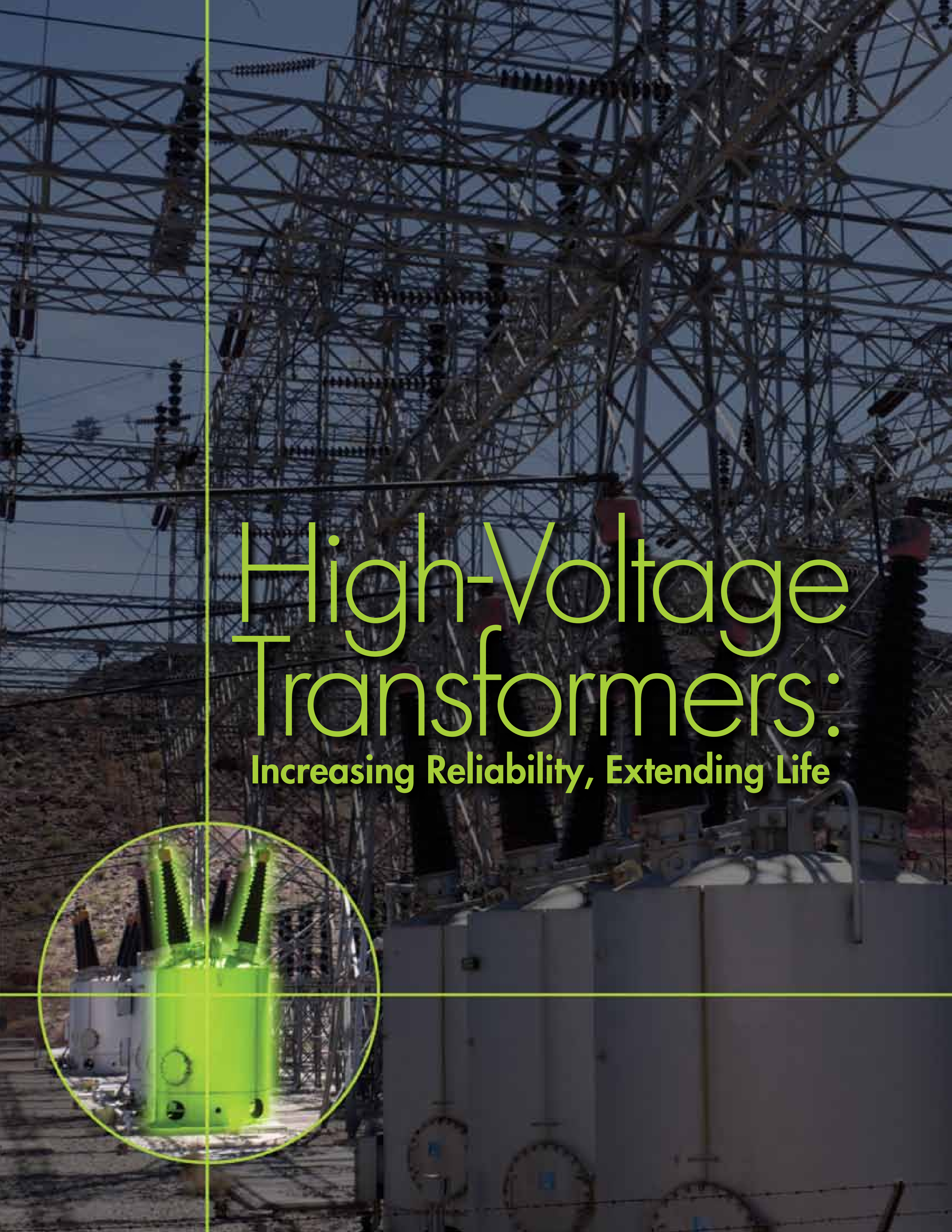
High-Voltage Transformers:

Increasing Reliability, Extending Life



In switchyards and substations around the world, high-voltage transformers operate around the clock to keep power flowing reliably through transmission grids. At nuclear and fossil-fired power plants, large transformers connect to the grid for delivering electricity and for powering auxiliary systems when a generator is off line. At substations across the power delivery system, other transformers "step down" the voltage for local distribution circuits. Transformers are crucial pieces of equipment, and expensive to replace. Keeping them operating reliably as they age is a key focus of research and development.

THE STORY IN BRIEF

The reliability of transmission grids depends on the condition of aging high-voltage transformers that are expensive and time-consuming to replace. EPRI is building on decades of R&D to develop improved maintenance practices, novel sensors, and risk-based analytic techniques that will help prevent failures and maximize transformer life and performance.

Many transformers were installed during the 1960s and 1970s and are nearing the end of their design lives. During the 1980s and 1990s, failure rates were low. But as transformers age, failure rates become higher; failures are difficult to predict, complicating decisions about resource allocation for repair or replacement. Over time, transformer loading levels have been increasing, along with demands for reliability. Step-up transformers at baseload plants typically are exposed to the most severe duty cycle, as these transformers continuously operate close to full capacity. Because they are connected directly to large generators, they can be exposed to extremely high fault currents.

Transformer failures can cause costly disruptions and sometimes involve oil spills, fires, and collateral equipment damage. It is expensive and time-consuming to replace transformers. Lead times extending to more than a year. The units' size and their weight—hundreds of tons—make them difficult to transport and install. Replacing the massive three-phase generator step-up units typically used at nuclear power plants often requires even longer lead times, and the units must be transported via special train car. A replacement unit might cost $3 million–$6 million, depending on the voltage and megawatt ratings.

"Power transformers present a point of vulnerability that can cause problems with the performance of the power system and with generation sources as well," said EPRI's Michael Howard, senior vice president of research and development. "If a transformer failure occurs in a switchyard that connects a power plant to the transmission grid, it has the same impact as a failure within the plant—and that could mean an involuntary plant shutdown."

"The consequences of a transformer failure at a nuclear plant can be severe," said Neil Wilmshurst, director of plant technology in EPRI's Nuclear Sector. "If a generator step-up transformer at a nuclear plant fails, it not only results in loss of generation but also challenges the operators and plant safety systems. If a spare or replacement transformer is not readily available, the lost revenue and cost of replacement power can be a million dollars or more per day. Catastrophic failures are of concern, since other switchyard equipment, including transformers, customized bus work, and buildings, are likely to be situated close by."

Concerted Effort

EPRI has performed decades of research focused on preventing failures and maximizing transformer life and performance. The research ranges from practical techniques and methods for transformer maintenance and life extension to the development of diagnostic and monitoring technologies that provide new insight into transformer condition and potential degradation conditions.

Currently, EPRI's Power Delivery and Utilization, Nuclear Power, and Generation sectors are collaborating to develop the *Power Transformer Guidebook*, referred to as the Copper Book, which for the first time will consolidate transformer information in one resource. EPRI and the Institute of Nuclear Power Operations also are working together to ensure that the Copper Book's guidance addresses needs and practices specific to nuclear plant transformers.

Collaboration among utilities, transformer suppliers, and users is central to the effort. To provide a forum for sharing transformer information and lessons learned, EPRI's Nuclear Maintenance Application Center formed the Transformer and Switchyard Users Group.

"The group's broad membership provides opportunities to collect, develop, and disseminate operating experience and best practices related to maintenance, equipment, and troubleshooting," said Wayne Johnson, senior project manager.

The users group consists of three working groups: Power Transformer, Switchyard Equipment, and Grid Reliability. The Power Transformer working group serves as a technical advisory committee for the Copper Book.

The *Power Transformer Guidebook* will contain the industry experience related to transformer design, factory testing, selection, purchase specification, procurement, operations, and maintenance, and also will explore research on advanced monitoring techniques, solar flares, and lightning strikes. It will provide guidance from a utility perspective on condition monitoring, testing, and maintenance of large power transformers and will serve as a resource for new component and system engineers. Because of the large volume of industry information, the guideline will take several years to complete.

"The Copper Book will be the first text that covers all aspects of transformer ownership from a utility perspective," said Luke van der Zel, a technical executive in EPRI's Power Delivery and Utilization Sector. "It will consolidate decades of EPRI research results and combine that information with the knowledge and practical experience of industry experts. It will complement EPRI's transformer R&D with analyses of failure mechanisms, advanced sensors, on-line condition monitoring, and transformer fleet management."

The Copper Book is produced by EPRI's substation research program, which develops technologies and tools to maintain and operate substation equipment, including diagnostics, monitoring, maintenance, and asset management.

Understanding Failures: Root Causes

Better understanding of transformer failure mechanisms and risk factors has helped guide research and development efforts to improve condition assessment and life extension.

"Transformers have four basic failure modes," said Nicholas Abi-Samra, senior technical executive in EPRI's Power Delivery and Utilization Sector. They are insulation failures, internal mechanical failures, failures due to severe internal overheating, and failures of ancillary equipment such as load tap changers or pumps. Risk factors include premature aging and degradation of insulation; insulation damage from applied voltage stresses such as lightning or switching surges; through-fault currents associated with external faults; and poor workmanship or design. In some locations, geomagnetically induced currents associated with solar storms overstress transformers and cause insulation failure.

"Transformer failure mechanisms are usually complex and difficult to classify," said Abi-Samra, "and may be due to a combination of factors. Internal insulation failures are the most serious and costly of transformer problems. Moisture is responsible for many premature failures of large extra-high-voltage units. Some recent failures have been attributed to corrosive sulfur in the transformer insulation cooling oil, which caused failure of insulating paper."

EPRI is compiling information from transformer teardowns to develop a forensics library that will provide new insights into degradation and failure processes.

Advanced Sensors for On-Line Monitoring

Transformer degradation mechanisms emit telltale signs that, if detected early, can provide condition and life expectancy information. These signs include partial discharge, hot spots in windings, and dissolved gases in the insulating oil that are produced by degrading insulation.

By measuring and tracking these signs, engineers can determine the rate of degradation and schedule preventive maintenance or repairs, possibly avoiding catastrophic and costly in-service failures. "Some of the best insurance for transformers is proper condition monitoring, which sets priorities for repair, refurbishment, or replacement," said Abi-Samra.

EPRI is developing sensors to provide insights into transformer health that can't be obtained with traditional techniques. As van der Zel put it, "We want to put sensors in places they've never gone before, we want sensors that are cheaper than ever before, and we want sensors that measure key condition indicators we've never captured before."

Fiber-optic sensors. Partial-discharge signals are typically difficult to measure. Traditional methods use sensors mounted outside the transformer, where they often pick up electrical interference signals. EPRI is developing fiber-optic sensors that extend inside a transformer tank to detect internal faults—both a transformer gas sensor and an acoustic sensor to detect partial discharge in high-risk regions of a transformer. Because the fibers are so small, a single sensor can be made up from a fiber bundle that can transmit many different signals—both electrical and thermal faults—pinpointing the origin of partial discharge and providing a temperature profile of the winding. Preliminary tests are promising, with additional lab testing and refinement needed before field testing begins.

Metal-insulator semiconductor sensors. EPRI's Office of Technology Innovation is developing solid-state microsensors that detect hydrogen (an indicator of partial discharges) and acetylene (an indicator of arcs) in transformers. These "sensors on a chip" promise to enable low-cost, on-line dissolved-gas monitoring. (See "Microsensors Show Promise for Transformer Monitoring," page 28).

Three-dimensional acoustic emissions sensors. Acoustic emissions technology is an established technique for detecting partial discharge. EPRI has conducted research into using it to detect the bursting bubbles of fault gases resulting from overheated transformer components. With the promise of locating bubbling sources in three dimensions, it is being demonstrated at member utility substations. EPRI research continues to refine algorithms to distinguish signs of incipient failure from signs of gradual aging and deterioration.

These technologies lay the groundwork for on-line continuous monitoring instrumentation to provide fast and economical methods for determining the condition of all transformers in a substation or power plant switchyard.

Analytics for Intelligent Fleet Management

Although advanced sensors will contribute to transformer condition assessment, utilities already possess information that can help them make better decisions regarding transformer repair and replacement, and ultimately increase reliability while reducing maintenance costs.

The key is an EPRI-developed methodology that ranks transformers on the basis of their operating environment and operating history—weighing factors such as thermal life consumption, lightning exposure, short-circuit magnitude and duration, insulation oil test results, and connected-load criticality.

"The ranking enables a utility to scan its transformer fleet and identify at-risk units for detailed testing and analysis," said Bhavin Desai, a senior project manager in EPRI's Substations program. "Focusing on high-risk units is far more cost-effective than conducting blanket inspections of an entire fleet. This approach uses available data from utilities' historical records, maintenance management systems, and rating guides. Diagnostic algorithms and expert system modules transform those data into useful information for decisions and action."

Duke Energy recently used the methodology to scan 222 transformers and identified 13 for detailed risk analysis. The system flagged units in two categories: those exhibiting abnormal conditions, which may be experiencing unexpected problems due to manufacturing defects or operating issues, and those exhibiting normal degradation, which may be approaching the end of their service life. Tri-State Generation and Transmission Association performed a similar analysis on 381 transformers in 2009 that flagged 12 for detailed analysis—five units for normal degradation and seven for abnormal conditions, including thermal, electrical, and internal copper core issues.

"As a new maintenance engineer with almost 400 transformers to evaluate, I've found this program a tremendous help," said Rosa DelaCruz, senior electrical engineer at Tri-State. "We can now concentrate on the flagged units to evaluate whether repairs can be made, or whether we should replace the units."

Transformer Database, Life Extension

To acquire additional performance data to support fleet management and maintenance, EPRI and member utilities are developing an industrywide database. This will allow broad-based analyses to better determine equipment failure rates, to identify bad actors early, and to help identify best maintenance and specification practices. The data include failure mode, operational and maintenance history, and equipment design and can be searched by transformer family, make, model, age, application, and risk profile.

"The industrywide database provides a means for sharing transformer data confidentially among participating utilities to support risk-informed asset management decisions," said Desai. "It supports maintenance scheduling, repair and replacement decisions, and asset management decisions to minimize life-cycle costs of equipment replacement and maintenance, including failure costs."

EPRI also publishes transformer life extension guidelines that provide utility staff with guidance on cost-effective transformer maintenance and condition assessment. The *Large Transformer End-of-Expected-Life* report, for example, alerts engineers to conditions indicating that long-term planning may be necessary to preclude failure or manage its impact. Making connections between condition monitoring and potential failure mechanisms enables plant engineers to assess alternatives, from replacement or refurbishment to using more robust condition-monitoring systems.

"Large transformers are essential to the reliable operation of generating stations and the power grid, and they represent the primary capital asset in substations," said Mike Howard. "EPRI's wide range of transformer R&D is helping utilities prevent transformer failures, extend transformer life, and improve reliability. The payoff is substantial savings in operating, repair, and downtime costs; delayed investment in new transformers; and a sound technical basis for transformer management decisions."

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Luke van der Zel is technical executive, transmission and substation in the Power Delivery and Utilization Sector. His current research includes work on gas-insulated substations, power transformers, and sensors for substation monitoring, with an emphasis on field applications of EPRI research results. Before joining EPRI in 2001, van der Zel worked for 11 years on substation projects at Eskom in South Africa. He received both B.S. and Ph.D. degrees in electrical engineering from the University of the Witwatersrand, Johannesburg, South Africa.

Bhavin Desai is a senior project manager in the Substations program area of the Power Delivery and Utilization Sector. His current research includes work on fleet management of substation assets, maintenance optimization for substation equipment, and circuit breaker life management, with an emphasis on developing analytics for risk-based decision making. Before joining EPRI in 2001, Desai worked for more than three years at Duke Energy in system and asset planning and technical studies. He received a B.S. from Saurashtra University, India, and an M.S. from Oklahoma State University, both in electrical engineering.