SHAFT RIDING BRUSHES TO CONTROL ELECTRIC STRAY CURRENTS

by

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Mr. Sohre worked in mechanical design of turbocompressors at the Elliott Company, Jeannette, Pennsylvania, for eight years. He served as Section Head and was responsible for all mechanical design and analysis of turbines, compressors, and other mechanical products.

Mr. Sohre then worked for Terry Steam Turbine Company, as Chief Development Engineer. He designed new lines of large, high speed, high performance mechanical drive turbines.

Since 1970, he has been a Turbomachinery Consultant specializing in design, installation and problem correction, working with many major firms in the petroleum, petrochemical, and power-generating industries.

He established Sohre Turbomachinery (1978), and is engaged in development, production, and marketing of shaft riding brushes and methods to control shaft currents. His various activities involve about 80 percent export, to about 35 countries.

Mr. Sohre has published about 100 papers, books, and lectures worldwide, in several languages. He holds 13 patents, domestic and foreign, on power-generation machinery. Mr. Sohre presented the first paper, at the first Turbomachinery Symposium, October 24, 1972, at 8:45 a.m. ("Turbomachinery Analysis and Protection"). The troubleshooting charts and reliability curves presented at that meeting are still widely used and have become the basis for several "expert system" computer programs. Mr. Sohre is a member of ASME and is a registered Professional Engineer.

ABSTRACT

Electric discharge causing bearing and seal damage may occur in any nonelectric machine as a result of static electricity, accidental electromagnetic self excitation of casings, rotors, piping, foundations, galvanic effects, faulty grounding, etc. [1]. In addition, electric machines may develop very high shaft currents (order of 100 amp in large generators) because of inherent electrical characteristics.

Shaft riding brushes can help detect problems and neutralize the currents by shaft grounding. Conventional brushes (carbon, graphite, solid metals, braids, and combinations thereof) have proved to be unreliable. They also develop excessive amounts of conducting dust, require frequent maintenance (cleaning, replacement), and it may be necessary to shut the unit down for servicing. Other problems include intolerance to oil, water, dirt, other types of environmental contamination, and high surface velocity, and high or low temperature. Some brushes require special slip rings.

The development, testing, and application of a patented line of wire-bristle brushes is described along with their electrical characteristics, life expectancy, specification parameters, maintenance and maintainability, etc. Design features, and over 12 years of field experience, especially with turbomachinery and for ship propeller-shaft grounding, are also described.

Results of an ongoing three year comparative test program (laboratory and operational) by a major user are described. Hardware will be available for inspection at presentation of paper.

INTRODUCTION

General

Shaft current (stray current) problems far more severe than the long known electrostatic and mild electromagnetic problems were encountered in troubleshooting work in 1971. Because of extensive use of arc welding, magnetic particle testing, and other techniques leaving strong residual magnetic fields, an epidemic of severe shaft current problems caused significant operating losses to the process and power industries. The current generation process may also be initiated by mechanical shock or vibration, or by a faulty grounding system. Reliable and suitable shaft brushes or demagnetization procedures were not available at that time; therefore, it became necessary to deal with these problems, both in theory, a number of publications were presented [1, 2, 3], and by developing and supplying suitable shaft brushes for turbomachinery applications, such as steam and gas turbines, gears, motors, generators, turbocompressors, ship propulsion trains (including propeller shaft grounding), and jet engines. The purpose of these brushes is to assist in bringing shaft current problems under control, especially where conventional brushes will not function.

The Problem

Shaft currents may be of electrostatic or electromagnetic origin (because of residual magnetism), and they can cause severe damage to bearings, shafts, seals, gears, etc. The application of brushes can help monitor the current generation and provide warning of dangerous current buildup (for example, self magnetization and self excitation). Residual electromagnetic currents of reasonable strength can be grounded by means of the brush, to protect the machinery against damage. If strong electromagnetic currents occur, the machine must be demagnetized. Electrostatic currents can always be grounded through a brush.

Large turbine generator units with static excitation systems require grounding of electrically excited shaft currents in the 100 amp range, to maintain safe, low residual shaft voltages. Conventional solid brushes or metal braids are unreliable, short lived, and require frequent maintenance (replacement, cleaning), which may require unit shutdown and/or present hazardous conditions.

Ship propeller shafts may also require high-amp grounding, to obtain very low residual shaft voltage, which solid brushes or metal braids cannot reliably provide.

Brush Types

Two basic brush types have been developed which are manufactured and stocked in various sizes and lengths to meet applications (Figure 1).

"Toothbrush" types: Best suited for tangential contact

• "LW" (large, wide). For high-current applications, to approximately 100 amperes, at extremely low contact resistance and having a long life expectancy (at least one year). They are used to ground ship propeller shafts (galvanic currents) and turbine generator rotor shafts (electrically induced).

• "L" (large). For use in the larger frames of turbomachines in process industries, such as air and gas compressors and turbines, pumps, motors. They are for static, magnetic, or groundfault induced stray currents.

• "S" (small). As previously described, but for the small, very high speed turbomachines in process plants, where space is extremely limited.

"Plunger" type:

• "A" (axial). Especially suited for axial installation against a shaft end or collar. For field retrofit, this is often the only accessible location, especially if the brush is to be installed in the endplate of the bearing case while the machine is operating. However, this medium size brush is also well suited for radial shaft contact.

All types can be mounted to ride on a shaft tangentially, radially, or axially, or skewed in any position with respect to rotation, including upside-down (for example against the bottom of the shaft). All types are available in varying standard lengths, to suit mounting conditions. Presently, the shortest assembly is six inches long, the longest is 20.0 in. The brush element is 0.6 in wide for "L," "S," and "A." The "LW" is 2.0 in wide.

Installation and Operation

Brushes are typically installed on turbomachinery in chemical or petrochemical plants, power plants, ships, offshore platforms, hydroelectric plants, etc. The operating environment is often hostile, and/or hazardous. Failure of the brush to function even for a few hours can result in severe damage to the machinery and consequent extended plant shutdown. Almost 1000 brushes are in operation (1991) in 36 countries, throughout the world. Basic brush features are shown in Figure 1.

PRINCIPLES OF ELECTROMAGNETIC INDUCTION

A Brief Memory Refresher

Figures 2, 3, 4, 5, 6 are essentially self explanatory.

Simple Motion of Electric Conductor in a Magnetic Field (Figure 2)

Any conductor moving relative to a magnetic field so as to intersect the field lines will generate a voltage across the conductor. If an electrical connection is made across the ends, a current will flow. Reversal of motion will reverse polarity. Velocity of motion, strength of field, and length of interacting components (immersion) will determine voltage and current.

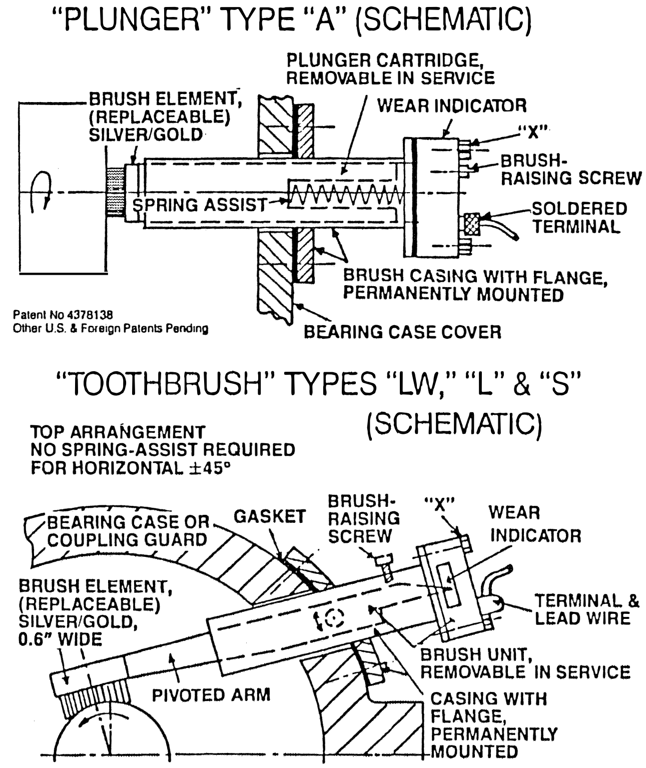

Figure 1. Summary of Basic Requirements of Shaft Brushes for Turbomachinery Applications (Typical). This applies to all shaft brushes, regardless of type. Models shown for illustration are of a patented line of metal fiber, bristle type brushes. Requirements: · to remove electricity from shafts of electrical or nonelectric machines; · must be fully self-sufficient and self-cleaning (shaft and brush); · accessible from outside for continuous wear observation and for inspection of brush element during machine operation; · no adjustments and calibrations to be required. Features of brushes shown: · for all types of shaft currents, no slip rings required; large and small sizes; special designs; · working parts removable during operation without risk of contacting adjacent moving parts, (remove screws at "X" to pull entire brush assembly out of brush casing; · wear and position indicator visible form outside of machine, wear alarm available; · brush voltage is insulated from casing, allowing voltage and current monitoring, and selective grounding; · provision to raise brush from shaft during operation, to inactivate if contact is not desired, and to allow measurements at other locations; · bristle type brush element, made of silver and gold composite, replaceable during operation, currents to 100A, extremely low, adjustable resistance; · Inert gas purge, or oil injection, optional; · operates dry or in oil spray, oil splash (preferred), or oil immersion; · shaft surface velocity: in operation to approximately 500 ft/sec (150 m/sec); · life expectancy of replaceable element: at least one year, no cleaning, adjustment, maintenance; no deterioration of contact characteristics (shaft filming); · minimum axial shaft space required; approximately 0.75 in; · suitable for temperatures to at least 400F; · oil and gas tight assembly; · nonmagnetic construction; · meets API standard 612; · also suitable for transmission of instrument signals from the rotor without need of special slip rings; this allows continuous monitoring of vibration, torque, etc., during normal field operation.

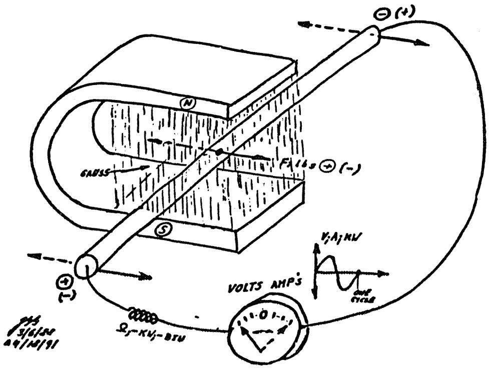

Figure 2. Simple Motion of Electric Conductor in a Magnetic Field. Conductor moving in magnetic field. A simple, moving wire and permanent "horseshoe" magnet are shown. This is the most basic configuration possible. All others are elaborations. Important: in the case of stray currents within a nonelectric machine, there are no defined wires and magnets, but rather conducting paths and accidentally magnetized zones within the solid structures of rotors, casings, piping, etc., which interact with each other as rotation provides the necessary motion. Self excitation occurs as these electrical paths and magnetized zones arrange themselves so as to generate maximum electricity, sometimes thousands of amperes (Figure 6). This is called "self induction."

Basic Alternating Current Generator (Figure 3)

Instead of transverse motion, the conductor is now rotating. Electricity is removed from the shaft by sliding contact "brushes" (the very early machines actually used wire-filament brushes, and the name has persisted, even though modern machines use solid blocks made of carbon, graphite, metals, etc.).

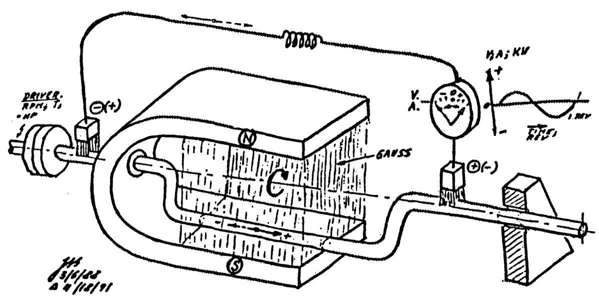

Figure 3. Basic Alternating Current Generator. Shows how the motion of the conductor within the magnetic field (Gauss) can be obtained by continuous rotation. Brushes conduct electricity from the shaft surface to a load (resistor at top.) A meter indicates current (amperes), or voltage (volts), or power (watt). Because magnet polarity reverses from top ("North", or "positive") to bottom ("South," "negative"), the current reverses direction twice per revolution (frequency, Hertz).

As the wire turns from bottom (south pole) to the top (north pole), voltage polarity, and thereby direction of current, reverse, an "alternating current" (AC).

Basic Direct Current Generator,
Permanent Magnet (Figure 4)

The shaft now has two loops. Current will still reverse as before, but the brushes now contact top and bottom of the shaft, which are insulated from each other, at the brush end only. The top brush will, therefore, always see a zero to (+) voltage, the bottom zero to (–). Zero occurs at the horizontal position. There will still be two half-sine waves per revolution, but of the same polarity—"direct current." The insulated split shaft under the brushes is the "collector." In an actual machine, a large number of such "windings" are used, each pair being connected to its individual collector piece, forming a "collector ring." The voltage and current now have a number of peaks per revolution of 2 × number of loops, per revolution. Zero voltage will no longer occur because the waves overlap.

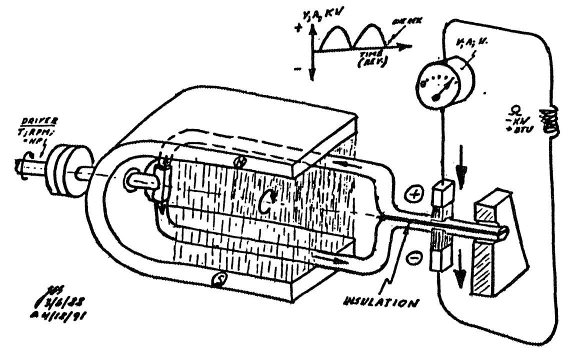

Figure 4. Basic Direct Current Generator, Permanent Magnet. Here is how the polarity reversal can be eliminated, generating a current which always flows in the same direction (direct current). Same as with a battery, but still having two nonreversing cycles (top diagram) of current, voltage and power. It is done by splitting the shaft under the brushes, inserting electrical insulation (a commutator.) The more loops, or "windings", the smoother the current. As with all illustrations in this series (2 to 6), only the absolutely essential components are shown (except for the gauge). The machine is driven from the left side, the driver supplying the mechanical power (torque and horsepower) as required to generate the rpm, and thereby, the desired electrical power at the brush connections (V; A; W).

Basic Direct Current Generator,
Electromagnet, Series Wound, Self Excited (Figure 5)

The action is the same as in the previous cases; however, an electromagnet has been substituted for the simple (and weak) permanent magnet. With the series-wound arrangement shown, current flowing through the magnet coil will cause a magnetic field in the iron core. Strength of field is a function of current, and current being generated in the rotating wire is a function of magnetic field. So, starting from standstill, only a very small residual field will be left in the iron core of the magnet, but as the rotor starts turning, the machine "self excites" itself very suddenly (a fraction of a revolution). IMPORTANT: The ultimate limit of the excitation (amps) occurs when the iron core material reaches "magnetic saturation."

Self Excitation

If, at the start, the iron core is completely free of magnetism (new machine), the self excitation can be initiated by a mechanical shock to the short circuited, spinning (handcranked) machine the experienced mechanic will first of all give the generator a sound kick with his boot. More refined individuals use a soft mallet. It depends on generator size, of course (the author's experience comes from repairing 500 V DC streetcar motor/generators). However, the polarity could come out wrong. Aligning the ma-

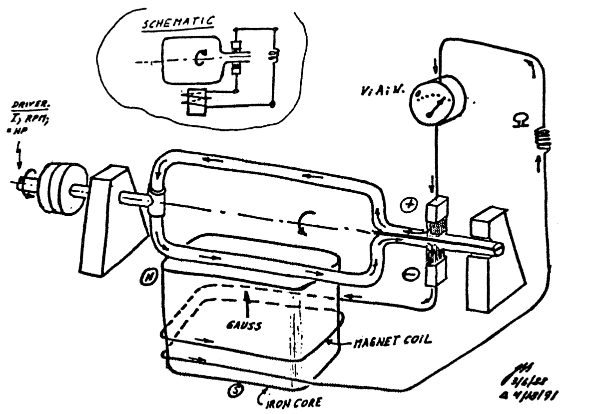

Figure 5. Basic Direct Current Generator, Electromagnet, Series Wound, Self Excited. The permanent (horseshoe) magnet is replaced by an electromagnet, which develops a magnetic field only when a wire coil ("winding") around it is energized by sending electric current through it. Otherwise, the action is as shown in Figure 4. The current for the magnet coil could come, for example, from a battery. In this case, the current is generated in the rotor windings, by rotating them through the magnetic field. A very small residual magnetism in the core is sufficient to get the "self excitation" started. The small field generates a small electric flow, which is routed through the magnet coil, amplifying the current, and so on, until magnetic saturation is reached. This figure illustrates the self excitation and self magnetization we see in the rotor and stator metal of nonelectric machines. The current can whip itself up to tremendous strength, destroying a machine by literally melting down critical components, such as bearings. More often, the unit can be shut down in time to prevent the final phase. The schematic diagram on top shows the electrical hookup. the magnet coil with its soft iron core is at the bottom.

chine with the earth's magnetic field before giving it a blow will usually take care of this. Otherwise, a car battery must be briefly connected to the coil.

Here is how this shock therapy works: Each atom of a magnetizable material has a north-south magnetic field about which the neutrons rotate, similar to the earth's magnetic poles. In the demagnetized condition, all these fields are at random, and the component itself has no external field. If an external field is applied, all these quadrillions of little magnets will feel the pull, but they may not want to come about. The mechanical shock prompts them to do so. The earth's magnetic field and a shock are strong enough to do it. To demonstrate this, take a steel rod, hold it magnetic north-south, and tap it with a piece of non magnetic material. It will become magnetic. To demagnetize, reversing fields are applied, at diminishing strength, to scramble the little atomic fields.

The preceding points are extremely important to the understanding of self induced electromagnetic shaft currents in nonelectric machines (turbines and compressors); also, of course, in electrical machines.

Magnetization/Demagnetization

Even a nonelectric machine has all the ingredients to make electricity: Electrically conducting, magnetizable materials (rotor, stator, piping, foundation), high speed rotation, and close clearances to provide efficient self excitation.

Without residual magnetism, the compressor train can run forever like this, never generating current. But magnetizing any part of the machine and/or its surroundings can cause all hell to break loose. Arc welding, magnetic tools, magnetically inspected parts—even lifting magnets used for the raw material will do it. The machine need not be running to get magnetized, although this would make it very much worse. A shock to the running machine can also set it off. Typical are internal rotor-to-stator rubs, bearing failures, all kinds of vibration, pile driving in vicinity, lightning strikes nearby, and so on.

If the magnetization and generation is not detected at an early stage—(by means of shaft current measurements), self excitation (Figure 5) can build up. The worst scenario is rapid buildup toward magnetic saturation. Short-circuited generation of up to 30 percent of rated horsepower has been observed. Parts weld together. The machine destroys itself ("meltdown") See [1, 2, 3]. The author has been personally involved investigating about a dozen such cases.

Actual magnetic and current patterns within nonelectric machines are much more complicated, and they vary with each case, and even within a given machine. There are no magnets, coils or armature wiring, nor any defined conductors at all. The self magnetization amplifies itself from residual magnetism as the machine runs. Unfortunately, the patterns of magnetism and current arrange themselves in such a way (within the solid steel of rotor and stator) that maximum current is generated, causing short circuited "self excitation." One version is shown in Figure 6.

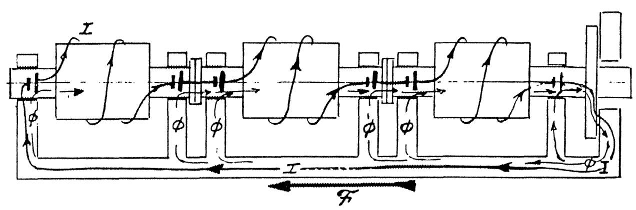

Figure 6. Inductive Effect of Self Generated Current [1].

In electrical machines, these self induced currents also occur, along with electrical problems, and cause severe damage, especially in very large generating units.

Eddy-Current Generator (Brake) (Figure 7)

This is the old standby, physics lab, eddy current apparatus, usually a thin disk rotating between the poles of a magnet. This type of generation will occur within any rotating machine which has magnetic fields crossing stator-to-rotor and vice versa. The good news is that generation can be stable. Self excitation cannot occur unless there is a shock and the self induction previously described is initiated. Currents can still be destructive. There will be heating in the affected areas, and power consumption could be significant. Whether or not the currents will go across bearings and other sensitive components depends on individual circumstances. If so, grounding brushes will be effective to prevent damage, and more important, allow measurements, to protect against slow or sudden self induction.

Very little is known about these things. But they do occur, and something can be done about it with relatively simple and inexpensive means.

TYPES OF BRUSHES FOR CONTROL OF SELF INDUCED SHAFT CURRENTS

General

Electromagnetic stray currents cannot be grounded or controlled by devices similar to the brushes used in electrical machinery, such as motors and generators, because:

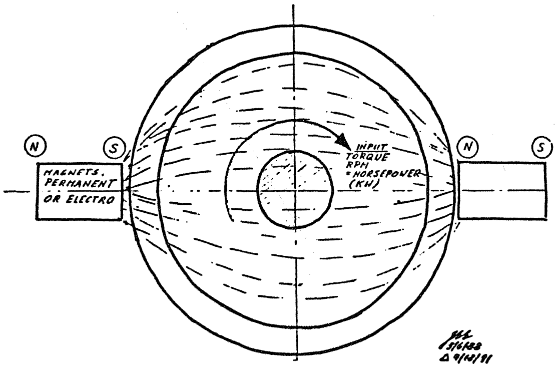

Figure 7. Eddy Current Generator (Brake). Here is an example how stray currents are generated in a ring by simply rotating it close to a magnet. No copper, wires, coils, windings required. This effect is found in any magnetized rotating equipment. It can destroy components slowly, but it also is the initiating mechanism for self excitation (Figure 5).

• The stray currents are unpredictable, since there are no copper leads, slip-rings, predictable sources of magnetization, excitation, current flow, and so on. Of all the thousands of shaft current problems, not two are exactly alike.

• Bearings, seals, gears, and so on, can suffer severe spark damage when shaft voltages and/or spikes of voltage exceed a few volts (say, one to six volts). This means that a shaft brush must be able to ground these currents with a shaft-to-ground voltage of, generally, less than one volt peak. This requires that the permissible resistance between the shaft and the brush element should not be more than a few milliohms.

• Brushes used in standard electrical machinery are mostly of the solid-block type (carbon, graphite, metal impregnated, like silver-graphite, etc.). These brushes are designed to carry a predetermined current across the sliding interface with a given, acceptable voltage-drop, which is much higher than the few millivolts acceptable for stray current removal. The higher resistance is acceptable for electrical machines because all electrical components (brush, slip-ring, windings of the machine) are insulated from the rotor and stator. Also, such brushes are designed for the expected current and voltage, and they do not function well (or at all) under conditions above or below design. Another requirement is a brush operating temperature which is suitable for the given conditions.

A film forms on the sliding surfaces. This is desirable for the operating conditions of electrical machines, but is highly detrimental for stray current removal, because it will prevent a brush from making electrical contact with the shaft—the brush simply stops working after some current has initially been transmitted and the film has formed.

• The environmental conditions in plants other than power plants can be highly detrimental to good brush operation. In process plants, there may be highly corrosive environments, abrasives in the air, atmospheric effects, very high sliding velocities (500 ft/sec and more), oil mist, oil splash, oil submergence, and/or high operating temperature near the brush element, or on the outside of the brush. There is usually no slip-ring; the brush must run directly on the steel shaft (without causing damage to it). There are many more factors involved.

Description of Various Brush Element Types And Their Characteristics (Figures 8, 9, 10)

• Solid block: The material may be carbon, graphite, metal impregnated, etc. The problems include loss of electrical contact due to filming, as explained previously. In order to make a solid-block brush operable, frequent cleaning of the shaft and brush surfaces is required, to at least get temporarily acceptable operation. However, sometimes a brush which has stopped transmitting current can be temporarily reactivated by tapping the brush, which may cause the contact to break through the film. Typically, a brush may stop working after two hours under certain current conditions. If tapped, it may work another two hours. One plant was kept operating by having the brush tapped every two hours, for nine months. In this manner, it was possible to bring the plant to a scheduled shutdown for the first time in its seven year life.

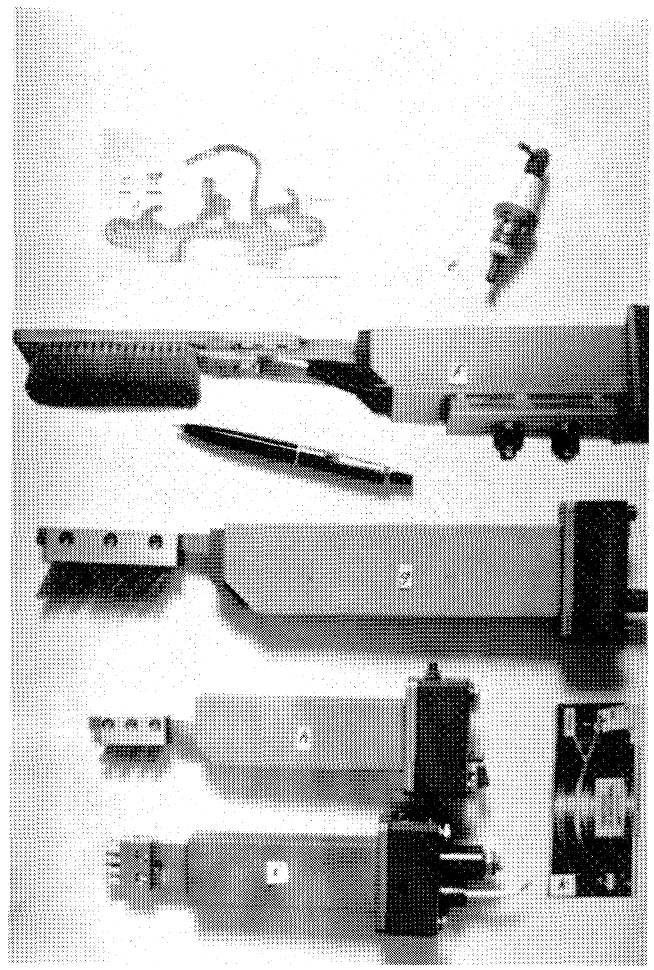

Figure 8. Brush Elements, Various Types, Side Views. Note: all brushes in Figures 8, 9, and 11 are to same scale, except as noted. a) small commutator brush from electric tool, carbon; very often used at shaft ends of turbines and compressors; ineffective for grounding stray currents; b) medium size, carbon, electric motor; same comments as above; c, d) graphite and metal impregnated brushes; fairly large; slip ring or commutator trains, but common to ground stray currents on large generators, running directly on shaft; ineffective; requires frequent cleaning of shaft and brush replacement; very dusty; e) "sparkplug" type grounding brush; element is packed, stranded copper wire in brass tube; used to run axially against shaft ends, near center; ineffective; loses contact and/or rapid wear; very small element, about 1/4 in diameter 5/8 in long; f) metal fiber (silver and gold) grounding brush for very high currents (to 100 A) at extremely low contact voltage drop (5-10 mv); designed to ground stray currents of large turbine generator rotors, ship propeller shafts, etc.; see Figure 1 for features, Figure

10 for performance characteristics of this type of brush; these features apply also to brushes g, h, and i; g) similar to f but smaller; for the larger, slower high speed compressor types (refinery and chemical plant air compressors, etc.); h) as above, but for smaller, very high speed machines where g cannot be fitted in because of space limitations; i) plunger type (see Figure 1), otherwise features are same as f, g, and h; can be fitted to ride axially against shaft end as well as on shaft diameter; this type is especially well suited for in operation retrofit; k) woven copper braid; unreliable contact (Figure 10); clogs up with debris; tendency to rupture; requires frequent maintenance.

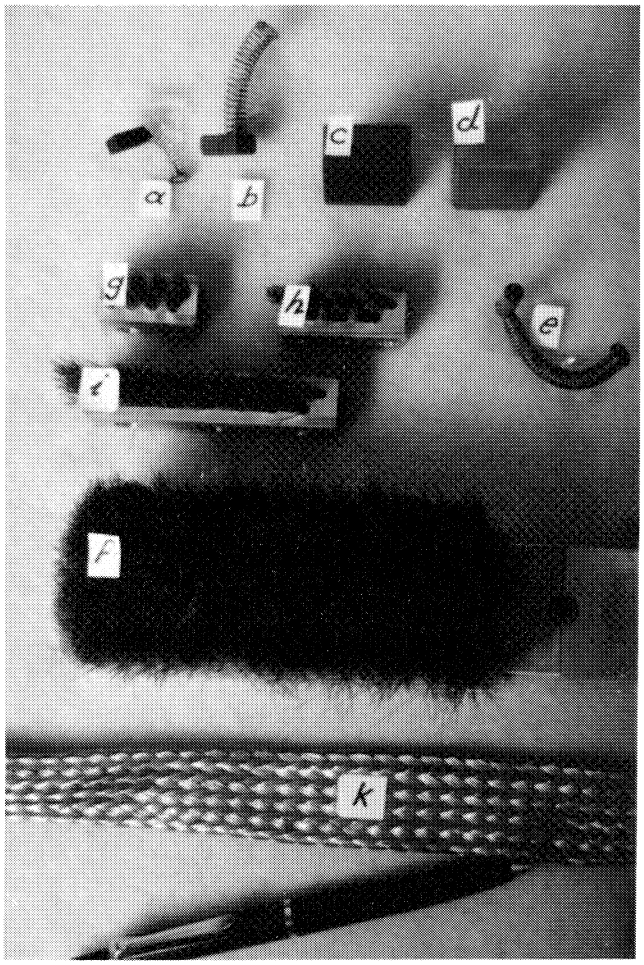

Figure 9. Contact Surfaces of Brushes Shown in Figure 8. Views of contact surfaces of brushes a-k; scale is same for all specimens.

Other factors include the requirement for frequent replacement of block-type brushes. Also, because of the relatively high rate of wear, conducting carbon dust spreads into the machinery and surroundings. Advantage of block-type brushes: Low price of original equipment and of replacement material. Conclusion: Brushes of this type are not suitable for stray current control.

• Solid metal or packed wire type: "spark plug type." Essentially a solid rod (often copper) of tightly packed wire strands in a brass tube. Problems include filming, high contact resistance and ultimately loss of contact if exposed to stray currents, as explained earlier. Note that any brush will have a low contact resistance to the shaft if no currents are transmitted, but will fail as soon as currents begin to flow. This often gives people a false sense of security if they measure the resistance and find it to be low, but then the brush fails to function when it is required to do so. These brushes are not suitable for high surface velocity, operation in oil, aggressive environment, and have a high wear rate at relatively low current load. Advantages: Low cost of original equipment and of replacement material.

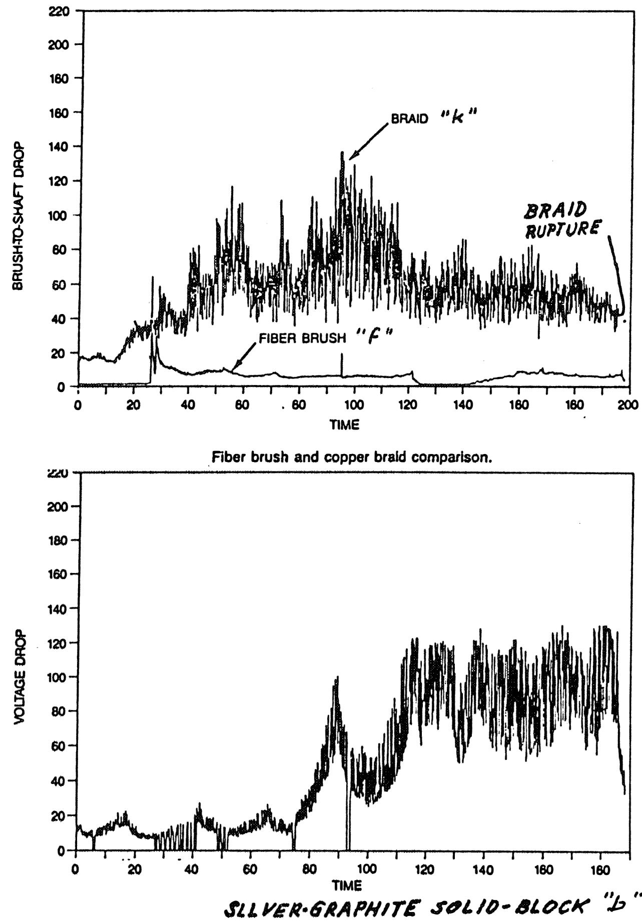

Figure 10. Voltage Drop Across Contact Surfaces of Several Types of Brushes, vs Time. Comparative performance test results (at 100 amperes DC) for braid k, fiber brush f, and silver graphite brushes d (six brushes in contact simultaneously); note the very high contact resistance of k and d and, especially, the very large "hash" component (AC); the spike off f at time 23 was caused by accidental shaft surface contamination; wear life expectancy of replaceable insert f was extrapolated to be greater than five years, at 100 amps, continuous operation. These tests were performed by a very large and highly reputable users laboratory; several years of field experience confirmed this data.

• Braids: Usually straps made of tinned copper wire which are draped over the shaft, with a spring or weight to pull the strap tight (Figure 9). Problems are as previously described. In addition, the cavities between the wires of the braid will plug up with debris, causing loss of electrical contact. Requires regular, frequent cleaning (removal or replacement). Wear of braid results in mechanical failure (rupture) after relatively short operating time, approximately when the braid has worn to half its original thickness. Replacement of the braid may be difficult during operation, requiring shutdown. Machinery may run unprotected if rupture is not immediately detected, with resulting damage to the machine. Advantage: Low price of original equipment, and replacement material.

• Wire bristle brush ("metal fiber brushes"): These are really wire "brushes," similar in appearance to cleaning brushes. Bristle material requirements: Must be designed for excellent electrical contact properties under adverse conditions, as mentioned previously. Also, sufficient mechanical strength of the bristles is required, including resistance to stress corrosion and corrosion fatigue. Copper and its alloys (brass, bronze, nickel-silver) are not permitted according to API Standards because of corrosion problems and other undesirable characteristics. The material must be able to withstand all chemicals in the environment, which may be highly corrosive. No detrimental effects of the material are allowed on working fluids, gases, and lubricating oil. Operating temperatures of at least 300°F must be expected. The small amount of debris resulting from operation must also be compatible with the application.

• Electrical current and wear rate: The brush should be designed so that, for an average application (amperes), the brush element will last about a year. If the current is higher than permissible, the wear rate may be much higher, and vice versa. Of course, the brush must have a wear indicator and the element must be replaceable during operation, without the risk of contacting rotating or stationary components, which could cause mechanical damage and/or sparking.

The "wear rate" is actually a result of electrical discharge—in other words "burnoff." A well-designed brush should not experience significant mechanical wear under any operating condition, dry or in oil. If no current is flowing, the brush element should last many years, and tests as well as operating experience confirm this.

The author uses a proprietary combination of silver and gold bristles, mounted in a block having suitable electrical, chemical, mechanical, and vibratory characteristics. These designs are patented and more patents are pending. Needless to say, the price of such a brush element does not compare favorably with the 30-cent price of a conventional carbon brush from the vacuum cleaner spare parts list. This remark may seem sarcastic, but in fact, many 30-cent carbon brushes are installed on multimillion dollar equipment right now. People often ask why specially engineered brush elements are so expensive. Advantages: Complies with all requirements of process plant service as listed under TYPES OF BRUSHES FOR CONTROL OF SELF INDUCED SHAFT CURRENTS with low maintenance cost, optimum protection of machinery and plant. Disadvantages: High cost of initial installation.

BRUSH HOLDING FIXTURES (BRUSH ASSEMBLIES) FIBER BRUSHES (FIGURE 9)

General

Operation in refineries or process plants requires a number of special features in the design of a reliable shaft brush assembly. This concerns choice of materials, quick serviceability during operation, high temperatures, high shaft velocities, corrosion resistance, minimum maintenance, easy maintainability, minimum space requirements, ability of running in oil or oil spray, self cleaning features (no debris accumulation allowed). Also, wear indicators (Figure 11) (some users also specify alarm switches), oil or inert gas injection, etc. Then a brush assembly must be sufficiently rugged for the kind of service it is going to experience in process plants and, above all, electrical reliability with stable, low contact resistance must be guaranteed at all times (Figure 10). Furthermore, there should be no risk of electrical shock to personnel, or of spark, if the device is accidentally touched. No oil or gas leaks, no mechanical rubs against internal components (especially during removal or reinstallation with the machinery in operation). Shaft voltage and current must be measurable, to provide protection against self excitation and possible unexpected, sudden destruction of the machine (Figure 15). This means the brush must be electrically insulated from its casing.

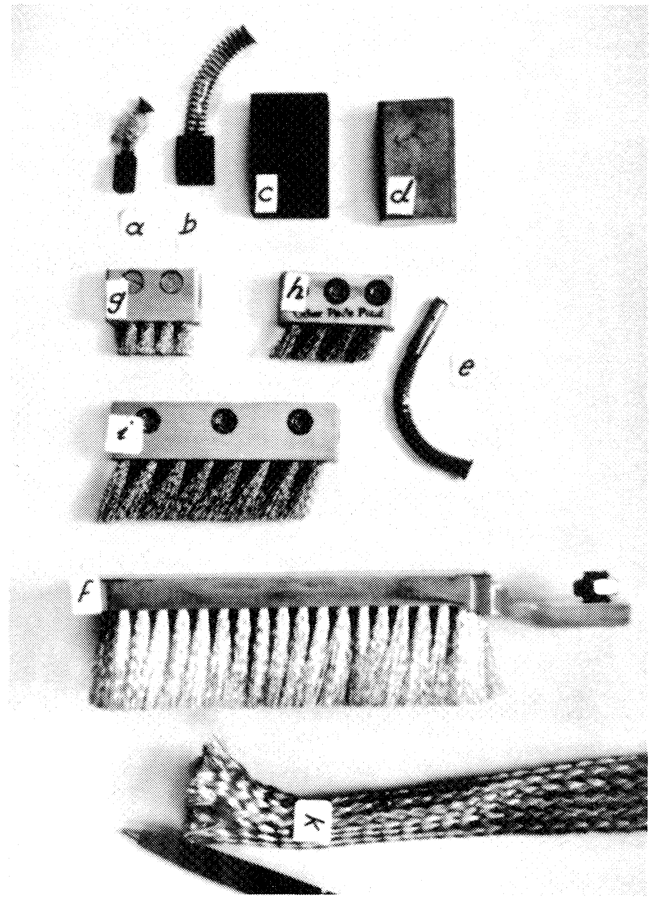

Figure 11. Brush Assemblies of Elements Shown in Figure 8. Brush assemblies a-k; all brushes except f are same scale; f is shown at a smaller scale; it is actually 1.5 times larger than shown.

Such features don't come cheap. These devices should not be compared with a motor brush for a vacuum cleaner, of the type often installed against the shaft end of a turbine "to comply with the API requirements" (which cannot even be observed in operation let alone be cleaned, serviced, or replaced during operation).

The solid-block brushes are usually installed in conventional, electric motor type holders. These are not suitable for process plant use, for the reasons given under "Solid Block." Braids are installed with provisions for tensioning and, in some cases, for manual feeding of the strap as it is being consumed and/or breaks. Only brush assemblies which conform to the requirements of refinery or process plant service will be considered here. At present, these include only wire brush type assemblies.

Assemblies suitable for process plant service are shown in Figures 11, 12, 13, 14.

The following features are provided.

• Movable mounting arm or plunger on which the brush element is mounted. This movable assembly is frequency tuned and damped to provide a smooth ride on the shaft, assuring continuous, uninterrupted electrical contact with the shaft (no jumping), even if shaft eccentricity is present and/or during episodes of vibration, such as caused by unbalance, rotor bow, oil whirl, etc. Note that solid brushes often jump and/or squeal even under normal operating conditions.

Figure 12. Wear Indicator. Typical wear indicator, f through i. Types a through k do not have wear indicators.

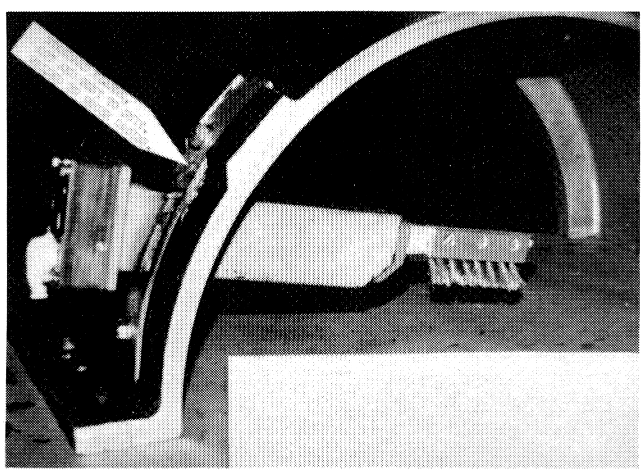

Figure 13. Typical Toothbrush Type Installation. Type g in coupling housing, to ride on shaft inboard of coupling hub.

• High strength, high temperature (400°F) construction, utilizing non-magnetic stainless steel and high strength, high temperature, thermally stable plastic materials for all inside and outside components. All materials must be suitable and compatible with the environment encountered in refineries and chemical plants, including outdoor installation.

• The replacement brush element and its holder is assembled in a cartridge, which can be pulled out during operation if inspection

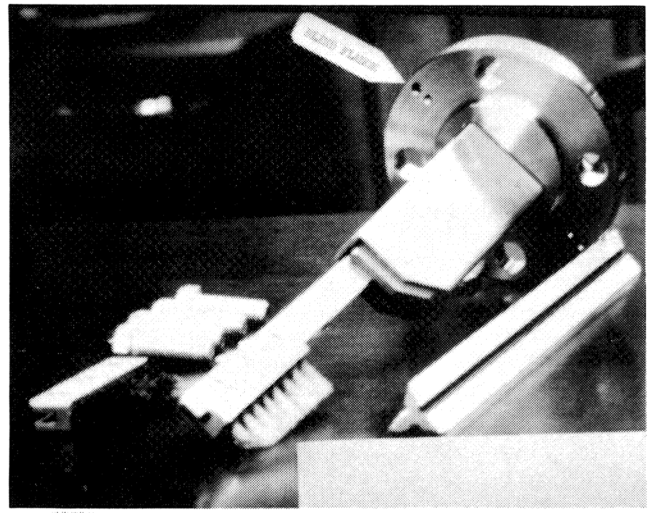

Figure 14. Typical Toothbrush Type, Using Standard Piping, Blind Flange. Similar to Figure 13, but utilizing a stainless steel (for welding), blindflange for mounting, where space is available.

or replacement is required. This can typically be accomplished within less than 10 minutes. The fit of the cartridge in the brush casing allows precise removal and replacement of the cartridge, without risk of contacting the shaft or adjacent rotating or stationary components.

• A brush raising device allows the brush to be disengaged from, and reengaged to the shaft during removal and/or reinsertion. This prevents possible electrical shock to personnel and/or sparking which could be dangerous in explosive atmospheres.

• A window and brush wear indicator are provided (Figure 11). This is visible from the outside of the machine. A wear alarm switch can be provided as an option.

• The entire assembly is oil and gas tight. Hydrotest (in oil, water, or other fluid) to at least 30 psig (test is optional).

• Suitable for operation on dry shaft, conventional steel, or inside of a bearing or coupling housing, exposed to oil splash (preferred) or immersion.

• The proprietary brush material deposits a corrosion resistant, electrically conducting film on the shaft, and burnishes the shaft surface, reducing the risk of shaft damage

• No debris accumulation on the shaft or brush.

• All electrical components are insulated from the casing, to prevent shock, sparking, and to allow measurement of voltage and current.

• Load-matching resistors: Resistors are provided to match shaft current to brush size and type, and to obtain desired acceptable residual shaft voltage for a given type of machine. Matching of the brush to the application reduces the risk of self excitation due to internal current flow. It also allows current measurement (voltage drop across the resistor); See Sections on GROUNDING ARRANGEMENT FOR SHAFT BRUSHES, SHAFT VOLTAGE AND CURRENT MEASUREMENTS AND CRITERIA and see Figures 15, 16, and 17.

A matched resistor is supplied with each of the patented brush assemblies, the resistance varying with each type of application. An arrangement integral and internal within the oil tight brush assembly can be provided as an option, with separate, sealed, integral, high temperature grounding and instrument wires.

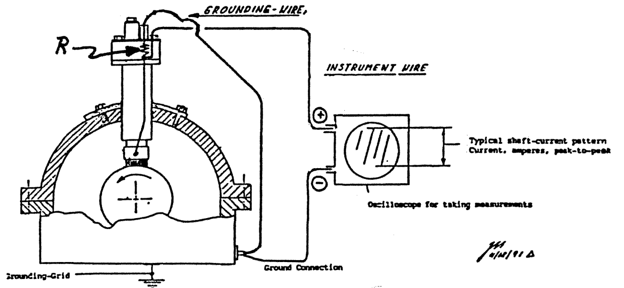

Figure 15. Shaft Current Grounding and Measuring Arrangement, Schematic. The voltage drop across stabilizing resistor "r" is displayed on the oscilloscope and converted into current units by A = V/R; the brush shown ("i" type) is equipped with an optional, built in resistor; most installations have the resistor arranged separately in the ground lead.

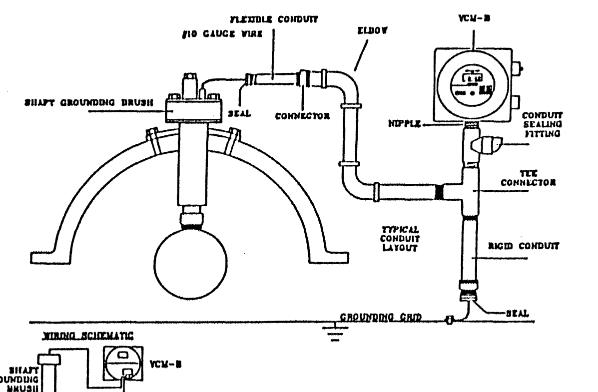

Figure 16. Shaft Current Grounding and Measuring Arrangement, Installation Drawing. This circuit uses an electronic "Voltage Current Monitor" (courtesy of Magnetic Products Services, Inc.) explosion proof version.

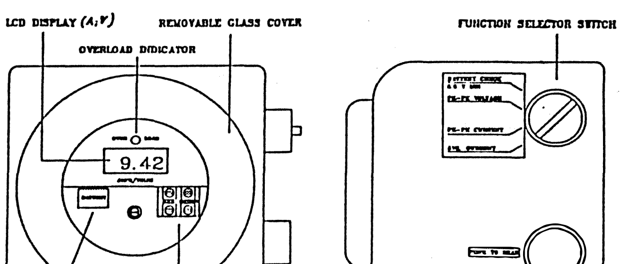

Figure 17. Voltage Current Monitor, Explosion proof box with switch to display peak- to-peak voltage or current, average current, and battery check, as well as an overload indicator. (Courtesy of Magnetic Products Services, Inc.)

Brushes For Very High Stray Currents

• Applications include turbine generators, especially very large units (500 to 1,500 MW). These brushes are primarily for grounding of electrically induced stray currents, originating in static excitation systems; 100 amperes and higher, often at a frequency of 6× line frequency and other multiples, plus superimposed currents of nonelectrical origin.

Parts to be protected are thrust bearing, usually the turbine bearing; main bearings on turbine and compressors; auxiliary drive gears.

In ships (especially large and/or fast ships), the high current brushes are located on the propeller shafts. The currents originate from the seawater/propeller "battery," and they are of a galvanic nature. Electrostatic currents may also occur from water friction against the hull. Electromagnetically induced currents may occur, generated in the machinery. Also, there may be differences in ground potential along the ship's hull.

Currents are in the order of 15 to 100 amperes. Extremely low voltage levels (DC and AC) may be required for some applications. Parts to be protected include propeller shaft thrust and main bearings, shaft seals. Main gear and auxiliaries. The propeller shaft brushes are used in addition to any brushes which may be required on the propulsion turbines and gears.

• Design requirements for high current brushes are essentially the same as for the other types. Special problems are contact maintenance; brush element inspection and cleaning; brush replacement during operation; wear indication. Long brush element life (years) is required, to minimize maintenance operations, and to provide protection against damage and stray current problems during replacement. Very low contact resistance is usually required, at very high current.

As with other previously listed applications, solid brushes like carbon blocks, etc., and braids have presented problems, especially poor and unreliable contact at the required levels of volts and amperes (Figure 10). Unpredictable element failures have occurred with braids (rupture). Also, as with other machinery, the braids need frequent cleaning, inspection, and replacement. On ships, there is the additional possibility of oil and/or seawater spraying into the brush contact area. Shipboard maintenance conditions may involve tight quarters, requiring close proximity of personnel to the large, rotating shaft, possibly with the ship rolling and pitching. On naval ships, there may be additional complications during combat conditions, such as shock, vibration, utility failure, and other problems during brush outage.

• Wire type brushes: They have worked exceptionally well on shipboard installations. Especially desirable is the self cleaning action of the wire bristles, which results in predictable, low contact resistance in possibly very hostile environments, and also, long life between replacement. No maintenance (cleaning) is required. Features are shown in Figures 8 and 9. Note the large size of the brush pad, the silver/gold bristles, large contact area, and a large volume of sacrificial material. The rugged construction of this brush incorporates all the requirements listed under TYPES OF BRUSHES FOR CONTROL OF SELF INDUCED SHAFT CURRENTS and BRUSH HOLDING FEATURES (BRUSH ASSEMBLIES), FIBER BRUSHES. The "toothbrush" type lends itself especially well to this type of application because of the modest space requirement, considering the large shaft diameter (25 in and more). Also, the brush may be mounted to contact the bottom of the shaft, which keeps the assembly out of the way, while it still keeps the brush accessible for maintenance.

INSTALLATION

General Principles

The basic purpose of a brush is to protect critical components of machinery (bearings, seals, gears) from electroerosion, by bypassing these components, forcing the electric current to go through the brush instead of arcing across component clearances [1, 2, 3, 4]. Of course, the brush will not prevent the turbine, compressor, or gear from generating electricity; it can only provide a "sacrificial bypass," i.e., the brush suffers the electroerosion instead of the machinery components. If currents exceed the capacity of the brush, for example, in a self excited machine, any brush will burn off ("wear") very rapidly, within days or hours. With very high, currents the brush will cease to function, and the components to be protected will then electroerode until the unit trips on bearing wear, high vibration, or as massive destruction is initiated. [1, 2, 3]. The brush cannot prevent this, but it can delay the catastrophic phase long enough to identify the cause (by measurements) and by providing enough time to bring the plant down safely, with a minimum of damage and operating loss. Also, by grounding across critical components, moderate currents (which exist in many units) can be tolerated, and safe operation can be continued to a scheduled shutdown, with little or no damage to the protected components. The important factors in locating brushes are:

- How many brushes are needed? Obviously, one brush on a, say, 70 foot-long, four-body syngas compressor train, cannot protect all 12 bearings, plus gears, oil bushing seals, and couplings. In fact, if the offending generating body is on one end of the train, and the brush is on the other, all couplings and gears in between may be damaged. Also, some types of electromagnetic generation cannot be grounded at all, others can only be grounded locally, for example, to protect one thrust bearing. All this gets very complex, and it varies for each application. Please refer Sohre [1], Sohre [2], Nippes, et al., [3], and to Figure 7. The basic idea is to protect the most critical component in a train first—the criteria being cost and length of shutdown, in case the component is damaged. Usually this is a gear in the middle of the train. Then work toward both ends from there. This may not necessarily be the best approach from the standpoint of electromagnetic theory, but may be the solution of lowest risk and minimized outage cost. If a gear fails and there is no replacement in stock, this can mean a very long and costly shutdown. Note: Faithful monitoring of the brush currents is the key to reliable operation and maintenance prediction.

- How to mount the brush in a machine: New machines are the best solution. The manufacturer selects the location and designs the machine to optimize grounding effectiveness. Retrofits are often difficult, with limited choices of locations and installation layout. One has to put a brush wherever he can get one in. Again, practical considerations dominate. Theoretically, all brushes on a train of machinery should be in the same plane, i.e., either on top, bottom, right side, etc. This somewhat minimizes the "coil effect" generated by shaft contacts, say 180 degrees apart, which would represent ½ turn of an electromagnetic coil, intensifying the magnetization. In the real world of hardware, operators very seldom have the luxury of such choices. Also, even with two brushes perfectly aligned at the end of the machinery (say 50 feet apart), who tells the current to run straight along the shaft, instead of going around the rotor like a corkscrew anyway? The author has seen a steam turbine rotor (without brushes) where each of the nine disks were very strongly magnetized with the plus and minus polarity reversed 180 degree at each successive disk rim. In other words, there was a 4.5 turn coil, perfect to start, self excitation [1]. This magnetization happened in a matter of a few seconds during a rather light axial wheel rim rub, induced by a thrust bearing displacement. The machine was immediately shut down, so the rubbing episode only lasted a few seconds.

There are hundreds of parts in any machinery train where contact or arcing may occur (seals, bearings, gears), in a random pattern, which can change rapidly due to wear, electroerosion, etc. These parts are certainly not lined up to present the best electromagnetic pattern, in fact, quite the contrary. The fields align themselves to generate maximum electricity. So, not much is risked by selecting brush locations to minimize risk of damage rather than according to electromagnetic theory. It is much more important to have brushes at all (which can be grounded and monitored) than to try to figure out what a given machine will do next, for example after a slug of fluid passes through and momentarily causes severe vibration. Or someone does a little welding on a casing drain 30 ft below the machine, where the welder is grounded to a nearby structural steel beam. Evidently, a good grounding system must be designed by specialists, for specific purposes.

Thorough demagnetization is, of course, the mandatory action to be taken, but sometimes it is not possible to disassemble the entire machine for this purpose. A compromise may be worked out by partly demagnetizing during a short shutdown and by adding brushes to protect the endangered areas. This will often allow operation to the next scheduled shutdown.

Another type of panic repair involves the installation of a brush with the unit in operation. For example, when the thrust position indicator, (or shaft-to-bearing position) indicates that the rotor is working its way slowly but steadily through the babbitt, toward the steel backing. Not much time is available for theoretical considerations under such circumstances. It is mandatory to get a brush on the shaft before the bearing fails. Maybe there is some exposed shaft surface somewhere, but usually it is corroded if it is accessible from the outside. The only good locations available may be axially on a free shaft end—at either end of the train, or at the free end of the bull gear or pinion shaft. Sometimes the plug of a vibration sensor, a breather cap, or other removable component can serve to make an on-the-run installation for a brush. To avoid having to operate with a big hole in the bearing case or coupling guard, or whatever, the logical thing to do is to make a new endcover or plug with the integral brush casing in it, with a blank plate instead of the brush. Then remove the existing endplate, put the new one on, remove the blank, and fit the brush, with a minimum of oil coming out of the machine (but it is still a good idea to bring your umbrella). The plunger-type brushes, Type "A" (for "axial"), shown in Figures 1 and 9, are especially suitable for such installations.

- Concerning shaft hardness under the brush: Any steel shaft will be suitable, but the brush should not be run on a hollow, thin walled and/or highly stressed shaft. Also, avoid materials which depend on an oxide film for corrosion resistance, i.e., austenitic (nonmagnetic) stainless steel (like 18 Cr 8 Ni), aluminum, titanium, and soft materials like copper.

BRUSH OPERATION AND MAINTENANCE

Block type brushes and braided straps need frequent and regular checking for wear and electrical contact, debris removal, shaft film removal, and brush element replacement. Otherwise, they will quit working. Braids, especially, will accumulate debris in the crevices between strands, which will increase contact resistance, with consequent shaft voltage increase. This condition is not visible during operation. The wear must also be observed in order to prevent the strap from rupturing.

Wire bristle brushes do not require maintenance, except observation of the wear indicator and infrequent bristle element replacement, normally once per year. This can be done during operation. Current-to-ground and shaft voltage should be religiously observed and logged or recorded (daily or at least twice a week), to warn of (slow or sudden) magnetization, and possible self excitation. The grounding grid condition of the unit and its connections should be checked frequently and kept in top-notch condition at all times. This is the first item to check if rapid brush wear occurs.

GROUNDING ARRANGEMENT FOR SHAFT BRUSHES

The basic arrangement is shown in Figure 15. Note the load matching resistor. For illustration, a one ohm resistor is shown, so that one amp current (which is about maximum for this particular application) results in one volt residual current on the shaft. This is just for the sake of illustration, since obviously the resistance must be matched to each application.

The brush-to-casing connection must receive the same great care as the rest of the grounding-grid, otherwise an astonishing variety of problems can develop, ranging from false instrument readings in the remote control room (which may be hundreds of feet away) to rapid brush wear and possibly machinery failures.

Before any type of brush is raised off the shaft or removed, the grounding wire must be very carefully disconnected and insulated against accidental contact with the casing. There may be a very high voltage on the grounding wire once it is disconnected (open circuit voltage, which can reach several hundred volts). Unless precautions are taken, there may be sparking which is, of course, dangerous in an explosive atmosphere. Once disconnected, the brush can be raised off the shaft by means of the brush raising device and then the cartridge can be safely pulled out of the brush casing. Special, explosion-proof ground-disconnect devices are highly recommended where the wire is connected to the machinery casing.

SHAFT VOLTAGE AND CURRENT MEASUREMENTS AND CRITERIA

Shaft Voltage, Grounded

In the arrangement shown in Figure 15, the voltage upstream of the one ohm resistor (shown for illustration only) is also the shaft voltage. In accordance with Ohm's Law, A = V/R, where V is the voltage drop across the resistor, R (ohms). For a good installation, having no additional resistances, V also represents the shaft-to-ground voltage.

The only voltage of interest is the voltage of the grounded rotor, i.e., during normal operation, which will vary with current A. Maximum acceptable values depend on type and size of machinery, and on clearances and electrical resistances of internal parts, usually the thrust bearing trailing edges, seal and bearing minimum clearances, oil pump, gear, worm drive contact resistance, gear tooth resistance, roller bearings, etc. With small, very high-speed machines, metal worm drives and roller bearings, the shaft voltage must be kept very low (well below one volt), in order to prevent damage to these parts. This means either the resistance in the grounding circuit must be very low, or the amperes must be low, preferably both. Most large, high-speed compressing equipment in process plants (10000 hp/10000 rpm or so) can tolerate about one volt (peak) on the shaft before electroerosion occurs, but this may not hold for highly loaded gears. On the other hand, manufacturers of large turbine generator sets allow up to six volts, with the journal bearings having a 25 in diameter and correspondingly large oil film clearances.

Shaft Voltage of the Ungrounded Rotor (Open-Circuit Voltage)

This is the voltage measured on the brush with the grounding wire disconnected. It is a function of the dielectric strength of the bearing oil film, the oil film thickness, the internal clearance, effects of vibration, thrust, etc. In addition to this, there is the capacitance effect of the rotor. This voltage can change with weather (humidity or water in oil), or any variation of the previously mentioned conditions, due to operational factors. Therefore, the open circuit voltage is only of interest at the moment of measurement. The number can vary from zero to several hundred volts within a matter of seconds or minutes ([1], case history 1). This voltage can cause severe electrical shock to people, and long sparks. For purposes of machinery protection, the open circuit voltage is of no consequence, and need not be measured as a matter of routine. If no grounding is provided, the electrical charge in the machine will naturally build up until an internal spark jumps across a clearance somewhere. After all, this is how the machinery is damaged by electroerosion, and why a rotor is grounded to begin with. There is no sense in measuring this open circuit voltage during normal or abnormal plant operation. However, an expert troubleshooter may measure this voltage, because its buildup rate, drainage rate, and frequency may give him a clue concerning the origin and severity of a problem.

After the brush is grounded, a high voltage of, say 500 volts, will instantly be reduced to something like one volt or less, depending on the watts being generated and, of course, on the grounding brush design and matching. There have been suggestions to add water or other conducting fluids to the oil for its grounding effect. It works, but how does one evaluate the electricity being generated in a machine? The first indication of electromagnetic self excitation could be a cloud of smoke coming out of the bearing case [3].

Shaft Currents

- General: As explained in publications [1, 2, 3], there are many sources for current generation, even in purely nonelectric machines, such as turbine driven compressors. These same currents occur in electrical machinery such as turbine generators, plus a variety of electrically induced stray currents. The strongest of the electrically induced currents, under normal operating conditions, may originate from the static excitation system, and they may exceed 100 amps during normal operation (see Brushes for Very High Stray Currents).

In this section, only self induced electromagnetic stray currents in nonelectric and electric machinery are covered, excluding the superimposed electrically induced versions, static electricity, currents introduced by ground-grid problems, galvanic action, etc. As explained in the INTRODUCTION and PRINCIPLES OF ELECTROMAGNETIC INDUCTION, REFERENCES, and BIBLIOGRAPHY these electromagnetic currents are initiated by accidentally introduced magnetic fields in stator, rotor, foundation, piping (or all of these) which then are slowly or suddenly amplified by self excitation within the operating machine. Only 100 percent effective demagnetization of all components of a machine and its surroundings could prevent current generation and re-excitation. One hundred percent demagnetization is, of course, impossible to obtain once magnetization has permeated an entire installation. Brushes can keep such situations under control.

- Current measurement: The setup is shown in Figure 15. References explain the details. Voltage/current/brush/ machine relationships and current criteria were discussed in the beginning of this section. Recapping briefly: The current (A) is represented by the voltage drop (V) across a resistor (R, ohms). A = V/R.

The current usually consists of spikes with an extremely fast buildup and decay rate, a series of slashes across the oscilloscope screen.

- The resistor R must be of the noninductive type.

- The voltage of a grounded brush must be measured by means of an oscilloscope, to determine peak voltage (not peak-to-peak), which is the voltage doing the damage to the machine.

- Maximum allowable current from brush to ground is very difficult to define, because of the unpredictable "wave" shape. However, we can say the following:.

  · the current and voltage going through the brush to ground (which is seen on the scope) represents the electricity (watts) which would pass through the bearings and other components if no grounding brush was present. The voltage would be determined by the "flashover voltage" in the respective components.

· grounding can prevent flashover voltage and allow monitoring of excessive current circulation.

· each machine is different. For example, gas turbines use nonmagnetic alloys in the hot section. This is radically different from the characteristics of a machine built of magnetic materials. However, gas turbine trains also have shaft current problems, because the hot section involves only a relatively small portion of the train.

· rational figures for limitations are not available, hence, operators must rely on experience with a given type (and brand) of machinery.

· to control the situation, brush, resistor, possibly also a capacitor, and allowable voltage must be matched.

· once peak voltage and current have been determined, a volt meter may be used for continuous monitoring, establishing a conversion factor scope/to meter, which is usually about 10/1. Otherwise, the meter readings have no clear physical or electrical meaning, they only give an indication of what is going on inside the machine, and even this only with the following restrictions: Data is valid only for:

· a given location, resistor, machine. Not to be extrapolated to other machines of the same type.

· a particular operating condition.

· a specific electromagnetic condition.

· the individual meter.

However, even with these limitations the machine can be protected from damage and sudden destruction, which is not possible otherwise. Of course, if meter readings change, the oscilloscope must be used again to determine the reason for the change.

NOTE: At least one instrument which is explosion proof is available, which is specifically designed for shaft current applications to assess peak voltages and currents, and average currents (Figures 15, 16). Note that this instrument has a builtin one ohm resistor for the current measurement. If a resistor is already built into the brush or circuit, use the peak voltage reading only and convert (A = V/R).

Remember: The load matching resistance must always be in the grounding circuit during operation, regardless whether this resistor is built into the brush grounding wire, or whether it is already available in the meter.

SUMMARY AND CONCLUSIONS

The trick is to design a brush and its mounting structure to fit the criteria of a given type of machinery, operating characteristics, and application. Some of the important factors are size and speed of equipment, number of brushes used, space typically available, maximum permissible residual shaft voltage, and acceptable wear life.

Extensive tests and field experience are required to define these parameters for each type and class of machinery, using statistics. A mismatched brush may have excessive wear and/or leave excessive residual shaft voltage, which may then cause self-excitation, machinery damage and shutdown. The bristle design is considerably complicated by the usually unknown, and variable, state of magnetization of any given machine.

One way to tackle this problem is as follows:

• If a machine has not had a magnetic problem, and Gauss readings are low inside and out, including rotor assembly, casing, piping, foundation, etc., a brush may not be required. However, keep in mind that magnetization may be introduced at any moment by welding, magnetic particle inspection, shock, vibration, internal rub, and so on, and without a monitored brush the machine may wreck without warning.

For a given brush installation, residual shaft voltage will represent a corresponding current-to-ground (amperes) as measured across a noninductive resistor (ohms) in the ground lead. In other words, the electrical power generated in the machine would be volt × amp = watts. If the brush is designed to have a one year burnoff ("wear") rate under these design conditions, a shorter life would indicate that the current is excessive, even without the aid of instrumentation. This is extremely important. Therefore, a reduced brush life indicates a serious condition which could cause severe damage. Immediate investigation is indicated if excessive brush burnoff is experienced.

The criteria given here vary for different machinery and installation, but it is possible to establish criteria for given classes of machinery once operators know how much electrical power a machine can generate and safely withstand. Grounding the rotor by means of brushes will obviously not eliminate the process of electromagnetic generation and self excitation, and in the worst case sudden self excitation ("meltdown") can occur with or without brushes, unless currents are carefully monitored. It can be seen that there is still much to learn. Careful observation and accumulation of experience is the key to the problem.

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