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TRANSFORMER TECHNOLOGY MAG

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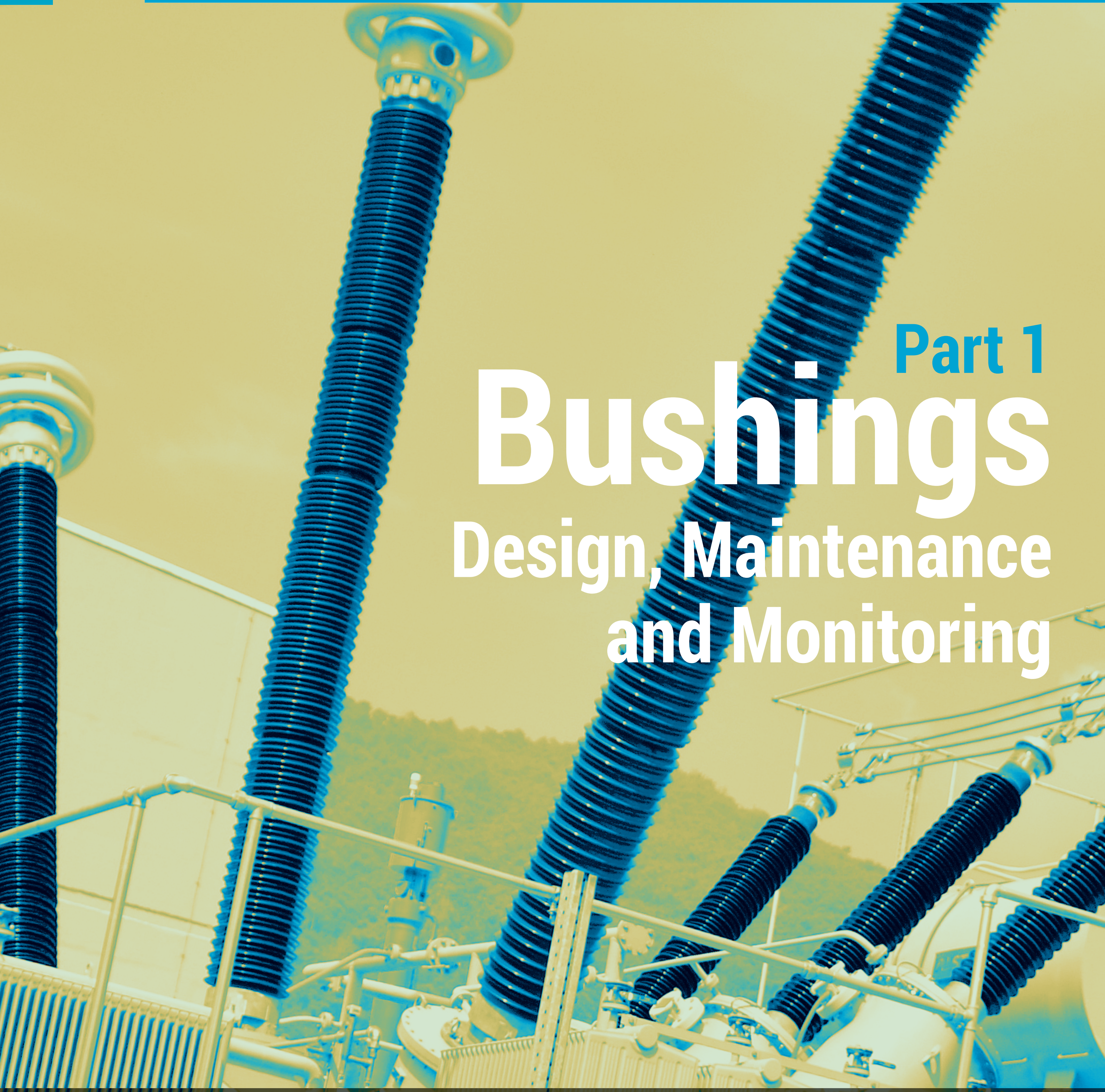


Part 1

Bushings

Design, Maintenance and Monitoring

Interview with Ronald Schmid, GM of Siemens Transformers Linz, Austria Bushings Breakdown Mechanism and the Appropriate Life-cycle Maintenance Implementation Three Steps for Diagnostic Testing of Bushings

TOTUS BUSHING MONITOR

Designed to detect and diagnose problems at the earliest stage, the TOTUS Bushing Monitor uses integrated intelligence and analytics to provide reliable and intuitive information to asset managers about bushing health.

Combining Partial Discharges, High Energy Events, Leakage Current Angles and Magnitude, Temperature, Load and Bushing Properties, the TOTUS allows for correlation and causation to determine failure modes, driving prescriptive actions.

Built to fit your monitoring program, the system can operate as a standalone device or as part of our TOTUS Total Transformer Monitoring Solution for a deeper understanding of transformer health.

DETECT

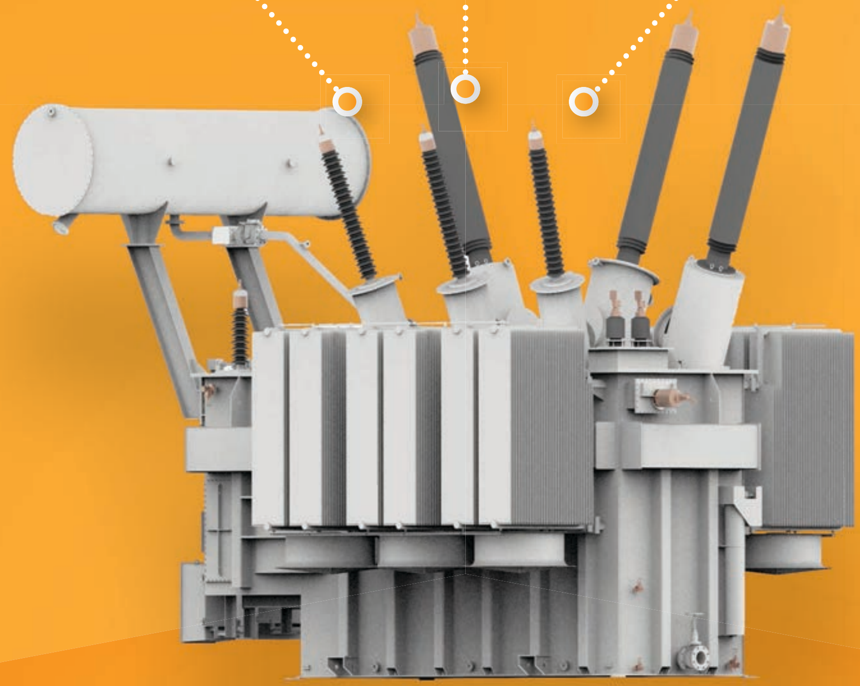
Anomalies under real operating conditions

DIAGNOSE

Risk, condition & failure mode

DECISION

Quick and actionable insight



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Bushing Failure Prevention Through Online Monitoring

In another excellent article, Marco Tozzi leads us through a primer of bushings, their failure modes and online and offline ways of monitoring bushings. Marco's vast experience in transformer and power system monitoring makes him uniquely qualified to share on this important topic. Enjoy! Learn! Apply!

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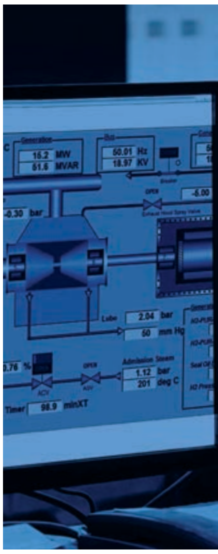
Technology Insights:
by Corné Dames

Effective transformer bushings diagnostic tools are of the utmost importance and should be an integral part of the life-cycle oriented preventative maintenance strategy. In this article, we will discuss the Dielectric Frequency Response (DFR) measurements as a supporting diagnostic tool for bushing condition assessment.



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Managing the Reliability of an Industrial or Commercial Electrical Power System: #4

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Three Steps for Diagnostic Testing of Bushings

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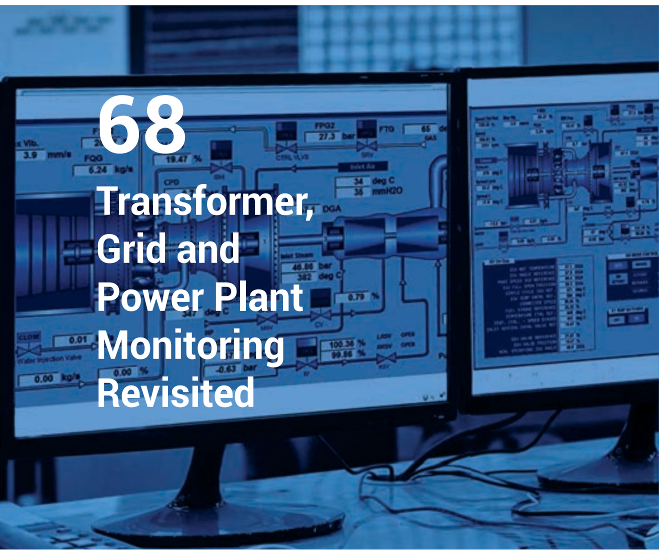

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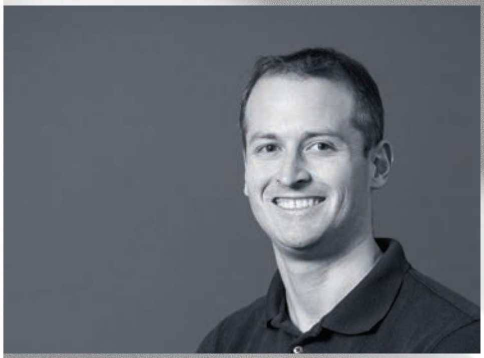


Dear Readers and Members of TT Community,

At a recent video conference with a group of marketing professionals, I told them. **"Great content is at the heart of, and powers, great Digital Communications."** At our Transformer Technology community, we couldn't agree more. But there can be an issue when you attempt to transform a magazine, with its time deadlines, into a community with information free-flow, well beyond merely printing interviews and articles separated by promotional pieces.

You may have noticed that we now ***feature*** articles and interviews on a weekly basis, along with news, webinar information and more, throughout every week, **making frequent visits to the site more important than ever**. Then we curated all of the previous weeks' interviews and articles into the Summer issue.

As the final piece of that transformation, we are introducing a "content-driven" strategy of continuing to feature weekly articles or interviews and curating them into a monthly issue.

Now all of the previous weeks' content from great authors like Corné Dames, Alan Sbravati, Chuck Baker, Marco Tozzi, Elm Costa and his team and more, and the insightful interview with Ronald Schmid of Siemens, is compiled into this, the first monthly issue of Transformer Technology.

Because bushings are so important to transformers and one of the leading causes of transformer failures, we will continue to feature articles and interviews on this topic in October, and then curate our second monthly edition called *Bushings: Part II*. I know that's not a very excitingly themed title, but it is the best way we know how to theme the issue.

As a preview of what is to come, we will combine November and December with the theme of Oils & Fluids. We have already lined up articles from the very best experts on the subject, and of course another feature from Corné Dames and Chuck Baker.

Finally, a new digital feature that we believe will take us into the next phase of our transition into being the "go-to" place for transformer knowledge and information, is the introduction of our **Video Content Feature** with exclusive interviews with leaders from all aspects of power systems and transformers, focusing on the seven fundamentals of the Electric Power Reliability Alliance (EPRA). We will feature these Alliance Member interviews as a way of showcasing the important changes the future brings, with the leaders who are making these changes happen.

> Welcome to the September issue of Transformer Technology, focused on Bushings.

The seven fundamentals these interviews will focus on are:

1. **Leadership commitment to reliability and safety.** How does your company align with the need to engage the marketplace into thinking this way? What is their commitment to safety and how do they approach it within their organization?

2. **Vision and Mission Commitment.** How does your vision/mission align with the vision of TT?

3. **Quality.** How do you address the need for providing quality in your products or services for TT members? What methods do they use to insure it?

4. **Continuous Improvement.** How do you apply the principles of Continuous Improvement and/or Innovation within your organization?

5. **Lifelong Learning & Lifelong Sharing.** "*In order to know, you must first learn.*" How do you engage your employees in continuous learning and how committed are you to sharing new knowledge, technology or methods with practitioners without regard to financial incentive?

6. **Generational Transition.** Both within your company and supporting the industry; what is the commitment to preparing the next generation of electric power and/or transformer professionals?

7. **Legacy.** What is the lasting imprint your company wants to have? Marketplace perspective? How do you make a good place for people to thrive at work?

We hope you enjoy these changes and become a contributing member of our community. Give us your feedback and stay informed. It has not been easy making the transition from a quarterly magazine to an up-to-date, web-based digital community and I would like to thank our team members who have made this happen and who have supported this vision from the start. I would also like to thank all of our contributors, from podcasts, to interviews and articles, because they are the power and source behind great content. I would also like to thank our advertisers and sponsors who have joined us in this journey and captured the vision for making the Transformer Technology community a significant part of their digital communications strategy.

And finally, I want to thank you, our readers, who are the motivation and who supply the energy we need to serve you on this journey. We will continue to build on our own seven fundamentals with the vision for making the TT community your trusted source for the best *BoK* (Body of Knowledge) on transformer design, application, life-cycle, maintenance, testing, monitoring, and critical components.

Thank You!

Alan M Ross
CRL, CMRP
Editor in Chief
Transformer Technology

Please feel free to contact me directly at alan.ross@transformer-technology.com, alan.ross@myepra.com or by phone at +1 404-992-5111.
It is time to lead.
It is time for a change.

Events Watch

IEEE Transformers Committee - Fall Meeting

October 18 - 22, 2020 / VIRTUAL

https://www.transformerscommittee.org/meetings/2020-fall-virtualmeeting/

CIGRE Canada Conference & Expo 2020

October 20 - 21, 2020 / VIRTUAL

https://cigreconference.ca/2020/en/about-cigre/cigre-canada/

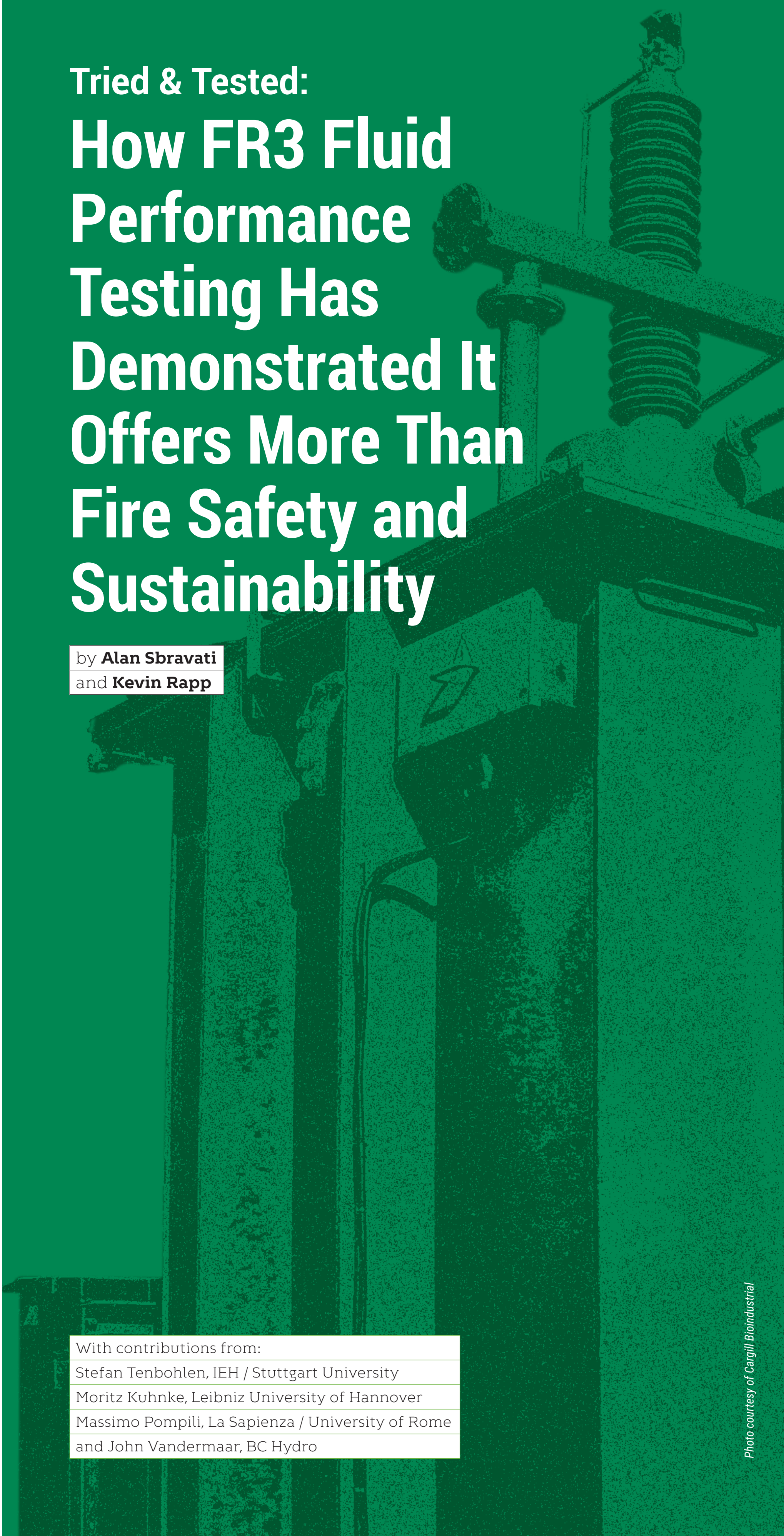
EuroDoble Colloquium 2020

October 20 - 22, 2020 / VIRTUAL

https://web.cvent.com/event/59f2753e-46c8-41ea-a077-5c12108749e7/websitePage:74af9572-128f-46db-a6b3-52d0a0535120?rp=

Natural ester liquids have been used as an insulator in power transformers for nearly three decades. They are the third generation of fire-resistant fluids – or "k-class" liquids – used in transformers, but their fire resistance was not their only benefit. In fact, it is outshined by the fluid performance. Prior to the introduction of natural ester liquids, mineral oil was the go-to transformer insulator, despite its known limitations, and the fact that it is highly flammable. The synthetic ester liquids were introduced more than 10 years before natural, but the seasonal availability of carboxylic acids (derived from petroleum), and its inherently higher cost limited its use to niche applications. To have an effective superior alternative for its transformers, Copper Power Systems (CPS at that time, now Eaton) began exploring alternatives. In 1991, Eaton's research found that vegetable oil was also an ester, but they needed a formulation that would assure long-term transformer performance. And so began a four-year research and development journey involving the evaluation of over 40 different vegetable oils and blends. From these, Eaton narrowed the list down to seven possible formulation candidates, taking into consideration many prototype pole and pad-mounted distribution transformers, ultimately resulting in what is now known as FR3 fluid.

The immense amount of data and information now available on natural ester liquids has demonstrated their functionality. Add to that the other undeniable advantages flash and fire point and environmental characteristics, and it's clear that natural ester liquids may be the future go-to insulation liquid.



Tried & Tested:

How FR3 Fluid Performance Testing Has Demonstrated It Offers More Than Fire Safety and Sustainability

by **Alan Sbravati**
and **Kevin Rapp**

With contributions from:
Stefan Tenbohlen, IEH / Stuttgart University
Moritz Kuhnke, Leibniz University of Hannover
Massimo Pompili, La Sapienza / University of Rome
and John Vandermaar, BC Hydro

Photo courtesy of Cargill Bioindustrial

Alan Sbravati started his career working for a transformer manufacturer, mainly developing calculation and design tools for power transformers. After almost 9.5 years in the same company, he was the R&D&E manager for power transformers in Brazil and responsible for two global R&D projects directly related to transformer design and thermal calculation. After three years in a commercial role, he moved back to a more technical position at Cargill. Over the last six years he has been working with the development and application of alternative insulating liquids, especially natural ester fluid (Envirotemp™ FR3™), holding the position of Global Technical Manager since 2018. Alan chaired the Brazilian Standards Committee from 2012 to 2016, prior to moving to USA. He participates in IEC TC 14 and Cigre working groups. Currently he is a member of IEEE Transformers Committee, and he is active in many subcommittees and task forces.

Kevin J. Rapp is the Principal Chemist for Global Dielectric Fluids of Cargill Bioindustrial. With over 40 years in the electrical industry, including 27 years in R&D where he invented Envirotemp™ FR3™ fluid and found that ester liquids enhance the life of cellulose insulation in transformers. Kevin is involved in standards as Technical Advisor/Chairman of USNC of ANSI/IEC TC10, ASTM D27.15 and D27.91 Subcommittees. Kevin was awarded IEC 1906 Award in 2011, US-EPA Presidential Green Chemistry Award in 2013, ASTM Service Award in 2015 and installed as ASTM Fellow with Distinguished Merit Award in May 2018. He holds many patents and has published numerous papers as a member of ACS, AOCS, ASTM, CIGRE, IEC and IEEE.

But First, Due Diligence Testing

Before it could be commercialized, the natural ester liquid underwent a series of required "due diligence" testing, including the electrical industry's Lockie Test (IEEE C57.100). This three-year functional test consisted of three groups of transformers:

- Each group of transformers had different thermal cycles of high peak temperature accelerated aging periods.
- The aging periods were evenly divided into 10 test periods with mechanical and dielectric testing performed at the end of each period, composed by four thermal cycles (from ambient temperature to the defined hotspot temperature, accumulating only the hours at peak temperature).
- The dielectric tests include a short-circuit test for generating mechanical stress to the insulating structure, followed by lightning impulse, applied voltage and induced voltage tests.
- The transformer containing the insulation system under test had to survive the entire test duration representing *five times* the IEEE nominal life expectancy period to be approved.

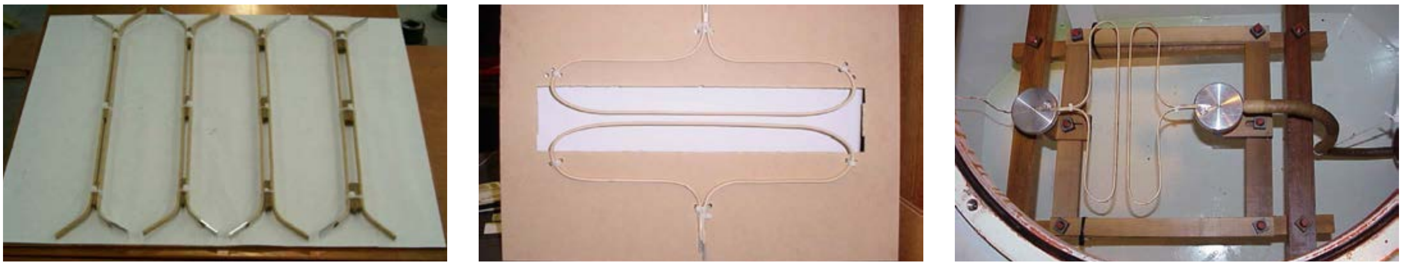
All mineral oil and the natural ester filled units completed five units of life successfully, in all three hotspot temperatures. Since the test duration was shorter for the group aged at the highest temperature, CPS decided to extend the test beyond the required time. While the mineral oil unit failed in the subsequent period, the last failure of the four natural ester units happened only after 19.5 times the unit of life, almost four times longer than the five units of life that were required.

While the test was still running, the first transformers filled with FR3 fluid were commissioned, including two units that provided power to the Eaton plant core annealing ovens, and another installed in a large amusement park in Florida. In the years to follow, also motivated by the outstanding results of the Lockie Test, production of 36 kV voltage class transformers was accelerated by Eaton.

Expanding Manufacturers, Expanded Testing

In order to expand the technology to other manufacturers, Eaton had to verify the standard dielectric design curves for the insulation system design. Transformer experts (including the one of the reference transformer designers, Harold Moore, who was the engineering manager in Westinghouse when the design curves were originally developed) helped to develop a testing matrix in the early 2000s.

Figure 1. Three "generations" of electrodes designed for testing the breakdown voltage of the insulating liquid gaps for the transformer windings.



Turn to turn oil gaps, from 3 mm to 12 mm	Stress between discs up to 12 mm, with radial spacers	Oil gaps up to 50 mm

Figure 2. Test setup and electrodes for testing the interfacial creep breakdowns.

Insulation design experts identified what they would classify "essential validation points" to allow the use of mineral oil design curves for the natural ester filled transformers. The matrix included dielectric tests for validating the dielectric capacity in comparison to mineral oil, as well as detailed measurement of its properties, such as: permittivity (dielectric constant), differences of power factor for insulation models, and even the volumes of gas formation under severe arcing conditions (flashovers).

These tests often had to be repeated and modified to ensure the accuracy of the results. As a transformer manufacturer, Eaton's highest priority was the high-quality standards of their transformers. Thus, the transformer designers were a very demanding first internal customer for the application of the fluid, requiring a thoughtful validation of the fluid performance for new transformers and on long term perspective. When their new fluid started to be offered to other transformer manufacturers, the road was already very well paved.

Figure 3. Tap changer selector rods and contacts used for comparative tests of FR3 fluid and mineral oil.

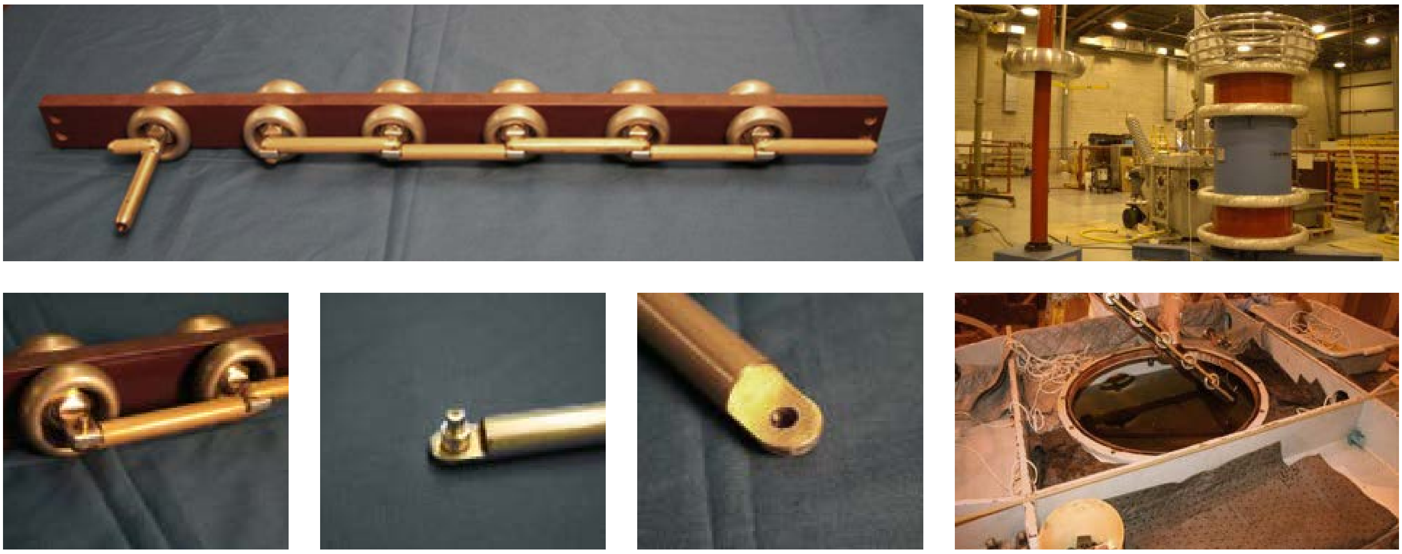
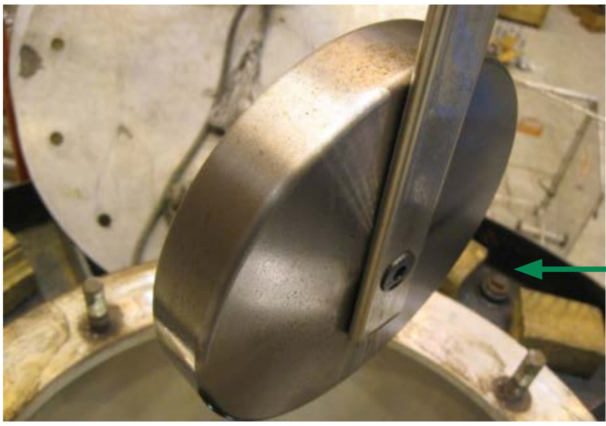


Figure 4. Electrode and test setup used for testing gaps up to 150 mm.

Steel ground plate 463 mm diameter, raised 310 mm off tank bottom



Bare bushing shield 216 mm diameter x 38 mm thick, top/bottom edge radius of 4.3 mm

Bushing shield electrode connected to 550 kV bushing (1800 kV BIL). Sealed steel test tank volume at 12,500 liters

The full test matrix was completed in 2010, totaling over seven years and millions of dollars across several research institutes and experts. The detailed results and insights from the test allowed for the optimization of a natural ester transformer design, alleviating the use and expense of additional safety margins. Most of the test details and results were published and are available in IEEE Xplore library, but the overall test conclusions were:

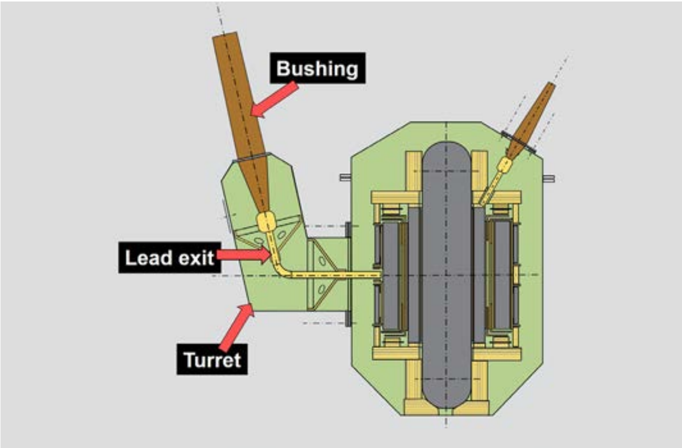
- The dielectric capacity of FR3 fluid, for all construction elements of a properly designed transformer, is equivalent to mineral oil. No additional safety margins are required.
- The different dielectric constant or permittivity of a natural ester liquid affects the distribution of the electrical field in a transformer. While the impact may be small for lower voltage classes, it is essential to be taken into consideration for higher voltage levels.
- Special attention is required for designing and performing the tests, avoiding the presence of sharp edges, oil wedges, gas bubbles and increasing the time for purging the gases formed after each flashover.

More Data, More Testing

The comprehensive testing program offered the required confidence level for the application of the natural ester liquids in higher voltage classes, achieving the first 420 kV transformer in 2013, before any other alternative liquid. This also drove the application of natural ester in instrument transformers used to monitor the voltage of the transmission line, and the development of a standard "lead exit" for transformers of such voltage class, used to connect the high voltage winding exit to the bushing. Cargill supported and joined the testing phase of the lead exit with EHV Weidmann, wherein the final configuration had the same diameter of the solution used for mineral oil, validating the equivalency of the dielectric capacity of the two insulating liquids. Moreover, the successfully performed tests exceeded IEC test protocols, including basic impulse levels applied for 765 kV transformers, and the achieved level of partial discharge was extremely low, outperforming what was obtained when testing the lead exit with mineral oil.

To understand the differences for highly divergent field configurations, a two-year investigation was initiated, exploring a sequence of sharp electrodes, ranging from sphere-to-sphere configuration to needle-to-sphere configuration. The tests were performed with different variables (i.e. gaps, electrodes, moisture contents

Figure 5. Images showing the position of the "lead exit" in a power transformer and a full representation of the final structure developed to be used with FR3 natural ester liquid.



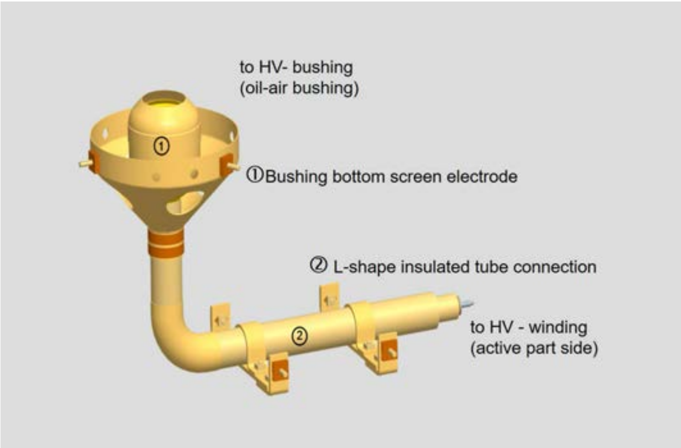
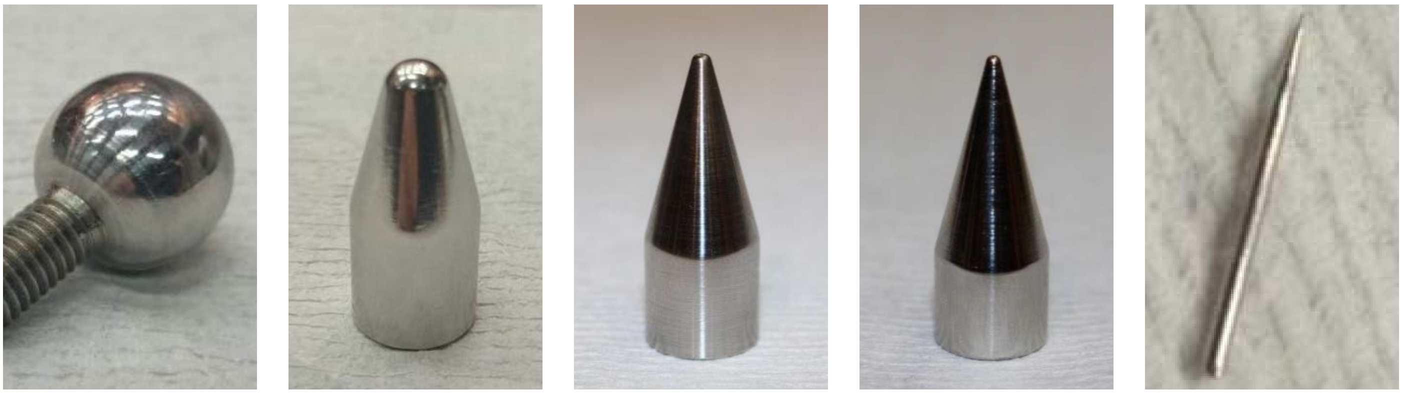


Figure 6. Electrodes designed for the investigation of the highly divergent fields behavior.



Ø 13 mm sphere

Ø 3 mm blunt point

Ø 0.8 mm blunt point

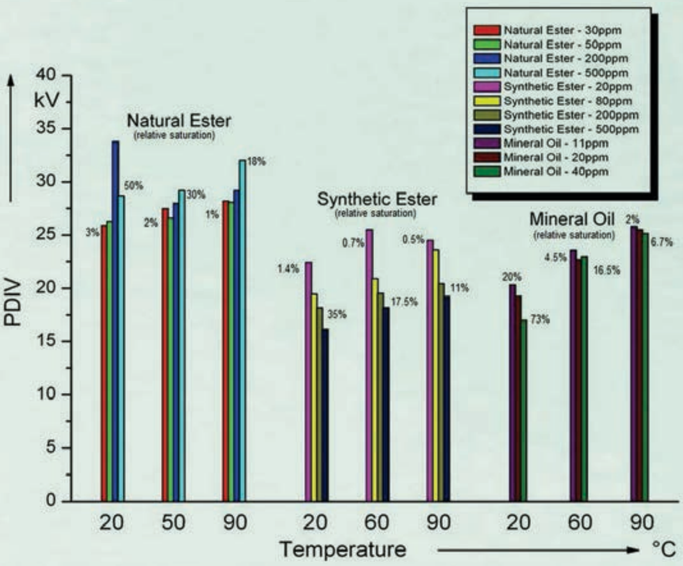
Ø 0.6 mm blunt point

Ø 0.12 mm Gramophone needle

and particle contents), testing the natural ester side-by-side with mineral oil. The obtained breakdown voltage for the different electrodes when tested in natural ester and in mineral oil were equivalent down to the 0.4 mm radius for a 25 mm gap. Since this is sharper than what would be acceptable for any medium and high voltage transformer, it does not imply larger gaps nor increased design clearances.

The most recent investigation projects are around the "pre-discharge" process, namely the inception and effects of partial discharges. Identified as a failure mode since a while, the generation of x-wax, a wax-like substance identified in failed transformers, especially lately in wind generators, is directly related to the presence of partial discharges, as reported by the published papers from Schering-Institute (Leibniz University of Hannover). Relevant advantages were identified when natural ester behavior was investigated, triggered exactly by the difficulties in reaching a stable level of partial discharges activities. While the tests with mineral oil and synthetic ester allowed for keeping the discharges along several days, with natural ester liquids the partial discharges were self-extinguished in a few hours, regardless of increasing the voltage almost to the breakdown level.

Figure 7. Results of Partial Discharge Inception Voltage (PDIV). Lower values indicate higher susceptibility to high voltage.



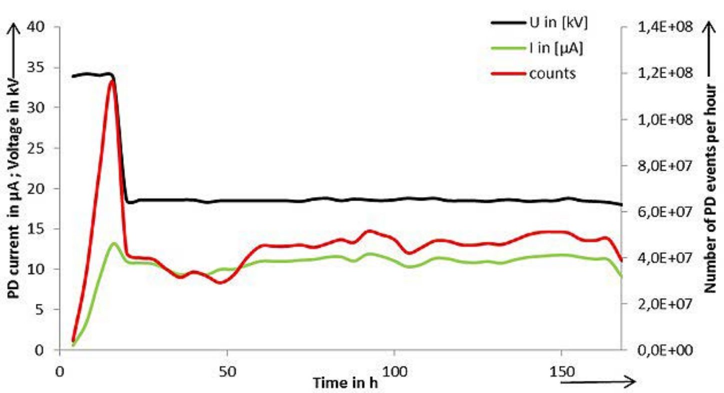
To date, the investment to test and validate the performance of natural ester liquids exceeds all other alternative liquids by far, totaling over 25 years of research. The potential of natural ester liquids to transition from an "alternative liquid" to a mainstream material – as the market share in some regions already indicates – is the driver for maintaining investments in research and development.

A deeper understanding of the inception and extinguishing process is expected as an outcome of the currently active project with Rome University. The differences of the molecular structure of esters may be key parameters for understanding the "quenching" behavior, as a side effect of the presence of double bonds.

The knowledge acquired from research and development activities continues to drive new tests and investigations. To date, the investment to test and validate the performance of natural ester liquids exceeds all other alternative liquids by far, totaling over 25 years of research. The potential of natural ester liquids to transition from an "alternative liquid" to a mainstream material – as the market share in some regions already indicates – is the driver for maintaining investments in research and development.

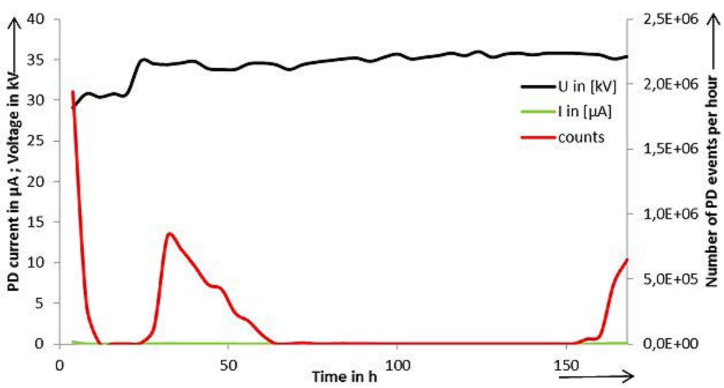
There is inherently a high level of responsibility with the design of power transformers, either due to the expense and complexity, or the decades-long life expectancy. But over time, transformer designers have increased their confidence level in applying transformer design limits with natural ester liquids, similar to those used with traditional mineral oil filled transformers. The immense amount of data and information now available on natural ester liquids has demonstrated their functionality. Add to that the other undeniable advantages flash and fire point and environmental characteristics, and it's clear that natural ester liquids may be the future go-to insulation liquid.

Figure 8. The charts (left) present the different profile for the partial discharges. The photos (right) show the solidified materials formed after the 200 h of ageing under PDs.

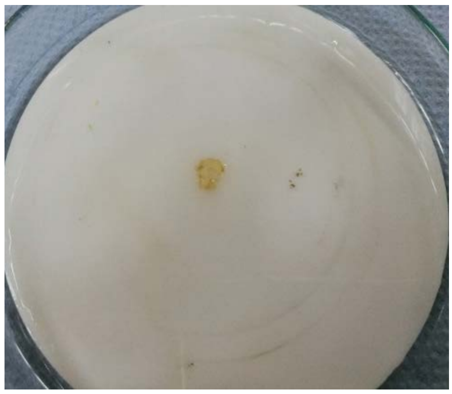


Voltage and PD activity during a typical test with synthetic ester

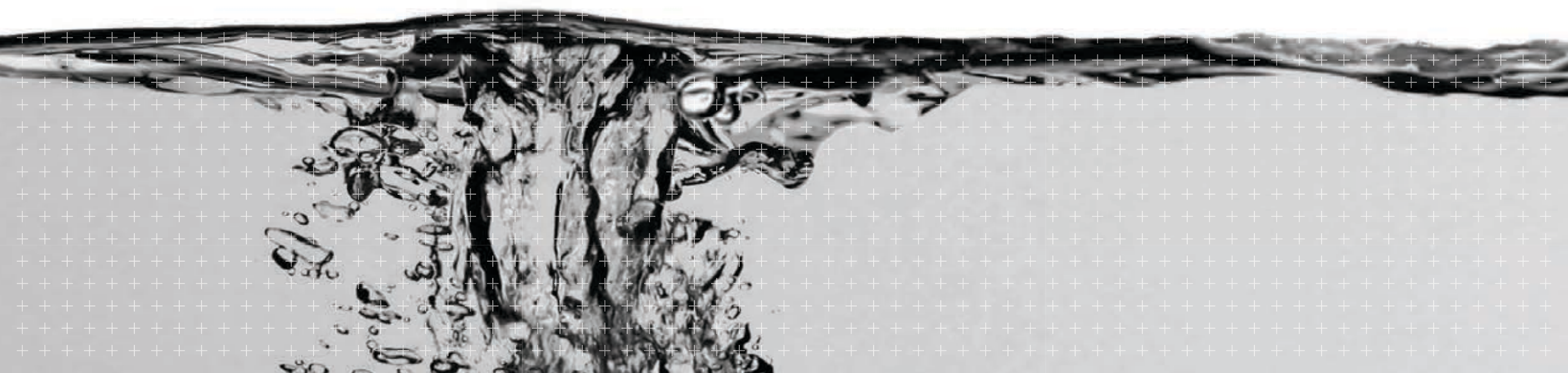
X-Wax formed from synthetic ester



Voltage and PD activity during a typical test with natural ester



Traces of solidified product from natural ester



DYNAMIC RATINGS

Bushing Monitoring Case Study: Rapid Changes in the Bushing's Health

Continuous online monitoring of bushings provides real-time information which can result in the early detection of a possible failure.

Photo: Dynamic Ratings

Continuous online monitoring of bushings with the C50 Transformer Monitor offers real-time information of bushing capacitance and power factor. It provides

- Temperature correlation
- Discrete readings
- Diagnostic web pages
- Diagnostic Software
- Superior Sensor Design

Challenge: A Major Alarm

A prominent U.S. utility was looking for a way to improve system reliability for their 138 kV assets. They researched and reviewed options available on the market that included affordable bushing monitoring. After review, the utility chose to pilot the **Dynamic Ratings' C50 Transformer Monitor** to see if it was worth the investment to become part of the overall solution.

The C50 Transformer Monitors were installed and serviced on the transformers by Dynamic Ratings Field Engineers. One day, after about two years in service, the utility received notification of a major alarm happening at one of the C50 installation sites. Upon further review of the online web pages, the C50 indicated that there was a rapid change happening in the health of a bushing on the transformer.

Solution: Engineer Collaboration

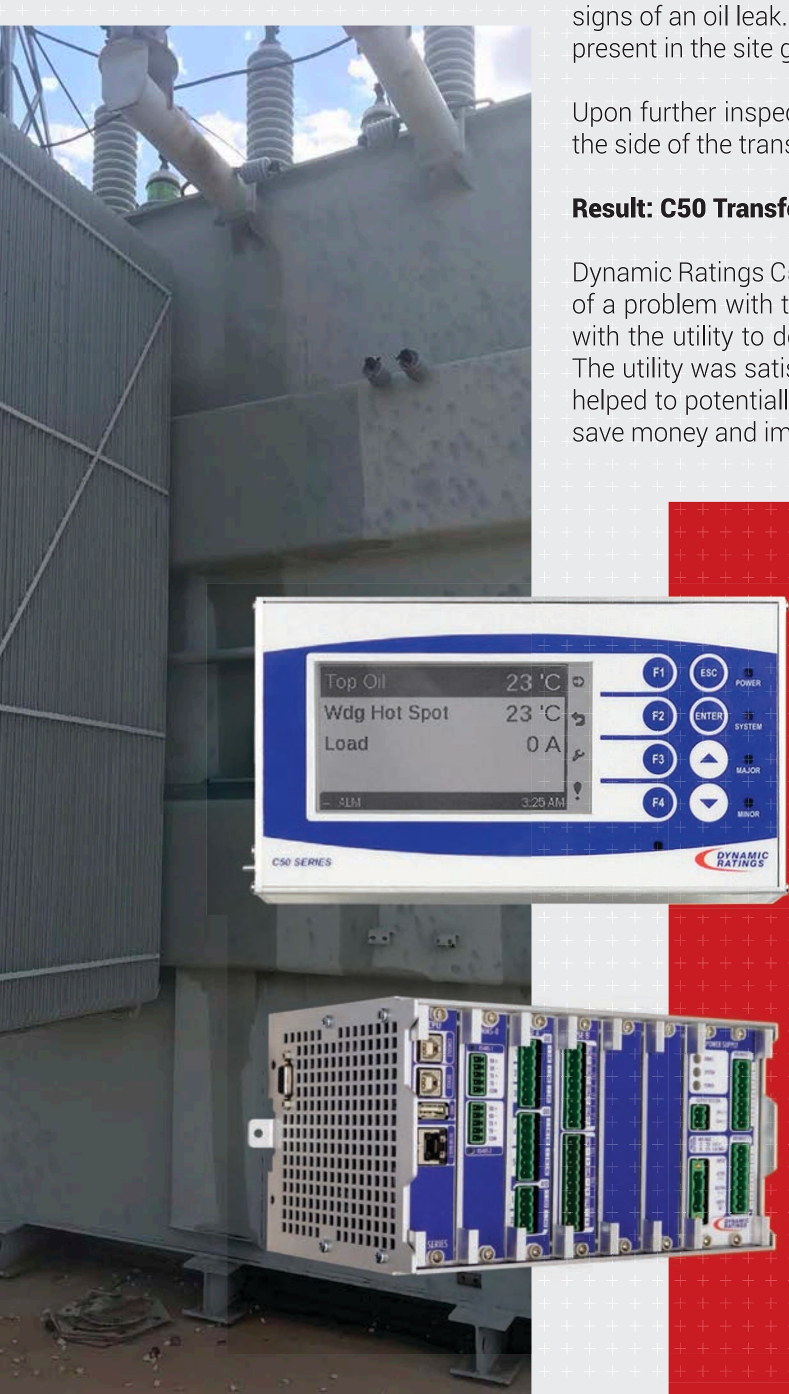
Dynamic Ratings engineering team took a closer look at the data and recommended that the utility inspect the bushings for a possible oil leak. Low oil in the bushing would explain the decrease in the C1 capacitance of the bushing.

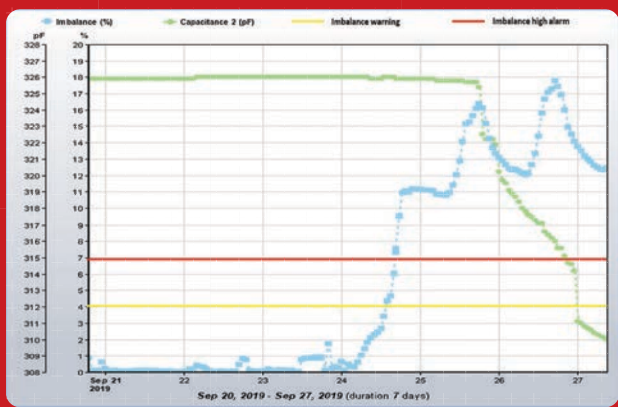
The utility dispatched an engineer to investigate the alarm and to look for any signs of an oil leak. During the investigation, the engineer noticed there was no oil present in the site glass.

Upon further inspection, he saw that oil had leaked out of the bushing and down the side of the transformer.

Result: C50 Transformer Monitor Prevents Potential Bushing Failure

Dynamic Ratings C50 Transformer Monitor was able to detect and notify the utility of a problem with the bushing. Dynamic Ratings team of experts worked closely with the utility to determine the problem and prevent a potential bushing failure. The utility was satisfied with their investment into bushing monitoring because it helped to potentially extend the life of their asset, improve situational awareness, save money and improve safety for workers.





To learn more about the C50 Transformer Monitor, visit our website at www.dynamicratings.com/C50.

Interview with **Ronald Schmid**

General Manager
of Siemens Transformers Linz, Austria

"I'm proud to be part of a company that makes a difference to society - locally and also globally - and that's helping its customers around the globe to transition to a more sustainable world using innovative technologies.

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Ronald Schmid

My personal highlight was in 2016, when I started my first General Manager position at the Siemens traction transformer site. Working with my colleagues, we almost doubled our output in less than two years. I feel the same great team spirit now at Siemens Energy Transformers Linz.

Transformer Technology: Ronald, thank you for taking the time to share your knowledge and insights about Siemens Transformers and your very successful career within our industry. First, tell me a little about the Linz factory, which is one of the oldest in the world for the manufacture of transformers. I believe you became General Manager in October of 2018, correct?

Ronald Schmid: Yes, I became General Manager in October 2018 and now have the privilege of shaping the factory for STL's next century of business. As you mentioned, we're a long-established factory with a 100-year tradition of delivering high-quality transformers. Our business managed to successfully thrive during inflation and the Great Depression, and it was bombed during World War II and rebuilt soon after. Ever since, we've basically transitioned from a regional transformer provider to a global market player with an export quota above 80 percent.

TT Ronald, what is the specialty focus of the Linz plant? What range of transformers are produced there?

RS Our main business is the development and production of innovative solutions for special customer demands. Nearly every transformer delivered out of Linz is unique. Special environmental conditions (like low/high temperatures and seismic zones), low noise-level requirements, restrictions in dimensions/weight, alternative insulation media, rupture-resistant designs, and many more special applications are integrated based on our customers' requirements. Our design range comprises transformers, both mineral oil as well as synthetic and natural ester from 10 MVA to 300 MVA and up to 500 kV.

TT One of the changes we see taking place in our industry is the focus on Reliability Engineering by Design or RED. How does Siemens integrate all aspects of the process from design to engineering, and from engineering to integrating production, quality control, testing, and commissioning?

RS We're aware of the importance of reliability engineering. That's why the Linz factory and a local IT partner developed a tool that uses artificial intelligence to analyze market, customer, and product-specific lessons learned from built units that will be automatically integrated in future designs. By closing the feedback loop with production and quality management, we're able to constantly improve the reliability of our designs in the engineering phase.

TT What are some of the biggest challenges you see facing the global market for transformers in the years and decades ahead?

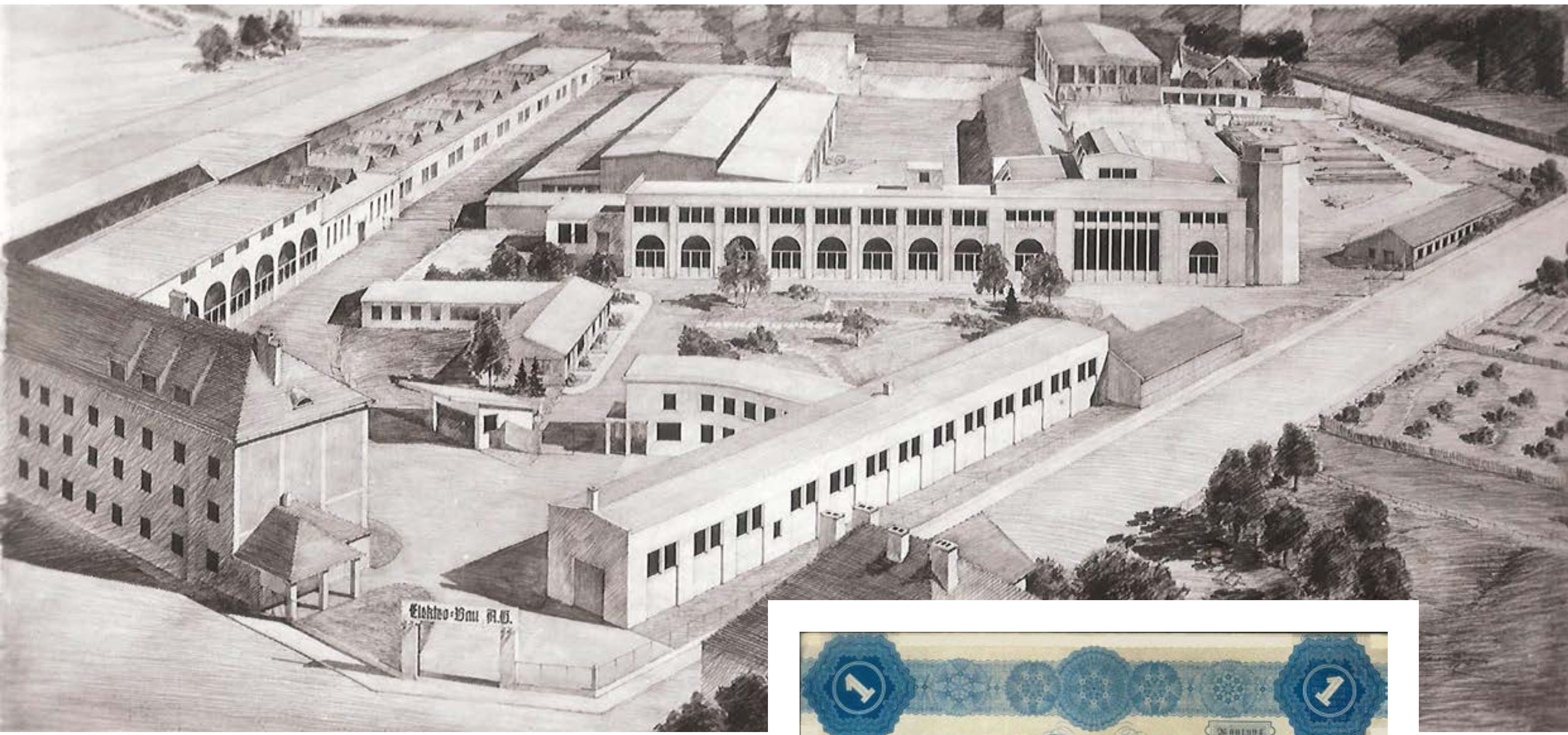
RS There's no doubt that decarbonization will play a central role in the decades to come. At Siemens Energy, we're committed to carbon-neutral operations. With regard to the energy market, the most pressing challenge is the integration of energy generation by renewables in the existing power grids and providing solutions for a smooth transition to a more decentralized power supply. With the ecological footprint gaining in importance, we're also noticing an increased demand for our experience in designing transformers with alternative insulation liquids.

TT How has Covid-19 affected or changed the approach you are taking in regard to these challenges?

RS The trends as such are neither sped up nor slowed down by COVID-19. By implementing stringent measures, we've been able to stay at full operation throughout the crisis. At Transformers Linz, the real change caused by COVID-19 was an acceptance of new technologies in the way we work together. Our clients came to accept and appreciate the advantages of remote inspections and FATs, and on the internal level, many prejudices about the home office diminished.

TT Ronald, you have spent a great deal of your time at Siemens working in the Distribution Transformer market, so share with us what you have seen changing in that specific marketplace over the past few years? Is there a regional response to market forces or is it a truly global approach? For instance, do you see changes between the US, Latin American, European, or Asian markets?

Photo: Siemens



The Siemens transformer factory in Linz (Austria) can look back on an eventful history of 100 years.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Linz, am 12. November 1937.
E. B. G. Oberösterreichische Elektro-Bau-Aktien-Gesellschaft

1920 is the year it all started with the foundation of the O.Ö. Elektro Bau Gmbh (EBG). In the picture: EBG share, 1937.

This year we're proud to deliver the one-hundredth unit to an important U.S. business partner.

Nearly every transformer delivered out of Linz is unique. Special environmental conditions, low noise-level requirements, restrictions in dimensions and weight, alternative insulation media, rupture-resistant designs, and many more special applications are integrated based on our customers' requirements.

RS My perception about the distribution transformer marketplace is that it's quite a local business. Nevertheless, the challenges have been the same globally, with a differing focus and intensity: Energy-efficiency, environmental sustainability, and integrating renewable power generation, just to name a few. In the upcoming years, digitalization will play a major role in every industry and every country.

TT I see that you were the head of R&D in Budapest and then working in Innovation management in Nuremberg. That must have been fascinating. Tell us a little about your time there and give us some insight into where innovation and R&D is affecting the future of transformer design, engineering or manufacturing?

RS Indeed, this has been a fascinating time and a great experience for me. I appreciate working in a strong global team and bringing expert and practical knowledge together. We've worked with our customers to make transformers more energy-efficient, reliable, and environmentally friendly. Our engineering and design processes entered a new era thanks to 3D modeling and simulation capabilities. It's now impossible to imagine transformer manufacturing without the support of digitalization. But manual work still plays an important role in the transformer business, and this will continue into the future.

Siemens Transformers Linz plant, around 1954 with new built high-rise building.

Siemens transformer factory in Linz, Austria, today.

Our engineering and design processes entered a new era thanks to 3D modeling and simulation capabilities. It's now impossible to imagine transformer manufacturing without the support of digitalization. But manual work still plays an important role in the transformer business, and this will continue into the future.

TT You must have seen a great deal during your career with Siemens. What would be one or two of the significant highlights of your career thus far?

RS My personal highlight was in 2016, when I started my first General Manager position at the Siemens traction transformer site. Working with my colleagues, we almost doubled our output in less than two years.

I feel the same great team spirit now at Siemens Energy Transformers Linz. This year we're proud to deliver the one-hundredth unit to an important U.S. business partner.

I'm proud to be part of a company that makes a difference to society - locally and also globally - and that's helping its customers around the globe to transition to a more sustainable world using innovative technologies.

TT Any final thoughts or advice you would give young engineers just starting their careers, thinking back to when you had just graduated from the University of Applied Sciences in Mittweida, Germany?

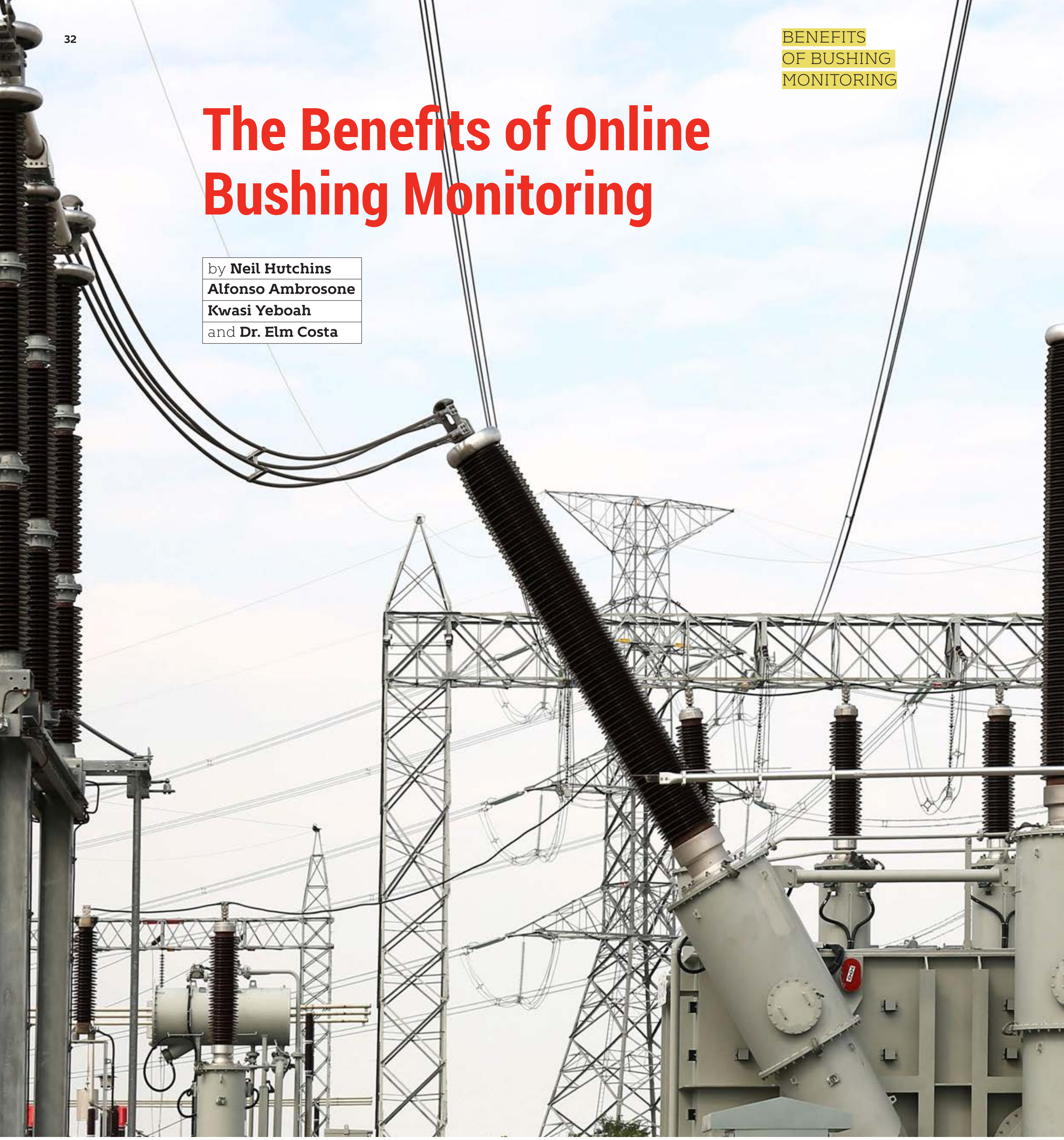
RS The advice I would give to any graduate is to seek a field of employment that they're really interested in and passionate about. I never once regretted my choice of Siemens because it offers a wide range of exciting opportunities for personal growth, as long as you're flexible in terms of relocation.

TT Thank you, Ronald. We greatly appreciate your time.

Photo: Siemens

The Benefits of Online Bushing Monitoring

by **Neil Hutchins**
Alfonso Ambrosone
Kwasi Yeboah
and **Dr. Elm Costa**



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Introduction

As utilities move from traditional offline, routine testing of power transformer towards online continuous monitoring, many benefits are realized. Online monitoring enhances the safe, reliable operation of substation power equipment, measured performance, reduced failure rates and provides more consistent and frequent information of the existing fleet. In addition to these benefits the end user realizes improved integration of relevant information so that operations managers are better positioned to make more informed decisions. As a result of this, online monitoring affords utilities the ability to refocus resources in the form of O&M and capital expenditures, which leads to operating flexibility with improved reliability.

Neil Hutchins has over 21 years of experience in transmission/substation maintenance. Neil is the Supervisor of the Southern Company Services, T&PS Equipment Services Group, which provides support to Southern Company OpCos and affiliates on major equipment. He is also the Chair of the Southern Company Major Equipment Committee and a Member of Southern Company Breaker and Substation Maintenance Committees. Neil is an IEEE Senior Member, Member of IEEE/PES Switchgear Committee and a Member of IEEE Alternative Gases to SF6 Task Force and Working Group. He is also a Past Member EPRI Substation Task Force.

Elm Costa is a Sr Lead Electrical Engineer within the GE Renewable Energy group, and currently is and has been the Technical Lead for several NPI projects. He is the subject matter expert on online bushing monitoring, partial discharge and transformer models. Elm obtained his bachelor's degree in physics from the Universitat de Barcelona, and a PhD in physics at the Queen's University, Belfast. After several years working as a Research Fellow at QUB, he moved to Andor Technologies Ltd. In January 2008 he joined Kelman Ltd (later acquired by GE) working in the field of high voltage asset monitoring using electrical signals, and later specialised in capacitive bushing and partial discharge monitoring.

A bushing monitoring system is an online system that continuously monitors the condition of the transformer bushings by monitoring the capacitance change of C_1 and the relative power factor change (tan delta) of each bushing.

Alfonso Ambrosone holds a degree in Analytical Instrumentation and Controls. He has worked in the field of online transformer monitoring for 15 years. His career in transformer monitoring began with Syprotec and then further evolved within GE, specializing in dissolved gas analysis using the Hydran technology and transformer online modelling. Alfonso has extensive technical and practical experience in using online transformer monitoring systems. In 2013, Alfonso moved to the position of Product Applications Specialist, focusing on understanding the technological benefits and limitations of all technologies industry wide, as well as looking to the future and emerging technologies.

Kwasi Yeboah has been with the GE Monitoring and Diagnostics business for the last 14 years supporting customers in various roles while based in Montreal, Canada. He holds a BSc in Mechanical Engineering and certificate in Management and Quality Assurance, both from École de Technologie Supérieure. Kwasi is also a Six Sigma Green Belt certified and RCA Leader.

Eliminating, or at a minimum mitigating typical time-based maintenance/testing schedules via online monitoring and moving towards a more diagnostic driven maintenance program will allow for a more focused effort, as opposed to the typical time-based response of the past. After all, why work on something that doesn't have a problem? To perform offline power factor testing on bushings, the transformer must be removed from service, grounded, disconnected and then prepared for test. The bushings, transformer and typically the lightning arrestors are also tested during this downtime. On average, this takes a full eight-hour day with a minimum of two employees and often can include up to a total of four employees for this task. The cost of this just for the labor can be as high as 32 hours, not to mention the cost of equipment in the form of tools, vehicles, etc. Monitoring the transformer via online dissolved gas and bushing monitoring will allow crews to find much better use of their time working to correct other, more pressing issues. The end goal is to reshape the current maintenance and testing programs of the utility's substation equipment fleet with video, as opposed to pictures, so to speak.

Time-based testing programs for bushings are a snapshot in time and there are no guarantees that a problem, or even a catastrophic failure, will not occur before the next testing cycle. This one single fact should cause us to hit the pause button in our approach to past, time-based diagnostic testing as our only avenue of securing valuable information regarding the condition of a bushing. Offline power factor testing is a time honored and proven test. However, it is limited to the frequency with which it is performed. Online bushing monitoring is a great solution for anyone looking to mitigate surprise failures of these critical transformer components.

The Facts

Oil impregnated condenser type bushings have a central conductor wound with alternating layers of paper insulation and conductive foil (known as condenser or capacitive layers). These capacitive layers are housed in a protective weather casing (typically porcelain) and filled with insulating oil. There are two main capacitances in a bushing, identified as C_1 and C_2 (Figure 1). C_1 is the total capacitance between the center conductor and the test tap. Where the test tap is connected to the outer most capacitive layer, this is the point at which bushing measurements are made. C_2 is the capacitance from the test tap to ground, where C_2 is not part of the circuit during normal operation of the bushing.

The layers are designed to provide uniform voltage drops between each capacitive layer, effectively acting as a voltage divider. When a capacitive layer shorts, the voltage across each layer increases, increasing the leakage current proportionally. The magnitude of the current is a measure of the capacitance of the bushing, and a change of current magnitude indicates a change of capacitance of C_1, which is an indication that the dielectric is not as efficient due to internal contamination of the insulation where the capacitive layers have been affected.

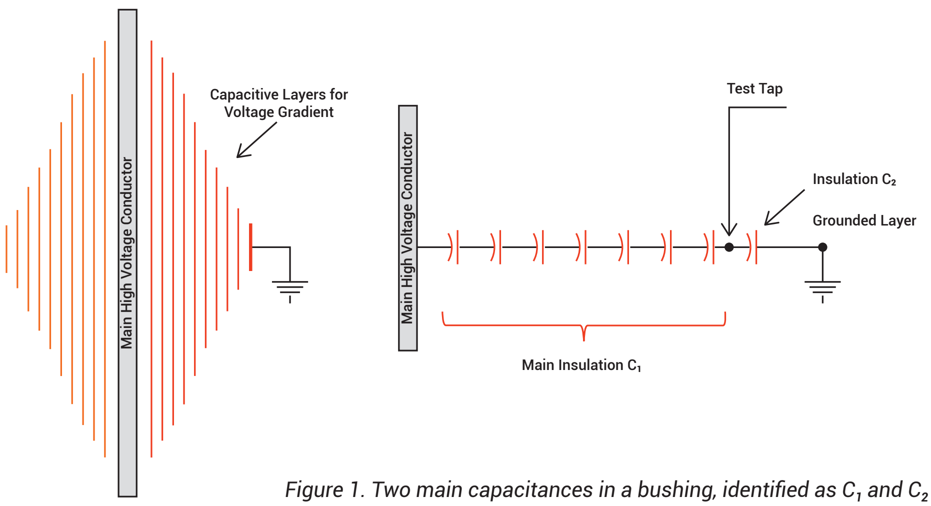

Figure 1. Two main capacitances in a bushing, identified as C_1 and C_2

A bushing monitoring system is an online system that continuously monitors the condition of the transformer bushings by monitoring the capacitance change of C_1 and the relative power factor change (tan delta) of each bushing. A system that has the ability to detect PD (partial discharge) activity generated in the transformer utilizing the same bushing adaptors (sensors) connected at the bushing tapping point, without any additional hardware mounted to the transformer, will provide further vital health information on the bushings and the transformer.

Bushing monitors should continuously measure the individual leakage currents of each of the bushings. A change in magnitude of the leakage current indicates a change in bushing capacitance. The change in bushing capacitance is then compared to the original nameplate capacitance to determine the bushing condition. The initial capacitance may be different from bushing to bushing. What is of interest is how much this capacitance has changed compared to when it was new.

Moisture is an enemy for bushings. Ingress of moisture into the bushing will deteriorate the bushing insulation, which will cause the dielectric losses to increase, driving an increase in the bushing dissipation factor (power factory; tan delta). Temperature and transients are also important factors that can also affect the bushing insulation, thus increasing the power factor.

Online relative power factor measurement has the timing differences among the three bushing leakage current phases, which translates to phase angle differences relative to each other. Since a change of phase delay equates to a change in power factor, we can determine for each bushing the relative (compared to the others) change of power factor as a percentage of the nameplate value.

Photo: General Electric

Eliminating, or at a minimum mitigating typical time-based maintenance and testing schedules via online monitoring and moving towards a more diagnostic driven maintenance program will allow for a more focused effort, as opposed to the typical time-based response of the past. After all, why work on something that doesn't have a problem?

Typical Requirements

The installation of the bushing monitor requires information which can be found on the nameplate, in addition to the transformer's operating voltage. This information consists of the mechanical aspect of the bushing tapping point, where the bushing monitor adaptor will be inserted. This is to ensure a secured installation and uncompromised contact with the test tap (Figure 2).

Figure 2. When installing a bushing monitor, it is important to ensure a secured installation and uncompromised contact with the test tap

With an expanded library of bushing types, the bushing model will generally suffice. However, the availability of drawings, which include the flange, can be beneficial. The electrical characteristics, such as the % power factor (tan delta) and C_1 capacitance values located on the nameplate, are used to configure the bushing system. The nameplate values also serve as the starting point of the bushing's life, in terms of its capacitance and relative % power factor change. In short, the mechanical and electrical parameters of a bushing are the key elements for a successful installation of a bushing monitor.

Success Story

Southern Power, a subsidiary of Southern Company, is a leading wholesale energy provider that operates 49 generating facilities with more than 11,200 megawatts of electricity generating capacity all over the USA.

Their 102-megawatt Henrietta Solar Project in Kings County, California, USA (Figure 3) achieved commercial operation in October 2016. Southern Power had the foresight to install a bushing monitoring system from GE to monitor a key 50 MVA transformer.

Henrietta Solar Farm (Photo: Southern Company)

The end goal is to reshape the current maintenance and testing programs of the utility's substation equipment fleet with video, as opposed to pictures, so to speak.

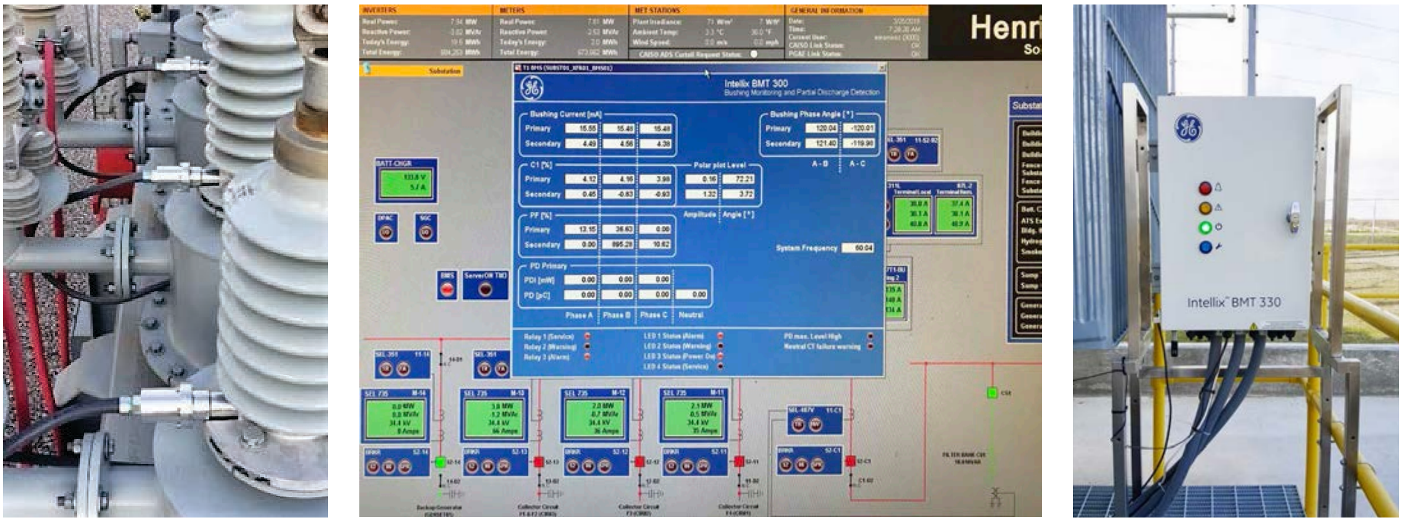

Figure 3. Bushing adapters (left); screenshot of SCADA screen (centre); picture of the bushing monitor (right)

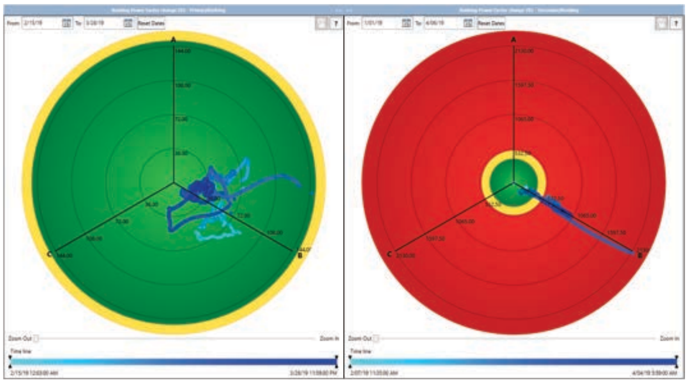

Figure 4. Polar Plots showing Relative % Change of Power Factor

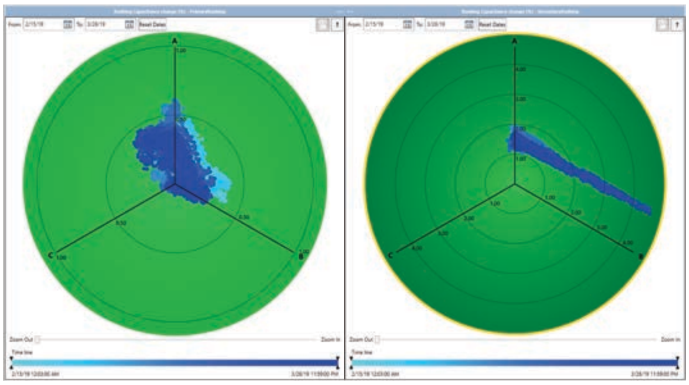

Figure 5. Polar Plots showing % Change of Capacitance C_1

The Problem

On 26 March 2019, the data being received from the bushing monitor through the SCADA system showed an alarm coming from the phase B bushing on the LV secondary side. It was indicating an increase of the relative percent change in Power Factor (PF) from 311% on February 27th to above 895% on March 26th, 2019.

Analysis

Figure 4 compares the primary and secondary polar plots for the relative percent Power Factor change. The data on the Primary side does not show any abnormal behaviour. Although the data points are not tightly packed together, they are in the same region and within normal range.

Compare this to the secondary side where the data clearly shows a very large and significant increase in the %PF generated by the phase B bushing. This increase in %PF started in February 2019.

Figure 5 below shows the polar plots for the primary and secondary bushing with respect to the % change in Capacitance C_1.
The data points on the left polar plot from the primary side are neatly packed and stable which is expected in normal operation.

However, on the right polar plot for the secondary side, data points show a change of ~1.5% on phase A, but the concerning element is the progression for phase B which reaches 4.2% on March 28th, 2019.

Online bushing monitoring affords utilities the ability to refocus resources in the form of O&M and capital expenditures, which leads to operating flexibility with improved reliability.

Based on the data from the bushing monitor, Southern Power decided to take the transformer offline to avoid a possible catastrophic failure of the bushing. They replaced the suspicious bushing and returned the transformer to service.

Subsequent offline tests on the suspicious bushing confirmed that the bushing had indeed significantly deteriorated from its original values and that the operational decision taken had been correct.

The bushing monitor had correctly highlighted that the Power Factor of that bushing was starting to change at a fast rate in the last month and that a precautionary replacement should take place whenever possible.

Photo: General Electric

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MSENSE® BM

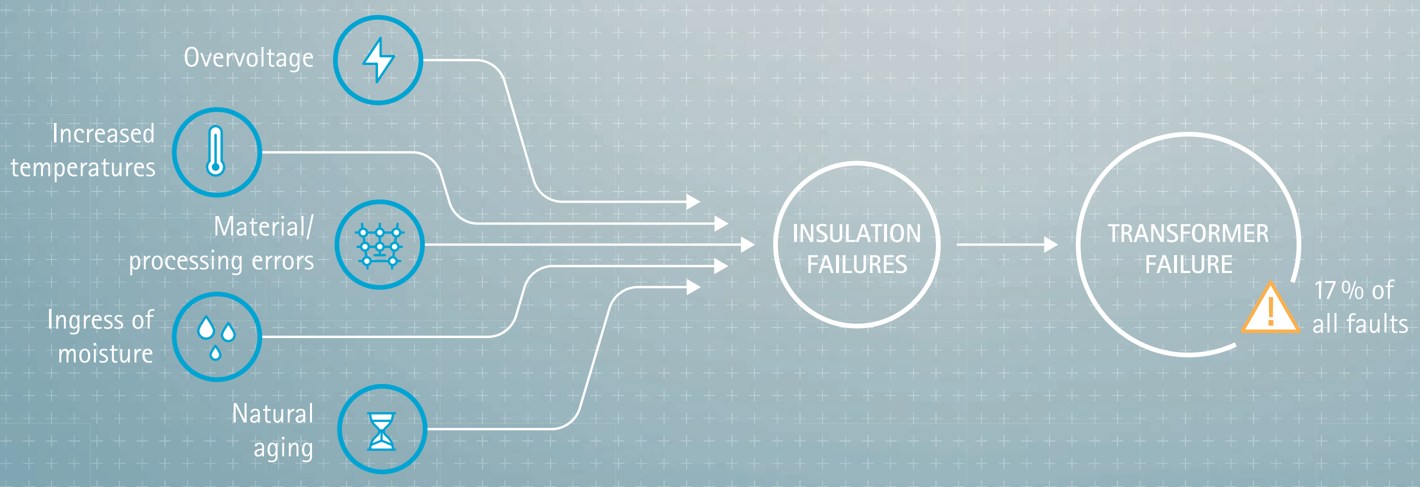
EARLY DETECTION OF ERRORS ON HIGH-VOLTAGE BUSHINGS

Availability and reliability requirements for power transformers are becoming increasingly demanding, while at the same time, the installed transformers are getting older, which can lead to critical problems. A good 17% (Source: Cigré A2.37) of transformer failures can be traced back to a defect in the bushings, which is also the main cause of transformer fires. The typical manufacturer-specific service life of capacitance-controlled high-voltage bushings is between 25 and 30 years and is therefore generally shorter than the service life of the transformer. Online condition monitoring and evaluation of bushings is therefore recommended. MSENSE® BM from Maschinenfabrik Reinhausen (MR) allows you to detect faults in the bushings early on so that you can intervene before the transformer sustains major damage.

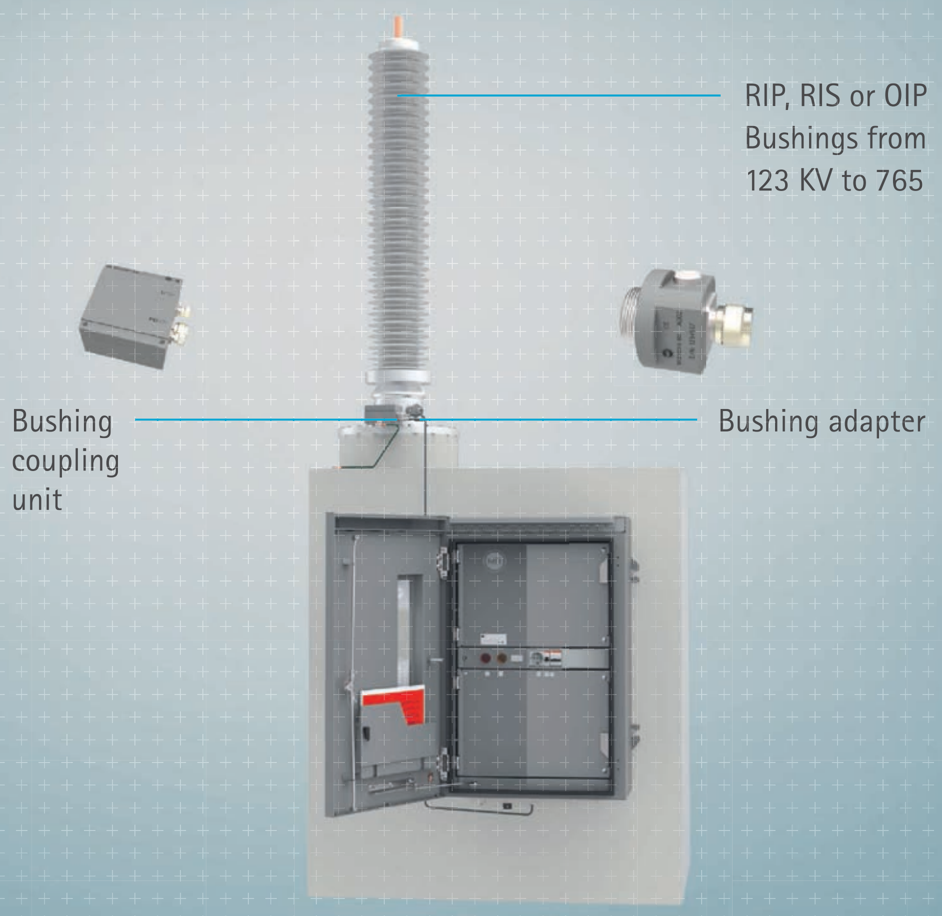
For electrical field grading, high-voltage bushings above a certain voltage level are almost exclusively equipped with capacitive grading layers. These are exposed to high electrical, thermal, and mechanical loads during operation. Bushings can age prematurely due to transient overvoltages, increased temperatures, temperature fluctuations, or the ingress of moisture. This can result, for example, in partial flashovers which can lead in a short period of time to failure of the insulation in the bushing or even to serious transformer failure.

MSENSE® BM ONLINE MONITORING SYSTEM CONTINUOUSLY MEASURES CONDITION-RELEVANT DIMENSIONS DIRECTLY ON OIL-IMPREGNATED (OIP) OR RESIN-IMPREGNATED (RIP) PAPER BUSHINGS IN THE VOLTAGE LEVELS UM = 123-765 KV. CONTINUOUS ONLINE CONDITION MONITORING ENABLES EARLY DETECTION OF CHANGES IN THE CONDITION OF THE INSULATION.

Photo: Maschinenfabrik Reinhausen (MR)



To optimally prevent this kind of damage, the MSENSE® BM online monitoring system continuously measures condition-relevant dimensions directly on oil-impregnated (OIP) or resin-impregnated (RIP) paper bushings in the voltage levels Um = 123–765 kV. Continuous online condition monitoring enables early detection of changes in the condition of the insulation.



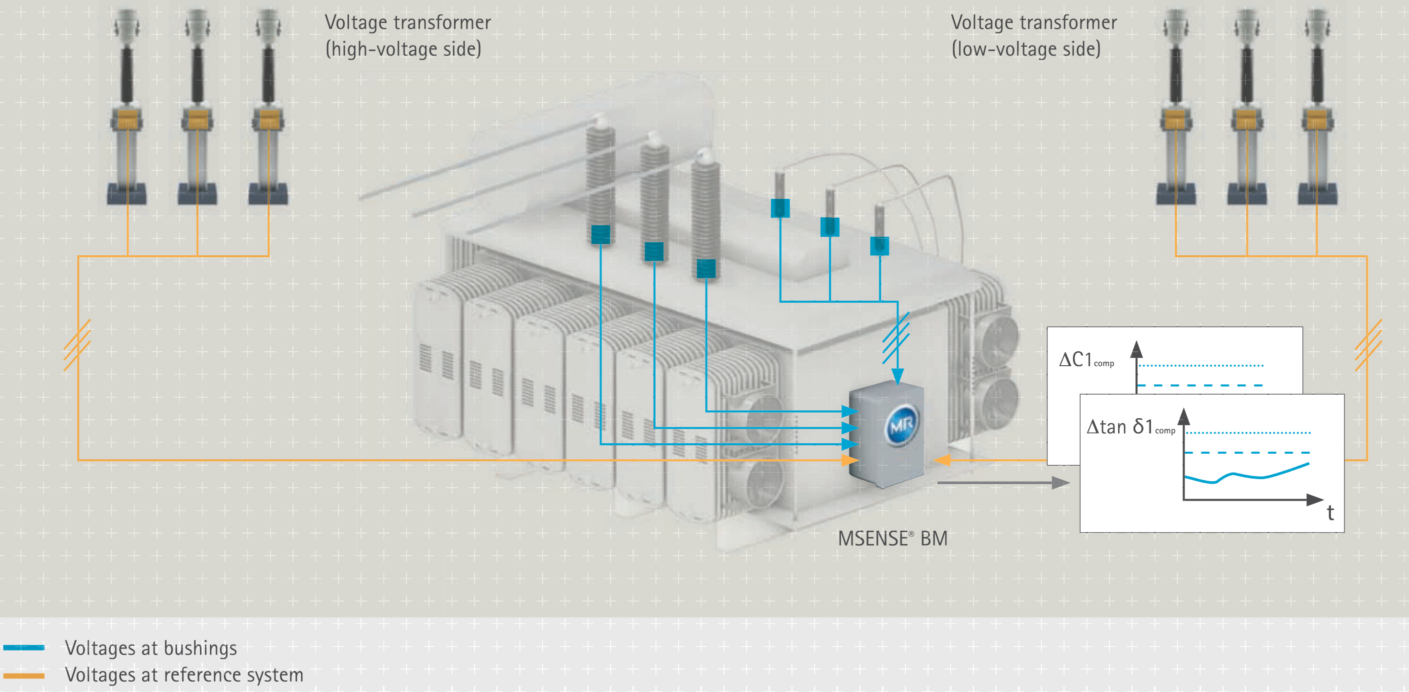
Several methods for online monitoring of the condition of bushings have been developed in recent years. Along with oil analyses and partial-discharge measurements, the main capacitance (C_1) and the dissipation factor (tan δ¬) are the two decisive dielectric parameters for determining the insulation condition of high-voltage bushings. With online monitoring, it is important to consider two things in particular. Firstly, a suitable reference system that functions under field conditions is needed. Secondly, the dielectric parameters of the bushings are heavily dependent on the operating conditions, e.g. temperature, which makes it difficult and complex to monitor an individual bushing online using specific temperature reference curves.

MSENSE® BM uses an innovative, field-tested 2/3 reference method that monitors the condition of the inner capacitance layers of the bushing field grading in terms of a change in capacitance (C_1) and dissi-pation factor (tan δ). The key aspect of this process is that because the algorithm continuously incorporates all three bushings in the mutual monitoring, the temperature dependence of other processes is eliminated due to the globally patented 2/3 reference method. Furthermore, the signals from the re-spective voltage transformers are used as a reference for detecting the symmetry of the three-phase current system. The measurement is checked for validity, and grid asymmetries are effectively equalized and eliminated. The 2/3 reference method ensures that the influence of temperature and voltage fluctuations on the bushing monitoring system are effectively limited.

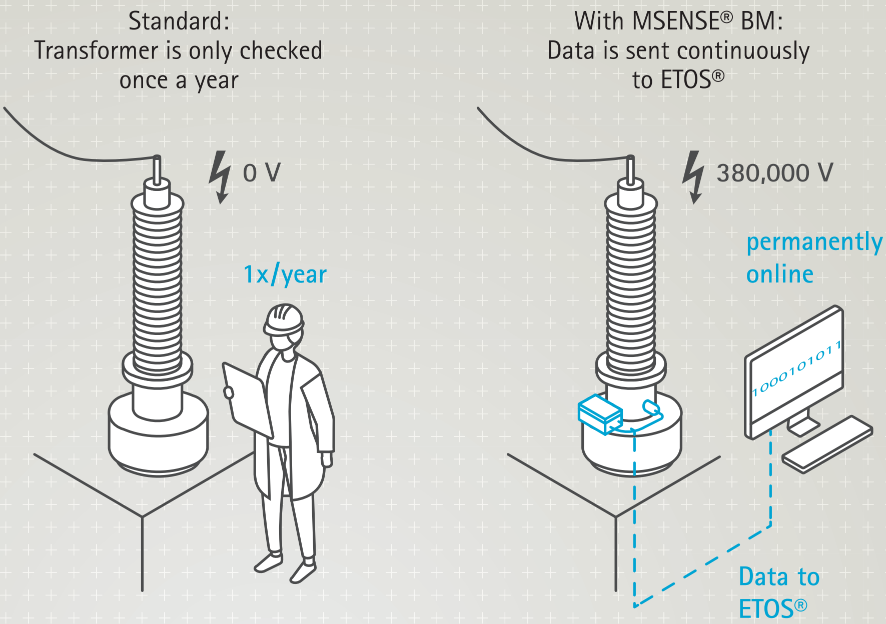
Changes in the capacitance and the dissipation factor of the bushings are compared with limit values. Only the measurement of system-side voltage transformers is required to determine the symmetry of the line voltage. Thus, a reliable and clear evaluation of the condition of the high-voltage bushings can be ensured – regardless of grid asymmetries or voltage fluctuations. If the bushing values of one phase (C_1 or tan δ¬) deviate from the specifications, the user is alerted via a two-stage limit-value process. This means that faults in the insulation system can be effectively detected and the user can intervene in good time, before a fatal failure occurs.

MSENSE® BM USES AN INNOVATIVE, FIELD-TESTED 2/3 REFERENCE METHOD THAT MONITORS THE CONDITION OF THE INNER CAPACITANCE LAYERS OF THE BUSHING FIELD GRADING IN TERMS OF A CHANGE IN CAPACITANCE (C_1) AND DISSIPATION FACTOR (TAN Δ).

MONITORING OF THREE HIGH-VOLTAGE AND THREE LOW-VOLTAGE BUSHINGS WITH REFERENCE SYSTEM



CONTINUOUS MONITORING OF HIGH-VOLTAGE BUSHINGS WITH MSENSE® BM



MSENSE® BM essentially consists of three bushing coupling units (one for each bushing), three bushing adapters (one for each bushing) and the evaluation unit. The bushing adapter accesses the measured voltage at the test tap of the bushings. The bushing coupling unit with suitable capacity is responsible for adapting the measured voltage and sends the values to the ETOS®.

All elements have an IP66 degree of protection. Communication takes place in all common control system standards (e.g. IEC 61850). The modern graphical display and intuitive user interface support the user and make the system easy to use.

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Bushing Failure Prevention Through Online Monitoring

by **Marco Tozzi**

The role of online monitors is not to eliminate standard Capacitance/Power Factor test or to provide identical results as offline tests. The real benefit of online monitors is their ability to detect anomalies under real operating conditions that otherwise would not be detected, and then follow it up with the best suitable offline test for investigation.

Dr. **Marco Tozzi** is Sr. Product Manager for CAMLIN POWER, responsible for product portfolio and an expert in diagnostic methods for high-voltage asset monitoring. After receiving his Ph.D. degree in electrical engineering in 2010 on methods for analysing partial discharges in medium-voltage asset, he worked as Project Manager and Technical Advisor in Techimp Srl, Italy, where he was involved in research on diagnostics of insulating systems through partial discharges analysis. In 2012 he joined Camlin based in Northern Ireland, where he was initially involved in developing partial discharge permanent monitoring systems for transformers and rotating machines. He is author or co-author of more than 40 technical and scientific papers, co-owner of patents on partial discharge denoising technique and UHF detectors, and an active IEEE Transformer Committee member.

Photo: Shutterstock

Introduction

According to statistics published in IEEE, IEC and CIGRE, bushings contribute to roughly 15-30% of transformer failures worldwide. In more than 40% of cases the failure is of violent nature followed by catastrophic consequences, such as fire, tank rupture and explosions. In particular, 30% of generator step-up transformer failures are caused by a bushing malfunction and more generally, bushings are the third single cause of transformer failures after winding and OLTC [1].

While DGA can help in assessing the condition of the main tank, it fails to provide any valuable information about the bushing health. Therefore, dedicated monitoring systems must be applied. These systems are connected to the test or voltage tap to measure and analyse the current flowing in the main capacitance C_1, which varies in amplitude and phase angle depending on the issues found in the bushings.

It must be understood that the role of online monitors is not to eliminate completely standard Capacitance/Power Factor (C_1/PF) test, nor to provide the same identical results. The real benefit of online monitors is their ability to detect anomalies under real operating conditions that otherwise could not be detected, and then trigger the best suitable offline test for investigation.

Some typical questions that are raised are, "Would you expect the offline measurement to be identical to the results of the online monitor?" The answer is: Potentially yes, but it depends on what the defect is, which offline measurement and in which testing condition, since there is not a single test or a single failure mode. Figure 1 shows a bushing which is in a critical condition due to the detachment of the conductive strip that connects the first foil layer [2]. The bushing was showing perfect Capacitance and Power Factor values in the offline test and it would have been returned to service based solely on these results. However, DGA showed >3000 ppm of C_2H_2 clearly indicating that the bushing needed immediate replacement.

Thus, it is not only about C_1/PF.

Figure 1. Discharge within bushing not detected by standard offline C_1/PF test [2].

Figure 2. Bushing adaptor connected to voltage tap

Indeed, selecting the proper offline test and combining the results with the online data will provide a more complete picture of the failure mode. Knowing not only that there is a problem but also what the problem is, can help the asset manager to prevent failures in similar bushings (from the same OEM, or of the same age or voltage, etc.) earlier by recognizing the failure mode whenever similar conditions are detected, and ultimately, to make better choices in the future when specifying a new bushing.

Successful cases have already been published, showing the ability of online monitors to detect early stage of degradation due to sudden capacitance changes [3] or internal contamination from metallic particles [4]. In this article, we will focus on a case study highlighting moisture contamination, where not only the bushing was saved but where the online monitor reacted to the real operating condition and provided a more accurate diagnosis than standard offline tests.

For the sake of clarity, the terms Power Factor (PF), Tandelta, Tangent-delta and Dissipation Factor are used interchangeably in this paper.

Bushings and Diagnostic Procedures Basics

Transformer bushings are made of a central conductor wound with insulating paper and conductive layers. The succession of insulation and conductive foils forms a cylindric condenser which controls the electrical field along the length and radius. The conductive layers are typically made of aluminium foils but, in some cases, they might be manufactured with conductive paint, printed semi-conductive ink or semi-conductive paper. There should be no air or bubbles present between the layers, so the paper/foil system is first dried and then impregnated with either oil (Oil Impregnated Paper – OIP type) or resin (Resin Impregnated Paper – RIP type). From the electrical point of view, regardless of the type, the bushing appears as a capacitor made of a number of capacitances in series, one in each layer, with the total equivalent capacitance C_1 in the range of hundreds of pico-Farad.

Causes of bushing failures are related to the loss of bushing properties, i.e. an inability for a bushing to act as an "ideal" insulating medium between the high voltage and the ground. This can happen for multiple reasons, such as:

- Ingress of moisture – increases the losses and causes the capacitor to become conductive
- Ingress of solid contaminants – increases the losses and causes the capacitor to become conductive
- Oil leakage (OIP type) – leads to electrical discharges
- Electrical short circuit between the layers – increases capacitance and creates a conductive channel
- Presence of voids, cracks and delamination between layers – causes Partial Discharges and insulation erosion, ultimately creating conductive channel and short circuit of the layers
- Surface cracks on the porcelain

Visual inspection and Thermal/IR scan are typically conducted on a monthly and annual basis, respectively, while traditional electrical tests are performed according to the time-based schedule, typically in four-to-eight-year intervals, including:

- Offline capacitance measurement
- Offline PF measurement

Additional tests are done exceptionally, not as a routine:

- Dissolved Gas Analysis, including moisture
- Oil quality
- Dielectric Spectroscopy
- Partial Discharges
- Tandelta tip up
- Tandelta at different temperatures

In terms of actions, there are no standards defining what action needs to be taken depending on the results of the tests. However, there are a few rules that utilities commonly follow:

- Bushing is replaced when the measured PF is more than twice the nameplate value
- Bushing is replaced when there is acetylene in the bushing oil
- Bushing is replaced when the measured Capacitance is X% higher than nameplate value, where X depends on the number of layers. Since the number of layers is not known and different tables are provided by bushing OEMs, a general rule of thumb is to take an action whenever X=10 regardless of the bushing voltage, while further investigation (and contact with OEM) is recommended when X is between 1 and 5 for bushings >100 kV, and between 5 and 10 for bushings <100 kV.

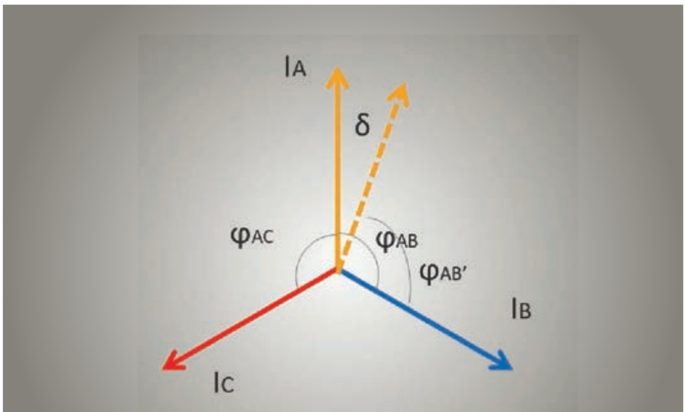


Figure 3. Bushing A failing due to increased losses – Angles AB and AC change to the same degree (one increases, the other decreases) with respect to the footprint.

Photo: Camlin Power

Online Bushing Monitor Principle

Bushings can be monitored by installing an adaptor at the bushing test/voltage tap, where an impedance is connected between the pin and the ground (typically a resistor or a capacitor, depending on the vendors), thus in parallel to Bushing C_2 and in series to Bushing C_1. The voltage/test tap pin must always be grounded, either directly or through the impedance to prevent it from floating, at free potential. For this reason, additional protection must be included inside the body of the adaptor (not just in the monitoring system at ground level).

The cases described in [2], [4] and in this paper were captured with a monitoring system that uses the so-called Relative Method. This method is based on the analysis of the amplitude and angle of the current that flows in the bushing C_1 and through the impedance at the test tap and its comparison with bushings in the same transformer or in other transformer connected to same busbars.

The principle is that whenever the bushing properties are changing, due to an internal short circuit or increased losses, the current of that specific bushing (and, thus, the voltage at the test tap) will increase accordingly, while the current of the other bushings will not. At the same time, the angle between the current of the failing bushing and the current of the other two bushings in the same winding (ideally 120 degrees) will change. The proportion between the change in the current amplitude and the change in the angles depends on both the failure mode and the degradation stage.

So, the relative method implies applying averages to reduce the day-to-day fluctuations due to grid imbalances and calculating a footprint after a learning period (after an hour, a day, a week or a month). The new readings are then compared to the footprint in order to determine relative variations.

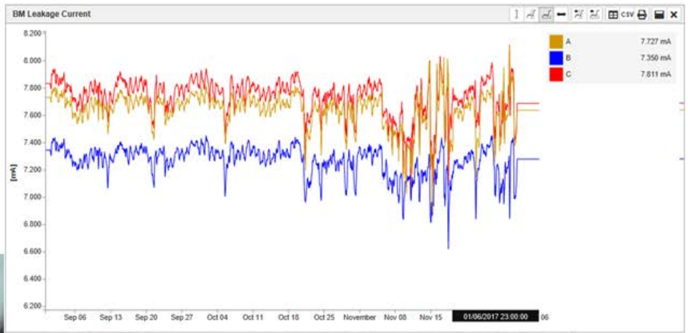
The challenge of the relative method is mainly on the PF side and lies in understanding whether the increase of the phase angle is caused by a failure or by normal fluctuations in the grid. Indeed, the angles between the bushings can normally swing between +/-0.5 degrees, whereas if there is a problem in the bushing, the angle variation could be only 0.1-0.2 degrees, and potentially masked by normal fluctuations. For this reason, bushings in the same winding and bushings in the same phase (in Y-Y or Δ-Δ connection) are used as a reference under the hypothesis that three bushings of the same winding cannot fail together simultaneously.

Despite the challenges, the relative method presents significant advantages in comparison to the other available method, known as Referenced Method or, misleadingly, Absolute Method. This method consists of collecting the reference directly from the Voltage (VT) or Potential Transformer (PT), in the following manner:

- Relative method allows the bushing monitoring to be applied in every situation (provided test/voltage taps are available), while the referenced method requires the accessibility to the voltage transformer, which is not always possible.
- Relative method has significantly lower cost, considering that the reference method requires additional hardware, very long cables to connect to VTs and higher cost of installation (nine bushings would require connection, one per phase, in three separate VTs), all contributing to a higher cost of the solution.

In terms of performance, the relative method is comparable with the reference method with respect to the detection of capacitance changes [2] (the % change in the current due to a short circuit is higher than typical voltage fluctuation) or significant PF changes, while it can be slower in detecting small PF changes due to the effect of averaging. However, it must be stressed that the PF changes are typically caused by slowly developing failures since the contamination process can last for weeks or even months.

There is a general misconception that online monitors should report data that perfectly align with the results of a standard Capacitance/Power Factor offline test.



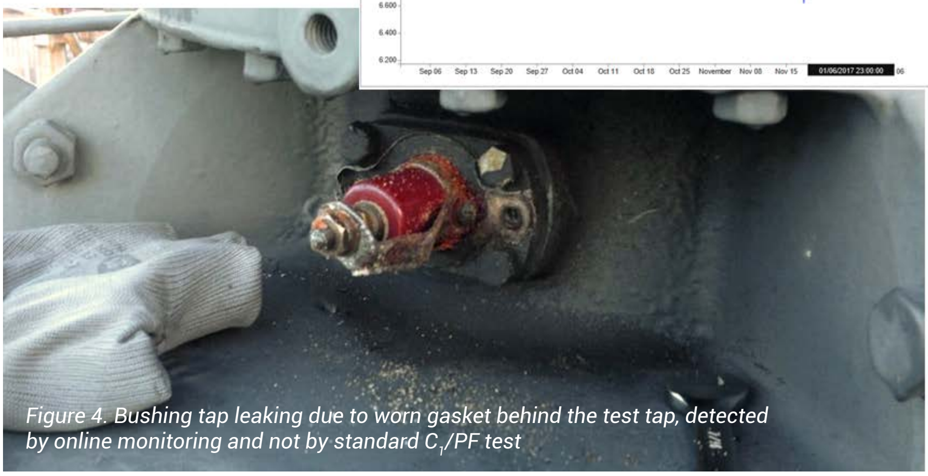


Figure 4. Bushing tap leaking due to worn gasket behind the test tap, detected by online monitoring and not by standard C_1/PF test

Data Interpretation: Building Trust

The relative method shows a very positive cost-benefit balance. It is, however, important that the results that the system provides are well understood to build the required confidence in managing the information and alarms. In particular, there are three important things to understand:

1. The online monitor does not measure C_1/PF quantities, nor does it replace the C_1/PF test typically done offline. The measured parameters are different, and the measuring conditions are different.
2. What the online monitor measures and monitors is the bushing current (sometimes called leakage current) at the test tap, under the assumption that the majority of the issues in the bushing will reflect in a change of the current in either amplitude or phase angle.
3. Not only are there two failure modes (capacitance increase and PF increase), there is also more than one way to assess the bushing offline.

These three principles are extremely important to understand before applying an online monitoring program. Indeed, there is a general misconception that online monitors should report data that perfectly align with the results of a standard C_1/PF offline test. However, an increase in the monitored current does not necessarily mean that there is a capacitance change, just as a change in the current angle does not mean there is a definite moisture ingress. There is actually a significant variety of possible failure modes and defects that could lead to a change in the monitored current, not just short circuits and moisture ingress. Failures can happen in each of the bushing components, with a multitude of failure modes depending on the nature of the contaminant, the location of the defect, the amount of insulation involved and the root cause (thermo, electric, mechanical stress, ageing, constructive defect, etc.). Furthermore, some defects could lead to a temporary change in bushing properties during real operating conditions as a result of temporary changes in the load, temperature, pressure or humidity, and it could be difficult to spot the defective condition during the standard C_1/PF offline test, which is typically carried out at just one temperature (ambient) and one voltage.

To illustrate, Figure 4 shows a test tap leaking oil: This was found in six bushings and in three of them it was captured through online monitoring. The symptom was a continuously dropping leakage current. The system gave an alarm of low current and this triggered an inspection where the problem was identified. Again, the standard test here would not have highlighted any issue since both PF and capacitance measured offline were matching the nameplate values.

CASE STUDY: OIP bushing replacement after PF increase due to moisture ingress

Online Data

A bushing and partial discharge monitoring system was installed in 2015 on a three-phase transformer in North America. The monitor was applied only to LV bushings due to a higher failure rate experienced in recent years and as part of a replacement plan of LV bushings, in particular the U-Type.

The installed device was continuously monitoring the bushing currents and partial discharges from both the main tank and bushings using properly designed tap adaptors installed at the test taps. The acquisition was continuous *(not scheduled)*, simultaneous in all phases and results were summarized every hour. The bushings, as shown in Figure 5, were from McGraw Edison 1988, OIP, 34.5 kV, around 590 pF of Capacitance.

Figure 6 shows the unprocessed data of the leakage current amplitude (top chart) and angles between bushings A and B (bottom chart, black line) and between bushings A and C (bottom chart, red line). It is easy to note that for several months the readings were very stable. After May, the angle between the bushings A and B started to increase while the angle between bushings A and C remained constant, thus suggesting that the change was related to some issue in bushing B. Looking at the readings of the current we notice that the leakage current of the bushing B also started to increase slightly after June, confirming something happening in bushing B.

Figure 7 shows the processed data using the algorithms embedded in the online monitoring system aimed at converting the current and angle readings in relative changes of Capacitance and Power Factor. It was estimated that the change occurred only in bushing B, showing a relative increment of around 5.5% from the footprint, which means that if the nameplate value is 0.53%, the actual tan delta is estimated to be higher than 6%.

Offline Investigation

The utility switched off the transformer to perform an offline test and the PF was found to be about four times higher than the nameplate, with a measured value of 1.99% while the nameplate is 0.53%, clearly justifying a decision for a bushing replacement.

Figure 5. Bushing adaptor connected at the 34.5 kV OIP bushings

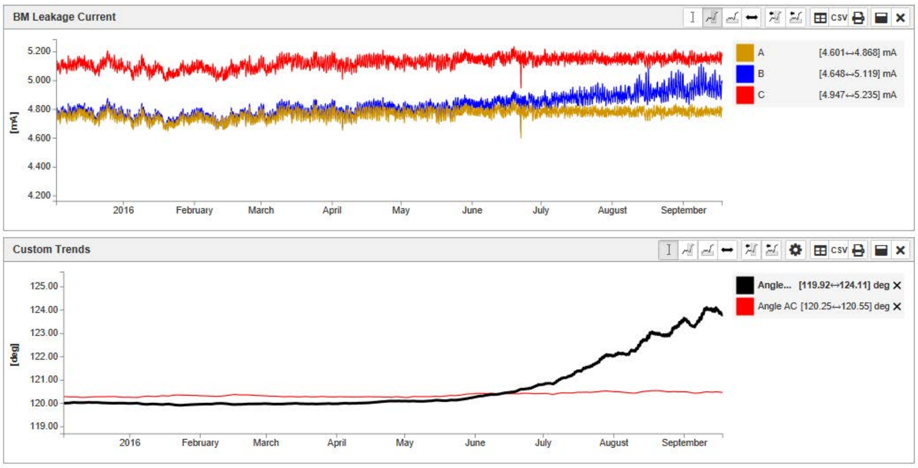


Figure 6. Test tap current magnitude (top) and angles recorded and summarized every hour (bottom). AB angle increased by about 4 degrees in 6 months.

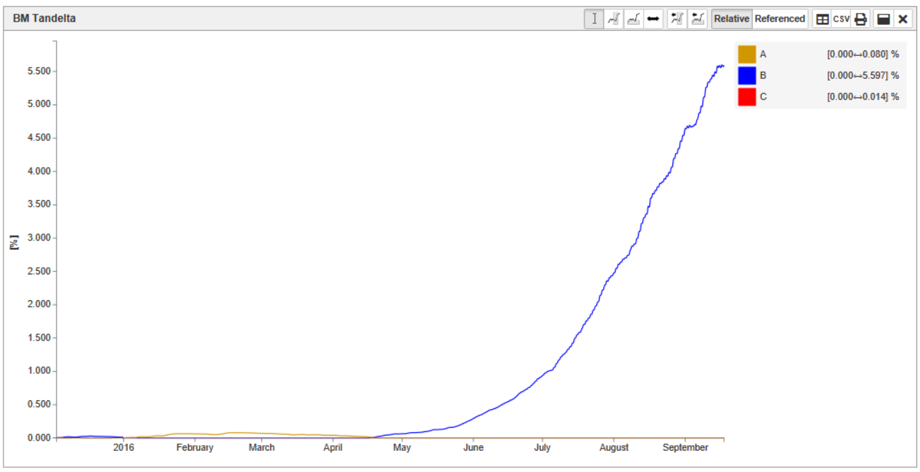


Figure 7. Relative PF increase displayed on the monitor.

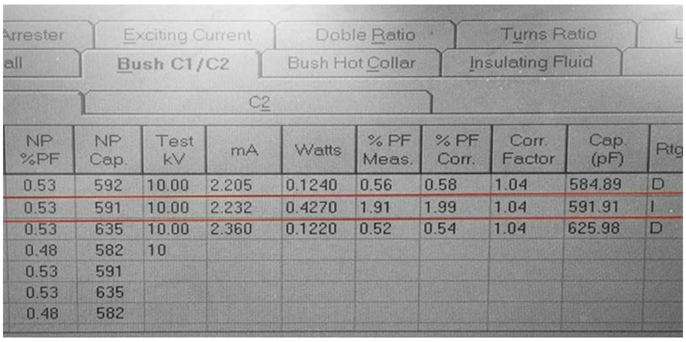
Photo: Camlin Power

However, although the offline measurement confirmed the presence of an anomaly as triggered by the online system, it is interesting to note that the measured value is three times lower than the one indicated by the online monitor.
In order to further investigate this difference, the bushing was removed and sent to a third-party laboratory to perform additional tests:

- Partial Discharges
- Dissolved Gas Analysis
- IR Scan
- Moisture Analysis, and
- PF vs. Temperature

The partial discharge test, DGA and IR scan did not show any critical values. However, the other two tests showed very interesting results. The bushing was tested at ambient temperature (15°C) measuring 1.8% for PF, which was very similar to the values measured offline by the utility.

Then the bushing was immersed in oil and the oil was heated up to 60°C for two hours. After 1.5 hours the bushing was tested again showing PF equal to about 9%, i.e. almost 20 times the nameplate value. After reaching the maximum temperature the bushing was left to cool down and PF was measured again at different temperatures. The final profile of the PF with temperature is shown in Figure 9, where both oil and bushing temperatures are reported. The exponential rise with temperature confirmed the critical stage of the insulation and, most importantly, the values measured at 30-40°C range were perfectly aligned with the variation measured by the online monitoring system in real conditions. Indeed, after May the ambient temperature started to rise, well exceeding 30°C, and thus causing the bushing PF to increase up to 6 -7%. The test demonstrated that the difference between the online and offline results were not caused by deficiencies in the monitoring system.



NP %PF	NP Cap.	Test kV	mA	Watts	% PF Meas.	% PF Corr.	Corr. Factor	Cap. (pF)	Rtg
0.53	592	10.00	2.205	0.1240	0.56	0.58	1.04	584.89	D
0.53	591	10.00	2.232	0.4270	1.91	1.99	1.04	591.91	I
0.53	635	10.00	2.360	0.1220	0.52	0.54	1.04	625.98	D
0.48	582	10							
0.53	591								
0.53	635								
0.48	582								

Figure 8. Offline test result showing bushing B having high PF

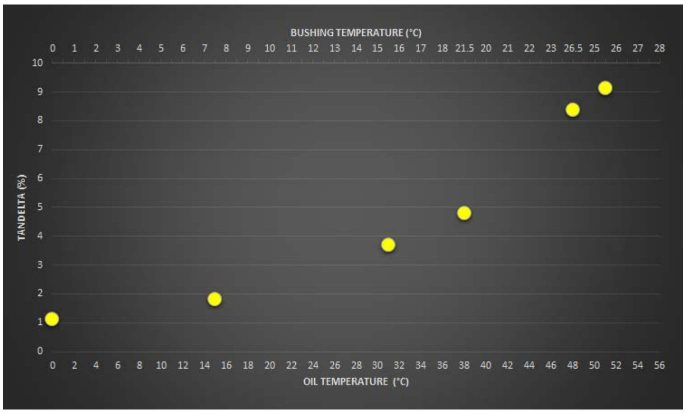


Figure 9. Offline PF test results at different ambient and oil temperatures showing that at normal operating oil temperatures (30-40°C) the PF readings match the online results.

Quite the opposite, the PF reading at the real operating temperatures were correctly estimated and reported, while the offline test was done in a different condition and with lower oil temperature.

Failure Mode Investigation

Whenever bushing PF exponentially increases with temperature, this might indicate high conductive losses due to the presence of moisture [5]. As an example, it has been published that the power factor can increase from 0.3% at 20°C to 1.0% at 70°C with 2% water content [6]. By looking at the curves published in [7] and [8] and comparing it to the lab measurement of the busing under investigation, it is possible to speculate that the bushing had an excess of moisture above 4% (Figure 10).

A similar conclusion can be drawn from the oil result. An oil sample from the bushing was analysed at different temperatures, showing 12 ppm at 15°C and 19 ppm at 2°C. Putting the recorded value in the moisture equilibrium plot from Oommen [9] it is clear that again the moisture is well above 4% (Figure 11). In particular, the sample at 2°C would fall outside the chart suggesting more than 10% of moisture.

Conclusions

Application of online bushing monitoring can prevent catastrophic failures which are responsible for up to 30% of transformer failures.

Cases have already been published [3,4] showing the online monitoring system was able to detect fast capacitance changes or power factor increases plus partial discharges due to metallic particles contamination. The case described in this paper shows the online monitoring system is capable of detecting a failure due to moisture ingress, which increased the bushing power factor up to 10 times the nameplate value.

Not only that, this case demonstrates the need to build trust in online monitoring systems since they can detect anomalies in real time under real operating conditions. Such anomalies do not necessarily lead to a permanent power factor or capacitance change, and in many cases, could not be detected using the standard approach of testing offline C_1/PF at just one temperature and one voltage.

Relative changes of the monitored current, whether in amplitude or angle, should trigger alarms aimed at reviewing the data and then selecting the most appropriate offline test and method among a variety of possibilities, including DGA, DFR, Tandelta Tip Up, etc. Thus, online monitors do not eliminate or replace offline tests. As a matter of fact, by combining online and offline results it is possible to better understand the failure mode and provide clear prescriptive actions for the most effective decision-making process.

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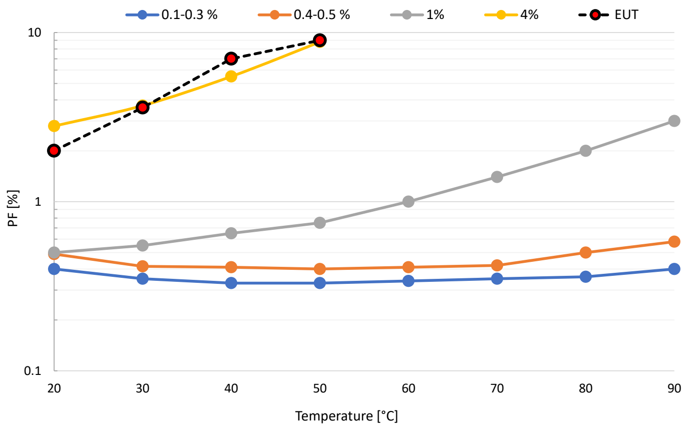


Figure 10. Bushing PF versus temperature. Redrawing of [8] comparing the results of the Equipment Under Test (EUT)

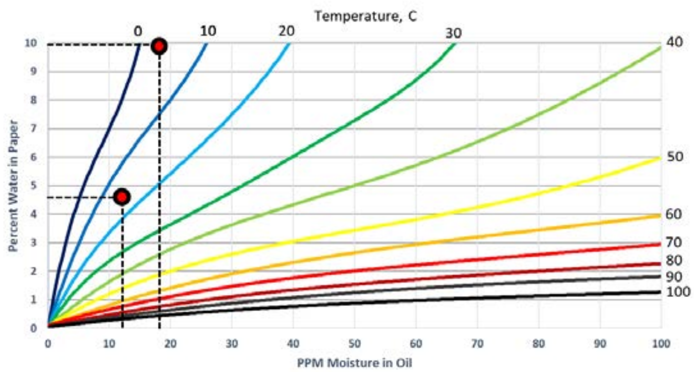
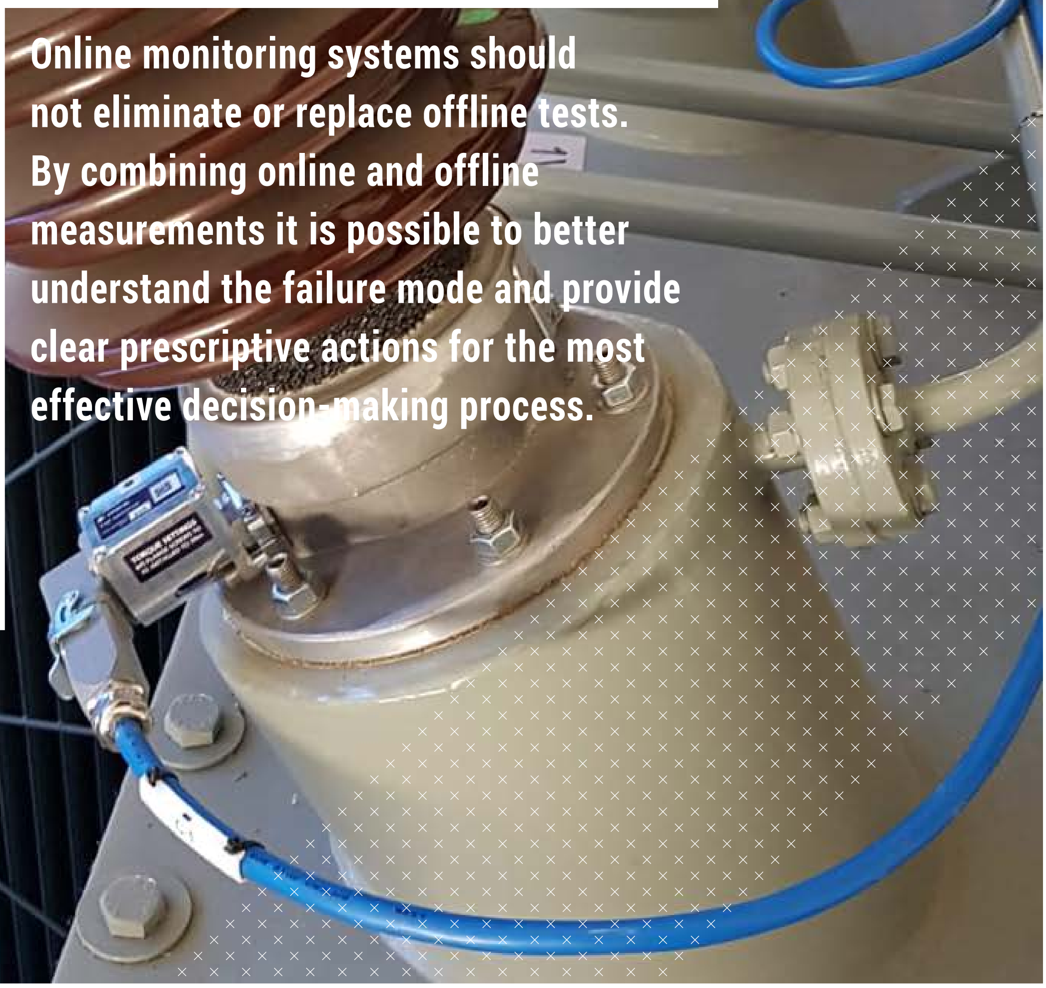


Figure 11. Moisture equilibrium isotherms (redrawing from Oommen curves [9]) showing that estimated water for the tested bushing exceeds 4%



Online monitoring systems should not eliminate or replace offline tests. By combining online and offline measurements it is possible to better understand the failure mode and provide clear prescriptive actions for the most effective decision-making process.

Photo: Camlin Power

Transformer Bushings:

Breakdown Mechanism and the Appropriate Life-cycle Maintenance Implementation

Corné Dames is the Managing Director of Independent Transformer Consultants, always striving to keep on top of new developments and research. She has expertise as Laboratory Manager in the analysis of transformer oils and as diagnostician identifying problem areas in transformers, as well as profiling of transformers according to available results thus empowering the customer to take preventative steps in maintenance. Corné has vast practical and theoretical knowledge on reliability maintenance programs. Coming from a strong chemical background she has insight in all the chemical processes that is part of the transformer system coupled with technical insight helps customers optimize their reliability maintenance and electrical asset lifetime.

Bushings cause 17% of all power transformer failures and are the third most common reason for transformer breakdowns.

Introduction

According to studies, bushings cause 17% of all power transformer failures and are the third most common reason for transformer breakdowns. High-voltage bushings contribute 30% to all fires and explosions associated with power transformer breakdowns. Effective diagnostic tools are therefore of the utmost importance and should be an integral part of the life-cycle oriented preventative maintenance strategy.

In this article, we will discuss the Dielectric Frequency Response (DFR) measurements as a supporting diagnostic tool for bushing condition assessment. The DFR method has proven to be very valuable to diagnose the bushing condition, plus has identified potential insulation system damage before a breakdown in various cases.

It is important to gain insight and understanding of the process of aging and the condition of the bushing.

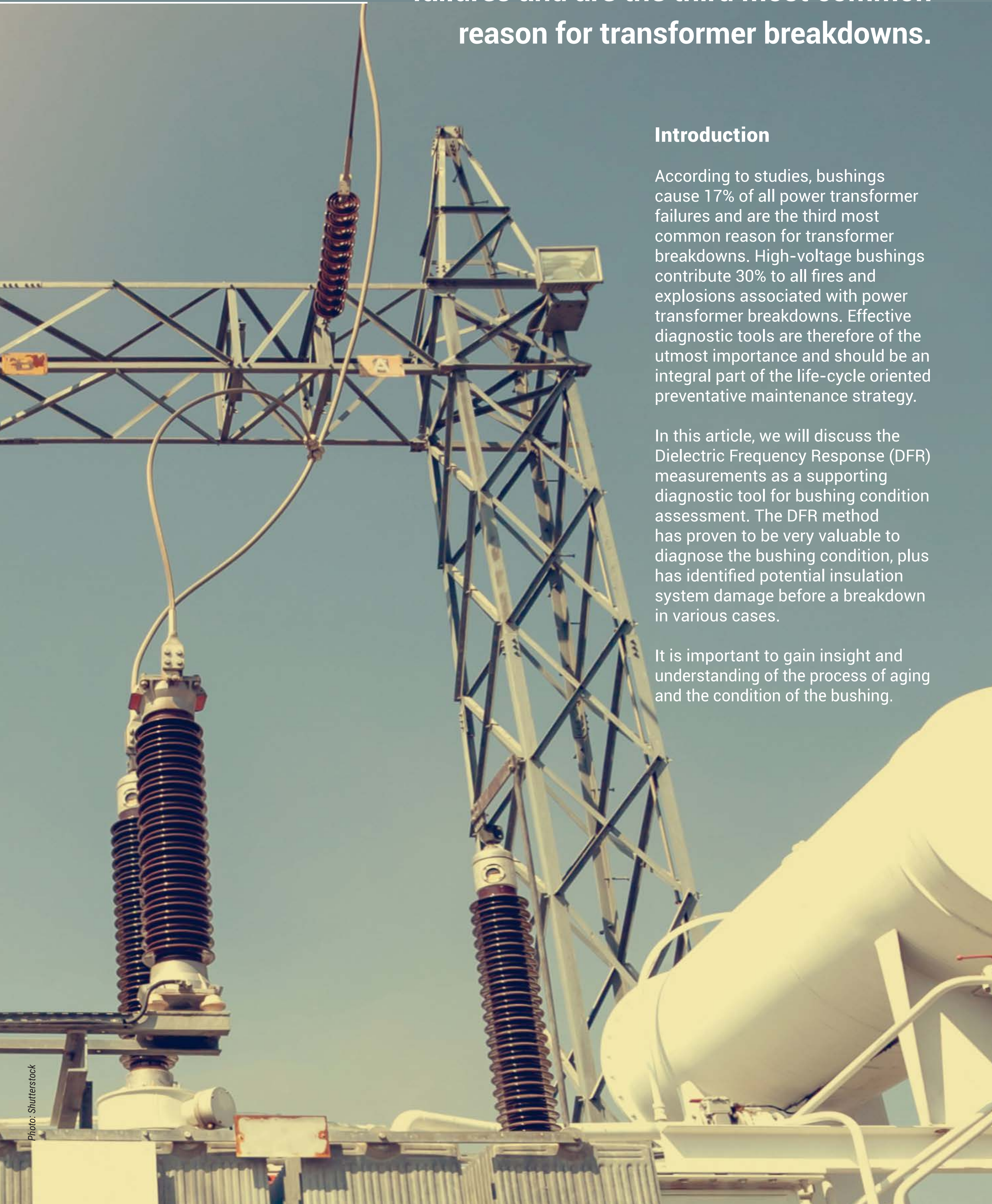


Photo: Shutterstock

Life-cycle Orientated Diagnostics and Monitoring

Available Bushing Technologies

Four main categories were developed over the years for condenser bushings.

One of the first technologies was **Resin Bonded Paper (RBP)** used for more than 100 years. The production process causes partial discharge to occur in the bushings and therefore shows high DDF values. This technology has been mostly phased out due to technical reasons.

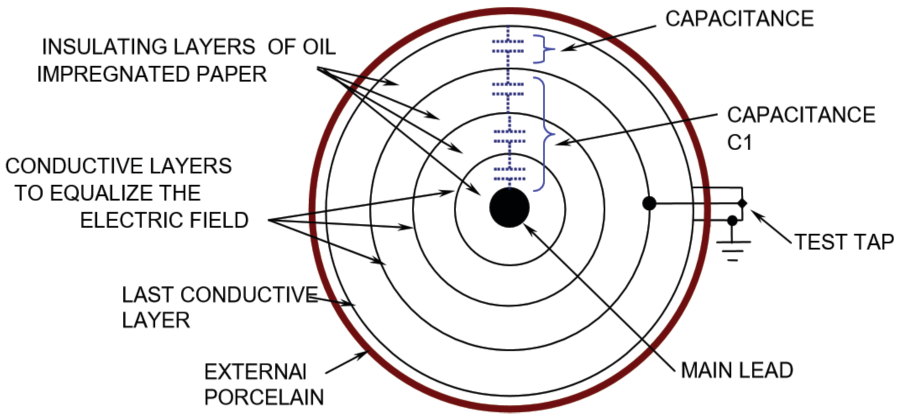
Second is **Oil Impregnated Paper (OIP)** technology, which is still used in about 60% of the market today. The condenser core is impregnated with transformer grade mineral oil and placed inside an insulating envelope built up from porcelain or composite material to seal the bushing against moisture ingress. These bushings can be manufactured at high quality with low capacitance losses and they can be free from partial discharges. The condenser core that is in a liquid environment may cause some leakage problems around the gaskets when the design is not properly done. If an internal electrical breakdown takes place (which is very rare) a high internal pressure can build up which can result in explosions of the bushings. Resulting from the explosion an arc usually originates, and this can result in a fire.

The **Resin Impregnated Paper (RIP)** technology is state of the art and consist of a wound core made of untreated crepe paper, which is then impregnated with a curable epoxy resin. For outdoor use, either porcelain or composite insulators are used. These bushings provide significant technical advantages such as being fully dry and pressure-free, feature a high-temperature class, normally stable and low partial discharge levels, low dielectric losses, fire-resistant, and outstanding mechanical properties. They tend to show higher procurement cost levels compared to OIP. They have lower life-cycle costs with reduced maintenance and monitoring efforts over the expected lifetime. These bushings are prone to moisture ingress into the paper layers of the insulation material if not stored or handled in the appropriate manner. This result in an increased loss factor which can cause a bushing to become unsuitable for operation.

Resin Impregnated Synthetics (RIS) technology where the hygroscopic paper has been replaced with non-hygroscopic synthetic materials. They are characterized by very low dielectric loss factor (tan delta), lowest possible partial discharge levels due to both the void free impregnation process and the electrical design. These bushings are almost immune to moisture ingress and therefore does not require special precautionary measures while being stored. These are expected to have the lowest lifecycle cost of all the bushings.

Close to 50% of serious transformer fires are initiated by Oil Impregnated Paper bushings and they are the most common cause of transformer fires.

Figure 1. Constructive details of a condenser bushing



The typical life expectation of any bushing type can be reduced by the following factors: excessive stress, voltage oscillations imposed by lightning strikes, frequent shunt reactor switching, and continuous high levels of harmonics.

One of the key factors in the successful management of bushings is to firstly avoid, but also detect PD activities to avoid breakdown.

Figure 2.
Bushings cause 17% of all power transformer failures and are the third most common reason for breakdowns [1].

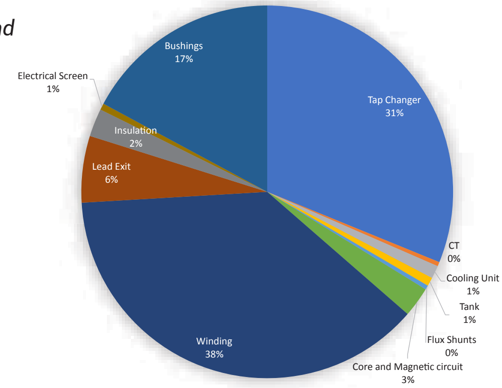
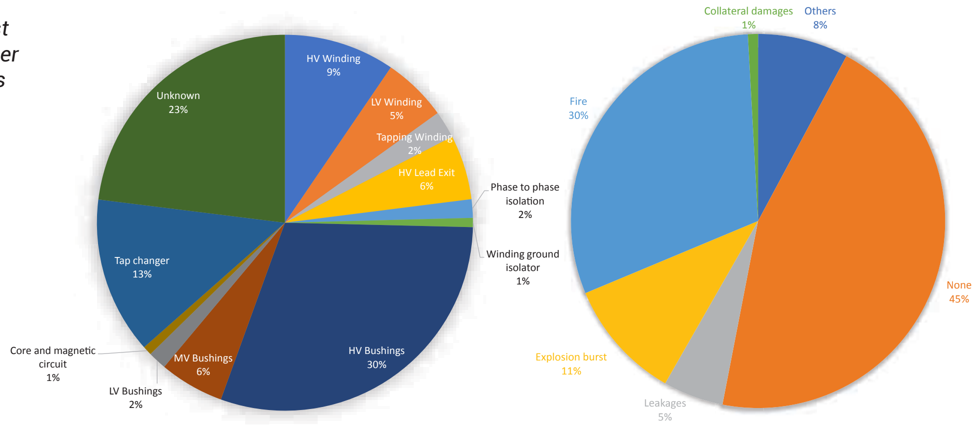


Figure 3.
Bushing failures are the most common cause of transformer fires and explosions: Failures with fire and explosion (left); Bushing failures (right) [1].



Bushings as the Main Contributors to Transformer Failures

Close to 50% of serious transformer fires are initiated by oil impregnated paper bushings and they are the most common cause of transformer fires.

Breakdown Mechanism of Transformer Bushings

The typical life expectation of any bushing type can be reduced by the following factors: excessive stress, voltage oscillations imposed by lightning strikes, frequent shunt reactor switching, and continuous high levels of harmonics. This may trigger premature breakdown of the bushings.

The characteristics of a distribution system may change due to expansion or a greater harmonic load due to installation on new equipment. A bushing breakdown can occur even when a transformer is operated within its maximum specified limits. This happens if the deterioration of the bushing's internal insulation system was not detected in time to act. All bushings will lose their electrical stress withstand capability over time – some quicker, other slower.

Over time the failure risk will increase because the capability to withstand stress will decrease as the equipment ages.

Often, the deterioration process of the bushing will start with Partial Discharge (PD), which initiates 'treeing' – small cracks. The discharge channels resulting from the treeing will carbonize further and the PD activity will increase up to a point where the inner foils of the field grading condenser core are being short-circuited. This will result in an increase of the electrical field stress on the remaining inner foils of the condenser core, and an interval flashover will finally occur and destroy the bushing.

One of the key factors in the successful management of bushings is to firstly avoid, but also detect PD activities to avoid breakdown. PD activity usually originates from excessive mechanical or electrical stress as well as the thermal ageing of the insulation material. Low quality bushings may show PD activity from the start. Bushings displaying PD activity at normal operating voltages should be avoided as they greatly increase the risk of premature failure. It is vitally important to determine the reliability of the infrastructure on a regular basis, and especially before exposing it to increased electrical stress. One way to reduce electrical stress would be by installing appropriate surge arrestors or by improving the grounding system.

Identifying the true state of the bushings is of the utmost importance to ensure a reliable network.

The tan δ measurement is a very strong tool to diagnose the bushing condition with respect to moisture ingress and the insulation deterioration resulting from this.

Establishing Diagnostic Methods to Determine Status of the Bushing's Insulation System

a) Measurement of the Dielectric Dissipation Factor Tan δ

An increased dielectric dissipation factor (DDF) leads to higher dielectric losses within the bushings. The temperature of the bushing will increase with higher dielectric losses and this will then increase the Dielectric Dissipation Factor again – creating a continuous cycle of degradation. A bushing of good design in good condition will have a capped temperature rise and the temperature rise will stop at an acceptable value without causing damage.

Frequently, when a bushing is in a bad condition – often due to moisture ingress over time – the positive feedback mechanism may not be stable anymore and the temperature will increase beyond the thermal stability limit. Now the busing will experience dielectric breakdown within the condenser core. Higher rated voltage bushings are generally more prone to this phenomenon.

Typical causes for an increased DDF (tan δ) over time include:

- Moisture ingress due to leakage
- Moisture ingress originating from the transformer oil
- Moisture ingress due to improper storage
- Ageing of paper (OIP, RBP and RIP technology) [1]

The tan δ measurement is a very strong tool to diagnose the bushing condition with respect to moisture ingress and the insulation deterioration resulting from this.

The DDF measurement should be done at high temperatures, close to the maximum permitted temperature for that specific type of insulation material, to ensure thermal stability of the bushing under demanding operational conditions and to identify possible moisture ingress. The practical application of this is sometimes not possible after the bushing has been installed in a transformer, here the DFR – dielectric frequency test has demonstrated that this method can deliver similar useful results at ambient temperatures, provided the relevant material specific technical data and properties from the bushing OEM is available and correctly incorporated. This might not be as easy, as only a few bushing manufacturers have these data available.

The DDF (tan δ) should be measured over a broader voltage range from about 2 kV to 12 kV. If the loss factor is not constant with an increasing voltage, this will typically indicate problems in high voltage or ground foil conditions.

b) Capacitance C Measurement

If the capacitance value increases, this is usually an indication of the partial breakdown on the inside of the condenser core. Due to this the field stress inside the bushing will increase and will lead to eventual breakdown of the condenser core of the bushing. Causes for this inner breakdown include:

- Over voltages – lightning strikes, reactor switching operations, harmonics
- Continuous PD activity
- Contamination and bubbles remaining from the production process
- Deterioration of the insulating material

The DDF and the Capacitance C measurement are probably the most powerful diagnostic tools for assessing the condition of a bushing that has been installed on a transformer. The most important factors for optimized lifecycle-oriented condition assessment of Capacitance and tan δ can be summarized as follows:

- Direct after installation an initial 'fingerprint' measurement should be done at a defined and recorded temperature – if possible – at different frequencies (DFR measurements) to ensure meaningful future diagnostics.
- The measuring of C and tan δ are performed at relatively low measuring currents and voltages, therefore other sources of electromagnetic interference can significantly impact the measurement results and cannot be avoided in most cases. These interferences are caused by circulating currents in grounding systems and radio interference and other sources. Ensure to document the setup for the initial measurement very accurately and repeat the follow up measurements under the same circumstances, if possible, with the same test equipment to achieve comparable meaningful results.
- Ensure identical temperature as during initial measurement: the condenser core temperature can take up to 48 hours to stabilize, which needs to be considered when performing follow up testing. If this is not possible, an OEM for interpretation of results is recommended as they might have the model and tools necessary for the correction of temperature measurement.
- Because increased DDF and C_1/C_2 may indicate increased moisture content with high probability, the lack of increase cannot guarantee the condition of the bushing insulation material to be acceptable. Therefore, the use of the DFR test method is recommended.

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The DDF and the capacitance C measurement are probably the most powerful diagnostic tools for assessing the condition of a bushing that has been installed on a transformer.

c) Dissolved Gas Analysis (DGA)

This test can only be performed on OIP bushings. Some OIP bushings are equipped with an oil release valve, where a small oil sample can be taken. However, there is great concern about this method as the bushing might fail after taking an oil sample due to moisture ingress because the gasket was damaged and not replaced. The oil level will also decrease when taking oil samples. This can result in low oil levels in the bushing. Special limits and interpretation of results are applied to bushing DGA analysis [2].

d) Online Monitoring Systems for Bushings

This method is effective for use over short periods. It is not recommended for long term use because the sensor tap is incorporated directly into the bushing's structure and well into the condenser core that is otherwise hermetically sealed. This might lead to bushing failure due to the continued moisture ingress. Incorporating the online monitoring unit might cause the RIP/RIS bushings, which are usually very reliable, to prematurely fail due to the additional component added to the bushing which decreases the reliability and stability of the bushings.

If deciding on the online monitoring system, care should be taken during installation to ensure that the unit is sealed properly not allowing any moisture to penetrate and cause harm to the system.

o Bushing Sensors

The mechanical installation of an online bushing sensor replaces the cap's function of rounding the insulation layers as well as protecting the taps internal components from contaminants. At the same time, the sensor creates an excellent electrical connection that allows the measurement of voltage and/or current present at the tap. With these measurements, changes in capacitance and partial discharge can be determined and trended.

o Online Partial Discharge Measurement

Partial Discharge (PD) is a localized dielectric breakdown of a small portion of a solid electrical insulation system.

Since partial discharges are early indicators of incipient faults, their online observation is of prominent interest.

o Electromagnetic Measurements with UHF Sensors

The transformer tank functions as a shield against external partial discharge, thus internal partial discharges can be detected relatively undisturbed by the electromagnetic waves. The combination of signals in the UHF range with electrical signals from the bushing tap provides a high sensitivity together with suppression of external noise like corona. The UHF signal serves as a trigger or gating signal for the electrical signals. The individual PD patterns do not allow for a pattern classification. After their combination, where the UHF signals serve as gating signals, a PD pattern can be recognized. The UHF signals that correspond to the partial discharge are transmitted to a display or measuring device. Online monitoring algorithms are used to decode the signals. The monitoring algorithm tells the users when there is any damage in the bushings of the transformers by measuring and sensing the partial discharge.

o Online Capacitance Measurement

Partial breakdowns between field grading layers result in an increase of capacitance. This change in the capacitance can be measured by electrical sensors.

o Sensing Capacitance Change

An electric sensor can indicate the change in the capacitance. When the sensor senses a change in capacitance in the bushing setup, the voltage signal corresponding to the change in capacitance is given by the sensor. These voltage signals are then transmitted to a display or a measuring device. They are decoded and evaluated using various online monitoring algorithms. This will be shown to the users by the intelligent system and the problem can be easily cleared without any major damage. Thus, the damage in the transformer bushings is measured and sensed by the change in the capacitance using this algorithm.

Some utilities have already started to apply regular DFR testing on their bushings, but the lack of knowledge to interpret the deviations over time from the original test causes a void in the application value of this test.

Table 1.
Useful diagnostic methods for transformer bushings

	tan δ	Capacitance	DGA	Partial discharge	Visual inspection	Thermal survey	DFR (C & tan δ)
On site, transformer not energized	X	X	X (if appl.)	-	X	-	X
On site, transformer energized	(X)*	(X)*	-	(X)*	X	X	-
High voltage test lab	X	X	X (if appl.)	X	X	-	(X)

Only possible with appropriate on-line measurement equipment

e) Partial Discharges

Partial discharges will lead to the degradation of electrical insulation material. This phenomenon occurs when there are defects in the electrical insulation like voids, cracks, and delamination. PD measurements are very difficult to perform on bushings that are installed on transformers. Online PD measurements may pick up on bushing issues that show high PD activity, but still, this will increase the risk of premature failure [3].

f) Visual Inspection

When assessments on bushings are done, a visual inspection is suggested. Any oil leaks, low oil level, damage to insulator should be noted and the impact assessed.

g) Thermal Survey

A handheld infrared scanner can be used to perform a unit baseload temperature measurement. This can be useful to detect hot joints, high stress areas and possible electrical breakdown.

Summary of Diagnostic Systems for Bushings

Four main categories were developed Follow-up measurements should be performed at time intervals recommended for the specific bushing type, the age of the bushing and the impact on the system if failure occurs. If the bushing was exposed to severe stress, it might require more attention to ensure that the internal insulation system has not suffered in any way.

DFR Measurements to Determine the Status of the Bushing's Insulation System

The Dielectric Frequency Response is done over a broader frequency range. This test is conducted when it is suspected that the bushings might have been damaged by exposure to excessive stress. The internal insulation system needs to be checked for damage to ensure that factory tested electrical insulation capabilities was not unduly compromised. If the withstand capability to grid disturbances is compromised, the overall reliability of the transformer unit is compromised. This test is also more accurate to determine moisture levels.

Some utilities have already started to apply regular DFR testing on their bushings, but the lack of knowledge to interpret the deviations over time from the original test causes a void in the application value of this test. If the measurements and deviations can be pinpointed to identify problem areas and show the degradation in the system, this can be a very valuable tool in the diagnostic chain [4].

Difficulties Experienced with DFR Measurements

Because of the frequency range for these tests, DFR measurements require a much longer measurement time. The additional testing hours increase the total working hours allocated to the field maintenance crew. Limited guidelines and models were developed to decrease the test time and to interpret the results of measurement. Operational asset performance leaders are currently developing guidelines in predicting remaining in-service life of an ageing bushing fleet.

Photo: Shutterstock

References

[1] Th. Schuette, E. Santos, Understanding the Breakdown Mechanism of Bushings and Implementing Appropriate Life-cycle Orientated Maintenance Strategies
[2] IEC 61464-1998, "Guide for the interpretation of dissolved gas analysis (DGA) in bushings where oil is the impregnation medium of the main insulation"
[3] IEC 60270, "High voltage test techniques – Partial discharge measurements"
[4] C. Sumereder, A. Gumpinger, "Latest findings at transformer bushings condition evaluation by dielectric response methods," Graz University of Technology, Austria

Managing the Reliability of an Industrial or Commercial Electrical Power System / E 04

by **Chuck Baker**

Chuck Baker is the President of PowerPro 360, a company offering power system reliability assessment and reliability maintenance programs for Industrial and commercial organizations. Chuck entered the world of Substation and Power System Maintenance 36 years ago and has spent a majority of that career on the operations side of power and distribution system maintenance and the development of power system maintenance programs.

Cast

Brian .... Regional Vice President (head person for this plant)

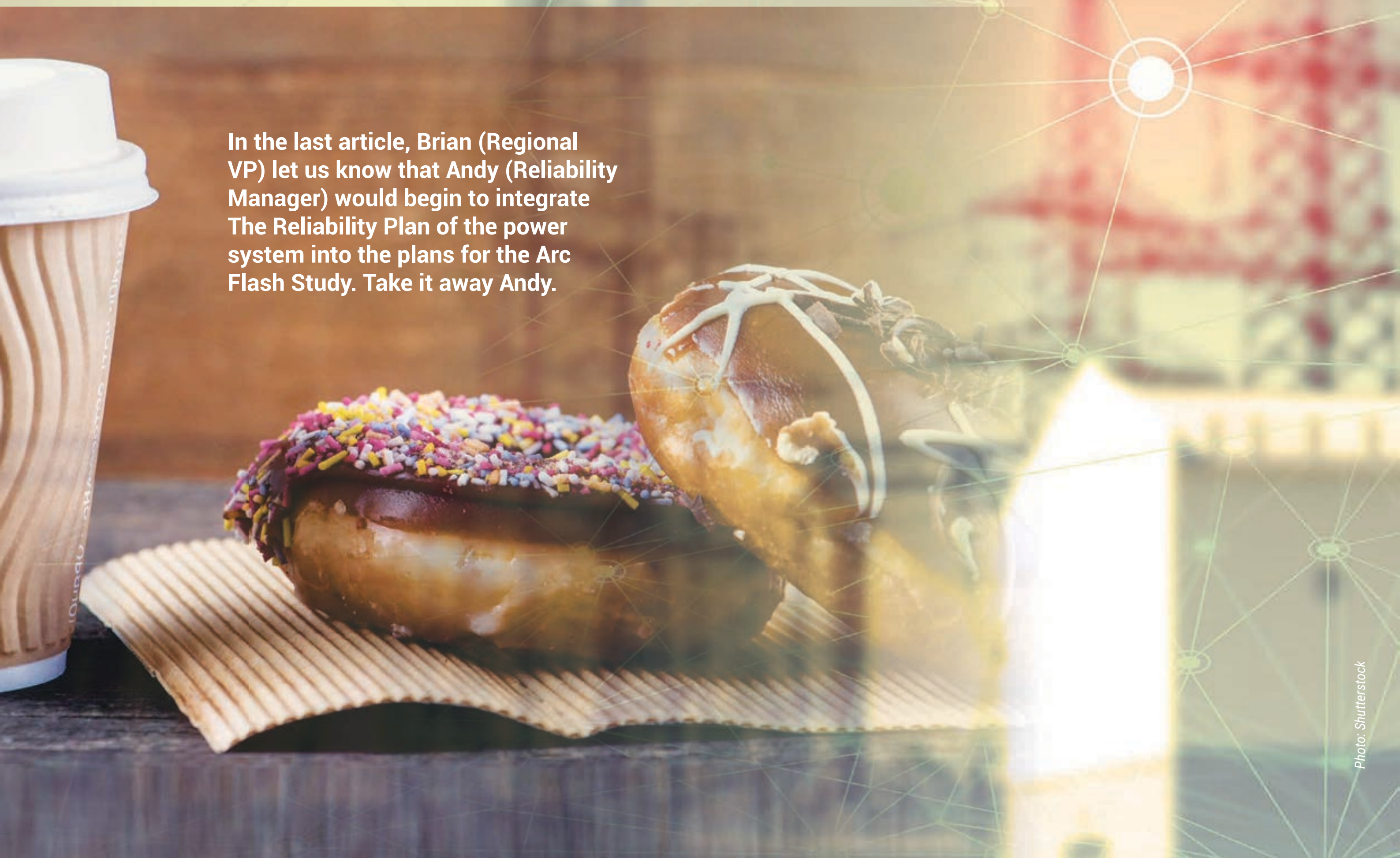
Andy .... Reliability Manager of Electrical Power System (recently hired by Brian, the Plant RVP)

Kevin .... Director of Reliability

Jill .... Director of Operations

Tina .... Maintenance Manager (who reports to Brian also)

Tim .... Electrical Engineer (who reports to Andy)



In the last article, Brian (Regional VP) let us know that Andy (Reliability Manager) would begin to integrate The Reliability Plan of the power system into the plans for the Arc Flash Study. Take it away Andy.

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Hello to everybody. A quick update: I have talked with the key players involved in the reliability movement within Smith Industries. As you recall, under the direction and expertise of Brian, most of the plant is in the process of building reliability programs. The area that lags is the power system and that is why Brian brought me on board.

I explained about the upcoming scheduled outage and the need to perform an arc flash study as the last one completed was over five years ago, and we are required by code to do it – now. I introduced the need to start to walk through the reliability program for the power system at the same time. Brian, Kevin (Director of Reliability) and Jill (Director of Operations) have given us the thumbs up, and so now it's time to take the first step – and that will be tomorrow morning with the core team: Tim (my EE) and Tina (Maintenance Manager). The three of us must be unified, maintain a clear understanding, and everything else Brian explained to us in last month's article.

Tim and I have a small conference room between our two offices, and it was perfect for our all-day meeting. I brought the coffee and doughnuts and figured we would need a break and going out to lunch would work.

I set up a small projector, hooked my surface up to it, brought up my very short, three-slide Power Point. Within a couple of minutes I was ready, and both Tim and Tina had arrived and were settling in.

I started the morning with a quick overview:

- Good morning all. Excited that we can get started on looking at what we want and need for a power system Reliability Centered Maintenance (RCM) program. Tina, I know you have been working on this for other portions of the plant, and Tim, I know your background centers on power system maintenance, so let me take a couple of minutes and communicate the way I think about this.

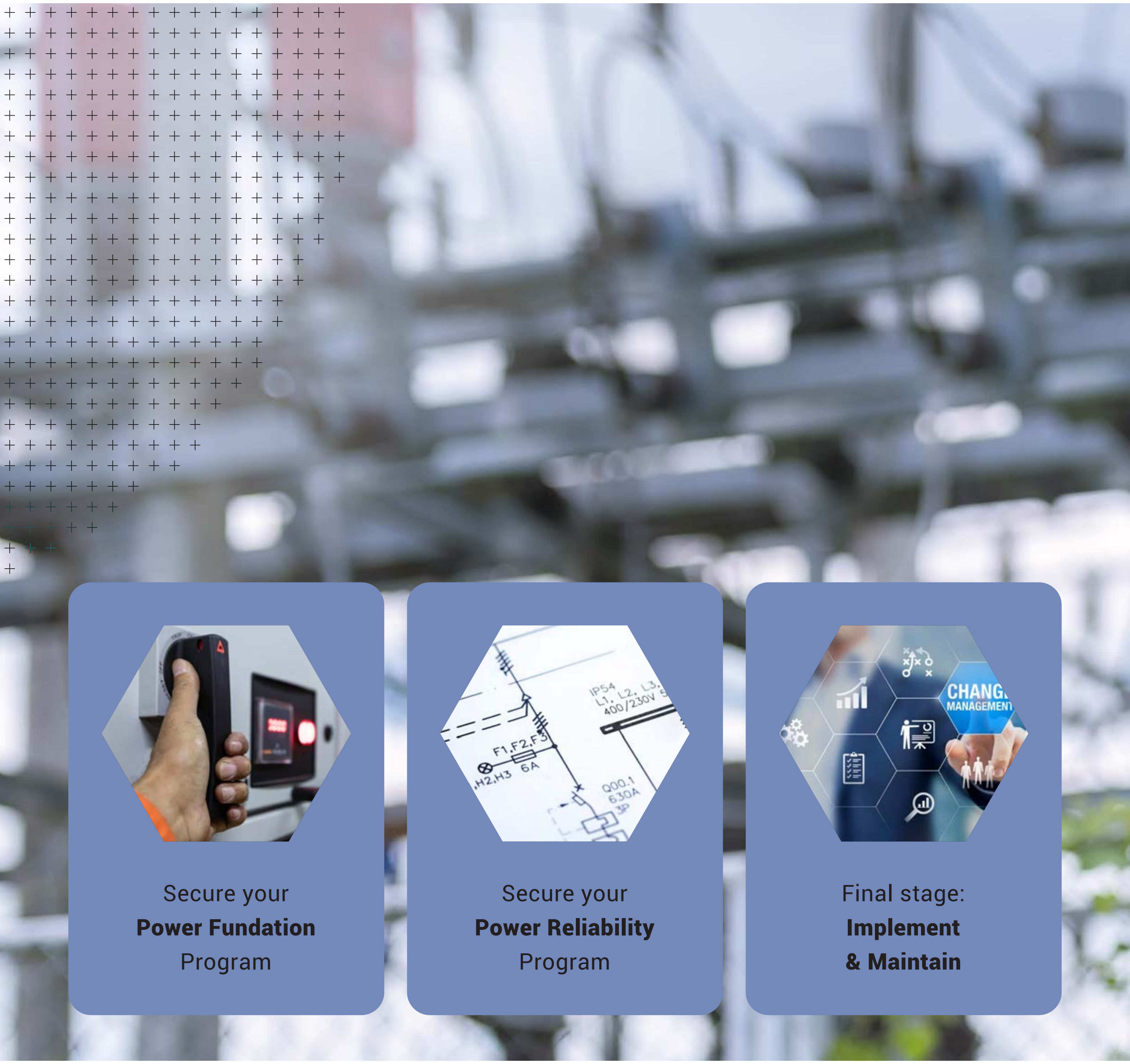
Tina interrupted and asked about how long the meeting is. She said a strange thing happened when she accepted the meeting; it filled both today and tomorrow on her Outlook. I explained that I was not sure and wanted to make sure nothing conflicted with all of us getting on the same page. Any other questions?

Both had a cup of coffee, sat back, and said: "Let's do it!".

- First, let me tell you my definition of an RCM program. Brian and I agree, and I think you will too:

> **An RCM approach is a corporate driven program to optimize the maintenance program so that the productivity of the plant is maintained using highly effective, priority and risk based, cost-effective techniques. When done correctly, the program will allow you to control what we have assumed was uncontrollable in the past.**

Tina, let me walk you through my program strategy and we can see if it is compatible with your plant RCM program. We cannot have any conflicts between the two.



I break it down into three key stages: Foundation, Reliability, and Implementation.

When we talk about our plants power system, we are talking about 25 individual components. The sum of these are the power system. Each component has its own key factors such as age, quality, health, load, or heat, etc. To build the program, we must go out into the plant, go through the engineered drawings, and utilize the information gathered during our arc flash investigation to collect all data required for a program.

The first step, Secure you Power Foundation Program, has 8 key stages that we will use to secure the program foundation:
1. One-Line Diagram
2. Short Circuit Study
3. Coordination Study
4. Arc Flash Study
5. Maintenance Standards
6. Service History – Current Status
7. Required Actions
8. Implementation

When we get through these 8, we will have a strong foundation to begin to build the reliability side of the program. As with any new program, we need to stay on the same page.

With that said, and before we start walking through each of the eight, we need to talk about the CMMS system the plant is currently using. I was not familiar with your program, but have looked at it, and see it is a good one for plant maintenance. I have used a different program that is specially designed for the power system and

Photo: Shutterstock

is set up with standards, work plans and methods to rate the value and reliability assignment for each piece. This would work in conjunction with your current one. The reason I mention this is that the exercise of the first 8 will generate critical information for our reliability program, and we want to have the right place and program to collect and organize what we generate.

A Reliability Centered Maintenance (RCM) approach is a corporate driven program to optimize the maintenance program so that the productivity of the plant is maintained using highly effective, priority and risk based, cost-effective techniques. When done correctly, the program will allow you to control what we have assumed was uncontrollable in the past.

Once we get through these 8, and have all data collected and entered, we will take the fun step – the reliability step. When we get there, we will have our 8 Reliability Steps to complete the program.

OK, let's walk through each of the eight steps and make sure we are on the same page.

One Line Diagram

This is a diagram that takes your three-phase power system and with single lines, component symbols show all arrangement of all components including key data (voltage, resistance, etc.), main connections, switching, etc. This is a key document in the management and servicing of your power system. More importantly, this is a critical document for maintenance of the system. A critical safety component is to verify switching, lock out etc. This is for our electricians, and just as importantly, our contractors who are servicing our system. They need to see the circuit and switching flow to assure the equipment is down before they ground it for service.

Obviously, there will be continual changes that will require for the one line to be updated.

Tina jumped in and reminded me that they do in fact have a good one line, and then Tim jumped in before I could say anything and explained to her that although they do have one, it is out of date. Regulations and codes require the one line to be reviewed and updated every five years or when a significant change is made.

I was pleased that Tim was onboard and was becoming a spokesman for the reliability program. He went on to explain that we would contract a PE to come in and perform this and that Tim would walk the system and provide necessary documentation and back up data for the PE.

I agreed with Tim and thanked him for updating us on those key points. I continued by saying that this is where it gets interesting.

- Think about this. We will review every component, its rating, etc., and will put all of that data into our power reliability CMMS. In a couple of minutes we are going to walk through the Short Circuit Study, Coordination Study and Arc Flash Study, which is also a requirement for program review every five years. And gang, these three all require the data that will be gathered in the one line, a perfect package.

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So, you can see why the updating of this document is important. Let us go over the other three that we will be doing to build our Power Foundation Program.

Short Circuit Study – Coordination Study – Arc Flash Study

The reason I want to walk through these three simultaneously is because they will all work hand in hand and be performed as a part of this requirement.

A quick summary:

- The Short Circuit Study will look at protective devices and calculate the line to ground fault currents that could be generated. This tells us about the available power and looks at the protective device duty rating that is responsible to clear the fault. When the PE performs this, we will use the updated one line diagram and use the information for these calculations from that.
- The Coordination Study takes the available fault current and looks at the nearest protective device upstream. It calculates if that device will do its job, isolating the fault and not allowing the impact to harm the feeder upstream. The PE will look at the time vs. current characteristics of each device and compare it to the protective devices upstream.
- The Arc Flash Study is critical, not just because it is a regulated requirement, but because it provides safety for those who are working on or around our Power System.
    - The first step in performing the arc flash is to gather all data on the equipment and system. It will start with the utility company's available short-circuit current and protective devices. We will then gather all data from components such as conductors and transformers and other sources of short circuit power. You can see how all the work done on updating the one line is important for all of this.

- The PE will then take all that data and calculate the potential "arcing" short-circuit current. The arcing current results when the short-circuit current jumps across an air gap. Again, remember we gathered a lot of relevant data when completed the short circuit analysis.
- The next calculation is to determine the Arc Flash Duration. This takes the amount of short circuit energy available and calculates how long it will take the protective device to open and end the short circuit.
- We will calculate the incident energy which tells us what the safe working distance is. If this switch were to arc, the person would need to be 18 inches, or 24 inches, or 36 inches, etc. from the source.

Tina jumped in and pointed out that the time, temperature, and damage all the way up to fatality was talked about in our first meeting with Brian and the gang. Tim jumped in and pointed out that this is regulated and required, but for all the right reasons pointing out the number of deaths and serious burns that happen every year from arc flash incidents.

I was encouraged that they were engaged and following the outline logic. I continue:

- Now that we know the energy and time that would be present in the event of an arc flash, we will calculate the arc flash boundaries. This begins to narrow down as each location will be labeled for safe working distance.
- A part of the calculation for distance also calculates the level of Personal Protective Equipment (PPE) that is required at that location. Length and strength of the potential arc helps determine the required PPE.
- The PE performing the study places arc flash warning labels where required. This label is what communicates the requirement for distance and PPE to the person performing the work.
- The last step is training the crews and those who could be exposed to an arc flash. I mentioned that the arc flash study was due every five years. The other part of the program is the crew training which needs to be performed every three years. I know that the power group does annual OSHA safety training and I am certified to provide this arc flash training. We will schedule that with this annual training every third year.

Tim did a great summary of the first four steps to a Power Foundation Program, saying that these four key requirements work in conjunction with each other. All the data is shared, key calculations are performed, and the results will work for each of these, allowing us to pull this into compliance. He also reminded Tina and I, I think mostly me, that not only would we be gathering key data, but we would also find settings and equipment that needed to be adjusted or replaced as we did each of these. He also pointed out that all the base data we needed for our reliability program would be gathered during this phase.

I agreed and proposed we run out for some lunch and a little fresh air; they were great with that.

I believe this is the end of this month's article. This afternoon, or I should say the next edition, will be our team walking through the last four items:

- Maintenance Standards
- Service History – Current Status
- Required Actions
- Implementation

These sound simple, but they are not. These are tough, but necessary steps for the foundation of the reliability program.

TRANSFORMER, GRID AND POWER PLANT MONITORING REVISITED

EFFICIENTLY LINK, MONITOR AND CONTROL YOUR UTILITY WITH OUR EZY DEVICES, SERVICES AND SOLUTIONS - AT A REMARKABLE ACCURACY LEVEL

By Dr. Bernhard Fruth with contributions from: Thomas Finstermann and Javis Chiu

Power Diagnostic Service

"The use of diagnostically supported maintenance requires reliable condition monitoring systems, reliable diagnostic results and extensive experience in determining the relationship between the measurement result and the condition of the component."

The implementation of a risk-oriented maintenance strategy based on measured data requires a high degree of plant-specific knowledge and highly developed sensor technology, sophisticated data processing, and information mining. Using suitable monitoring techniques allows operators to determine and know the condition of the plants, machines, and components at all times.

Risk Identification – Risk Elimination – Reliability Increase

If you want to avoid unplanned downtimes, it is imperative to forecast possible remaining running times until you will need to carry out a maintenance action. With the right technology, it is possible to plan future investments in detail, hire an expert (if necessary) and execute maintenance during planned operational downtime.

Machine Learning and Artificial Intelligence

We tackle the abundance of time-synchronized, real-time data of various origins with AI and Machine Learning tools. Our curiosity drives us to pioneer solutions. With a passion for sophisticated products, we create pioneer solutions to power the world, effortlessly and dependably.

Our mission is to make our customers' decisions easy and reliable. We synchronise big data in order to simplify our customers' decision-making and ensure reliability.

Synchronisation of data across systems provides a unique and unified evaluation of raw data. Our pioneering products offer our customers all the information necessary to integrate previously incompatible data and enable more economical processes.

International experts have come together to develop a unique solution to monitor and control your utility. The newly established EZY Family is fusing knowledge, experience and products to give customers a competitive industry advantage. By drawing on our individuality, we enable our customers to tap into the unused potential of their investment data.

Experience Counts

Our EZY family monitors over 15,000 objects, seamlessly 3,500 monitoring systems report seamlessly to our server and we monitor and control more than 400 gas turbines.

WITH A PASSION FOR SOPHISTICATED PRODUCTS, WE CREATE PIONEER SOLUTIONS TO POWER THE WORLD, EFFORTLESSLY AND DEPENDABLY.

GO BEYOND

You need an individual power plant solution information system which provides a unique state-of-the-art to the split second 'big picture' to efficiently monitor and control your utility.

- EZY Family devices conduct measurements that enable full data sharing between devices.
- This helps you to recognize correlations of events and signals based on fully automated assessments.
- EZY Family devices offer a unique analytical accuracy level with joint view and optimal evaluation capabilities.

Imagine having a network of devices, collecting and analyzing a full spectrum of information.

- With our 'Plug & Work' application, we aim to make connectivity easy – simply plug in your device without any setup requirements.
- The EZY devices provide a unique, state-of-the-art snapshot of your working environment – on one single screen.
- The high-level security of all EZY Family devices provides the efficiency and safety that every utility needs to push beyond the limit.
- Extensively tested embedded software/systems
- Robust and fault-tolerant product design
- Full integration into TMOS SCADA system over Ethernet
- User-friendly operator interface with individualized charts
- Accurate device-specific as well as customized limits
- Event-based audiovisual alarms
- Fully customizable long term data logging
- Customized control sequence
- Remote monitoring and configuration possible

It is necessary to have global expertise and human resources within the company to monitor a power plant 24/7 efficiently. If this is not achievable for your company, we offer comprehensive remote monitoring at numerous locations in highly specialized diagnose centres worldwide.

Dr. **Bernhard Fruth** is currently CEO of Power Diagnostic Service Switzerland and R&D Manager of the EZY Monitoring group. He obtained his PhD in 1986 from University of Technology in Aachen and worked in ABB Corporate Research in Switzerland where he designed the first commercial PRPDA 1988 for discharge pattern acquisition. He was one of the co-founders of Power Diagnostix in Aachen, and PDTECH in Switzerland, where he pioneered a line of monitoring devices. He authored more than 60 papers on PD Physics and monitoring.

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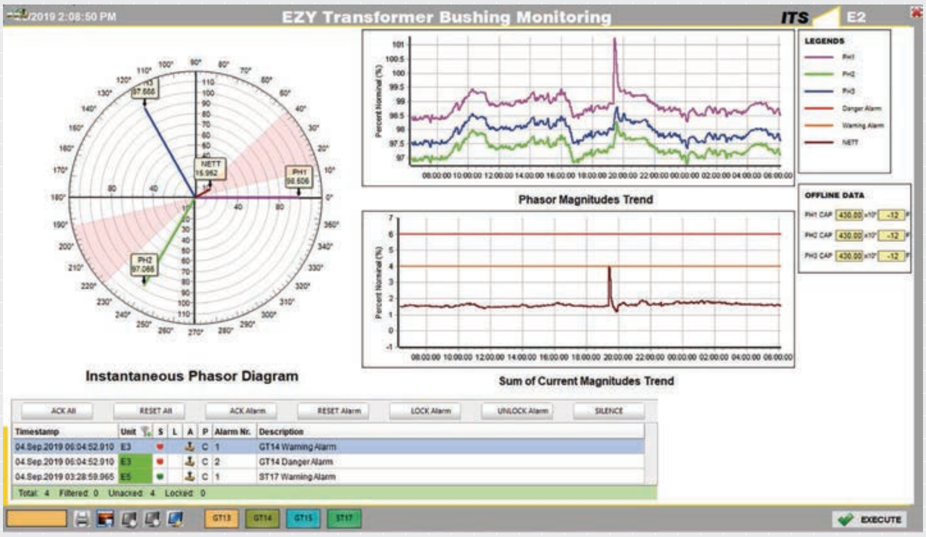
Here industry experts, with many years of experience, accurately monitor your utility around the clock. Benefit from extensive know-how and unique diagnostic tools that compile a detailed report with recommendations. Highly specific diagnoses, industry innovations as well as statistic data are considered in the reporting.

"The customer is always in full control of their data."

It is possible to send the data manually or allow the expert remote access to specific data areas.

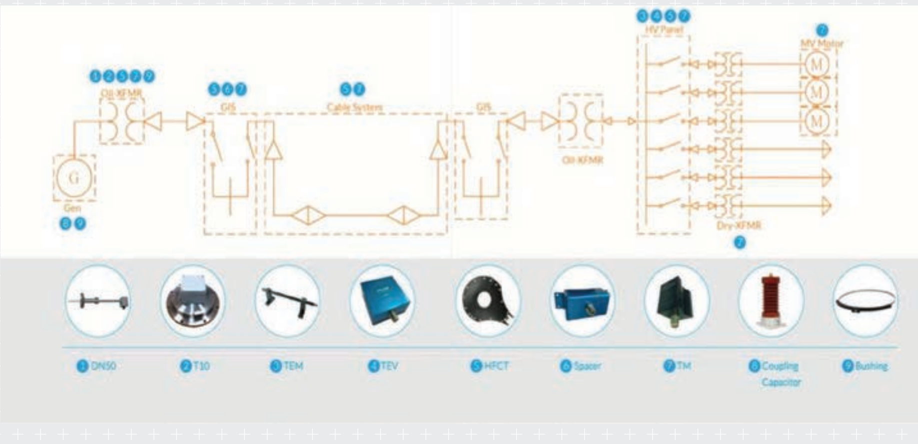
The Bushing and Transformer Monitor

The bushing of a transformer is a key source of trouble. EZY bushing monitoring allows measuring the dielectric properties of a bushing using real-time phasor diagrams to calculate capacitance and tan delta imbalance.

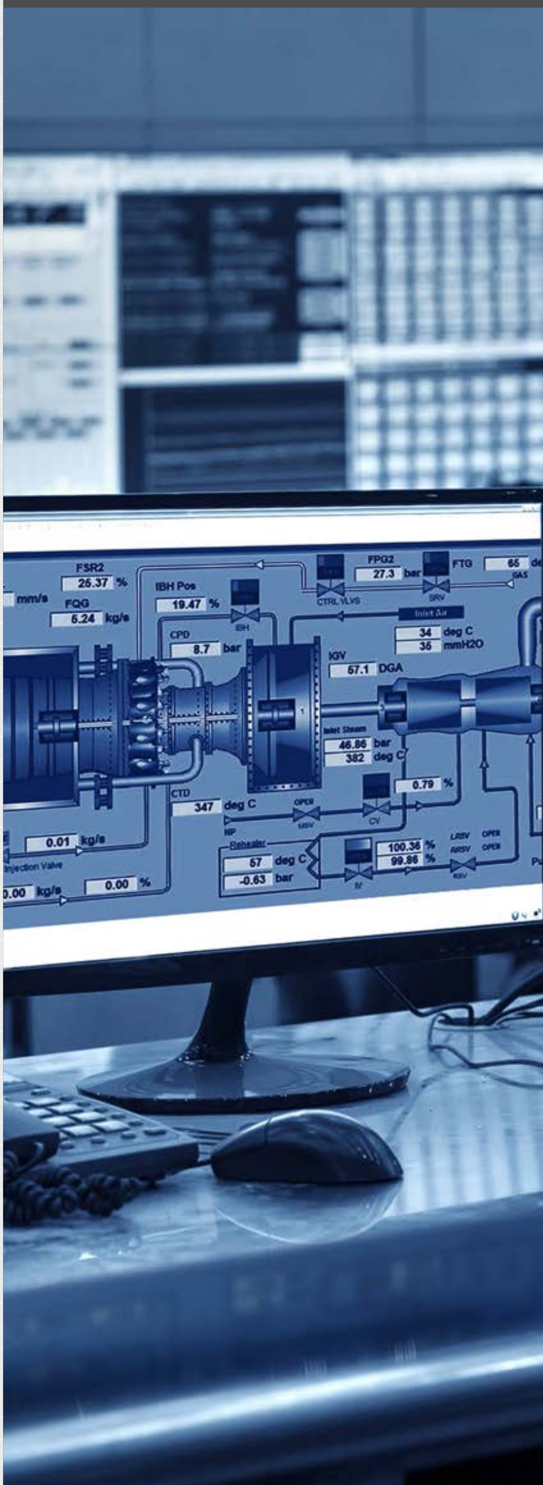


Phasor Diagram shows the instantaneous currents of each phase and the summed currents in angular domain. Note: The NETT (sum of current) vector shown is post-multiplied 10 times for visual amplification purposes.
Phasor Magnitudes Trend shows the magnitude trends of the current of each phase over the last hour.
Sum of Current Magnitude Trend shows the magnitude trend of the unbalanced current, and the alarm thresholds.
Alarm Table shows active and inactive alarms and allows user to act on them. Button functions are shown in the picture below.
Offline Data shows the initial bushing capacitances of each phase and allows user to adjust after offline test.

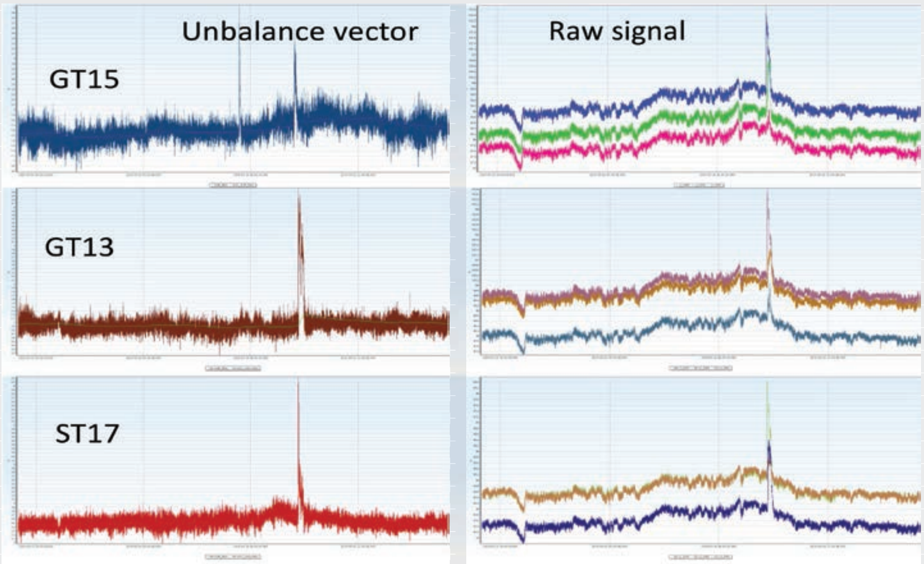
Combine this with UHF Partial Discharge Monitoring using our non-intrusve sensor design and you see the insulation state of the complete high voltage network.



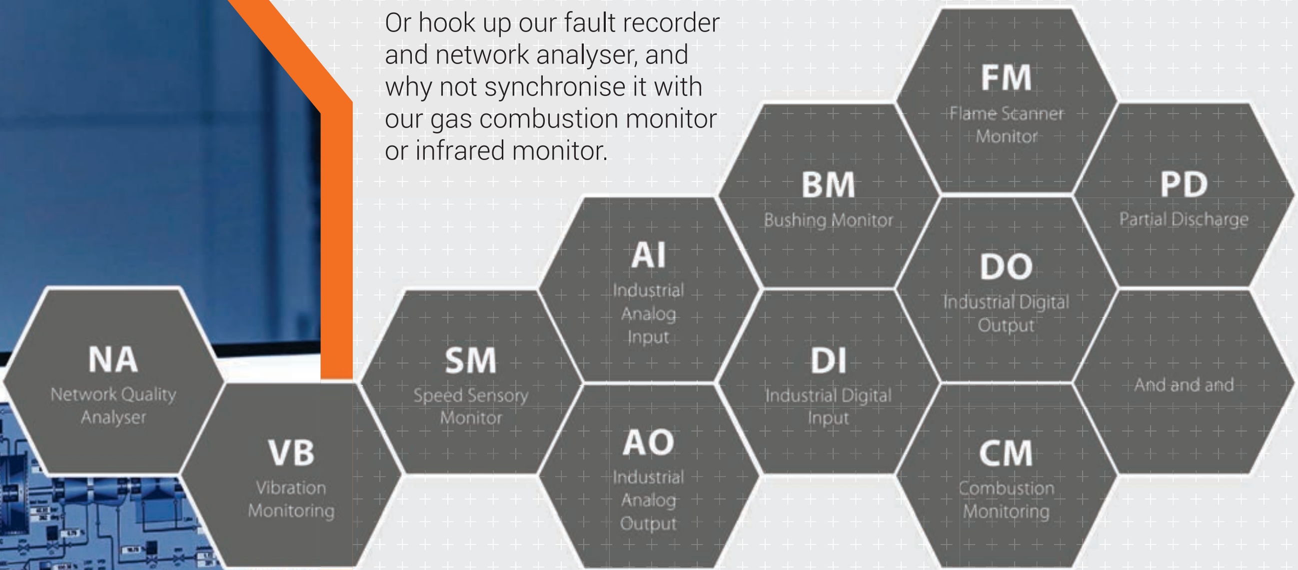
IT IS NECESSARY TO HAVE GLOBAL EXPERTISE AND HUMAN RESOURCES WITHIN THE COMPANY TO MONITOR A POWER PLANT 24/7 EFFICIENTLY. IF THIS IS NOT ACHIEVABLE FOR YOUR COMPANY, WE OFFER COMPREHENSIVE REMOTE MONITORING AT NUMEROUS LOCATIONS IN HIGHLY SPECIALIZED DIAGNOSTIC CENTRES WORLDWIDE.



Unbalance vector and current raw signal in each phase in three different power transformers in a powerplant with two gas turbines and one steam turbine.

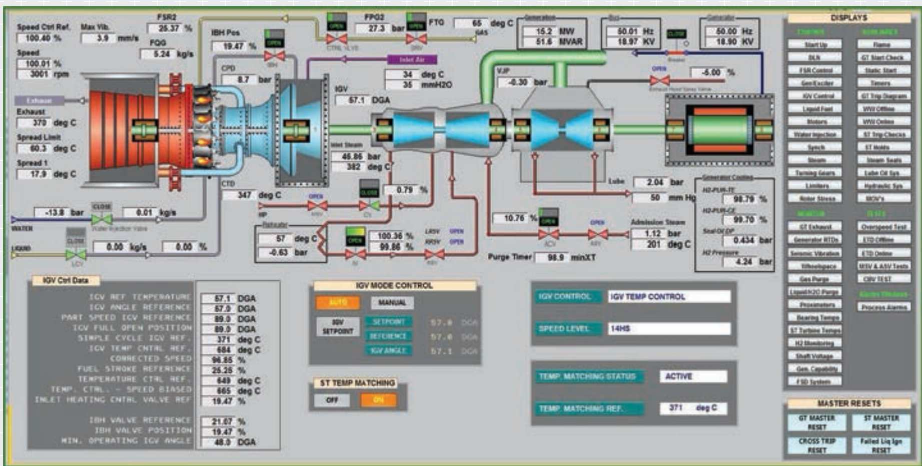


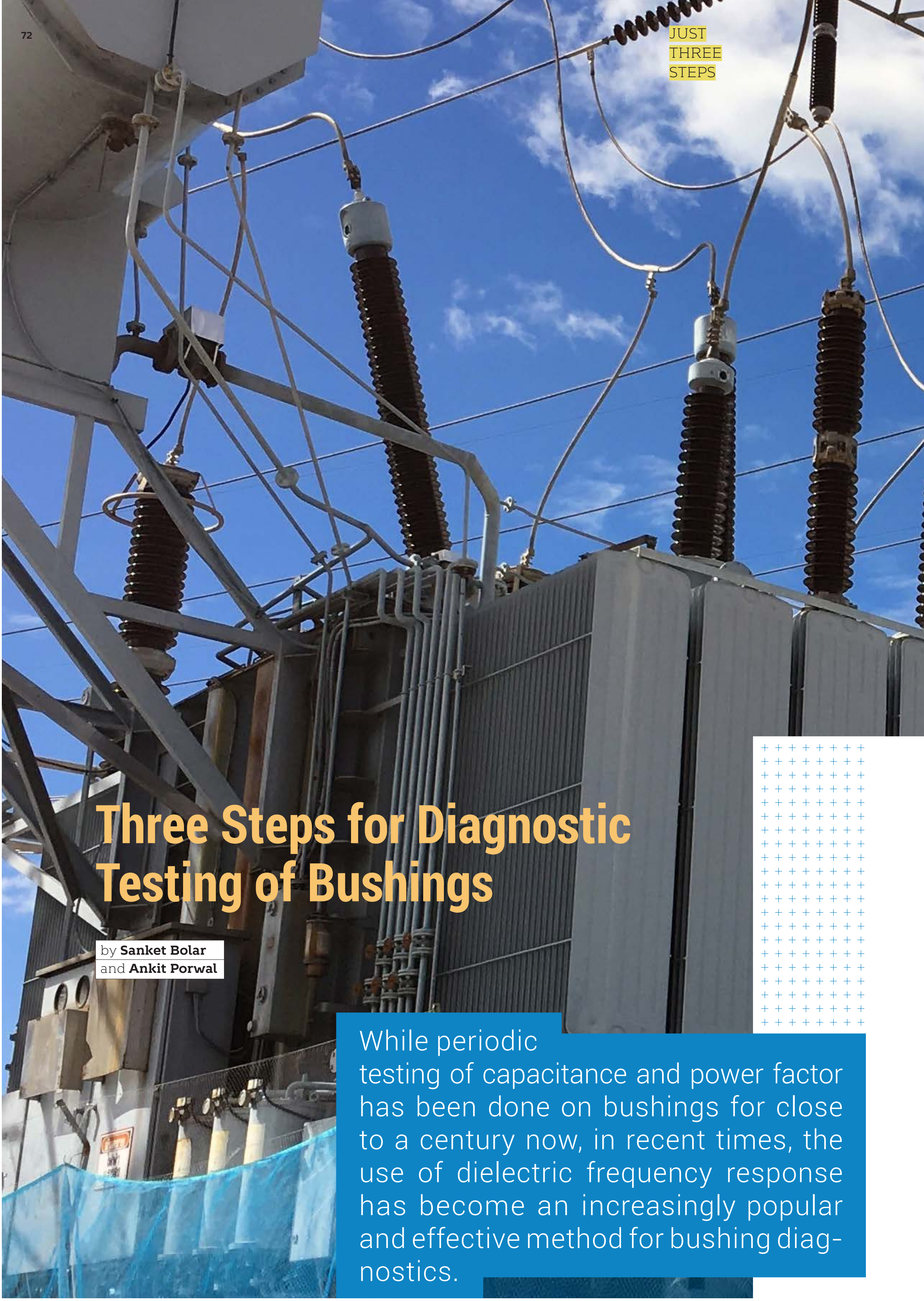
Or hook up our fault recorder and network analyser, and why not synchronise it with our gas combustion monitor or infrared monitor.



Everything is synchronised in real-time seamlessly and our artificial intelligence and machine learning algorithms keep it together, including third party devices – the possibilities are endless.

All at a glance...

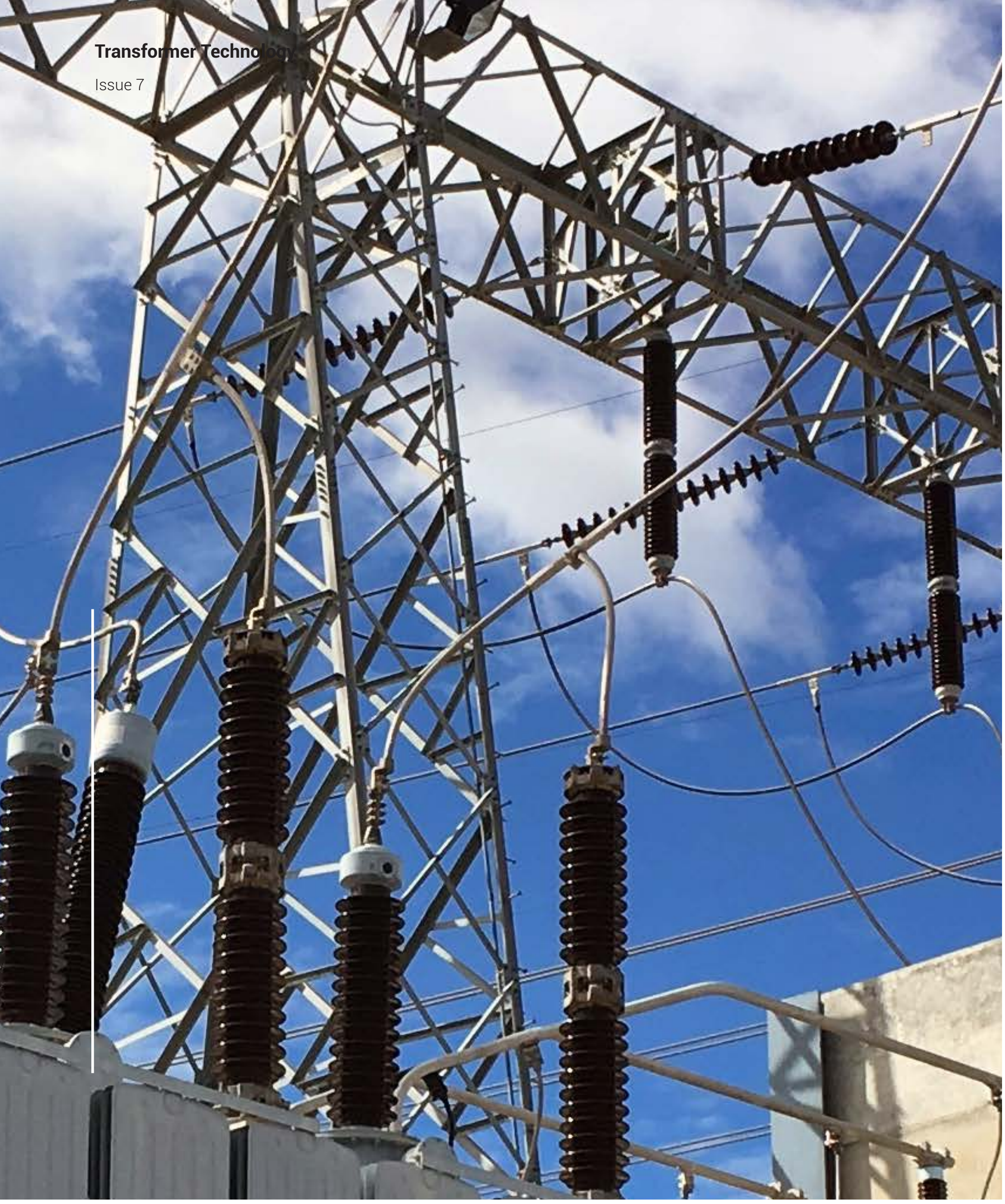




Three Steps for Diagnostic Testing of Bushings

by **Sanket Bolar**
and **Ankit Porwal**

While periodic testing of capacitance and power factor has been done on bushings for close to a century now, in recent times, the use of dielectric frequency response has become an increasingly popular and effective method for bushing diagnostics.



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Sanket Bolar, MSc is a Substation Applications engineer at Megger. From the beginning of his professional career, Sanket was directly involved with testing and condition assessment of power transformers working for Siemens Ltd (India). While working on his Master's Degree, Sanket became part of Megger as part of the internship educational program. In 2015 upon graduation, he joined Megger as Applications Engineer covering a broad spectrum of substation products from transformer to power quality applications. Sanket graduated from Mumbai University, India in 2009 with a Bachelor's in Electrical Engineering and received his Master's in Electrical Engineering specializing in Power Systems from North Carolina State University in 2015. He is a member of IEEE.

Ankit Porwal works for Megger India and is responsible for the power transformer segment in South Asia. More than ten years of experience in the area of substation apparatus testing allowed him to successfully support a large customer community in different commercial and technical topics. For the last 8 years working for Megger, Ankit has provided engineering consultation and recommendations to better test and evaluate the condition of substation equipment with special focus on power and distribution transformers. His expertise with routine and advance diagnostic methods led him to author and co-author several technical articles. Ankit received his Engineering degree from the University Uttar Pradesh in Lucknow (India) in 2009.

Introduction

In the early 1900s, it was demonstrated that a capacitance-graded design helps achieve a better radial voltage distribution, thus enabling relatively smaller bushings to be used in higher voltage applications. Today, condenser bushings are used everywhere in applications exceeding 25 kV. Based on the materials used in the insulation system, condenser bushings can be classified into – oil impregnated paper (OIP), resin impregnated paper (RIP), resin bonded paper (RBP) and resin impregnated synthetic (RIS) bushings. Among these technologies, OIP is perhaps the most widely used. OIP relies on the combination of mineral oil with kraft paper to make a composite dielectric with superior insulating characteristics.

In the substation, bushings serve as the interface between the transformer and the rest of the system. They are designed to withstand high voltage stress during operation, to carry a high amount of current, and to operate under high temperatures. Being external, they are exposed to atmospheric conditions which can be harsh at times. Before installation, they can be easily damaged during transportation and once installed are a target for vandalism.

Because of these factors, bushing failure is, alongside tap-changers, one of the main causes of transformer failure. A transformer failure can be an expensive affair. Hence, bushing insulation health needs to be monitored effectively during its service life to ensure bad bushings are replaced in a timely manner. Several online and offline testing methods exist to monitor the condition of transformer bushings. Periodic testing of capacitance and power factor has been done on bushings for close to a century now. In recent times, the use of dielectric frequency response, an advanced application of power factor testing, has become an increasingly popular and effective method for bushing diagnostics.

Step 1:
Line Frequency Power Factor Testing (LFPF) on OIP Bushings

The term power factor is used historically in the US, but the term dissipation factor or tanδ is used in other parts of the world. It is important to note that while power factor and dissipation factor are mathematically two different terms, they have numerically equivalent values when it comes to insulation. Hence, these terms can be used interchangeably for practical purposes with regards to insulation. These terms are related to each other through the formulae below:

Power factor = cos φ
Dissipation factor = tan δ
Delta = 90° – φ

Figure 1. The relationship between φ and δ

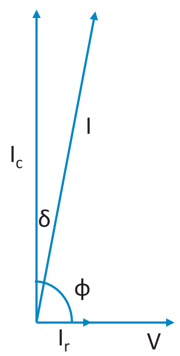
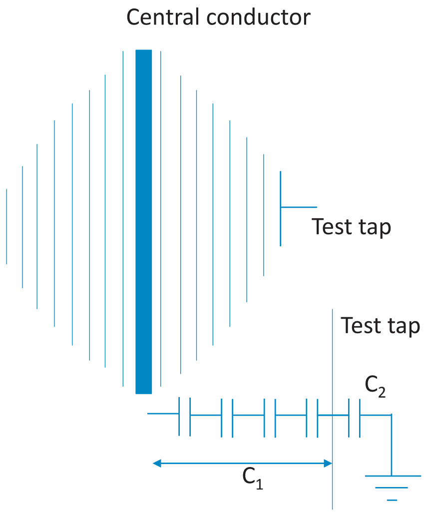


Figure 2. Insulation system of condenser bushing



Condenser bushing insulation system has two capacitance components – C_1 and C_2. In an OIP bushing, the capacitance grading is achieved by wrapping a conductive foil in oil-impregnated kraft paper multiple times around the conductor core. One of the outermost layers is connected to a test tap. The multiple layers of capacitors between the conductor core and the test tap can be represented by a single equivalent term C_1. The test tap itself is isolated from the grounded flange and this insulation can be represented by the term C_2. In service, the test tap is grounded. Capacitance and power factor measurement involves the measurement of dielectric losses in the C_1 insulation that lies between the conductor core and the test tap at 10 kV. Power factor values obtained are numerically low numbers and hence are expressed in % instead of absolute values. Typical factory values lie in the range of 0.2 – 0.4% [1]. Factory testing yields reference values which are etched on the nameplates of bushings. Field test values are compared to these nameplate values. Any significant change in C_1 power factor values points towards insulation deterioration of bushings.

Additional measurements may be done on the C_2 insulation that lies between the test tap and the grounded bushing flange. A fair C_2 comparison may not be possible as different values could be obtained when the bushing is on a stand, and when it is mounted on a transformer. Besides, most of the time the C_2 values are not even provided on the nameplate of the bushing. There are several other reasons why people tend to stay away from C_2 analysis and focus on the C_1 power factor values.

It is important to look for changes in C_1 capacitance too. An increase in capacitance can be a result of shorted layers, whereas a decrease in capacitance most commonly results from a test tap connection problem.

There are several documents available that provide guidelines on interpretation and validation of power factor test results, both during factory acceptance testing (FAT) and field testing.

The following standards provide acceptance limits for C_1 power factor:

IEEE C57.19.01 – IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings [2]; and

IEC 60137 – Insulated bushings for alternating voltages above 1000 V [3]

The limits are specified in Table 1.

Table 1. Bushing C_1 acceptance %pf limits specified in standards

Bushing type	**C_1 acceptance Power factor limits as per IEEE C57.19.01 [2]**	**C_1 acceptance Power factor limits as per IEC 60137 [3]**
OIP	0.5%	0.7%
RIP	0.85%	0.7%
RBP	2%	1.5%

All of the limits specified in Table 1 are meant for power factors measured at 20°C or normalized to 20°C.

IEEE C57.152 – IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors [4] says:

- A change from the initial reading by 1.5 to 2 times warrants more frequent testing of bushings;
- A change from the initial reading by more than 3 times warrants removing the bushing from service;
- A change in capacitance by more than 5% is a cause to investigate the suitability of bushing for continued service;
- These guidelines are in line with the guidelines provided in IEEE C57.19.100 – IEEE Guide for Application of Power Apparatus Bushings [5].

As can be seen from these guidelines, validation involves either comparing power factor values against the set limits or observing the change in power factor over time. One point that is often overlooked while analyzing power factor results is the effect of temperature. Measuring at different temperatures can yield different values, so it is important to normalize the measured power factor values by correcting them to a reference temperature (20°C). There are correction factors available from manufacturers or other references, but those are generic and cannot be relied upon in all cases.

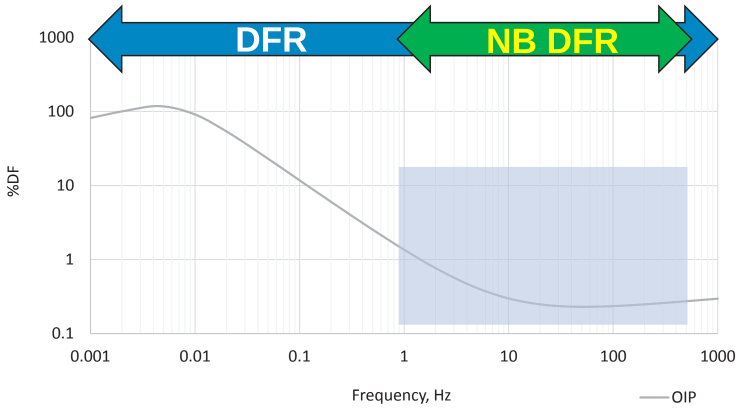
Step 2: Narrowband Dielectric Frequency Response (NBDFR) on OIP Bushings

Standard 10 kV power factor test sets with expanded capabilities of frequencies from 1 Hz to 505 Hz can run power factor measurements at multiple frequencies. The curve obtained by plotting these power factor values, called **Narrowband Dielectric Frequency Response (NBDFR)**, gives us additional information on the overall insulation condition of the bushing. This reduced frequency band does not provide the level of moisture in the insulation, but it does point to the presence of moisture and/or impurities in the insulation.

NBDFR is a continuum in the evolution of power factor testing. In about three minutes, valuable information is added to the routine power factor test. It provides early indication of changes in the dielectric response, potentially related to aging and insulation degradation. This measurement can reveal an emerging problem in the insulation at an early stage and represents a proactive way to prioritize maintenance activities and dedicate resources to more advanced testing practices.

NBDFR is typically performed at a low voltage of 250 V. As a low energy test, it is safer to perform so that it allows visualization of the unique dielectric signature of the object under test. Therefore, a graphical comparative analysis between sister bushings mounted on one common object is possible and it also provides the opportunity to set limits and analyze the dielectric behavior in other frequencies more sensitive than line-frequency (50/60 Hz) i.e. 1 Hz and 10 Hz.

Figure 3. Dielectric frequency response



Measuring at different temperatures can yield different values, so it is important to normalize the measured power factor values by correcting them to a reference temperature (20°C). The correction factors that are available from manufacturers or other references are generic and cannot be relied upon in all cases.

NBDFR also provides the means to determine a specific insulation system sensitivity to temperature and an accurate temperature correction factor (ITC) to correct to an equivalent 20°C power factor.

Effect of Temperature

IEEE C57.12.90 section 10.10.4 Note 3 (b) states that "Experience has shown that the variation in dissipation factor with temperature is substantial and erratic so that no single correction curve will fit all cases." [6]

Power factor is temperature dependent. It has been found that the frequency response and thermal response of a dielectric are related. The dielectric frequency response of an OIP system shifts horizontally with change in temperature, without any change in the shape of the curve itself.

Using Arrhenius equation, it is possible to determine the exact horizontal shift that would occur in a curve for a certain change in temperature.

$$A_{x,y}(T_1,T_2) = e^{\frac{-E_{x,y}}{k_B}\left[\frac{1}{T_1}-\frac{1}{T_2}\right]}$$

This enables us to determine the power factor that would be obtained at 20°C, while running a DFR measurement at any other temperature. Figure 5 shows dielectric frequency response curve obtained with the temperature correction applied, alongside the measured curve. Figure 6 shows the temperature dependence curve obtained for the same bushing utilizing the data obtained from DFR.

Getting temperature corrected DFR curves enables us to assess the correct values at 1 Hz, 10 Hz and 60 Hz without having to worry about the effect of temperature on the assessment. There is no need to wait until the temperature is close to 20°C to test the bushings, or to rely on generic correction factors which may or may not be apt depending on the insulation condition of the bushings.

This method is known as Individual Temperature Correction (ITC). More information about ITC is provided in [7] and [8].

Figure 5. Measured and temperature corrected DFR curves

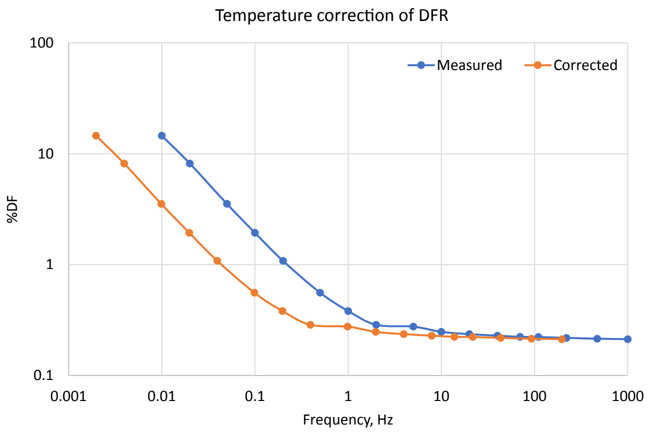


Figure 4. DFR curves obtained at different temperatures

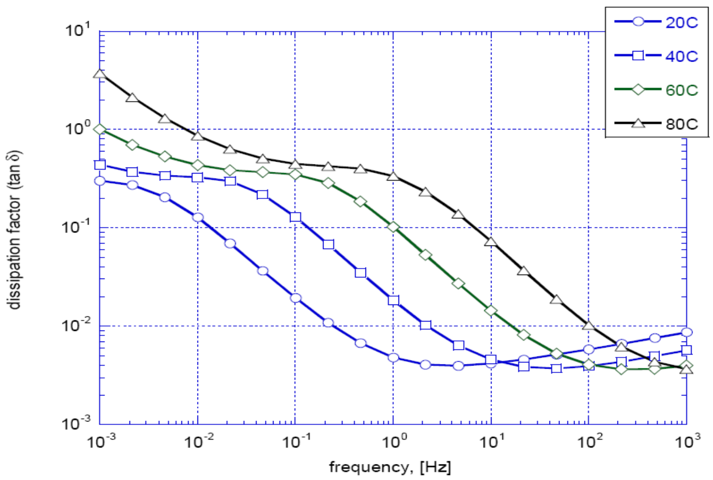
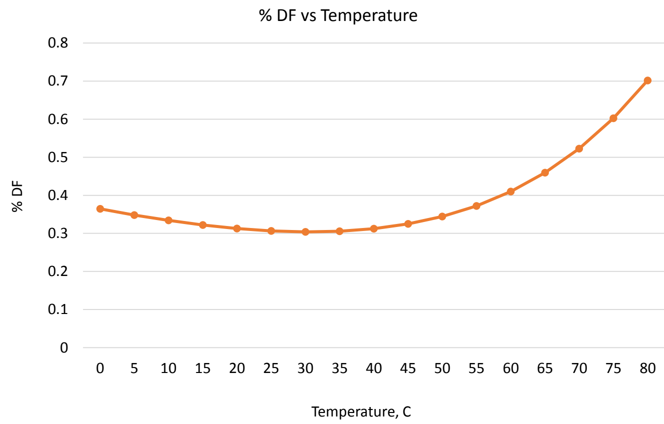


Figure 6. Temperature dependence of bushing dissipation factor determined from DFR measurement



Step 3: Dielectric Frequency Response Measurements on Bushings

The insulation system of an OIP bushing is made up of multiple layers of capacitors formed by conductive foil wrapped in oil impregnated kraft paper. The oil and paper form a composite dielectric system, and the dielectric frequency response obtained from the bushing is a combination of the individual responses from the oil and paper insulation. The permittivity of the insulation can be expressed as a complex term:

- The relative permittivity of a dielectric is a complex term and can be represented as

$$\varepsilon^* = \varepsilon' - j\varepsilon''$$

- The dissipation factor is related to the permittivity by the following equation:

$$\tan\delta = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)}$$

The dissipation factor varies with frequency as both dielectric constants are frequency dependent. The behavior of these constants differs for oil and paper. Figures 7 and 8 illustrate how the typical response obtained from a bushing is an amalgamation of the individual responses from oil and paper.

In cases where it is not possible to get definitive answers through narrowband dielectric frequency testing, a more in-depth analysis can be carried out by measuring the dissipation factor over a wider range of frequencies. Analysis of DFR curves can yield important information such as moisture content or contamination in the paper, and conductivity of the oil. The presence of contamination or other physical issues can result in atypical responses with the most prominent deviations seen in the lower frequencies.

Effect of Noise

DFR measurements are typically carried out at a low voltage of 140 V. Because of the test involving a wide range of frequencies and low currents, the presence of noise can adversely affect the accuracy of the measurements. This can happen in highly noisy environments even though the instrument may have a high signal-noise ratio. The influence of noise can easily be observed in the obtained DFR curves.

Figure 7. DFR responses from individual dielectrics and composite dielectric

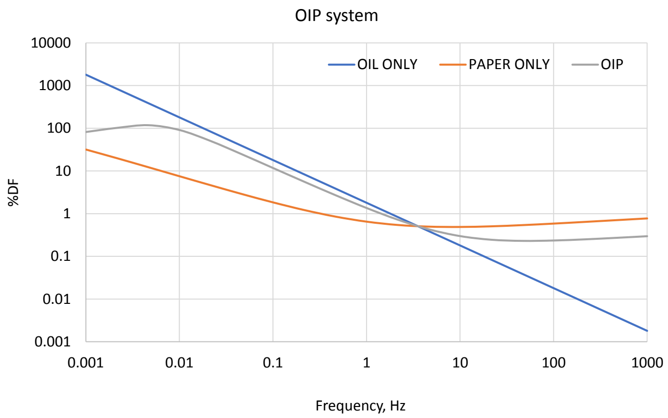


Figure 8. Dielectric Frequency Response of an OIP bushing

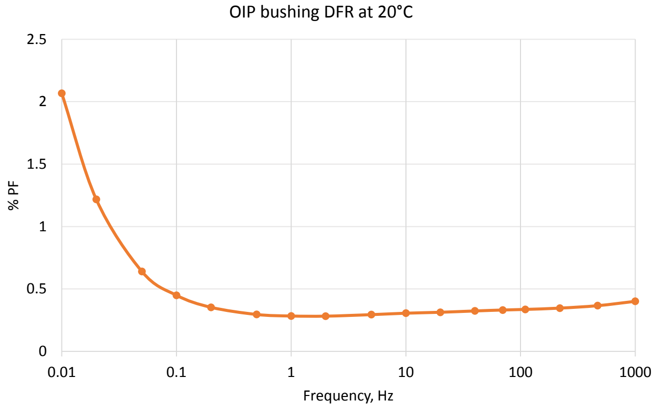


Figure 9. DFR measurement under the influence of noise

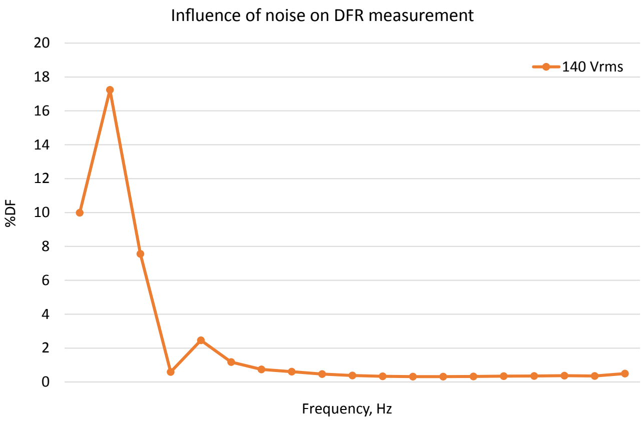
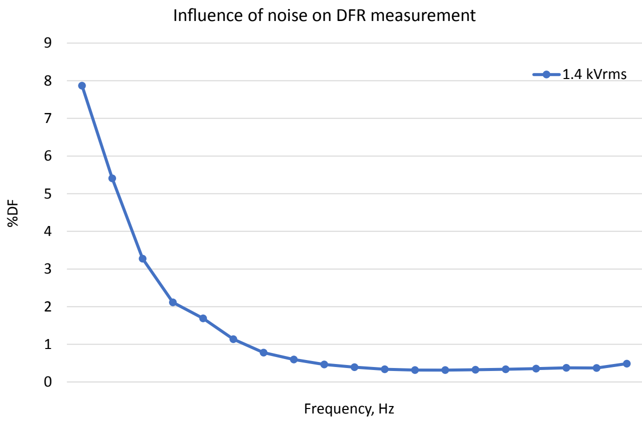


Figure 10. The noise was overcome by conducting a DFR test at a higher voltage of 1.4 kV rms



Noise disturbances can be overcome by testing at a higher voltage. The use of a voltage amplifier in conjunction with the DFR measurement device can significantly improve the signal-noise ratio, resulting in accurate and reliable DFR measurements.

Figure 9 shows the measurement curve on the B phase bushing obtained through a DFR test that was carried out on the line bushings of a 50 MVAr reactor using an IDAX. As can be seen, there is a fluctuation in the measured power factor values due to the presence of noise. The effect of noise is more commonly observed while testing objects with low capacitance like bushings, instrument transformers, etc. because in these cases the magnitude of the measured current is lower, and hence more susceptible to noise. The magnitude of the capacitive component of the current is given by the following equation:

$$I_c = 2\pi f \times C \times V$$

In cases where it is not possible to get definitive answers through narrowband dielectric frequency testing, a more in-depth analysis can be carried out by measuring the dissipation factor over a wider range of frequencies. Analysis of DFR curves can provide important information on the moisture content or contamination in the paper, and conductivity of the oil.

The DFR test was repeated on the same bushing at a voltage of 1.4 kVrms by using a voltage amplifier VAX. The results are shown in Figure 10.

Field Experience

Step 1:
PF Analysis

Out of three OIP HV bushings, an increase in the power factor was observed on two bushings: X1 and X3, at line frequency as illustrated in Table 2.

Table 2. Nameplate and measured pf values for three bushings

Bushing	Nameplate % power factor	Measured % power factor
X1	0.23	0.47
X2	0.23	0.27
X3	0.24	1.40

a. According to IEEE C57.152, the line frequency power factor values for X1 and X3 at 20°C exceed acceptable limits.
b. According to CIGRE TB 445, the power factors of the bushing X1 and X2 come within limits, while only bushing X3 comes outside acceptable limits.
c. Based only on the line frequency power factor values, we may say that the bushings X1 and X3 are not in good condition, and the bushing X2 should be investigated further.
d. Hence, we move onto step 2 and run a narrowband DFR test to evaluate power factor at other frequencies (20°C corrected).

Step 2:
Narrowband DFR Analysis

NBDFR test was carried out on three bushings from 1 Hz to 500 Hz. Figure 11 shows an increase in %power factor for the bushings X1 and X3 at lower frequencies.

The obtained thermal response curves were different for each bushing because of the variations in dielectric frequency responses. These are shown in Figure 12.

The temperature corrected power factor values obtained at different frequencies are shown in Table 3.

Table 3. Temperature corrected %pf values obtained for three bushings at different frequencies

Bushing	%pf at 60 Hz	%pf at 15 Hz	%pf at 1 Hz
X1	0.454	0.514	1.32
X2	0.271	0.278	0.660
X3	1.14	2.76	11.9

For a "good" component, the temperature dependence is weak. When the component gets older and/or deteriorates, the temperature correction factor becomes much higher, which means that the temperature dependence is directly related to the dielectric response of the bushing. In the above example, the bushing X3 shows a huge temperature dependency as compared to bushings X1 & X2. An increased dissipation factor at higher temperatures is a good indicator of bushing problems.

As per the studies carried out by Megger based on over 20 years of expertise in DFR, the limits shown in Table 4 have been proposed for analysis of %pf measured at the frequency of 1 Hz.

Table 4. Proposed limits for %pf at 20°C and 1 Hz

Bushing condition	%PF at 20°C and 1Hz
Good	0.2 – 0.5
Moderate	0.5 – 0.75
Severe	0.15 – 0.2 and 0.75 – 1.25
Extreme	<0.15 and >1.25

A high power factor measured on bushings X1 and X3 at 1 Hz indicates insulation-related problems. But we do not know if the cause lies in the solid insulation or the liquid insulation. In order to establish this, a further analysis can be carried out by doing a full dielectric frequency response measurement.

Step 3:
DFR Analysis

The results that were obtained from the full DFR analysis are shown in Table 5. The limits for %mc and conductivity of the oil proposed by Megger are shown in Table 6.

Figure 11. NB DFR measurements on all three bushings

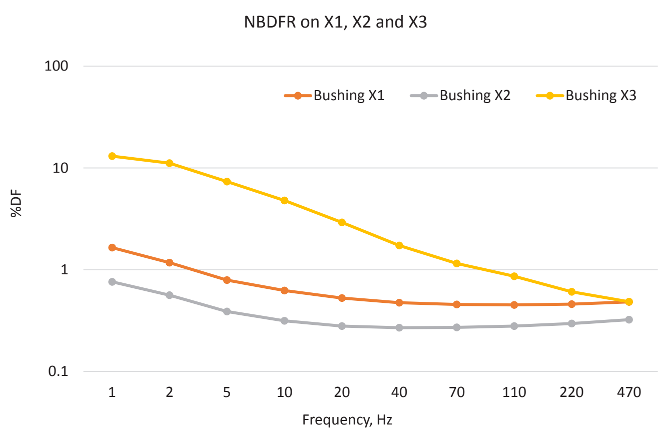


Figure 12. Temperature dependence curves for all three bushings

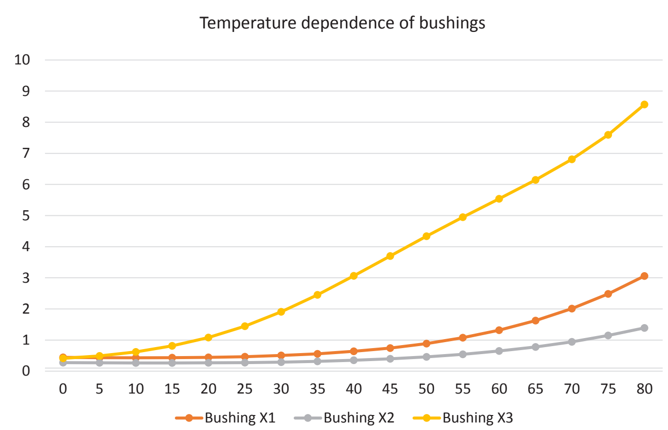


Figure 13. DFR measurements on all three bushings X1, X2, X3

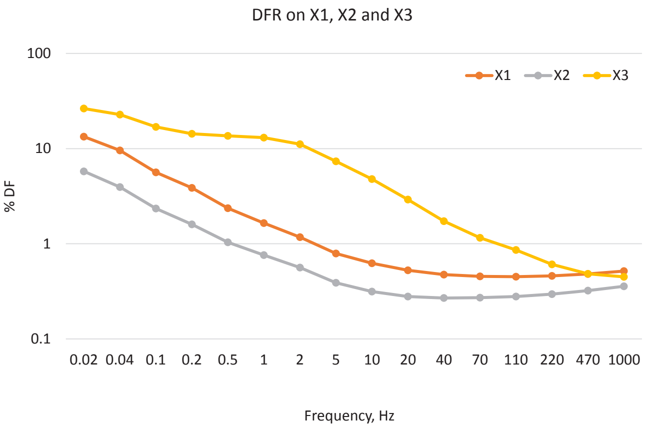


Table 5. %mc estimation and conductivity of the oil obtained from full DFR analysis

Bushing	%mc or contamination	Conductivity of the oil at 25°C (pS/m)
X1	2.5	0.185
X2	1.9	0.05
X3	4.8	0.034

Table 6. Proposed limits for %mc and conductivity of the oil by Megger

Bushing condition	%MC or contamination	Conductivity of the oil (pS/m)
Good	0.15 – 0.5	0.001 – 0.37
Moderate	0.5 – 1	0.37 – 3.7
Severe	1 – 2.5	3.7 – 37
Extreme	>2.5	>37

Overall diagnostics

Table 7 summarizes the final assessment that is obtained from the combination of all discussed measurements.

Conclusion

The line frequency power factor testing, which has traditionally been used for the bushing condition assessment, has its limitations. These limitations can be overcome by conducting dielectric frequency response tests. Owing to the increased sensitivity of power factor to moisture and contamination at lower frequencies, DFR enables us to detect bushing insulation problems at an earlier stage. Any indecisiveness over the course of action to be taken after the conducted narrowband dielectric frequency response test can be eliminated by conducting a full dielectric frequency response test, which enables us to estimate the presence of moisture in the solid insulation and conductivity of the oil. DFR also solves the problem of temperature dependence of the power factor, enabling us to get values for the power factor corrected at 20°C. Testing in a noisy environment can lead to disturbances in the DFR measurement caused by the frequency range and the low currents involved. In this case, testing at higher voltages (1.4 kV rms) enables us to get better DFR results.

References

[1] W. A2.34, "Guide for transformer maintenance," Cigre, 2011
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[4] IEEE C57.152-2013 - IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors
[5] IEEE C57.19.100-2012 - IEEE Guide for Application of Power Apparatus Bushings
[6] IEEE C57.12.90-2015 - IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers
[7] Dr. P. Werelius, Dr. D. Robalino, J. Cheng and M. Ohlen, "Dielectric Frequency Response Measurements and Dissipation Factor Temperature Dependence," 2012
[8] Dr. D. Robalino, "Accurate Temperature Correction of Dissipation Factor Data for Oil-Impregnated Paper Insulation Bushings: Field Experience," 2011

Table 7. Final assessment based on all measurements

Bushing	%LFPF	LFPF as per IEEEC57.152	LFPF as per Cigré TB 445	%PF at 1Hz	%PF at 10Hz	%mc	Conductivity of the oil (pS/m) at 25°C	FINAL DECISION
X1	0.454	Bad	Good	1.32	0.55	2.5	0.185	Severe
X2	0.271	Good	Good	0.660	0.29	1.9	0.058	Severe
X3	1.14	Bad	Bad	11.9	3.6	4.8	0.034	Extreme

Touchless Transformer Monitoring with Energy 4.0 Technology

by **Richard Harada**

This article outlines the challenges that utilities are facing to reduce operating costs and how the latest Industrial IoT technology with sensors to monitor transformers and assets in the substation can help to reduce those costs.

Some utilities are hesitant to adopt IoT due to security concerns but others see the benefits and are embracing the technology.

The article will cover the technologies available and the inevitable shift to their adoption as well as why the technology is secure and economical.

Richard Harada has more than 20 years of experience in industrial networking communications and applications. Prior to joining Systems with Intelligence, Richard worked at RuggedCom and Siemens Canada, where he focused on industrial communications in the electric power market. Richard is an electronic engineering technologist and has a Bachelor of Science degree in computer science from York University in Toronto.

Introduction

The Internet of Things is reaching into many industrial areas including the electric power segment. Some utilities are already deploying the same emerging technologies that are driving the fourth industrial revolution in the manufacturing sector. The Industrial Internet of Things, (IIoT), machine learning, and cloud computing together are among the new technologies being called Industry 4.0 and they are already being used by a few electric companies around the globe for asset monitoring [1], smart metering [2] [3], predictive maintenance [4] and the operations of distributed energy resources, (DER) [5]. Some industry experts have started calling this trend Energy 4.0, to highlight the magnitude of the transformation they expect it will bring to the electric power industry. However, given the traditional slow rate of adoption of new technologies as well as the high reliability standards in this sector, it is not unreasonable to doubt the massive adoption of these technologies to the point of calling it a revolution. On the other hand, the electric energy market in developed countries is at the verge of experiencing dramatic changes that will affect the capacity of utilities to be self sustainable. The emerging technologies that are making possible Industry 4.0 in the manufacturing market, can be a lifesaver for electric companies, helping them adapt to what may be soon the new normal in the electric energy market.

Some utilities are hesitant to adopt IoT due to security concerns but others see the benefits and are embracing the technology.

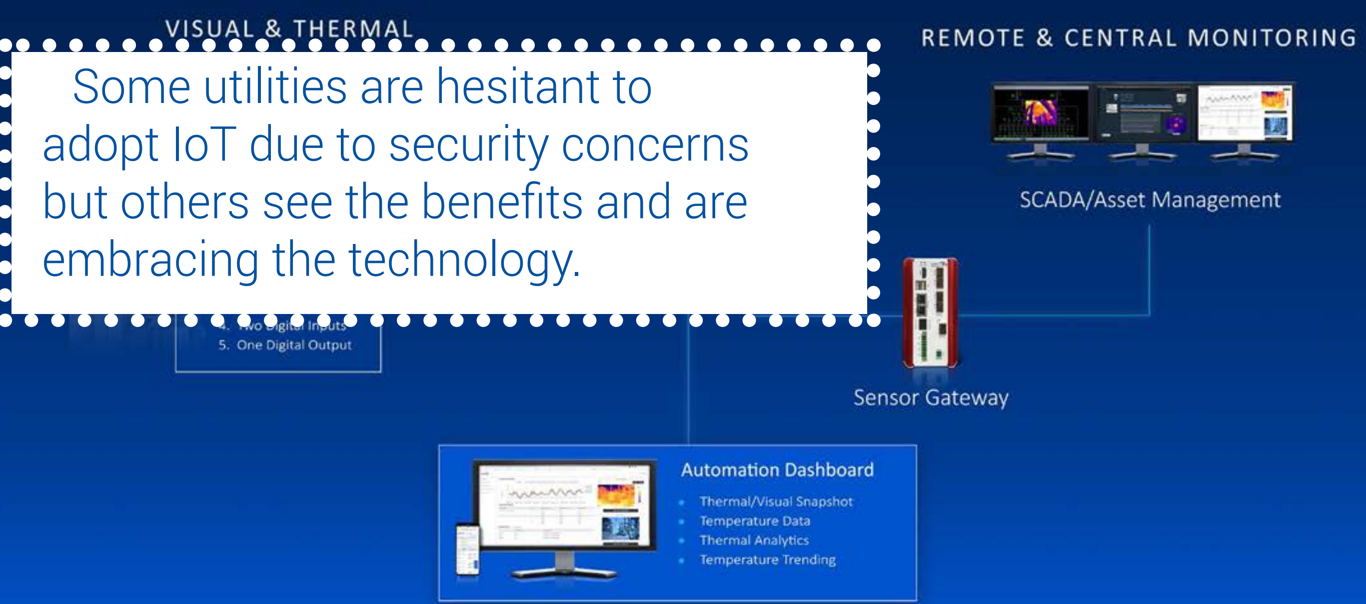


Photo: Systems With Intelligence

Maximizing Profits while the Market Slows Down

The continuous demand for electricity that fueled the growth of the electric industry during the 20th century seems to be coming to an end. Despite the increase in population and the fact that we are living in a time when most activities depend 100% on electricity, its demand in developed countries is plateauing [6], mostly due to more energy efficient appliances and buildings, as well as the off-shoring of power-intense industries [7]. Electric companies have felt the impact of this decline in their revenues, which have not increased for the past 10 years, as shown in Figure 1 [8].

Businesses that are high electricity consumers are also leveraging Industry 4.0 technologies to minimize their energy costs. Energy management systems based on Artificial Intelligence (AI) analyze the electricity market, the global electricity consumption and the business' energy needs to automatically decide when it is a good time to buy electricity from the distribution company, and when it is better to get it from an alternative source of energy, like storage devices or solar panels. In jurisdictions where the annual cost of electricity for businesses is based on their contribution to the major global peaks of consumption during the year, AI systems can provide up to 30% reduction in energy costs [9]. As the use of these solutions becomes more popular, the global consumption of electricity among businesses during a year will eventually flatten out, reducing even more the revenue of utilities and leaving them with under utilized assets.

With decreasing consumption, and since it is not easy to increase electricity rates in regulated markets, electric companies are left with only one option in the short and medium term to maintain their current profits: reduce their operations and capital expenses. Something very difficult to achieve in the coming years given the reliability demands from customers and regulatory bodies, and the

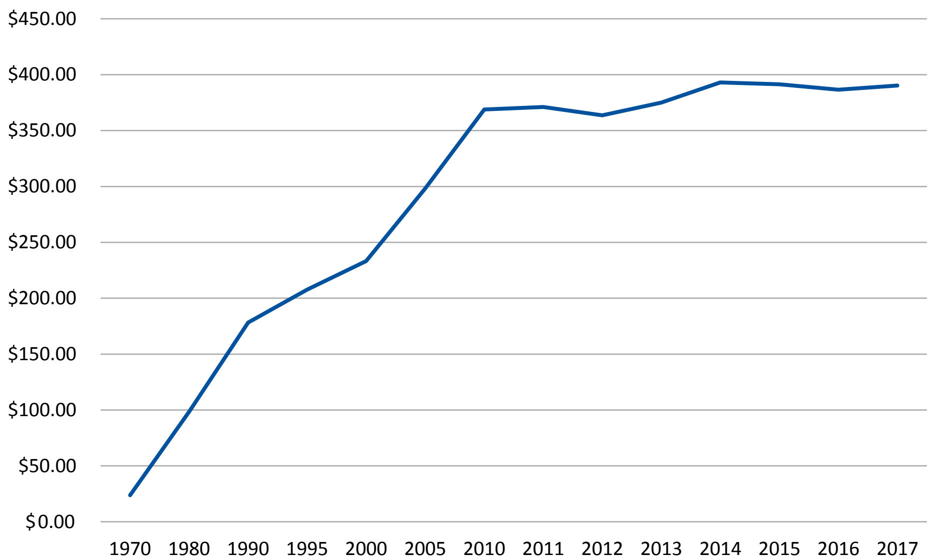


Figure 1. Revenue of the electric power industry in the United States from 1970 to 2017 (in billion U.S. dollars) [8]

The Industrial Internet of Things, machine learning, and cloud computing together are among the new technologies being called Industry 4.0 and they are already being used by electric companies for asset monitoring, smart metering, predictive maintenance and operations of distributed energy resources.

Some industry experts have started calling this trend Energy 4.0.

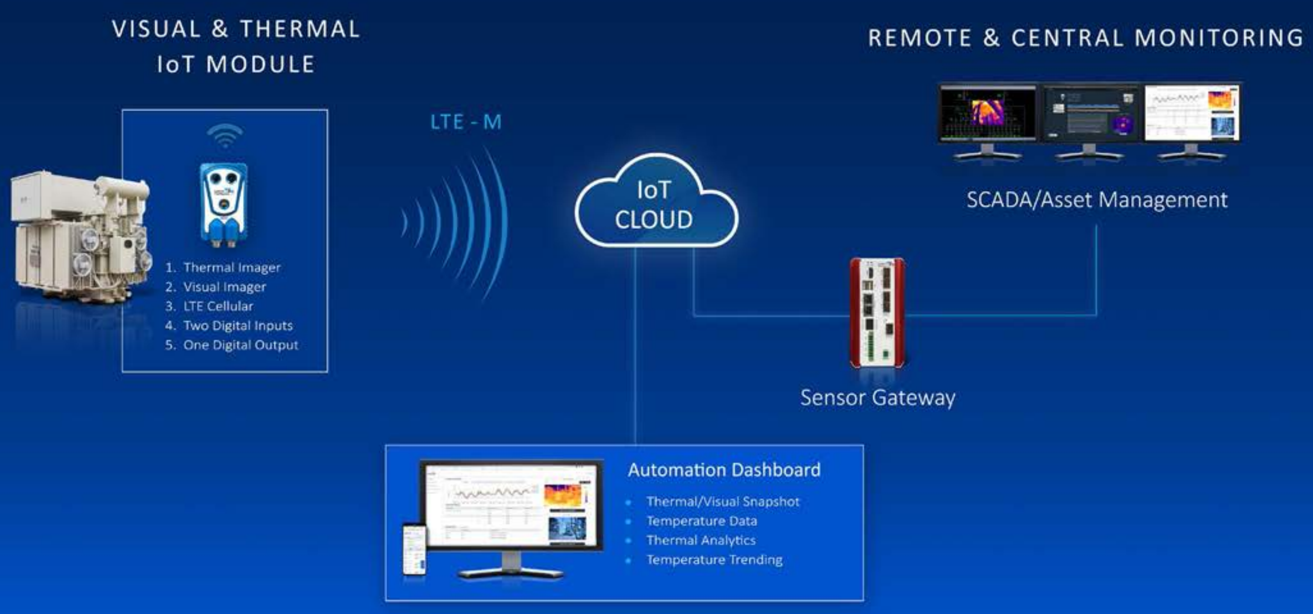
fact that many assets in the grid are reaching their end of life and will soon need to be replaced. Many utilities have implemented preventive maintenance plans, based on manufacturer recommendations of each equipment, in an effort to maximize the lifetime of their assets, reducing this way their capital expenses and the losses from asset downtime; however the labour costs involved in these plans can easily offset the savings in capital. It is here that the emerging technologies of Industry 4.0 can provide a solution.

Electric companies can use IIoT sensors to gather behavioural information about their assets that can then be analyzed together with the data from the rest of the power network using machine learning algorithms and big data techniques, to predict issues and help operations managers decide the right time to maintain or replace an asset. The approach of predicting the time when equipment will need maintenance not only maximizes its lifetime, but also reduces the amount of truck rolls, personnel deployed in the field and material stock, which all translates into savings for the utility, Figure 2.

It is important to note that the use of sensing devices to monitor assets is not a novelty for electric companies. They have been using sensors in their operations for decades already. These sensors are used to monitor load, voltage, phase, temperature and oil viscosity among other parameters, and provide SCADA operators an early warning of the malfunction of specific equipment. There are however two main differences between the existing sensing and actuating devices in the power grid and IIoT devices proposed in Industry 4.0: First, the smaller size as well as lower power requirements and price of IIoT devices, compared to incumbent technologies, make them much easier to deploy in larger quantities in any equipment or at any point in the network. Given that most legacy equipment does not have embedded sensing devices, IIoT sensors are the best solution to acquire the data needed for predictive maintenance plans for older assets, as well as areas in the network that were not previously monitored.

There are two main differences between the existing sensing and actuating devices in the power grid and IIoT devices proposed in Industry 4.0.
First, the smaller size as well as lower power requirements and price of IIoT devices, and second, the use of the Internet for communication instead of private networks to bring the data from the sensors.

Figure 2. Using Industry 4.0 technologies to enable predictive maintenance in the electric industry.



The second main difference is the use of the Internet for communication instead of private networks to bring the data from the sensors. This characteristic is crucial to deploy these devices in a fast and cost-effective way all over the power grid. It is estimated that in order to manage the number of sensors and amount of data needed for an application like this one, the investment required to upgrade an existing communication network will be at least 60% its initial cost [10]. By relying on Internet Service Providers, (ISP), to manage the communications, utilities are diverging the enormous cost involved in building up, upgrading and maintaining a private communication network, to a third-party company whose core competency is communications, and therefore can provide a better service at a lower price.

Emerging technologies like IIoT and machine learning are thus the best options electric companies have when they migrate to predictive maintenance plans. No legacy technology can match what these technologies can offer today at the same cost, reliability and time of implementation.

Dealing with The Democratization of Energy

The electric energy market, that has been an oligopoly for the past hundred years, might soon resemble a perfect competition with multiple buyers and sellers, exponentially increasing the complexity of operating and maintaining the grid to levels beyond the capabilities of the current monitoring and control systems. This shift in the market means that utilities will have to look for faster and more efficient ways to operate their power networks.

Physical constraints for electricity transmission as well as the high amount of capital required for infrastructure and operations, limited the number of sellers in the market since the beginning of the electric industry. However, technological developments in recent years have resulted in cost reductions and increase in efficiency in the technologies involved in the use of, Distributed Energy Resources, (DER), favouring the adoption not only in utility and industrial sites, but also in commercial and residential buildings. Many of these buildings and houses can now generate and store electricity and can decide when to consume the electricity they generate and when to consume electricity from the power grid. Sometimes they will generate more electricity than they can consume, which means they have the potential to become sellers of electricity. Although the current regulatory environment in most countries will not allow individuals to become sellers of electricity at their will, at least not using the power grid, the political support for an open market of electricity is gaining momentum as it is seen as the only way to achieve the commitments made regarding climate change [11].

A democratization of energy will create enormous challenges for electrical companies, as the distribution grid was never conceived or designed to convey power in two directions, as it is required for the incorporation of DER into the grid. Therefore, overvoltage problems and power quality issues will be introduced to the grid when the use of DER starts scaling. The growing popularity of electric vehicles, (EV), adds another level of complexity to the topology of a future electric grid with multiple sellers of electricity. EV can use their batteries to buy or sell electricity from the grid or a building, depending on their energy needs and the electricity rates, and behave as a mobile DER, transforming the topology of the grid from a static to a dynamic one [12]. Electric companies will then have to monitor and control voltage and power flow at every potential point of connection with DER's to eliminate their impact to the reliability of the grid, creating a wave of petabytes of data that must be stored and processed.

Utilities will have to rely on better technological tools than the ones currently in use to adapt their operations to the new power grid. The capital and maintenance cost involved in deploying sensors all over the grid and building a communication infrastructure to support them can be extremely high, so it is a dead-end road for many companies. As previously mentioned, IIoT technology would be the perfect solution to monitor the entire grid at almost an atomic level while minimizing costs and deployment time. IIoT sensors and actuators, designed to consume very low power and using the Internet for communication, can be deployed very fast, most of the time without causing any disruption to the grid, and without having to build a communication infrastructure to support them.

Utilities will have to rely on better technological tools than the ones currently in use to adapt their operations to the new power grid. IIoT technology would be the perfect solution to monitor the entire grid at almost an atomic level while minimizing costs and deployment time.

Electric companies will also have to deal with the constant petabytes of data generated from these devices, a task that will require a computational power that most of these companies can't support. Some of the operations needed for data analysis use peaks of computational power, meaning a utility will have to own expensive hardware that will probably be under utilized most of the time. The best solution would be to share this resource with other companies in the same situation, something difficult to do with in-house servers and computers, but easily done with cloud computing. After accounting for hardware, software and maintenance, the cost of sharing a computing resource on the cloud can be around 20% of the cost of owning it on-premise, as shown in Figure 3 [13]. Reputable providers of cloud computing services, like Google, Microsoft or Amazon, have secure facilities with many reliable and powerful computers that can be used on demand by people, businesses and institutions to process high amounts of data at a fast speed. The several distributed locations of these facilities and the use of the Internet to receive and transmit data, ensures the availability of the service. The high-tech cybersecurity tools and strict physical security policies guarantees the integrity and anonymity of the data. Cloud computing also allows for easy and cost-effective scalability and technology upgrades, making it the best option to deal with the processing requirements of managing the new grid, from a technical and economic view.

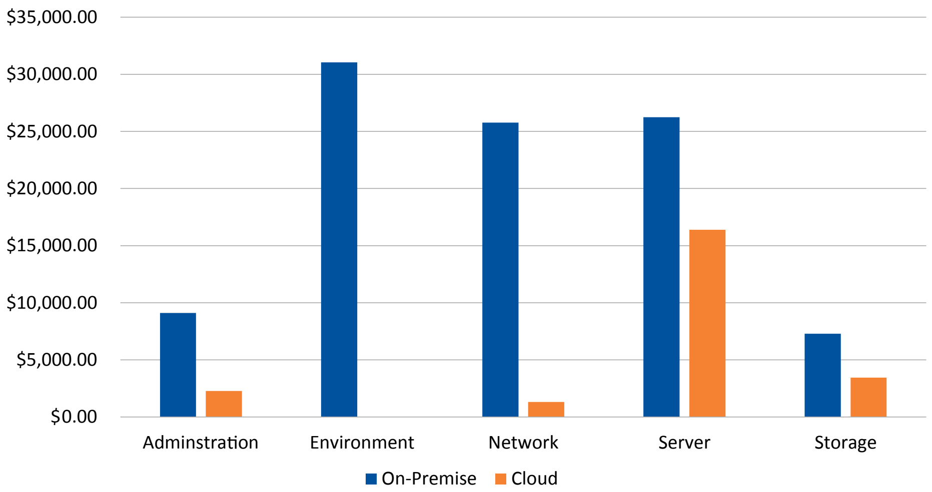


Figure 3. Cost comparison exercise between On-premise and Cloud computing. The cost of accessory hardware and space required for On-premise service (Environment) as well as the Network makes this option the most expensive [13].

There is enough evidence to believe that the revolution some people are calling Energy 4.0 is happening.
It is not just about the implementation of novel, nice-to-have technologies, but it is a response to real changes in the electric market, to which electric companies will have to adapt if they want to remain self sustainable.

What's Next

The previous paragraphs provided arguments to support the adoption of Industry 4.0 technologies by the electric industry. There is enough evidence to believe that the revolution some people are calling Energy 4.0 is happening. It is not just about the implementation of novel, nice-to-have technologies, but it is a response to real changes in the electric market, to which electric companies will have to adapt if they want to remain self sustainable. It is now clear why some electric companies around the world have already started to try these technologies in their operations, despite the risks involved.

The applications of Industry 4.0 technologies shown previously (i.e. IIoT and Cloud computing) are just two examples of how these new technologies can become extremely valuable for electric companies in the coming years. However, there are still some very important issues regarding the implementation of these technologies that must be addressed before they will be adopted massively within this industry. Issues like cybersecurity, service availability, reliability and data ownership are among the common concerns raised by operations and information technology stakeholders in utilities. While these issues have been accounted for and accepted by most other industries and by some in the electric power industry, it may take a while longer before Energy 4.0 becomes widely accepted.

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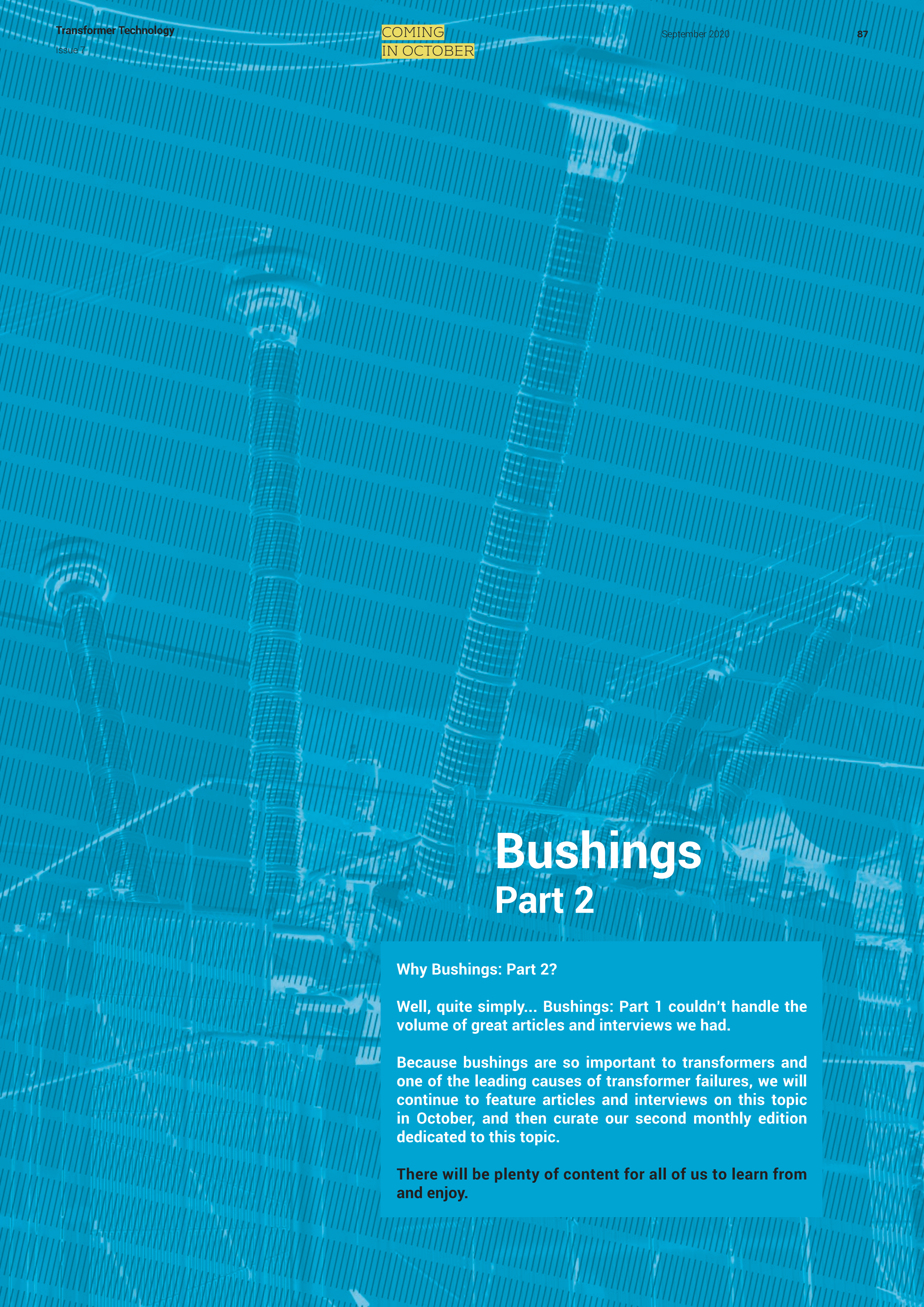

Bushings
Part 2

Why Bushings: Part 2?

Well, quite simply... Bushings: Part 1 couldn't handle the volume of great articles and interviews we had.

Because bushings are so important to transformers and one of the leading causes of transformer failures, we will continue to feature articles and interviews on this topic in October, and then curate our second monthly edition dedicated to this topic.

There will be plenty of content for all of us to learn from and enjoy.