Online Component Monitoring for Increased Reliability in Substations and Switchyards

Advanced Technologies to Cut Costs and Increase Reliability

Overview

Reliability of power delivery components has been at the heart of EPRI's substation and transmission research programs. The research has helped in understanding the dominant failure modes of the key high voltage components within the substation. These components include transformers and circuit breakers as well as key auxiliary equipment such as current and potential transformers.

Reliability of critical components is especially essential when operating a power plant. It does not matter if the critical component is located within the plant or in the switchyard that connects the plant to the transmission grid. A component failure in the switchyard may have the same impact as a failure within the plant, and that could mean an involuntary shut down of the plant.

Research has confirmed that preventive maintenance and cumulative operating history affects the failure rate of these components. Presently, preventive maintenance is still performed on a defined schedule, more or less independent of the health status of the component itself. In order to get a more accurate measure of the condition of the component, it needs to be monitored on a continuous basis and maintenance should be performed only as necessary.

Continuous monitoring can be performed by sensors designed to detect the physical signs of component degradation or impending failure condition in combination with sophisticated digital signal processing. The sensors become the eyes, nose, and ears of the substation as they monitor the indicators of degradations. These include electromagnetic and audio patterns caused by partial discharge, gas imbalances by chemical processes and corona through surface contamination. Applying signal-processing capability, it is possible to recognize patterns of the degradation within a noise spectrum many times the level of the signature.

EPRI's research in power delivery has focused on component reliability in substations and along the transmission line. That has led to:

- Understanding the dominant failure modes of key substation components such as transformers, high voltage circuit breakers, current transformers and voltage transformers
- Developing sensors and signal processing algorithms to detect the degradation and possibly anticipate component failure
- Field testing the technology in several substations around the globe

Although the base sensor technology and algorithms are in place, the time has come to apply it in active substations and nuclear switchyards. Key research questions that will be answered from the field deployments include:

- Climatic and electromagnetic environmental conditions
- Power harvesting and extreme low communications power requirements
- Packaging
- Digital signal processing and algorithm refinements
- Experience and further understanding of signals and imminent component failure.
- Cost reduction

The expected impact of this research includes significant maintenance cost savings and the possibility to anticipate component failure to prevent emergency outages of the component and the plant, which could result from the failing component.

There are a number of sensor research projects underway at EPRI that are applicable to the nuclear generation industry. These include:

- Substation-Wide Antenna Array Diagnosis of Circuit Breakers and Disconnects
- Development of an Acoustic Emissions Technique for the Detection and Location of Gassing Sources in Power Transformers & LTCs – Phase III, Detection of Precursors to Electrical and Thermal Faults.

- Development & Demonstration of Low Cost-Robust Leakage Current Sensor System to Evaluate Contaminated Insulation
- On-line Load Tap Changer Fault Gas Monitor
- Load Tap Changers Contact Wear Indicator

These programs can prove to be beneficial to plant and station operations, especially since experience has already been acquired through the power delivery research group.

Antenna Array Application to Determine the Health of Switching Devices in Substations

Research has led to the development of an antenna array that is effective in detecting and locating electrical discharges in a substation. Electrical discharge can be a first sign of potential deterioration of components or may be used to trigger scheduling of preventive maintenance. The antenna array has been successfully demonstrated in eight pilot installations in six member utilities. The demonstrations have already shown the ability to accurately and effectively locate partial discharges produced by failing equipment.

There is, however, opportunity to apply the same technology to diagnose the condition of circuit breakers and disconnects by analyzing the radiated electromagnetic signatures when operating the devices. This project will perform the necessary research to evaluate the effectiveness of the antenna array in determining switching device condition.

Initial research has shown that circuit breakers and disconnects radiate a large amount of electromagnetic energy during each operation. The antenna array may be able to extract from these signals valuable information on the condition of these switching devices. The goal of this project is to extend these insights and develop robust algorithms to provide an early warning of impending failure.

The project use data collected by existing antenna array sites and recorded in the laboratory in develop algorithms that will try to determine the contact wear, pole synchronization, and evaluate timing for opening and closing device operation.

The algorithm developed will be validated in the field using existing antenna array sites.

Online Frequency Response Analysis

Overview

Transformers are durable assets that are the key enablers for power delivery. It can be very expensive to a utility if they take a transformer out of service for repair. This hardware is not invulnerable to faults that could damage their ability to operate effectively. These faults could be caused by a through fault, a seismic event or even from damage resulting from transportation from the factory to the installation site. Transformer condition assessment inspection methods are valuable tools for utilities. Offline frequency response analysis has been a typical method of transformer assessment, but it is an infrequent and expensive process. This method involves sending current at various frequencies through the transformer and measuring the output.

Project Summary

The Electric Power Research Institute is pursuing research to develop an online frequency response analysis (FRA) system that will enable utilities to continuously monitor the health of the transformer. This system waits for the natural impulses that come through the transformer and records them. As data is accumulated by sensors, it is fed into a computer. When a defined data threshold is met based on a series of impulses resulting in an FRA result or trace, an alert is sent as to whether the transformer has experienced any damage since the last reading. The data is then available for download and analysis.

Value

There are a number of reasons why utilities may want to consider an online frequency response analysis system. 1. This system will enable utilities to monitor the health of their transformer without the costly effort of taking it offline. 2. This system can help utilities extend or even reduce their outage schedules. 3. This condition-based monitoring system continuously measures the health of the transformer leading to timely preventive maintenance actions rather than periodic measurements that may or may not catch a fault in time.

Deliverables

Utility that participate in this research will receive an onsite installation of the online frequency response analysis system which includes all sensors on each bushing TAP of the transformer. Members in the project will also be provided with the FRA software and the benchmark test of the transformer during the outage when the sensors are fitted to the transformer.

The research and development findings from other member sites will be shared with the group and this information will help EPRI develop improved algorithms.

Timetable

This research will be conducted over a 12-month period.

Technical Contact

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Detection of Precursors to Electrical and Thermal Faults Using Acoustic Signals

Power transformers represent the primary capital asset in substations; the financial impact of losing a unit can be in the multimillion-dollar range. By contrast, a failing transformer taken out of service in time can often be economically reconditioned.

Fault conditions in a power transformer can be detected in several ways. One method is based on detecting dissolved gasses, the byproducts of abnormal energy dissipation of insulating oils and paper within the transformer. A second methodology is to detect the bursting of gas bubbles through Acoustics Emission monitoring

However, the same gasses and bubbles can be created by non-catastrophic events such as boiling and micro turbulences of oil when overheating.

Filtering the information to identify the possible catastrophic future events from slowly deteriorating aging process is critical when evaluating the transformer condition.

Prior EPRI research demonstrated that the AE technology can detect and locate active gassing sources in power transformers. In addition, results indicate that AE is able to detect minor non-gas accumulating faults in critical areas. It is believed that these minor faults are precursors to major failures. Evaluating these signals may help utilities to anticipate transformer failures and to prevent forced outages.

In the long term, it is the intent to use the results from this research to lay the groundwork for the development of on-line instrumentation for continuous asset integrity monitoring and management.

The project will extend the capability of the existing technology identify units exhibiting the precursors and active faults by relating Acoustic Emissions data with data from other sensors, in order to provide a quick, economic method to determining the condition of the all transformers within a substation. New algorithms will be developed and integrated to lead to a device capable of continuously monitoring the condition of the transformer.

Project Summary

This project effort will be divided into two parts. Part one, concentrates on developing advanced post-test analysis algorithms for rapid data filtering, analysis and report generation. In addition, the source location and characterization algorithms will be expanded to apply signal processing on the captured waveform information.

Utilities joining the phase three effort will need to identify and provide access to substations with multiple transformers for screening and to provide the data for the algorithm development. Utilities with known gassing transformers may also have these tested using the previously developed twenty-four hour test procedure to assist in characterizing and locating the gassing faults.

Part two includes the development and supply of a prototype system that can be used for economic screening of all transformers within a substation and then be left behind for continuous remote monitoring of candidate transformers. Algorithms developed in part one would be implemented so that fault tracking could be automated and health condition monitored with very little human intervention.

A follow-on project may pursue commercialization the technology developed.

Deliverables

- A report at the end of part one and two detailing the test protocols and results excluding utility specific data
- A database of field-test results, data analysis, and progress reports on hardware development.
- Individual, proprietary reports will be delivered to each participating utility detailing the test results and analysis of data from all of the transformers tested at that utility.

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Development and Demonstration of Low Cost-Robust Leakage Current Sensor System to Evaluate Contaminated Insulation

In practice, it is difficult to determine the level of contamination for insulators and assess the risk they may pose to the grid. This project's objective is to develop and demonstrate sensor technology that will provide essential information to support decision making when to initiate corrective action.

One of the best methods to determine the risk-contaminated insulation may pose requires continuously monitoring of the magnitude and distribution of leakage currents flowing on the insulator surfaces. Leakage current monitoring systems consist of powerful digital signal processing units hardwired to current sensing elements at the end of insulator strings. Today these units are costly, difficult to install, and often unreliable.

The second-generation leakage current monitoring technology developed by EPRI addresses the technical barriers for widespread use—sensor reliability and cost. This project is demonstrating and refining this second generation sensor technology.

The solutions to overcome the barrier are challenging and were achieved using the following approaches:

- Simple rugged packaging designed to operate reliably over the expected lifetime.
- Eliminating all hard-wired connections for communicating or powering the devices. This eliminates the need for additional expensive high voltage components that may reduce the overall reliability of the monitored insulator. This approach also enables low cost installation
- Extreme low sensing and processing power requirements that can be met by harvesting the power from sources available at the location of installation, or by use of a battery that can power sensor operations for longer than ten years
- Low energy storage and wireless communications technology that can report the collected monitoring information upon request during scheduled inspections or continuously for on-line operations

Current Status and Project Scope

Demonstrations of the technology are being conducted at four installation sites in different climatic regions, both in substations and on transmission lines. Three of the sites utilize an on-line monitoring approach to collect and process the information and trigger alarms. In addition, the sensors are being exposed to long-term accelerated aging in a laboratory environment for two years to determine performance and life expectancy. Operating the sensor technology for two years in the accelerated aging chamber corresponds to approximately YYY years of natural aging when operated in substations or on lines. Artificially contaminated sensors are used to verify proper function and refine the alarm algorithms for natural wetting conditions.

Research continues to improve packaging, antenna performance, and on-board algorithms to improve sensor functionality.

Deliverables

- Installed sensor system, for on-line or inspection on request
- Assessment of insulation design and application for specific environment
- Test and observation protocol
- Data analysis and algorithm verification and refinements over a defined project duration
- Participation as an advisor in the sensor research and development project

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On-Line Load Tap Changer Fault Gas Monitor

One of the first problem signs with a load tap changer (LTC) is an increase in the concentration in oil of ethylene. Chemically, that usually indicates overheated oil. In LTCs, this overheating is often due to high resistance across load bearing contacts caused by the accumulation of carbonaceous deposits (coking) between the contact surfaces. A corresponding drop in the acetylene concentration frequently precedes this, which may be due to the acetylene being consumed in the chemical formation of the coking deposits.

The ratio of acetylene to ethylene concentrations in the oil is a traditional indication of LTC condition. A decrease in this ratio indicates a more thermal, or carbonizing, mode of operation from a more normal arcing mode, where there is a prevalence of the arc gases hydrogen and acetylene. A drastic change from an arcing to a thermal mode is quite distinct and often results in an immediate internal inspection. The change in this gas ratio is occasionally noticed when the situation is critical due to oil sampling frequency.

This problem could be prevented by utilizing on-line monitoring techniques. On-line monitoring has the advantage of detecting this change and the rate of change earlier. With this knowledge, utilities will have more time to plan repair outages and potentially prevent catastrophic failures.

The presence of faults or failures in most load tap changers can be characterized by increasing concentrations of ethylene with an accompanying drop in the concentration of acetylene to ethylene ratio. Therefore, a simple on-line monitor for LTC condition in real time will need to distinguish between the gases generated by thermal (ethylene) and normal (acetylene) modes.

Project Summary

This project is based on previous EPRI research, in which an LTC fault gas analyzer was designed, built and bench-tested using commercially available technologies.

The work program for this project consists of building LTC fault gas monitors intended for mobile field applications and on-line use of an LTC in active service at the participant's site. The tasks will include:

- Site, LTC and gas sampling method selection
- Designing and building the on-line monitor
- Installation and commissioning of the on-line monitor
- Periodic gas sampling for laboratory confirmation

While the initial focus of these demonstrations is on the on-line monitoring of LTC fault gases, there is the possibility of adding contact wear indication capability.

Deliverables

Participation in the demonstration project will include:

- On-line monitoring
- Field evaluation of the on-line monitor
- Final report on the field trail results

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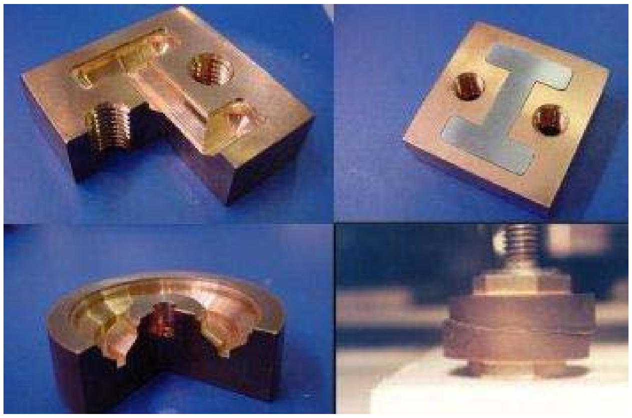
Load Tap Changers Contact Wear Indicator



Load tap changer (LTC) maintenance represents one of the most critical issues facing substation engineers. LTC inspections and overhauls, which involve equipment shutdown and removal/storage of oil, are costly, averaging $5,000 to $15,000. The expense of inspecting contacts is often so great when compared with the cost of new contacts that they are exchanged during every inspection, even if the contacts have significant useful life remaining.

To reduce the costs of routine inspections and overhauls, many utilities today are applying predictive or diagnostic methods for improved maintenance scheduling. For LTC these methods fail because there is no method available to determine level of contact erosion, and therefore cannot perform a health condition assessment without a full-blown disassembly and inspection. Today there are techniques developed that have the potential for continuously monitoring the wear of LTC contacts, and providing an information when wear has reached a critical level that replacement is required.

A compound could be embedded in the contact at a predetermined depth corresponding to the manufacturer's recommended level for replacement. When the contact wears to the point where the tracer materials become exposed, they are released into the insulating medium or decomposed by the arc. Periodic withdrawal and analysis of the insulating medium for these products indicates that wear has proceeded beyond the safe level. Another method involves the use of specific tracer compounds that emit light at discrete wavelengths when the high temperature of the arc causes the tracers to vaporize. The tracers are selected to emit light at different wavelengths from the light of the arc.

This project is based on previous EPRI research, in which contact wear indicators have been designed, developed, tested, and proven in laboratory analysis, and in an accelerated field tests.

This project consists of conducting demonstrations in field environments to assess the reliability of the detection methods. The tasks will include:

- Fabrication of contacts, containing the wear indicators
- Fabrication of the on-line monitor that tracks the tracer compound released into the oil
- Installation and commissioning of the contacts and on-line monitor
- Data tracking and trending

While the initial focus of these demonstrations is on the on-line monitoring of LTC, the wear indicators may also applicable for use in circuit breakers.

Deliverables

Participation in the demonstration project will include:

- Contacts containing the wear indicator
- On-line wear indicator monitor
- Field evaluation of contact wear indication
- Final report on the field trail results

Utilities will install contacts in conjunction with the proposed project during their normal LTC overhaul. EPRI will provide monitoring capabilities to assess the performance of the materials and methods.

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Unmanned Infrared Imaging Cameras for Switchyards and Substations

Overview

Utilities are continuously looking for technologies that can help them maintain or improve power delivery reliability. One available technology, infrared imaging, is already used at substations and switchyards because of its fault detection capabilities. The challenge of this technology is that the infrared cameras that are used are portable and require manual operation. While the technology is effective, the process can be time consuming and it requires scheduling personnel to perform the camera work and later feed the data into a system for analysis.

Project Summary

The Electric Power Research Institute is pursuing research to intelligently process the data from unmanned infrared imaging cameras for use at substations and switchyards. The resulting system will operate continuously and will automatically feed data into a computer system for analysis. This system will provide utilities with a 24/7/365 representation of the substation or switchyard and enable them to identify fault situations and take action prior to an outage. EPRI will seek to develop these algorithms for the automated processing of video feeds from infrared cameras through both laboratory and field research. In addition to equipment monitoring, the cameras will also have the capability to alert on to faults. In parallel, high-accuracy data-logging temperature sensors will be deployed within the field of vision. The data from both sources will allow for the development of robust alarming limits for automated monitoring of substation equipment.

Value

There are three reasons why utilities may want to consider an unmanned infrared monitoring system. 1. The technology can help increase substation reliability, as there are many types of faults that can rapidly fault to failure. This system gives operators the capability to identify these instances and take action to mitigate the possibility of an outage. 2. Infrared technology can help increase security at the site through intrusion detection as well as alarming on animal intrusions. 3. The technology can also lead to decreased inspection costs, as condition-based monitoring is relatively inexpensive and provides feedback every day. The unmanned cameras can also monitor a wide range of devices in the substation or switchyard.

Deliverables

Utility that participate in this research will receive a field deployment of unmanned infrared imaging cameras at a site of their choice. They also receive the initial algorithms and the improved algorithms that will come from what is learned through the research. EPRI will also perform demonstrations of the results on site, as this process will go on as it develops the more sophisticated algorithms.

Timetable

This research project will be scheduled over a 12-month period, as EPRI wants to capture 12 months of data from the site.

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