including inert gases and vacuum levels as low as  $10^{-12}$  Torr. Table 1 shows some of the key parameters that have been achieved to date.

Parameter	Value	Comments
Life	1 billion ( $10^9$ ) revolutions	Test terminated prior to failure
Number of Circuits	1 to 120	
Steady State Current Transfer	200 Amps	
Surge Current Transfer	5000 Amps	420x steady state. Can be tailored to each application.
Voltage	3000 VAC	
Data Rate	1553 & Ethernet (up to 2 MHz)	
Dynamic Resistance (Noise)	1 to 20 m $\Omega$ typical	Can be tailored to each application
Rotational Speed	0.001 to 10,000 RPM	
Envelope ID	No ID to 6.5"	
Envelope OD	.38" to 16"	
Axial Length	.5" to 44"	
Mechanical Shock	300 g's peak over 11 ms	
Vibration (sine)	5 g's peak	
Vibration (random)	14.4 g's rms	

Table 1: Key parameters achieved to date by Roll-Rings®

### Important Attributes

Extensive research and development has been expended on a variety of rolling interface configurations and designs since 1975. The rolling interface technology is “new” by comparison to slip rings which have been used in crude to sophisticated configurations for hundreds of years. Two primary ring-to-ring coupling arrangements have been configured to date. The first, which is used in a number of applications, is classified as a “flexure”. It is a well understood and mature component of the rolling transfer technology today. The second uses various configurations of “couplers” to bridge the radial annulus space. Each of these ring coupling arrangements has distinct operational advantages. The features of each will be discussed separately. This discussion includes summary details of each feature which highlights their individual importance.



Figure 2: Functional components of the rolling electrical interface

### **Flexure Interface**

Roll-Rings use flexures to bridge the gap between the two concentric and coplanar rings. Tracks are machined into the facing surfaces of the two concentric electrically conductive rings and flexures are the cylindrical thin wall members which are captured in the grooves fabricated into the ring surfaces. Since the two rings are not perfectly round nor are their two ring track surface centers perfectly concentric, the coupling flexure must have sufficient compliance to bridge the radial gap between the two ring tracks for all rotational positions of the rotating ring at all times. This is required to provide a low absolute, and a low position variant, coupling transfer resistance.

**Continuous Connection** - As the rotor ring rotates within a second stationary ring, the flexure rolls within the radial annulus space between the two. For a clockwise rotation of the rotor, the flexure rotates about its own axis counterclockwise and the flexure center translates clockwise within the annulus space. This makes it obvious that the flexure radial deflection resulting from its compliance must be large enough to accommodate the radial space variation for all positions of the flexure within the annulus space while maintaining contact preload at the interfaces. The flexures do not fulfill the role of a support member but are so designed as to accommodate the annulus space which is established by the primary mechanism support; usually a ball bearing system.

**Capture Tracks** - Precise grooved tracks are machined into the inner cylindrical surface of the outer contact ring and into the outer surface of the inner contact ring. These two grooves are designed to capture the edges of the flexure ring at its outside diameter when the flexure is inserted into the space between the ring grooves. This flexure edge is machined with a transverse radius which mates to the contact ring track. After the flexure has been installed into the ring space it is very stable if the various radii have been selected properly. This will assure not only very high environmental shock and acceleration load resistance capability but acceptable stability at rotational speeds between the two contact rings as high as tens of thousands of rotations per minute. This includes a built-in ability to accommodate a variety of misalignments between the contact rings as will be discussed in the “Alignment” section of this paper. The contact track designs are also important from an operational dynamics consideration as will be discussed in the “Dynamics” section.

**Current Paths** - Each interface of the flexure at each ring track has two contacts which branch into two paths through the flexure. This provides a redundant ring-to-ring current path since each flexure provides two parallel paths through that circuit. The total current through each flexure is, therefore, divided.

**Current Density** - The contact area is larger than that of a similar sized brush wire-on-cylindrical slipping contact. Existing relay (make-break) contact designs are based on current densities as high as  $10^6$  amperes/in<sup>2</sup>. Standard rolling interface contacts are designed so that even with continuous contact, the current density is minimized, allowing for a wider margin of safety. Power transfer systems have been to surge currents as high as 5 million amperes/in<sup>2</sup> but are typically designed to

only handle one-tenth of that power. The standard rolling interface is designed so that it can handle three times the current densities which have been established by steady-state and surge current tests. Current density tests have included both ESCA (Electron Spectroscopy for Chemical Analysis) and EDEX (Electron Dispersion for Elemental Examination) inspection for carbon and burn through by using 300x optical evaluation, and have confirmed the capacity of the rolling interface.

**Contact Resistance** - Of primary importance in the design of an electrical connecting member is the effective path resistance. This not only is important from the standpoint of circuit function considerations but also by reason of its thermal effect. Resistance along the path of a transfer assembly is converted to heat loss as the square of the transfer current. One important parameter to be considered for the rolling interface transfer units is the consistent and very low contact resistance at each ring track. The  $I^2 R$  heat loss at these contacts is also very low which eliminates the current related degradation of life associated with composite slipping contact interfaces.

**Interface Conformity Ratio** - The rolling interfaces of Roll-Ring components are designed to have an optimum conformity ratio which is suitable for anticipated contact ring and flexure anomalies while providing low and acceptable contact pressures. These relationships have been developed by carefully executed testing of design perturbations in rolling interface assemblies.

**Contact Pressure** - The flexure contact pressure at each interface is designed to be lower than that of a typical slipping contact while at the same time having greater normal preload forces at the contact zones. This results in a positive contact without imposing undesirable wear and drag torque levels. These rolling contacts do not have “run-in” characteristics because of the more precise interface geometry. In addition, it is noted that the contact area does not increase with time nor is it related to radial contact preload level. This quality results in more rapid assembly and electrical check-out abilities, especially as compared to typical brush sets. Typical slipping transfer systems require long run-in periods and sometimes require a clean and reset of preload during this longer run-in mode.

**Fatigue** - The bending stress levels of the flexure wall is an important design parameter. As the flexure rolls in the annulus space between the grooves of the rings the entire circumferential wall is subjected to reversing bending cycles. The design of the flexure must consider the magnitude of the bending stress in the wall as it relates to anticipated operational life. Fatigue life must be controlled by establishing a safe magnitude of both the number and the stress level of the bending cycles. The maximum bending tensile stress occurs at the inside surface at the contact region of the flexure and is a traveling point in the flexure as it rotates. Fabrication processes of the flexure have been established to assure that the completed part meets a stringent set of dimensional parameters. The design of the flexure also considers the fabrication procedures and regimen of heat treat and cold working processes to validate the required physical properties of the material.

**Transfer Efficiency** - The contact resistance at the gold-gold rolling interfaces is typically in the range of 50 micro-ohms. Additionally, the parallel circuit paths through the dual contacts at the rings, and those through the flexure, result in lower path resistance than are achievable with typical slipping contacts. The rolling interface design offers the ability of adding flexures or other coupling elements in parallel through each ring set. The net result is high transfer efficiency as defined by the effective heating loss to total transfer energy ratio. Life testing of an eight circuit rolling electrical transfer unit at the NASA Lewis Research Center in 1988 demonstrated 16 Watt dissipation (loss) while transferring 100,000 Watts. This represents a transfer efficiency of 99.866%.

**Heat Transfer** - Since the electrical contact interfaces travel in the mass of the flexure as it rotates, the heat transfer is enhanced. Additionally, since the flexure is mechanically connected to both contact rings, the heat transfer path is enhanced. The heat transfer from the flexure into both relatively large ring heat sinks results in more efficient thermal smoothing of the total mechanism. This is true for even mechanically static electrical operation.

**Rolling Dynamics** - The selection of contact angle, as defined by the skew of the contact line through the center of the ring groove transverse radius center and the plane of the flexure, is a critical parameter which has been selected from many tests and design perturbations. Both the stability and the ability to define proper radial load levels are dependent upon this choice. Once established, the dynamic qualities of the rolling interface are assured even over wide speed ranges. The inter-relationship of several design parameters are understood which assures obtaining predictable performance.

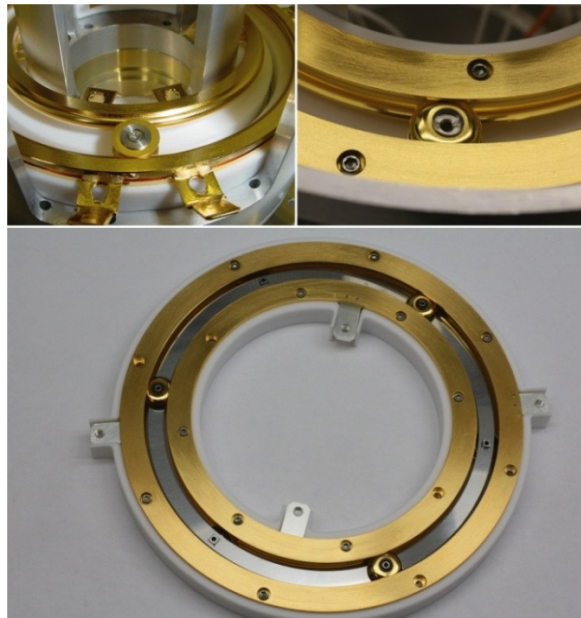
**Interface Mechanisms** - The contact interfaces are characterized as micro sliding which is similar to the Heathcote slip of a conventional ball bearing. This occurs because the planetary ratios of the flexure centroid, as determined by the radial diameter of the ring track radii at the extremities of the small flexure contact area, are slightly different. As compared to slipping contact sliding velocity, that of a Roll-Ring is negligible. This is one of the most significant advantages since the elimination of the sliding contacts results in greatly reduced wear debris. One operating quality which gives testimony to that fact is the greatly reduced rotational torque of rolling systems as compared to slip ring systems. The torque ratio between the two is  $> 200:1$  for a comparable system. The lower transfer torque level of the Roll-Ring system represents reduced drag energy which translates as reduced wear. Further evidence of the importance of low sliding velocities at the contact interfaces is the fact that gold interfaces of rolling contact systems do not require organic lubrication. The ISS system discussed previously does not use any lubricant for its power and its signal rolling transfer units and is presently operational after greater than eight years in the hard vacuum of the space environment. Lubrication of some type is essential for slipping contact power transfer.

**Misalignment Compensation** - In any rotating mechanism, it is not possible to totally avoid radial, angular and axial misalignments between the fixed and the rotating axes. In addition, these misalignments include both initial, time variant and environmental terms. An ideal solution to this potential difficulty is to desensitize the mechanism to the influence of these anomalies for a reasonable level of imperfection which is easily established. The Diamond rolling interface transfer unit designs utilize simple geometry to provide this decoupling from the effects of misalignment. By selecting the contact ring and flexure track radii center locations and magnitudes, the rolling flexure has built-in freedom to automatically adjust position to equalize the contact loads at all times. As one example, a typical rolling interface design can accommodate as much as  $\pm 0.1$  inch of ring to ring axial misalignment without disturbing the two normal contact points. In a similar manner, skew of the two contact ring axes is also compensated.

**Increased Capacity** - The configuration of the rolling interface units allows for design flexibility for such things as increased current transfer capacity in small space. One means for achieving this is to configure the design to use several flexures within a single ring annulus space. These designs require that the flexures are maintained in circumferential spacing.

## Coupler Interface

The second important circuit interface used in the family of rolling electrical connectors is that provided by couplers. These coupler assemblies mechanically and electrically bridge the radial annulus space between nested concentric coplanar outer and inner contact rings maintaining positive electrical contact between the two. This function is similar to that of the flexure components described earlier in this paper with the exception that the coupler halves maintain contact with the ring surfaces. This contact occurs by reason of their axial position adjustments as the annulus radial space changes as one ring rotates with respect to the other due to imperfect geometry between the two rings. The coupler consists of either a pair of conductive concentric adjoined disk shaped members or a number of single disk shaped members located circumferentially around the annulus space which, after assembly with the contact rings, are forcibly captured with track adapted outer surfaces and a controllable axial force arrangement. The rotational axis of the coupler assembly lies parallel to the symmetry axis of the contact rings and operationally rotates about its own axis while orbiting about the ring axes. The axial loads are applied by a variety of means. This loading is applied in a manner which forces the coupling members into rolling contact with the ring tracks which approximate grooves for the case where the coupler pairs are pushed apart, or rails for the case where they're pulled together.



*Figure 3: Rail-style individual coupler (upper left), Groove-style individual coupler (upper right) & offset caged coupler-halves(bottom)*

The selection of flexure versus coupler bridge member designs is based upon many factors. For instance, couplers are basically better suited for power transfer in a small volume. The  $I^2R$  heat loss in the coupler can be minimized by designing the disks with sufficient cross section to achieve very low path resistance between the ring contact points. This can be difficult to achieve using flexures since the wall thickness must not only satisfy the electrical path resistance but must also achieve a desired radial stiffness/stress goal to meet a desired fatigue life requirement. This separation of mechanical and electrical properties in the coupler design brings significant design advantages. Another advantage the coupler bridge configuration offers is an ability to accommodate a wider range of adjustment for radial annulus path perturbation.

There are no significant fatigue considerations to design for coupler bridge members. This is true since the annulus radial gap perturbations are accommodated by disk axial movements at less than rotating member rotational speed (orbit rate) instead of multiples of that speed (flexure rotation rate)

and because the fatigue member for a flexure is the flexure wall and that of a coupler is the secondary preload spring. Additionally, the perturbation stress level of a coupler preload spring can be designed to be a small percentage of the preload stress.

***Additional Attributes*** - All of the attributes listed for the flexure interface member are applicable for the coupler. In addition, the following is true:

***Current Paths (Coupler)*** - Each coupler disk member makes contact with the curved edges of the two respective rings. The contact resistance is typically in the micro-ohm range. The path through the coupler half is designed to be very low by way of the design freedom to increase the wall thickness as required with no restraints to accommodate a specified compliance. The result is that the total path resistance can be made quite low to minimize  $I^2R$  heat loss. Inserting multiple coupler disks in the same ring pair allows one to obtain further reductions of effective circuit path resistance and associated transfer efficiency.

***Interface Conformity Ratio of Couplers*** - The design flexibility to achieve optimum conformity ratio when designing coupler bridge members is enhanced because of the available thicker walls on the coupler halves.

***Heat Transfer of Couplers*** - The attributes of the flexure are also attributable to couplers with the added advantage that the thicker walls of the coupler halves and the associated reduction of path resistance provide additional heat transfer advantages.

***Increased Capacity of Couplers*** - The thicker walls of the coupler lend themselves to reduced transfer resistance and associated increased current capacity.

## **Summary**

Roll-Rings<sup>®</sup> represent the next-generation in rotary contact technology. Invented by Honeywell and installed on the International Space Station, Roll-Rings pass current across the rotary interface using a rolling, instead of slipping contact. Low contact resistance at the rolling interface affords high power handling without heating and wear, resulting in longer life, smaller size, and lower life-cycle costs. Very low wear at the rotary contact eliminates field maintenance and the high reliability of Roll-Rings allows operators to avoid down time and unscheduled interruptions.