ELECTROMAGNETIC SHAFT CURRENTS AND DEMAGNETIZATION ON ROTORS OF TURBINES AND COMPRESSORS

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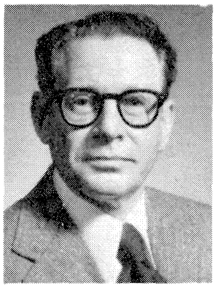

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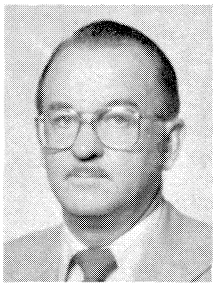

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ABSTRACT

A high percentage of large, high-speed compressor trains has suffered serious failures which were initiated by shaft current damage. These currents are generated by electromagnetic effects. The basic mechanics of various types of shaft currents are briefly reviewed, and the electromagnetic type is discussed in detail. Part I covers the theory of current generation, sources of magnetism, symptoms, modes of failure, remedial action, and case histories. Part II explains in more detail how small residual magnetic fields can generate currents, and how self-excitation and consequent self-magnetization may occur. Principles of demagnetization are also covered.

PART I

INTRODUCTION AND SCOPE OF PRESENTATION

This presentation includes a review of literature and of personal experience with a number of serious shaft current problems on compressor units. This type of problem is now a major cause of serious damage to equipment, and of frequent, unscheduled shutdown of major trains, with consequent plant outages involving considerable economic loss. Compressors are affected as well as turbines, and the most serious problems are with very large, high speed, high pressure compressor trains, such as compressors in ammonia, methanol, and ethylene plants. Damage levels range from mild to very severe. The final phase of the shaft current syndrome is initiated by failures of thrust bearings, main bearings, couplings, compressor gas seals, and gear teeth. If impending failures are not detected in time — by fast acting protective instrumentation and automatic shutdown devices — major components of the machinery may be destroyed.

In this presentation the emphasis will be on how to recognize a shaft current problem, identify the type of current-generation involved, and correct the problem. A brief description of the various current-generating phenomena will be given, but for detailed explanation of the electrical phenomena involved please refer to Part II of this paper and to the major references quoted at the end.

While shaft grounding may help in some cases, the only certain remedy is complete demagnetization of rotors and/or stators.

GENERATOR OR MOTOR INDUCED CURRENTS

About four or five different types are encountered, see [3] and [4]. These will not be discussed here, being an electrical-equipment related specialty. Note, however, that the possibility of accidental electrification of the shaft should always be considered if line-frequency or double line-frequency is present in the shaft-current frequency spectrum.

ELECTROSTATIC TYPE (DIRECT CURRENT)

This paper deals with magnetically induced currents, but a brief review of electrostatic currents is necessary to define the distinctive differences between the basic types of current generation.

Origin and Characteristics

1. Impinging Particles, or Droplet Atomization

In wet stages of turbines and in wet-service compressors, references [1], [2], [3], and [4].

2. Dry Gas-Friction Induced

Generated in high-temperature piping and in the hot portion of the turbine, [3] and [4], or in compressors handling dry or charged-particle gases.

3. Charged-Lubricant Induced

Generated by certain types of oil filters, [4]. Also, if suspended-particle type lubrication is used in an oiling system, (molybdenum disulfide, graphite, etc.), extremely high voltages can be generated by means of particle friction against piping walls.

4. Charged Drive-Belts

Under certain conditions a drive belt can act as a Van de Graaff generator, producing a very high electrostatic potential. This form of electrostatic current is not normally encountered with turbomachinery.

5. Voltages and Currents

The voltage measured on the shaft will depend mainly on whether or not discharge occurs within the machine, and on the resistance across the discharge. If seals are rubbed, or if a governor drive gear is present, there may be no apparent voltage on the shaft. If no such direct contacts exist, breakdown occurs mainly across the oil film of the thrust bearing or, if thrust loads are light, across the main bearings or seals of a machine. Breakdown occurs when the electrostatic field gradient reaches the breakdown threshold. This depends not only upon the electric potential developed across a particular dielectric but upon the dielectric field withstand, power-factor and physical configuration. The measured voltage buildup ranges from 1 volt to 250 volts before discharge occurs, and then the voltage drops to near zero. Voltage may reverse polarity, depending on the balance of shaft currents of different origin, which may have different polarity. Typically, voltages reach about 70 volts, with currents in the order of several milliamperes. Therefore, there will be no significant heat generated where the current discharges or crosses interfaces, and simple, small grounding brushes will do the job. Deterioration of bearings and other components occurs over a relatively long period of time, never very rapidly (as may be the case with electromagnetic currents), and therefore this type of problem is relatively easy to deal with. Damage progression can be observed and monitored by means of distance detectors and temperature detectors in thrust and journal bearings, and by vibration instrumentation, so that the situation is under some control. Usually the damage is corrected during routine maintenance. This is one reason to always inspect bearings. However, failures will definitely occur if the situation is neglected. If damage is permitted to progress unchecked, instantaneous, catastrophic failures may finally occur. Therefore, electrostatic currents must still be treated with respect.

Since electrostatic currents are very well documented in the literature, and since they are easily and satisfactorily neutralized by simple shaft brush arrangements, this type of current will not be described in detail. Please refer to the literature for more information.

Note, however, that grounding a train at the end only may cause considerable damage to gear teeth and coupling teeth, since the current may have to pass across these components. Many steam turbines have a worm-gear governor drive, or oil-pump drive, which usually provides good grounding if the worm gear is made of metal. However, the drive gear itself may suffer shaft current damage, and consequent failure of the drive. In many cases where metal worm gears were replaced by fiber gears, shaft current damage began to show up at other parts of the unit.

In practically all cases it is impossible to eliminate the cause of the problem, therefore the only remedy is prevention of damage by suitable grounding of the rotor, and of the entire unit.

Symptoms Peculiar to Electrostatic Shaft Currents

These are relatively mild, the damage consisting mainly of frosting in the babbitt. Progress is relatively slow. The distinctive feature is the *absence* of the earmarks of the electromagnetic type current, as explained below. One important characteristic is the location of the damage, which is *always* at the point of the lowest resistance to ground, usually at the governor drive gear or the thrust bearing. With electromagnetic currents, damage can also be at locations having higher electrical resistance, but being in areas favoring shortcircuited loops.

To check for electrostatic currents, an electro*static* volt meter or oscilloscope can be used, or a "static gun" with radioactive source, if the shaft is visible. The common type of volt-amperemeter is not suitable, because of the low currents. A wire held against the shaft may draw a long, high-voltage spark. However, always remember that no voltages will be present if the currents can easily discharge inside the machine.

Electrostatic Current Grounding Devices

One small ground brush for each machine will effectively ground electrostatic currents. Preferably the brushes should be in the axial direction, near the shaft center (to reduce circumferential velocity), at the outboard ends of a shaft. The "Bendix" stranded copper brush (Figure 1) has been popular and reasonably successful where oil lubrication is available. For machines not having accessible shaft ends and running at high circumferential velocities (in excess of listed maximum permissible values) the situation becomes difficult.

A "conducting coupling" may be used to get the current to the brush without damage to flexible couplings. These couplings have a sort of coil spring inside the hollow spacer sleeve. Reliability has not been well demonstrated so far, and for high speeds there could be considerable problems with unbalance, and possibly with friction-excited whirl phenomena or other rotating instabilities. Also, coupling disassembly may be difficult under field conditions. However, this is a promising approach.

The alternative is to use high-speed wire brushes, made of silver or brass wire, or simply laying a brass welding rod across the shaft like a leaf spring. In any case, if gas or explosive mixtures are present, care must be taken that the material is compatible with the gas, to avoid acetylizing or corrosion of the material. Also the possibility of sparking must be considered with all brushes. This could occur after tension is lost, and it could cause an oil vapor explosion or gas fire.

Where the electrostatic currents are light it might be decided to let the currents go through the coupling teeth, even if it causes some problem, because coupling deterioration would be relatively slow. However, coupling lock-up may occur.

The best way to lead current from the inner bodies of a train to the grounding brush is to use a membrane-type (= flex-disk) coupling, which is inherently conducting. These couplings are now fairly widely used for critical, high speed, high HP service, and generally with better success than the traditional gear-type couplings.

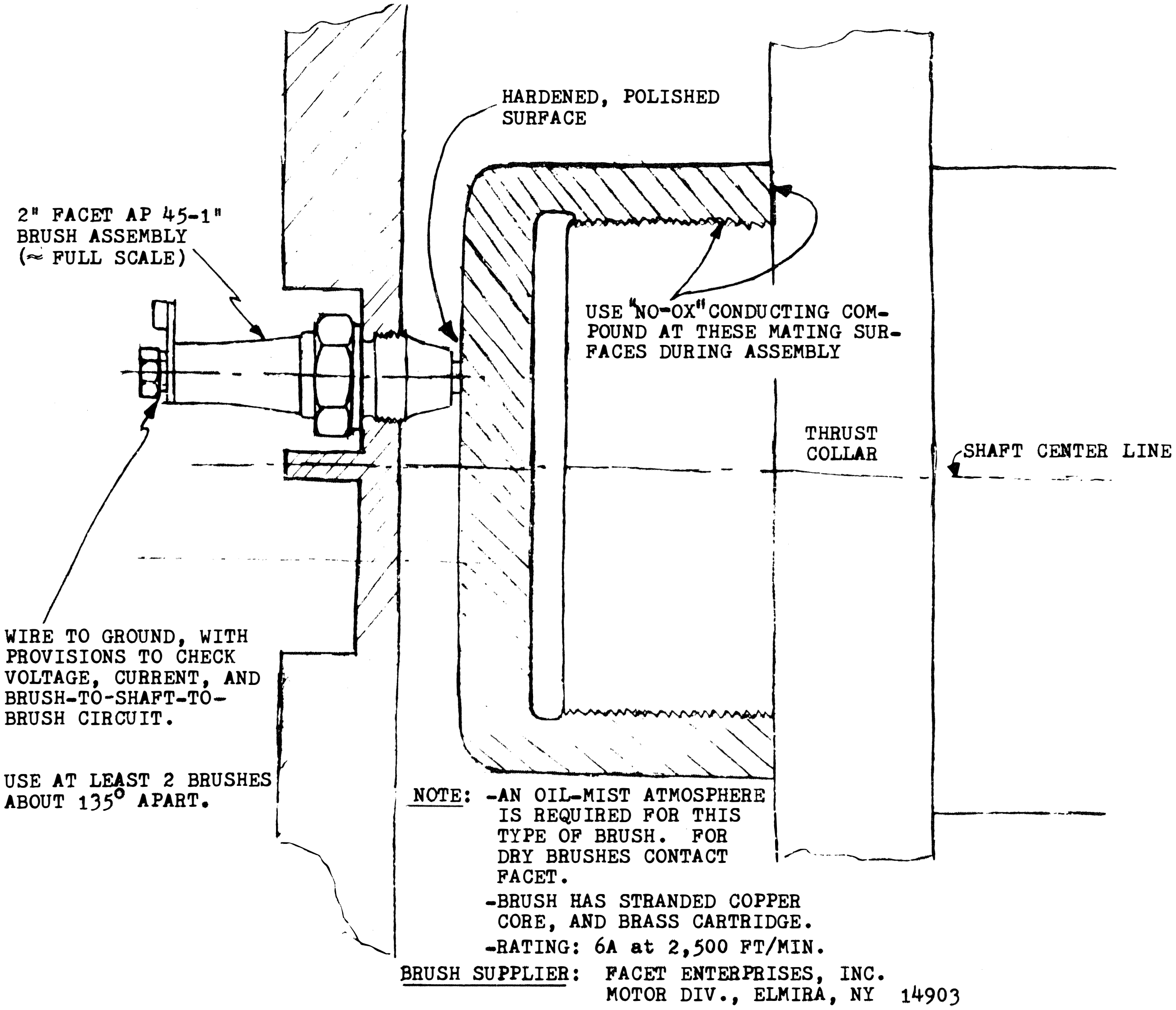


Figure 1. Typical Installation of Axial Shaft Brushes (Removable in Service).

ELECTROMAGNETICALLY-INDUCED SHAFT CURRENTS

General

While the electrostatic voltages are unpleasant but controllable, the electromagnetic type can be extremely destructive. It afflicts mostly large units and/or high speed machines. Little practical information is available in the literature, and since the problem is widespread throughout the industry, causing very large losses of production each year, this problem will be explained in some detail, although in a simplified manner. The best reference I could find is reference [3], which gives a complete explanation and good theoretical documentation of the phenomena involved. However, this reference is in German, and therefore of limited value to the average reader. Furthermore, only problems with turbine-generator units are described. Reference [6] is the best reference in English, but it is also limited to electrical units. As far as I know, there is no reference at all dealing with turbo-compressor units. The electromagnetic principles involved will be explained in Part II of this paper.

Distinguishing Characteristics of Magnetic Shaft-Current Problems

- Magnetization of rotating and/or stationary components.
- Presence of severe damage due to high current-density, such as indications of heat, burned areas, welding of components at point of contact, and significant metal removal at contact points between parts (such as seats of seals and bearings) due to electric discharge machining ("EDM"). The currents flowing between rotor and stator can reportedly reach several thousand amperes [3].

The following mechanisms may be involved in generation of shaft currents of this type:

Eddy-Current Effect

This is exactly the same process as with the well known eddy-current brake, which is simply a disk rotating near a stationary magnet. The currents excited in the disk by the magnetic field produce a braking action, and the energy is transformed into heat within the disk. In a rotating machine the magnetism may be stationary, generating the currents in the rotor, or the magentic element may be on the rotor, generating eddy-currents in the stator metal.

Magnetic Field Rotating with the Shaft

If a rotor has an axial field, part of the magnetic flux will go to the stator at a close-clearance point, or where rotor and stator are in contact. The loop will then try to close at another seal, or at any small gap along the shaft. At the location where the field transfers from rotor to stator, the magnetic lines may be fixed with the shaft, rotating like the spokes of a wheel. This effect will generate a unipolar voltage in the stationary component, (a pure alternating current). This current is then automatically shortcircuited at this same location.

Magnetic Field Stationary in Casing (Bearing Case, Seal Case, Coupling Case)

This generates a unipolar voltage in the shaft, see Fig. 2.

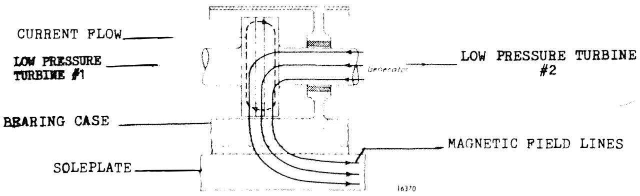


Figure 2 (Ref. 3). Example of Short-Circuited Unipolar Shaft Currents Being Generated in a Solid Coupling, by Means of a Magnetic Field in the Bearing Case.

As shown, current flow is dissipated with the rotating component without harmful effects on bearings or seals. However, if the magnetic field is located in the rotating component, the situation is reversed, and a current will now flow where the magnetic field lines are shown in the above illustration. The rotating magnetic field lines will pass to the stator metal, where axial-oriented voltages will cause currents, resulting in breakdown of the dielectric space between rotor and stator.

Combination of Rotating and Stationary Field

This will occur in many cases. There will be a "slip" between the field lines, of a magnitude depending on the magnetic characteristics of the material. The unipolar voltage in the stator and rotor will have opposite polarity, and shortcircuit can occur through the oil film of a bearing or a seal. This causes a current to flow across the bearing or seal, for example in such a way as to form two zones of current transfer, one at each end of a bearing, or from one bearing to a seal, etc., as shown in Figures 3a, 3b, and 3c.

If the magnetic field crosses several points, the unipolar voltages can become additive, reaching several volts. If there is a ground at the far end of the train (a grounding brush or governor-drive gear), the voltage will reach a maximum at the opposite end of the shaft system. For example, if the last compressor has the ground brush, the maximum voltage will occur at the outboard end of the turbine. If a compressor train has a worm gear drive or pump drive at the high pressure end, the maximum voltage will occur at the outboard end of the last compressor of the train (see Reference [3] for a detailed explanation).

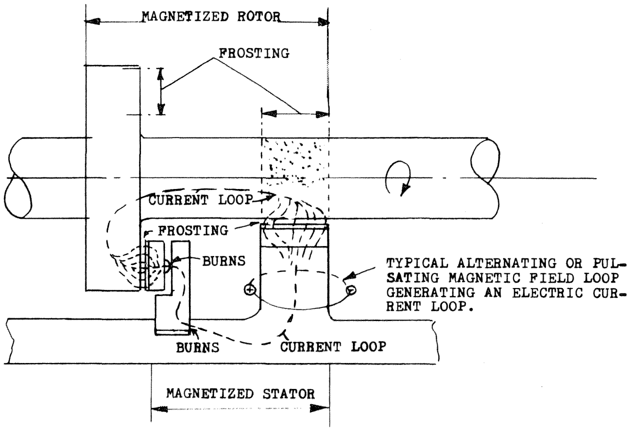


Figure 3a. Short-Circuited Current-Loops Across Thrust and Journal Bearing (Schematic).

Magnetized rotating or stationary components may be the source of alternating or pulsating magnetic flux.

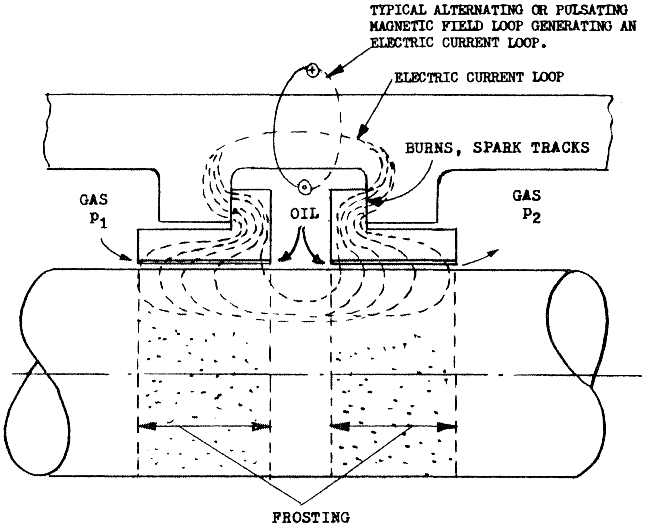


Figure 3b. Short-Circuited Current Loop Across Two Compressor Seals of Floating-Bushing Type. (Schematic, Typical).

If, together with the presence of magnetically induced voltages, the rotor also experiences shaft instability or vibration, the oil film will have reduced electrical resistance. This explains the often observed phenomenon that no shaft current damage is observed until a unit experiences oil whirl. I have seen several examples where units ran for years without having a shaft current problem. Then, for one reason or another, an oil whirl occurred, and severe shaft current damage began to develop very rapidly afterwards. Evidently, the reduced electrical resistance of the oil film during periods of oil whirl provided the necessary bridge for the currents to jump between rotor and stator, and to initiate the process of self-excitation, (see below) which now left the rotor and stator components strongly magnetized. Because of the stronger magnetism the shaft current phenomenon then continued even after the oil whirl was eliminated. A period of heavy vibration could do the same, and so could a seal rub or similar contact, or close proximity between rotor and stator.

For example, a thrust bearing is a prime candidate for a current to cross, because of the extremely thin oil film between the thrust runner and thrust shoes, especially when the thrust bearing is highly loaded. As we have said, the highest voltage buildup may be at the end of the train. In most units, thrust

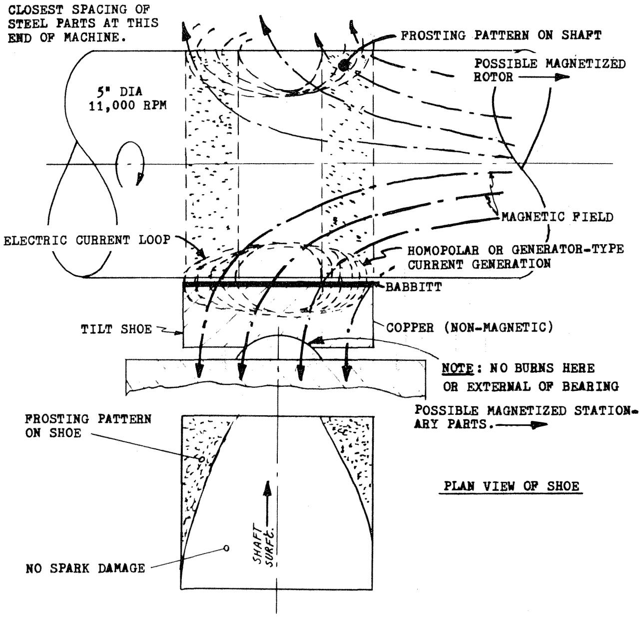


Figure 3c. Short-Circuited Current Loop Within One Journal Bearing.

A tilt-shoe bearing is shown (based on a specific case-history), but the same pattern occurs also with any other type of bearing. The shoe in this case was non-magnetic, damage would have been worse with a steel-backed shoe.

Note that this type of damage would not be prevented by isolating the bearing, nor is there any effective method of grounding. It is theoretically possible to reduce damage by grounding at both sides of the bearing. However, this would require 4 brushes, running at 240 ft/sec surface velocity. Heat generation would be considerable.

bearings are also arranged at both ends of the train. With the low electrical resistance across the thrust bearing it seems quite logical that the outboard thrust bearings would be very vulnerable to current transfer. Once a circuit is established at one end of the machine, the voltage will rise at the other end of the train, and quite likely a current transfer will occur there also. In other words, the points of maximum current transfer may very well shift from one location to another, and the magnetic field which is generated by the shortcircuited currents will also build up at various locations of the rotor, depending on which location is the most active at any given time; for example, as the electric resistance of bearings changes with rotor position, thrust, current damage, and operating conditions. However, remember that each loop has a strong current flow and will leave the rotor permanently magnetized from then on. In this way we can visualize how the action progresses from one region of the train to another, until finally strong magnetism results, throughout the unit, and very high currents are generated. This explains the curious fact that, with some trains, all magnetic fields are oriented in a rather unique pattern all along the train. For example, the positions of maximum field strength may be in the same plane (say at 12:00/6:00) in all five or six rotors of the train, and also in the coupling sleeves and thrust collars. It would be almost impossible for this to occur by coincidence.

It can also be seen that the logical place to arrange grounding brushes would be at both ends of the train. It is not logical to provide only one grounding brush at one end, as this would allow high voltages to build up at the other end of the compressor train. But, with only two brushes on a train of machines connected by flexible couplings, there will still be current-transfer across couplings and gears, and this can cause damage to these components. Also, if a coupling or gear has a high electrical resistance, for some reason, then the currents will not go to the end-brushes, and voltage will again build up within the individual machine. The usual bearing and seal damage pattern will then again become evident. For this reason it is most desirable to arrange grounding brushes at each end of each individual shaft. However, where the surface velocities of the shaft are high, this will present considerable difficulties, as will be explained in a separate chapter.

Instead of grounding the ends of each shaft, it is theoretically possible to insulate each bearing from the rest of the casing and from the ground. However this type of arrangement is not practical for compressor units, although it has been used successfully for turbine generator units. Also, some types of currents will not be eliminated by insulating, see Figure 3c.

The above explanation is obviously highly simplified, based on [3]. However, this reference covers only large turbine generator units, where the situation is much simpler, because of the solid-coupled shaft and the absence of flexible couplings, gears, and tight-fitting seals. Under these conditions a brush at each shaft end would be a very satisfactory arrangement. By comparison, a typical large compressor train has not only the bearings for magnetic field interaction and for current transfer between rotor and stator, but also many tight seals and flexible couplings. A typical 40,000 HP/11,000 RPM syngas train of a 1,500 ton ammonia plant may have two turbines (high-pressure and low-pressure), and three compressor cases, the train having a total of 10 bearings, 5 thrust bearings, and some 12 to 24 oil film bushing seal rings, each having only 1 to 3 thousandths of an inch clearance. In addition, there are some 30 labyrinth seal rings in the train, each with a dozen points or more. These seals may rub on the rotor under some conditions allowing a loop to be completed. There are 4 gear-type couplings, of unknown electrical resistance, which varies with operating conditions, wear, and shaft current damage. Bearing diameters are about 5″, which gives a surface velocity of ≈ 240 ft/sec at the bearings. Seals are larger in diameter and the surface velocities are even higher. The thrust bearings may have surface velocities of 600 ft/sec and may be operating in the turbulent-oil-film region, where the electric resistance is very low. The electric resistance across the thrust bearing may vary greatly with speed and operating conditions (surge, etc.), and so will the current-transfer across these bearings. Other large trains — for example the air units of ammonia plants — may have gears. Often there is also a mechanical-drive type governor and/or oil pump drive, which may ground one end of the train. Evidently, we are dealing with an exceedingly complex situation, as compared to a turbine-generator unit. It is easy to see that under these conditions there is a great potential for generating shaft currents, provided there is some residual magnetism which can be amplified by self-excitation. A similar situation can exist with the slower running, but much larger trains in other plants, for example in ethylene plants, and in LNG plants, which now require units in the 100,000 to 135,000 HP range.

Self-Excitation and Self-Magnetization of Components in Service

So far, we have considered what will happen *if* areas of rotors and/or stators get magnetized, but we have not defined the source of the magnetism. With electrical machines in the train this would be fairly easy to understand, but many trains without electrical components are experiencing essentially the same problems. Since all references concern turbine generator units, we can disregard these machines in this presentation, because they are so well documented. With turbine-driven compressor units the situation boils down to the following possibilities:

a) Starting with the residual magnetism left from manufacturing, welding, or, magnetic-particle inspection, a small unipolar current will be generated as soon as sufficient speed has been reached. This current may arrange itself in an external loop around the rotor in such a way as to reinforce the existing residual magnetism, forming a self-exciting circuit.

b) Currents in the rotor will generate magnetic fields around lines of current-flow. These currents can arrange themselves around the centerline of the rotor in such a way that they are no longer parallel to the axis of the rotor, but rather in a corkscrew pattern, similar to a coil. This allows self-excitation to develop from the internal region of the rotor.

c) Both mechanisms are likely to occur simultaneously.

This explains how very strong magnetic fields may result from relatively weak residual magnetism, and now we only need to define the source of the residual magnetism to understand the process of electromagnetic shaft current generation.

Source of Residual Magnetism in Rotor and Stator

a) Magnetic particle inspection without subsequent demagnetization, or with insufficient demagnetization. Note that many new machines come with strongly magnetized components.

b) Use of strong magnetic tool bases on stator and/or rotor, in areas of strong field-interaction during operation.

c) Electric-arc welding in areas close to the rotating element (or even on rotor components) in such a way that the path of the current from arc to ground — which will be permanently magnetized — passes through areas where current-to-field interaction will occur during rotation. Welding could cause fields to line up uniformly along the axis of multiple components. The ground electrode of an electric welder could easily be placed in such a location that return current from the welding rod to the ground electrode may seek a path through the structure composed of the rotating and stationary machinery parts, or may seek a path which sets up a flux which passes through the machine parts.

d) By coincidence, the original fields of several components may be lined up in a way to promote strong currents. If so, it is sometimes possible to install spare components having fields of the same strength, but oriented in a different way, and the shaft current phenomena will no longer be observed.

No matter how the currents were generated, if the currents are of electromagnetic origin and relatively strong, there will be residual magnetism in the rotor and stator, which can be detected using a simple magnetometer ("Gauss-meter"), or with a "Hall-probe". It will be found that magnetic fields are of a magnitude between 5 Gauss and 30 Gauss, or even higher. It seems that most components having 3 Gauss or less operate satisfactorily. Three Gauss is a level of demagnetization which is practically obtainable. However, much work will have to be done to define permissible limits — and methods to obtain them — as there is no practical information available on this subject. This will be different with each train, because of different sizes, configurations, velocities, and clearances.

Demagnetization can best be achieved by subsequent reversals at ever decreasing flux levels, starting at a level exceeding that of the residual magnet's motive force field level. For details see Part II.

The permanent magnetic fields in rotor and stator interact with each other at a velocity somewhere between 200 ft/sec, at the bearings, to 1,600 ft/sec at the blade tips. The gap between rotor and stator at the critical areas is generally between 0.001″ minimum radial clearance (at the oil bushing seals) to $\approx$ 0.040″ at the blade tips or shroud seals. There may also be occasional metal-to-metal contact at the labyrinth seals, at highly magnetized areas. Some compressors have "contact seals". If the thrust collar is magnetic (and it often is), the gap (oil film) between stationary metal and rotating field is a fraction of a thousandths of an inch. By comparison, the air gap between the stator and the armature of a motor or generator is far larger, and the circumferential velocities are much lower but, of course, the fields are much stronger.

Recapitulating the situation we can say that, any way we look at this problem, it is rather evident that the potential for strong current generation is present if we have some residual magnetism, and sufficient surface speed to initiate the process. Even without the detailed explanations above we know perfectly well that to generate an electrical current we need only have a relative change in the magnetic field — or motion of a metallic member through a fixed magnetic field — plus a closed external electrical circuit. After all, this is the basic principle of any commercial electrical generator. We may get an alternating current — unipolar or with reversing polarity —, or an eddy-current, with the currents either in the stator or in the rotor. If the current arranges itself in a coil around the center of the magnetic field, we will evidently get self-excitation, and possibly extremely strong current buildup. Summarizing the conditions which will result in significant shaft currents, we can say that we must have:

a) A high circumferential velocity, either because of large diameters or because of high RPM. In other words, the machine must be large for its speed. (This, in addition to the increased use of magnetic tools and magnetic inspection, is the reason why the problem is encountered more frequently now than it was in the past, when units were smaller and shorter, and ran at lower surface speeds).

b) A possibility to let the current pass from the rotor to the stator, or vice versa, even if only momentarily. If normally no such provisions exist, a strong current and subsequent magnetization can be initiated by seal rubs, high momentary thrust load due to fluid slugging or surging of compressors — or by oil whirls, labyrinth seal rubs, blading rubs, etc. It is for this reason that sometimes the shaft current phenomenon does not show up for years of operation, until such a situation develops.

c) To initiate self-excitation, the resistance in the circuit must be relatively low, to allow large currents to flow. These currents will, in turn, produce strong, permanent magnetic fields. Self-excitation is not always necessary to produce shaft current damage.

d) Sudden buildup of strong, very destructive currents may occur in the case of self-excitation, with instantaneous component failure (thrust or journal bearings). Seals or coupling teeth may weld together. In such cases the typical evidence of shaft current damage may be destroyed, and it will then be very difficult to identify the reason for the failure.

It should be noted that it may be very difficult to successfully ground these currents, because grounding brushes normally cannot carry much over 20 amperes. The currents can be much greater, and this would cause wear and failure of a brush in a relatively short time. Also, there is a considerable problem in finding brush designs which can tolerate high circumferential speed, as is required for grounding at all locations, except the ends of the shaft. Note also that conventional brushes can develop an insulating film very readily because of adverse atmospheric conditions or because of improper filming. This renders the brush shorting-action undependable.

IDENTIFICATION OF SHAFT CURRENT TYPE

It is very important to properly identify the type of shaft current involved, because otherwise it may not be possible to bring the problem under control, and to prevent future component damage and plant outage.

Symptoms Common to All Types of Shaft Currents

1. Appearance of Affected Parts

Spark damage starts with fine individual pits, like pin pricks, which may occur in babbitt and/or steel parts (these are the materials most often involved, any other conducting material could be similarly damaged, for example copper alloys and carbon rings). The identifying feature of these individual pits is the round, shiny appearance. The bottoms of the pits have a round, "melted" appearance, when viewed under a strong magnifying glass or a microscope.

As damage progresses, the pits overlap, and the entire affected area is covered with a uniform, continuous, satin-like surface, similar to a sand blasted or shot-peened surface. It looks very much like a piece of frosted or etched glass, hence the name "frosting" or "spark etching". The metal is actually removed by a process very similar to Electric Discharge Machining, generally referred to as "EDM". As the sparking continues, more and more material is removed. This may be only a few thousandths of an inch, but in severe cases ⅛", and much more, can be EDM'd from a part in this manner.

It is important to note the isolated, individual pits near the boundary of the damaged zone, because these pits still have the original characteristic of spark pits — which is obscured as overlapping and consequent loss of features occurs — namely roundness, a smooth, melted bottom, and freedom of corrosion products. If the oil was also contaminated with corrosives, surface corrosion may also be observed, making it more difficult to identify the problem. In this context it is interesting to note that certain oil contaminants reduce the electrical resistance of the oil film, and therefore may initiate the arcing process. Also, some oils have conducting additives, for example EP oils.

The appearance of this frosting is rather striking, because of its uniform and attractive appearance. After contaminants such as burned oil are washed off with solvent, the color varies from a light gray (especially on steel) to a beautiful silver, satin texture (on good babbitt). There may be a bit of a rainbow-hued blush, presumably from oil breakdown, or from heat. It is this harmless appearance which sometimes leads people to believe that they are looking at a surface which was produced at the factory, probably at great expense.

IMPORTANT: Spark frosting is often diagnosed as "acid etching", "corrosion pitting", etc. There is no significant resemblance between appearances of corrosion and spark pitting. See Reference [4] for details and for excellent photographs.

The major distinctive characteristics of spark pitting can be summarized as follows:

a) Isolated pits at the early stage, or at the periphery of the damage area.
   - Essentially round in shape, before pits begin to overlap.
   - Clean, round, shiny, "melted" bottom.
   - 0.001 to 0.008" diameter.
   - Crater-like appearance.
   - By comparison, chemical pitting looks ragged and dull, and usually there are corrosion deposits, or coatings.

b) Overlapping pits
   - Smooth, shiny bottom.
   - Often producing a smooth, even, frosty-looking surface, sometimes fairly sharply delineated at the boundaries. The color is a light gray or shiny silver. Sometimes a yellow to golden tint can be observed. It seems that this occurs mainly in areas where considerable heat was generated at the same time, either as a result of sparking (as on the faces of compressor seals), or in areas of bearings where oil temperatures may reach high levels, as a result of surface damage.
   - No corrosion products are present after simply wiping the surface and/or washing with a solvent.
   - Damage may occur in any conducting material, usually in steel, babbitt, bronze, or carbon.
   - Occurs at points of contact or near-contact, and in areas of oil turbulence. Corrosion pitting is not nearly as selective and would extend into many other areas where spark pitting could not occur.

As destruction progresses, the pits may become much larger and pieces of babbitt may come loose and fall out. Scratches and wiping will occur, and heat will be generated as parts begin to fail. A carbon-like, dark-brown sludge or deposit is often found in the frosted areas if oil was present, especially on stationary interfaces such as the faces of compressor seals, buttons on thrust shoes and, especially, on coupling teeth, where this sludge may be mistaken for the commonly occurring sludge resulting from centrifugal action in the coupling or from misalignment.

But even in bearings this sludge can sometimes be noted in the sparked area, or downstream of it. Unless there has been subsequent heat from impending component failures, this sludge film wipes off very easily as the oil is removed, exposing the clean-looking frosting.

2. Location of Damage Areas, Type of Damage, and Some General Considerations (Approximately in order of importance)

   a) Governor and pump drive gear, especially if worm drive, but only if the wheels are of conducting material. Any failure of these drive mechanisms should be regarded as a possible indication of a shaft current problem. If replacement parts are non-conducting, severe damage may occur at other locations.

   b) Coupling teeth. EDM may be severe on the loaded flanks — ⅛" or so — and this is often misinterpreted as coupling wear. There may be a fair amount of sludge present. A similar damage pattern could, of course, also result from other causes, such as misalignment or dirty oil. The presence of the characteristic pitting and frosting would decide this question, but sometimes subsequent mechanical damage to the surface can obscure the pitting, and the identification can then be difficult, unless isolated pits can be found on the periphery of the damaged area and, for some reason, occasionally on the backside of the teeth. It is not immediately apparent why the sparks should jump across the gap on the inactive side of the teeth, but it may be because a layer of higher electrical resistance begins to form as damage on the active side progresses. It may also be that the damage on the inactive side is caused during periods of deceleration, or during other periods of torque reversal (torsional vibration, reverse rotation).

c) Thrust bearings. The "classic" damage location, because the oil film is very thin. The frosting usually covers only part of the thrust shoes or tapered lands, towards the trailing edge, where the film thickness is a minimum (in the order of a couple tenths of a thousandths of an inch). The appearance of a partly frosted shoe is quite striking, even to a casual observer, and a mechanic is not likely to overlook it. In spite of the smooth looking surface appearance, there may have been substantial loss of material, and the shoes should not simply be cleaned up and reinstalled. As a minimum, shoes should be checked for flatness and carefully scraped and blued on a surface plate. This may only be done with Kingsbury type, equalized shoe bearings. It should never be done with tapered-land thrust plates or with other fixed-wedge geometry bearings, because these bearings will lose their oil wedge if scraped, and since the oil wedge is only about 1 mil deep, there can be a very considerable reduction of load capability. If the situation is not corrected, sudden failure of the thrust bearing will occur when the damage has progressed sufficiently, and/or when unusual demands are made on the bearing, for example during periods of compressor surging, fluid slugging, changes of speed and load, or changes of coupling thrust.

d) Compressor seals of floating-bushing type, or any other contact-type and near-contact type seals. Spark damage occurs on the contact faces of these seals, and also in the bore. The seal usually is immobilized because of the surface roughness on the face, and this may lead to seal-induced oil whirl (at a subsynchronous frequency), or to the very destructive seal-induced critical speed phenomenon (having 1 × Rev predominant frequency). See [7] and [8] for explanations of these phenomenon. As the oil film in the bore breaks down as a result of the vibration, its electrical resistance is sharply reduced, and more current is drawn into the area. Spark damage can be very heavy, there may be a distinctive step EDM'd into the seal face, and there may be burned areas, cold welding, etc.

Spark roughening of the surface of the seal bore — which has only about 2 to 4 mils radial clearance — can also promote oil whirl, but ultimately the seal will fail by wiping, or by blow-through resulting from the excessive clearance as EDM progresses.

e) Gear teeth of main gear. The initial frosting will lead to wear, rough operation, and ultimate failure of the gear. For proof of shaft currents look for the characteristic frosting and for the isolated spark pits in peripheral areas not affected by subsequent mechanical damage. Gears, as well as couplings, must transmit current from one part of the compressor train to the other, and therefore they are very vulnerable to shaft current damage. If gear-tooth surface damage occurs, it is always a good practice to check for spark-pitting before an investigation for the usual causes of gear problems is initiated.

f) Main (journal) bearings. Frosting occurs at the areas of minimum oil film thickness. This is normally near the bottom of the bearing, but it can well be at any other location, including the top half, because the rotor may be running in the top as a result of gas forces (partial admission in steam turbines, side streams and nozzle arrangement in compressors) or as a result of coupling forces, especially when the coupling has locked, possibly as a result of current damage. Sometimes the bearing is not round and the frosting shows at odd locations. Other susceptible areas are regions of high oil turbulence, for example at the corners of oil inlet grooves, or at oil dams.

With tilt-shoe bearings the damage pattern is similar to the pattern experienced with thrust shoes of Kinsbury-type thrust bearings, affecting only part of the shoe surface, towards the trailing edge. The same precautions as for thrust bearings apply when repairs are made to these shoes. The final phase of bearing failure is initiated by overheating, and then follows wiping of the bearing, which may occur quite suddenly once damage has progressed to a certain point.

The oil whirl phenomenon is often observed in conjunction with shaft currents, either because the rough surface promotes the whirl or because the whirl draws currents across the bearing. Possibly both phenomena complement and reinforce each other.

g) Labyrinth seals and carbon-ring seals in turbines and compressors. Spark damage and shaft surface frosting can occur and may lead to increased leakage. This type of damage is often not properly identified, but it should always be looked for. The damage to these seals does not normally lead to a catastrophic failure, (as with bearings and thrust bearings) but it can increase the clearances of the seals and cause local damage to the hardware. However, increased leakage may overload the thrust bearing.

NOTE: Damage to babbitt is more frequent than to steel, and in steel the pits are usually smaller. Whether or not steel journals, thrust collars, and seal sleeves will be affected seems to depend on the polarity of the currents. My personal observation seems to indicate that electrostatic currents damage the babbitt, while electromagnetic currents damage both the babbitt and the steel.

Symptoms Peculiar of Electromagnetic Shaft Currents

1. Location of Damage

Damage does not necessarily occur at the point of lowest electrical resistance to ground, although it will usually show at such points also. The distinctive characteristic of electromagnetic currents is damage which indicates an internal loop through which the current is shortcircuited, in such a manner as to reinforce the magnetic field which is exciting the current generation.

For example, a current-loop may run within the shaft from the thrust bearing to the adjacent journal bearing, and then within the stator metal back to the thrust bearing, closing the shortcircuit. The oil film is crossed at both the thrust and journal bearing surfaces, and spark damage will be noted at both locations. Or a loop may run between two adjacent seal rings, or even within a single journal bearing, in which case the damage will be at the end regions of the bearings only, with no damage in the center portion, near the bearing centerline. See Figure 3 for some possible patterns. There are, of course, many other possibilities, and these loops will continuously rearrange themselves as rubs, whirls, vibration, or close proximity occur in service — generating new magnetic fields — and also as sufficient metal is removed from some components to interrupt a circuit. It is for these reasons that damage is often very extensive throughout an entire train, which is rarely the case with electrostatic currents, which are usually satisfied to find one convenient way to ground, at any location.

Please note in this context that these current-loops cannot be "grounded". Since they are shortcircuited within themselves, they don't really care whether there is a "ground" or not. This will depend on the exact nature of the loop, which can seldom be satisfactorily determined in the field, especially since it also changes during operation. All we can do by grounding is to relocate the loop away from critical bearing areas, but this involves a good deal of wishful thinking! It can be seen that this will set up a new loop geometry, and we may well end up with a much stronger current than before, which may rapidly damage the other crossover points, as well as the brush itself. For example, Figure 3a shows that a brush near the thrust bearing would not prevent damage to the adjacent journal bearing. The reduced resistance at the brush could actually induce much stronger currents, with increased magnetization, and consequently heavier damage at the journal bearing. The thrust bearing, on the other hand, would probably not be damaged in the same way as before. Also, with the brush, we may have two loops instead of one. Evidently, this is a real serious predicament, since we have no predictable way of correcting a shaft current problem of this type by means of shaft brushes. On the other hand, brushes have worked fine in many cases, which seems to indicate that these problems were not of the shortcircuited-loop type (which may become self-exciting) but probably were of the eddy-current type. However, there are a few notable exceptions where the brushes did not work, and where destruction was very rapid. Very careful demagnetization of stator and rotor components is the only safe and predictable way for eliminating electromagnetic shaft currents.

If this peculiar pattern of damage is evident, there can hardly be any doubt that electromagnetic currents are involved.

2. Damage Severity

Is usually much greater than with electrostatic currents, with respect to the number of affected locations as well as to density of pitting, and to rate of metal removal. While steel surfaces — such as journals, thrust collars, seal surfaces, etc. — are seldom severely attacked by electrostatic currents, this is often so with electromagnetic currents. In some cases the currents have caused babbitt to be deposited on steel journals and thrust collars.

3. Type of Damage

a) Frosting. As under 1. above, but frosting may be very severe, with large areas affected, and with considerable metal removed even from steel parts.

A strange-looking phenomenon can often be observed: The frosting on the rotating surface may reach only half way around the shaft, or maybe only say 10°, leaving the remaining portion of the circumference in its original, shiny condition. This is definitive evidence of electromagnetic shaft currents. I am not aware of a reference mentioning or explaining this condition, but it is evidently caused by an interaction of standing and rotating magnetic fields, which will generate currents only during part of each revolution, and the sparks will fire across the oil film at only this point, working somewhat like a magneto-type ignition system. This pattern can be quite frequently observed. Sometimes only a small section of a thrust collar is frosted, and if a gear is in the train, there may be quite a number of clearly defined *axial* stripes on the journals, sometimes on both the bull gear and pinion. The damage to the teeth may follow a similar pattern. It seems that this is caused by the following mechanism: For example, with a 3/1 gear ratio, when the current is generated somewhere in the low-speed train but fires across a high speed journal, there should be one line of frosting on the pinion for each line on the bull gear, the pinion firing only every third revolution, but at the same point on the shaft. On the other hand, if the current originates on the high speed side, but fires across a low speed journal, there should be three stripes on the bull gear for each stripe on the pinion journal, evenly distributed over the circumference of the bull gear journal — or on other low speed journals and thrust bearings. Also, there should be one region of tooth damage on the pinion, and three regions on the bull gear. Unfortunately, real life is rarely so simple, gear ratios usually being odd numbers, and current being generated in both portions of a train. Consequently, one can sometimes see the oddest looking patterns, with some stripes wider than others, but still very clearly defined against the shiny, original surface of the shaft. I have seen journals with 8 to 10 clearly defined axial stripes, extending across the entire journal width, and then continuing under the oil seals, along the same axial lines.

b) Spark tracking. The tracks may be very fine, and about 2 to 5 mils deep, having an appearance as if drawn with a sharp needle, or they may be as much as 1/8″ wide and 1/16″ deep. The tracks vary in length from less than 1/8″ to several inches. The direction of the tracks is oriented generally in the direction of rotation, but it may be 45° or even more towards the side. The point of origin can be anywhere, but often the tracks originate at points where one would expect high voltage concentrations, for example at the corners of relieved areas in journal bearings, especially at the corners of pressure dams, where these tracks are often so deep that people think they have been intentionally provided, by means of a pointed scraper, for the purpose of dirt purging. Sometimes such purging channels are scraped into pressure dams, but closer inspection will reveal the irregular nature of the tracks, and often multiple tracks can be found, radiating from the same corner. Please note that these tracks are not necessarily in the minimum clearance area, where the frosting occurs, but even in the upper half of a bearing, opposite the minimum clearance area. This is definitely the case near a pressure dam. See photos at the end of this paper for examples.

As far as I know, these tracks have not been mentioned or described in the literature, but they are very much in evidence. Therefore, a detailed description will be presented here. Please keep in mind that this description is based on extensive field observations, but no attempt is made to provide a fully satisfactory theoretical analysis and explanation. We are still very much in the dark on many essential points. However, the remedy will most likely be the same, no matter whether or not we understand the disease. It will always boil down to demagnetization of all critical components.

The appearance of the tracks is similar to foreign-particle tracks, or to tool-scratches. However, positive identification is possible, using a magnifying glass or low-power microscope. The following features will be noted:

- The bottom of the track has a clean, "melted" appearance and is often quite flat, giving the track groove a somewhat rectangular cross section, with sharp corners or melted ridges at the babbitt surface, and also with relatively sharp corners at the bottom. Neither dirt nor tools will produce this type of a groove.
- The groove is often of about the same width and depth over its entire length. There is no foreign particle (or its impression) imbedded at the end, which would be characteristic if dirt had caused the groove.
- Under a microscope it can be seen quite clearly that melting of the babbitt has occurred. Sometimes there is a very distinctive burn of crater-like appearance at the end, and there may be molten ridges.
- The tracks are found most often in babbitt, in the running surfaces of bearings and seals. In steel the tracks seem to be shorter, and they are found on or near contact surfaces, for example on the faces of bushing type compressor seal rings, and on shoulders and cylindrical fits of thrust assemblies. So far, I have not noted tracks in the running surfaces of the shafts, at bearings or seals.
- There may be quite a large number of such tracks, sometimes fairly close together, and they may be branched.
- Tracks are often found in severely frosted areas, where loss of metal would be sufficient to obliterate any scratches which may have been there when the bearing was installed.
- Tracks are usually so deep, and there are so many, that even a very unobserving mechanic would notice them and would not have installed such a bearing or seal into a machine if they had been there when the bearing was new.

It seems to me that these tracks are the result of arcing, similar to the type of arc produced by Heliarc welding, but they are obviously not generated by the same type of current and voltage. Once the process has started, the arc begins to travel at a steady speed between the two surfaces, until the arc stops, sometimes abruptly, possibly jumping to another location.

Spark tracks do not seem to occur with electrostatic currents. Probably because these do not develop sufficient current strength.

c) Burned spots and welding of contacting parts. This occurs at contact areas, for example between thrust collar sleeves, nuts, and shafts. Also at the seating surfaces of floating bushing oil seals in compressors, where holes of about 1/16" diameter were observed, with some of the burned-off material sticking to the opposite surface. Evidently, spot-welding occurred at these locations, and the weld was then broken during disassembly. Such seals are, of course, immobilized, and seal-induced vibration problems are likely to develop. If parts of thrust assemblies are spot-welded together, a great deal of tearing will occur during disassembly. Similar spot-welding may occur at coupling teeth, and the coupling will then lock, exhibiting the typical symptoms of a locked coupling (vibration, thrust).

Fairly large hot spots may occur at the mounting seats of bearings and thrust bearings — and at their retainers — and at the support links and buttons of tilting shoe thrust and journal bearings. There may be heat discoloration, melting, burning, and spot-welding. These spots are located where one would expect the current to transfer between parts. The spots I have seen were up to ½" wide, and 1" long. They are usually mistaken for "corrosion" or "fretting" because there is some resemblance. However, cleaning and close inspection will reveal the difference. First of all, there is not likely to be that kind of corrosion — or corrosives — in these areas and, furthermore, neither fretting nor corrosion would destroy the steel or cast iron to such an extent, and in such a localized area.

d) Electro-discharge machining (EDM) also called "current etching", "spark etching", "spark coining", etc. This term describes noticeable metal removal by the sparking process. It occurs at interfaces, for example on the contact faces of floating bushing seals, where a step may be EDM'd into the seat of the seal as a result of current transfer. The depth of such steps may be 2 to 10 mils, but I have seen the corner of a compressor thrust shoe "spark coined" into the outer thrust bearing case to a depth of about ¼". Essentially the same happened on a number of other machines of this make, because the shoes can turn, and they may also drag on the shaft, which provides a point of current-transfer between rotor and casing, through the shoe. Usually the depth of the depression in the casing is only around 10 mils to ⅛". The identifying feature of EDM is the frosted surface at the interfaces. The OD of thrust shoes and the ID of the retainers should always be inspected for evidence of this coining. The ID of the shoes should be inspected for signs of dragging.

Severe EDM of the shaft can occur under grounding brushes having insufficient contact pressure, or after they have worn and lost contact, possibly because of excessive current-density.

e) Magnetism of rotor and stator. This is an essential symptom. There are no standards of acceptable residual magnetism, but on the basis of past experience it seems that units having this problem show fields exceeding 3 Gauss, as measured with a simple, inexpensive magnetometer. Couplings and thrust collars showing current-transfer generally had readings of 4 to 6 Gauss, sometimes more. The faster and larger the machine (= high surface speed), the lower will be the magnetism required to excite shaft currents. It seems that demagnetization below 3 Gauss is difficult for large parts, especially for casings, and that many components have readings between 1 and 3 Gauss. Higher readings may be acceptable at regions where no interaction of rotating and stationary fields is likely — i.e.

far away from the rotor — but in areas near buckets, diaphragms, bearings, bearing cases, seals, couplings, and coupling guards, the situation is obviously always very critical.

The above applies to levels of magnetism of a new or troublefree machine. Once the currents have been active, the magnetism may build up tremendously during operation, and this will also permanently magnetize many components of the unit. At the beginning of the process the relative position of the fields with respect to each other is of considerable importance, but once the self-excitation and magnetization has occurred, the fields seem to line up so as to produce a maximum current flow. On machines where this has occurred it may be noted that the radial fields along the entire train line up in the same plane, as if they were poles of a generator. This is a very curious symptom. For example, if we use the keyway of a compressor as a reference for the entire train, calling its position 12 o'clock, we may find that all machines and couplings in the train (which may consist of 2 turbines and 3 compressors, having 4 couplings) show the strongest field at either 1:00 or 7:00 position, on every component, (wheels, thrust collars, coupling sleeves, etc.) of every one of the five individual machines. To expect this to be a result of manufacturing techniques makes no sense, because such fields would occur at random positions. Furthermore, turbines, compressors, and couplings are usually made by different manufacturers, and they would certainly not all have the same way of lining up residual magnetic fields. The original fields are left from magnetic particle inspection from welding and from the use of strong magnetic tools, for example drill bases. These fields would certainly come in a random pattern.

In addition to the radial fields (mainly in wheels and thrust collars), it will be noted that fairly strong axial fields protrude from the shaft ends. Coupling spacers may also indicate strong axial fields, the line of maximum strength again lined up with the plane characteristic for a given unit. However, in most components both axial and radial fields will be noted simultaneously.

Strength of residual magnetic field after operation: Troublesome machines have indicated between 6 and 30 Gauss, on both stationary and rotating components.

4. Measurement of Rotating Magnetic Fields in the Operating Machine

   a) Telephone pickup. If a strong rotating field is driven around in the stator metal, it should be possible to detect this with an antenna or with a simple inductor coil and amplifier, in the same way as with 60 cycle interference of a fluorescent light, for example. Not having time to assemble sophisticated instrumentation, I have used a telephone pickup of the suction-cup type, and a portable tape-cassette recorder. A good setup for noisy field conditions is a recorder having an earphone plug (to put into the earmuffs) and a "monitor" position, allowing listening without running the tape. A recorder with manual volume control is preferable — because it allows an estimate of signal strength — but an automatic volume control will still work well enough to identify the nature and severity of a given problem.

   To map the location of the rotating fields, plug the phone pickup into the microphone receptacle, place the earplugs in the sound protector earmuff, push "monitor" switch, and walk around the unit holding the pickup near the casing, and listening for signals, which will become evident as a fairly loud "hum", at the running frequency of the machine. When a strong signal is found, run the recording tape to get a permanent record, and then switch to the microphone to record a message onto the tape, identifying the location of the signal, which may be marked on the casing with chalk.

   It will be found that the rotating fields come out into the air near the horizontal-split lines of the casing. This seems logical, because magnetic fields do not like to go across "cracks" — this being the principle of magnetic-particle crack inspection, such as Magnaflux and Magnaglo. Strong signals are often found towards the end of a compressor, near the seals, and around bearings and coupling guards.

   The recorder tape can then be evaluated as to frequency and signal strength, using an oscilloscope or oscillograph. For a very crude strength-of-field comparison I use any handy fluorescent light. Strong signals are about the same as the static noise of a fluorescent tube at 3″ distance, but much stronger signals have been recorded — it can get quite "noisy". There are also some real odd "hissing" and "sparking" noises of unknown origin. Maybe these are actually the fields around fast-moving, electrostatically charged gas particles, and around the sparks eating away at the bearings. It sure sounds like it, and it occurs at the right locations, but I have no good basis for such a rather wild guess. At any rate, the noises are quite striking.

   It is extremely important to keep in mind that the phone-pickup coil cannot pick up audible noise. It would take a microphone to do this. Only fluctuating magnetic or electric fields will produce a signal. This is also quite evident because the 130 dB noise near the casing of an operating machine is not picked up at all. Nevertheless, it seems that people are hard to convince that they are listening to a strictly electromagnetic phenomenon, and they have to be continuously reminded that this is not an acoustic noise.

   One concern, however, is that misleading information may be derived. The strongest projected field, capable of being picked up by the phone pickup, will occur at points of maximum flux-density, and not necessarily at areas of maximum flux, where larger areas may result in lesser flux density.

   With the areas of strong response mapped out, it will be possible to identify active regions in the train, and to prescribe corrective action such as demagnetization procedures, and location of grounding brushes. It will also be possible to define the precise area on a machine which needs more detailed magnetic inspection. For example, the location of magnetized compressor impellers can sometimes be determined through the casing of the running machine.

   b) Spark test. Ground a piece of electrical wire on one side and touch the other side to the rotating shaft, preferably in darkness. A strong spark may be seen, but only if the resistance inside the machine is high enough, rotors being isolated by oil films. Since this is not always the case, this is not a definitive test. CAUTION: Currents as well as voltages may be high. Do not touch the wire, because it could result in electric shock. Watch also for combustible gas, oil vapor, and/or flammable material in the area.

c) Erratic readings on non-contact types of vibration-monitor equipment. On several occasions erratic gap readings and orbit distortion have been reported on machines having shaft current problems. This would probably depend a good deal on the type of equipment used, and only the probe manufacturer can give a valid opinion on the effects of rotating and stationary magnetic fields, currents of several amperes, and spark discharges in the immediate vicinity of the probe. It should be noted that the currents, fields, and sparks all occur with a strong 1 × Rev frequency, synchronized with the rotor revolution. Since the 1 × vibration component is usually predominant and also synchronous, it seems that an influence is possible, and that it would be hard to separate the electromagnetic phenomena from the vibration phenomena. Also, the probe and its lead wire and grounding shield may well be part of the shaft current circuit, transmitting 1 × Rev currents and flux variations. The gap variation noted could be the result of metal loss in the bearing, but we do not really know. At any rate, this situation also deserves closer investigation. An "Applications Note" by Bently Nevada Corporation (11/77) states that " — Certain types of "Glitch", especially those magnetically induced, may change with time". This would mean that field strength is changing, probably because of self-magnetization, or as a result of shifting current patterns.

Grounding of Electro-Magnetic Currents

Brushes must be used very carefully, because of the high currents which may have to be transmitted, and which may be well in excess of the 20 amperes which a good brush can transmit. There is also the possibility of setting up new loops of excitation. Furthermore, a shortcircuited loop cannot be controlled by grounding, as was explained above.

In fact, there is no effective way to ground some types of electromagnetically-induced currents. Demagnetization of rotating and stationary components is the only way to positively control this type of problem. However, on certain other types grounding has been successful. Since we usually do not know what type of current is present, the best approach is probably to proceed in steps. This is dictated by the nature of these problems anyway, where compromise solutions are unavoidable. A program of this kind would be somewhat along the lines given below:

- Find location of current-generating mechanism by use of the phone-pickup technique described above, and by using a Gauss meter.
- If the offending machine is at the end of the train, apply at least two axial brushes at the outboard end, about 120° to 150° apart, so that the currents will not be interrupted due to brush lift-off, which may be caused by an axial runout. This will also reduce the risk of sparking, improve the Amp rating, and make continuity checks possible. Ground these brushes against the bearing case in such a way that continuity may be checked by means of an Ohm meter. If practical, arrange a discontinuity-alarm to guard against brush wear and failure. Carefully check the grounding of bearing case, baseplate, concrete reinforcement in the foundation, etc., and check the potentials and resistances of these components against each other. Check for shaft voltage and for shaft current, but remember that currents are very likely discharging inside the machine, and therefore neither voltages nor currents may be detectable at the brush locations. However, quite often some currents will become evident. I have seen cases where 120 volt AC was measured on a machine that did not have any voltage at all on the previous day. The frequency of the AC current is, of course, the running speed of the offending machine.
- If the machine has no free ends, use a membrane type or conducting coupling, (if at all possible) and ground the shaft ends as described above. If surface velocities are low, use a radial brush. If none of this can be done, a special wire brush design must be used, on the shaft OD. This brush must be capable to withstand the extremely high surface speed without excessive wear, or heat development. The brush should have provisions for: Checking wear, replacement in service, measuring contact resistance and current, alarm to indicate wear or failure. The material should be non-sparking, compatible with gas and oil, have low electrical resistance, and excellent rubbing characteristics. Shaft runout and vibration up to 10 mils should not affect the brush performance, wear particles should not interfere with bearings or with the oiling system. Accidental reverse rotation should not damage the brush, and any mode of failure or excess wear should not be capable to damage the machine or require plant shutdown. This is evidently not an easy design job, and it would be beyond the scope of this presentation to describe such arrangements in detail. However, suitable designs have been developed and tests for current-transfer capability, heat, wear, etc. are in progress, using a specially designed test apparatus to simulate actual field conditions.

  Remember that brush failure is very likely to cause severe shaft-current damage, in a very short time, forcing a shutdown.
- Theoretically it would be necessary to install at least two sets of brushes (= 4) on each machine in the train. However, on the average trouble job this can hardly be accomplished during a single shutdown period. Therefore, a run will usually be made with only a few brushes in service. It may well turn out that the brushes keep the damage under reasonable control, at least until demagnetization can be scheduled. If not, additional brushes may have to be provided.

DEMAGNETIZATION OF CASING AND ROTOR

This is the only sure-fire solution. It must be performed by specialists. Great care must be taken to avoid damage which may be caused by the very high currents which must be passed through the components, the currents being several thousand amperes. If this is not carefully done it may leave burned spots on critical areas. The connections should never be made at a journal, seal surface, coupling taper, or on a part mounted on the shaft, like a disk or coupling. The rotor should be removed if at all possible, or bearings and seals must be protected against accidental current damage.

TYPICAL CASE HISTORIES

In order to clarify this very prevalent problem and help analyze the failures that occurred, the two actual cases are investigated.

Figures 4 and 5 are included to point out two very severe cases of shaft current induced failures. This bearing is remarkable because it has some very well developed, heavy spark tracking, especially in the upper half shell. Also, there is pronounced electric discharge machining (EDM) extending into the steel backing, at "A". Also remarkable are the well developed spark tracks at "B" which are located in the 0.030" deep relief area.

There are some mechanical scratches, but ≈ 80% of the damage is caused by sparking. Note the extreme sparking at the pressure dam, with some tracks about 1/16" wide, at "C", while frosting is only slight.

This machine operated for ≈ 10 years with a few occasional problems, until an oil-whirl developed, initiating the current discharges and consequent self-excitation. In Figure 5, the bearing at the exhaust end, note the rainbow-hued discoloration at the bottom end of tracks and in the EDM areas.

Case History #1

Ammonia plant. Air compressor unit. Approximately 16,000 HP. 5,600 RPM at the low pressure end, geared to 9,900 RPM at the high pressure compressor.

The unit ran for approximately seven years without any diagnosed case of shaft current damage. At that time an oil whirl developed in the high-pressure compressor, and it was also noted that one of the thrust shoes of the high-pressure compressors had coined into the thrust bearing casing to a depth of approximately 0.100", and on the ID this same thrust shoe was dragging on the shaft. Other thrust shoes also showed indications of dragging and of coining into the casing, but not to the same extent. It was noted that there was strong heat discoloration in the coined areas, but the reason for this was not properly diagnosed at the time, and the presence of shaft currents was not recognized. The thrust shoe situation was corrected by machining the OD of the shaft sleeve, to clear the thrust shoes. The oil whirl was corrected by means of properly fitting the sleeve type bearings, and tilt shoe bearings were installed at a later date. The machine was placed in operation.

Within less than one month the unit had to be shut down again because of abnormal gear noise and vibration, and increasing shaft vibrations. Shaft current frosting was noted on the journal bearings and journals of the high-pressure case, and in all bearings and journals in the gear, including the thrust bearing. The damage was severe at the high-pressure inboard bearing, and at the gear thrust. The coupling between the low-pressure compressor and the bull gear was severely EDM'd, the teeth having worked into each other to a depth of approximately ⅛". The teeth of the main gear were severely damaged by shaft currents.

Especially notable was the severe frosting of the gear journals and the fact that some journals were frosted only on ½ of their circumference. The gear journals of both the bull gear and pinion had many axial lines of frosting across the entire width of the journal and continuing under the oil seals, but with a gap between the journal and oil seal area; in other words the frosting was only present under the close-contact regions.

It had been reported that the orbits and vibration readings as well as gap readings on several locations of the unit looked abnormal and kept changing. These vibration measurements were made with non-contact probes.

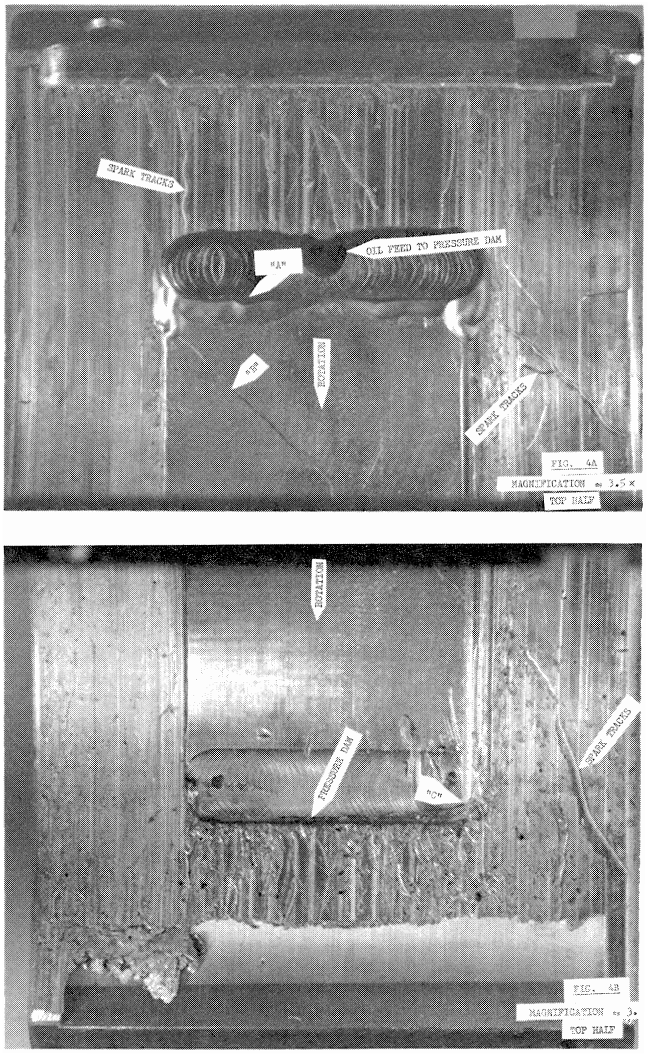


Figure 4 A & B. Dam-type bearing of turbine, steam end, refrigeration compressor damage caused by magnetic currents. (≈ 7,000 HP/11,500 RPM).

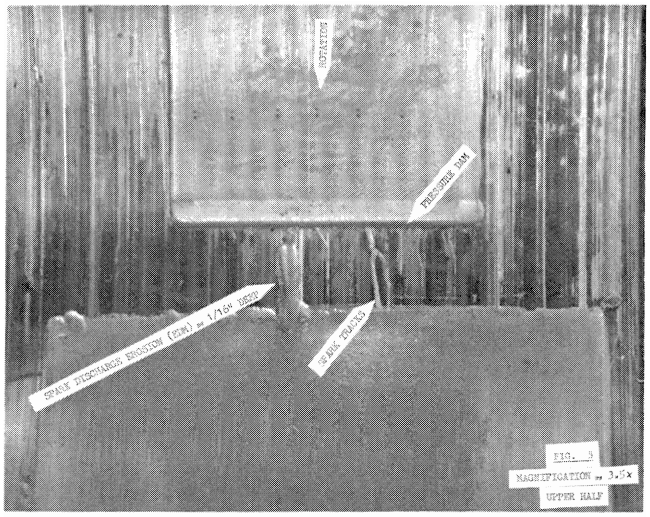


Figure 5. Details of exhaust-end bearing (same turbine as Figure 4).

The following new components were installed:

- New gear box; new coupling; new high-pressure compressor rotor; new compressor bearings; using tilt-shoe bearings at the coupling end of the high-pressure case. Shaft brush provisions were installed at three locations on the train: at the outboard of the turbine, on the coupling of the low pressure compressor (next to the gear), and at the outboard end of the high-pressure compressor.

The unit was then placed in normal operation, and an attempt was made to measure shaft voltages. No voltage was detected, and it was decided not to lower the brushes onto the shaft. Periodic voltage readings were taken, but there appeared to be no voltage on the shaft.

During a shutdown for the installation of tilt-shoe bearings on the HPC outboard end it was again noted that the journals on the high-pressure case were frosted halfway around the circumference, and so was the shaft under the thrust bearing oil seals.

For the second time an attempt was made to measure static currents, by means of a "static gun", but no static current whatsoever was indicated on the end of the high-pressure compressor shaft.

A survey of rotating magnetic fields was made, using the phone pickup/tape recorder method described above. It was found that strong rotating fields existed in the low-pressure compressor, and in the low speed couplings at both ends. Also, at the turbine exhaust and at the bull gear bearings. These signals were of low-speed running frequency. In the high speed portion of the train signals were noted at the pinion shaft and at the high-pressure casing. These were at high-speed shaft running frequency.

The shaft voltages were not checked for a couple of weeks, and then it was suddenly discovered that an alternating current was present, the voltage being approximately +100 volts to −9 volts, see Figure 6. At this point the brushes were lowered. However, extensive damage had already occurred, and the machine had to be shut down because of an apparent gear thrust failure. The total running time was about 12 months.

It was found that, on one of the thrust faces of the gear, approximately 50 mils of babbitt had then been lost, due to EDM (there was no wiping) and also there was fairly extensive frosting on many other components of the unit. It appears that the voltage was grounding through the gear thrust bearing at the time of the zero shaft voltage measurements, and as the thrust bearing damage progressed, ground was lost and the shaft voltage level increased, probably grounding at some other location. It can be seen that the absence of voltage on the shaft is no guarantee that no currents flow, and therefore brushes should always be used, at all times, and they should be monitored continuously.

The only reason for the damage not being more extensive was the fact that the locked couplings of bull gear and pinion apparently kept the gear approximately centered between the severely damaged thrust bearings.

The unit was opened and it was found that the turbine rotor had a field of 15 Gauss at both ends of the shaft. The other components did not have fields of this strength, including also the gear and compressor rotors. Apparently, most of the magnetic excitation was coming from the turbine rotor. It was now attempted to demagnetize the rotor in the casing, which required a current of several thousand amperes. The magnetism was reduced to +6 Gauss at one end and −5 Gauss at the other. This was the best that could be done without rotor removal.

At a later time the components of the train were more thoroughly demagnetized, and brushes were always kept in operation. Severe damage due to shaft currents was not experienced again with this unit.

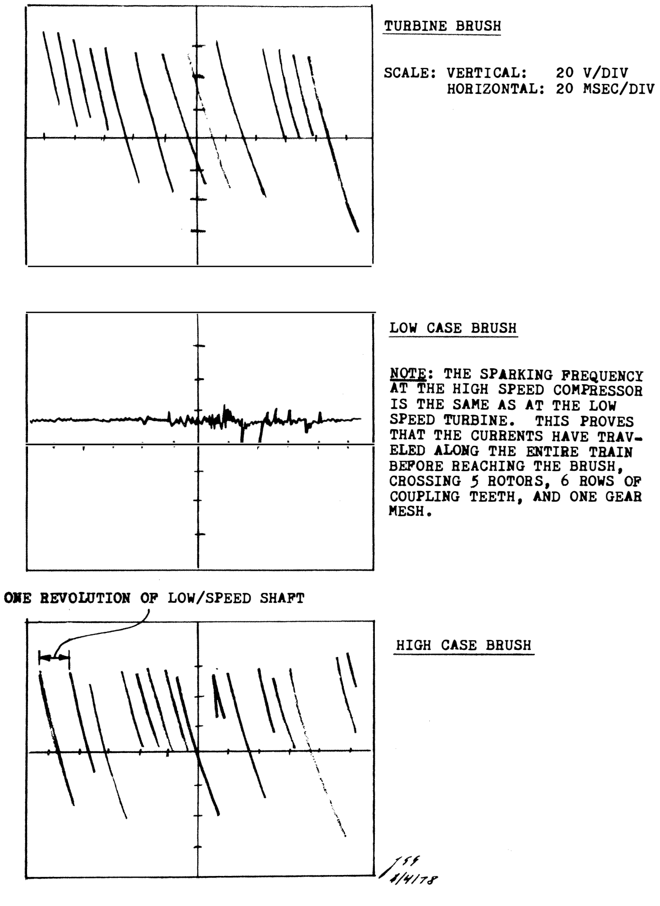
It was interesting to note that the 100 volt alternating current at running frequency appeared at both ends of the train, but that the center brush did not indicate a high voltage, although a strong spark could be drawn with a grounded wire, at that point. If one of the brushes was grounded at any point of the train, the voltages disappeared at all other points of the train also. In other words, if the low pressure end was grounded, the 100 volt AC voltage at the high pressure end would also disappear, and vice versa. Obviously, the currents had to travel the full length of the train (about 60 ft.) to do this.

This case history is interesting because it shows many typical symptoms of shaft currents and, especially, because of the presence of the gear. The downtime of the plant and the economic losses due to this problem were quite significant. In other cases damage was of similar severity, or worse, but many of the typical symptoms of the electromagnetic type of current are quite well illustrated in this particular case history.

Case History #2

Syngas Compressor Train, approximately 40,000 HP/11,000 RPM. Two turbines, two centrifugal compressors.

This compressor unit operated for about 9 years and experienced many failures of couplings, compressor seals, thrust bearings, and main bearings. In retrospect it can be said that most of these failures were initiated by shaft current damage.



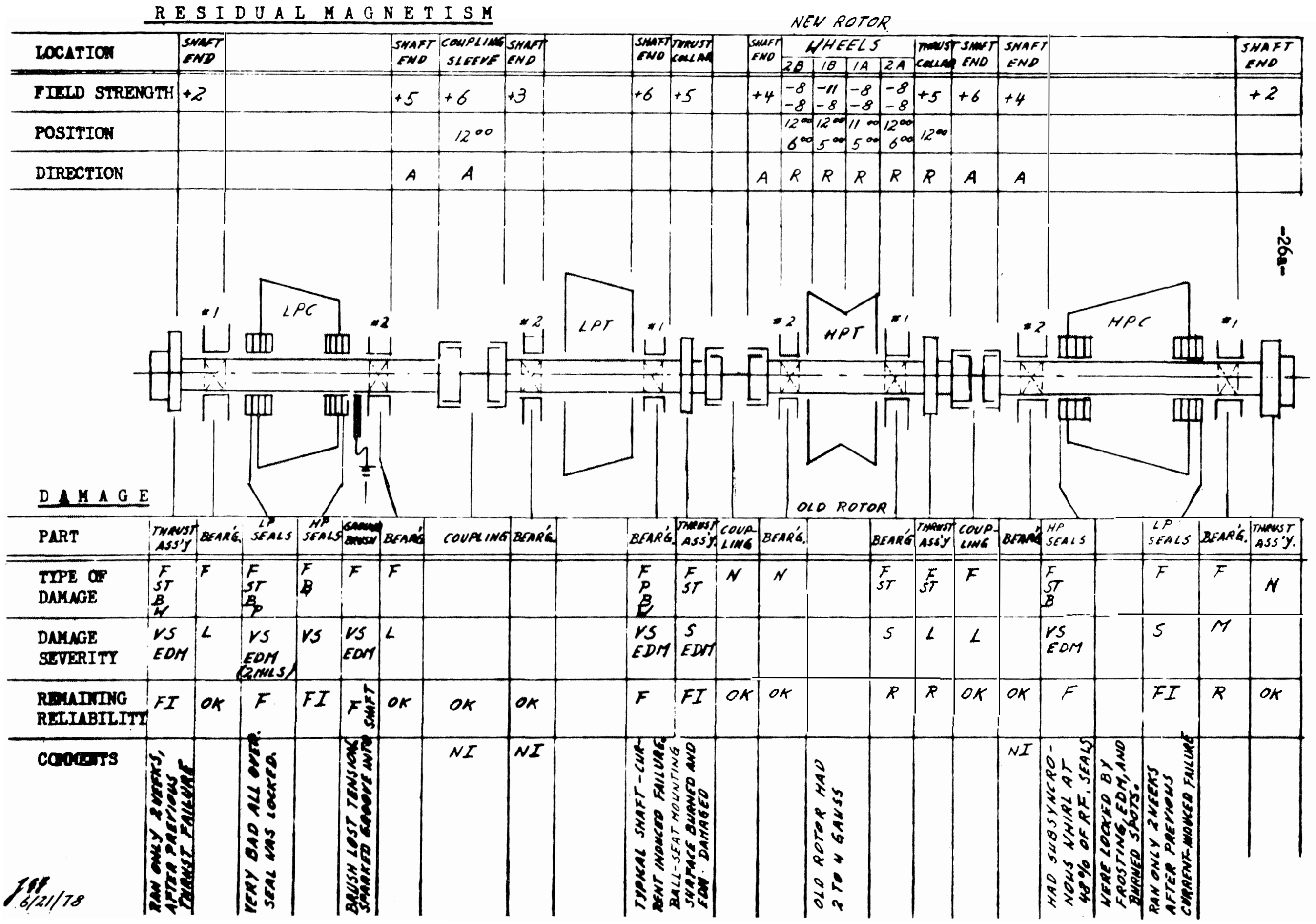
NOTE: THE SPARKING FREQUENCY AT THE HIGH SPEED COMPRESSOR IS THE SAME AS AT THE LOW SPEED TURBINE. THIS PROVES THAT THE CURRENTS HAVE TRAVELED ALONG THE ENTIRE TRAIN BEFORE REACHING THE BRUSH, CROSSING 5 ROTORS, 6 ROWS OF COUPLING TEETH, AND ONE GEAR MESH.

Figure 6. Oscilloscope Tracings of AC Type Shaft Currents.

Finally, a thorough inspection was performed during a scheduled turnaround. Strong magnetic fields and extensive shaft current damage were found. Figure 7 shows a summary of the findings. Many vital components had either failed or failure was imminent, over-all damage level was extremely severe and very extensive. There was a pronounced orientation of the magnetic fields in the 6:00/12:00 plane throughout the train. Magnetic fields were found on most parts. There was bad frosting on the low pressure compressor thrust bearing at the 1:00 plane only. Components of the thrust bearing assembly had spot-welded together. The thrust collar was welded to the shaft shoulder and to the retaining nut. Welding had also occurred between the shaft OD and the ID of the thrust components. These welds were local spots, with significant metal transfer from one component to the other. During disassembly, the mating surfaces were badly torn.

Figures 8 and 9 show the bearings that were affected greatly by the generated shaft currents. In Figure 8 frosting is medium to severe. The thrust capability was significantly reduced. The area near #3 land was overheated. Note the land discoloration, yellow blush (≈ 450°F) on steel next to land #3. Thrust failure was imminent.

Observe that thrust contact was not uniform, lands No. 1 and 3 carrying most of the load. This is a basic problem with



TYPE OF DAMAGE

F = Frosting
P = Pitting
ST = Spark Tracking
B = Burned
W = Welded

REMAINING RELIABILITY

OK =Not Affected
R = Reduced
FI = Failure Imminent
F = Failure has occurred

SEVERITY OF DAMAGE

N = None
L = Light
M = Moderate
S = Severe
VS = Very Severe
EDM = Significant metal removal by "Electro-Discharge Machining"

COMMENTS

NI = Not Inspected
Unavailable, inaccessible, or reported in good condition.

Figure 7. Map Showing Magnetism, Failure Location and Severity.

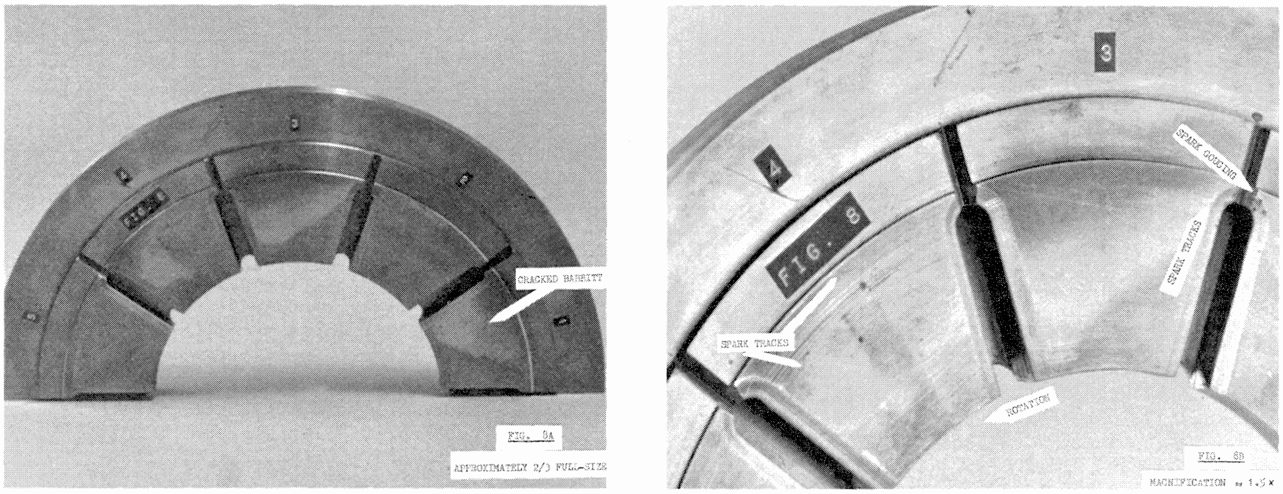


Figure 8 A & B. Tapered-land thrust plate, steam turbine, magnetic currents (40,000 HP/11,000 RPM Train).

Land #1: Severe spark frosting, most of the oil wedge is lost. Heat discoloration (≈ 375°F) and babbitt cracking from excessive load.

Land #2: A few isolated, light pits, over entire surface, heavy pitting at trailing OD. Note that this pad and #5 carried much less load than #1, #3, and #4. This is a result of manufacturing defects, these pads being slightly lower than 1, 3, and 4.

There are several small spark tracks at the leading OD. At least some of the gouging and pitting at the end of the oil groove between #2 and #3 appears to be caused by sparking. In this case all gouging is in the babbitt, making positive identification difficult. Sometimes the damage extends into the underlying steel, which clearly identifies sparking.

Land #3: Badly frosted and overheated near OD. This pad was ready to fail at the slightest provocation. Moderate spark-tracking, especially at leading OD, with well-defined melting and pitting at the bottom of the grooves.

Land #4: Medium-to-heavy frosting at the end of the taper. Several small, but well developed tracks show the often observed "step-pattern", i.e. the track follows rotation, then steps sideways and continues in direction of rotation. Many branches and burn holes can be seen. An interesting group is at the center of the pad, ¾ towards the OD, at the end of the remaining tapered land (not visible in photos). There are also many mechanical scratches (foreign particles) of no significance with respect to shaft currents, except that some tracks start at such scratches.

The radial depression near the center of the pad is caused by a salvaged manufacturing error (oil groove cut at wrong location). It greatly reduces thrust capability.

Land #5: Similar to #2.

fixed-geometry bearings, as compared to equalized-shoe design.

Figure 9A shows the shoe surface of the thrust bearing. Note the many medium size spark tracks with branches. There is also a "spider web" pattern near the center of this shoe, which is not well visible in the photograph. All these very fine lines are deep spark tracks. Frosting is mild and of very fine texture, covering almost the entire surface of this shoe. The dark spot at the outside diameter of the trailing edge is burned oil from excessive load on the thrust shoe, indicating impending thrust failure. The shiny, unidentified markings are caused by handling damage after removal of the shoe. Figure 9B shows a burn at the shoe to back up plate contact point. This is a relatively small burn, but it indicates significant current transfer. Minor spark burns were noted at the thrust button.

Of particular interest was the very severe frosting and spot welding at the contact surfaces of many of the oil bushing seals of the compressors. EDM was severe at several seal faces, with 1 to 5 mils of metal removed. There were deep burn holes, and the spot welded areas had again metal transfer between parts, which resulted in tearing during disassembly. There can be no doubt that these seals had been completely immobilized.

The high-pressure compressor bearing at the thrust end had a frosting pattern as shown in Figure 3c. This bearing had run only for two weeks, after a shaft-current induced failure which caused a plant shutdown. The high pressure compressor had a history of severe, locked-seal induced oil whirl, the vibration amplitude reaching 4.5 mils, with a predominant frequency at 47% of running speed. The bearings in this unit were of the tilt-shoe type.

Only the high-pressure turbine was opened, and the rotor was replaced. Please note that the damage as recorded in Figure 7 was experienced with the old high-pressure turbine rotor, which had only 2 to 4 Gauss residual magnetism. The rotor rotor installed at this turnaround had up to 11 Gauss at the shroud of the blading. We had no way to estimate the level of magnetism of the low-pressure turbine and of the compressors. However, there were indications that especially the low-pressure turbine was heavily magnetized.

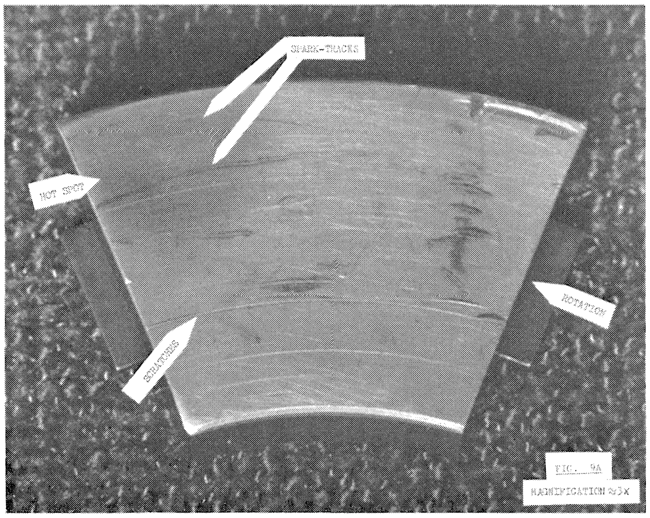
Because of time limitations and difficulties in locating a capable demagnetizing crew, none of the components of this train were demagnetized. However, new shaft brushes were installed at both ends of the train, similar to the arrangement shown in Figure 1. These brushes should have operated satisfactorily because two brushes were used at each location, and the surface velocities were low. Also, the brush resistance and condition were periodically checked and found to be satisfactory. Brush wear was negligible. Two other brushes had been installed, on the shaft at each turbine, near the journals. The surface velocity at these locations was approximately 250 ft/sec. However, it was not possible to obtain a polished, perfectly round surface at these locations, because of previous damage. Both of these brushes failed at startup, with considerable heat generation, and the adjacent bearings failed also. It is not clearly understood why these bearings failed, it could have been that the currents being generated were extremely high, or that the rough surface caused sufficient heating to fail the bearings. This latter possibility seems very remote, because of the amount of cooling oil flowing through the bearing and along the shaft. After the unit was placed in operation, several additional component failures occurred, and when the machine was inspected after approximately one year of operation, it was reported that the shaft current damage was as bad, or worse, than previously.

It seems that the shaft brushes at both ends of the train did not have a measurable beneficial effect, although these brushes were in excellent operating condition. Unless the entire unit is very thoroughly demagnetized, this unit will remain to be unreliable, with a poor prospect for its availability.

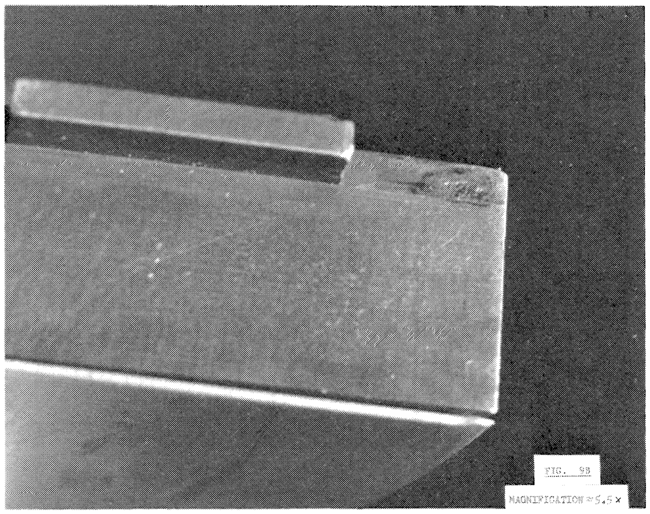
We do not know the cause of the original magnetic fields which, without a doubt, caused self-excitation and magnetization of the rotor system. Most likely these magnetic fields resulted from omission of demagnetization after magnetic particle inspection. This was verified. Also, there is a strong possibility that field welding was performed on the unit.

PART II

This part of the paper deals with electromagnetic generated shaft currents and not electrostatic generated shaft currents. For the latter the cause and remedy are more straight



9A Shoe Surface



9B Burn at Shoe-to-Backup-Plate Contact Point

Figure 9 A & B. Syngas compressor thrust shoe, damage caused by magnetic shaft currents (40,000 HP/11,000 RPM Train).

forward and are usually related to an electric by-product of mechanical process. The former, on the other hand, can be very evasive both as to cause and remedy.

Two types of magnetic field sources to be considered are: (1) Residual magnetism remaining in a previously magnetized component and (2) electromagnetically induced magnetism. The latter is usually associated with electric machinery, however, there is evidence that it occurs under certain circumstances in mechanical equipment as well. Also, both (1) and (2) can occur simultaneously and may, in some instances, reinforce one another. The magnetic field in machine parts may or may not cause problems, depending on its orientation, the available paths for the magnetic field and the ensuing electric current. Obviously, a major problem develops when shaft and bearing currents reach levels which cause electrical arcing and erosion.

Magnetism can originate from many different causes extending from use of welders, magnetic tools, lifting magnets to simple concentration of the earth's field. As an example of this, on early self-excited D.C. electric generators unless some residual magnetism existed in the field structure, the voltage would refuse the build up. It was not uncommon for the installer to align the field frame for favorable orientation of the earth's field, then to strike it with sledge hammer, thus aligning and magnetizing the field poles. Following this the voltage would build up as desired.

Residual magnetic fields exist in some degree in all materials. The orientation and location of residual magnetic forces depend upon the magnetizing medium and the "magnetic hardness" of the material. Under consideration here are those fields of sufficient strength and of proper orientation to cause damage to rotating machinery.

A simple example of a machine rotor resting in bearings on a baseplate, Figure 10, is used to illustrate various field and current configurations. In this example an elementary and perhaps most effective magnetizing method is illustrated. The current, I, could originate from a direct current field welding machine. The current path depends upon where the welder places his ground electrode with respect to his work, plus the electrical current return path whether it be through the machine base, rebar or other. In this example the resulting flux path is substantially closed, there being but two non-magnetic bearing gaps in the path. Once the welding is complete current I ceases to flow; however, residual magnetic force may have been induced into components in the magnetic circuit. The amount of residual magnetic force remaining depends on the field strength peak level caused by the welder current plus the "magnetic hardness" of the component. In the example, assume the shaft to be "hard" and the frame to be "soft" magnetically, and that because of cross section area differences, the peal flux densities imposed by the welder were 15 kilogauss and 6 kilogauss respectively. An example of the magnetic hysteresis curve and residual magnetism is shown on Figure 11. For both the rotor and the frame zero initial residual is assumed. Thus as the welder current grows, the magnetic field progresses to the maximum point "A". The rotor and frame magnetic hardness levels are proportional to the "open eye" areas of the hysteresis curves. As the welder current decays, the magnetic operating point falls to the residual value B_R. It will remain here unless there is an alteration in the magnetic current. Such an alteration would be removing the rotor from the stator. In this event the residual field operation would drop to a location such as point "D". On reassembling of the rotor the stator magnetic operation would rise to a point at or slightly below the original B_R following a minor hysteresis curve. Note that for the magnetically hard rotor, substantial residual (B_R) exists relative to the magnetically soft stator.

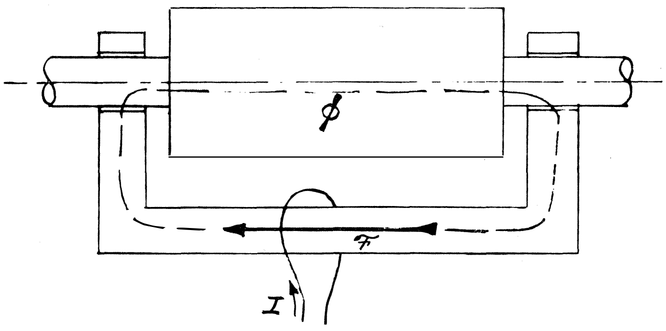


Figure 10. Field and Current Configurations in a Simple Machine Rotor in Bearings on a Baseplate.

In the above example, a residual magnetic force "F", which is proportional to "$-HC$" remains and substains flux through the shaft, bearings and frame. Since the source of magnetism is in the shaft, the magnetic field will rotate with the shaft and unipolar voltage is generated into the bearing shell, or in the case of anti-friction bearings, in the balls, rollers and outer race. Localized circulating currents (i_L) tend to circulate depleting somewhat the level of generated potential as shown in Figure 12. Still, as evidence confirms, sufficient voltage exists across the bearing to cause oil film electric breakdown, current (i_B) flow and erosion. Actual breakdown is a function of the oil film clearances, oil conductivity and dielectric breakdown plus presence of impurities or discontinuities in the oil film area.

If the magnetic properties of the frame and the rotor are interchanged in the above example, the following occurs. Assuming a residual magnetic force to exist in the frame and substantially none to exist in the rotor, the same phenomena occurs in reverse and the voltage generator action is the same as that of the conventional brush type homopolar electric generator. In this case, the magnetic field is fixed in location with the stator and the rotor turns as an electric conductor in the field. The resulting generator is that shown on Figure 13. Here localized currents, if they can exists, circulate within the shaft while the bearing oil film breakdown currents follow a return path in the bearing shell.

As can be realized, residual magnetic forces in the rotor and stator can result in combined effects as described above with a good possibility that the emfs are additive around the bearing current path causing earlier or more destructive bearing problems.

The magnetic forces and resulting field tend to become higher or larger equipment. This is believed to result from the longer "magnetically hard" components plus the relatively small reluctance path offered to the magnetic field by the bearing and other path non-magnetic components. In such cases presence of a non-magnetic component in the flux series path may be insufficient to reduce fields to non-destructive levels. This is believed to be the case for Figure 3c where a non-magnetic copper shell did not eliminate damage. Placement of electric current brushes at both edges of the bearing shell could, in some instances, shunt currents around the oil film in case of sleeve type bearings. Positive, low-resistance contact must be maintained between the brush and the shaft, and this is very often a problem, especially in an oil environment. In anti-friction bearings, currents do not flow in a simple path but are affected by the ever changing relationships of balls and

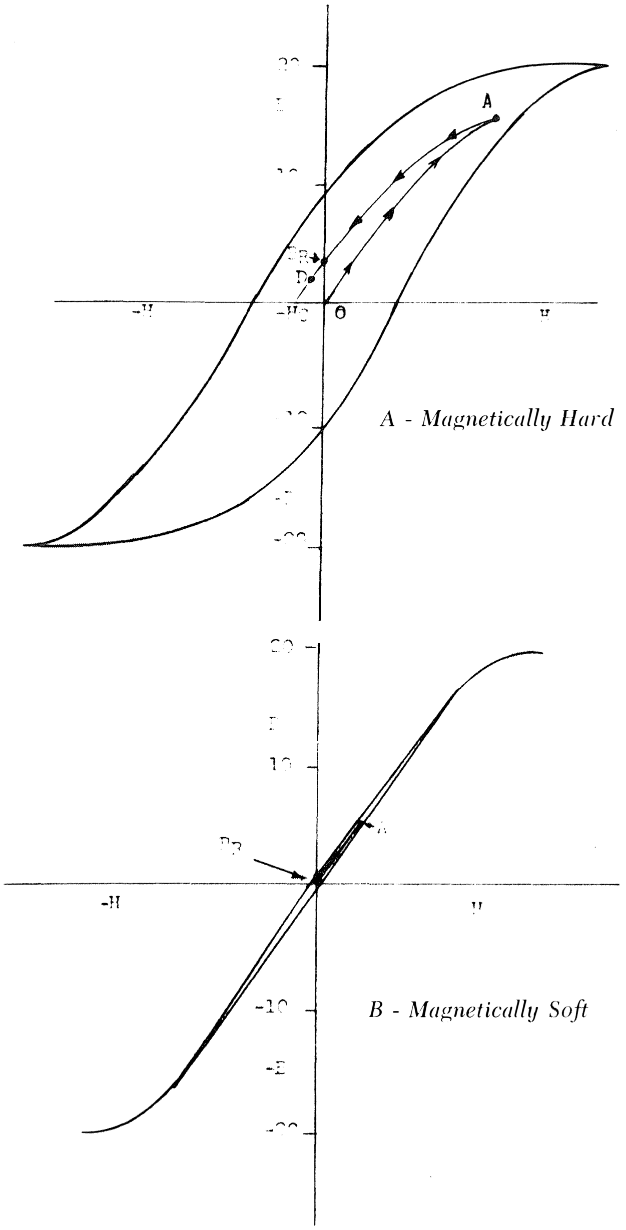


Figure 11. Magnetic Hysteresis Curve and Residual Magnetism.

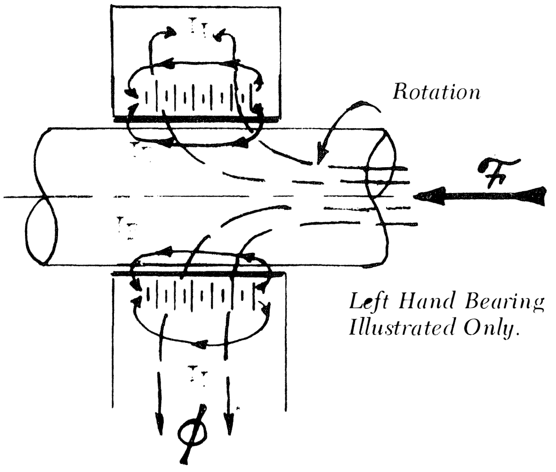


Figure 12. Localized Circulating Currents.

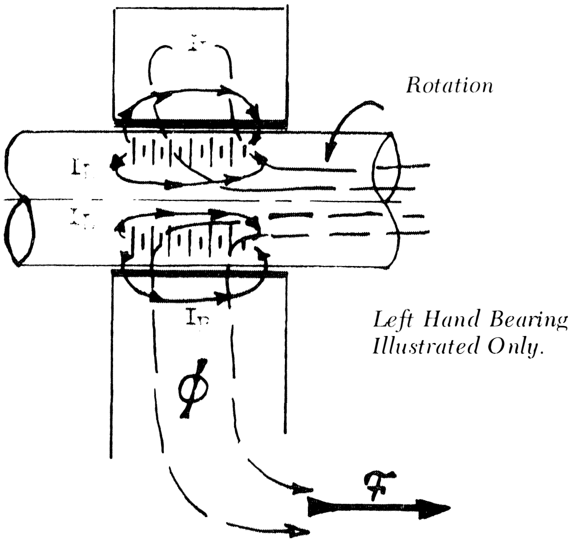


Figure 13. Localized Circulating Currents with Residual Rotor Magnetism.

races. This accounts for "fluting" often observed on these components.

An additional factor, difficult to evaluate but certainly present, is the occurrence of unusually large voltage across the oil film caused by the inductive effect of the current path. This could well account for film breakdown where oil film resistance and dielectric strength are somewhat high. As has been observed, sustaining or cascading of magnetic fields occur especially on larger or long trains of components. This is believed to be caused in a manner similar to self-excited D.C. generators. Figure 14 is an example of how this could occur. The basic requirement for this to occur is that generated currents encircle the magnetic field path, increasing even further the level of magnetism. This is a function of the mechanical configuration of the rotor, stator and base assembly. The same effect occurs if localized rotor circulatory currents accumulate and spiral around the rotor exterior surface down the shaft length in this case reinforcing the residual rotor axial and residual magnetic fields.

The second type of shaft currents to be discussed are those indicated by electromagnetic induction and are alternating fields and currents, as opposed to those previously covered, which are primarily direct fields and currents. Those to be discussed here, while usually associated with A.C. electrical machinery, occur in mechanical equipment as well. In one case, A.C. magnetic flux flow is shown in Figure 10 where it passes through the rotor, bearing and frame. In the second case, induced electric current flows as is shown in Figure 15. In this latter case bearing currents exist over the entire bearing surface as opposed to end concentrations.

Typical sources for the electromagnetic fields and currents are discontinuities in the magnetic circuit. These are well documented in literature on A.C. electric machines but apply equally to mechanical equipment which have pulsating mag-

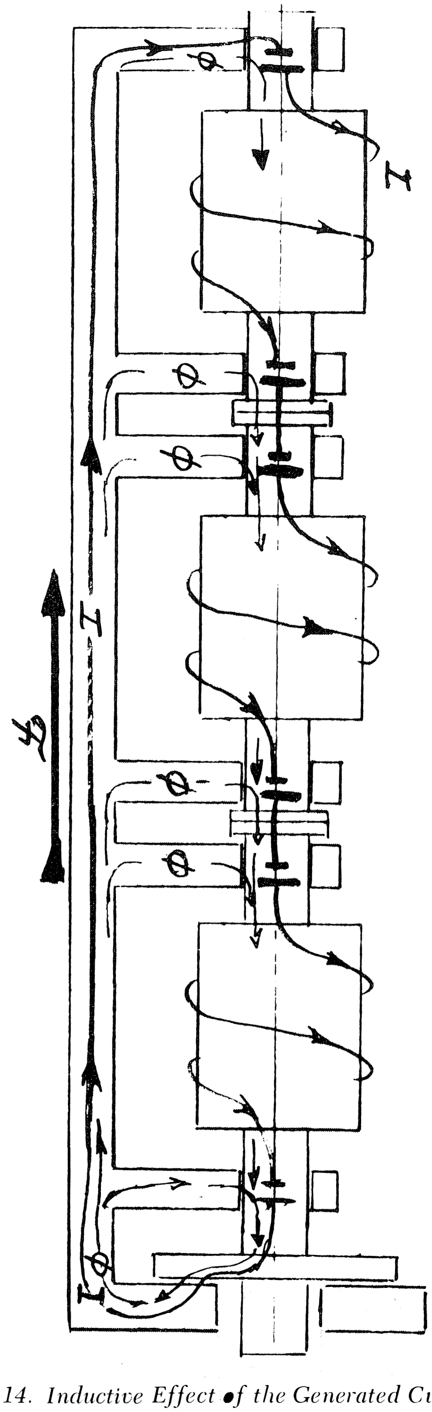


Figure 14. Inductive Effect of the Generated Currents.

netic fields linking a bearing current circuit. Often these are inherent to the unit construction and cannot be corrected. It is for this reason that manufacturers have on larger units adopted the practice of insulating electrically key bearings. This breaks the otherwise low resistance path for flow of shaft currents. Another corrective measure has been the use of grounding brushes at the edge of the bearings which are not insulated. As is mentioned previously, the uncertainty of low resistance brush contact makes this correction somewhat unreliable.

The case of electromagnetically induced flux in the shaft (Figure 10) a pulsation of the unipolar generated current occurs as discussed previously but at the frequency of electromagnetic inductions. This occurs in electrical machinery typically because of current encircling the shaft or frame magnetic circuit. It can usually be overcome by making electrical connections to prevent the interlinking of electrical and magnetic circuits. Insertion of a non-magnetic member into the flux path may not be adequate to prevent damaging fields, depending upon the effective reluctance imposed in the magnetic circuit.

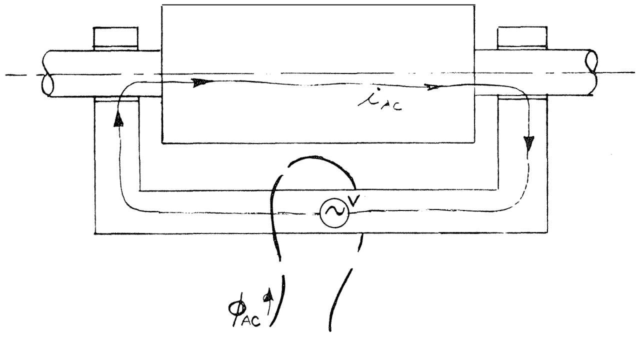


Figure 15. Effect of Induced Alternating Current.

Obvious corrections for reducing bearing currents as discussed above may or may not work. The exact source and character of the basic shaft currents are sometimes difficult to determine. Magnetic field measurements made external to the unit can sometime give guidance. Often this measured field is unrelated or not indicative of the fields that exist with the bearings, seals or other close running components. It is best to make measurements in the affected area plus the suspected return path areas where higher flux densities would exist. If the field is direct, resulting from residual magnetic force and does not change or increase with operation, there is a good chance that it can be reduced to a level of minimum damage through demagnetization. This can be accomplished by inducing magnetic fields in excess of the saturation values alternately in the positive and negative directions ever decreasing the magnetizing strength.

This, in effect cycles residual magnetism of the hysteresis loop of Figure 11A to ever decreasing sized loops until the origin is reached. This may be all that is needed. If additional magnetism is induced as is discussed above, physical alterations of the magnetic circuit may be required so a low level of flux passes through the bearing even though a residual of electromagnetic source of field force still exists.

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