Electrostatic Discharge on a Large Steam Turbine Generator

[Editor's Note: The first portion of this article is extracted verbatim from a February 2001 ORBIT article by Mark Snyder. It is reprinted here in its entirety to provide a review for our readers and the necessary background for the attendant case history.]

Electrical or mechanical characteristics can induce an electrical potential (voltage) on the rotors of some rotating machines. If this voltage is not managed, or if the voltage mitigation system (often a shaft-grounding brush) fails to operate properly through lack of maintenance, the voltage seeks an alternate path to ground. That path will be the metal component—typically a bearing or seal—closest to the shaft. The electric arcing to that component as this voltage is discharged is termed electrostatic discharge. Arcing erodes metal surfaces and opens the tight clearances that these components depend upon for proper operation. If undetected, electrostatic discharge will gradually destroy the bearing or seal, change the rotor dynamics of the machine, and may ultimately result in damage to the shaft that requires expensive rework.

Properly maintaining and inspecting the voltage mitigation system and monitoring the rotor dynamics of the machine with a Bently Nevada® machinery condition monitoring system can help avoid this problem.
Fluid-Film Bearing Machines

In an operating steam turbine generator (STG), there are at least three possible sources of voltage between the shaft and ground:

1. Electromagnetic loop voltage due to asymmetries in the generator magnetic paths may create an electric potential between opposite ends of the generator shaft.

2. Static charges may build up from droplets of water being thrown off blades in wet stages of the turbine.

3. A capacitive voltage due to a ripple on the DC field voltage may result in a voltage from shaft to ground.

Manufacturers take these voltages into account when they design their machines. The bearing at one end of a generator is normally insulated to create an open circuit and prevent electromagnetic loop voltage (this is why special care must be taken to ensure the insulating properties are maintained whenever instrumentation is installed in insulated bearings). Voltages between the shaft and ground, due to a static charge or DC voltage ripple, can be mitigated by the installation of grounding brushes that ride on the shaft near the uninsulated generator bearing. The brushes keep the shaft-to-ground voltage at a safe level by bleeding off current and causing the weak source voltage to decay.

Rolling-Element Bearing Machines

Industry observers suspect that similar mechanisms are behind a rise in rolling-element bearing failures in motors controlled by adjustable-speed drives [1]. These drives simulate three-phase power by creating a series of voltage pulses that only approximate the smooth sinusoidal waveform of each phase.

Since the roughness of the “pulse width modulated” waveform prevents them from adding vectorially to zero at every given instant, a “common mode voltage” relative to ground is created. This common mode voltage can generate bearing currents in at least three possible ways:

1. The air gap between rotor and stator acts like a capacitor that periodically discharges when bearing components contact. This is believed to be the major cause of bearing damage.

2. Another phenomenon causes current to flow when the effective bearing impedance is very low, and the bearings become the path to ground for parasitic winding capacitances.

3. An inductive effect causes a current to circulate through the bearings, shaft, and stator enclosure when the impedance of this circuit is low. Mitigation techniques for these situations either block bearing currents or provide a low-impedance path to ground. These techniques include shaft grounding brushes, bearing insulation, ceramic rolling elements or conductive grease, a Faraday shield, and dual-bridge inverters that balance the excitation of the motor.

Failure Mechanisms

Occasionally, insulation or grounding brushes wear out or become ineffective, resulting in a large current flow through the bearings. In fluid-film bearings, this can lead to electrostatic discharge through the oil film, resulting in the melting of a tiny area of the babbitt metal. Continued discharges over a period of time can lead to pitting erosion, visible as a frosted appearance of the bearing surface, and ultimately a wiped bearing. If the problem goes undetected long enough, the shaft surface at the bearing may become pitted to the extent that surface repair is required. This results in a significant machine outage to remove and repair the shaft. In some cases, the shaft also requires degaussing to remove a high level of residual magnetism.

A similar pitting occurs in rolling element bearings. In the early stages, the bearing race exhibits a satiny finish that is evenly distributed. In advanced stages, evenly spaced deep flutings appear on the outer bearing race. The fluting is especially distinct when the motor runs at a constant speed.
Detection

In fluid-film bearings, electrostatic discharge results in erosion of the bearing and is observable by changes in the bearing clearance. For machines instrumented with proximity probes, this can be monitored via the probe gap voltages; as the bearing clearance opens, gap voltage will change. Therefore, the following are recommended practices for monitoring:

- Enable gap alarming on your monitoring system. This is available on numerous Bently Nevada monitor modules including 3300/16, 3300/61, and selected 3500 monitors.
- Regularly review shaft centerline plots and gap voltage trends using diagnostic and trending tools such as System 1® software.


Some machines have voltage and current measuring instrumentation in the grounding brush circuits that will alarm on a high level of either parameter, and this instrumentation is typically provided by the Original Equipment Manufacturer (OEM) with the machine’s control system. Both the voltage mitigation system and its associated instrumentation should be checked regularly.

For rolling element bearings, seismic transducers can be used to trend bearing vibration levels. In the advanced stages of pitting on the outer race, higher vibration levels can be detected. However, electrostatic discharge can be difficult to differentiate from other rolling element bearing problems based solely on examination of the vibration signals. Typically, visual inspection of the bearing is required after failure to positively confirm the root cause.

Historical Perspectives

One of the earliest complete references to this specific malfunction was an ASME paper [3] by two General Electric engineers: J.M. Gruber, and E.F. Hansen. Gruber and Hansen dealt primarily with large turbine generator sets, and they addressed the destructive effects of shaft voltages upon bearings.

Categorically, they identified five distinct types of shaft voltages:

1. The electromagnetic or 60-cycle ac voltage.
2. The ground detector 120-cycle ac voltage.
3. The ignitron excitation voltage.
4. The high-frequency exciter ripple voltage.
5. The electrostatic dc voltage.

In their review of these categories they went into considerable detail on electrostatic voltage where they stated: The electrostatic shaft voltage has been found to have several reasonably well-pronounced characteristics as follows:

- The voltage between shaft and bed plate is direct current. This means that the polarity does not reverse periodically.
- The magnitude is not usually constant and in some cases falls repeatedly to low values after which it climbs back up to higher values. This means that the voltage contains both a-c and d-c components even though the polarity does not reverse.
- The maximum magnitude observed by oscilloscope was about 250 volts peak.
- The rate of rise of shaft voltage was often in the range of 200 volts per 1/60 sec. or 12,000 volts per second.
- The voltage decay when falling to zero is less than 0.1 millisecond.
• The minimum magnitude observed was a few tenths of a volt.

• Typical magnitudes were between 30 and 100 volts peak value.

• The shaft polarity was positive on many turbines and negative on fewer turbines.

• The potential at any instant is essentially the same anywhere along the turbine or generator shaft. The shaft voltage appears between shaft and bedplate, which is grounded.

• The maximum current observed in a resistance circuit connected between shaft and ground, regardless of how small the magnitude of resistance, was approximately 1 milliamp.

Sound engineering conclusions are timeless. This technical summary by Gruber and Hansen is as applicable now as it was in 1959. Certainly this list could be modified to reflect some different measurements, or different machines, but the fundamental concepts, descriptions, and characterizations of the phenomena are still the same. It is comforting to note that physical principles remain constant, and that our understanding of many of these physical principles has a tendency to grow with improved technology, measurements, and communication.

Case History

A 340 MW Steam Turbine Generator (Figure 1) tripped twice within two weeks due to intermittent high vibration on the generator outboard bearing (bearing 6). Unfortunately, there was no online vibration monitoring system to provide data that would have enabled straightforward diagnosis and identification of root cause. As such, investigation done by mechanical and instrument teams after the trips did not yield any evidence of a problem, and the machine was restarted with the caveat from plant management that vibration data be obtained to further investigate the problem. The plant enlisted the services of one of GE’s Bently Nevada machinery diagnostic engineers to collect and interpret this data using an ADRE* system.

Figure 1 - Machine train diagram.
The data collected on the machine train bearings at steady-state conditions revealed erratic and high overall vibration amplitudes on bearing 6; however, the filtered 1X vibration amplitude was fairly low and steady. Figure 2 shows the direct and filtered 1X vibration trends on bearing 6. Vibration trends recorded on all other bearings of the machine train showed some spiking (Figure 3), but to a lesser extent than on bearing 6. The spectrum waterfall plot on bearing 6 was also examined and found to be clear of any significant harmonic or subharmonic components other than a small amount of 2X (100 Hz) vibration as shown in Figure 4.
Figure 3 – Trend of overall vibration levels from Y probes on bearings 1-5 showing stable behavior.

Figure 4 – Full-spectrum waterfall plot from bearing 6 showing predominantly 1X (50 Hz) vibration and small amount of 2X vibration (100 Hz), free from other harmonics or subharmonics.

None of these plots explained the presence of the erratic signals on bearing 6. However, the orbit/time-base plots shown in Figure 5 exhibited numerous spikes superimposed on the vibration signal. The spikes were non-repeatable and were randomly distributed in both positive and negative directions. They were also absent or considerably attenuated on some of the other probes along the machine. And, they were present on both X and Y probes at the particular bearing. This is a classical signature of electrostatic discharge induced in rotating machinery for the following reasons:

1. It is clearly impossible for the shaft to physically move that quickly and to such an extent as shown by the spikes, and then immediately resume its “normal” orbital path inside the bearing clearance.
2. The spiking is non-repeatable. If the spike were the result of a scratch on the shaft, it would be repeat-
able from one rotation to the next. It would also yield distinct spectral components since it is periodic in nature.

3. The spiking has both positive and negative excursions, again ruling out a scratch on the shaft (a scratch always results in an instantaneous increase in gap between the probe tip and shaft surface).

4. The electrostatic discharge will typically be on the order of several thousand volts when it arcs and is modeled by a mathematical impulse function. This function generates a broadband frequency spectrum, typically known as “white noise,” some of which can be picked up by the coil in a proximity probe. The closer the probe is to the arcing, the more pronounced the observed spiking. As one would expect, the spiking is considerably more pronounced at the probes closest to the discharge location—in this case, bearing 6. It was also observed on both X and Y probes for bearing 6. If the spiking were due to a loose or intermittent wiring connection, it would only be observable on the affected probe (not both X and Y probes), and nowhere else along the machine train.

“CONFIDENT THAT ELECTROSTATIC DISCHARGE WAS THE CULPRIT, THE ROTOR GROUND SYSTEM WAS INSPECTED, INCLUDING A SPRING-LOADED GROUNDING BRUSH WIRED TO THE PLANT GROUND. TESTS SHOWED THAT ADDITIONAL SPRING FORCE WAS REQUIRED ON THE BRUSH TO MAINTAIN A PROPER GROUND.”

Figure 5 – Series of unfiltered orbit/timebase plots from bearing 6 showing random positive- and negative-going spikes due to electrostatic discharge.
Confident that electrostatic discharge was the culprit, the rotor ground system was inspected, including a spring-loaded grounding brush wired to the plant ground. Several tests were conducted while the machine was running, one of which included adding additional spring force to the grounding brushes and trending the vibration with and without this additional spring force present. Figure 6 shows the result, clearly indicating that additional spring force on the brushes provided the necessary path to ground to mitigate the electrostatic discharge problems.

![Figure 6 – Vibration trend showing effect of spring force on grounding brush.](image)

Signal stabilized when additional force was added to the grounding brush, pushing it into proper contact with the shaft.
Summary

Electrostatic discharge causes bearing and machine damage when electrical currents pass through bearing areas on their way from shaft to ground, or as they circulate through rotating and stationary components. This malfunction often goes undiagnosed because of its subtle symptoms and gradual effects, and because it is an electrical phenomenon that manifests itself as mechanical damage. Even non-electrical machines, such as turbines and gearboxes, are susceptible because rotating motion can induce voltage on the shaft without the presence of a generator. Although proper maintenance of brushes and insulators is the first line of defense, failures can occur between maintenance intervals and inspections. Ideally, instrumentation that directly measures voltage and current in the voltage mitigation system will be available. However, when it is not, a properly configured vibration monitoring system can also detect electrostatic discharge and allow timely intervention before bearing, shaft, or seal damage occurs.

References