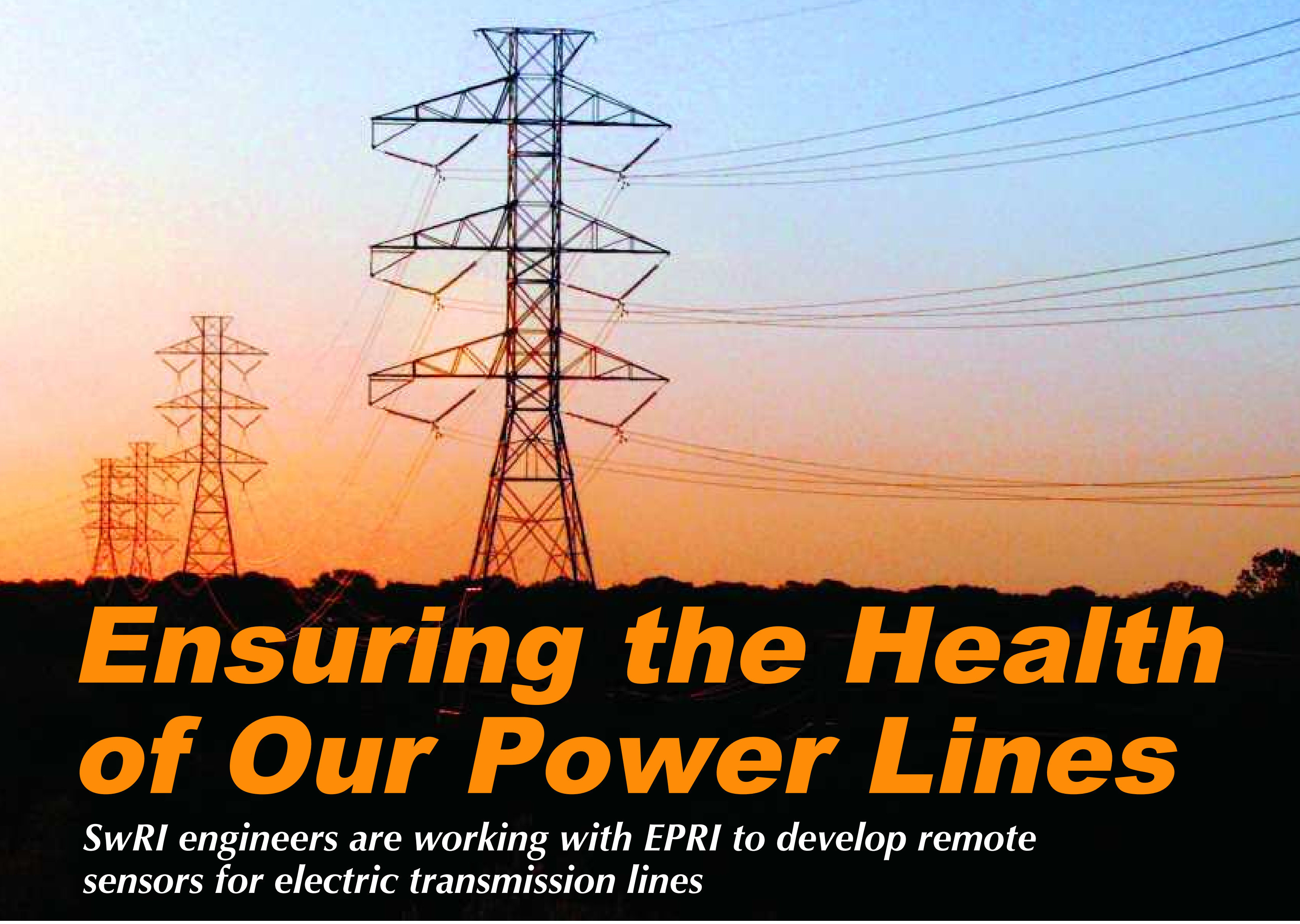


15277-3962

Ensuring the Health of Our Power Lines

SwRI engineers are working with EPRI to develop remote sensors for electric transmission lines

By J. Mark Major

Although electric power is essential to our everyday lives, it is taken for granted until an outage strikes and the conveniences of modern life are interrupted. Power plants and major arteries of the grid are potential targets for terrorism because of the panic that would likely be inflicted by widespread disruption of services. Natural disasters such as hurricanes, and system breakdowns such as the Northeast U.S. blackout of August 2004, are catastrophic, with loss of electric power to many residences and businesses for days on end requiring government and public support for the victims.

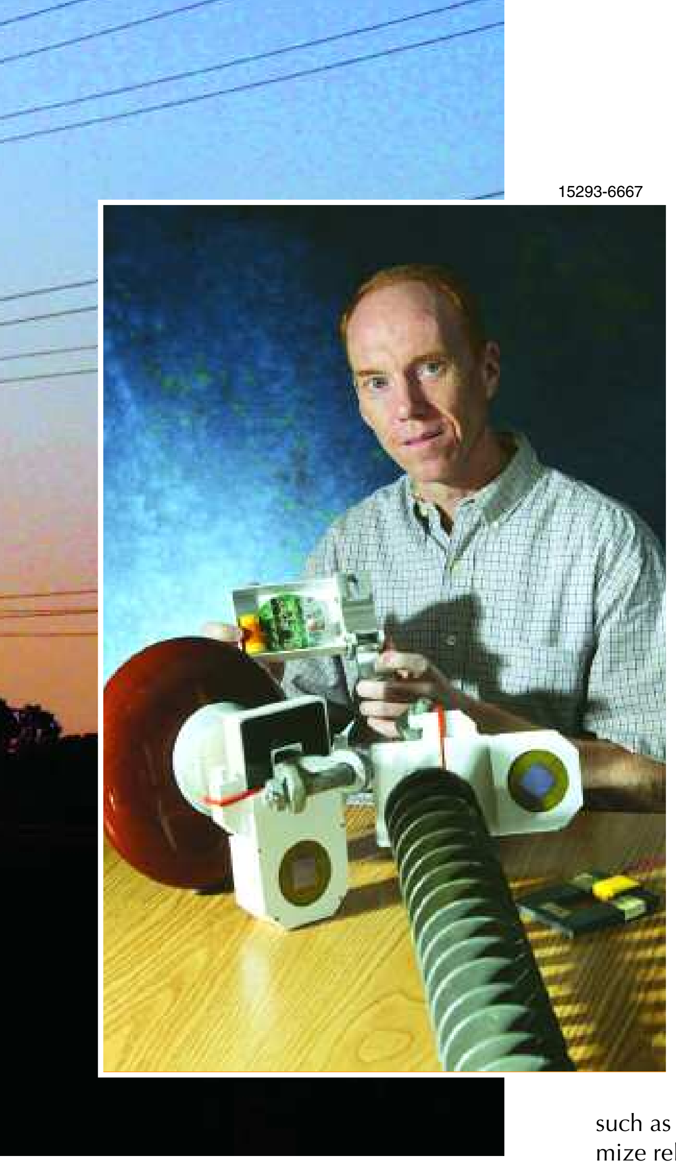
Fortunately, significant redundancy is built into electric power transmission and distribution systems and components. Most problems are handled automatically, and consumers barely notice when a disruption causes their lights to blink. Critical failures may result in temporary outages, but utility workers are on call to respond to these emergencies and generally are able to restore power within a matter of hours. Still, the critical public and commercial reliance on electric power dictates an ongoing need for utilities to improve component diagnostic and prognostic capabilities, to increase the health and longevity of transmission and distribution systems, and to mitigate outage vulnerabilities.

The Electric Power Research Institute (EPRI), a nonprofit organization that specializes in technology development for the electric power industry, works closely with utilities to understand their most pressing problems and to identify and develop the best solutions. EPRI identified a need for remote sensing to diagnose weak and failing components in the field, so that corrective maintenance actions can be taken to prevent catastrophic failures that would otherwise lead to outages and the need for emergency maintenance. EPRI researched the requirements and enabling technologies, then came to Southwest Research Institute (SwRI) with a concept that was studied for feasibility and has led to a series of development efforts for wireless sensors based on radio backscatter technology.

The EPRI remote sensing program has been active at SwRI since 2003. Several contracts have been successfully executed with incremental development progress achieved on specific sensor designs and a common reader design. The approach has been to address critical design areas first and prove these with laboratory and field demonstrations before proceeding to the next phase. This has been important in establishing credibility with the utilities that are funding the effort and in marketing the program for continued development funding. SwRI has received approximately $1 million in funding to date on this program.

EPRI and SwRI are working together closely as a team to develop the best sensor solutions for power industry applications.

15293-6667



J. Mark Major is a staff engineer in the Surveillance and Geolocation Department in SwRI's Signal Exploitation and Geolocation Division. Major has more than 20 years of experience in electronics design and development, with an emphasis on analog and radio frequency circuits and systems.

EPRI has the unique industry insight that is necessary to identify and define the most valuable parameters to sense. SwRI has the electronics and wireless communications expertise to derive the underlying requirements and implement the sensor designs. EPRI has the high voltage engineering expertise and test facilities to ensure that the designs are suitable. The EPRI/SwRI integrated product team concept enables the development of sensors that are viable and vital to the power utilities.

Program goals

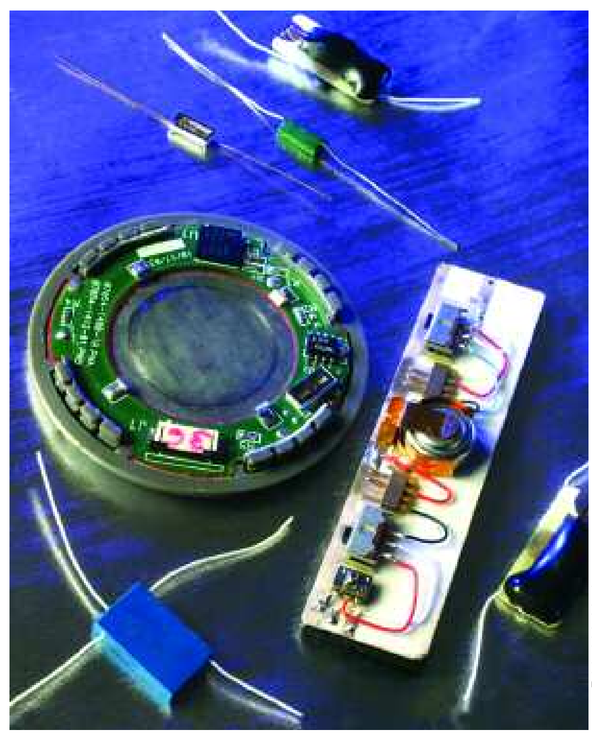
Electric power component sensing applications have unique and stringent requirements that are usually not met by commercial-off-the-shelf products. There are niche industrial sensing products that are specially designed and well-suited for particular electric power applications, but these don't meet the focused goals of the EPRI remote sensing program.

The primary goal is to develop a flexible remote sensing system architecture, protocol and core sensor design that can be applied to a wide variety of field applications for measurement of voltage, current, temperature, pressure, vibration and other valuable parameters of interest.

Sensors capable of multi-decade, maintenance-free longevity are needed because most envisioned utility applications involve remote locations that are expensive to service. Where practical, renewable environmental power harvesting techniques, such as solar panels, are desired to minimize reliance on non-rechargeable primary batteries, which require periodic replacement. To keep sensors affordable for the utilities, designs must be lean, with an emphasis on standard components, common materials and features that are inexpensive to manufacture.

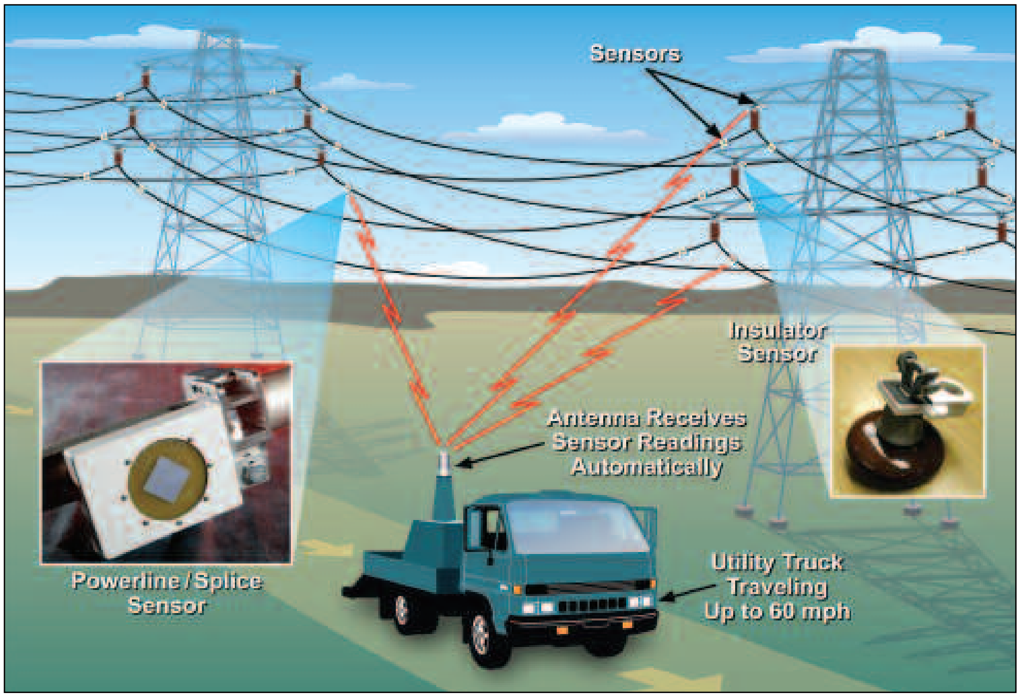
The system must provide a standoff range of at least 150 feet for the safety and convenience of data collectors. The system interrogator or reader must be able to collect readings from as many as 50 sensors that are simultaneously in sight to support clusters of sensors at tower installations. Overall, the system must be able to accommodate a sensor population of millions. Sensors must be readable at speeds of up to 60 miles per hour so that a motor vehicle or helicopter can be used for data collection. In this case, the system could be effectively transparent to the operator, with sensor readings automatically collected during a normal maintenance drive along the line. Alarms would alert the operator to problems; otherwise, no system interaction would be necessary. Critical sites, such as substations, would use a dedicated unmanned system interrogator to periodically read sensors and report data over a standard communications link or network.

Sensor packaging must be designed for secure attachment to electric power components, must allow safe and easy installation on energized lines using existing lineman tools, and must avoid interference from electric and magnetic fields. The housing cannot have sharp edges or protrusions that would generate corona when energized and must be able to withstand exposure to harsh weather conditions.



D015293-8871

SwRI is taking radio backscatter tag technology originally developed for asset tracking and monitoring applications and extending it to sensor data acquisition applications for the electric power utilities.

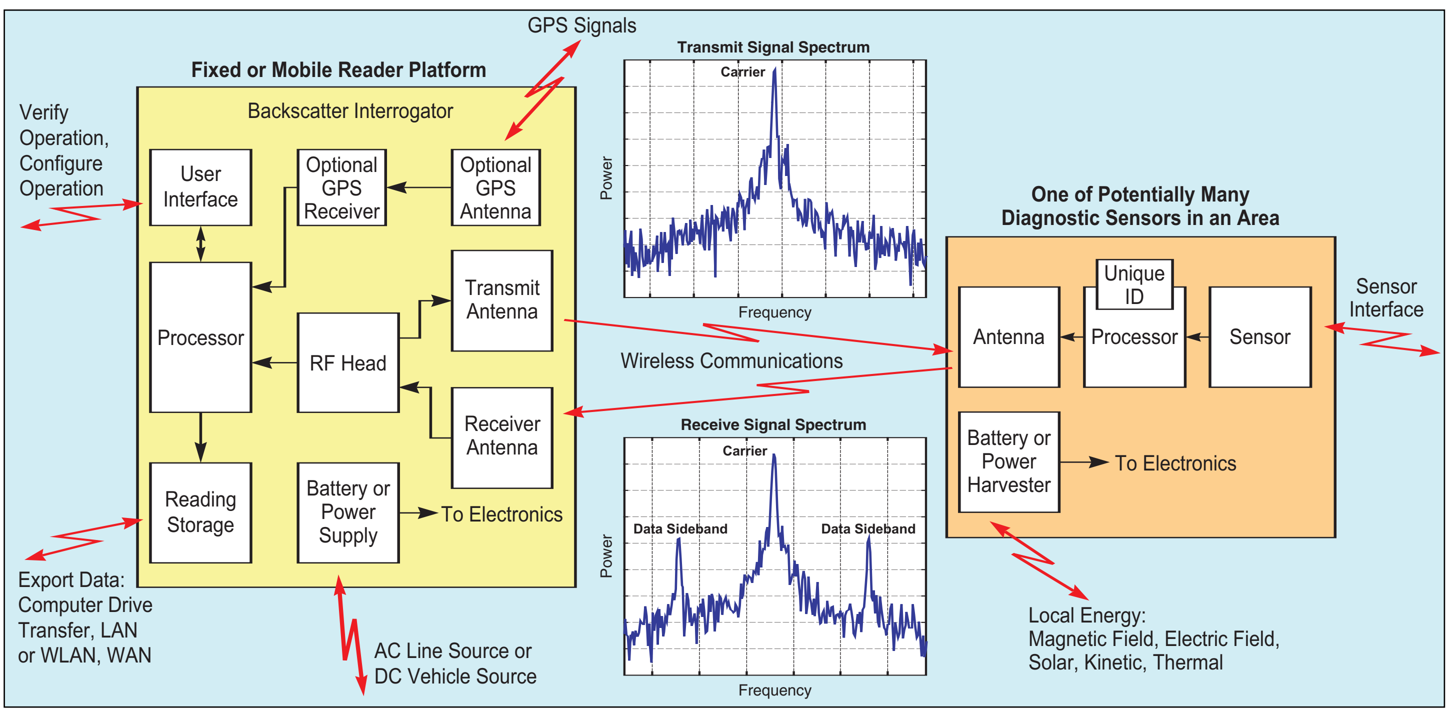


The EPRI concept is to automatically collect readings from power line sensors as part of normal maintenance and line inspections.

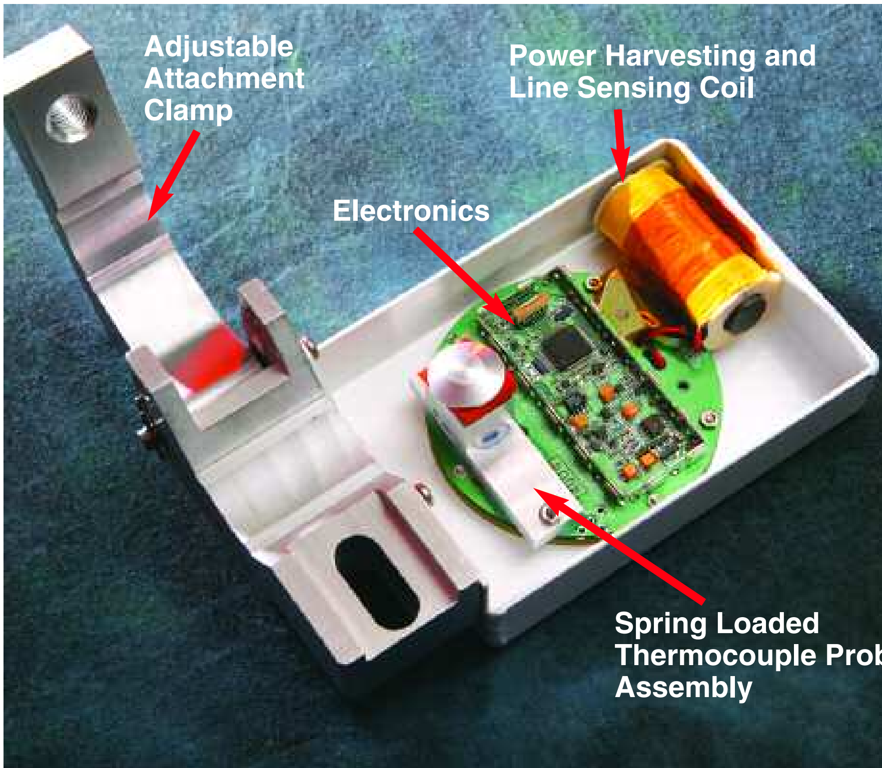
Radio backscatter technology

Radio backscatter technology is recommended for the envisioned electric power diagnostic sensing applications. SwRI's Signal Exploitation and Geolocation Division has used this technology in its designs since the early 1980s. Radio backscatter techniques are commonly used in RFID (radio frequency identification) to provide the automatic electronic identification of tags. This has grown into a huge market encompassing applications such as retail product inventory management, military logistics and asset management, personnel access to buildings and facilities, and automobile toll collection and traffic management. Many RFID tags require no battery, but these purely passive devices can only be read at very short range, a few feet or less. Most of SwRI's experience centers on coin cell battery-powered tags that provide much greater range, on the order of hundreds of feet. This meets the range requirements for the electric power industry, and its microwatt consumption enables environmental power harvesting as a viable alternative to batteries.

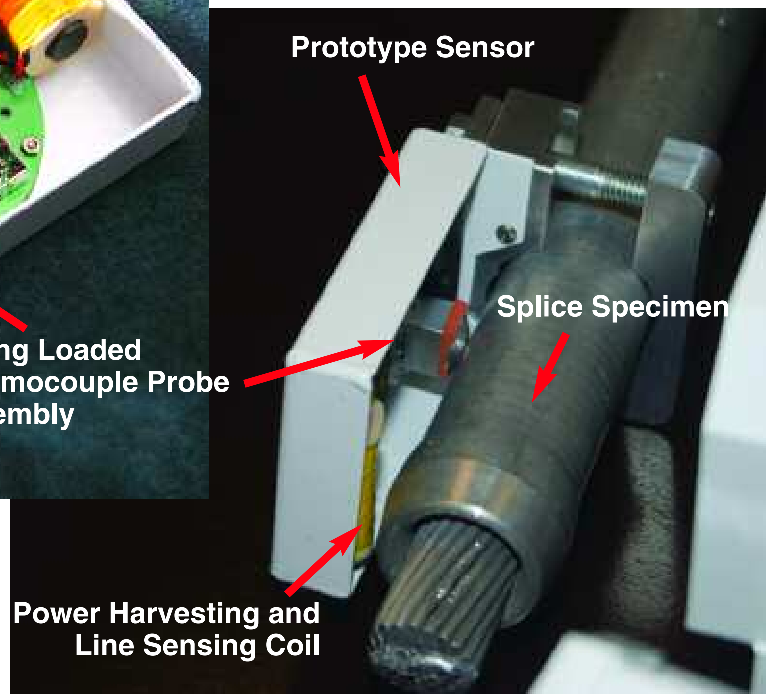
Radio backscatter was selected over more conventional wireless transceiver designs because the sensor electronics are inherently less complex. In a radio backscatter sensor system, the system interrogator or reader provides the radio carrier that enables wireless communications. The sensor merely modulates its antenna state with a digital message that is encoded with a unique identification code and data payload. In other words, the backscatter sensor



Backscatter tags do not transmit or receive RF signals, they simply reflect an AM sideband (with the data message) onto an incident carrier supplied from the remote reader. Purely passive tags work at just a few feet or less, but with only microamps of supply power to modulate a diode, a 200+ foot range can be achieved. This lean design consumes much less supply current than typical RF transceivers.



15293-6742



The splice sensor is designed for attachment to 795-kcmil Drake power lines and the associated splices, which are approximately 2 inches in diameter. A spring-loaded thermocouple probe head is used for direct contact with the line or splice. The coil is positioned orthogonal to the line to align the magnetic flux, generated by the current flowing through the line, with the core.

does not require radio electronics circuitry (such as oscillators, mixers and amplifiers).

Radio backscatter sensors do not transmit or receive radio signals, can be made smaller and less expensively, and provide longer life than more complicated designs. Because backscatter sensors do not actively transmit or receive, they consume less power. The system interrogator or reader provides the radio carrier signal only when needed and sweeps the carrier frequency for robust performance. Consequently, interference and compatibility concerns with other radio systems and products are mitigated.

The backscatter sensor data message is short enough to allow many sensors to be effectively read simultaneously, and can be repeated at a sufficiently fast rate to enable high-speed data collection.

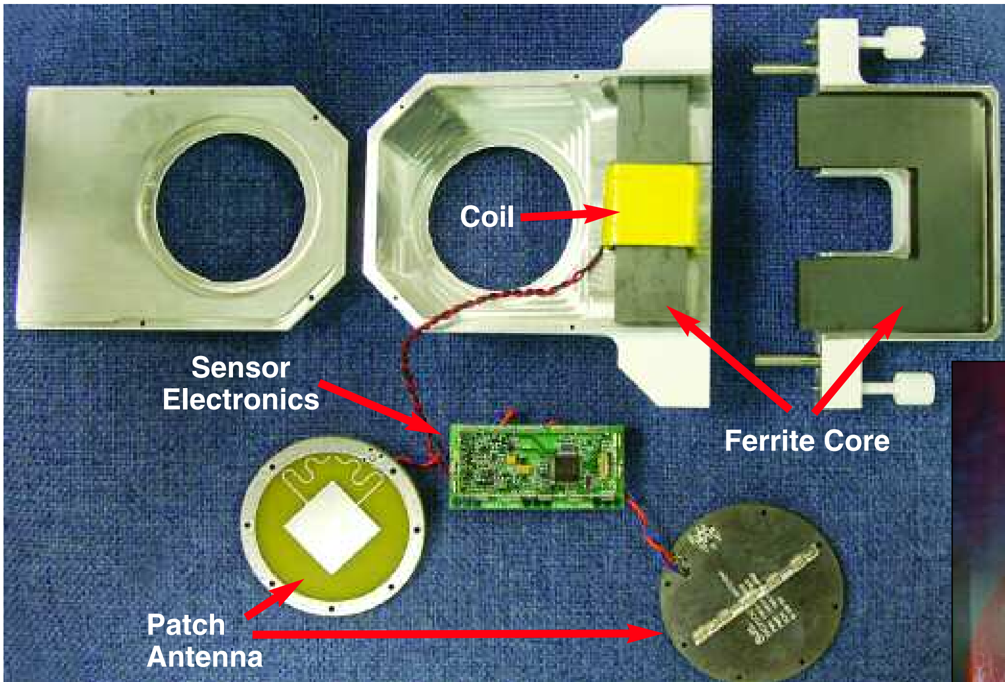
Backscatter sensor design

SwRI engineers have developed a flexible, low-cost electronics design for backscatter sensors that can be applied to different sensing applications. The core circuit is based on a low-power, low-voltage microcontroller that can be interfaced as required with analog and digital sensing circuits. The microcontroller formats the sensor data and ID into a digital message according to the system protocol. The microcontroller generates two digital clock signals at different frequencies and switches between the two frequencies according to its digital message to generate an FSK (frequency shift keyed) signal.

The FSK signal is applied across a Schottky diode that loads the sensor antenna. As the FSK signal alternates between logic low and logic high states, the Schottky diode alternates between non-conducting and conducting states, and the antenna terminating impedance is modulated at the digital clock frequencies. In one state, the antenna scatters incident radio energy and, in the other, it absorbs energy at the system nominal carrier frequency. When the system interrogator provides a carrier, amplitude modulated (AM) sidebands containing the sensor FSK signal are backscattered from the sensor on both sides of the carrier. The system interrogator receiver mixes the carrier with the received signal (carrier plus sidebands) to remove the carrier and recover the sidebands. This is known as a homodyne receiver architecture. An analog-to-digital converter (A/D) digitizes the FSK signal, and SwRI-developed signal processing algorithms are used to decode and recover the sensor digital message.

Power line and connector splice sensor

The first application targeted for this technology is power line connector splices. These components connect sections of power line and are critical to reliability because they are in the series path of power transmission. With current levels commonly more than 1 kA (kiloAmpere), excess resistance in a splice connection will cause it to overheat and make it susceptible to catastrophic failure (such as a downed power line). Presently, line inspectors use infrared imaging to look for hot spots, but this has been ineffective because the emissivity of conductors and splices varies, making it difficult to interpret results. The approach to the splice sensor is twofold: to directly measure the temperature of the conductor/splice using a thermocouple, and to measure the current flowing through the line using a coil with a high-permeability core to sense the magnetic field strength. Both pieces of information are important because the temperature rise depends on the amount of current flowing through the line.



The insulator sensor is designed to fit around the Y-bolt that attaches the bell to the grounded structure. Thumb screws are used to secure the two halves of the current transformer. Leakage currents are continually monitored and peak levels are stored in a histogram.

15293-6756

When the current through the line is at least 80 Amps (which is normal), the signal from the coil is sufficient to self-power the sensor and a separate battery is not required. The sensor reading for this design contains four values: the present temperature, the present line current, the peak temperature and the line current measured at the time of the peak temperature. Prototype backscatter splice sensors were successfully tested at EPRI's high-voltage test facilities in Lenox, Mass., with currents up to 2 kA, voltages up to 140 kV and line temperatures to nearly 150 degrees Celsius. Mechanical testing was successfully performed at SwRI facilities for vibration and slip using existing standards for power line vibration dampers. Range testing beyond 200 feet was also successfully demonstrated.

Insulator contamination sensor

Another application of this technology is insulator contamination detection. Insulators are the mechanical components used to hold up power lines at towers. On one side, the insulator connects to the power line, and on the other, it connects to the tower structure. Insulators consist of a number of "bells," or sections that are specially designed to minimize the possibility that current might leak from the power line to the grounded tower structure. The more bells in the chain, the more voltage the insulator can stand off. Over time, pollution buildup on the surface of the insulator bells provides a leakage path. This contamination eventually leads to "flashover," whereby a large current arc flows from the power line to the grounded structure, resulting in an outage. Maintenance crews periodically wash insulators that are susceptible to contamination to avoid flashovers, but this is expensive and difficult to schedule.

EPRI and other independent researchers have shown that the insulator leakage current correlates to the level of contamination, but the leakage current is not stable because of environmental variables such as dew, wind and humidity. These research projects typically use laboratory-grade instrumentation to continuously monitor leakage currents for several day periods with insulators whose contamination conditions are known. The result is large amounts of data documenting the current waveform over time, which can be analyzed to show that the number of waveform peaks and the peak amplitudes indicate the level of insulator contamination.

The key to the sensor design for this application is the development of a low-power, low-cost circuit to replace the expensive test equipment and reduce the data within the sensor to a manageable figure of merit that effectively reflects the contamination level. The SwRI/EPRI design does that; with electronic component costs well under $100 and power consumption of about 500 microwatts, it can be operated using two "D" size lithium batteries for an estimated life of more than 15 years. With the sensor located at the insulator's grounded end, it is not close enough to the line's magnetic field to harvest power similar to the splice sensor. Solar power could be used if a renewable energy source is required.

Backscatter demonstration at the TVA Paradise Power Plant

Another application for backscatter sensors is high-voltage disconnect switches. These switches are used at substations to control the flow of power between circuit feeds. They are similar to the splice sensor in that the switch contacts normally present low resistance through which large currents flow. Excess resistance will generate heat and requires maintenance to avoid a sudden failure and consequent outage. The splice sensor prototype design has been repackaged for the high-voltage disconnect switch application. Again, both the temperature and current are of interest. SwRI delivered seven prototype sensors along with a reader system to EPRI at the Tennessee Valley Authority (TVA) Paradise Power Plant in Drakesboro, Ky. These sensors are operating as a backscatter sensor system demonstration. The reader equipment is set up in a trailer adjacent to the

photo courtesy of TVA

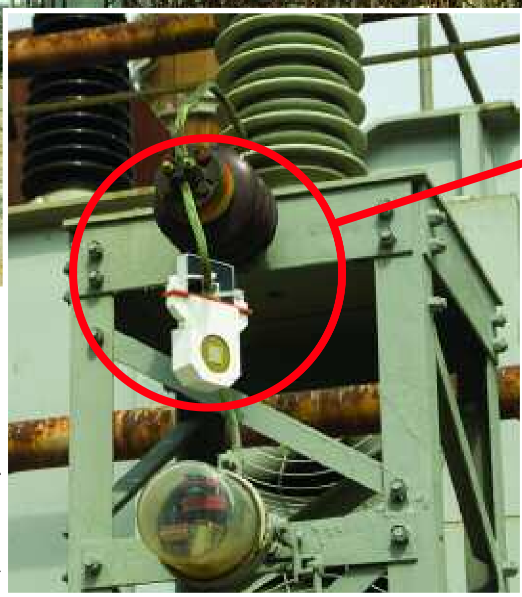


photo courtesy of TVA

A backscatter sensor demonstration is in place at the TVA Paradise Power Plant substation in Drakesboro, Ky. Temperature/current sensors are installed on high-voltage disconnect switches and leakage current sensors (pictured) are installed on lightning arrestors.

switchyard. Every 15 minutes, the reader turns on and reads the sensors. TVA installed a remote connection to the reader computer so that SwRI and EPRI staff can collect the data and monitor the system.

Conclusion

EPRI/SwRI development efforts continue on the program as the sensor designs and interrogator/reader design mature to a state where they can be transitioned to a commercial manufacturer as coordinated by EPRI. The TVA demonstration at the Paradise plant has been extended to add leakage current sensors. Also, a separate demonstration at a TVA facility in Nashville, Tenn., is being arranged for the splice sensors. Leakage current sensors are being delivered to the EPRI Lenox, Mass., facility for accelerated aging environmental tests. A new wrap-around sensor antenna design is being developed and integrated into the packaging designs to improve omni-directional wireless coverage. An embedded signal processing design is being developed to complete the interrogator reference design and enable high-speed drive-by testing. These efforts will help utilities to diagnose possible problems more effectively and efficiently, thereby ensuring the health of our nation's power lines. ❖

Comments about this article? Contact Major at (210) 522-3775 or mark.major@swri.org.
To discuss this article see www.swri.org/forums

Acknowledgments

The author acknowledges Dr. Andrew J. Phillips of EPRI, an integral part of the design team, for his technical expertise, leadership and insight. The EPRI program has required the skills of a number of SwRI staff members from several technical divisions. They include Principal Engineer Mike Koets (protocol design), Research Engineer Larry McDaniel (microcontroller design), Research Engineer Jeremy Pruitt (coil design for the splice sensor), Senior Technician Matt Lucero (prototype fabrication and field testing) and Research Engineer Helene Webb (reader software), all of the Signal Exploitation and Geolocation Division; Principal Engineer Dave Moore (antenna design) and Senior Research Engineer Cliff Scribner (packaging design for the insulator sensor) of the Applied Physics Division; Staff Technician Dennis Guerrero (current transformer design for the insulator sensor) of the Space Science and Engineering Division; and former SwRI employee George Wilburn (packaging design for the splice sensor).