ELECTRIC SHAFT CURRENTS IN TURBOMACHINERY

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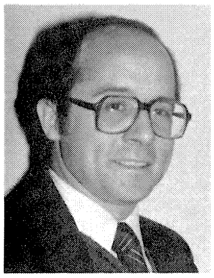
Dr. Vance came to Texas A&M from the University of Florida, where he developed a Rotordynamics and Vibrations Laboratory and conducted research on squeeze film bearing dampers, helicopter propulsion systems and other topics related to rotordynamics of turbomachinery.

Prior to joining the Mechanical Engineering faculty at Florida, he worked for five years as a Mechanical Engineer in industry, holding positions at Armco Steel, Texaco Research, and Tracor, Incorporated.

Dr. Vance is currently conducting research on rotordynamics, electromagnetic shaft currents, and bearing dampers in the Turbomachinery Laboratory. He has published more than fifty technical articles and reports on rotordynamic instability, squeeze film bearing dampers, vibration isolaters, and related subjects. He is an active consultant to industry and government laboratories, and has held eleven summer appointments at Pratt & Whitney Aircraft, USATL (Helicopter Propulsion Lab, Ft. Eustis), Southwest Research Institute, and Shell Development Company. He organized a short course for industry at Texas A&M on "Rotordynamics of Turbomachinery," and co-organized the biennial "Workshop on Rotordynamics Instability Problems in High Performance Turbomachinery."

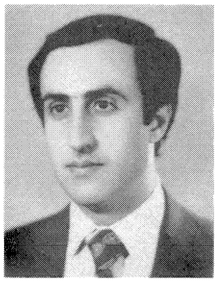
Dr. Vance was named the Dresser Industries Associate Professor at Texas A&M in 1979-80, was Associate Head of the Department of Mechanical Engineering in 1980-81, and was named a Halliburton Professor for 1986-87. He is a member of ASME and ASEE, and is a registered professional engineer in the State of Texas.



Alan B. Palazzolo, Assistant Professor of Mechanical Engineering at Texas A&M, received his B.S. (1976) from the University of Toledo, and his M.S.M.E. (1977), and Ph.D.M.E. (1981) degrees from the University of Virginia. He worked for Bently Nevada (1977-78), University of Virginia (1980-81), Allis Chalmers (1981), and Southwest Research Institute (1981-85) before joining Texas A&M, in 1985. He researched during the summers of 1986 and 1987 at NASA Lewis, as a Faculty Fellow.

Dr. Palazzolo's expertise is in vibrations, rotordynamics, finite and boundary elements. He has also been extensively involved with field troubleshooting of mechanical malfunction in rotating and reciprocating machinery. Dr. Palazzolo has presented papers at ASME Gas Turbine and Vibration Conferences and has published many papers in various engineering journals.

Dr. Palazzolo is a newly elected member of the Turbomachinery Symposium Advisory Committee.



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ABSTRACT

Electrical damage to turbomachinery parts has caused a number of machinery failures and many hours of costly downtime. The problem of electrical voltages and currents being generated in non-electrical machines has puzzled both users and manufacturers of these equipment, and has prompted on-

going research at Texas A&M to help identify and better classify the different sources of these voltages and the mechanisms by which they cause damage to bearings, seals, and other critical machinery parts.

Electrostatic and electromagnetic type voltages are often misidentified, a situation that might lead to a wrong or costly remedy. The distinctions between these two major sources of shaft voltages and currents are clearly drawn herein. Lubricating oil characteristics and their influence on the buildup of shaft voltage potential have also been carefully scrutinized. Breakdown voltages were generated and measured at different operating conditions to help highlight the influence of the different variables such as bearing clearance and dielectric strength of the oil.

INTRODUCTION

The phenomenon of electrical damage to machinery components is not new and has been addressed in several articles and technical publications. Sohre and Nippes were the first to identify the different types of shaft currents generation and to present a theory that explains some aspects of electromagnetic shaft induction [1]. A research effort at Texas A&M University has been funded by the Turbomachinery Research Consortium since 1981. It was originally directed at verifying the theory introduced by Sohre and Nippes [1] in a laboratory controlled environment. These efforts have since been expanded to include studies of other mechanisms of shaft voltage generation, as well as field measurements. This research will be referred to hereafter as "the TAMU project."

Research to date has suggested the following classification of the sources of shaft voltages/currents:

- Electrostatic.
- Electromagnetic.
  - AC induced by rotating or alternating residual magnetic poles, usually localized and possibly self-exciting as described by Sohre and Nippes [1, 14].
  - DC Homopolar ([1]) induced by magnetic fields fixed in the stator interacting with eddy currents in the rotor, as in a Faraday disk.
  - DC self-exciting, as demonstrated experimentally by Schier [2] in Germany. This phenomenon can produce thousands of amperes with no measured voltage exceeding one volt.

The principle of operation of electric generators centers around the fact that a conductor travelling through a magnetic field will generate a voltage at its two ends, one end being positive, the other negative. If the ends are electrically connected, a current will flow. This current will be proportional to the dimensions of the conductor, the strength of the magnetic field, and the velocity with which the conductor is travelling through the magnetic fields. If the above prerequisites are met, any machine will generate internal currents. In a turbine compressor unit, these currents are short-circuited, with the electric energy transformed into heat in the rotor and stator. Where the currents travel across the interface between parts, for example, the very thin oil film at bearings and seals, or at any other contact point offering an electrical resistance, there will be sparking and surface damage. If currents are high, and they can reach the very high values of several thousand amperes, there can be massive arc-welding. As contacting points are consumed by arcing, clearances will increase. This raises the electrical resistance at this given location until another location offers a lower resistance, and the current will change to another location path. This process continues until vibration or leakage becomes excessive, or a failure occurs in the thrust bearings, journal bearings, or seals. A typical damage from this type of currents is shown in Figure 1, which is a photograph of the steel backing of a tilt pad that was welded to the bearing shell. The weld spots illustrate the high current densities that must exist to cause such damage. This is supported by the discoloration due to the high thermal effects.

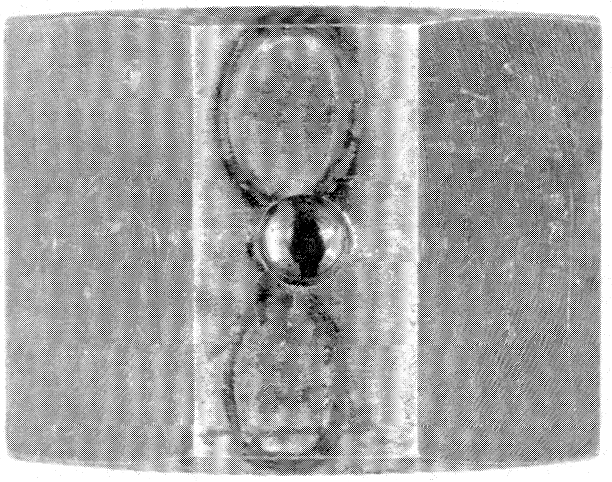


Figure 1. Welding Spots on a Radial Tilt Pad Bearing.

Another important aspect of shaft currents which is of prime importance, but which has not been adequately addressed by previous publications on the subject, is the oil dielectric strength or breakdown voltage. This topic has been under study in the TAMU project and is included under a later section heading *Breakdown Voltage.*

Chronological Perspective

The origin of shaft currents research began in the study of electrical machinery. Merrick [3] published extensive results on shaft current causes and effects in generators. His results suggested that dissymmetry in the magnetic circuits was the principal cause of induced voltage in the shaft. This dissymmetry could result from mechanical joints in the stator, a difference in the permeability of the magnetic material constituting two flux paths, or by difference in the effective lengths of these paths. In addition, Merrick showed that shaft currents could exist in both AC and DC machinery, and that it was strongly dependent on bearing clearance. He suggested two fixes for the shaft current problem:

- Brushes are placed on both ends of the shaft and are either grounded on the bearing pedestals or connected together by a heavy copper conductor. Merrick felt that this may not be the best fix, because the objective of reducing the amount of current passing between the shaft and bearings would not be met, if the oil film resistance is less than the contact resistance of the brushes.
- Insulation is inserted between one or more of the bearing pedestals and the machine base. In addition, it would be necessary to insulate all piping, stairs, etc., which would otherwise complete the electrical circuit. Merrick felt that this method, if properly applied, would provide absolute protection to journals and bearings.

Buchanan [4] made similar observations to those of Merrick noting that shaft currents could be caused by:

- Unequal reluctances of the main field circuit, due to unequal air gaps, pole joints or permeability of poles.
- Unequal air gaps, due to eccentricity of the rotor relative to the stator.

- Joints in the stator core.

His final conclusions were:

- If the number of stator joints are equal to the number of field poles, and all joints have the same reluctance, no shaft electro motive force (EMF) will occur.
- If the stator can not be constructed as a continuous ring, the bearings should be completely insulated or an opening EMF coil should be installed, or an impedance coil should be placed around the shaft.

Alger and Samson [5] expanded on the work of Merrick, Buchanan and others, mentioning the possibility of shaft current damage from homopolar voltages caused by permanently magnetized shafts, bearings, or casings.

The concern about shaft current damage in non-electrical machinery was initially directed towards electrostatic voltage damage because of its prevalence. The discussion here will be restricted to the chronology of *electromagnetic shaft* currents in non-electrical machinery. Research in this area seems to have originated in the early investigations of electrical engineering; i.e., generating currents by rotating a cylindrical magnet in contact with a stationary closed circuit, or by rotating a cylindrical rotor in a stationary magnetic field. The latter case is the familiar "Faraday Disk" [6]. Many authors gave various qualitative explanations for the production of current by a rotating magnet [7, 8, 9]. The schools of thought between these investigators was divided into those who believed that the field of the rotating magnet was stationary, and those who believed it was rotating with the magnet. Both points of view are examined and compared in Appendix III of Cullwick's study [9]. These types of generators are generally referred to as unipolar, homopolar, or acyclic machines, since as the conductor (shaft) rotates, it traverses the same polarity, in distinction with bipolar or multipolar machines, in which the conductor passes two or more poles during each revolution [7]. The acyclic descriptor refers to the DC nature of the unipolar induced voltage. One of the most complete theoretical treatments of unipolar generation may be found in Tsien's dissertation [10].

The study by Boyd and Kaufman [11] appears to be one of the earliest that alluded to the presence of damaging shaft currents due to a magnetized shaft in non-electrical machines, although their most direct reference to this effect is in electrical machinery. Schier [2] was the first to employ a laboratory model that simulated the shaft current generation in non-electric machines, and was successful in initiating a self excitation process which developed thousands of amperes of current. The explanation provided for this self excitation phenomena was an analogy with series wound, self excited DC generators. Schier reports a case of shaft current damage to the main centrifugal oil pump of a 150 MW turbo set.

Schier's paper was followed by Braun's study [12]. Braun examines shaft current damage resulting from electrostatic voltage discharge, along with shaft currents generated by magnetized shafts and casings. The fixes suggested by Braun are:

- locate brushes where the oil film is thinnest, i.e., the front end of turbine or thrust bearing end.
- demagnetization of components.
- insulation of turbine bearings.

The 1978 paper [1] of Sohre and Nippes is an excellent reference on shaft currents in non-electrical machinery. A thorough discussion is given of electrostatic and electromagnetically induced shaft currents, and several case histories are presented. The electromagnetic shaft current phenomena is examined according to the basic physics of shaft current generation, the causes of magnetization, the symptoms of shaft currents, detection methods and remedies. Sohre and Nippes have expanded the explanation of their theories and the records of case histories [13, 14]. Their joint report contains an interesting description of the effectiveness and limitations of shaft brushes [14].

FIELD MEASUREMENTS BY THE TAMU PROJECT

Electrostatic

Several field trips have been made to conduct onsite investigations and measurements on equipment that experienced shaft voltage/current damage. The first survey was done at a refinery in Ashland, Kentucky which had three identical trains, each consisting of a steam turbine directly coupled to a horizontally split eight stage axial compressor as shown in the schematic diagram of Figure 2. The compressor had 29 blades on the first three stages and 41 blades on the last five stages, while the stator had 42 blades. Phone pickup measurements closer to the last five stages are shown in Figure 3, and indicate a high amplitude at a frequency equal to 43 times the running speed frequency. A phone pickup measurement is shown in Figure 4, at a location closer to the first three stages, and indicates a higher level at 31 times the running speed frequency. It is interesting to note in these cases that the frequencies are consistently just over the blade passing frequencies (29 and 41). Measurement on the second train (109-GB-1) also indicated similar frequencies of 31 and 43 times running speed frequency and its frequency spectrum is shown in Figure 5. A 29 times running speed component again measured with the phone pickup, but closer to the steam turbine drive end is shown in Figure 6. A survey of the magnetic field on the compressor is shown in Figure 7. The gauss levels ranged from five to ten gauss on both rotor and stator blades, with no particular pattern or orientation discerned. The maximum gauss reading was obtained on the thrust collar at the outboard end of the compressor. This field was oriented radially (south pole) all around (360 degrees), with average readings of about 20 gauss and a peak of 40 gauss.

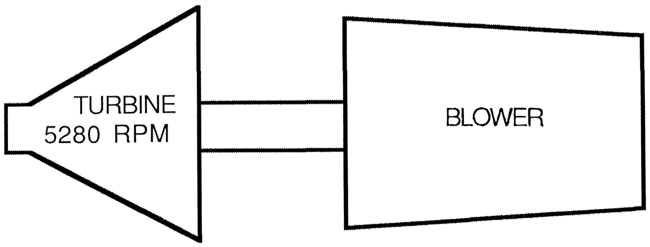


Figure 2. Schematic of the Machinery Train at Ashland.

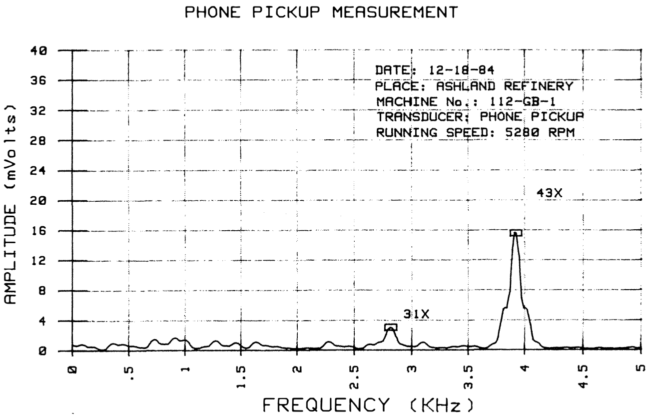


Figure 3. Phone Pickup Measurement Close to the Last Five Stages on 112-GB-1 Compressor.

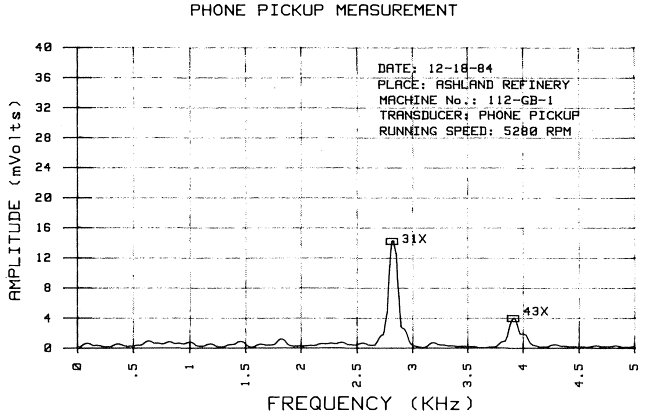


Figure 4. Phone Pickup Measurement Close to the First Three Stages on 112-GB-1 Compressor.

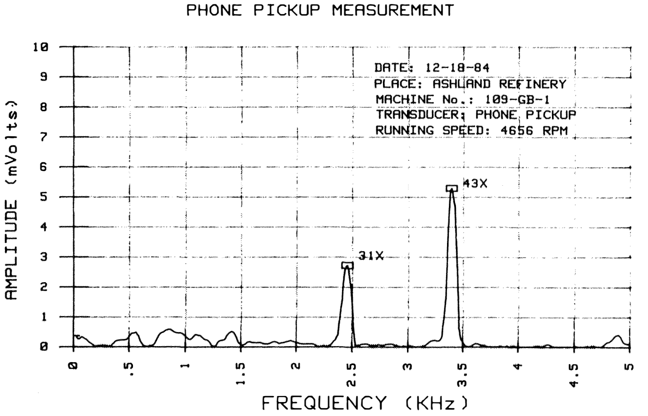


Figure 5. Phone Pickup Measurement Close to the Last Five Stages on 109-GB-1 Compressor.

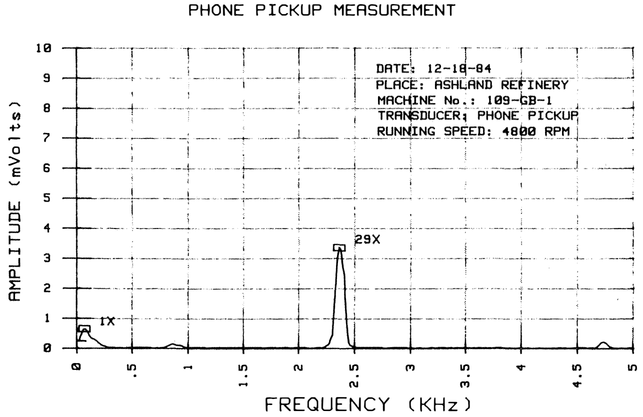


Figure 6. Phone Pickup Measurement Close to the Turbine Coupling End.

While the magnetic field survey and the phone pickup measurements seem to indicate the presence of electromagnetic type voltages, the measured brush voltages were characteristic of electrostatic type phenomena. These are shown in Figure 8, and are noted to have only positive peaks which reach 90 volts to several hundred volts before discharging to ground. The voltage off the brush was put across a one ohm resistor to obtain a voltage signal directly equivalent to the current. The signal reduced to a very low amplitude level in the range of milliamps, as shown in Figure 9. The damage that occured on the radial bearing pads is shown in the photograph in Figure 10. Frosting damage on the thrust pads is portrayed in Figure 11.

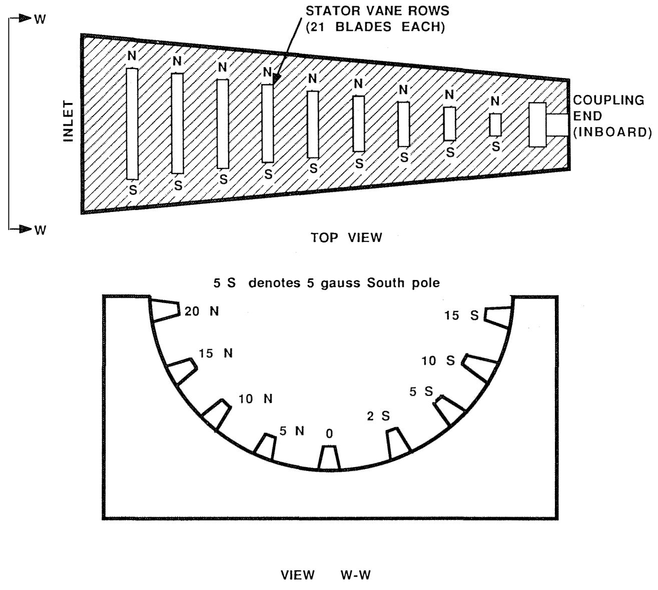


Figure 7. Magnetic Field Survey on Stator Blades.

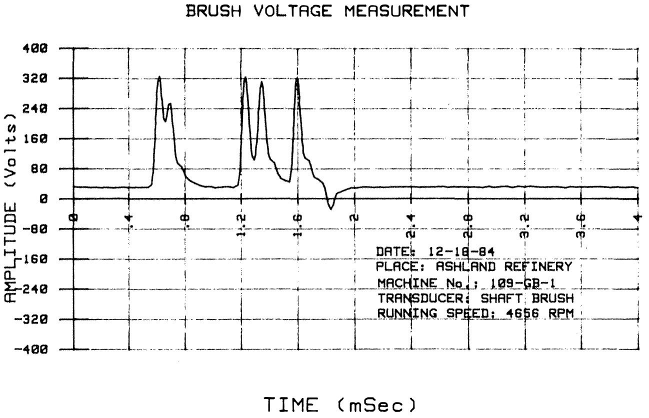


Figure 8. Brush Voltage Measurement on 109-GB-1 Train.

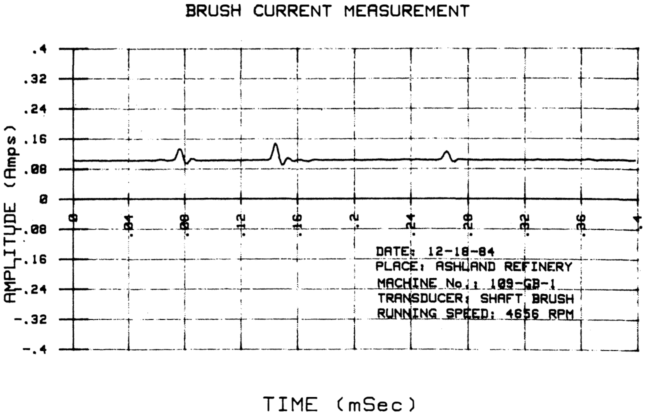


Figure 9. Brush Voltage across One Ohm Resistor (Current) on 109-GB-1 Train.

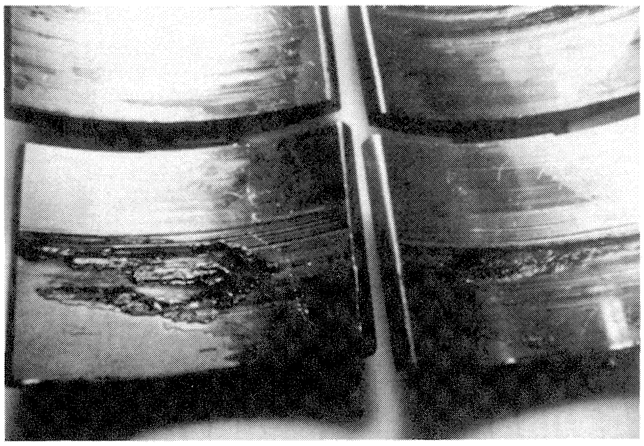


Figure 10. Radial Bearing Damage, Ashland Oil Company.

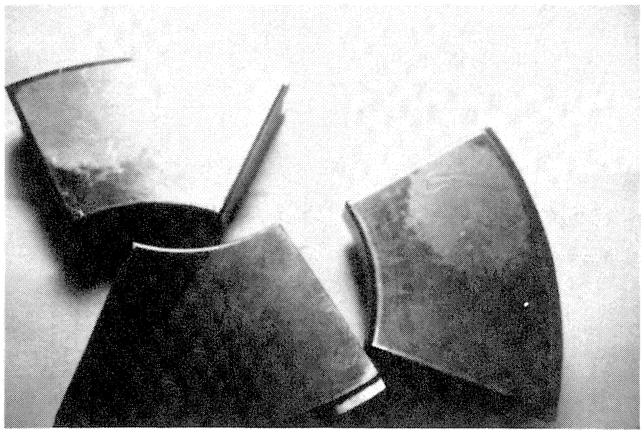


Figure 11. Thrust Bearing Damage, Ashland Oil Company.

The second field study was conducted at a chemical plant near Tulsa, Oklahoma on two CO_2 trains consisting of a 7000 horsepower (hp) condensing turbine driving two barrel compressors as shown in the schematic diagram of Figure 12. Severe and rapid thrust bearing wear was noted on the high pressure compressor. Disassembly and inspection showed evidence of sparking damage on the thrust and radial bearings. Voltage readings through a brush installed on the high pressure (HP) compressor were consistently above 300 volts (320-370 volts), as shown in Figure 13. However, passing this voltage through a one ohm resistor connected to ground reduced the signal to very low amplitude in the milliamps range.

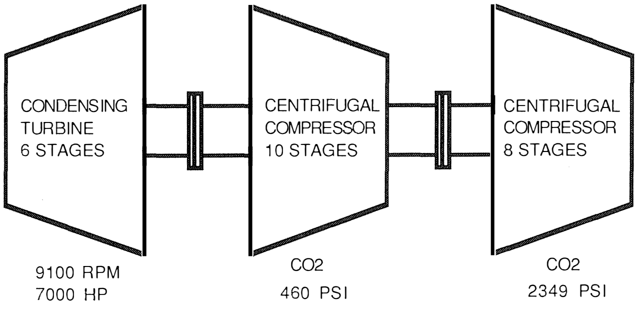


Figure 12. Schematic of The Machinery Train at Agrico Tulsa.

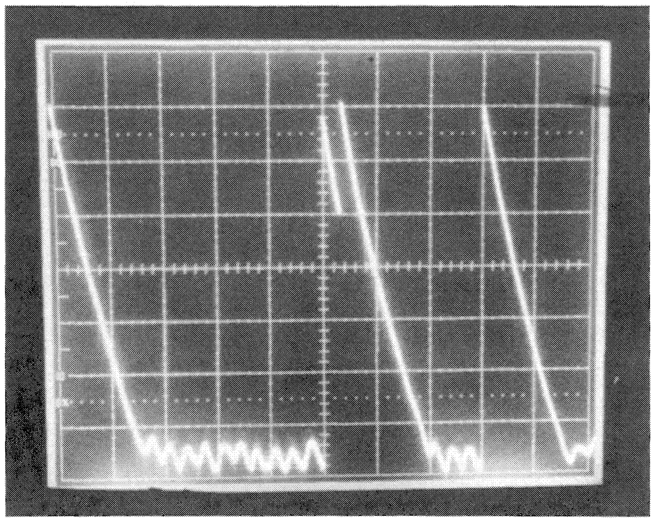


Figure 13. Electrostatic Voltage Signal from the HP CO_2 Compressor at Agrico Tulsa (50 V/Div).

Electromagnetic

Brush voltage measurements were carried out on two trains in a Louisiana ammonia plant. The first train has a steam turbine drive directly coupled to an low pressure (LP) compressor, with the high pressure (HP) compressor driven through a speed increasing gear box as shown in the schematic representation in Figure 14. The second train (Figure 15) has a condensing steam turbine directly coupled to a topping turbine driving an eight-stage syngas compressor at an operating speed of 10,200 rpm. Both trains had brushes installed at the governor end of the condensing turbines only, but the brush voltages from the two trains were markedly different in character and magnitude. The two trains receive their steam from the same source and exhaust to the same condenser. The signal obtained from the first train (Figure 16) has a running speed frequency with an amplitude of 0.2 volts. The brush signal from the second train is shown in Figure 17. It has a predominant frequency of 0.44 times the running speed frequency, but a larger amplitude which reaches a maximum of 3.0 volts. The vibration signal from this train shows no component at this frequency, but, at other locations, these compressors were reported to have experienced subsynchronous vibrations at this frequency in the past. Both trains were surveyed with a telephone pickup, but no signal indicating magnetic activity could be obtained. The phone pickup was checked and found to be operational.

LABORATORY MEASUREMENTS

Electrostatic

Positive identification of electrostatic voltages is considered to be important, since it is the most common type of shaft

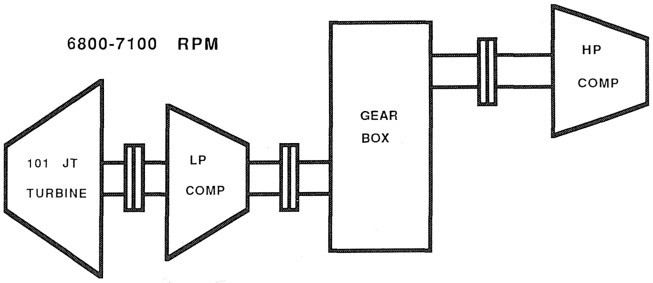


Figure 14. Schematic of Machinery Train 1 at CF Industries.

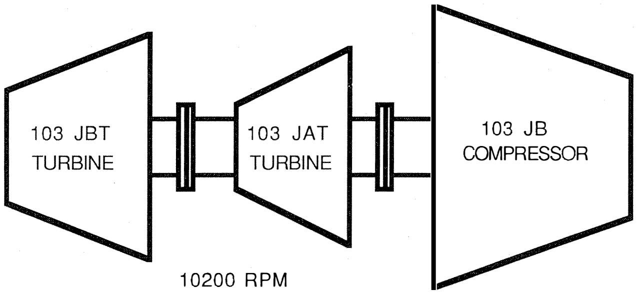


Figure 15. Schematic of Machinery Train 2 at CF Industries.

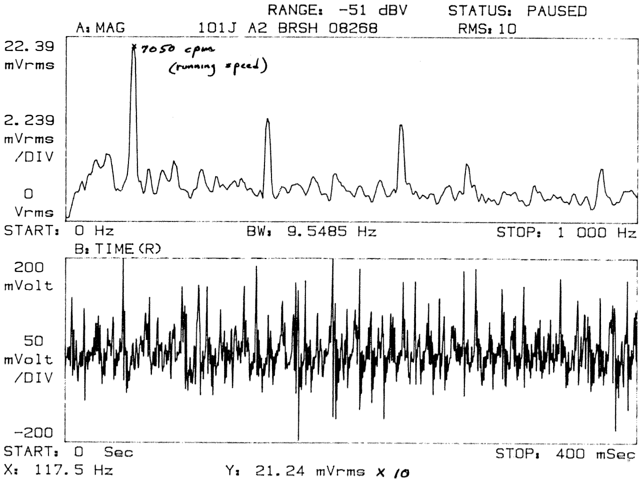


Figure 16. Brush Voltage Signal and Its Frequency Spectrum Obtained from Train 1.

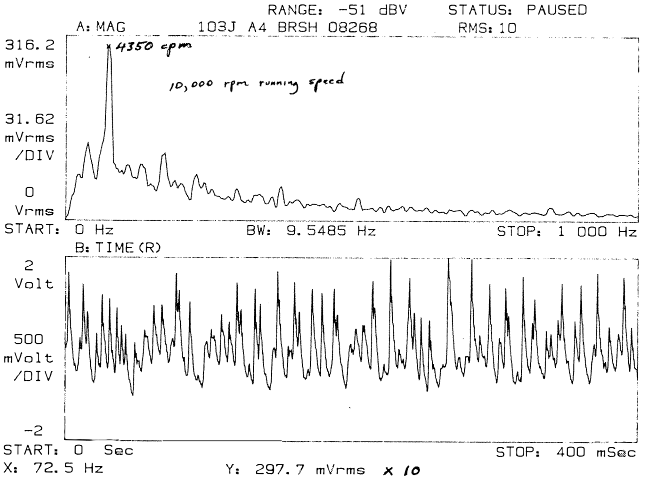


Figure 17. Brush Voltage Signal and Its Frequency Spectrum Obtained from Train 2.

voltage in non-electrical machines. The source of this voltage is usually traced to impenging droplets in the wet stages of steam turbines, or wet gas droplets at the inlet stages of compressors, when liquid knockouts or separators are not capable of removing all the moisture from the gas. Static charges on the rotor build up to a certain voltage level, after which they find their way to the ground by arcing across journal bearings, thrust bearings, or seals, depending on the location of the minimum oil film thickness (i.e., the path of minimum resistance).

A point of controversy on this subject, and critical in diagnosis of shaft voltage problems in general, is the determination of whether the measurement of voltages on problem machines are indicative of electrostatic type voltages (type I) or of the type hypothesized to be caused by electromagnetic phenomena (type II). This identification is very important towards the recommendation of the appropriate remedy to the problem, in order to ensure a minimum of cost and downtime. Therefore, proper characterization of the voltage signal was addressed in the TAMU project, by both laboratory measurements and field measurements. For the purpose of the laboratory investigation, the test aparatus shown in Figure 18 was utilized. This experimental set up includes a Van de Graaff generator, utilized as the voltage source, with its positive side connected to one of the angle irons shown in the figure. Another angle iron with a milled face of one square inch is connected to ground. Both angle irons are mounted on a plexiglass plate to keep them isolated from each other, while still allowing for an accurate measure of the clearance between the two. A high voltage probe (which provides a source of high internal resistance) was utilized with the oscilloscope in these measurements to prevent underestimated voltage values, and to protect the scope from overload due to the high voltages encountered at large clearances. For a clearance of five mils between the angle irons the wave form produced is shown by the oscilliscope photograph in Figure 19. The voltage builds up to the value indicated by the highest peak and then arcs across the angle irons to ground, after which the voltage builds up to the previous level and the cycle keeps repeating. The characteristic of this waveform is identical to the one obtained by Vance from a field measurement on a CO_2 compressor at a fertilizer plant near Tulsa, Oklahoma, and is shown in Figure 13 for comparison. In the laboratory measurement the period of arcing is consistent (producing a distinct frequency). The field measurements on the other hand rarely have a distinct frequency. The reason for this discrepancy is attributed to the varying oil film thickness due to vibration in the actual machine and the fact that the static voltage build up depends on the speed and moisture level in the gas, while in the experiment both clearance and rate of voltage buildup are steady and well controlled. The current was also investigated by measurement of the voltage across a one ohm resistor to ground, which gives a voltage reading equal to the current. The signal becomes fuzzy in appearance, similar to white noise, with an amplitude in the milliamps range.

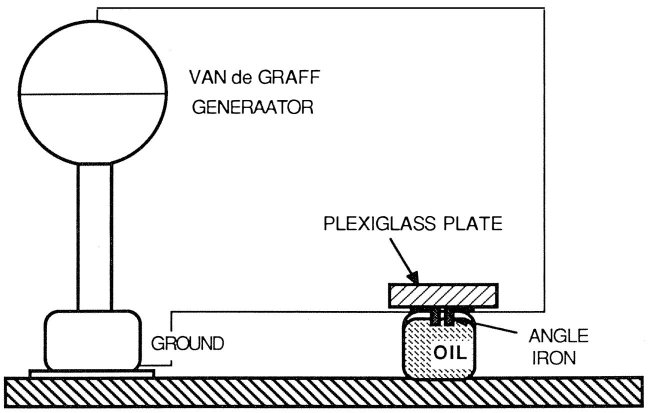


Figure 18. Test Apparatus Utilized for Investigating Electrostatic Voltage Characteristics and Oil Dielectric Strength.

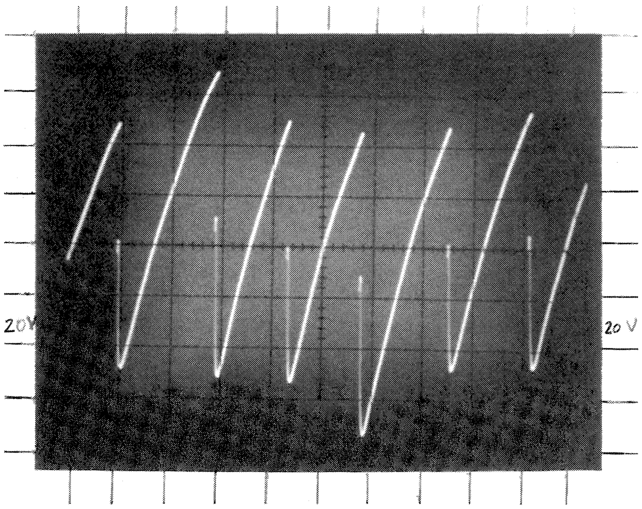


Figure 19. Electrostatic Voltage Signal across a Five Mils Clearance (20V/Div.)

There have been several cases where electrostatic type voltages were measured, but the machines in question were also found to have high levels of magnetization. The field investigation conducted at a refinery, and reported in the previous section, is a good example of such a case. While the possibility of both types of voltage generation taking place independently of each other in a particular machine cannot be eliminated, experiments are underway to determine whether an electrostatic type voltage generation can lead to magnetization of the shaft, or if magnetization of the shaft can contribute to a buildup of static voltage potential.

Another phenomenon under investigation by the TAMU project is the frosty appearance often reported on babbited bearings and seals subjected to shaft voltages such as the one shown in Figure 20. There are some who argue that electrostatic type voltages cannot cause such damage. It has been noted in measurements of oil dielectric strength that arcing causes bubbles to form in the oil. In a bearing this would normally occur at the minimum film thickness where the pressure would be high enough to cause these bubbles to collapse and implode resulting in cavitation damage. This topic is scheduled for further investigation in the program for the coming year.

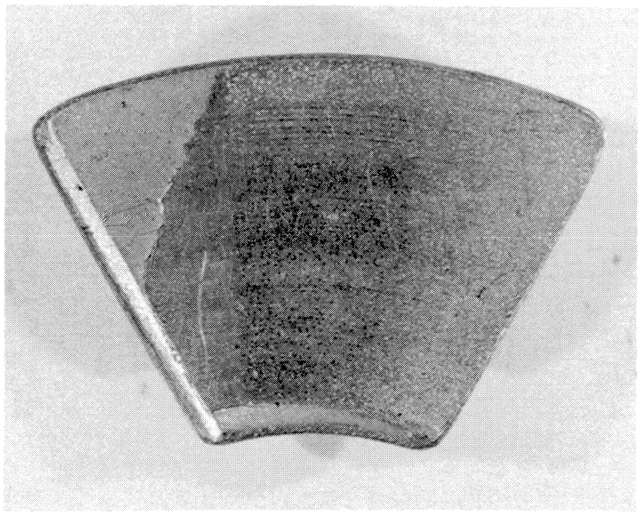


Figure 20. Electrostatic Voltage Damage on a Steam Turbine Thrust Bearing.

These investigations, both in the laboratory and from field measurements, confirmed the nature and some of the general characteristics of electrostatic type voltages (type I), and they center around the following facts:

- The wave form is characterized by recurring discharge, a positively or negatively going spike, or step, as shown in Figure 13 and Figure 19.
- The amplitudes can range from few volts up to 400 volts, depending on the clearances in bearings or seals, vibration levels, and the oil electric resistivity or dielectric strength.
- The current which is obtained from this signal by measuring the voltage across a one ohm resistor, reduces to a fuzzy white noise signal with no distinguishable frequency content and of amplitude levels in the microamps range.
- The frequency content of electrostatic type voltages is still a point open to debate. In some instances, other investigators have found it to be equal to the synchronous vibration frequency, while in the field studies described herein, it was found to be erratic with no frequency related to machine parameters. Yet others have noticed a frequency equal to that of the oil whirl subsynchronous vibration frequency.

Based on these seemingly conflicting observations, it is reasonable to conclude that the frequency is dependent on the rate at which minimum film thickness is reached in a machine experiencing high synchronous or subsynchronous vibrations.

Electromagnetic

The rotordynamics test rig shown in Figure 21 was modified for experiments with the magnetization effects of shafts and casings. For this purpose, the three disks were enclosed in housings with close tolerances and various combinations of magnetization on the disks and casings were tested. Residual magnetic fields of up to 45 gauss were imposed on the rotor and housings as shown in Figure 22 to simulate comparable magnetic fields measured in the field investigations. During all of these tests, voltages of no more than two volts were measured between shaft and ground (across the oil film). The bearings, in an early configuration of this rig, were mounted on aluminum base plates which were in turn electrically isolated from the steel base. Therefore, the currents and the magnetic fields were isolated. The base of the test apparatus was later modified and the aluminum plates were replaced by a steel mounting plate that connected the two bearings and the shaft both electrically and magnetically.

During the summer of 1985, it was decided to perform some measurements simulating a homopolar generator (Faraday

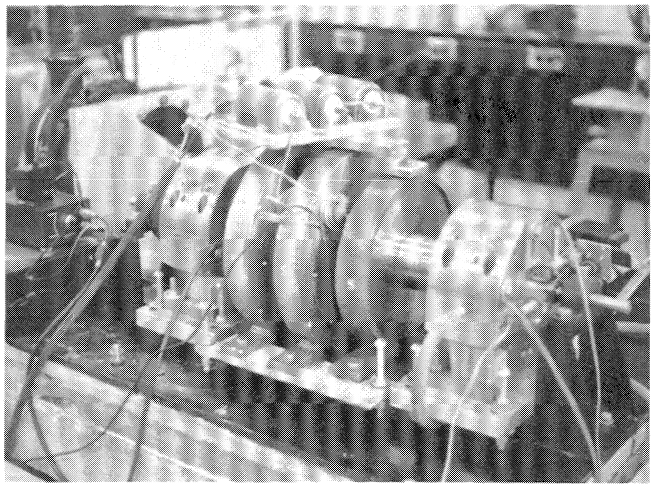


Figure 21. Shaft Currents Test Rig.

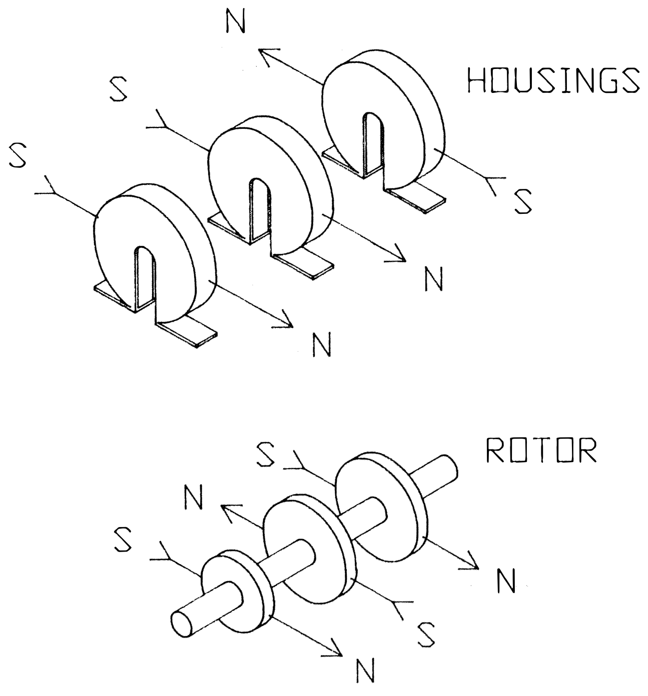
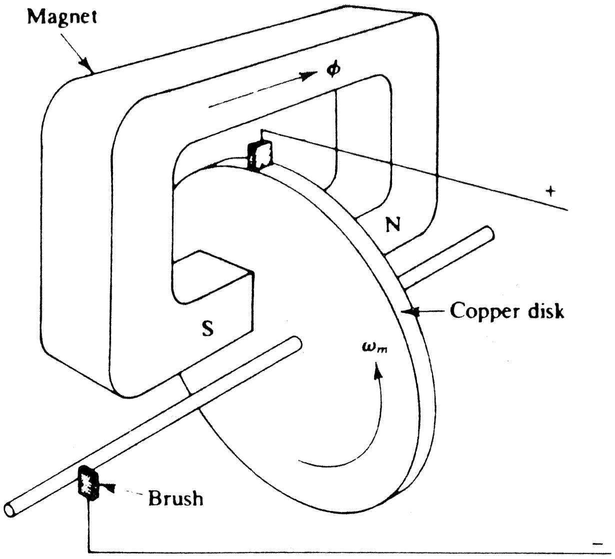


Figure 22. Orientation of Magnetic Fields Imposed on Stator and Rotor.

disk), as shown in Figure 23. The test rig, in which steel nipples were threaded into the wheel housing and wrapped with insulated wire is presented in Figure 21. These electromagnets were used to maintain a magnetic field of 900 gauss. The voltage potential between shaft and ground never exceeded a few millivolts in these tests.



$$\text{terminal voltage} \equiv V = \frac{\omega_m}{2\pi}\phi - RI$$

$$\text{flux} \equiv \phi = 2\pi a \ell B$$

$$\text{current} \equiv I = 2\pi a c J$$

$$\text{resistance} \equiv R = \frac{\ell}{2\pi \sigma a c}$$

Figure 23. The Faraday Disk Circuit.

A simpler rotor configuration was assembled utilizing a Bently Nevada rotor kit. Two permanent magnets were aligned to produce a stationary field of about 800 gauss around the rotating disc. Two Sohre brushes were placed in contact with the disk and connected to an A/D measurement plotting system. The induced voltage varied linearly with speed as predicted, and is shown in Figure 24. The same type of data after the stationary magnets had been removed are shown in Figure 25. Only an axial remanence flux of 50-60 gauss existed in the disc. The induced voltage again varies approximately linearly with speed and achieves a maximum value of 1.8 millivolts at 10,000 rpm.

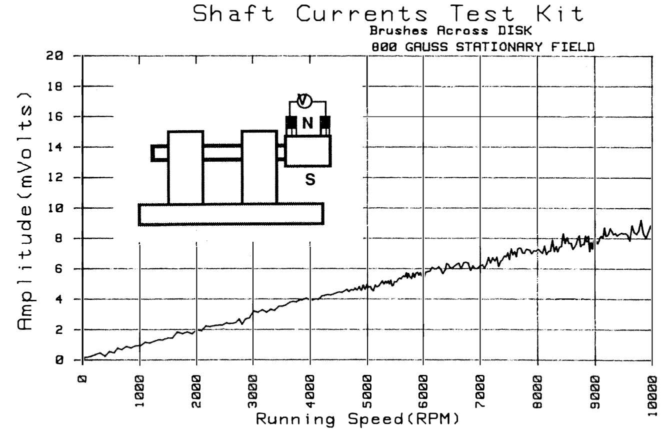


Figure 24. Voltage Induced in the Rotor by a Stationary Field as a Function of Speed.

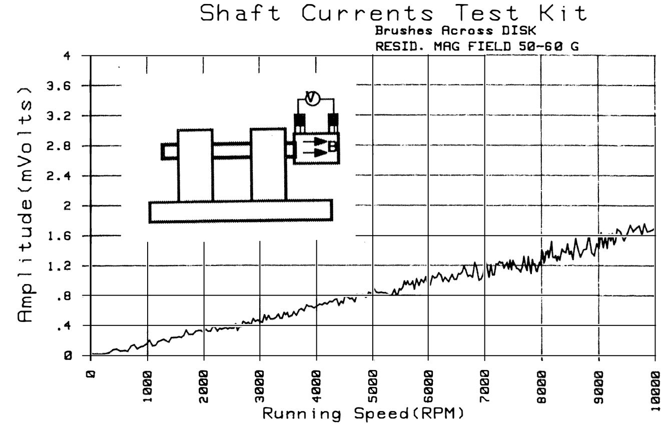


Figure 25. Voltage Induced in the Rotor due to Residual Axial Magnetic Field as a Function of Speed.

The results of these experiments indicated that small voltage drops could be induced either by rotating a non-magnetized shaft in a stationary magnetic field or by rotating a magnetized shaft in the absence of an external field. The next step toward obtaining a self excited state was to demonstrate that current circulating through the stator could cause an increase in the induced voltage through the shaft. The rotor was modified as shown in Figure 26. A controlled current was passed through the stationary coils and the induced voltage was measured across the shaft through Sohre brushes. A plot of induced voltage *vs* the field current at a constant speed of 4000 rpm is shown in Figure 27. The voltage is seen to vary between 0.0 and 10.0 millivolts, as the current changes from 0 to 30 amperes. A similar plot for a constant speed of 6000 rpm is depicted in Figure 28. The obvious trend in these two figures is a significant

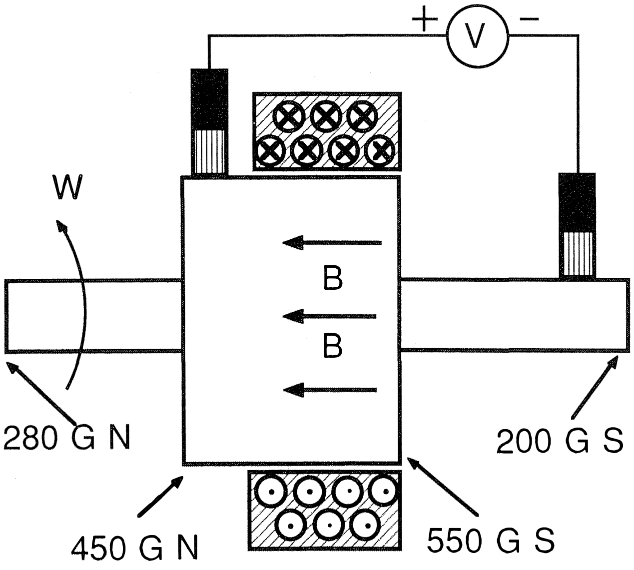


Figure 26. Schematic of the Test Rig Utilized in the Critical Resistance Measurements.

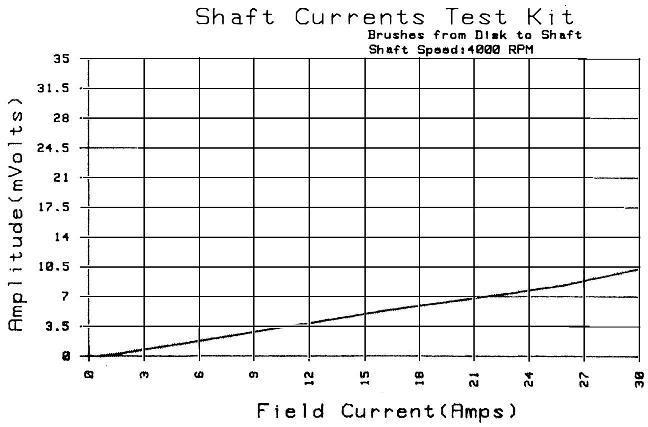


Figure 27. Induced Voltage in the Shaft as a Function of the Field Current at 4000 RPM.

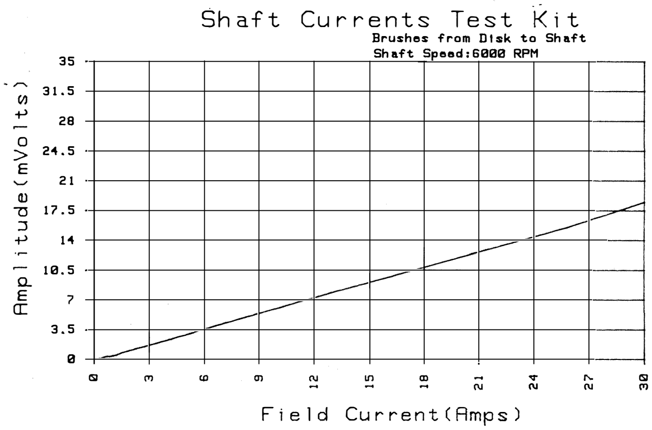


Figure 28. Induced Voltage in the Shaft as a Function of the Field Current at 6000 RPM.

increase in induced voltage with increasing speed. A classical measure of this characteristic is the slope of the V *vs* I curve. Obviously, a much larger induced voltage for a given field current is expected, if the shaft speed is increased. These slopes of the V *vs* I curves are analogous to the so called "critical resistance," measured from the no-load characteristics of self excited, DC series wound generators. The critical resistance represents the maximum load resistance which may be present and still allow self excitation.

Tests are currently being conducted at Texas A&M University to reproduce self excitation in a laboratory test rig which simulates the eletrical and magnetic characteristics of turbomachines. As mentioned, voltages have been induced in a spinning magnetized rotor, and it has also been verified that the voltages in the shaft are affected by the current circulating in a path that surrounds the rotor. With these steps completed, efforts are now being directed towards constructing the closed loop apparatus required for self excitation. Correspondence with Schier [15] and Whitney [16] have established two key factors in this endeavor. The first is construction of a magnetic return path with a sufficiently low reluctance. This requires a large diameter shaft and a stationary return path of large cross sectional area, in addition to minimal clearance air gaps. The second factor is minimizing the contact voltage drop at the interface points where the electrical return path enters and leaves the rotating shaft. This will require that the electrical return path be pressed against the shaft with a large preload. (In machine failures a rub satisfies this condition). Schier [2, 15] has reported that a preload level between 150 and 200 pounds was required to initiate self excitation in his test apparatus. Results of the self excitation tests will be forthcoming in the literature.

Phone Pickup Measurements

Sohre [1] suggests the use of a phone pickup to measure rotating magnetic fields in rotating machines. The phone pickup is basically an inductive coil which gives a voltage signal proportional to the fluctuating magnetic or electrical fields and their respective strengths. A plot of the voltage obtained from a phone pickup when placed close to an axially magnetized disk of 50 to 60 gauss is shown in Figure 29. The phone pickup voltage increases linearly with speed along with the voltage measured across the ends of this disk using the Sohre brushes (Figure 25). A frequency spectrum of the voltage induced in the phone pickup with the disk rotating at 4860 rpm is presented in Figure 30. Two and three times running speed frequencies are noted. When the phone pickup was placed next to a diametral field of 500 gauss, the dominant frequency in the frequency spectrum was that of the running speed as shown in Figure 31. The amplitude and frequencies obtained when placing the phone pickup next to a fluorescent light for a strength of field reference are shown in Figure 32.

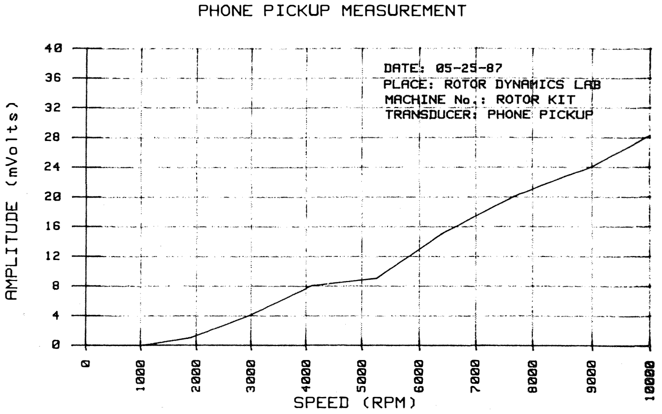


Figure 29. Phone Pickup Voltage Induced by a Rotating Axially Magnetized Disk.

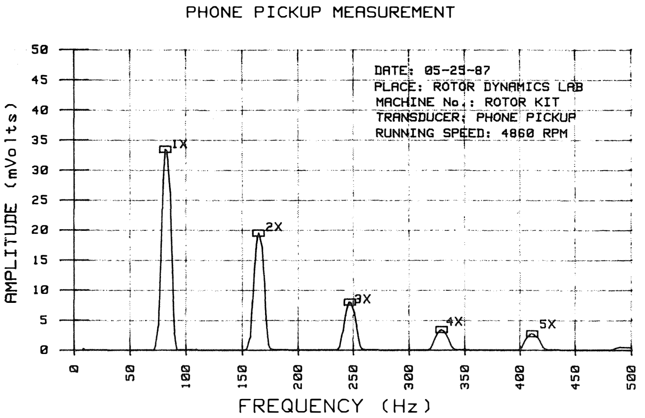


Figure 30. Frequency Spectrum of the Voltage Induced in the Phone Pickup by the Axially Magnetic Field in the Shaft.

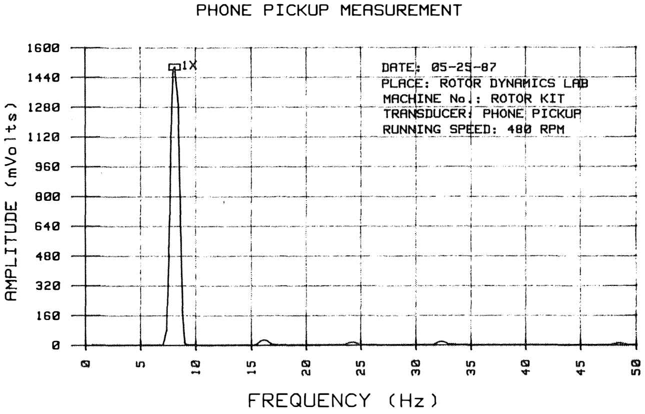


Figure 31. Frequency Spectrum of The Voltage Induced in the Phone Pickup by a Magnetic Field Aligned Along the Diameter of the Disk.

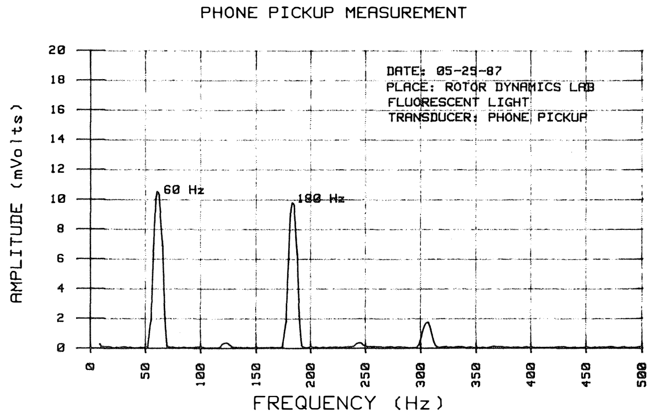


Figure 32. Frequency Spectrum of the Voltage Induced in the Phone Pickup by a Fluorescent Light.

While the phone pickup produces a voltage signal proportional to speed and to the strength of the magnetic field in the rotating shaft, it does not provide a positive identification of the presence of electromagnetically induced shaft currents. The field measurements at the ammonia plant described previously, did not indicate the presence of magnetic fields when the machines were surveyed with a phone pickup, even though the brush voltage showed electromagnetic type characteristics. Conversely, the measurements at the refinery in Ashland, which were discussed under electrostatic field measurements, showed significant voltages from the phone pickup measurements, even though the brush voltage was characteristc of electrostatic type voltages.

Breakdown Voltages

In an effort to quantify and clearly identify the important parameters by which voltages or currents flow from a rotating shaft to ground in a bearing, a number of experimental measurements have been conducted. One of the experimental aparatus utilized to conduct these measurements is shown in Figure 33, with the housings removed from around the disks. The rotor consists of a 4340 steel shaft with three solid disks mounted on it, and radially supported by two tilt pad bearings. The bearings have four pads with a load on pad configuration. The schematic diagram shown in Figure 34 illustrates the circuit utilized to conduct the measurements. A DC power supply was utilized as the voltage source. The voltage was transferred to the shaft using a Sohre brush, and a voltmeter measured the voltage potential from shaft to ground. The current was obtained by measuring the voltage drop across a one ohm resistor to give a voltage signal equivalent to current flow.

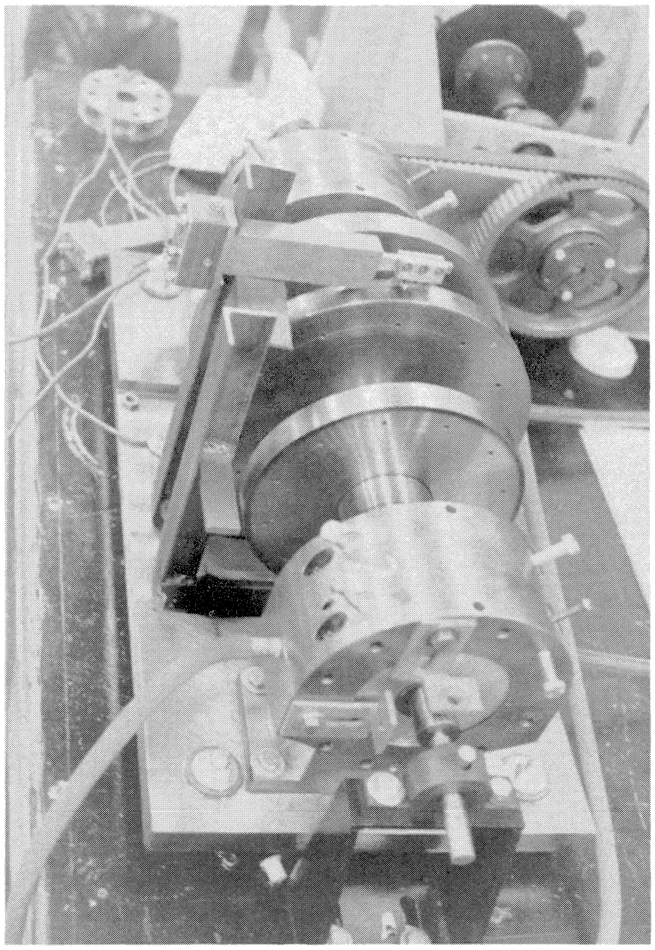


Figure 33. Modified Test Rig for Breakdown Voltage Measurements.

The first tests of breakdown voltage were conducted by running the shaft to a speed of 8000 rpm, and then allowing it to coast down while measuring the voltage and current versus speed. This test procedure was repeated with four different voltage potentials applied across the oil film. The results are shown in Figures 35, 36, 37, and 38, which correspond to voltage potentials of two, five, eight, and ten volts, respectively. As can be seen from the plots, the current is zero (no flow) until the speed declines to a certain value. By comparing these four plots, it is found that the speed at which the current starts to flow is also dependent on the voltage potential across the oil film. These measurements help to identify the voltage potential and the bearing clearance (or more appropriately the oil film thickness) as the two important factors in determining whether current will pass across the oil film and through the bearings. The next set of tests, which utilized the same test apparatus, but with a slightly different circuit, resulted in similar conclusions. The circuit is shown in the schematic presentation of Figure 39. The difference, compared with the previous tests, is that the current which had only one path to ground through the oil film bearings, is now provided with an alternate path to ground via another Sohre brush. The shaft is coasted down from 8000 rpm and the measurements are conducted using voltage potentials of 0.16 and 5.0 volts, respectively. As shown in the plot of Figures 40 and 41, the current flow is through the bearing at low speed, since it then provides the lowest resistance path to ground. At higher speeds when the oil film is thicker, the second brush provides the lower resistance path. These tests indicate the necessity to have a very low brush resistance, and demonstrates the fact that in cases where a machine is experiencing high vibration levels, it is possible for the currents to flow through the bearings even though a brush is installed on the shaft.

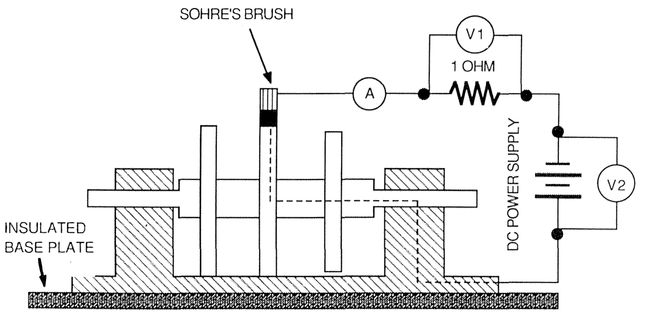


Figure 34. The Circuit Utilized for Breakdown Voltage Measurements.

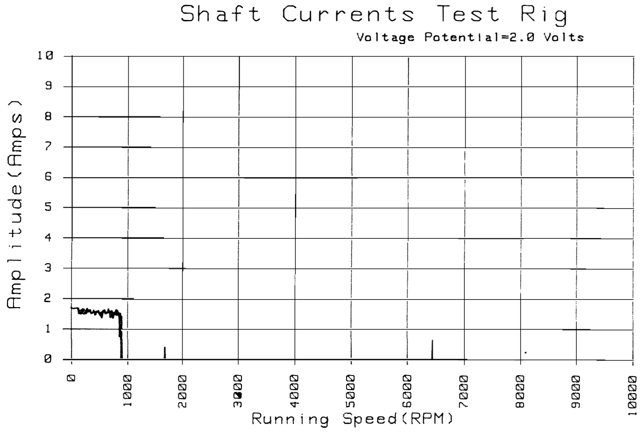


Figure 35. Breakdown Voltage vs *Speed for a Voltage Potential of Two Volts.*

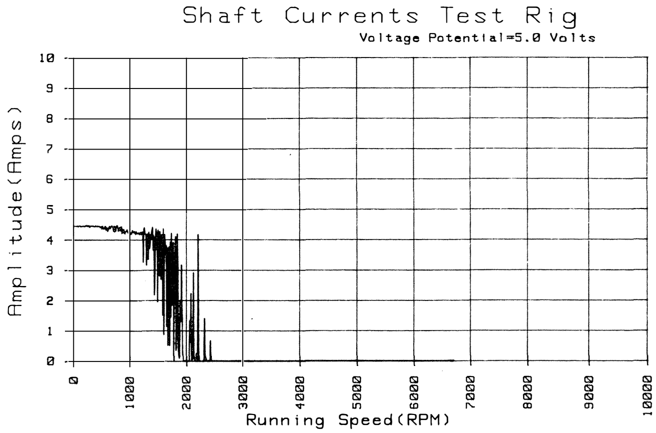


Figure 36. Breakdown Voltage vs *Speed for a Voltage Potential of Five Volts.*

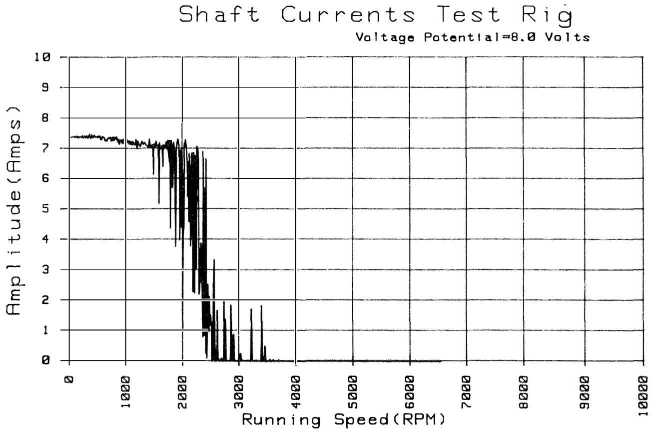


Figure 37. Breakdown Voltage vs *Speed for a Voltage Potential of Eight Volts.*

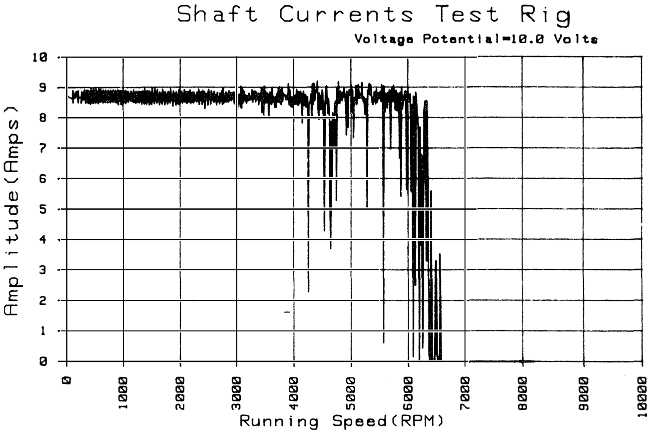


Figure 38. Breakdown Voltage vs *Speed for a Voltage Potential of Ten Volts.*

The measurements described above provide some qualitative measure of the amount of voltage potential and bearing clearances required for currents or voltages to flow or arc across the bearing. A more quantitative measurement was established using the experimental setup shown in Figure 18 which was previously described in the electrostatic voltage investigation. The probe which consisted of the two angle irons was adjusted for a clearance range of two to ten mils. For this investigation, five different lubricating oils were used, including one obtained from an ammonia plant in Louisiana that had suffered shaft voltage problems. The results are shown in Figure 42 which plots the maximum voltage measured versus the clearance.

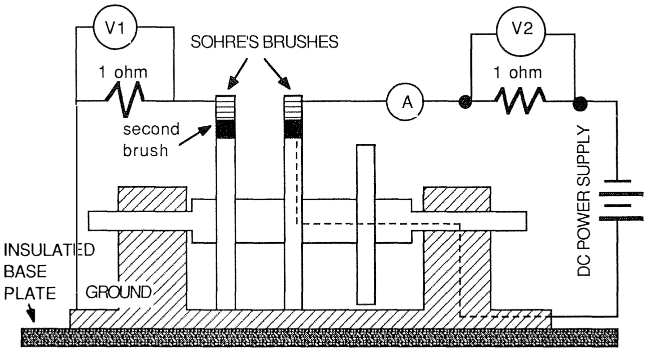


Figure 39. Schematic of The Modified Circuit Showing the Alternate Path to Ground Via The Second Brush.

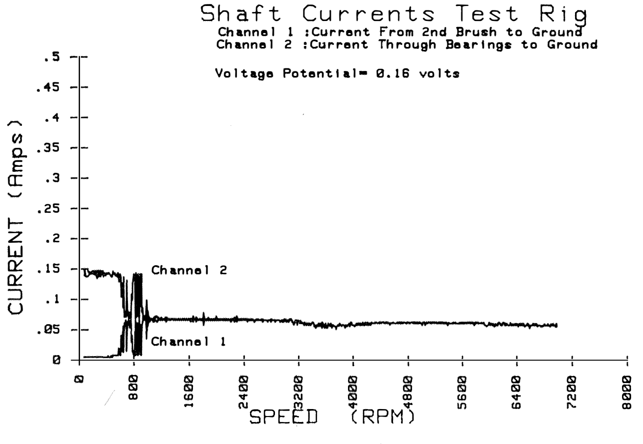


Figure 40. Current Path vs *Speed for a Voltage Potential of 0.16 volts.*

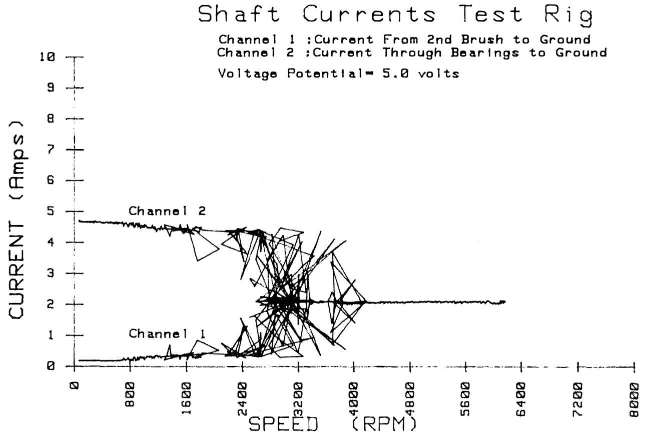


Figure 41. Current Path vs *Speed for a Voltage Potential of 5 volts.*

Note that the voltage levels for the SAE 30W motor oil are considerably lower than the other oils, due mainly to the detergents and additives it contained, which made it more conductive. Another point to note in this plot is the voltage level obtained for the turbine oils in the upper half of the clearance range. The voltage in this range was noted to be of the same level as many of the voltages measured in the field on machines operating with these typical clearances.

The distinctive behavior of the SAE 30W oil prompted an investgation of additives in the ISO-VG-68 turbine oil in order to reduce the voltage potential buildup and act as as anti-static agent. Preliminary tests with one particular additive indicate that a concentration of around 4000 ppm reduces the voltage potential across a ten mil clearance from 300 volts to 90 volts. There is no significant increase in the measured oil viscosity with the additive, and the supplier confirms that it has no harmful influence on the foaming or air release capability of the original oil.

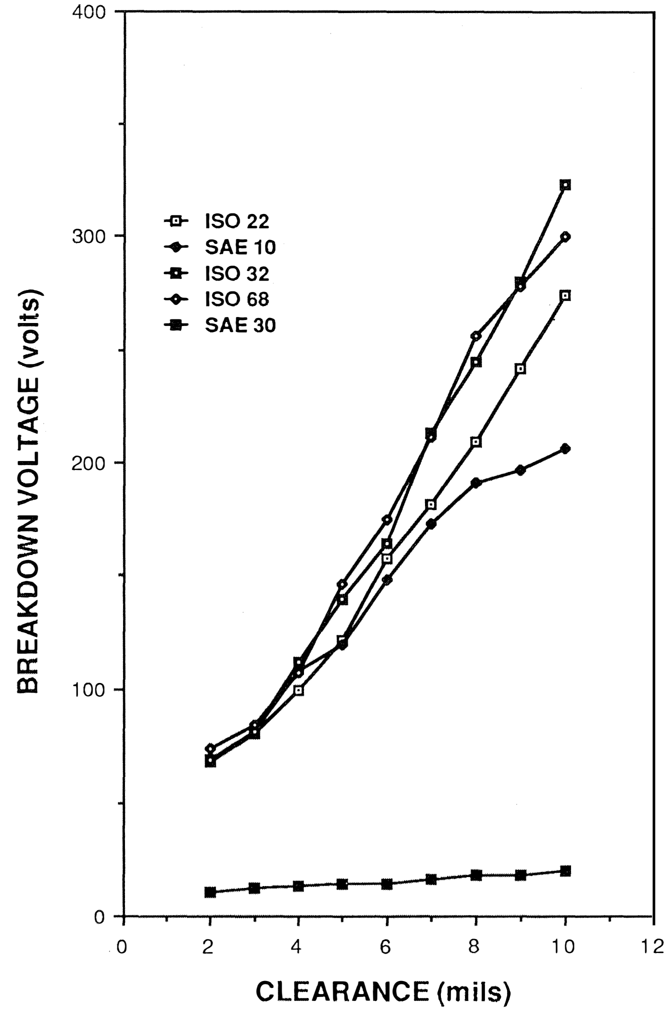


Figure 42. Dielectric Strength of Some Industrial Lubricating Oils vs *Clearance.*

CONCLUSIONS

Based on the laboratory and field measurements to date, the following conclusions and opinions can be stated:

- Electrostatic voltages continue to be the most common source of electrical damage to bearings and seals in turbomachinery. They are usually characterized by high voltage spikes (up to several hundred volts) with random discharges to ground potential, and with very low currents in the milliamps range. The current signal appears as white noise on the signal analyzer. Damage is gradual and extends over a period of several months to a year or two. There appears to be some evidence, yet unexplained, that these electrostatic voltages are influenced by residual magnetic fields in the machine.
- Electromagnetic type shaft currents appear in two categories:
  - Characterized by very low voltage and very high current in the range of thousands of amperes which can occur suddenly

(especially when shaft rubs occur) and result in catastrophic type failures (the Schier phenomenon).

- Characterized by voltage and current signals which contain discrete frequencies related to shaft speed. In all cases measured by the authors to date, the voltage amplitudes in this category do not exceed three volts.

- Electrical discharge across a bearing or seal may occur even when shaft brushes are installed if bearing clearances are diminished by high vibration or a large operating eccentricity. This may occur while traversing a critical speed, operating at lower than design speeds, or if there is significant misalignment.

- A magnetic remanence in the rotor or stator can induce a potential voltage drop in the rotor. This may drive a circulating current that reinforces the remanence and leads to self excitation, (subcategorized under electromagnetic shaft currents) as described by Schier [2]. Laboratory experiments are being conducted to determine the requirements for this phenomenon. These efforts are concentrated on the following factors:
  - Reluctance of the magnetic return path including the casing and rotor.
  - Contact voltage drop in the electrical return path.
  - Level of initial magnetic remanence.
  - Shaft speed and diameter.

- The breakdown voltage between journal and bearing surfaces is highly dependent on lubricant additives, moisture content, and filtration effectiveness.

- Based on a non-rotating test, the breakdown voltage was invariant with the source of voltage applied across the gap. Both an electrostatic voltage source and a DC voltage source produced similar results.

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1. Sohre, J. S., and Nippes, P., "Electromagnetic Shaft Currents and Demagnetization on Rotors of Turbines and Compressors," *Proceedings of the 7th Turbomachinery Symposium,* Gas Turbine Laboratories, Department of Mechanical Engineering, Texas A&M University, College Station, Texas (1978).
2. Schier, W., "Self Excited Homopolar Direct Currents in the Shafts of Machines," Elektrotech ZA, *86,* (23), pp. 737-741, Translation No. 3925, Associated Electrical Industries Power Group (November 1965).
3. Merrick, E. G., "Bearing Currents," General Electric Review, *17,* pp. 936-940 (October 1914).
4. Buchanan, W., "Currents in Bearings of Electrical Machines," The Electrician, pp. 266-267 (May 28, 1915).
5. Alger, P., and Samson, H., "Shaft Currents in Electrical Machines," Transactions of AIEE, pp. 235-245 (February 1924).
6. Sears, F. and Zemansky, M., *University Physics*, Addison Wesiey (1970).
7. Steinmetz, C., *Theory and Calculations of Electrical Apparatus,* New York:McGraw Hill (1917).
8. Seely, S., *Introduction to Electromagnetic Fields*, New York:McGraw Hill (1958).
9. Cullwick, G., *The Fundamentals of Electro-Magnetism*, Cambridge at the University Press (1939).
10. Tsien, T. N., "Electromagnetic Induction of Rotating Magnets," Ph.D. Dissertation, University of Houston (1970).
11. Boyd, J., and Kaufman, H., "The Causes and Control of Electrical Currents in Bearings," Lubrication Engineering (January 1959).
12. Braun, R., "Magnetic Voltage on Turbine Rotors and Magnetization of Rotors and Stators," Allianz A. G., Maschinenschaden, *41*, Heft 3 (in German)(1968).
13. Sohre, J., "Are Magnetic Currents Destroying Your Machinery," Hydrocarbon Processing, pp. 207-212 (April 1979).
14. Sohre, J., and Nippes, P., "Electromagnetic Shaft Currents in Turbomachinery - An Update", AICHE 25th Symposium in Ammonia Plants, Portland, Oregon (August 1980).
15. Schier, W., Series of personal correspondence with Dr. Palazzolo, (1987).
16. Whitney, E., Series of personal correspondence with A.B. Palazzolo (1987).