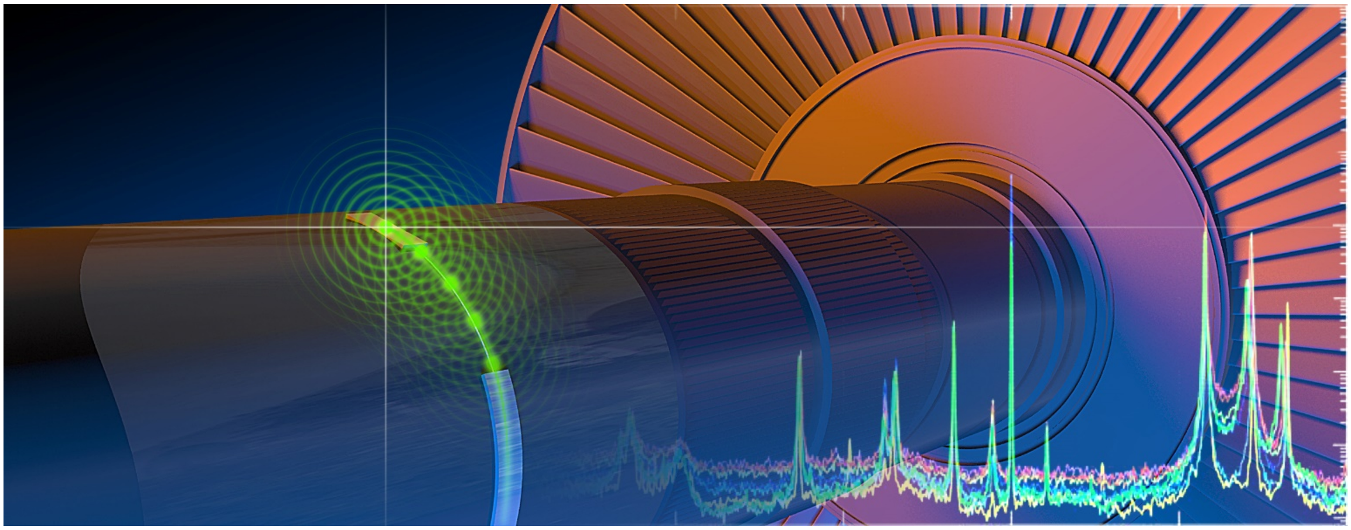
# A Real-Time Eye on Turbines



*EPRI's Wireless Sensors Continuously Monitor Vibration to Help Prevent Failures*

***By Matthew Hirsch***

One evening in September 2008, the control operator at American Electric Power's Donald C. Cook Nuclear Generating Station Unit 1 in Michigan recorded strong vibrations and felt severe rumbling. The operator shut down the reactor, quickly sending the turbine-generator from 1,800 revolutions per minute to a standstill. Three turbine blades dislodged from the rotor, and two blades fractured. This created a severe imbalance on the rotor, damaged a hydrogen seal in the main generator as well as other connected systems, and led to a small fire in the turbine building. Altogether, repairs and lost power output from the turbine failure and fire cost $468 million.

At the time of this event, there were very few commercial systems available for continuous monitoring of turbine shafts for torsional vibration, leaving many turbines unmonitored. These systems are now readily available. Spurred by a new nuclear industry insurance standard, EPRI engaged New Hampshire–based Suprock Technologies to develop a system that continuously measures how turbine shafts twist and shake while spinning at high speed. The system, successfully demonstrated at several power plants and now commercialized, provides real-time information to plant staff, enabling early detection of conditions that cause turbine blades and other rotor elements to fail.

Widespread deployment of torsional vibration sensing will also provide the power industry with some of the data needed to assist in determining the root cause of turbine-generator rotor cracking. Indeed, the cause of the Cook Unit 1 event in 2008 remains unknown. Unconfirmed possibilities include torsional vibration of the turbine shaft, a defect in turbine blade material, workmanship, and vibrations due to blade interaction with the steam flow.

"About 80 percent of power in the U.S. comes from a turbine driving a generator," said EPRI Project Manager Stephen Hesler. "Until now, there hasn't been a commercially available sensor for continuous monitoring that you could put on the turbine shaft to easily acquire and process vibration data."

## From Periodic to Continuous Monitoring

When a single manufacturer designs all the components of a new turbine-generator—including the turbines, the generator, and the exciter—the supplier has the design data needed to assess shaft vibration and risk of cracking from fatigue. But because plant operators often procure replacement components from different vendors, the integrated rotor design data can be more difficult to obtain, and the risk increases for unexpected vibration. In this situation, plants can use sensors to test periodically for vibration as an early sign of component failure. But vibrating components can fatigue in a matter of hours—too quickly for this approach to be effective. Over the past 30 years, the industry has experienced several catastrophic failures similar to the one at Cook Unit 1 (see box at end of article).

Recent advances in sensor technology created an opportunity for plant operators to improve monitoring and analysis of turbine shaft vibrations. When Nuclear Electric Insurance Ltd. (a mutual insurance carrier for electric utilities) revised its standards in 2013, it provided plant operators with criteria to determine when it is appropriate to use available technology to test for torsional vibration on the turbine-generator shaft instead of relying on computer algorithms to analyze and predict susceptibility to such vibrations. Some manufacturing industries were using continuous monitoring sensors on rotating shafts in machine tools, but the power generation industry had not yet adopted the technology.

The EPRI-Suprock torsional monitoring system: The thin yellow strip on this turbine shaft is an epoxy-infused fabric that keeps electrical devices bonded in place when the shaft is spinning. Sensors and antennas are concealed under this strip.

That same year, EPRI contracted with Suprock Technologies to develop the concept for a small, sensitive, and energy-efficient sensor to perform reliably for unlimited operation on a turbine-generator. It uses transceivers that continuously measure strain and acceleration on the turbine shaft and wirelessly transmit data, stationary receivers that capture the data, and a computer to archive them.

During prototype development and field demonstration, three key improvements advanced the use of telemetry in power generation:

**1. Use of Radio Frequency for Power and Data Transmission:** Because turbine-generators stop producing power when the turbine shaft stops spinning, plant operators use every precaution to keep them running as long as possible—stopping them for critical maintenance only. For sensors used in periodic testing, batteries must be replaced about every three days. Adding energy storage to the sensors would result in more bulk for equipment already constrained by space. The solution is to reduce energy consumption. With the EPRI-Suprock system, stationary radio frequency transmitters located about one meter from the shaft send power to the rotating sensors. Consuming 50 milliwatts of energy, or less than half a percent of the energy used by a single LED lightbulb, the sensors stream data to stationary receivers.

**2. One Device to Measure Strain and Acceleration:** The conventional approach to wireless monitoring on a rotating shaft is to place sensors in locations specified to collect strain and acceleration data. Because the strain and acceleration sensors in the EPRI-Suprock system are so small, they can be installed just millimeters apart—in effect, the same location on a shaft. This results in significant savings in installation costs for the plant operator. “The technical advantages of the EPRI-Suprock system have lowered overall testing costs considerably compared to existing shaft-mounted sensor options,” said Chris Suprock, principal investigator of Suprock Technologies.

**3. Epoxy and Fabric Attachment:** While power generation engineers typically employ hardware to attach sensors, EPRI and Suprock decided to use an epoxy-infused Kevlar and carbon-fiber fabric for attaching the device to turbine shafts. With this adhesive, there is no need to wrap the fabric around the shaft's full circumference, saving installation time while reducing the system's size and weight. "People build airplanes out of epoxy and carbon fiber now," said Hesler. "It's a viable method for building structural elements." EPRI has demonstrated its ability to withstand operating temperatures of 150–250°F and sustain superior bond strength at the shaft's full speed, where centrifugal acceleration increases the weight of attached sensors by a factor of 6,000. Field testing has shown that the epoxy performs as well as conventional attachment methods.

## Field Demonstrations

In spring 2015, EPRI and Suprock Technologies installed the first torsional monitoring system for field testing at Duke Energy's Marshall Steam Station. Researchers found that it provided more detail than conventional sensors, enabling them to identify strong vibrations and their causes before turbine failures occur. After more than a year and a half of operation at the Marshall Steam Station, there have been no failures with the installed EPRI-Suprock system.

Later in 2015 at Salt River Project's Navajo Generating Station Unit 3, a side-by-side comparison with a conventional battery-powered torsional monitoring device highlighted two main advantages of the EPRI-Suprock system. First, Salt River Project was able to order all the parts of the EPRI-Suprock system and install them in three days. Second, the EPRI-Suprock system continues to collect a stream of data after operating more than a year while the other system ran out of power and stopped collecting data after three days. Changing batteries on the other system would require shutting down the plant for 36–48 hours.

In spring 2016, Salt River Project installed a version of the EPRI-Suprock system with the telemetry components repackaged in a more compact, field-ready enclosure and the user interface more than 100 feet away from the turbine. "Smaller equipment makes a speedy installation possible," said Colsen Jim, a senior mechanical engineer at Salt River Project. "There are a lot more places on the shaft where you can install it."

In fall 2016, AEP installed the EPRI-Suprock system during its retrofit of Cook Unit 2's turbine-generator. In Unit 1, AEP used a torsional monitor from a different vendor that must be attached around the full circumference of the shaft. An off-the-shelf version wasn't available for Unit 2's larger shaft size, and the vendor could not prove that its product could withstand the centrifugal force on the shaft.

According to Greg Smith, lead project engineer at AEP, the utility supported the other vendor's attempts to produce a torsional vibration sensor for Unit 2, but a suitable product was never delivered. The EPRI-Suprock system's dynamic monitoring and communication system captured AEP's attention. "We were all-in when we realized that the design could withstand the centrifugal force," Smith said.

At the Cook plant, EPRI added multiple sets of transmitters and receivers so the system will continue operating even if one set fails.

### Other Applications of Torsional Monitoring

Applications of the torsional monitoring device go beyond nuclear and fossil plant turbines to include any components with a rotating shaft, such as hydropower and combustion turbines. As with steam turbines, hydro turbines can be expensive to operate and maintain, and monitoring provides considerable savings potential. Hydropower turbines have little instrumentation, and the industry has limited understanding of turbine cracking. Insurance carriers are not creating a need as they have in the nuclear industry, but hydropower operators are motivated by the potential to enhance long-term system health.

## Commercialization and Growing Importance of Monitoring

In three years, the EPRI-Suprock system has advanced from concept to prototype to demonstration to commercialization, making it one of the fastest development efforts in which Hesler has been involved at EPRI. Suprock Technologies will manufacture the commercial product—the Turbine Dynamics Monitoring System—and sell the equipment and installation service to plant operators.

Torsional monitoring at conventional plants will increase in importance as the grid responds to the change in mix of generation assets. For example, the increase in wind and solar generation is expected to produce more frequency excursions on the grid. These events can increase the torsional response of turbine-generator shafts and result in more fatigue damage.

Hesler emphasizes that the power industry is still learning how to recognize the role of torsional vibration in turbine-generator reliability and that this system can help to fill this gap.

“Until a turbine-generator’s torsional vibration characteristics are measured, there is risk of damaging vibrations that can occur without operator knowledge,” said Hesler. “The EPRI-Suprock system can significantly reduce this risk.”

### Landmark Turbine Failures Caused by Torsional Vibration

In 2005, EPRI published a report on torsional vibrations and fatigue, including a review of major failures and their causes. Here are some examples.

**Dresden Generating Station (Chicago, Illinois metropolitan area)**
In 2004, inspectors discovered a 13-inch crack in the generator shaft of Dresden Generating Station’s Unit 3 turbine-generator and a slightly smaller crack at the same location of Unit 2. Both units experienced a steady increase in lateral vibration at the generator bearings after their rated capacity was increased from 810 to 912 megawatts in 2002. The root cause of the shaft cracks: intermittent oscillating torsional loads on the generator rotor.

**South Texas Project (Houston, Texas metropolitan area)**
In 2002, shortly after the 1,300-megawatt South Texas Project Electric Generating Station restarted following a refueling outage, numerous cracked blades were discovered in a low-power turbine. The following year, the unit was restarted and then shut down again due to excessive torsional vibration that caused another set of cracked blades in the low-power turbines.

**Maanshan Nuclear Power Plant (South Bay, Taiwan)**
In 1985, a 952-megawatt turbine-generator unit at the Maanshan Nuclear Power Plant tripped from high load with no warning. The lateral vibration at the bearings increased, a fire occurred under the generator, and the machine stopped abruptly. Eight turbine blades had fractured, and 12 blades had cracked attachment fingers. Unbalance forces that arose from the blade fractures may have been the cause of further fracturing on a turbine shaft. The turbine-generator also experienced fire damage and abrasion. Testing confirmed that the cause of the blade fractures was shaft torsional vibration resulting from large grid frequency excursions.

## Key EPRI Technical Experts

Steve Hesler