



An EPRI White Paper

Sensor Technologies for a Smart Transmission System

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Aging equipment and tight O&M budgets are putting the squeeze on transmission line and substation managers. A new generation of low-cost sensors can help diagnose equipment health to optimize maintenance and prevent catastrophic failures.

Power delivery systems are among the largest and most diverse, remotely located investments. There are a number of challenges that utilities face with their transmission line and substation assets:

- Existing transmission lines and substations are aging while the required reliability is increasing and the availability of clearance to perform maintenance is decreasing.
- Need to maximize the utilization of the system, and thereby operate closer to the edge of reliability
- Need to increase the available capacity of the existing transmission system
- An increasing penetration of distributed generation and power electronics
- The shift to an intelligent grid with less traditional oil and iron-ore equipment and to more controllable solid-state and SF₆ technologies. This new fleet of

components will include automated smart diagnostics and condition assessment enabling the shift from resource-intensive time-based maintenance to more cost-effective condition-based maintenance.

- Need to integrate increasing amounts of renewable energy. These sources, especially wind, can be highly variable, intermittent and unpredictable.

Electric Power Research Institute (EPRI) researchers have an ongoing effort to research and develop sensor technologies and the associated infrastructure needed to aid utilities in addressing an aging transmission fleet, as well as to increase the capacity of existing assets, and help develop the next generation of equipment and technologies.

Research and development efforts are underway in the following areas:

- Application of Sensor Information
- Sensor Developments
- Communication and Sensor Data Collection
- Security
- Power Harvesting
- Algorithms and Data Visualization

A review of these areas, from sensor applications to visualization, is described for transmission lines and substations.

Application of Sensor Information

A wide range of applications exist and are possible for the use of transmission and substation sensor information. It is possible that one sensor type can address multiple applications:

Safety: The application of sensors for transmission line or substation components will allow for the monitoring and communication of equipment conditions continuously. Knowledge that a transmission line or substation component is in imminent risk of failure will enable

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actions to be taken to address the safety of both utility personnel and staff.

For example, the failure of a current transformer can result in explosions, fire and possibly flying shrapnel. With monitoring, sensors, the existence of internal discharge activity could be detected and communicated enabling barriers to be put in place or work practices adjusted to reduce the risk to personnel or public until a maintenance action can be taken.

Workforce Deployment: If the condition of a component or system is known to be at risk, personnel can be deployed to address either an imminent outage or possibly prevent an outage.

For example, ice build-up on substation insulation substantially increases risk of flashover. If excessive icing is detected early, staff and resources can be deployed prior to the flashover, thereby reducing the outage duration.

Condition Based Maintenance: Knowledge of component condition enables maintenance actions to be initiated at appropriate times rather than relying on interval based maintenance that may not be cost effective and can, in some cases, be less reliable.

An example would be the washing of substation insulators in a contaminated environment. By applying sensors the risk of flashover can be predicted and washing can be initiated when the risk exceeds a predetermined level. This increases reliability since the risk due to contamination deposition does not increase at regular, predictable rates. Along with additional costs, unnecessary washing can increase the risk of flashover and increase the damage to equipment.

Asset Management: Improved knowledge of the condition of equipment and stresses that they have been subjected to will allow asset managers to better manage the fleet. Sensor data is used together with similar vintage performance information, failure databases and operational data to better allocate resources.

For example management of the transformer fleet can benefit significantly from additional sensor data on

gassing levels and rates in the oil insulation.

Increased Asset Utilization: The rating of transmission components is influenced by a range of factors such as ambient weather conditions, previous loading history and component configuration. In order to address this complexity, static ratings are usually based on conservative assumptions of these factors, e.g., assuming worst case ambient temperatures. Higher dynamic ratings may be achieved if more precise, real time knowledge of the components condition can be obtained from sensors.

For instance, monitoring the present conductor temperature and current ambient conditions could result in higher, real time dynamic rating of transmission lines. Increasing the ratings in this way would allow for the maximum current that can flow without exceeding clearances (overhead lines), or insulation ratings (underground lines) and thereby reduce the need and expense for new transmission lines.

Forensic and Diagnostic Analysis: After an event occurs, investigating teams often have little information to understand the root cause. This limits the ability to address similar situations or to improve designs or components based on the lessons learned.

An example of this is the occurrence of bird related outages on transmission lines. Investigators often have little to no evidence that the event is bird related. Usually the problem has to be widespread before enough evidence is obtained. Sensor deployments can provide the information needed to identify the root cause and even help understand the species and behavior of the birds so that the design can be modified to prevent future occurrences.

Probabilistic Risk Assessment for Operations: Increased utilization of the grid is possible if contingency analyses were performed using a probabilistic, rather than the currently used deterministic method.

An important factor in probabilistic methods is knowledge of the condition of components and the risks they pose. Sensors have the potential to provide some of the missing data to these methods.

Sensor Developments

There are currently sensor systems available for purchase from vendors and there are a range of sensors being developed by EPRI and others. Table 1 lists EPRI's

Transmission and Substations sensor development projects currently underway. More detail can be found in the appendix.

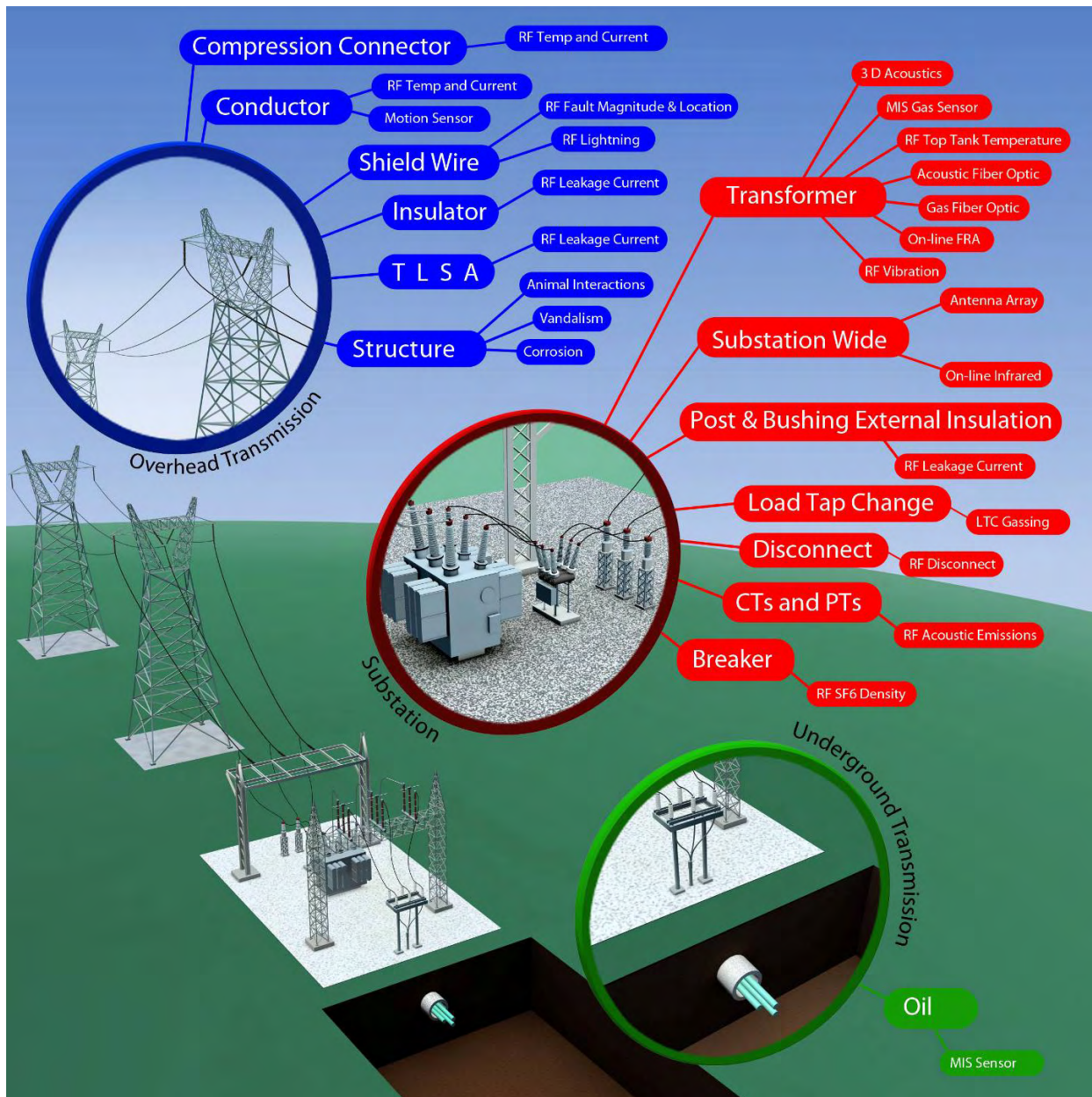


Figure 1
Various Sensor Technologies for Transmission and Substations



Area	Component	Sensor	Application	R&D	Demo
Substations	Substation Wide	Antenna Array	Location and identification of discharging components	X	X
		On-line Infrared	Automated processing of video thermal images of components	X	X
	Transformer	MIS Gas Sensor	Low cost sensor to measure H ₂ and C ₂ H ₂ in headspace and oil	X	X
		3D Acoustics	Location and analysis of discharge activity in transformers		X
		Acoustic Fiber Optic	Identify low level internal discharges in high risk regions	X	
		Gas Fiber Optic	Identification of gassing in high risk regions	X	
		On-line FRA	Continuously monitor frequency response using natural transients		X
	Load Tap Change	LTC Gassing	Identifying overheating or coking or worn contacts	X	X
	Post and Bushing External Insulation	RF Leakage Current	Identification of high risk insulation requiring washing	X	X
	Disconnect	RF Disconnect	Identifies high risk contacts wirelessly	X	X
	CTs and PTs	RF Acoustic Emissions	Demonstrating wireless mesh to identify internal discharges wirelessly	X	X
Breaker	RF SF ₆ Density	Demonstrating wireless mesh to trend SF ₆ density wirelessly	X		
Underground Lines	Oil	MIS Sensor	Low cost sensor to measure H ₂ and C ₂ H ₂ gases in oil	X	
	Underground Cable System	Various	Development of a vision document identifying potential applications and prioritizing research.	X	
Overhead Lines	Compression Connector	RF Temp and Current	Measures connector temperature and current to determine risk and identify high risk components	X	X
	Conductor	RF Temp and Current	Measures connector temperature and current for rating	X	X
	Insulator	RF Leakage Current	Identification of high risk insulation requiring maintenance		
	TLSA	RF Leakage Current	Assesses condition and number of operations	X	
	Shield Wire	RF Fault Magnitude and Location	Determine location and magnitude of fault current	X	
		RF Lightning	Distribution of lightning current magnitudes	X	
Structure	Sensor System	Integrates RF and Image Recognition Sensors to investigate transmission line issues	X	X	

Table 1
Transmission and Substation Sensor Development Projects Conducted at EPRI



Summary of Research Activities

Communication and Data Collection

EPRI is developing and assessing a wide range of options for communication and data collection from sensors.

Substations

Wireless Sensor Mesh: Using this approach, sensors in a substation communicate with each neighboring sensor to form a communication mesh that is robust since it has many redundant paths – plus it is flexible to allow for easy addition of sensors. EPRI research has focused on building upon newly available industrial hardware – and developing both software and hardware to make the sensors as useful and intelligent as possible within a substation environment.

A wireless sensor mesh of 75 nodes has been deployed that has been in operation since 2008. This mesh is being expanded to 150 nodes to research the impact of large mesh populations on power consumption and data traffic.

Wireless Point to Point: EPRI has also investigated the use of wireless point-to-point solutions in numerous substation deployments of wireless sensor meshes. These solutions are commercially available and the research focus has been on the specific issues related to substation use, such as cyber-security, electrical interference and challenges posed by transmission paths blocked by large numbers of metal structures.

Transmission Lines

Direct Communication from Sensors: Individual sensors communicate back to a central storage and processing location using radio frequency satellite or a cell phone networks. Although this is generally simple to implement, there are challenges such as: power required at each sensor, hardware cost, and cost of multiple communication paths.

High / Low Speed Rounds Inspection: Installed sensors collect information constantly and process and store the

results in the form of peak values or histograms. The data is collected during normal walking / driving patrols (low speed), or during the periodic fast flyby inspections. Researchers are also looking into the possibility of conducting future inspections by unmanned airborne vehicles (UAVs). The advantage of this approach is that the data collection from the sensors does not require additional communications infrastructure and can be implemented together with existing visual inspections. This concept is currently being demonstrated and inspection speeds of up to 70 mph have been achieved.

Wireless Transmission Line Hub: Using this approach, data collection units (hubs) situated at critical structures collect data from wireless sensors within range (2 to 3 structures). The data is then wirelessly transmission back to the central data storage and processing location together with information from sensors hardwired to the hub such as cameras and weather stations. Where possible the sensor data is processed at the hub level and only alarms are communicated. This concept is currently being demonstrated.

Transmission Line Robot: A transmission line inspection robot that travels on the shield wire is being investigated. This robot will optically identify high risk vegetation, right of way encroachment, component condition, location of discharge activity and collect data from deployed sensors. This robot concept is currently being investigated.

Mesh / Daisy Chain: Using this approach sensors communicate with one another along the line until the final sensors communicate to a base station installed in a substation or via a hub installed along the line. The advantages of this approach are that the sensor deployment forms part of the sensor communication architecture. However it does require small enough distances between sensors to communicate with some sensor redundancy. Power considerations are also a challenge. This approach is currently being developed.

Power Harvesting and Storage

Sensors require a power source to measure and communicate results. A 110/220V AC power supply is not always available – even in many substations and certainly not on transmission structures. Two solutions exist: a) high density non-rechargeable batteries, and b) power harvesting and storage of energy from the environment. EPRI has research and developments using both approaches.

EPRI continues to investigate the harvesting of energy from a range of sources. These include:

- Solar
- Vibration
- Magnetic and Electric Fields

- Thermal Differences
- Radio Frequency (RF) Energy

Currently available technologies are being evaluated and in some cases new solutions are being developed. An important component of power harvesting for substation and transmission applications is the storage of the energy so that the sensors can read and communicate when the energy source is not available, e.g., when harvesting from solar sources and operating sensors at night. Storage presents a number of challenges including the charging of electrochemical devices such as batteries at sub-zero temperatures as well as the life expectancy of rechargeable batteries. EPRI is evaluating technologies to overcome these issues.

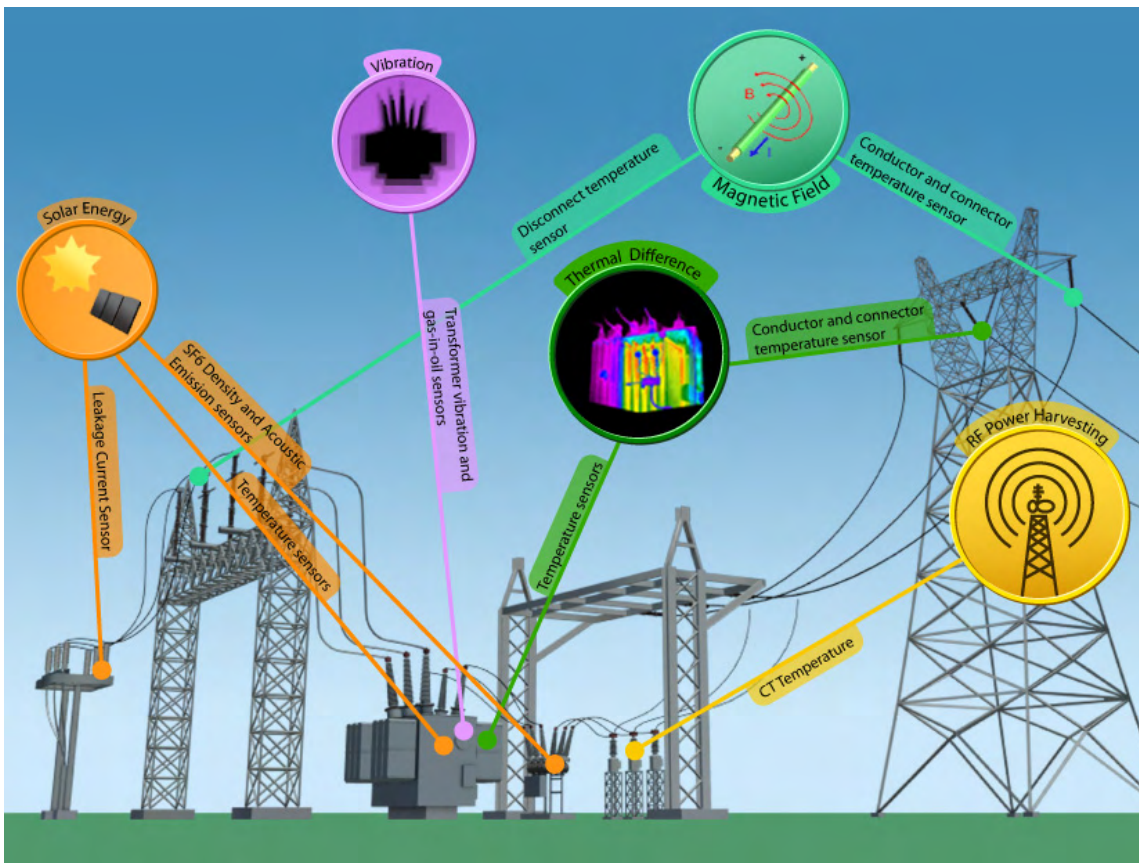


Figure 2
Power Harvesting Solutions



Algorithms and Visualization

Two important components for developing sensor applications relate to the need to output useful information based on the sensor data collected and the visualization of this information. This is achieved by first developing algorithms that relate to components condition, rating or actions, and second, by filtering out noise from results. This poses a significant challenge.

Understanding sensor output and relating it to component condition, rating, alarms or actions is being conducted for each sensor type. For example EPRI is performing teardowns of large power transformers that have been flagged as high risk from new sensor technologies. This activity effectively “closes the loop” and vital information is gained that not only allow users to gain confidence in the technologies but also guides future developments. Similar efforts are underway for other sensors including the leakage current; compression connector; conductor; pip-type cable fluid leak detection, and load tap changer sensors.

Also under development is the concept of a Virtual Condition Monitoring Control Room. This project is outlining the requirements for data collection, storage, analysis and display. The Virtual Control Room is intended to be flexible so that it is applicable to a wide range of users, e.g., equipment experts, asset managers, and operations personnel.

Research and Development

Although a wide range of sensor technologies are under development, or even currently available, these technologies are relatively new and untested. Continual research and development is needed to:

- Identify and develop new sensor technologies
- Improve cost effectiveness
- Increase reliability
- Understand and expand applications

Much of this research and development requires leadership and a long-term plan. EPRI’s approach to sensor technology development varies from application to application. Some sensor technologies may be revolutionary over the long term with widespread deployment, but could potentially solve issues at specific locations in the short term.

Many sensor technologies and the associated applications are challenging to justify with an 18 month outlook. However with a 20 year outlook these technologies can be revolutionary.

Demonstrations

Demonstrations / deployments are essential to develop new sensor technologies and understand how their application can benefit the transmission system.

Numerous demonstrations are needed since failures of transmission components are relatively rare. A large number of components need to be instrumented to obtain sufficient results to draw conclusions that will aid in developing algorithms to effectively use sensor results.

Multiple demonstrations enable the assessment of sensors over a range of environmental conditions and component configurations. In addition a wide range of sensor signatures and trends maybe obtained enabling the development of improved algorithms for alarming and noise rejection.

By demonstrating these new technologies, utilities will not only be able to potentially resolve some short term issues, but they will be gaining experience with the next generation of sensor technologies. This will allow the utilities to guide continued development to meet their specific needs.



Appendix: Description of EPRI Sensor Reports

Documenting currently available sensors and those under development. This project continues to track the industry and document: a) currently available sensor technologies and their application, b) sensor technologies that are under development (both inside and outside of EPRI.) Areas of interest that are observed include transmission substations and overhead and underground transmission lines.

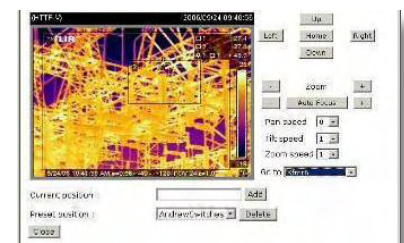
Virtual Equipment Monitoring Control Room: This project is developing an approach for a virtual equipment monitoring control room integrating data from a wide range of sources including a variety of sensors, system operational data and other relevant environmental parameters. The control room will also include equipment zone band limits derived from equipment specifications, failure data-bases and environmental conditions, etc. The project is documenting the requirements for an interface, data integration, visualization and algorithms. The project will create a working prototype of the essential components. This is under development.



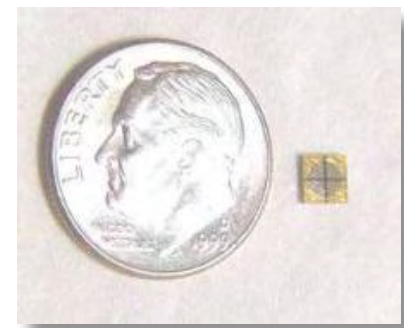
Substation Wide Antenna Arrays: New technology developed and demonstrated in the United Kingdom, USA and Australia has the potential to continuously monitor and accurately locate partial discharges from failing equipment throughout a substation by means of a fixed antenna array. A supplemental project is building on early success to develop an improved prototype that promises to reduce risk of catastrophic failures. This sensing system is being demonstrated in EPRI Supplemental Project 1013324.



Substation Wide – Online Infrared: This project is developing algorithms for a wide range of substation components to be utilized with the application of an on-line automated infrared thermographic camera applied in a transmission substation. This project is being demonstrated.



Transformer-Metal Insulated Semiconducting (MIS) Gas in Oil Sensor: A lower cost hydrogen sensor on a chip has been developed and is ready for field demonstration in transformers and other applications. An acetylene version of the sensor is currently under development. This project is being demonstrated. EPRI report 1013084.





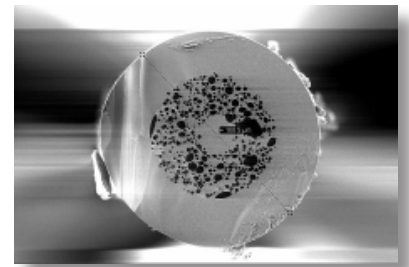
Transformer-3D Acoustic Emissions Technique: This technique enables the detection and location of gassing sources in power transformers and LTCs. New technology to locate in 3D the discharge or bubbling sources in a transformer are ready for demonstration in EPRI member substations. The field demonstration results further aid in the development of algorithms. An exciting recent expansion of this opportunity will allow utilities to trial a new on-line acoustic emission solution that can trend high-risk transformers identified with a 24h test. This project is being demonstrated. EPRI report 1014767.



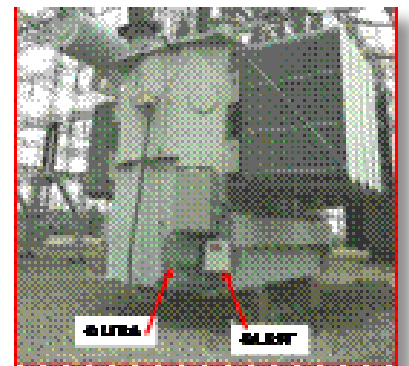
Transformer-Acoustic Fiber Optic: A technology is being developed which will enable the measurement of internal partial discharges using fiber optics installed in high risk regions of a transformer. This sensor is still under development.



Transformer-Gas Fiber Optic: A fiber optic sensor to measure the presence of different gases at the tip of a fiber optic cable. By positioning the cable tip close to high stress regions, issues may be identified early on in the degradation/failure mode process. This sensor is still under development.



Transformer-On-line Frequency Response Analysis (FRA): The FRA of a transformer is developed by measuring the response of a transformer to normally occurring transients on the power system (e.g., lightning and switching). Changes in the frequency response can identify changes in the internal geometry of the transformer. This sensing system is being demonstrated.





Load Tap Changer (LTC) – Monitoring Gas Ratios: A lower cost technology has been developed to monitor gas ratios in LTCs without measuring each gas individually. This project is being demonstrated. EPRI Supplemental Opportunity Notice: 1014767.



Post and Bushing External Insulation – RF Leakage Current: This sensor technology measures the leakage current levels and provides an indication of when to wash insulation or when a high risk of flashover exists. Associated projects are developing algorithms for specific types of insulation. These sensors are being demonstrated.



Disconnect: RF Temperature Sensors: These sensors measure disconnect jaw temperature and present loading to identify high risk units. These sensors are being demonstrated.



Current and Potential Transformers – RF Acoustic Emissions: These sensors measure acoustic emissions due to internal discharge activity and wirelessly transmit the results. This project is being demonstrated.

Circuit Breaker – RF SF₆ Density: These sensors measure SF₆ density and wirelessly transmit the results. This project is being demonstrated.



Underground Transmission Oil Filled Cable Metal Insulated Semi-Conductor (MIS) Sensor:

This cost effective sensor will measure the level of hydrogen and possibly acetylene in cable oil. This sensor is under development.

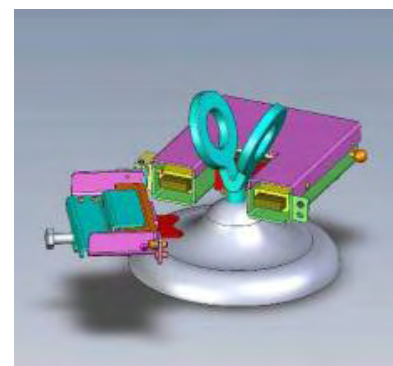
Compression Connector – RF Temperature and Current Sensor: This sensor records overhead transmission conductor compression (splices and dead-ends), connector temperatures and current magnitudes and develops histograms to provide an indication of loss of life and whether the connector is a high risk. These sensors harvest power from the magnetic field This sensor is being demonstrated. EPRI Supplemental Project 1012846.



Conductor – RF Temperature and Current Sensor: This sensor records overhead transmission conductor temperatures and current magnitudes and wirelessly transmits the information for rating applications. These sensors power harvest from the magnetic field. This sensor is under demonstration.



Overhead Insulator RF Leakage Current Sensor: This sensor technology measures the leakage current levels and provides an indication of when to wash insulation or when a high risk of flashover exists. Associated projects are developing algorithms for specific types of insulation. These sensors are being demonstrated.



Shield Wire – RF Fault Current Magnitude and Location: These sensors measure the time and magnitudes of fault currents flowing in the shield wires. These sensors provide more precise location of faults on transmission lines. These sensors are under development.

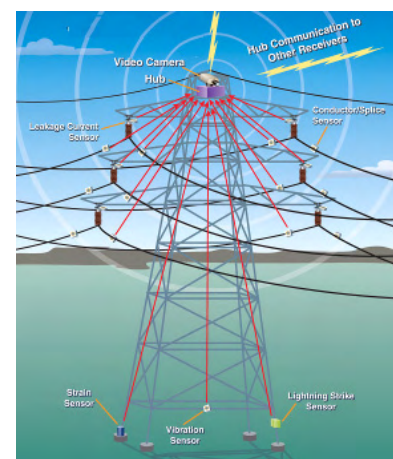


Transmission Line Surge Arrester (TLSA) RF Sensor: This sensor records the number of events and the total charge seen by the arrester to provide a life expectancy and cost benefit of the application. These sensors are under development.

Shield Wire – RF Lightning Sensor: These sensors measure the peak magnitude and time of lightning currents flowing in the shield wires. These sensors are being researched to understand the distribution of lightning currents on transmission lines and to validate lightning location systems. These sensors are under development.

Overhead Transmission Structure Sensor System: This system fuses RF sensors with image processing and environmental data. The data is wirelessly communicated in real time with built in alarming functions. The system is used in solving specific issues on transmission lines such as unknown outages, avian activity, etc. This sensor system is being demonstrated.

Wireless Mesh Sensors: Wireless mesh sensor systems—consisting of distributed autonomous sensor / communication devices—promise unique advantages for cost-effective substation online monitoring. These advantages include low power requirements for extended sensor life, multiple radios in one sensor, self-healing behavior that automatically routes signals around failed areas, and on-board processing to reduce the data sent wirelessly. EPRI is conducting wireless mesh demonstrations and adaptations to obtain real world experience with the technology in a substation environment – and to embed EPRI algorithms into the devices. Report: Wireless Mesh Network Deployment 1012356.



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