ELECTROMAGNETIC SHAFT CURRENT CONTROL

by

John S. Sohre

Turbomachinery Consultant

Ware, Massachusetts

John S. Sohre is an independent turbomachinery consultant with experience in turbine and compressor design, installation, and problem correction. He is working with many firms in the chemical, petrochemical, and power generation industries. He is a member of ASME and a registered professional engineer in the State of Pennsylvania.

Problems with electromagnetic shaft currents are nothing new [1, 2]. Many turbomachinery users have had problems for many years, but failed to identify the cause, and just learned to live with the problem by periodically replacing bearings, seals, thrust bearings, gear units, couplings, governor drives, and so on. Most of these components are not wear parts and they should not require replacement unless something is wrong. The fact that many turbomachinery maintenance persons now regard bearings and seals as wear parts may give an idea of the extent of the problem.

As long as there was only periodic replacement of these parts plus an occasional failure or wreck, it was possible to put up with this situation. But during the seventies more and more cases occurred where damage was very severe, and where operating cycles between failures became successively shorter, until a unit would operate only a few days between emergency shutdowns, and sometimes only a few hours. The mode of failure became more destructive with the larger, high-pressure, and high-speed machinery going into service in the 1970's for such processes as ammonia and methanol synthesis, gas reinjection, and other high-pressure processes. It is not exaggerated to say that during the last few years the frequency of failures has reached epidemic proportions. Cost to the industry is in the hundreds of millions of dollars per year, quite possibly into the billions. The main components of the cost are loss of production, loss of raw material for flaring and repair costs.

Since the mechanics of electromagnetic current generation in turbomachinery are explained in the reference papers and other literature [3, 4, 5, 6], the reasons for this phenomenon and for the recent epidemic will only very briefly be explained, to enable people who are not familiar with the references to understand the basic mechanics.

One point should be made crystal clear at the beginning: We are *not* talking about electro*static* charges of the rotor which can result from droplet atomizing in the condensing stages of turbines, and from a number of other sources. Electrostatic currents represent a well recognized problem which is not nearly as troublesome as the electromagnetic type, because it has very low current density and therefore it is slow-acting and relatively easy to control. By comparison, electromagnetic problems can destroy a unit in a matter of hours or even minutes. Currents can reach many thousands of amperes during the terminal phase of self-excitation.

How does this work? Detailed explanations can be found in the references. The based mechanism is the same as for a series-wound DC generator. Some residual mangetism in the core of the coils causes currents to flow in a manner which will reinforce the existing residual fields. As the fields increase, currents also increase, and so on, until the fields are saturated. In electrical machinery these currents flow in well-defined paths of copper wiring; in nonelectrical machines such as compressors and turbines, the currents flow through the metal in an unpreditable manner, which depends on the geometry of the machinery and upon the location and strength of the residual magnetic fields. The currents may cross at interfaces between parts, and they can go across the oil film of bearings and seals. As the currents encounter electrical resistance, sparking or burning will occur and parts will be damaged until the machine is either shutdown on high vibration or leakage, or a catastrophic failure may occur, for example, a thrust bearing failure, main bearing failure, or seal-lockup with all its consequences. Examining the parts after such a shutdown, a skilled observer can determine the cause of the failure from the appearance of certain critical parts, which have not been completely destroyed. These parts show frosting on the bearings and shafts, metal loss because of electrodischarge machining, spark-tracking in the babbitt and sometimes in steel parts, burnt spots, spotwelding, and possibly severe local heating of certain components. Additional proof of electromagnetic currents is the high level of magnetism which will be found in certain parts and in certain regions of the unit. A rough check of the magnetism can be made by using a simple magnetic field indicator.

Why are the levels of damage so severe? First of all, much larger and more massive machines were built during the last ten years, for new processes, and these machines run at higher speeds. They also have much smaller clearances — for example, a typical clearance on a six-inch oil-bushing seal is one to two mils total on the diameter of the seal. Then, a proliferation of magnetic tools has come into wide use during this last decade, and therefore machinery often has strong residual magnetic fields. This holds especially for parts which have been repaired or inspected in the field. Typical examples are lifting magnets, drill press bases, magnetic particle inspection, and many more sources of permanent magnetization. Finally, it has become standard practice to do electric arc welding or burning on an operating platform — or even on the machinery itself. Arc welding leaves paths of strong residual magnetism. A dozen years ago welding around a unit was absolutely taboo.

The above factors result in a very effective combination of larger machines, tighter clearance (which give smaller magnetic and electrical gaps), and increased levels of residual magnetism. Once this stage is set, a shock, such as compressor surge or vibration, can cause reorientation of the magnetic fields and either progressive or sudden self-excitation

What can be done? The best and only sure-fire cure is the complete demagnetization of the entire unit and its surrounding structures, such as piping and supporting bases. This requires the services of an expert who is thoroughly familiar with both the identification of the magnetic fields and methods to eliminate them. However, complete demagnetization can only rarely be achieved once an entire installation has experienced a high degree of self-excitation and self-magnetization. This is true even if the machinery is completely disassembled. Some residual magnetism is likely to remain in the main piping, baseplates, and other structural members of the installation. Unless the remaining voltages and currents are monitored and grounded, a unit may remagnetize itself over a period of time by just sitting there and running smoothly. This will usually take a few months, or it may be accelerated by mechanical shock and operating upsets.

Effective shaft-riding brushes which allow monitoring of the voltages and currents have been developed and can be used to ground such residual currents, and thereby prevent damage to sensitive machinery parts. Such brushes will evidently not prevent the currents from being generated, and they cannot prevent self-excitation if the currents reach very high levels. Up to a certain level of current density these brushes have been effective in preventing damage, allowing units to run to a scheduled turnaround, at which time additional demagnetization can be performed as required. Detailed information on arrangements for current monitoring and grounding can be found in References [5] and [7].

A very considerable amount of work and testing was required until a reasonably successful brush design was developed. The main reason for the difficulties is the unfavorable working environment for the brushes which have to operate at extremely high surface speeds, vibration, with oil splash and corrosives in the oil or in the atmosphere, etc. Combine this with the very stringent requirements for reliability, safety, material considerations, extreme space limitations within the bearing cases of the unit, wear life requirements, the need for alarms for brush wear and excessive currents, and an idea why it was rather difficult to come up with a fully satisfactory solution can be realized.

By far the major problem was to find a brush material which would maintain electrical contact with the shaft for a sufficient length of time (years) while exposed to realistic levels of shaft currents. The conventional materials such as solid graphite, carbon, metal-impregnated materials, solid metals, and stranded metals would simply quit working after relatively short exposure to shaft currents, and the shaft surface was left with extensive pitting and grooving. One important finding resulting from these tests was that the effective life and low contact-resistance of the brushes does not so much depend on surface velocities, contact pressure, presence or absence of oil, but rather on the strength and type of the currents being passed. The situation is evidently quite different from the conditions in an electric machine, where the currents reach the brush under controlled conditions, travelng along defined electrical paths on the surface of such special components as slip rings or collector rings. The best compromise was found to be a wire-bristle brush [7]. Brushes of this type have been in continuous operation since 1979, without contact deterioration or significant wear in two years.

This concludes the results on the work which was performed during the last three years. The solution to the problem is admittedly very crude and leaves much to be desired. A lot of work remains to be done by all parties concerned, including the machinery manufacturers, and construction and maintenance personnel. At least some practical means have been developed to prevent severe damage and to extend the operating life to at least one year or more, if a combination of demagnetization and grounding brushes is provided, and if currents are monitored in service so that corrective action can be taken before extensive damage occurs.

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ELECTROMAGNETIC SHAFT CURRENTS IN AMMONIA PLANT TURBOMACHINERY AT CF INDUSTRIES, INC.

by

Lester E. Sutherland

Chief — Plant Engineering

CF Industries

Donaldsville, Louisiana

Lester E. Sutherland is chief of plant engineering, CF Industries, Nitrogen Facility, Donaldsonville, Louisiana. He has been with CF Industries for eleven years and is responsible for engineering assistance to maintenance and operations in several areas, including rotating equipment. He is a member of AIChE and a registered professional engineer in the State of Louisiana. He holds a Bachelors' and a Masters' degree in Chemical Engineering from the University of Louisville.

CF Industries operates two 1000 ton per day and two "stretch" 1000 ton per day ammonia plants at Donaldsonville, Louisiana. A sister company, CFL, operates two "stretch" 1000 ton per day units at Medicine Hat, Alberta, Canada. The "stretch" 1000 ton per day plants have identical compressor trains and are easily capable of 1200 tons per day. The failures to be related occurred in the turbine drivers of the air compressor trains. These turbines operate at approximately 6800 RPM on 550 psig, 610°F steam which exhausts to 4 in. Hg abs. They each develop approximately 13,000 HP.

On June 29, 1979, a severe thrust bearing failure occurred in the air compressor turbine of the Number Two Ammonia Plant at Medicine Hat. The failure took place shortly after 2:00 PM. Vibration readings recorded by the previous shift at 6:00 AM showed normal operation and the process variables logged at 6:00 AM and 10:00 AM indicated normal stable operation. Shortly after 2:00 PM the control panel operator requested that the compressor operator speed up the turbine to compensate for a slight reduction in process air flow. Variations in air flow are not unusual and arise from changes in the atmospheric air inlet conditions, and steam pressure or temperature variations. When the operator approached the turbine, he noted the bearing oil outlet temperature had risen to 186°F from his 2:00 PM reading of 134°F. Likewise, the ring pressure had risen from 325 psig to 365 psig. He reported this to the control room and was told not to increase the speed. The maintenance supervisor was advised and preparations were made for a controlled shutdown. There were no vibration alarms, indicating that radial vibration was less than one mil. At 2:15 PM the turbine exhaust end bearing began smoking and the oil outlet temperature fluctuated between 160°F and 185°F. The machine became noisy so the operator activated the emergency trip and shut it down.

Inspections of the turbine showed the thrust bearing had failed and the rotor had moved downstream, rubbing severely on four diaphragms. The turbine wheels were dished and the rotor was declared scrap. The thrust bearing pads had machined deeply into the thrust disc, transferring metal from the disc to the pads, and the thrust area of the rotor was blackened from the heat. The radial pads had spots of missing babbit and the pads were found to be welded into the housing. All ten of the pads on the turbine were found to have what appeared to be ½ in. diameter spot welds on either side of the pad retaining pin (Figures 1 and 2). The thrust disc showed severe frosting on its outside edge, almost as if it had been sandblasted.

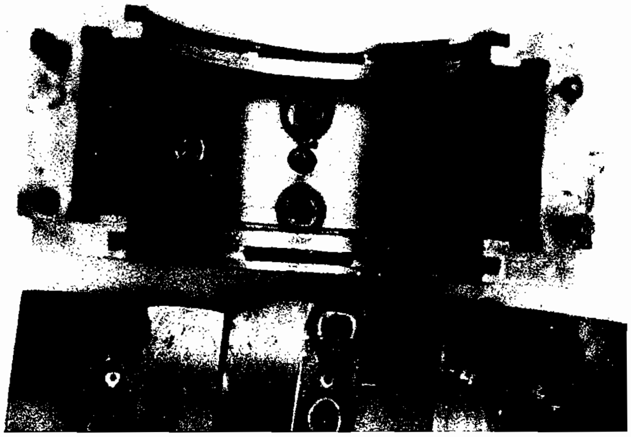

Figure 1. Turbine Radial Bearing Pads Showing Weld Spots.

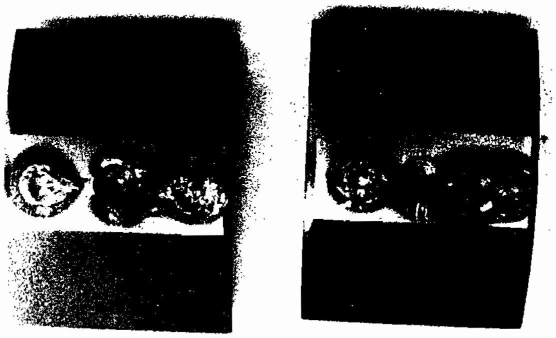

Figure 2. Backs of Two Radial Pads. Note the Weld Spots.

Based on these observations, electrical discharge phenomenon was suspected. Magnetic field strength measurements were taken and levels of up to 30 gauss were detected. The field readings showed several changes in polarity within each part. For example, the rotor had positive polarity at each end with a negative pole in the middle. The rotor wheels showed several changes in polarity around the periphery and some frosting of bearings was detected in the air compressor (Figure 3). The bearings in this turbine had been inspected ten months prior to the failure and found to be in good condition.

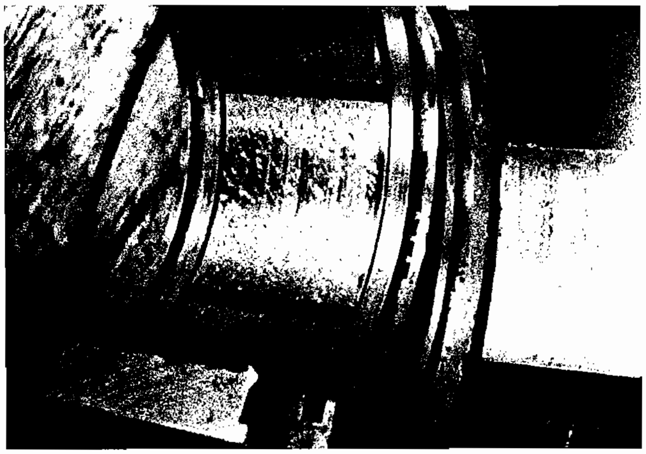

Figure 3. Radial Bearing Pads with Spark Tracks.

A new rotor, bearings, and diaphragms were installed and the unit was returned to service with no problems. The turbine and compressor, along with the other compressor sets, were surveyed and demagnetized on the next turnaround. No subsequent failures have occurred.

The Donaldsonville Number Three Ammonia Unit was shutdown in June of 1980 for a routine turnaround and catalyst change after completing an uninterrupted production run of 633 days. As a result of the Canadian experience, consultants were retained to conduct a magnetic field strength survey of the plant's large turbomachinery. In accordance with original equipment suppliers' recommendations and hoping to provide a means of current dissipation, spring loaded carbon brushes were installed on each condensing turbine. The bearings were checked and the rotor was inspected by "Magna-glo". The magnetic field survey revealed normal levels in the air compressor turbine and the rotor was magnetically clean. Field strengths of 400 gauss were detected in the blade-casing clearances of the low pressure air compressor. These areas were demagnetized as were various areas of the syn-gas compressor turbine.

On September 3, 1980 at 1:50 PM, the panel operator noted a fluctuation in the air flow and asked the compressor operator to check the air train. No air flow fluctuation could later be found on the charts. The compressor operator reported an unusual noise coming from the exhaust end of the turbine. This was accompanied by an alarm on the radial vibration monitor indicating vibration in excess of one mil. The thrust monitor had been swinging that morning and was thought to be malfunctioning. The operations superintendent went to the compressor deck to investigate and noticed that the recently installed grounding brush holder plate, at the exhaust end of the turbine, had apparently warped and was rubbing on the shaft. When he attempted to push the plate away from the shaft, sparks or fire shot out approximately two feet from the plate area. The oil temperature at the bearing outlets began rising and the radial vibration levels went off scale (i.e., above five mils) and the turbine shut itself down. This turbine can be manually tripped out by an operator or automatically tripped by loss of either governor oil or lube oil and can also be shutdown by the overspeed safety device. All of these "trips" close the trip and throttle valve. This valve closed, although there was no loss of oil pressures nor did anyone manually trip it. The most likely explanations of this are that the spring loaded overspeed trip device was thrown out by the high vibration or that the vibration simply shook the trip and throttle valve until it unlatched.

The thrust bearing housing was opened and the thrust bearing was found to be severely wiped. The housing had many pieces of steel magnetically attached to its internals. The radial bearing pads were inspected and found to have arcing and spot welds on their back sides. Two of the bottom three pads were firmly welded into the housings. Preliminary measurements were taken and the field strength readings were beyond the range of the meter. The consultants were contacted and engineers were sent to demagnetize the case.

The turbine case was opened and inspected. The rotor had shifted approximately 5/16 in. and the second through sixth wheels had rubbed hard on their respective diaphragms. A step on the exhaust end of the shaft had pushed against the aluminum brush holder, distorting it. The radial bearings on the air compressor showed welding on two pads. The turbine rotor was highly magnetic, showing over 90 gauss at one end, and could support ⅛ in. welding rods by magnetic attraction (Figure 4). The turbine case and diaphragms were also highly magnetic. The field flux between the case halves, when separated ⅛ in., was 180 to 300 gauss and levels of 80 gauss were found in the thrust bearing area. The rotor wheels showed levels of 40 gauss and the turbine exhaust piping had flux levels of 25 gauss.

Figure 4. Thrust Disc on Turbine Rotor. Note the ⅛ in. Welding Rod Magnetically Attached.

All magnetic turbine and compressor parts were demagnetized to approximately 2 gauss, except for the turbine case which was reduced to 40 gauss at the horizontal split when measured with a 1/16 in. gap. Special attention was given to the bearing areas. The spare rotor was magnetically clean, but the new diaphragms showed fields of 10-20 gauss at welding points. These were localized and easily reduced to below 2 gauss.

All brushes were removed and the plant was started up. Twelve hours into start-up, the air compressor turbine experienced another thrust bearing failure. No welding occurred in the bearings and there was very slight frosting on the edge of the trust collar. There were no significant levels of magnetism detected. New thrust bearings with imbedded RTD's and a new thrust disc were installed. The plant was started up successfully and the turbine has run since then without incident. We believe this second failure could have been the result of some unremoved trash left after the first failure.

On September 29 the air compressor turbine in the Number Four Ammonia Plant experienced a thrust bearing failure. The machine was promptly shutdown and damage was limited to the thrust bearing area. Magnetism in the bearing area was found to be low level. No welding was found in the radial bearings, although there was a very slight frosting on the edge of the thrust collar. The thrust bearing was upgraded to a higher capacity design. The unit was returned to service and has been trouble free since that time. This unit was inspected in July 1980 and checked for magnetism. Nothing of consequence was found. There were readings of 6 gauss in the bearing area of this turbine, which were reduced to 2 gauss.

Since September of 1980, during a short outage, the Number Three Plant was upgraded to higher capacity thrust bearings. The Canadian plants are still running successfully with the originally supplied bearings. It is not certain why these failures occurred, but the evidence of strong electric currents provided by the welded bearings is undeniable. The existence of strong magnetic fields in the equipment cannot be disputed. Several theories have been advanced.

Oil contamination and high or low dielectic strength have been suggested as possible factors. Low conductivity would be suspect in that it might allow large charges to build up in the rotor rather than allow a continuous low energy discharge. Highly conductive oil might permit the continuous discharge across the oil film and establish a field as a result of the current flow. This current flow would strengthen the magnetic field, thus increasing the current flow. This could then continue to destruction. The current path and failure site would be in the area of lowest resistance, such as a highly loaded thrust bearing. Oil analysis showed nothing unusual. The dielectric strength was 22.5 kv, which is consistent with other consoles at Donaldsonville. The oil was changed in the consoles where the failures occurred during the preceeding summer turnarounds and the units had run without incident for ten weeks on the new oil prior to failure. The console which serves the air compressor train also serves the refrigeration train. This unit has a turbine which is essentially identical to the air compressor turbine except for direction of rotation. No frosting, bearing deterioration or high levels of magnetism have been found in this unit.

The carbon shaft brushes have been blamed as the cause of failure. The theory is that the brushes provided a new current path, thus completing a circuit for current flow across the thin oil film at the thrust bearing and out the brush at the exhaust end. While this could be considered possible, it is believed unlikely. The Canadian plant did not have brushes prior to the failure. Many companies employ brushes for discharge of electrostatic energy on condensing turbines. It should be pointed out that at high surface speeds the carbon brushes glaze over in a matter of weeks and become nonconductive.

Welding, either on the compressor train or near it, could have induced magnetic fields in the unit subsequent to demagnetization. Neither in Canada nor at Donaldsonville was there welding near the unit at the time of failure. Records do not show any significant welding in the area for several days prior to the failures.

High thrust bearing loads have been blamed. The original 1000 ton per day plants at Donaldsonville were designed with six inch thrust bearings. After a number of thrust bearing failures in the early 1970's, a seven inch thrust bearing was installed. The 1000 ton plants were being pushed above 1100 tons at that time and after installation of the seven inch bearings the failures ceased. The stretch 1000 ton plants were producing approximately 1400 tons per day when the failures occurred and were operating with the original six inch bearings. While the six inch bearing has the capacity for the design load, its safety margin is dramatically reduced at the higher production rates. It was elected to install seven inch bearings with copper backed pads and embedded RTD's to attain higher load capacity. There is speculation that a portion of the thrust load from the low pressure compressor was being transferred through the gear coupling and resulted in a bearing overload situation in the turbine. It was felt the seven inch bearings would help in this situation.

The limited demagnetization effort conducted at Donaldsonville ten weeks prior to the failure could have changed the magnetic fields such that they were more dangerous. This was not believed to be the case. All evidence indicates that the lower the field strength, the lower the shaft currents. The demagnetization efforts left the machines with lower gauss readings. The consultants inspected or demagnetized 24 cases on six turbo-compressor trains during June and July and demagnetized the Number Three Plant air compressor train after the failure. No demagnetization work had been done in the Canadian plant prior to their failure. Had the efforts been detrimental, it would have been evident in other machines by now.

Magnetic field measurements are strongly dependent on where they are taken. If there is a piece of steel close to the magnetized part the magnetic flux density will be higher than when measured in air. An example of this was when measuring the flux between the top and bottom halves of the turbine case the level was found to average 80 gauss when there was a 1½-inch air gap between them. When the gap was reduced to ⅛ inch the field was 180 to 300 gauss. Bearings with low readings in air could have much larger flux densitites when separated by a thin oil film.

Various other possibilities have been advanced including lighting, sunspots and the North-South orientation of the units. All of these ignore the many other machines at these locations which escaped damage. It is believed that internally generated electromagnetic shaft currents played a part in the Canadian and Donaldsonvile Number Three failures. The situation was aggravated by a heavily loaded thrust bearing. Additional thrust may have been transmitted to the turbine through the coupling. The thin oil film resulting from high loads facilitated the conduction of high shaft currents. These factors probably resulted in the thrust bearing failures, but seem insufficient to explain the high currents necessary to weld ten bearings into their housings simultaneously. In both of these failures there was no longer than desirable delay in shutting down the machines. The contact of the turbine rotor wheels with the diaphragms at 6800 RPM may have provided sufficient energy to weld the bearings into the housing.

It is unlikely that the welding damage could have occurred over any extended period of time without observable changes in the vibration or oil temperatures. It also seems reasonable that if the damage occurred over some extended time period, a low resistance current path would have been developed through the first spot welded bearing and its damaged surface. The most likely explanation of these failures is that electromagnetic activity precipitated the failure of an already heavily loaded thrust bearing. Failure to shut down the machines promptly resulted in the turbine wheels rubbing on the diaphragms. This high speed rubbing in some way generated the power necessary to make twenty, ½ inch spot welds simultaneously.