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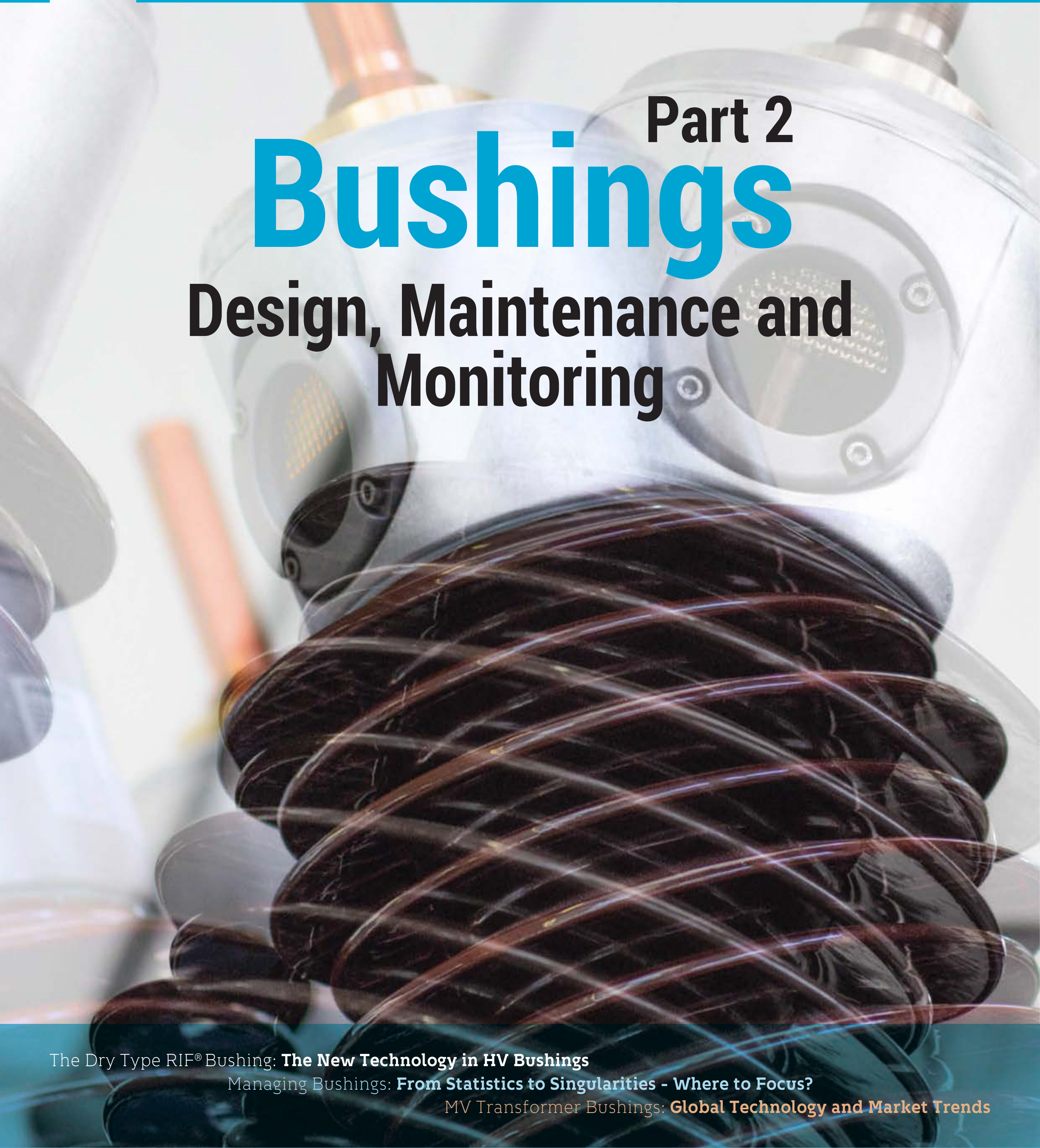

Part 2 Bushings

Design, Maintenance and Monitoring

The Dry Type RIF® Bushing: **The New Technology in HV Bushings**

Managing Bushings: **From Statistics to Singularities - Where to Focus?**

MV Transformer Bushings: **Global Technology and Market Trends**

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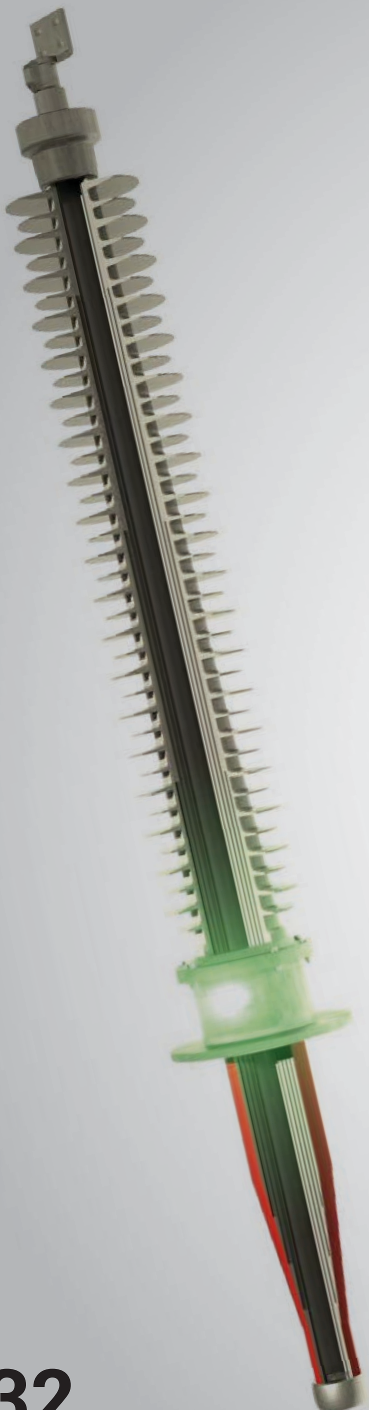

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The Dry Type RIF® Bushing: The New Technology in HV Bushings

This article presents the dry type, high voltage Resin Impregnated Fiberglass (RIF®) bushing technology. The authors have been able to walk the fine line between promoting their unique bushing solution and providing leading edge information that every transformer professional will value.

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Insulator Bushing Containment

Whether storing the bushing for reuse, or preparing it for transportation for recycling or disposal, containing the bushing is a crucial and necessary step for crew safety to prevent spills and unnecessary cleanup costs.

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Transformer Bushings – What Can Go Wrong?

Even a failing bushing which will not lead to a catastrophic failure can harm people due to burst porcelain insulators and broken fragments that can be catapulted through the air by the force of the breakdown arc. This article as a first of the series of two will discuss different failure mechanisms and causes for failures.

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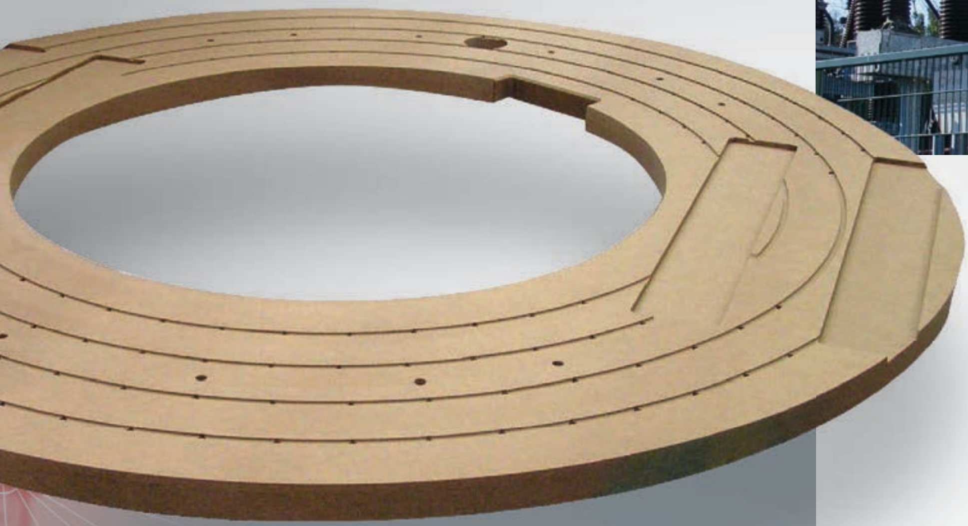


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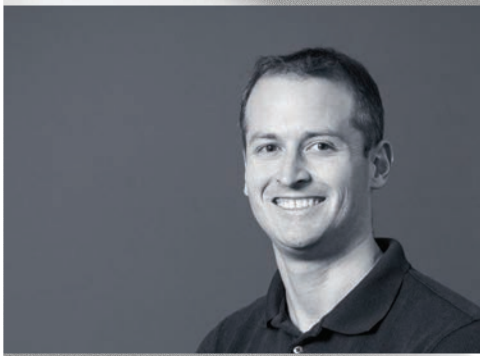


Alan, why Bushings Part 2?

Well, quite simply, because Bushings Part 1 couldn't handle the volume of great articles and interviews we had so we decided to divide the coverage into two monthly issues.

And here you have it - Bushings: Part Deux! Ok, we will stick with Bushings: Part 2.

"One of the most significant principles we adhere to in our community is that we want content that informs, educates, inspires or entertains. The best content does all of that. Transformer Technology is committed to bringing the best of the profession.

I have two great sons. Let's call the eldest, Patrick, Son Part 1 and Michael, his younger brother, Son Part 2. Now when asked which of your sons is your "favorite son", I answer, "My favorite eldest son is definitely Patrick." You get the picture. Which is my favorite Bushings issue, September or October? My answer is much like it is when asked about my favorite son. They are both my favorites, just different.

If you missed September, go back and download and read it at your leisure. That, by the way, is what makes digital copies so great. **Download! Archive! Access on your timeframe!** Of course, you could do that with print, but that costs a lot and leads to clutter. (I must admit though, I do love the smell of a newly printed magazine and the feel and smell of a book as you turn the pages. My Kindle and I are one, but it's just not the same, is it?)

What I love about the October Bushings: Part 2 Issue is much the same as what I like about its older brother - the breadth and the depth of the knowledge shared by our great contributing authors. If you don't think it is a lot of work, try it sometime. Writing an article, I mean. First you have to get by the topic editing, which makes sure we don't become nothing more than a commercial community, but rather a community committed to bringing knowledge and awareness of the past, present and future of transformers.

These critical assets are the heart of any electrical system and are so unique in their design and application, but all based on magnetic fields. The only moving parts are the electrons (Ok and on-load tap changers for you purists. By the way, **the OLTC Month is coming next March**, so if you are an OLTC purist and know a lot about them, become a contributing author for that issue.) As Hassan Zaheer of Powertech Research shows us in his market update, there are great differences in regional market aspects as well as technical aspects.

Writing a quality article takes three things once you get past our Editorial Team:

1. Having something "read-worthy". Why write something unless you know someone who wants or needs to read it? **One of the most significant principles we adhere to in our community is that we want content that informs, educates, inspires or entertains.** The best content does all of that. Transformer Technology is committed to bringing the best of the profession, not just filler.

2. Since most authors also work for a company in our industry or consult for the industry, avoiding commercial content is very difficult, especially when the sales and marketing teams want you to point to their solutions. It is a fine line and I can tell you; we are serious about screening out content that is too commercial. We can't always be purist either, in that there are times, especially in case study-based articles, that mentioning of products or services is necessary to tell the whole story. Even then, we want to focus more on the case study and the knowledge it shares, and less on the brand.

3. We learn in the ways our brains are wired: watching, reading, listening, touching, and sometimes even smelling. That means the article has to provide more than words. We expect great graphs, pictures or charts to bring the article to full color life. But adding all of these for the sake of visual appeal is not the purpose; adding them to better educate, inform, inspire or entertain is.

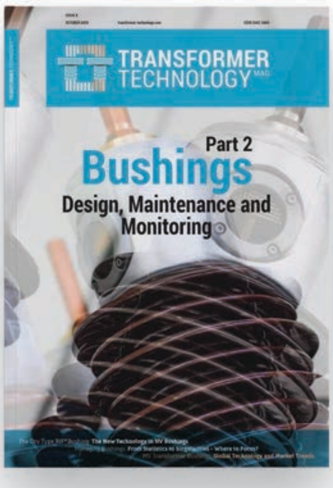
With all that said, we bring you **"Bushings: Part 2"**, my favorite second issue. And remember to visit www.transformer-technology.com for our daily feed of news, articles, videos, webinars and a plethora of powerful content.

And support those who support us... please. While I attempt to make sure we are not too commercial in our articles and digital content, none of this would be possible without the support of companies as they serve our market.

We stress developing a **"Digital Communications Strategy"** with our advertising and promotional partners or Resource Practitioners at EPRA*, and that includes **providing the authors and interviewees, promoting them within their circle of influence and sharing new and promising innovations.** You, our community members, are the most important aspect of that strategy. Without you, we just become billboards on the backroads that nobody sees. We want to be on the superhighway of knowledge in the new informational age. You make that possible. I hope you download and enjoy.

Finally, November and December will be combined into one Issue, themed: **Oils & Fluids: Better Solutions for a Changing World**. We already have an amazing line-up of contributors, with content that will definitely **educate, inform, inspire and entertain**. If you have something to share, even if it not something that would fit into an article, we also have begun taping **Take 5** segments and sharing them with our community on one topic that can be presented in five minutes or less. It is bite-sized knowledge, but knowledge that builds up our community. Let us know if you would like to become contributors to the community.

Alan M Ross
CRL, CMRP
Editor in Chief
Transformer Technology



Please feel free to contact me any time at alan.ross@transformer-technology.com, or by phone at +1 404-992-5111.

It is time to lead.
It is time for a change.

Managing Bushings:

From Statistics to Singularities – Where to Focus?

Dr. **Tony McGrail** is Doble Engineering Company's Solutions Director for Asset Management & Monitoring Technology, providing condition, criticality and risk analysis for utility companies. Previously Tony has spent over 10 years with National Grid in the UK and the US; he has been both a substation equipment specialist and subsequently substation asset manager, identifying risks and opportunities for investment in an aged infrastructure. Tony is a Fellow of the IET, a member of the IEEE, CIGRE, ASTM, ISO and the IAM, and is currently active on the Doble Client Committee on Asset and Maintenance Management and a contributor to SFRA, Condition Monitoring and Asset Management standards. His initial degree was in Physics, supplemented by an MS and a PhD in EE followed by an MBA.

Dr. **Ronald D. Hernández** holds Ph.D., M.S. and B.S. in EE. He also holds a global MBA. Dr. Hernández joined Doble Engineering Company in 2012 and is currently its Diagnostic Analysis Research Manager. He has developed applications in the fields of moisture in insulation systems, dielectric frequency response, transformer failure rates and statistical analysis, and has authored multiple articles related to these topics. He is a member of the IEEE Transformer Committee and is active in several working groups.

Managing a population of bushings presents challenges – but also opportunities. The challenges are to identify those bushings which are most worthy of more detailed attention or intervention. The opportunity is to use the latest in statistical analyses of populations to augment traditional limit-based approaches to determine bushings of interest.

Photo: Shutterstock, Doble Engineering

Figure 1. Overheating bushing

Bushing Basics

A bushing is a means to allow a conductor to pass through a barrier. Bushings can be quite complex as they need to distribute the electrical stress from the conductor evenly across their insulation [1]. Bushings are used with several asset types and are usually reliable devices, but, as with all assets, deterioration will occur and failure is a possibility.

An organization may have a large number of bushings to manage and will need data to support bushing decisions: the default position usually being *"We have no new data, but it is still in service, so it must be OK."* This "Fix on Fail" approach can lead to problems as there is no warning of failure, and the bushing may well fail in a way which also destroys the power transformer it serves. The use of visual inspection, Infra-Red (IR) and Partial Discharge (PD) surveys can provide useful data and may help identify where deterioration is occurring, and where to focus attention, such as the overheating bushing in Figure 1.

Regular offline testing of bushings provides information about capacitance and power factor of the bushing insulation, checked against benchmark values (nameplate or first test measurement) to indicate if there has been any deterioration [2]. Note that bushings may have expected values for insulation power factor, but these will depend on the manufacturer and the individual design of the bushings. A common approach to evaluation is the following: If the test result exceeds 0.5% or double the nameplate value, then the bushing may be in a condition requiring replacement [3].

Photo: Shutterstock, Doble Engineering

CASE 1

Analysis of Test Results Referenced to Nameplate

One of the three GE Type U 345 kV high voltage bushings on a 375 MVA transmission class autotransformer manufactured in 1986 showed elevated power factor of 0.45% compared to the nameplate value of 0.27%. The other two bushings in the set were at 0.30% against the nameplate of 0.26% for each bushing. With no spare bushing available and the transformer needed in service for operational reasons, the transformer was returned to service with a bushing monitoring system in place to indicate any further deterioration. Ten months later, an outage was taken and the suspect bushing was replaced, using a Lapp Type POC. The other GE Type U bushings gave test results at nameplate values when tested, and the transformer was returned to service [4].

Less than four months later, the bushing monitor indicated an elevated power factor on one of the original GE bushings. The rise in the daily trend reported for the two remaining GE Type U bushings is shown in Figure 2. A rising trend had occurred after the return to service, and an offline test confirmed that the bushing had elevated power factor of 1.36%. The capacitance had increased by just 2 pF against the nameplate value of 398 pF. The bushing was thus replaced.

The approach described in the original paper that outlined this case [4] is useful, and it involves identifying a bushing of interest through standard testing, but then applying monitoring to track the deterioration directly. A response plan is necessary to make sure that intervention is undertaken when alarms are issued. However, for the two bushings which were replaced it is interesting to note the following:

- the original suspect Type U bushing remained in service for more than 10 months while being monitored and issued no alarms;
- the subsequent Type U deterioration of the second bushing took place over less than 4 months to issue the alert.

The deterioration rate of an individual bushing may be different to others of the same type – and the future rate of deterioration may not be predictable, as it may depend on variation in load, ambient conditions, repeated energizations and other factors.

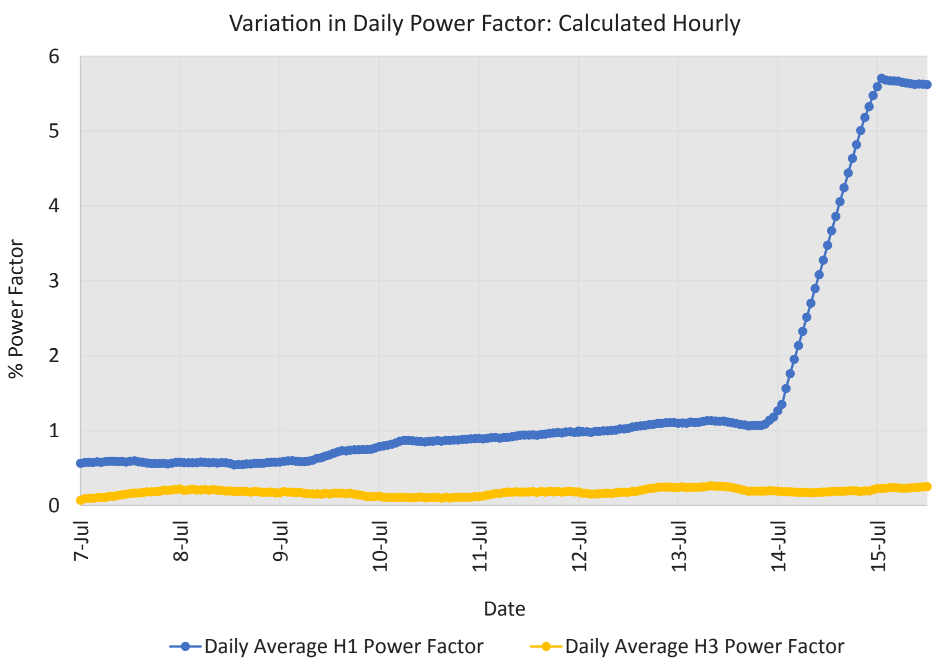


Figure 2. Case 1 - Monitoring detects rising power factor trend

CASE 2

Checking Against a Population – Is It an Outlier?

A deeper statistical analysis can be performed by comparing an individual bushing results to those of its 'peer group' or family: bushings of the same manufacturer, design and voltage rating.

A useful analysis for a population of bushings is to look at the *difference* (or delta) between the measured value of power factor (or capacitance) for each bushing and its own benchmark value; then use those results for the population to calculate the population mean, *m*, and standard deviation, *σ*, of the deltas by modeling the observed data. Anything lying more than three standard deviations away from the mean is considered to be an outlier [3] and worth investigating.

The statistical analysis uses a large population of results, providing a usable distribution of expected variation between test results and a benchmark value (nameplate or first test measurement).

Note that the approach is not a diagnostic as we are looking for variations in 'symptoms' (the measured values) to allow subsequent investigation and diagnostics to identify the failure mode(s) in operation [2]. The data is also modeled against probability distributions to identify the one which gives the lowest deviations from the observed data.

A utility electrical testing group obtained power factor test results for three ABB, 69 kV, type AB bushings, which seemed 'a little high' at ~0.5%. The utility compared the three results against their own database of 390 test results from 105 individual bushings. The delta values were calculated with respect to the first power factor measurement of each of the bushings. Figure 3 shows the distribution of delta values found, in red, and the gamma function resulting with the best fit, in blue. Bushings H1 and H2 are more than three standard deviations from the expected value (i.e. the mean), with only 2.22% of the population expected to lie in this region. They do appear to be outliers in the utility's database.

The same analysis was performed using the Doble database population of the same manufacturer, bushing type and voltage rating – with a total of 5,278 test results available for 2,723 individual bushings, as shown in Figure 4. Against this population, the anomalous results do not lie beyond three standard deviations – so they are no longer 'outliers'.

As a result of the analysis, it was decided to leave the bushings in service: condition monitoring and increased frequency of testing are being considered.

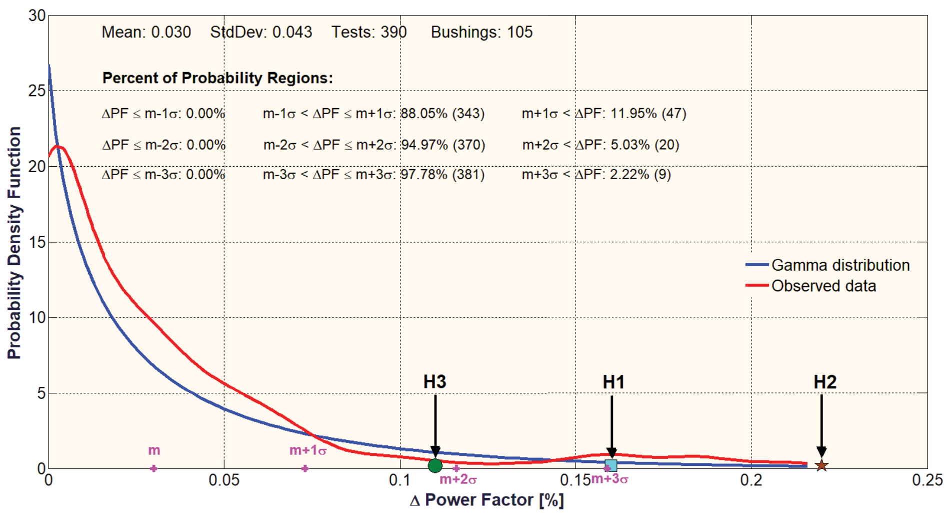


Figure 3. Case 2 - Bushing statistical analysis using utility's database population

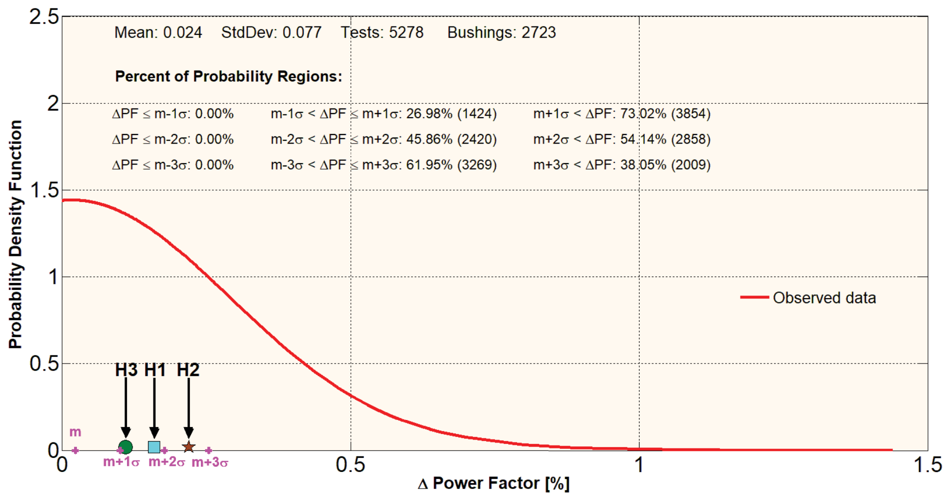


Figure 4. Case 2 - Bushing statistical analysis using Doble's database population

Photo: Shutterstock, Doble Engineering

CASE 3

Not an Outlier – But Still Suspect?

It has been reported that the failure rate of Trench COTA 230 kV bushings, manufactured at three different bushing factories (in France, Switzerland and Canada) between 1994 and 2000, is higher than expected for bushings of this type [5]. A utility had 52 bushings of this type, with 108 individual test results, and wished to know if they had any instances of 'outliers' which could help focus their replacement program. Two bushings had seemingly acceptable power factor values, being <0.5%, but were outliers for the utility: maybe they should focus their attentions on those two? Figure 5 shows the actual C1 delta between nameplate and test results distribution, in red, and the exponential model (best fit), in blue. The two bushings of interest are outside of three standard deviations from expectation – so acceptable results in terms of absolute C1 power factor values, but outliers in the utility population.

Figure 6 shows the same analysis but using the entire Doble database population (442 bushings and 680 data points). The two bushings have C1 delta power factor values which are just outside of one standard deviation from expectation.

Consequently, the two bushings are outliers in terms of the utility population but are not with reference to the larger Doble database population. But the fact that the larger distribution is very compressed, with ~96.5% of test results being below one standard deviation from the mean, indicates that the two bushings are anomalous – they are unusual, and the history for this type of bushing would imply that they should be prioritized for replacement, and/or condition monitoring should be considered to track their condition online.

Intervention requires evidence, and the statistical analysis provides that.

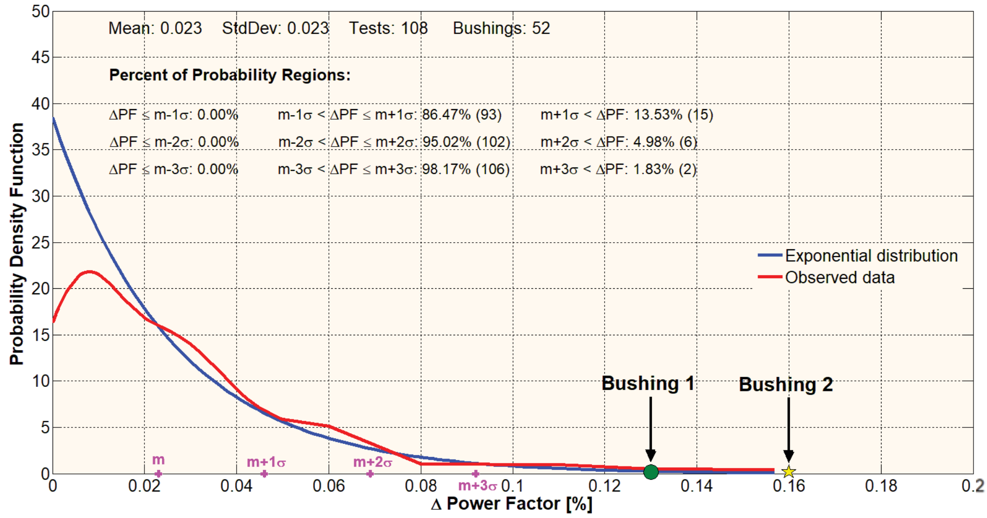


Figure 5. Case 3 - Bushing statistical analysis using only utility's database population

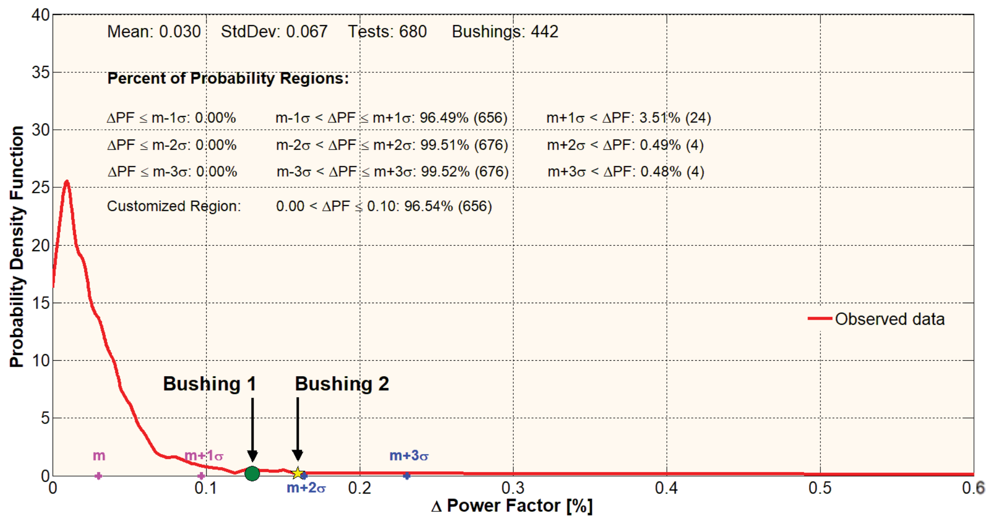


Figure 6. Case 3 - Bushing statistical analysis using entire Doble's database population

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Discussion

Managing a population of bushings presents challenges – but also opportunities. The challenges are to identify those bushings which are most worthy of more detailed attention or intervention. The opportunity is to use the latest in statistical analyses of populations to augment traditional limit-based approaches to determine bushings of interest. The statistical analysis uses a large population of results, which relies on Doble's daily updated database of more than six million individual test results. It provides a usable distribution of expected variation between test results and a benchmark value (nameplate or first test measurement); the approach benefits from a use of mean and standard deviation limits, but also allows for determination of just how many results lie below our individual result – indicating just how 'different' our result is. Intervention requires evidence, and the statistical analysis provides that.

Acknowledgment
The authors would like to thank our colleagues at Doble and across the industry for their discussion of bushings and related matters.

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MV Transformer Bushings: Global Technology and Market Trends

by **Azhar Fayyaz**
and **Hassan Zaheer**

Introduction

Both power and distribution transformers are the most critical and expensive assets of any power system, and their failure leads to significant financial and, in worse cases, fatal losses. Due to urbanization, industrialization and electrification, global demand for energy is on the rise, overloading the network and eventually jeopardizing the reliability of power supply. Therefore, utilities are bent on, more than ever before, assessing the operating conditions of transformers as well as their components with a special focus on insulation system to minimize the failure risks and avoid unplanned power outages.

Bushings, one of the essential components of transformers are the third major cause of transformer failures, after tap-changers and windings failure [1], as shown in Figure 1. Despite being a relatively low-cost component (accounting for only ~5% of the total transformer price), bushings ensure safe operation of a comparatively high value asset. They connect the transformer windings to the inlet or outlet conductors while providing an insulation resistance between the live conductor and grounded transformer body.

According to a transformer reliability survey conducted by CIGRE, nearly 17% transformer failures are caused by bushings fault, 30% of which resulted in fire incidents and 10% in explosions [1]. Bushings have a high failure rate because they are subjected to strong electric field intensity resulting from high potential difference at a close distance between HV terminals and the grounded body. Realizing its importance, many utilities and power generation companies are pursuing preventive maintenance of bushings by proactively monitoring their aging and degradation, even if it is complex and quite expensive.

Despite being a relatively low-cost component, accounting for only ~5% of the total transformer price, bushings ensure safe operation of a comparatively high value asset.

Photo: Shutterstock

Azhar Fayyaz is a Market Analyst at Power Technology Research. He is involved in projects on the power grid topics at Power Technology Research gathering data on network structure of distribution utilities, estimating the installed base of T&D equipment and analyzing the information to predict future market trends. As a market analyst at PTR, he performs competitive analysis of different companies operating in a region and determine their market share for a specific product. He also has more than 2 years of experience working as a senior shift engineer at Chashma Power Generation Station. Azhar has a M.Sc. in Power Engineering from Pakistan Institute of Engineering & Applied Sciences.

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Key Technology Trends in Transformer Bushings

Bushings are generally designed to minimize field stress by uniformly distributing electric field intensity in both radial and axial directions when passing through the grounded metallic flanges. For this HV bushings typically employ capacitance-graded design i.e. their core is formed by wounding different layers of paper insulation with metallic foils to optimally distribute the electric field. There are three different types of HV bushings: Oil Impregnated Paper type (OIP), Resin Impregnated Paper Type (RIP) and Resin Bonded Paper Type (RBP). MV and LV bushings, on the contrary, are composed of hollow porcelain housing filled with resin or transformer oil surrounding the current carrying conductor.

RIP Bushings

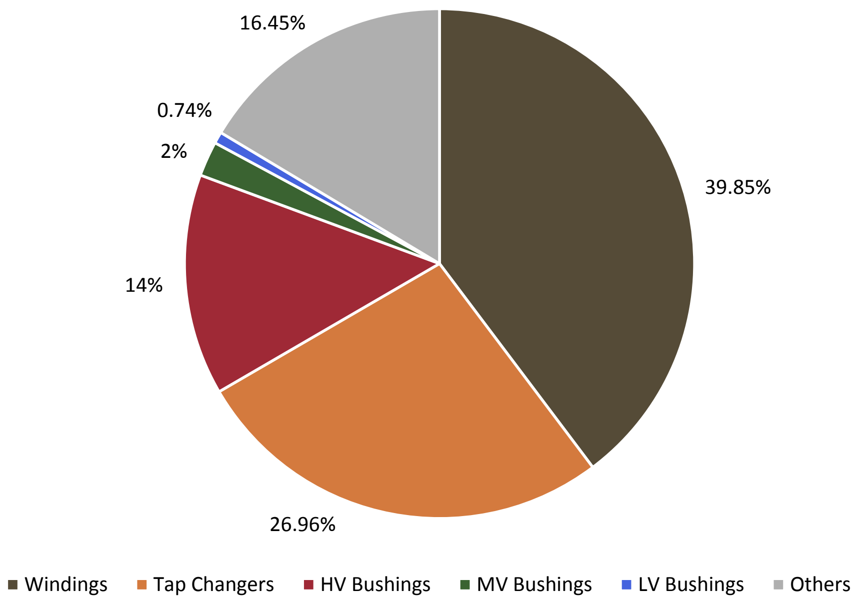
Almost 65-75% of the bushings installed in the market are OIP, however trend is slowly shifting towards RIP. In RIP bushings, the paper insulation is placed inside a housing after impregnation with epoxy resin, thus resulting in gas tight and void free product. RIP bushings are relatively higher in cost compared to OIP and RBP type, but this cost difference is easily compensated by added benefits such as better thermal advantages and oil free solution.

Composite Housings

Porcelain and the silicon based composite insulators are the most common materials used to design housings for transformer bushings. Most of the bushings currently in service are porcelain based, but composite insulators have significantly increased their market share in the recent years successfully penetrating developed markets due to the following advantages:

- Due to hydrophobic nature of silicon, composite housings can operate under heavily polluted

Figure 1.
Reasons for transformer failures
Source CIGRE [1]



environment without compromising the performance, thus minimizing the maintenance cost.

- Being lightweight and less fragile, they are easy to handle and assemble during in-house installations.
- They have very short lead times compared to their counterparts, porcelain housings.
- Inherent safety features of composite housings, owing to their design and manufacturing technology, prevent explosion in case of a fault thus ensuring the safety of workers and public in the vicinity.

Online Condition Monitoring of Transformer Bushings

Statistics identify bushings faults as the major reason for transformer failures, thus incentivizing the operators to continuously monitor integrity of the bushing's insulation. Also, bushings are usually as old as transformers themselves, which makes it essential to continuously monitor them in decades-old grid infrastructures. Another reason for utilities to adopt online condition monitoring is the recent shifting trend towards smart grid infrastructure.

While there are several online monitoring techniques have been developed over the years, periodic offline testing still plays the dominant role. Most commonly employed tools for online detection of incipient faults in transformer bushings are electrical tests, such as capacitance, partial discharge, and dissipation factor (tgδ) measurements.

Global MV Transformer Bushings Market

Global Market Overview

Bushings demand is directly coupled with transformers market as transformers are one of the major applications of bushings. Globally, the primary market driver for transformer bushings is the increasing demand for a stable and reliable power supply. High penetration of the renewables and electric vehicles (EVs) charging infrastructure at MV level has been instigating major grid expansion projects worldwide. Also, high replacement rates to refurbish aged grid infrastructure from developed countries, along with increasing electrification and urbanization from developing countries are to further spur the demand for transformer bushings. APAC market is by far the biggest market of MV transformer bushings globally, followed by Americas market. Most of the growth in APAC region is attributed to grid expansion plans by utilities to cater for the increase in generation capacity. However, in developed regions of Europe and Americas, replacement plans by utilities to enhance system reliability are primarily instigating the bushings market.

EMEA Bushings Market 2019

The combined distribution transformer bushings market for Europe, Middle East, and Africa (EMEA) region observed a total sale of 2.56 million units in 2019, 57% of which was captured by Europe alone. Biggest markets in the Europe are Germany and UK, while Saudi Arabia and South Africa are the leading markets in Middle East and Africa, respectively.

Transformer bushings market in Europe is primarily replacement driven, especially in Nordic region where the emphasis is to replace 40-year-old grid infrastructure. Renewables penetration and installation of EV charging infrastructure in the Western European countries is also instigating the expansion of distribution grids, consequently driving the bushings market.

Key market drivers in the Middle East, especially GCC countries are large infrastructure projects planned in the region to develop it as a financial and tourism hub to diversify the economy and lessen its reliance upon oil resources. Also, for the first time in history of Saudi Arabia, biggest market in the Middle East, large renewable energy projects planned under Vision 2030 are to instigate a demand for distribution transformer bushings. New power generation projects, capacity expansions in grid to accommodate power injection and increased electrification are to majorly drive the bushings market in Africa. Figure 3 depicts some of the major markets studied in the region for analysis.

Figure 2.
EMEA distribution transformer bushings market (units)
Source: Power Technology Research [2]

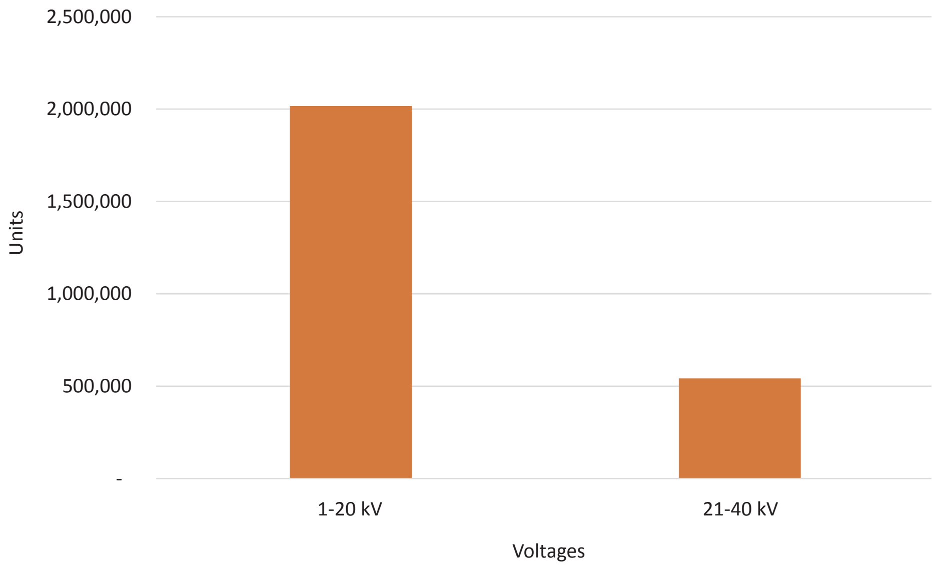


Figure 3.
Key EMEA markets
Source: Power Technology Research [2]

The combined distribution transformer bushings market for Europe, Middle East, and Africa (EMEA) region observed a total sale of 2.56 million units in 2019.

Americas Bushings Market 2019

Bushings volume for both North and South America was 3.37 million units in 2019. USA was the largest market in the region with a total sale of 1.35 million units.

Bushings market in USA, the biggest market of North America is primarily driven by government initiatives to revamp electrical infrastructure [3], [4].

Unlike North America, greenfield market overshadows replacement market in South America as most of the utilities have adopted failure replacements approach rather than preventive replacements. Distribution companies in the region plan to invest heavily in the expansion of the grid to cope with the planned generation capacity additions. Also, electrification remains the key investment driver in the region. Even though the current electrification in Brazil is close to 98%, the topic remains a major reason for investments in the grid. Figure 5 shows the markets in the region presenting the highest opportunity based on a myriad of reasons along with market sizing.

Figure 4.
Americas distribution transformer bushings market (units)
Source: Power Technology Research [2]

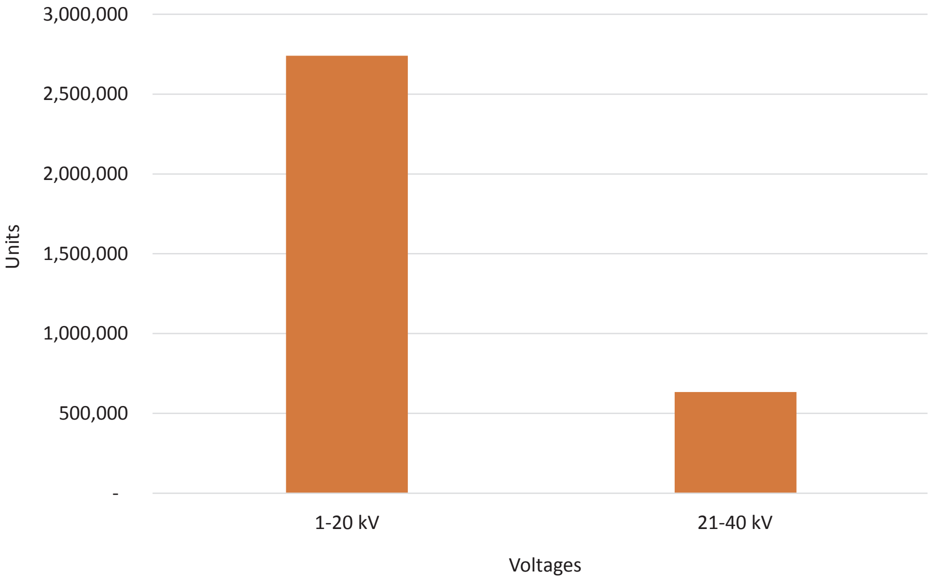
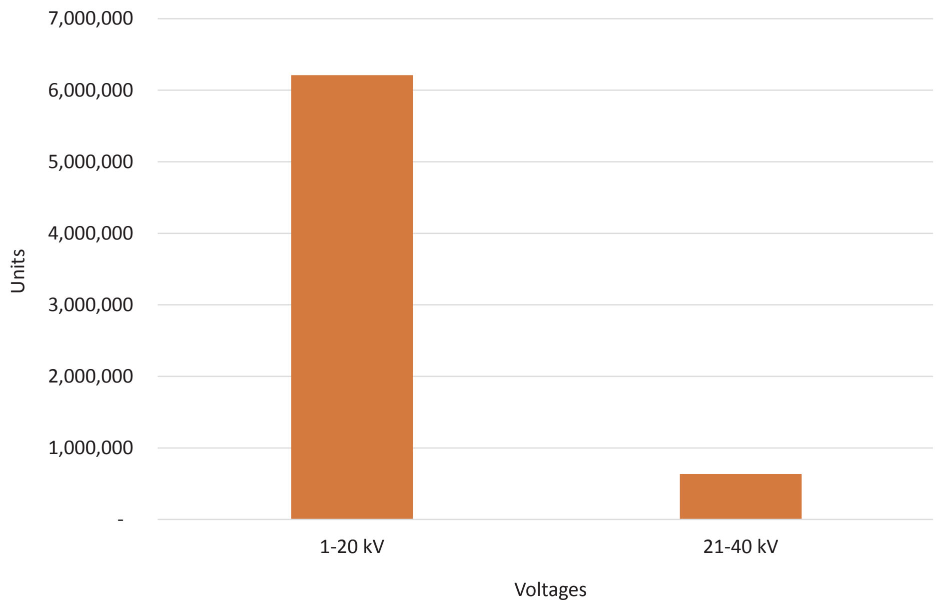


Figure 5.
Key Americas markets
Source: Power Technology Research [2]

USA was the largest market in the Americas region in 2019, with a total sale of 1.35 million units. Bushings market in USA is primarily driven by government initiatives to revamp electrical infrastructure.

Figure 6.
APAC distribution transformer bushings market (units)
Source: Power Technology Research [2]



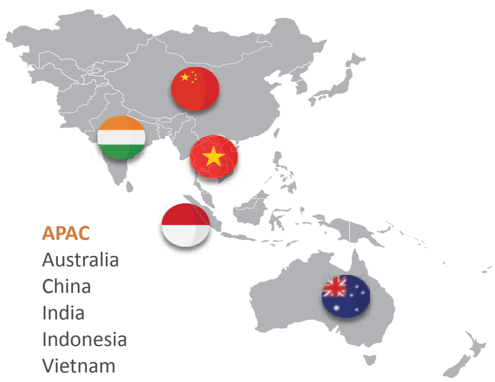


Figure 7.
Key APAC markets
Source: Power Technology Research [2]

APAC Bushings Market 2019

In 2019, ~6.84 million units of MV transformer bushings were sold in APAC. China, as expected, was the biggest market in the region with 37% market share, followed by India at 22%. It is also noteworthy that China is not only the largest market in the region but also globally.

Electrification and urbanization are the two key factors driving the greenfield investments in the distribution grid for APAC. Additionally, developments in power generation sector also require capacity additions in the distribution grid for countries like China, India, and Indonesia thus fueling the demand for bushings. High number of failure replacements in India and environment driven replacement programs in China are also a major driving factors for the distribution transformer bushings market. Figure 7 shows some of the key markets in APAC region to keep an eye on in future years.

According to U.S department of energy, nearly 70% of the transmission and distribution equipment in US grid is more than 25 years old [5], replacement of which will fuel the demand for bushings.

Conclusion

Bushings are a critical part of transformers, and their failure can not only lead to total loss of a transformer but also to a loss of many other equipment in the surrounding. Thus, it is of paramount importance to continuously monitor bushings condition to increase system reliability. Also, online condition monitoring has become the key objective for many utilities as part of their smart grid initiatives.

Future market demand for transformer bushings looks promising as most of the utilities are upgrading and expanding their MV distribution network owing to increased penetration of renewables and EVs into the grid infrastructure. Steady growth is expected from APAC and South America markets where electrification is high on agenda. Major infrastructure and power generation projects in MEA region are to further drive the future bushings market. However, Europe and North America markets are expected to see a combination of both greenfield and brownfield additions in the coming years.

Bushings market demand in 2020 has also been impacted badly by the COVID-19 pandemic. Supply, however, was comparatively less affected as most of the manufacturing facilities continued production except for 1-2 weeks when COVID-19 impact was at peak in a country and strict lockdown was implemented. Moving forward, market is expected to bounce back from Q1 of 2021.

With the advent of renewable energy, Western European countries are concerned about grid reliability and are planning to introduce stricter grid compliance codes, thus more utilities are expected to adopt online monitoring techniques. OEMs offering turnkey asset management solutions can capitalize this opportunity by targeting these markets.

Bushings market demand in 2020 has also been impacted badly by the COVID-19 pandemic. Supply, however, was comparatively less affected as most of the manufacturing facilities continued production except for 1-2 weeks when COVID-19 impact was at peak in a country and strict lockdown was implemented. Moving forward, market is expected to bounce back from Q1 of 2021.

References

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[2] "Distribution Transformers Global Market Analysis," Power Technology Research, 2019

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The Dry Type RIF® Bushing: New Technology in HV Bushings

by **Robert Middleton**
and **Eric Euvrard**

WHEN DEALING WITH WHAT APPEARS TO BE PROPRIETARY OR PROTECTED INFORMATION RELATED TO NEWER TECHNOLOGIES, IT IS HARD TO SEPARATE THE COMPANY FROM THE TECHNOLOGY AND PROVIDE VALUABLE, LEADING EDGE INFORMATION. IN THIS ARTICLE, ROBERT AND ERIC HAVE BEEN ABLE TO WALK THAT FINE LINE BETWEEN PROMOTING THEIR UNIQUE BUSHING SOLUTION AND PROVIDING LEADING EDGE INFORMATION THAT EVERY TRANSFORMER PROFESSIONAL WILL VALUE. WELL DONE ROBERT AND ERIC.

Robert L. Middleton was born in Winnipeg, Canada. He received his degree in Electrical Engineering from the University of Manitoba in 1971. He is a registered professional engineer in the Province of British Columbia. He has an extensive background in generation and transmission engineering including quality assurance. He has served on several CSA, CIGRE and IEC working groups and co-authored numerous technical papers. He is presently Chief of Technology and Engineering for RHM International, a manufacturer of high voltage dry type current transformers, bushings and cable terminations. Prior to joining RHM International he worked over 40 years at two western Canadian provincial electrical utilities.

Eric Euvrard is President of RHM International, the specialist of high voltage dry type insulation technologies. With a background in material science engineering and business he held positions in research, manufacturing and marketing in different large traditional and high-tech industries in Europe and North America. In 2004 he founded RHM International which is based in Brookline, MA USA with operations in Hudson, NH USA and Beijing, China.

Photo: RHM International

A Short Bushing History

To better understand the latest developments in bushing technologies it would certainly be helpful to readers not fully familiar with this segment of the power industry to understand how we got there.

HV AC bushings appeared in the late 19th century with the first AC transformers. Those first bushings were bulk bushings, meaning the insulation relied on the thickness of a solid material placed around the high voltage conductor.

As voltages increased, the diameter of those bushings became quickly prohibitive.

About a century ago the capacitance graded insulation structure was introduced. It inserts a succession of capacitive layers within the core insulation, providing a more linear and controlled electric field distribution. A key benefit of this technology was the significant reduction of the bushing's diameter. It has been the core design concept for HV bushings ever since.

Still, from this same concept, differences between the successive bushing technologies are directly related to the type of materials and fillers used to create the capacitive structure.

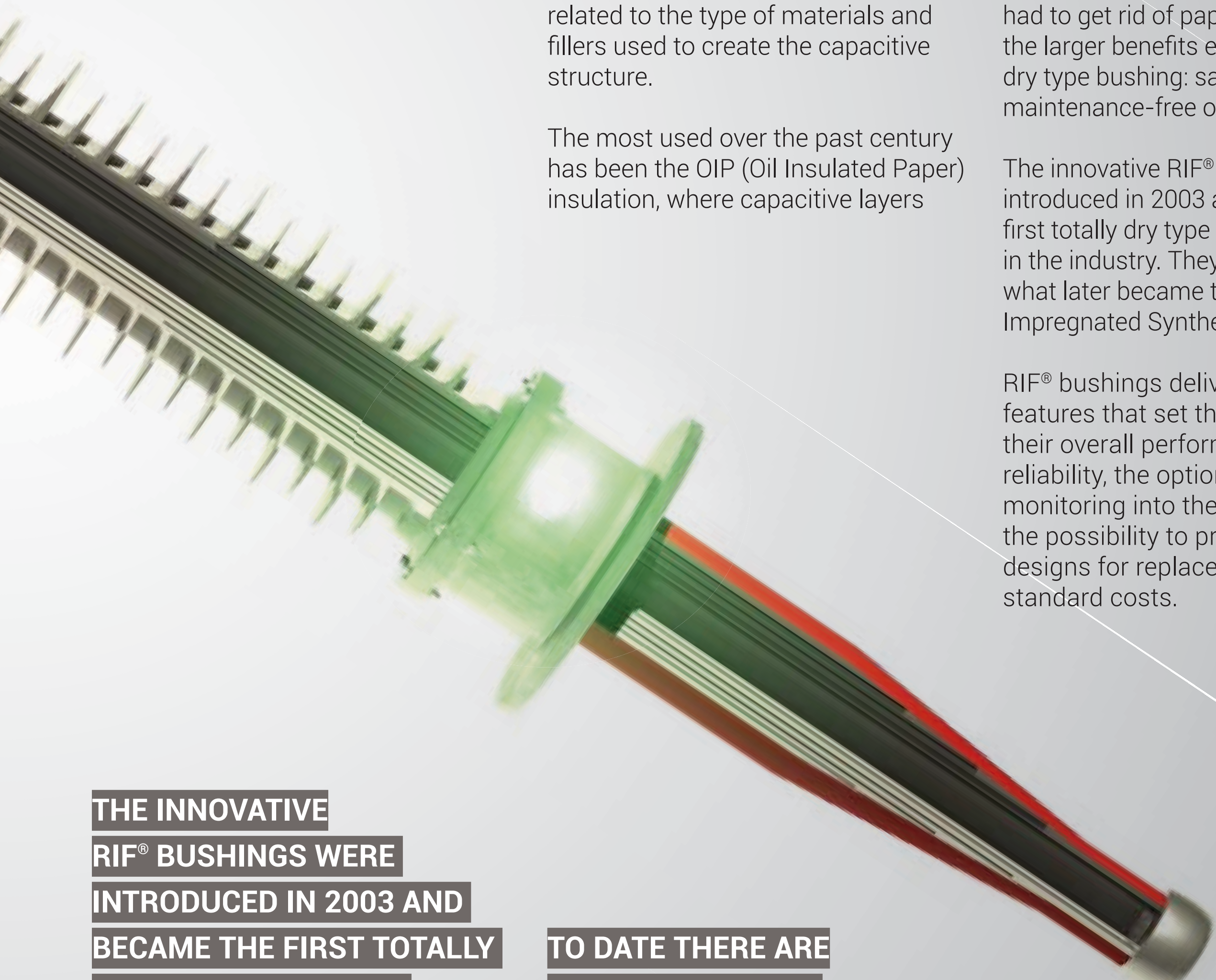
The most used over the past century has been the OIP (Oil Insulated Paper) insulation, where capacitive layers are separated by a special paper and immersed in insulating oil.

To try to mitigate the challenge of managing large volumes of oil, from leaks to potentially dramatic failures, the RIP (Resin Impregnated Paper) insulation was introduced in the mid-20th century. This technology substituted a resin for the insulating oil. Leaks were eliminated, but the presence of paper still presented a potential hazard if stored incorrectly or operating in high humidity conditions. But it was considered a "dry type" bushing.

The next generation of bushings then had to get rid of paper to fully deliver the larger benefits expected from a dry type bushing: safety, reliability and maintenance-free operation.

The innovative RIF® bushings were introduced in 2003 and became the first totally dry type *paperless* bushings in the industry. They pioneered what later became the RIS (Resin Impregnated Synthetics) category.

RIF® bushings deliver a unique set of features that set them apart; namely, their overall performance for high reliability, the option of integrating monitoring into their structure and the possibility to provide custom designs for replacement needs at standard costs.



THE INNOVATIVE RIF® BUSHINGS WERE INTRODUCED IN 2003 AND BECAME THE FIRST TOTALLY DRY TYPE PAPERLESS BUSHINGS IN THE INDUSTRY.

TO DATE THERE ARE OVER 22,000 UNITS IN-SERVICE WORLDWIDE.

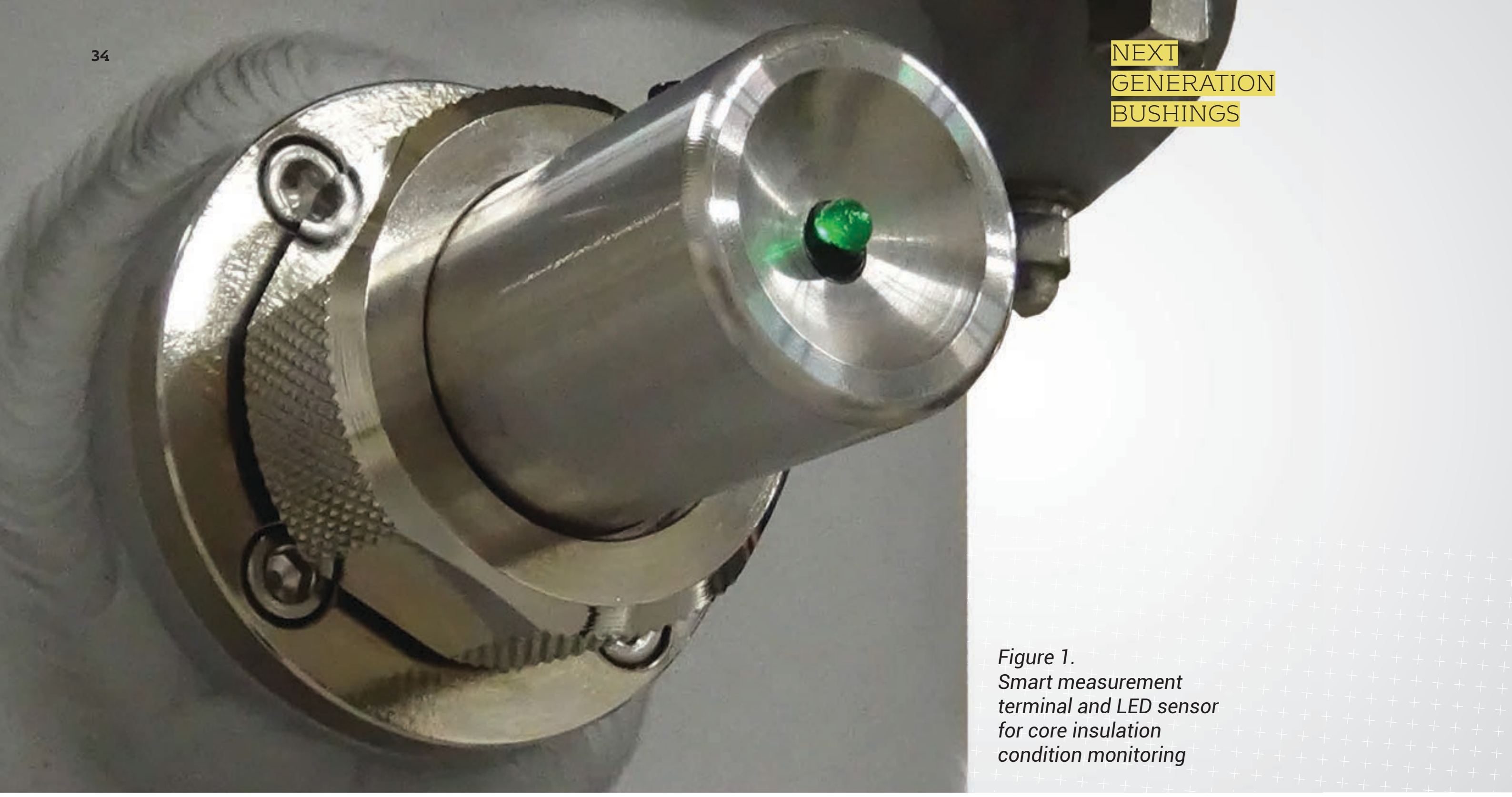


Figure 1. Smart measurement terminal and LED sensor for core insulation condition monitoring

Photo: RHM International

RIF® BUSHINGS DELIVER A UNIQUE SET OF FEATURES THAT SET THEM APART: THEIR OVERALL PERFORMANCE FOR HIGH RELIABILITY, THE OPTION OF INTEGRATING MONITORING INTO THEIR STRUCTURE AND THE POSSIBILITY TO PROVIDE CUSTOM DESIGNS FOR REPLACEMENT NEEDS AT STANDARD COSTS.

RIF® BUSHING TECHNOLOGY HAS INTRODUCED THE NEXT LEVEL OF RELIABILITY AND SAFETY THAT OPERATORS NEED FOR THEIR TRANSFORMER ASSETS.

RIF® Bushing Technology

RIF® transformer bushings were introduced to the market in 2003 and to date there are over 22,000 units in-service worldwide. These bushings have proven to be ultra-reliable under all types of operating and environmental conditions.

The RIF® bushing utilizes a finely graded condenser design and a core insulation that is composed of fiberglass impregnated with epoxy resin wrapped between capacitive screens. The outer insulation for the RIF® bushing is silicone rubber sheds that are adhered directly to the condenser core. This ensures there is no gap or opening in the overall bushing structure and eliminates the need for filler fluid or material.

The electrical field is controlled by a finely graded capacitive core which ensures a linear surface potential profile from the conductor to the grounded flange (100% to 0%) which greatly improves its flashover resistance. Additionally, the thermal insulation strength of the resin-impregnated fiberglass is IEC Class B (temperature limit rating of 130°C), which gives the RIF® bushing a larger thermal margin than other bushing types. The simpler manufacturing process, which is primarily a wrapping and heat curing process, introduces minimum internal stresses in the capacitive core that can affect the long-term operational life of the bushing. Finally, RIF® bushings require no special storage conditions, thereby reducing the handling costs.

In summary, the RIF® bushing technology has introduced the next level of reliability and safety that operators need for their transformer assets.

The Smart RIF® Bushing

RIF® bushings can be provided with built-in smart measuring circuitry that continuously monitors the bushing's core insulation condition. Sealed within the primary core is a built-in signaling capacitance to collect and measure stray capacitive current generated by a damaged condenser screen layer.

A self-powered LED sensor collects and processes the signal which is compared to a benchmark voltage. The sensor is factory-calibrated to provide a GREEN LED indication for a normal insulation condition and RED LED pre-alarm indication for a deteriorating insulation condition.

The RIF® bushing's built-in sensing circuitry can also be used to capture high frequency signals generated from partial discharge activity inside the power transformer by installing a PD sensor in the smart measurement terminal. This monitoring can be continuous without any need to shut down the transformer.

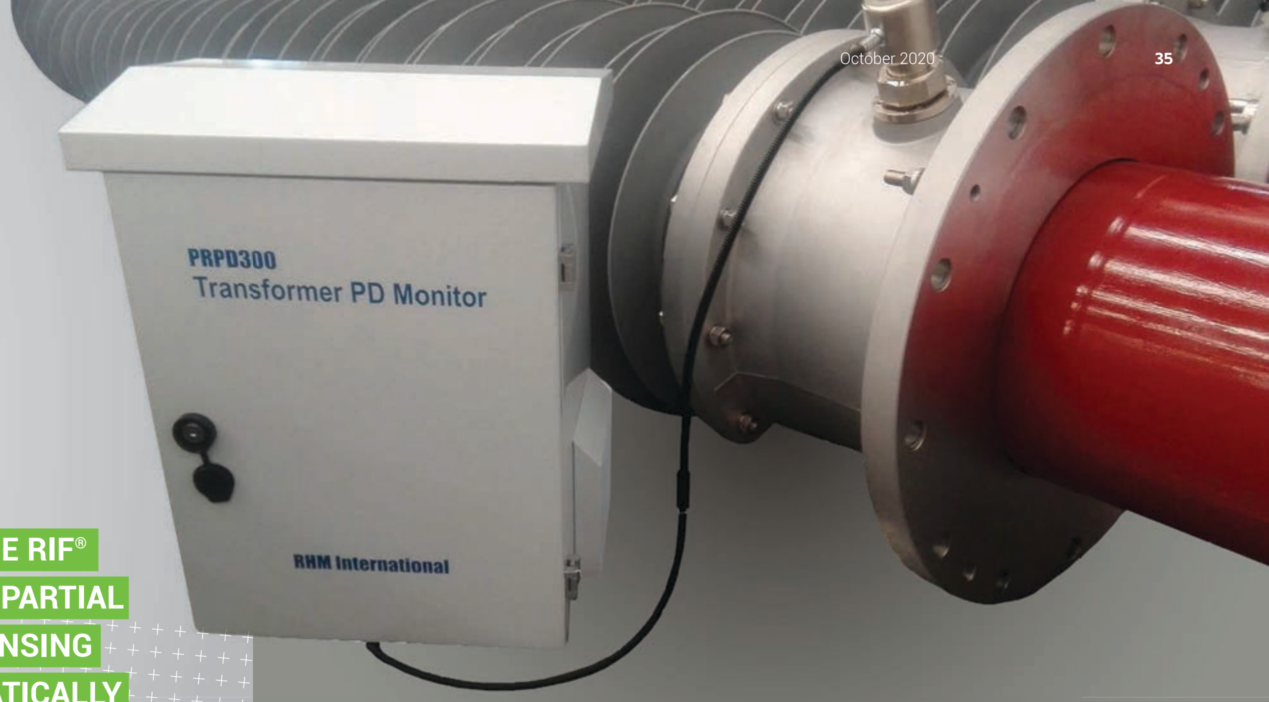


Figure 3.
RIF® bushing with smart terminal and PD sensor

THE USE OF THE RIF® BUSHING AS A PARTIAL DISCHARGE SENSING DEVICE DRAMATICALLY SIMPLIFIES TRANSFORMER MONITORING WHILE PROVIDING HIGH PD MONITORING RELIABILITY AND ACCURACY WITH ITS DIRECT COUPLING AND SHIELDING DESIGN. THIS CAN PROVIDE SIGNIFICANT ADDED VALUE FOR CRITICAL SYSTEM TRANSFORMERS.

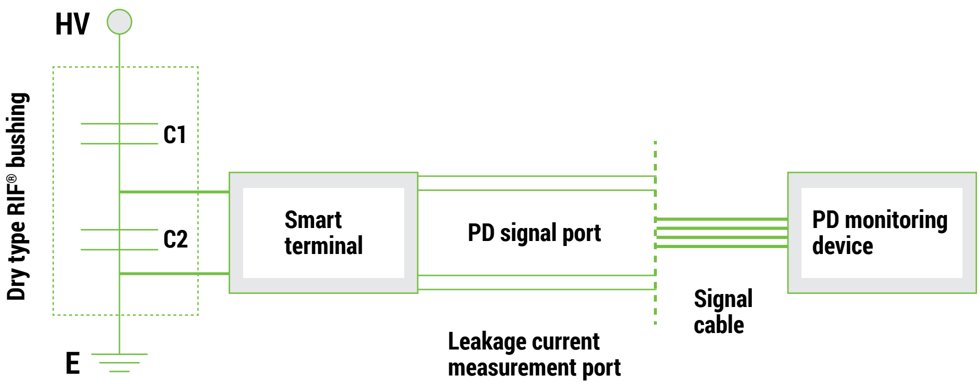


Figure 2.
Signal coupling

If the transformer is equipped with all smart RIF® bushings, the location of the PD within the transformer can be accurately determined. The use of the RIF® bushing as a PD sensing device dramatically simplifies transformer monitoring while providing high PD monitoring reliability and accuracy with its direct coupling and shielding design (Figures 2 and 3). This can provide significant added value for critical system transformers.

Custom-designed "Like for Like" Replacement Bushings: The Strength of the RIF® Bushing Technology

OIP and RIP type bushings have been the industry standard for transformers for many years and in general have performed satisfactorily. However, as transformer assets age, paper deterioration in these bushings can eventually cause the bushings to fail, some even catastrophically. If you are seeing deteriorating test results (power factor) and sealing systems, it may be time to consider a bushing replacement program. When considering a replacement program, it is important to remember the age of your operating transformer inventory and the standards that the originally supplied bushings were built to, which may be obsolete today. Because of the age of many transformers, the biggest challenge for the program is to be able to get custom-engineered "like for like" replacement bushings at reasonable prices and lead times. Also, to alleviate safety and environmental concerns dry type bushings should be specified for your replacement program.

THE VERY SIMPLE MANUFACTURING PROCESSES INVOLVED IN THE PRODUCTION OF RIF® BUSHINGS ALLOWS FOR COST EFFECTIVE CUSTOM-ENGINEERED DESIGNS WITH MINIMAL EFFECT ON LEAD TIMES. TRANSFORMER OUTAGES CAN THEREFORE BE SCHEDULED WITHOUT THE WORRY OF INSECURE SUPPLY AND LONG DELIVERY TIMES.

The value-added benefits of RIF® bushings over other bushing technologies

Feature	RIF® Dry type, paperless. (Resin Impregnated Fibreglass)	RIP Dry type, paper. (Resin Impregnated Paper)	OIP Oil filled, paper. (Oil impregnated paper)
Maintenance	Maintenance-free.	Tan δ and C1 need to be checked regularly.	Tan δ and C1 need to be checked regularly. DGA testing older bushings. Leak mitigation.
Explosion resistant	Yes (31.5 kA, 150 ms internal arcing fault test performed on a 230 kV bushing).	No	No
Thermal temperature rating of insulation	130°C A higher thermal margin.	120°C	105°C
Optional built-in insulation condition monitoring	The test tap can also be supplied with an LED sensor that provides visual indication of a real-time change to the C1 capacitance.	Not provided.	Not provided.
Cost to produce custom design "like for like" replacement bushings	Low No re-tooling required for custom designs.	High Expensive re-tooling required for custom designs. Cost and lead time significantly impacted.	High Expensive re-tooling required for custom designs. Cost and lead time significantly impacted.
Cost of ownership	Low Lower production costs than RIP. Maintenance-free. High reliability. Explosion resistant.	Medium High production costs. Regular offline testing required. Expensive long-term storage requirements.	Higher Lower production costs than RIP and RIF®. Regular offline testing required. DGA testing of bushing oil recommended for older bushings. Leak mitigation. Can fail catastrophically.
Long term storage	No special requirements. Can be stored horizontally in their shipping crate.	This technology uses creped insulating paper. Therefore, RIP is sensitive to humidity ingress. Long term storage requires the oil end to be fitted with specially designed metallic covers filled with dry transformer oil.	Must be stored in an upright position to avoid creating air bubbles.

In summary, the RIF® bushing technology provides the safety and environmental benefits that customers want to see in transformer bushings. This technology offers the customer an explosion-resistant design, a proven record for reliability under all types of extreme operating conditions and a maintenance-free bushing.

It is particularly noteworthy that long term operating experience has shown that the dissipation factor and partial discharge level remain stable over its lifetime.

Further to those performance gains, the optional built-in monitoring features increase significantly the value that RIF® bushings can bring to grid operators at a reduced cost when compared to existing solutions.

Last, RIF® bushings are available in custom sizes that allow economical replacement of older difficult-to-procure bushings while improving the transformer's safety and reducing maintenance costs.

Photo: RHM International

INSULATOR BUSHING CONTAINMENT

In the conversation of electric utility operational integrity, the topic of upgrades, regular maintenance, testing and avoiding system failures must be considered as part of an overall continuity plan for system reliability.

Utility crews involved in upgrades, maintenance and the process of avoiding system failures are ultimately going to have to face the challenges of removing, containing and disposing of used insulator bushings. The simple truth of the matter is that insulator bushings are difficult to contain and even more troublesome to handle while transporting for recycling or disposal.

Utility crews, faced with the challenge of electrical equipment retirement and/or their associated bushings, must first identify the hardware and determine if the equipment poses any risk regarding the possibility of PCB (Poly Chlorinated Biphenyls) contamination. Although most utilities have phased out "known" PCBs and the associated equipment, according to many experts "... there are still unknown PCBs hidden in most utilities." (Pennell 2019, 1)

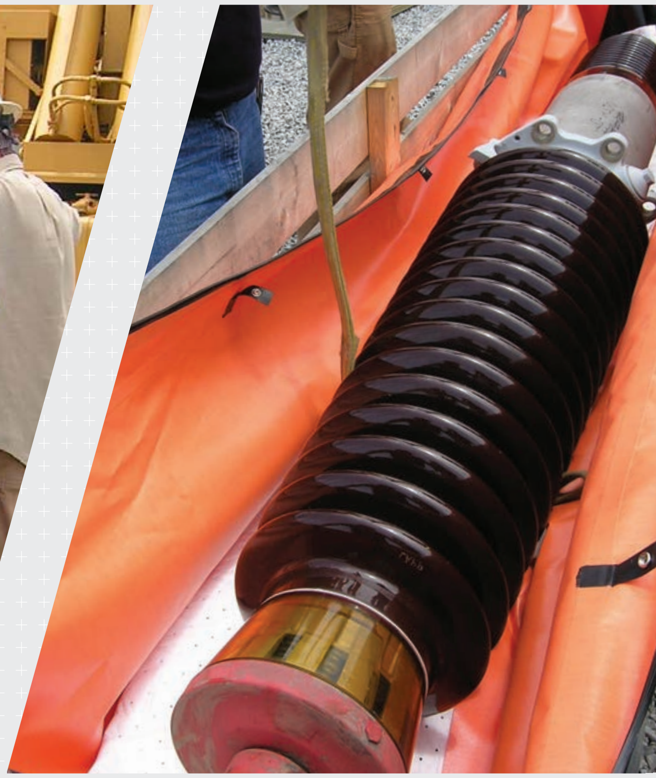
PCBs can be found in everything from a simple cooling fan motor start capacitor to insulator bushings containing contaminated oil or tar compounds. Askarel™ filled (liquid) small capacitors contain the highest level of PCBs ever used in equipment and can exceed 900,000 ppm. Utilities have found that bushings manufactured before 1980 can contain a tar compound made with Askarel™ that when tested are consistently found to be "hot" with PCBs. In one recent example, a utility found 100% of the bushings tested contained PCBs from 60,000 ppm to in excess of 230,000 ppm. Even though the electrical equipment ID plate on the side of a 500-gal capacity substation transformer can read less than 50 ppm of PCBs, the attached bushings may be a different story.

Regardless if the equipment contains contamination or where no PCBs are present, there is still a major obstacle that the utility crew must address once the bushing has been removed from the transformer or other equipment. How do utility crews contain the bushing once removed?

Back in the day, crews might have simply placed the bushing on the ground and gone home for the day. In other circumstances, they might have wrapped it in plastic and duct tape and called it good. Today, however, neither one of those options will win your utility the award for environmental stewardship. In fact, you might just end up being charged with safety violations, significant fines and clean-up costs starting in the tens of thousands of dollars for leaks and spills from bushings.

Most experienced utility crews will admit that even if a bushing is removed as a matter of preventative maintenance and is not leaking, once it is laid down, there is a pretty good chance it will start leaking. Some contributing reasons may be the age and condition of the bushing or just the change in the physical position. Either way, whether storing the bushing for reuse or preparing it for transportation for recycling or disposal, containing the bushing is a crucial and necessary step for crew safety, to prevent spills and unnecessary cleanup costs.

The simplest way to address this step is to use the Andax Bushing Sac™. The Bushing Sac™ is a field tested, proven solution for bushing containment for over 20 years.



Advertorial by
Patrick McAtarian
General Manager
Andax Industries

The Bushing Sac™ is a field tested, proven solution for bushing containment for over 20 years. Purpose built, designed and manufactured in the United States, the Bushing Sac™ provides 100% leak proof containment of the bushing.

Purpose built, designed and manufactured in the United States, the Bushing Sac™ provides 100% leak proof containment of the bushing. Constructed of heavy duty, puncture resistant reinforced PVC, the Bushing Sac™ is built using advanced high frequency welding methodologies that ensure all flexible seams are liquid tight. It has a built-in super oil absorbent core to lock in any leak, drip or spill from the bushing while in storage or in transit. Designed with an unobstructed full access opening, the Bushing Sac™ simplifies the containment process for the utility crew while loading the bushing inside the Sac™. Once loaded, the Bushing Sac™ maintains its leak proof status by incorporating a proprietary closure system that is self-locking and liquid tight.

The Bushing Sac™ has a host of features that are engineered, making it the right tool for utility crews. Each Bushing Sac™ includes a separate bushing "Flange Cushion", designed to wrap around the steel mounting flange of the bushing, adding additional protection when loading the bushing into the Bushing Sac™. Additionally, the Bushing Sac™ provides the utility crews with built in size gauges to assist the utility crew in the field while closing and sealing the Bushing Sac™.

After the bushing is in the Andax Bushing Sac™, the utility crew can safely store the bushing inside or outside for reuse. If the bushing contains PCBs, then the Bushing Sac™ can be used while the 30-day clock is ticking for onsite storage while awaiting disposal.

Use of the Bushing Sac™ answers the question of how to contain bushings once removed from the electrical equipment. Because of the fragility of older bushings and the propensity for the porcelain insulators to break, most utility crews are accustomed to building cradles to support the bushings during transport or for storage. The Bushing Sac's™ flexible reinforced materials easily facilitate and adapt to use with cradles/boxes for ease of use and provide the complete containment solution.

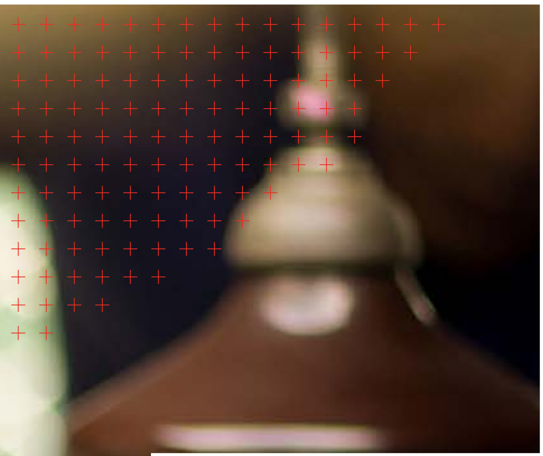
Considering the utility's "cradle to grave" risk and responsibility, the potential consequences and cost of leaks or spills while in transit, the Bushing Sac™ provides peace of mind. Many utilities have experienced the unfortunate circumstances of receiving that phone call from the disposal company that their bushing leaked in the truck while in transit for disposal and the subsequent bill. Use of the Bushing Sac™ is a 100% containment solution and is DOT compliant. Because the Sac™ is completely sealed and incorporates a fluid absorbent core, it prevents potential leaks, drips or sprays from escaping during transportation. Additionally, the Bushing Sac™ is 100% OSHA compliant. Utility crews can safely rig the Bushing Sac™ (load) with a sling, ensuring a balanced and secure load. This allows them to safely lift, move and store the bushing while being 100% contained and compliant in the Andax Bushing Sac™.

Andax Industries manufactures multiple sizes of stock Bushing Sacs™ from 6 feet in length to 18 feet. However, since the age, style and manufacturers of bushings have varied over the years, common sizes of bushings may not be what your crew needs every time they are scheduled to do equipment retirement or a change out. Andax Industries manufactures custom size Bushing Sacs™ for just about any size bushing that has been made. Current projects include custom sizes over 30 feet long and 8 feet in diameter for large generating station bushings. Given the custom manufacturing capability and the fast turnaround, Andax can meet your utility's work schedules and support your crews to ensure the continued operational integrity, continuity and reliability of your electric utility system.

1 Pennell, Mark, 2019 *Regulatory Compliance Services Annual Conference*

Transformer Bushings - What Can Go Wrong?

by **Thomas Linn**



Transformer bushings are one of the most critical components of a transformer. Today, up to 20 % of major failures on high voltage transformers can be tracked back to bushings [1]. Almost half of these failures result in catastrophic failures like explosions, fires or oil spills. The cost of these damages and the lost opportunity to deliver energy could be several hundred times higher than the price of a bushing. Even a failing bushing which will not lead to a catastrophic failure can harm people due to exploding porcelain insulators and broken fragments that can be catapulted through the air by the force of the breakdown arc. The safety implications of this are tremendous. This article as a first of the series of two will discuss different failure mechanisms and causes for failures.

Thomas Linn graduated from the Technical University of Dresden with a degree in Electrical Engineering, specialized in High Voltage Techniques. In 1998 he joined ABB in Switzerland and was responsible for high voltage onsite testing for GIS and cables, PD measurements onsite and PD monitoring of Gas Insulated Switchgear. Afterwards he worked for 10 years with high voltage transformer bushings at ABB Micafil and became a senior technical expert for high voltage techniques and equipment. In March 2013 Thomas joined Qualitrol as Technical Application Specialist. As a TAS, Thomas can leverage 20+ years of experience in high voltage equipment such as GIS, high voltage bushings, cables, transformers, high voltage testing, partial discharge measurement and monitoring, and high voltage test equipment. Thomas is a member of CIGRE and IEC TC42 in Switzerland and is contributing as an expert to different CIGRE Working Groups internationally. Today Thomas resides in Singapore and is the Director for Qualitrol Services in Asia. He also leads Qualitrol global T&D Asset Expert team.

Introduction

Today, most power transformers will have two sets of bushings during their lifetime because transformers are expected to last 50 years, while bushings have an expected lifetime of 25 years. Experience suggests there are two points of failure within the lifetime of the bushings.

1. When a bushing reaches an age of 10 to 13 years, failure is possible due to the design, transformer operation and potential quality issues, even though they are not "aged out" in life-cycle management terms.

2. When bushings reach 20 to 30 years of age, which is considered the normal lifetime, they are more prone to failure merely because of age. While bushings can fail before reaching the age of 10, it is also true that there are bushings installed in transformers that are more than 50 years old, so age alone cannot be the determining factor.

To avoid costly replacements of bushings based on age alone, and not due to their real condition; while detecting upcoming faults, it is essential to know the failure mechanism and failure causes for bushings. Bushing conditions are often influenced by different operating conditions of the transformer. These operating conditions can be overheating, load variations, frequent exposure to transients and intensive pollutions. Designs, types and manufacturing processes can have a significant impact on the lifetime of bushings as well.

Failure Mechanism

Impact of Operating Conditions

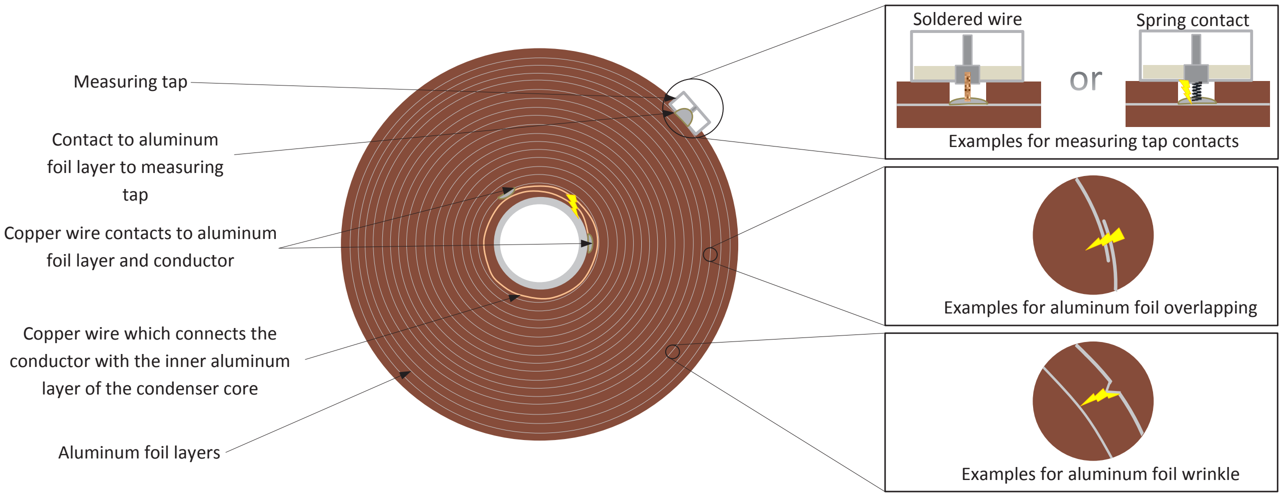
The operational environment has quite a big influence on the stress on electrical assets, and some assets react uniquely to different stresses. Over the years, transformers have improved in design, especially for handling transient voltage stress. Further, local overheating especially due to bad contacts or overloading can be another factor for degrading the bushing health. Changes of load conditions, especially for the air insulated side of bushings which are connected to overhead lines, will results in changing mechanical forces, pulling on the bushing heads. Through-faults provide an additional transient mechanical stress.

Impact of Electrical Transients

Electrical transients are short bursts of energy introduced into the network which results in short term over-voltages with the duration of several nanoseconds (ns) up to hundreds of microseconds (s). Depending on the duration and length of transients there can be Very Fast Transients (VFT – rise times in ns-range), Lightning Transients (low s-range) and Switching Transients (hundreds of s-range). Amplitudes of transients are measured in a factor per unit (p.u.). This factor measures how many times higher the transient voltage peak is than the peak voltage of the line voltage. In a 220 kV network, the phase-to-ground peak voltage would be 179.6 kV. A transient with a voltage peak of 1.5 p.u. would be 269.5 kV peak. Obviously then, the duration of an overvoltage is relevant for the risk of a bushing.

Photo: Shutterstock

Figure 1. Contact designs and foil overlapping in a bushing condenser core



Bushings are designed based on the Basic Insulation Level (BIL-representing the lightning impulse level), according to IEC 60137 or IEEE C57.19.01. The lightning transient stress as well as the switching transient stress for bushings seem to be well covered by that standard. Further, the maximum amplitude of transients can be effectively controlled by using surge arrestors.

Very Fast Transient (VFT) Stress

VFTs are relevant for SF_6/oil bushings where a Gas Insulated Switchgear (GIS) is directly connected to a transformer. The SF_6/oil bushing in this case is providing the interface between the GIS installation and the transformer. VFTs can happen due to an operating circuit breaker, but more likely due to an operating disconnect switch. Depending on various parameters (which will not be discussed in this article) the peak amplitude can be up to 2.5 p.u. or higher. These transients provide a high voltage and high frequency stress to the bushings. The condenser cores of bushings in most of the cases are not specifically designed and tested for that type of high voltage combined with high frequency stress.

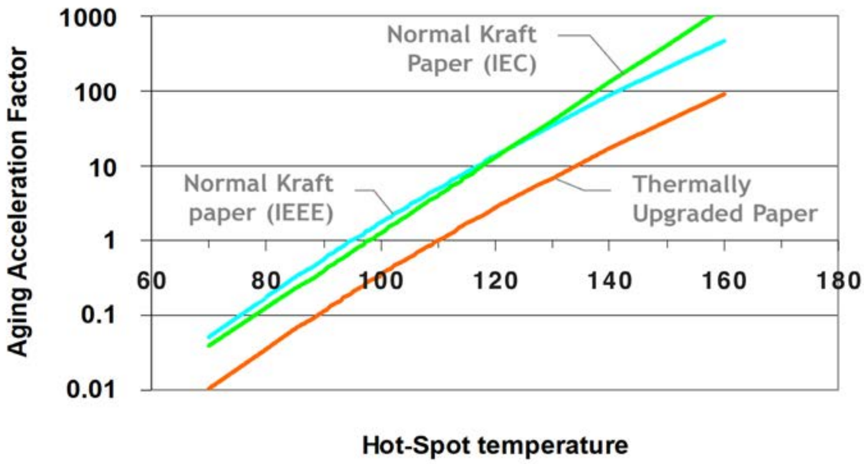
For these high frequencies, the inductances of the conducting materials used to produce the bushing condenser cannot be neglected, since the electrical field distribution is different than the one for normal operation frequency application.

Figure 1 shows some critical points for transients. In some designs the connection of the conductor or conducting tube is contacted to the inner foil with a copper wire, which is winded together with the paper. This provides a relatively high impedance for VFTs and creates a high voltage drop which can create sparking in the area of this wire. Over frequent occurrences the insulation material and even the connecting wire can slowly be destroyed. This will lead to a permanent or periodic sparking due to normal operation. It can further erode the insulating material and can lead to partial breakdowns, followed by a potential complete breakdown.

The measuring tap design is also relevant for transient stress and sparking. Figure 1 presents two different designs of measuring taps. The first one has a copper wire soldered to the contact system of the last aluminum foil and the inner pin of the measuring tap. The second design is using a spring as contact, which makes the assembly easier, but it is more prone to transient stress since the spring provides a comparably high impedance. Each transient event can generate a sparking in the bushing tap and can lead over time to bushing failure.

Photo: Shutterstock

Figure 2. Aging acceleration due to temperature for different papers [2]



A third sensitive point for transients is the overlapping of the foils. The insulation layer between the two foil ends is only one thin layer, either impregnated with oil or resin. During a transient event, these two foil ends can have different potentials where the potential difference is high enough to create a sparking between the overlapping foil ends. Over a longer time period, this can lead to material erosions and finally the failing of the bushing.

Wrinkles or kinks in the foil or at the foil edges can also be introduced during the manufacturing process. If very serious, they usually get detected during the HV routine test as part of the manufacturing process. Nevertheless, non-detected wrinkles or kinks under normal operating stresses are not a concern. Only under frequent transient stress can they develop the same behavior as described. Ultimately the high electrical field caused by the sharp edges under a fast rise-time impulse stress is the dominant factor for causing a partial or complete breakdown.

Switching and lightning transients

Switching transients are important for transformer bushings, where transformers are installed close to high voltage breakers or disconnect switches, which are frequently being operated. This applies to transformers close to capacitor banks or reactors, where switching will take place almost every day. Depending on the distance and how the transformers are connected to the breakers/disconnect switches, the impact can be significant. A long overhead line connection will provide high impedance, which will attenuate the wave and minimize the impact. A cable connection with its high capacitance will attenuate the switching wave as well. The parts involved and the failure mechanisms and developments are similar to the VFTs, but the severity is lower due to a slower rise time.

High temperature

High temperatures due to overloading or overheating of bad contacts can cause the bushing insulation material to degrade. For resin impregnated paper bushings (RIP) or resin impregnate fiber bushings (RIS), the "glass transition temperature" determines the maximum permittable hotspot temperature. The glass transition temperature is a material property which can be influenced by the resin system composition and is usually above 130°C and below 140°C.

High glass transition temperatures lead to higher brittleness and the material tends to create micro-cracks, which can lead to partial discharge (PD). Conversely, too low glass transition temperatures limit the maximum allowed hotspot temperature. The glass transition temperature must always be higher than the maximum allowed hot spot temperature given by IEC 60137 and IEEE C57.19.01.

For oil impregnated paper bushings (OIP), the decomposition of the paper insulation and the insulation oil are important considerations. Figure 2 presents the relationship between accelerated aging expressed by the aging factor for different temperatures. The paper that is usually used in bushings is normal kraft paper (IEEE or IEC). At about 95°C the aging acceleration factor will be about 1. The increase of the operating temperature by 5K will increase this factor to 2, which means doubling the aging speed.

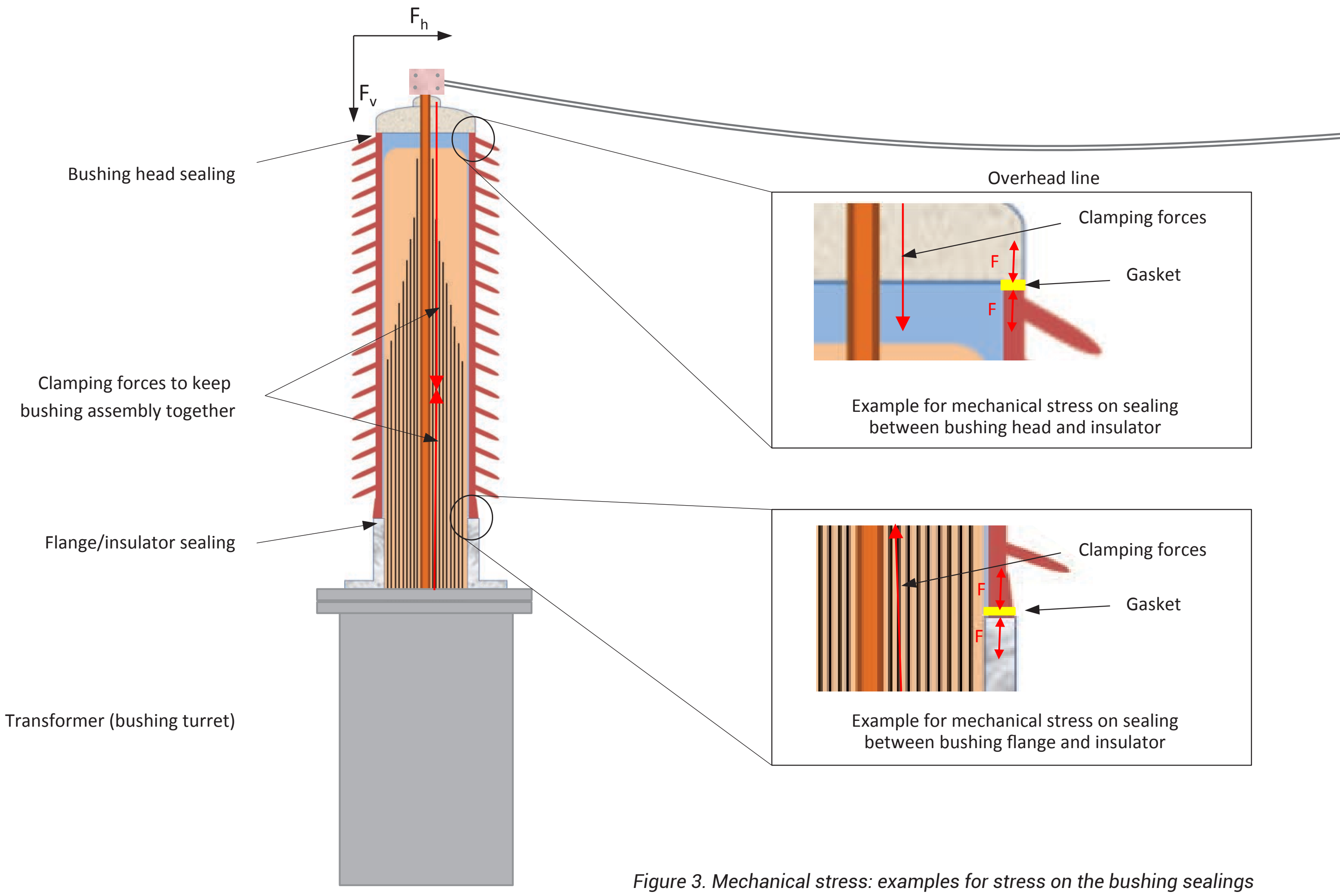


Figure 3. Mechanical stress: examples for stress on the bushing sealings

The diagram in Figure 2 has been established for insulation paper in transformers, but is valid for the insulation paper in OIP bushings as well.

Mechanical stress

For transformer oil/air bushings, only the permanent and transient mechanical stress introduced by overhead lines will now be considered.

As shown in Figure 3, mechanical forces are being introduced by a connected overhead line for the air part of the bushing as vertical and horizontal forces. Static forces are determined by the weight of the overhead line and the designed tension to guaranty the minimum safety clearance of the overhead line to the terrain at maximum sag. Additional loads, typically snow, can contribute to the static loads along with seasonal and temperature related, slowly changing variations. Additionally, the changing load current of an overhead line will result in different temperatures of the wire conductor itself and result in a different quasi-static mechanical force. Transient mechanical forces can also be introduced by wind and through-faults.

Bushings are designed to withstand static and transient mechanical forces. Nevertheless, excessive mechanical forces can mechanically destroy a bushing. The quasi-static forces and the transient force do have the potential to weaken the sealing system of bushings. The details in Figure 3 show the compressing of the gaskets on the pulling side. It could pull open between the sealing and flange/porcelain/head (depending on the design) as a possible defect. This would lead to moisture ingress. The moisture would in this case presumably stay between the bushing core and the inner porcelain or inner composite insulator surface. The moisture will, over time, migrate into the condenser core as well, but before that, it can also result in a breakdown along the inner insulator surfaces.

It needs also to be mentioned here that there are differences in design of the sealing systems, not only between different manufactures, but also between different types of bushings from the same manufactures.

Moisture

Moisture in bushings can be caused by several situations. Leaking gaskets due to mechanical stresses, or aging as explained above, will be the most common cause for allowing moisture to ingress into the bushings. Moisture can be found in the insulation paper and/or in the insulation oil.

When it comes to moisture, OIP bushings behave similarly to transformers, with the difference being that within the condenser core the oil cannot circulate that freely. This means that if the moisture slowly creeps into the

bushing, it will initially remain outside of the condenser core and within the outer layers of the core. Over time the moisture will ingress further into the bushing. It is also important to understand that the aluminum layers are also slowing down the crosswise distribution of the moisture. The moisture will mainly impregnate lengthwise into the bushing core.

Since moisture cannot impregnate pure resin, the moisture in a RIP bushing will be found in the paper. Comparing the RIP bushing cores to OIP bushing cores, the resin will provide an additional barrier against the crosswise moisture impregnation. As for the OIP bushings, the lengthwise moisture impregnation will be the major way for moisture to migrate into the bushing. Besides leakages, RIP bushings can also get "wet" due to improper storage. To address this issue, a plastic bag covering the transformer side of the bushing, wrapped air-tight with tape and a silica gel package inside will work) to keep the bushing moisture free for shorter term storage (just a few months. For longer storage periods the transformer side of the bushing needs to have a storage tank filled with transformer oil.

RIS bushings do not have any paper involved. The winding material is a synthetic mesh, and the resin is a filled epoxy system. Due to that, no moisture can migrate into the RIS bushing core.

Process/ Design

Today the design, production and manufacturing systems for bushings are very well controlled through quality control processes and they must be tightly controlled and monitored. Common throughout all bushing types are: the contacts between the inner foil layer and the conductor/conducting tube; and the contact between the outer foil layer and the measuring tap (see also Figure 1). There are different techniques to making this connection, like conductive gluing, soldering, spring contacts or combinations of these. It may be necessary to drill into the RIP body or cut into the insulating paper to access the contacts system of the respective foil layer. It is extremely important not to drill or cut through the aluminum layer as that would make the bushing unusable.

During the winding process any wrinkles and kinks need to be avoided, as mentioned previously. The homogeneity of the foil layer distances is very important to achieve an equalized field distribution across the whole bushing condenser core. Further, cleanliness is an important factor as well. Avoiding foreign particles (especially conductive particles) that can fall on the paper or the aluminum foil during the winding process and being wound into the bushing condenser core will create potential failure points when in operation.

The casting process for RIP bushings must be controlled in a way that delamination cannot take place and that there are no voids that can build up. Voids are sometimes difficult to be detected during routine testing due to the known ignition delay for PD in voids in solid insulations. If not detected, they can cause severe problems for bushings in service.

Conclusions

The knowledge about operating conditions, different designs, technologies and stresses for bushings will allow operators to gain more confidence in their assessments of the actual bushing condition. Not only electrical stresses but also mechanical and thermal stresses on the bushings need to be known.

In a future article, we will describe how this knowledge can be combined with different detection methods and approaches to detect incipient faults and minimize bushing failures.

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Ester-impregnated Bushings: One Step Closer to Sustainable Energy

by **Esseddik Ferdjallah**

Capacitive ester-impregnated transformer bushing is an innovative, eco-friendly solution that not only helps achieve substation decarbonization but also increases the performance of high-voltage equipment.

Photo: Trench

Esseddik Ferdjallah is an electrical engineer who graduated from Ecole Polytechnique d'Alger in Algeria in 2012. He obtained his PhD from Polytech'Nantes in 2015 on the monitoring of insulation system for hydrogenators. He has been with Trench France, a Siemens subsidiary, since 2016 as an R&D engineer working on the development of new insulation technologies, topics related to monitoring, as a technical advisor for the service department, and as a technical manager in high-voltage laboratories.

Introduction

We need to ensure access to affordable, reliable, sustainable, and modern energy to drive manufacturers worldwide and support the development of environmentally friendly high-voltage equipment. One of these eco-friendly innovations is the capacitive ester-impregnated transformer bushing, an innovative solution that not only helps achieve substation decarbonization but also increases the performance of high-voltage equipment.

Motivated by feedback from site investigations and discussions with customers who are continuously looking for ways to improve service conditions and minimize costs, the first high-voltage bushing insulated with biodegradable ester fluid was introduced into the market in July 2020 (Figure 1).

The use of ester has been widely studied and promoted for power and distribution transformers over the last two decades. Ester-based dielectric fluids were found to outperform mineral oils in terms of their thermal and environmental benefits. Indeed, hundreds of ester-filled transformers are now in service and the feedback is consistently positive. The need for monitoring solutions for predictive maintenance strategies is also increasing on a global scale. Using ester-filled bushings on ester transformers expands the monitored parameters and allows dissolved-gas analysis (DGA). This type of monitoring is not possible with dry bushings.

Combining the monitoring options with the high thermal performance of synthetic ester allows ester-impregnated bushings to meet the technical requirements of high-voltage transformers, making it possible for customers to mitigate the risks of operating in overload conditions for longer periods than those allowed by international standards. The thermal aging behavior of ester-impregnated paper has been widely studied, and the results confirm an improvement in the aging resistance of paper in ester compared with standard mineral oils.

The first high-voltage bushing insulated with biodegradable ester fluid was introduced into the market in July 2020.

Why Use Ester?

Four years ago, a fundamental research was conducted on several types of esters to be used in high-voltage bushings [6]. Eventually, the company carrying out these studies chose to use a synthetic ester thanks to its high performance that offers all the benefits of ester technology in addition to its sustainability and ready biodegradability according to OECD 301 (OECD Guidelines for the Testing of Chemicals: Ready Biodegradability), which states that:

- 60 percent biodegradation occurs within 10 days after exceeding 10 percent degradation;
- 89 percent occurs by day 28 of the test.

In the first development stage, the synthetic fluid was intended for special applications in order to minimize the risk or consequences of failure: for example, wind turbines, traction, and applications near population centers. Today, due to its enhanced technical performance its use has been extended to standard applications.

Thermal Performance

One of the key advantages of using synthetic ester for bushing application is its enhanced thermal performance compared with mineral oil. The international standards organizations IEEE and IEC agreed that the thermal class of the complex kraft paper/synthetic ester is 120° (E); as opposed to 105° (A) for the complex kraft paper/mineral oil (IEC 60076-14). For liquid-filled bushings, this is a huge improvement because they are vital components in the power system network. The increased thermal performance of bushings can positively impact transformer's condition by allowing many options for overload operation. It also offers a greater design margin than can be exploited to improve the thermal performances of transformers.

Increased Fire Safety

The risk of failure is always present in power networks. Depending on the extent of the failure, insulation liquid can cause fires that spread very quickly, resulting in extensive damage. Using synthetic ester can mitigate the fire risk. The fire-point and flash-point of synthetic esters compared with mineral oils are shown in Table 1 [1]. The synthetic ester used in the new bushing portfolio is classified according to IEC 61039 as a Class K3 fluid, which provides the following advantages:

- No fire risk in the event of a major failure: even if ester ignites, there is insufficient energy to sustain a fire, and any pools of liquid would rapidly stop burning.
- Low-density non-toxic smoke: ester is a hydrocarbon and complete combustion will yield water and carbon dioxide. Mineral oil is a mixture of multiple compounds (paraffinic, iso-paraffinic, naphthenic, aromatic, poly-aromatic, and cyclo-alkanes) that tend to have more dense, sooty combustion products.
- Lower costs for installation and maintenance of fire safety equipment.
- Lower associated insurance costs.

It has also been proven that power transformers filled with synthetic ester can be energized at -50°C [2]. For bushings, this is even more advantageous because no cooling function is required. The electrical insulation performance is ensured at such a low temperature.

Figure 1. The first capacitive ester-impregnated transformer bushing

Photo: Trench

	Natural ester-type 1	Natural ester-type 2	Synthetic ester	Mineral oil
Fire safety class	**K2**	**K2**	**K3**	**O1**
Readily/fully biodegradable	✓	✓	✓	✗
Breakdown voltage kV (regular configuration)	>75	>75	>75	>70
Moisture saturation (ppm) at 20° C	1,100	1,100	2,700	55
Kinematic viscosity at 40° C	32	37	29	8.7
Relative permittivity	3.1	3.1	3.2	2.2
Pour point °C	-18	-31	-56	<-50
Flash-point °C	>315	>315	275	150
Fire point °C	>350	>350	316	170
High temperature performance	Good	Good	Excellent	Poor

Table 1.
Basic properties of different insulation fluids

Ester bushings are a result of the combination of historically proven experience with liquid-insulated bushings and the demonstrated technical performance of ester fluid.

Moisture Tolerance

Synthetic ester has a very high moisture tolerance. This means that it maintains its electrical characteristics even with a high volume of water content (Figure 2) [5]. Its use in ester bushings prevents several known failure modes, including:

- Bubble formation during overloads: according to IEC 60076-14, the temperature for bubble creation is directly related to the moisture content of cellulose. For example, at one percent paper humidity, bubbles will form at 170°C, while, at three percent, bubbles will appear at 125°C.
- Condensation: during cyclical service conditions (solar energy), water migration between paper and liquid is contained by ester with no effect on electrical performance.
- Hydrolysis: water is one of the degradation products of paper. Unlike mineral oil, the water tolerance of synthetic ester allows more water to be trapped, which may slow down cellulose aging.
- Oxidation: the ester bushing development included a completely sealed design, and so there is no risk of cellulose oxidation.
- Corrosive sulphur: synthetic esters do not contain sulphur because they are manufactured from sulphur-free raw materials. This means that ester-filled bushings won't have corrosive sulphur problems (like reactions with the copper conductor inside the bushings).

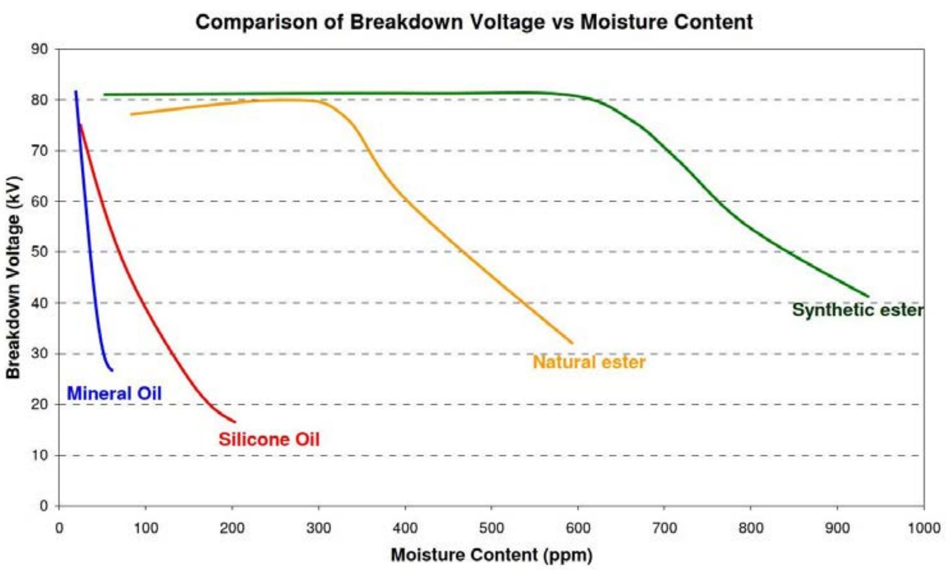

Figure 2. Breakdown voltage dependence on moisture content with common insulating fluids

Figure 3. Active part: Winding of kraft paper on a central conductor including electrodes

Technical Challenges

The new ester-filled bushing portfolio has been developed using feedback from transformer experience and research results. Considering the vast experience and history of the company producing liquid-insulated products, the engineers started with the established production process for conventional oil-impregnated paper (OIP) bushings and made the needed improvements. Basically, the production process for ester bushings (almost the same as for OIP technology) is divided into four main steps, as follows.

Process Improvements

1. Winding

During the winding of kraft paper on the central conductor, aluminum foil is placed in extremely precise positions to create a homogenous electrical field distribution. This operation is now completely automated to eliminate human error.

2. Drying

In this step, the active part – the result of the first step – is dried in a vacuum chamber using a well-established process to remove as much humidity from the paper as possible. The vacuum level and heating temperature are optimized to prevent premature aging of the paper. The measured polymerization temperature of the paper at the end of the drying process is higher than 1,100. When the required humidity is reached, the temperature is decreased, and the impregnation starts.

3. Impregnation

Due to the different viscosity and surface tension of synthetic esters, the impregnation process is different than with mineral oil. State-of-the-art analyses show [3] that a high temperature may reduce the viscosity to improve impregnation, but it adversely reduces the surface tension of esters. Experiments showed that a temperature of 60°C is a balance point. At this temperature, the viscosity and capillarity action of esters are similar to those of mineral oil at 20°C.

4. Assembly and filling

The impregnated active parts are then assembled (avoiding humidity recovery) and filled under vacuum with ester fluid. Obviously, the synthetic ester is filtered and degassed according to supplier recommendation to meet the international standard requirements (IEC 61200 and CIGRE recommendations) for insulation quality. Although there is no miscibility problem, new treatment, storage, impregnation, and filling installations are used for the synthetic ester that are completely separate from the installation for mineral oil.

Design Improvements

Cumulative knowledge over the last decades about ester-filled transformers has highlighted the need for design improvements – mostly due to the high viscosity of ester. However, the design of the bushings is also different, as are the stresses on the bushings. The insulating liquid in the transformer acts as electrical insulation and circulating cooler. Therefore, the higher kinematic viscosity of synthetic ester must be considered to avoid delamination. In liquid-filled bushings, no liquid flow is needed for cooling. Accordingly, no modification of this element is required.

With respect to the electrical design, a substantial amount of research has been performed to determine the fundamental behavior of esters both in laboratories and in transformers. The studies indicate that there are differences between ester-based liquid and mineral oil in terms of dielectric behavior. In fact, the difference primarily involves the ester withstand under transients with a particular shape of electrodes [4]. As for the new ester-filled bushings, the required improvements prevent these issues during service. Some research has found that these differences can be attributed to the difference in dielectric permittivity. It is an unchangeable intrinsic characteristic of liquids, but it brings advantages: the relative permittivity of synthetic ester is 3.2 as opposed to 2.2 for mineral oil. This helps to create more homogenous electrical stress inside the bushing between the liquid and the impregnated paper.

Photo: Trench

Figure 4. Bushing active parts impregnated with ester fluid

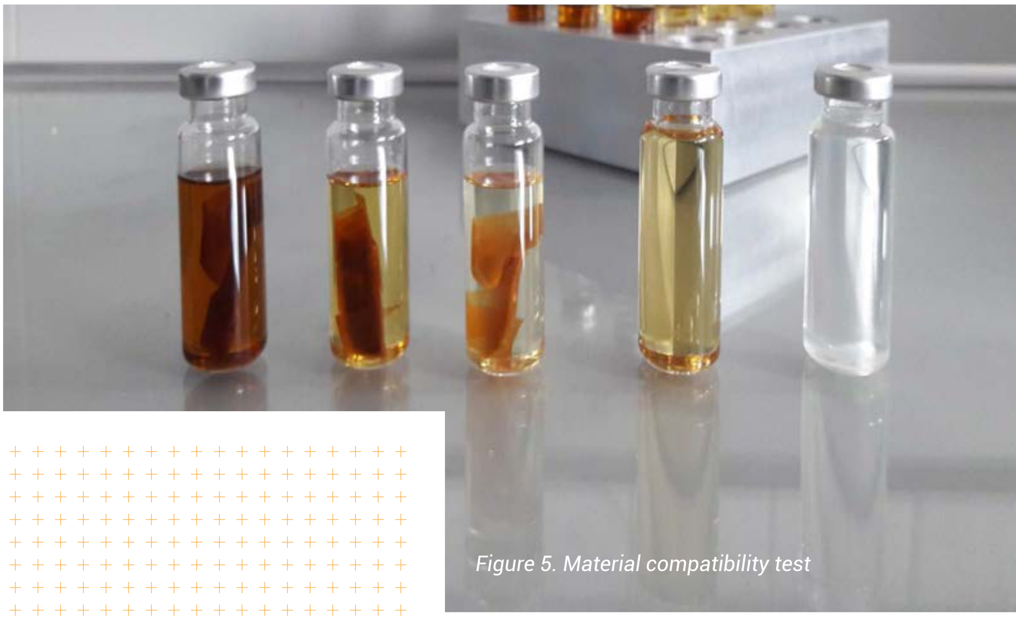

Figure 5. Material compatibility test

The use of synthetic ester as an insulating liquid ultimately improves the aging resistance of the ester bushing portfolio and can prevent several well-known failure modes of conventional OIP bushings.

New Ester-filled Bushing Portfolio: Is It Reliable?

The validation of a new insulation technology is a long and complicated process. The performance of complex kraft paper/synthetic ester has already been proven for transformer applications. However, its use in other substation components must be evaluated and approved. To validate the new portfolio, the following validation criteria has been followed:

- Standard type tests according to IEC 60137-2017
- Qualification and special tests according to IEC 60505 and experience feedback

Rated highest voltage U_m (kV)	C_1 (pF)	Tg δ (%)	PD (pC)	Temperature of test (°C)
72.5	237	0.27	<2	16
100	266	0.27	<2	17
123	198	0.25	<2	21
145	237	0.28	<2	24
170	300	0.32	<2	23
245	375	0.31	<2	24

Table 2.
Electrical parameters measured on ester bushings during routine tests

Type Tests

Bushings for voltage levels up to U_m = 245 kV have been type-tested according to IEC 60137. The bottom part was immersed in ester fluid. In addition to electrical routine measurement (Table 2), each prototype was approved through:

- Long-duration withstands test (ACLD)
- Dry and wet power-frequency voltage withstand test
- Dry lightning impulse-voltage withstand test
- Dry switching impulse-voltage withstand test
- Electromagnetic compatibility test
- Temperature-rise test with current values higher than rated current to check the thermal performance of ester-filled bushings
- Cantilever load withstand test

Table 2 shows the main electrical parameters of ester-filled bushings subjected to the tests. The results are very promising: capacitance values in the same range as the values for mineral oils; very low dielectric losses, which is very important to avoid heating the bushing (direct comparison of different ester-filled products isn't possible due to temperature variations); and partial discharges lower than 2 pC, mainly due to the noise level in the test field.

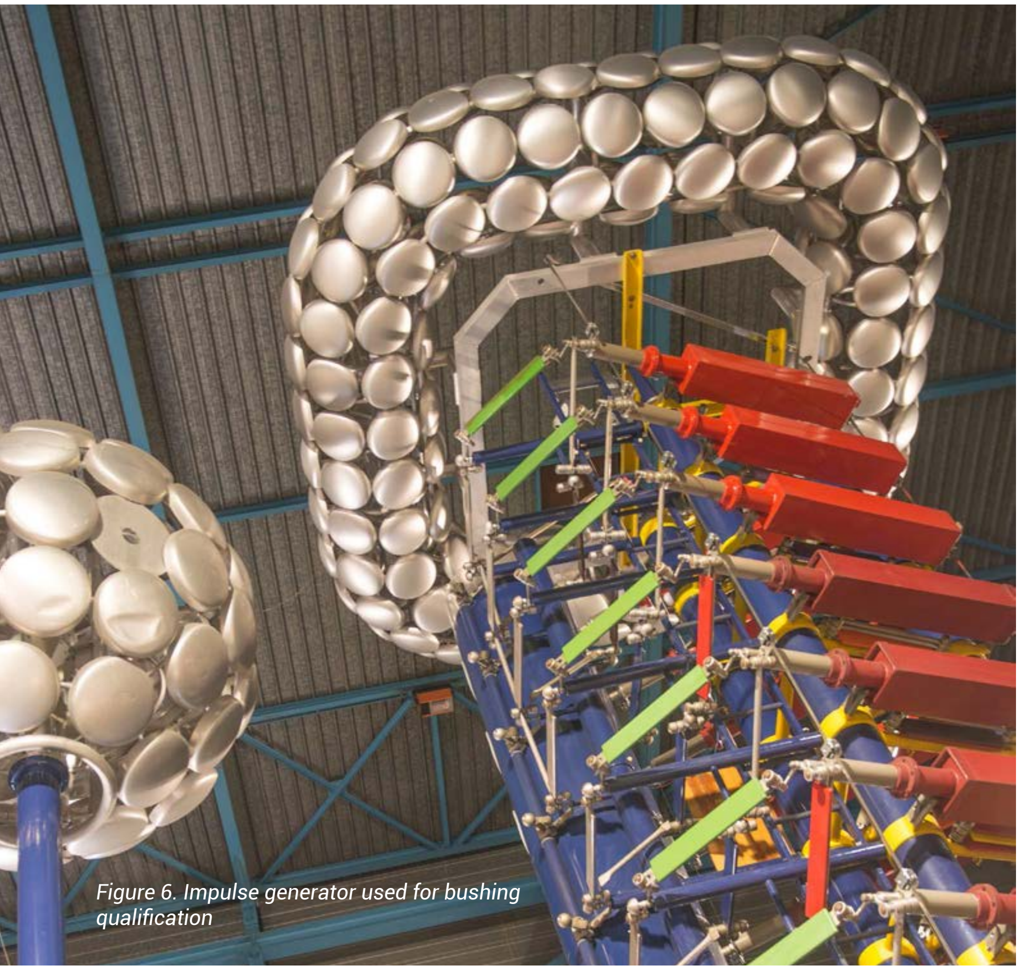

Figure 6. Impulse generator used for bushing qualification

New ester-insulated bushings have been developed to be 100 percent interchangeable with the corresponding OIP bushing, and they can be used in conventional oil transformers as well as ester transformers.

Special Tests

In parallel with the type tests, several special tests have been conducted.

- **Long-duration test (electrical aging test)**
  IEC 60505 recommendations for the evaluation and the qualification of new electrical insulation systems (EIS) include conducting comparative experiments between a candidate EIS, the ester-impregnated bushing in this case, and a reference EIS, which is the consolidated OIP bushing. For this test, six bushings were produced: three prototypes for each technology (bushing design is identical, U_m = 72.5 kV). The standard requires the application of three different voltages higher than the rated voltage: one voltage level for each two bushings until the bushing failure. The candidate EIS should withstand for at least as long as the reference EIS in order to be approved. Testing at 140 kV (193 percent of U_m) is complete, while the test at 110 kV is ongoing. At the end of this test, we will be able to draw the lifespan curves of synthetic ester bushing insulation using the results from the three voltages level.

- **Test of limits**
  Identical bushings with ester and OIP insulation (U_m = 145 kV) have been tested.

Figure 8. Long-duration test on ester bushing: Comparison between the candidate EIS and a reference EIS

Figure 7. Long-duration test on ester bushing

- **Power frequency voltage withstand limit (ED).** The bushings were tested as follows:
  - start from standard test voltage V_1 = 305 kV for 60 seconds
  - back to 0 kV for 90 seconds
  - increase the voltage to $V_2 = V_1 + 10$ kV
  - back to 0 kV for 90 seconds
  - continue until breakdown

- **Dry lightning impulse-voltage withstand limit (BIL).** The bushings were tested as follows:
  - for each level of voltage, we apply 1 reference (+), 2 positive full waves, 1 reference (-), and 2 negative full waves
  - each level of voltage V_n is calculated as shown below:
    - V_n+1 (-) = V_n (-) + 20 kV
    - V_n+1 (+) = V_n+1 (-) – 10%

Both bushings have shown a very high electrical margin. In both ED and BIL tests, additional withstand capability varies between 35 and 50 percent compared with the test requirement from IEC60137.

- **Internal-arc fault test**
  This test is intended to verify the capacity of ester fluid for extinguishing fires. It was performed in the ICMET test center in Romania on two identical bushings (U_m = 123 kV): one was filled with synthetic ester and the other with mineral oil. The results showed fast fire extinguishing for the ester bushings.

Conclusion

New ester-insulated bushings have been developed to be 100 percent interchangeable with the corresponding OIP bushing, and they can be used in conventional oil transformers as well as ester transformers.

Numerous benefits offered by technical performances cited above will allow ester bushings to fulfill the growing demand for reliable and sustainable energy generation and transmission. Their improved thermal class can reduce the risk of transformers overloading for long periods. The use of synthetic ester as an insulating liquid ultimately improves the aging resistance of the ester bushing portfolio and can prevent several well-known failure modes for conventional OIP bushings.

In reality, ester bushings are the result of the combination of historically proven experience with liquid-insulated bushings and the demonstrated technical performance of ester fluid. The result of this union provides one of the best solutions for meeting market expectations.

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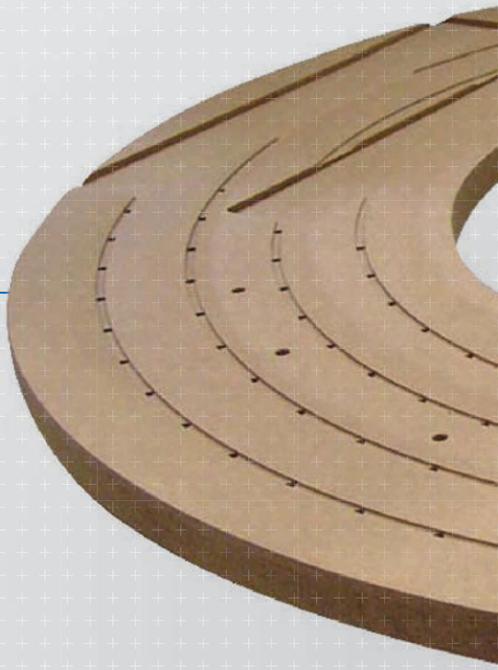
More reliable transformer thanks to phenolic-glued pressboard

Röchling improves the electrical properties of Trafoboard® – How reliable is the material?



Since 2010, Röchling has been offering an insulation material made of high-quality laminated pressboard for the highest demands on electrical properties in the form of Trafoboard®. Trafoboard® HD-PH consists of high-density pressboard layers, made from pure cellulose according to IEC 60641, bonded together using a phenol-based resin matrix.

Röchling has several decades of experience with the phenolic resin for use in oil-filled transformers, thanks to the high-voltage insulation material Lignostone® Transformerwood®, which is also part of the company's product range. The properties of phenolic resin remain constant in oil-filled transformers even over a very long period of time and thus offer very good conditions for the construction of transformers. Against this background, Röchling developed the phenolic-glued pressboard, Trafoboard® HD-PH.

The very low moisture content and the very good drying behaviour characterise the material. Trafoboard® HD-PH meets the mechanical and electrical requirements for laminated pressboard according to IEC 60763-3 type 3.1 A.2 and in part clearly exceeds them. Unlike polyester-glued laminated pressboard, this material does not release styrene during machining. This avoids an unpleasant smell and a possible health hazard for the employees.

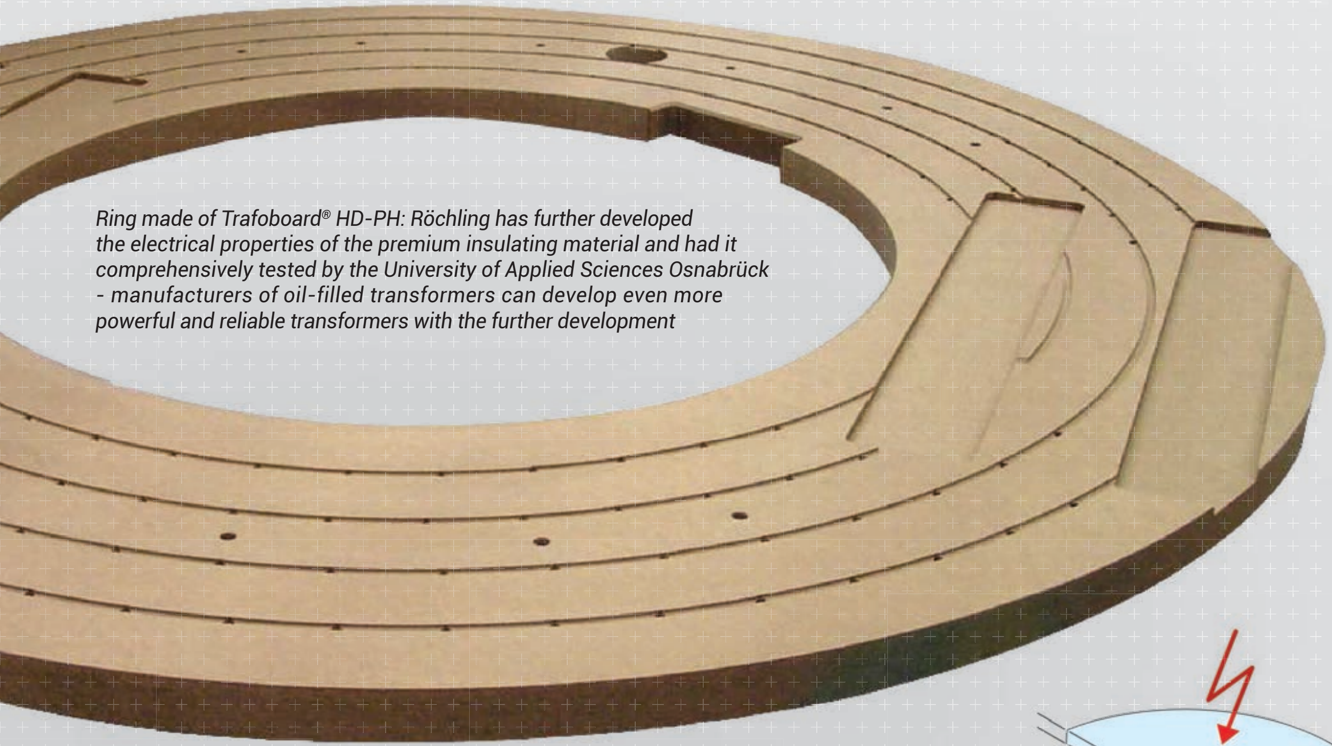
Röchling has been cooperating closely with the University of Applied Sciences in Osnabrück for years in the development of insulating materials for transformer construction. This also applies to Trafoboard® HD-PH, which has been approved for many years by renowned manufacturers of oil-filled transformers after thorough examinations of the properties and has been successfully used worldwide as insulating parts, such as rings, platform and fasteners.

To enable transformer manufacturers to make allowance for the requirements for increasingly powerful transformers, Röchling has now further optimised the electrical properties of the material and had them tested in the modern high voltage laboratory of the University of Applied Sciences in Osnabrück. A high partial discharge inception field strength in the bonded seam between the laminated pressboard layers is the greatest challenge for the electrical properties. Consequently, Röchling has further optimised the manufacturing process of Trafoboard® and once again improved the bonded seam of the premium insulating material.

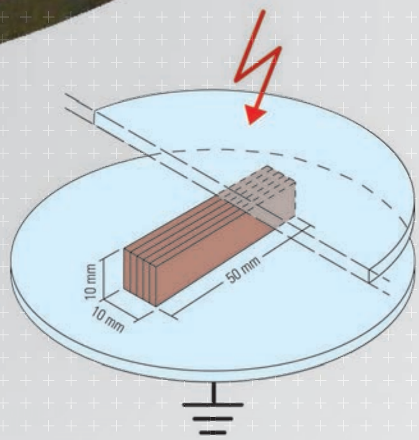
No partial discharge

The University of Applied Sciences in Osnabrück tested 40 samples parallel to the lamination in mineral oil for partial discharge with a measurement precision of <1 pC. The results on Trafoboard® show no continuous partial and only two samples broke down. All the other tested samples were stopped due to a flash-over at the sample surface or a breakdown of the test sample. These events occur mainly by the surrounding mineral oil rather than by the sample, since the average event voltage corresponds to the electric strength of the oil. The samples did not show any partial discharge within the material at an average maximum field strength of 10 kV/mm (see the diagram).

The demands placed on oil-filled transformers are constantly increasing. Ever greater efficiency and operational reliability are desired, even at high operating temperatures and heavy electrical load. Especially for the construction of modern transformers, Röchling Industrial has further developed the properties of its premium insulating material, Trafoboard®. Trafoboard® has been subjected to comprehensive testing by the University of Applied Sciences Osnabrück.



Ring made of Trafoboard® HD-PH: Röchling has further developed the electrical properties of the premium insulating material and had it comprehensively tested by the University of Applied Sciences Osnabrück - manufacturers of oil-filled transformers can develop even more powerful and reliable transformers with the further development



Test set-up: Arrangement of the sample between the electrodes

Test result: The University of Applied Sciences Osnabrück tested 40 samples of Trafoboard®. None showed any partial discharge within the material at an average value of 10 kV/mm.

- *BT = breakdown of test setup*
- *BS = breakdown of sample*
- *FP = flashover of sample on the pressed side*
- *FS = flashover of sample on the sawn side*
- *PD = onset of partial discharge – did not occur*

TEST SETUP

Test direction:	Voltage increase:	Measurement precision:
Parallel to the lamination	Incremental	<1.0 pC

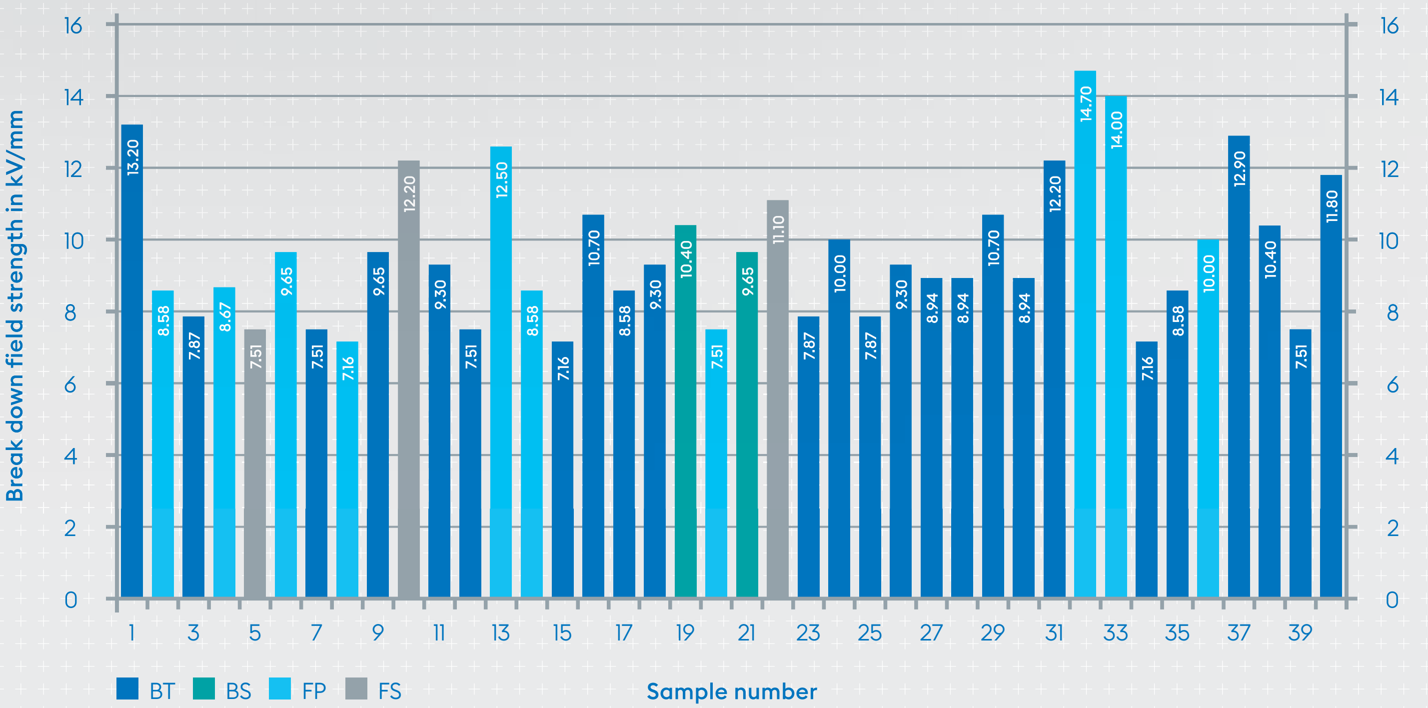


Photo: Röchling

Trafoboard® HD-PH platform (size 3150 x 3100 mm) manufactured and machined by Röchling

Hans-Jürgen Geers, General Manager Marketing & Technology, explained, "The results confirmed the very good electrical values of our material. The phenolic resin we use results in extraordinarily high breakdown resistance without partial discharge. We are very pleased with this result. We can provide our customers in transformer construction with more advantages for the construction and dimensioning of their transformers."

Greater efficiency and more compact designs

The very good electrical properties make it possible to design even more efficient transformers and contribute to operational safety and reliability. Thanks to the further improved bonding with phenol-based resin matrix, the premium insulation material can be used in higher electrical field areas, permitting even more compact transformer design. Furthermore, the mechanical properties remain at an excellent level even at elevated temperatures, which means that the Trafoboard® HD-PH also ensures increased operational safety in overload operation.

Premium materials for the transformer industry

Röchling insulating materials have been used in transformers for over 60 years and meet the highest dielectric and thermal requirements. Apart from Trafoboard® HD-PH, Röchling provides the laminated densified wood Lignostone® Transformerwood® for use in oil-filled power transformers. Both materials support transformer manufacturers in the development of powerful and safe transformers.

Lignostone® Transformerwood® - Proven for over 60 years

Lignostone® Transformerwood® is a laminated densified wood according to IEC 61061 for the construction of transformers made of selected red beech veneers (Fagus sylvatica), which are joined together with thermosetting synthetic resins under pressure and heat.

Ring made of Lignostone® Transformerwood®: Apart from Trafoboard® HD-PH, Röchling provides the laminated densified wood Lignostone® Transformerwood® for use in oil-filled power transformers – a laminated densified wood according to IEC 61061 that consists of beech veneers (Fagus sylvatica), which are densified and glued together with specialized phenolic resins under high pressure and heat.

Photo: Röchling

Röchling

The Röchling Group has been shaping industry. Worldwide. For nearly 200 years. The company transforms the lives of people every day with customized plastics: they reduce the weight of cars, make medication packaging more secure and improve industrial applications. The workforce of around 11,500 people is located in the places where the customers are – in 90 locations in 25 countries.
The Group's three divisions Industrial, Automotive and Medical generated joint annual sales of 2.352 billion euro in 2019.

The Industrial division, to which Röchling Engineering Plastics SE & Co. KG in Haren belongs, is the expert for optimal materials for every use. Röchling Industrial develops and supplies individual products made of plastic for all industrial areas.
This is why Röchling Industrial has the broadest product range of thermoplastics and composite materials. The division supplies customers with semi-finished products or machined components.

Lignostone® Transformerwood® has an excellent reputation in the international transformer industry. The material combines outstanding electrical and thermal insulation properties with a very good oil intake, low weight and high resilience. Typical components include pressure rings, platforms, pressing beams, pitch rings, pressure segments and connection elements.

Röchling as the inventor of laminated densified wood has a unique know-how of the application of the material in transformer construction. Besides the patent from 1916, Röchling is a pioneer in the utilization of Lignostone® Transformerwood® in transformers. This started in the 1950s with the first oil-filled transformers built by Siemens.

Durostone® CR - for higher temperatures

With the challenge of increasing power density, higher temperatures are required. This results in the need for high temperature insulation materials, which is Durostone® CR with a temperature class of up to 180°C.

Durostone® CR is a new product range of fiber-reinforced plastics especially for the transformer industry. Due to technical know-how with different manufacturing processes, resin systems and glass reinforcements Röchling can offer tailor-made fiber-reinforced plastics even for highest electrical insulation requirements. The extremely high mechanical strength makes steel replacement also possible, since Durostone® CR is available in big dimension. Chemical resistance and dimension stability are further advantages the materials offer.

TRANSFORM network

As a member of the TRANSFORM network, the partner network of European premium suppliers for the transformer industry, Röchling has set itself the task of helping to configure the standards of tomorrow's transformers.

Managing the Reliability of an Industrial or Commercial Electrical Power System / E 05

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

in the order of appearance:

Andy .... Reliability Manager of Electrical Power System (recently hired by Brian)

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

Brian .... Regional Vice President (head person for Smith Industries plant)

Lucy .... Brian's Executive Secretary

Jill .... Director of Operations

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

Kevin .... Director of Reliability

**Good morning,
hoping this finds you well.**

I know I have updated you on the Key People at this Smith Industries plant. However, it has been a while and I wanted to go over the team again.

You know me (Andy) and I believe you have met my partner, Tim, who is our plant EE. I've been enjoying working with Tim and as we look at our maintenance program today, I will be working even closer with him.

You have heard quite a bit from Brian, and you understand his passion for Reliability. There are a lot of people who must change the mindset of Senior Management to build Reliability in the Power System, not only at this plant. Lucy keeps him on track.

And the other three (along with me) that are a part of the Reliability Team and report to Brian are Jill, Tina and Kevin. They are solid in their positions and are supporting bringing Reliability into the Power Program.

Photo: SDMyers, Shutterstock

If you remember, in the last article I had spent the morning with Tim and Tina. We had talked through the **first four fundamental steps** in the core of our power maintenance program – those were One-line Diagrams, Short Circuit Study, Coordination Study and Arc Flash Study. By the way, did I mention that we have the Arc Flash Study underway? If not, it is, and we will have the results and findings to you in the August update.

Well, we are back from a nice lunch and are ready to tackle **the other four** in the foundational program which include:

1. Maintenance Standards
2. Service History and Status
3. Required Actions
4. Implementation

We sat down with a fresh cup of coffee and started into the first topic – Maintenance Standards. I looked at the two of them and started out by stating that it was my understanding that this Smith Industries plant trusts the vendors that service the electrical equipment to use the proper standards. They also trust the vendor to determine if the results or inspections are acceptable, questionable, or unacceptable. And lastly, they trust the recommendations of the vendors. I was straight forward when I explained that you can trust the vendor as much as you want, the responsibility remains in this room.

I also explained that we are looking at our Maintenance Standards as the foundation, but once we are done with these four topics, and the Arc Flash Study, we are going to start considering the importance and health of each piece of equipment.

The next step was received well; they seemed very interested as I handed them the ANSI/NETA MTS-2019. These are standards for maintenance testing specifications for electrical power equipment and systems. I explained that these are the maintenance standards that I have used for many years and believe they were ahead of the reliability curve. They also have standards for new equipment, but let's concentrate on our maintenance standards.

Photo: Shutterstock

I spent the next hour walking through the standards. Some highlights of my presentation and their thoughts and observations included:

1. The General Section

a. Safety and Precautions:
We need to specify standards to be followed for us and for our contractors.

b. Test Equipment Calibration:
This needs to be a part of every specification.

2. Power System Studies

a. Short Circuit and Coordination Studies and Incident Energy Analysis, which will be a part of our Arc Flash Study.
b. Load-Flow Studies, which is a necessity in our power system maintenance goals.

c. Harmonic-Analysis Studies, which becomes more and more important and we advance in the equipment we provide power to.

3. Inspection and Test Procedures

a. Detail of the equipment including switchgear, transformers (dry and liquid filled), cables, switches, circuit breakers, capacitors, arrestors, and the list goes on.

b. I randomly opened it up to walk them through an example and found "Circuit Breakers – Air, Low-Voltage Power".

c. We walked through the steps for inspection (which we perform), mechanical inspection (which is done by our contractors), and the electrical tests and standards.

4. I then guided them to the back of the standards where things started getting interesting…

a. I walked them through the base guidelines on frequency of tests and we looked at "Circuit Breakers – Air, Low-Voltage Power" which we had just read the maintenance standards on and saw the following:
i. Visual inspection – monthly
ii. Visual and mechanical Inspection – every 12 months
iii. Visual, mechanical inspections and electrical testing every 36 months

b. This made sense to everyone and then I asked them to go back a couple pages entitled "Maintenance Frequency Matrix" which had an interesting table in it:

MAINTENANCE FREQUENCY MATRIX

		Equipment Condition		
		Poor	Average	Good
Equipment Reliability Requirement	Low	1.00	2.00	2.50
	Medium	0.50	1.00	1.50
	High	0.25	0.50	0.75

ANSI/NETA MTS-2019

We talked about Equipment Reliability, and this is where we sat back and all agreed that our maintenance strategy needs to be improved, and we have to take control of the equipment and begin to look at it differently.

As you can see, this asks us for two things:

1. Current Condition
2. Reliability Requirements

So, we need to first confirm our standards and review the last data generated on each piece of equipment. What standards have we been using to determine the health of each piece?

Tim replied that we have not actually specified specific standards but have stated that we want the contractors to comply with current industry standards. We get their service and test reports and it always comes with a rating: acceptable, questionable, or unacceptable. We look at the result and decide when we do the repair: immediately, during the next scheduled outage, or when we can get it in the budget.

Tina then jumped in and carried on. She agreed and said that establishing the Poor, Average and Good condition is important, but, she noted, as I see in the table, we also have to determine a reliability requirement: low, medium or high. What system do we use to rate the reliability requirements?

Great definition and summary team, as you know, once we are done with the foundational maintenance plan and standards, and have completed the arc flash study, we are going to dig into the reliability side. But let me take a couple of pieces of our current equipment and show the fundamental logic of this process.

We have two 750 kVA cabinet transformers: TC7 and TC23. TC7 feeds the product warehouse and north parking lot, while TC23 feeds the offices, but that also includes the IT center. Here is the example of considerations when choosing reliability requirements:

1. If TC7 were to fail today, the lighting, office power and conveyor transfer system would go down in the product warehouse. I have only watched that process a couple of times, but I know from a few questions and the one-line that:

    a. The plant can produce at full capacity for 48 hours before exceeding the plant capacity and requiring product to be transferred to the product warehouse, which gives us a little time.

    b. I know that we have emergency lighting for 24 hours, so safety is addressed.

    c. As far as office and conveyor and long-term lighting are concerned, it is a rather light load and I know we can rent one of four things:
        i. Cat generator: this can be delivered within 24 hours.
        ii. Spare transformer: this is a common voltage and we can find one.
        iii. Purchase a new one: I know that with this size and voltage class the average is four to six weeks.
        iv. A combination of these.

    d. I would say that we can implement a reaction plan that would streamline the process. Furthermore, if we want to increase reliability without increasing cost, we can go ahead today and:
        i. Get a service agreement and credit check with the generator dealer. If we need one, we can launch a single call and streamline the process. In an unplanned outage, that is priceless.
        ii. We can contract the manufacturer and ask for a quote on the replacement unit that fits the size, capacity, voltages, and impedance. It will include delivery time, pricing and we can finalize the terms, conditions, warranty and get the price for them to deliver and install it.
        iii. Thirdly, we can contact a couple of used transformer representatives for the used transformer market, set up agreements with them, and have their number on our phones for a quick text should this happen.

    e. If we go through this process, we can control the risk to the plant with no expense and just a little effort.

2. If TC23 were to fail, I understand that everyone is comfortable because we have a good UPS system and a spare transformer on a tie breaker. If the unit fails, the power will be uninterrupted. But did you know the financial impact of a total outage on that feed? The cost impact is $100,000 a day, and 75% of production would be shut down. Keep in mind:

    a. The UPS system is temporary.

    b. If the first unit fails and the second unit is put into service, we no longer have a spare.

    c. We also know from TC7 that it will take four to six weeks to replace.

    d. We would carefully need to map this out and look at options; would we:
        i. Auto order the generator for backup of the spare transformer;
        ii. And here is where I am going to bring us back around to base maintenance: Should the health of this unit be assessed? If it is in poor condition, do we recommend that we purchase a spare 750 kVA transformer? You get the idea.

So, you can see that setting acceptable, questionable, and unacceptable standards will be foundational for our program.

You can also see that we now need to pull up all current data and rate the equipment in its "as is" condition. We are in the process of purchasing a power system asset maintenance program and will use that program to rate the condition against our standards. We would get temporary help to enter data and then the three of us will look at condition and flag potential immediate problems. Your thoughts?

Tina responded quickly and endorsed the concept with the statement that she needs to make some adjustments in their other reliability maintenance programs; not many, but some adjustments. She also pointed out that when we get to the reliability discussion for the power system, they already have a lot of the required data.

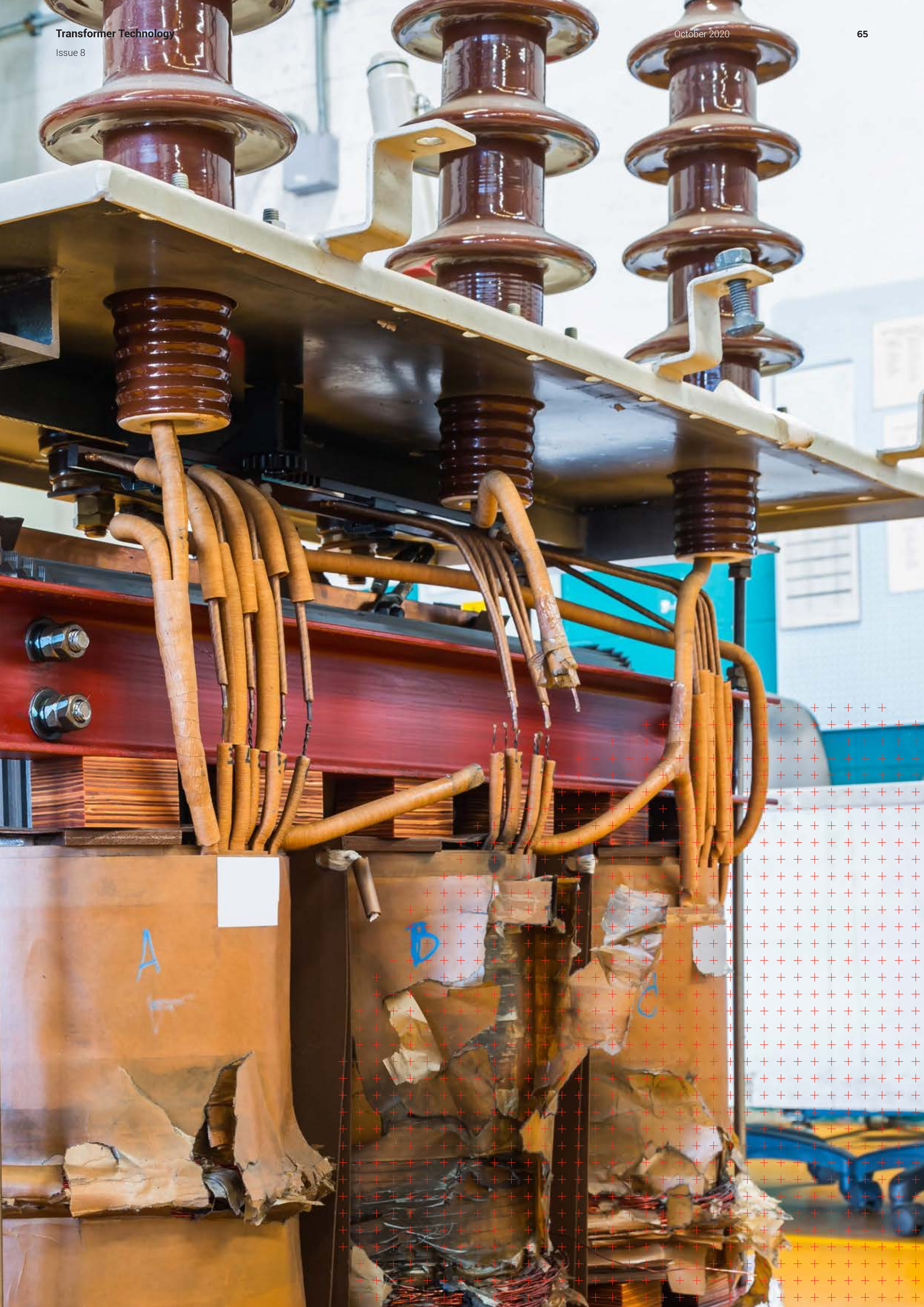
Tim endorsed that explaining that although it is not all together, we probably have 90% of the raw numbers to begin to pull them into our new program.

We set up a meeting for next week to begin to work through setting our standards, inputting historic data (Tim took the lead in working with maintenance to collect data, he mentioned that when I first came on board; I saw the hard copy filing system we use) and identifying where we need to get additional information. We will then develop the detail of what needs to be done today and how we are going to implement corrections.

As we are walking through this process, I have initiated the Arc Flash Study and Tim is working with the contractor and PE that is performing this program for us. We selected a contractor that could provide project assessment and recommendations with the same program and software that we manage our Electrical Power System Analysis with.

Next month, I want to walk you through that arc flash study. We have talked about the overview of key steps such as short circuit and coordination study. I would like to walk you through our experience, our results, but more importantly, how we will use the data generated into our maintenance and reliability program.

In two months, we will get back to the program and tackle reliability. And that is where it really gets fun.


A
B
C

Investments for Growth

A Success Story at YASH Highvoltage Ltd., India An Independent Bushing Manufacturer

YASH Highvoltage
Transformer Bushing Manufacturing Unit Bay 2, Halol-Gujarat, India

Yash Highvoltage Ltd. (an ISO 9001 company) is an independent, indigenous manufacturer of niche condenser graded transformer bushings (for High Voltage and High Current applications).

The company is located in Western India near the city Vadodara, popularly known as a transformer hub with presence of major OEMs such as ABB, GE, Transformers & Rectifiers, TBEA, BTW, Schneider, Voltamp, and Atlanta, all located in the vicinity.

Since inception in 2002, YASH has emerged as one of the preferred solution providers catering to the upper segment of the power transformer industry (generation and transmission) globally.

Today, YASH is synonymous to a solution provider for all combinations of OIP/RIP/RIS bushings, whether in terms of the insulator material, or the standard.

A few of the innovative solutions include:

High Current Bushings up to 25,000 Amperes for generation station transformers*	**High Voltage oil to air/air to air/oil to oil type OIP condenser bushings/wall bushings up to 170 kV***
High Voltage air to oil, dry type RIP & RIS condenser bushings up to 245 kV (under equity partnership with MGC Moser Glaser – Switzerland)**	**Highly customized and special bushings as retrofit & replacement for existing & old transformer bushings of any reputed global make**

* *External envelope available in Porcelain (Grey/Brown), or Polymer Silicone Grey, Standard: IEC 60137:2017/IEEE C57.19.00/01*
** *External envelope available in Polymer Silicone Grey, Standard: IEC 60137:2017*

YASH made RIP bushings for 220 kV/66 kV transformer

Today YASH is unanimously accepted across all major transmission/generation utilities, power producers, contractors and transformer OEMs in the global markets. The comprehensive product basket of OIP bushings and High Current Bushings has seen now a seasoned export reference to more than 35 countries over the past decade, including some noteworthy executions for discerning customers in USA, Italy, Australia, Korea, Brazil, Columbia, Mexico, Ecuador, Spain, Turkey, Bulgaria, Abu Dhabi, Saudi Arabia, Oman, Kuwait, Ghana, Congo, Bangladesh, Nepal, Tanzania, Taiwan, Israel and many more.

Global MNCs the likes of Siemens, GE, Hitachi-ABB, Toshiba, CG, Schneider, Hyundai, BTW, and many more are highly satisfied with the quality standard and industry best lead times offered by YASH.

In 2016, YASH charted new horizons by localizing the production of dry type-Resin Impregnated Paper (RIP) condenser bushings under technology from **Moser Glaser (MGC) – Switzerland (A Pfiffner-Group Company)**, and since have manufactured thousands of RIP bushings up to 145 kV, with recent addition of orders under execution for RIP/RIS bushings up to 245 kV.

170 kV & 72.5 kV YASH OIP bushings.
Transformer: Hyundai Heavy Industries.
Site: Geothermal Power Plant – Turkey.

MOSER GLASER are the pioneers of dry RIP technology operating since 1958, and are an established manufacturer of a product range up to 400 kV RIP bushings and RIP busbar systems, catering to global customers for decades. Headquartered at Basel Switzerland, Moser Glaser share with YASH several connections, as a technology partner and a principle, a supplier and most importantly a strong **Equity Partner**, adding immense value to the organization structure combining Swiss Engineering with Yash's ingenuity.

MOSER GLASER is a PFIFFNER GROUP company, a globally renowned manufacturer of niche Instrument transformers up to 550 kV. Headquartered in Hirschthal, Switzerland, they also have manufacturing units in Germany, Turkey, Brazil and most recently in Nashik, India for localized manufacture of instrument transformers up to 420 kV.

The Board of Directors at YASH –
Mr. Keyur Shah (Managing Director-YASH) and
Mr. Oliver Haerdi (CEO - Moser Glaser, Director - YASH)

From a manufacturing volume of less than 500 bushings annually in the year 2008, YASH has continuously expanded its state-of-the-art manufacturing facility and product range to reach a volume of more than **8,000 transformer bushings annually**, with the capability to serve major volumes, and the vision to aggressively expand its reach to serve all global customers. Several thousands of bushings supplied by YASH are performing successfully in domestic and global transmission grids for over a decade.

*Mr. Fritz Hunziker (Chairman at Pfiffner Group),
Mr. Juergen Bernaur (Pfiffner Group CEO) and
Mr. Keyur Shah (Managing Director of Yash Highvoltage Ltd.)
at Gridtech Expo – 2019, Delhi – India*

Solutions for the IEEE Market

With an offering of comprehensive range for IEEE style OIP condenser bushings from 25 kV up to 161 kV fully compliant to IEEE C57.19.00/01 standard, customers catering to the rapidly expanding power infrastructure demand in USA/ Latin America market have come to appreciate supplies from an established global brand like YASH, which possesses the capability to offer interchangeable solutions.

Recent exports for the IEEE market include 34.5 kV 1200 A 534BCT OIP condenser bushings to a transformer customer in Korea, a prestigious end project in USA, as well as 69 kV 1200 A 534BCT OIP condenser bushings for a discerning transformer customer in Ecuador, again for transformer export to USA. The bushings are compatible and will be utilized for online monitoring by using a reputed European condition monitoring system by the end customer.

Recently, YASH executed a contract for a major thermal power generation plant in **USA** supplying 36 kV 16,000 Ampere High Current Bushings, in addition to several OIP bushings supplied to the Latin American region with support from The H-J Family of Companies.

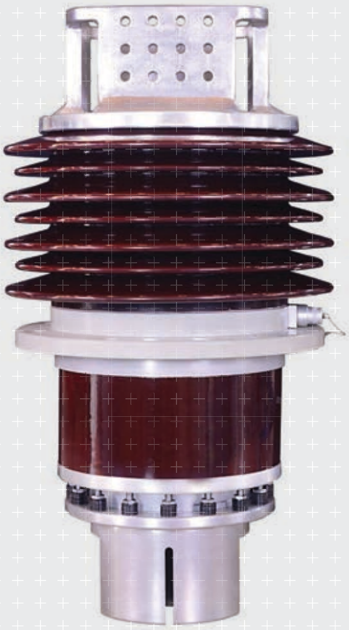
Through our established bushing retrofit business, we exported a large shipment of YASH made 36 kV 16,000A High Current Bushings were also recently exported to **Turkey**, for replacing existing transformer bushings of another reputed global bushing supplier. The bushings were installed on 270 MVA Generator Transformers at a 2x660 MW thermal power plant in Turkey. The retrofit bushings were customized to meet the mounting and termination needs of the end user, and were executed in record lead times in-spite of pandemic related lockdown conditions with full satisfaction to the customer.

In 2020, YASH successfully executed High Voltage OIP bushings with polymer/ silicone insulator for a renowned transformer OEM in **Italy**, for an AC project run by the utility **ENEL**, with many more projects in the pipeline for the Italian market.

Recent Success Stories

The company is expanding rapidly across the globe through an established network of agents in several parts of the world and continues to explore strong agency partnerships. YASH holds a very special partnership with the renowned Missouri, USA-based company **The HJ Family of Companies**, a well-established group with a vast product range of IEEE style bushings for power distribution as well as many innovative products for transformers and accessories. H-J with their well-established local offices are aggressively promoting YASH products in several South American countries.

69 kV 1250 A 584BCT OIP bushings as per IEEE standard, for export to Latin America



36 kV 16 kA High Current Bushing exported to USA and Turkey

Superior Capability for Product Development and Type Testing

The critical operation requirements for transformer bushings also warrant an utmost attention to detail regarding quality and testing. One of the key strengths of YASH is its swiftness in product development and type testing. **The complete YASH range of bushings are type tested at ILAC accredited test laboratories, with more than 75 standardized model type tests readily available, which makes the acceptance process by users an extremely efficient one.**

Being an independent manufacturer solely focused on transformer bushings, YASH possesses the ability to offer flexible and highly customizable solutions to all customers alike. Whether the requirement is for a few bushings or for many, the lean and responsive team at YASH is able to respond with an equal conviction and attention while keeping costs well optimised to provide a niche competitive edge to customers.

50-year old 145 kV SRBP bushings replaced at site with interchangeable OIP solution, including special mounting and 600 mm BCT space

BEFORE

AFTER

YASH HIGHVOLTAGE

This is probably a key reason why YASH has flourished not only as a supplier for large volumes of standard IEC/IEEE style bushings, but also as a solution provider for highly specialized repairs and replacements as well as retrofit solutions to old or existing transformer bushings, which may have developed deficiencies or damage over years of service or during transportation, handling or commissioning at site.

Guided by the team of highly experienced technical experts hailing from transformer bushing industry from Europe as well as India having a combined experience of 100+ years between them, as well as utility stalwarts in field of HV/EHV power substation and engineering design holding distinguished memberships at CIGRE and other notable national and international forums, the team of experienced and passionate engineers at YASH Highvoltage Ltd. leave nothing to chance right from the engineering and design stage till final execution.

36 kV 3150A OIP bushings with Polymer insulator for export to Italy, A/c. Project for ENEL utility

1500 kVp In-house impulse test lab

One stop shop for High Current, High Voltage, OIP/RIP/RIS bushings, wall bushings

Enclosed, ambient controlled, dust free assembly areas for bushings

State of the Art Infrastructure

Yash has now entered into their 19th year since incorporation, and so have the matured and precise manufacturing methods reflected in the industry-best infrastructure. The factory owns world class equipment imported from Germany, Switzerland, USA, China and other parts of Europe to enable a facility which is second to none for bushing manufacture. The factory is at present under upgradation to enhance capacity for OIP condenser bushings, by installation of brand new SCADA controlled Autoclave system for OIP condenser cores processing, along with fully integrated oil storage & handling system and oil flooding system. The aggressive investments in manufacturing, testing infrastructure and new product range development have led to doubling of production quantities and global sales volumes in a short time frame of three years. Still the investment drive continues aggressively.

With a commitment to offer appropriate solutions to customers, while ensuring best value for money and a goal to provide competitive products and services on time, YASH is set to serve global customers for years to come.

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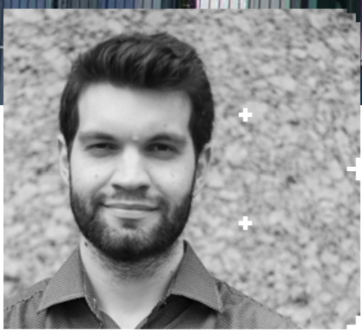
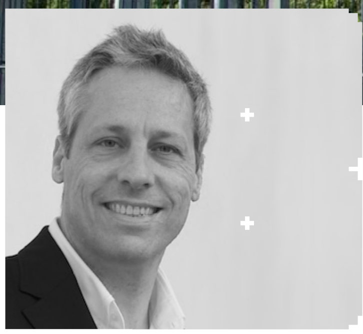
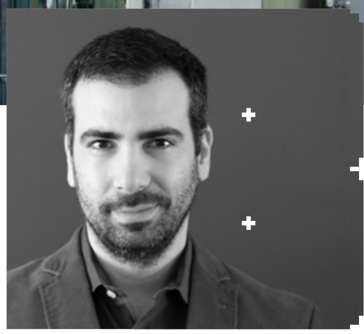
Digital Asset Management: Overload of Power Transformers

by **Helder Pereira Martins**
and **Ricardo Nuno da Silva Ribeiro**
and **Valter Filipe Carvalho Pimenta**

Photo: Efacec







Helder Martins is a Digital Asset Management R&D Specialist at Efacec Service Business Unit where he is responsible for complementing the asset management solutions with the latest technological advances and scientific knowledge. Helder has a degree in Electrical and Computer Engineering. He completed his Master's Dissertation on Overload Capability of Power Transformers, developing algorithms for determining overload capability based on the transformer thermal behavior in order to help decision making and extend the life of the asset.

Ricardo Ribeiro is the Head of Digital Asset Management & Digital Transformation at Efacec Service Business Unit where he is responsible for the development of asset management solutions for the energy sector. Before that Ricardo worked for 10 years at Efacec Power Transformers R&D department and has an extensive professional career mainly in software engineering. Prior to Efacec he worked for major industrial & technological companies. Ricardo has a degree in computer sciences, and he is writing his PhD thesis on process optimization and continuous improvement.

Valter Pimenta is the Technology Manager of Digital Asset Management at Efacec Service Business Unit supporting the development of asset management solutions for the energy sector. Previous to that, Valter worked for 10 years as Field Engineer at Efacec Service and has a vast professional experience in power transformer commissioning. Previously, he worked mainly as IT service field technician. Valter has a degree in Electrical Engineering and is currently finishing his master's degree in Electrical Power Systems.

With a continuous change in electricity demand, asset operators face a difficult challenge of predicting sudden changes in load cycle patterns, which occasionally require loading transformers above their nameplate ratings.
While overloading transformers can damage transformer windings and insulation, overloads are sometimes necessary and are important to ensure a continuous supply of electric energy.

Introduction

The energy transition that we are experiencing, which is highly motivated by environmental reasons, is pushing the limits of energy grids. Paris Climate Agreement includes the European 20/20/20 target, which, for the year 2020, in comparison to 1990, aims at a 20% reduction of carbon dioxide emissions, a 20% renewable energy market share increase, and a 20% increase in energy efficiency. The decarbonization of the energy system represents a disruption in the use of fossil fuels as a power source and a more committed adoption of renewable energy sources.

Redefinition of energy policies will constitute a big challenge for asset operators to manage their energy grids since the power generation paradigm will change quite drastically. The common structure of power grids (generation-transmission-distribution) will be completely redefined: the generation will no longer be centralized, becoming distributed across the whole grid as microgeneration and self-consumption become more adopted technologies. The conventional grid management will need to evolve to a more intelligent and flexible grid in order to fulfill the energy demand and the dynamic behavior of the energy flow. The need for smart grids is propelled by the incoming high rate of alternative energy sources to fossil fuels adoption as this is the next energy revolution.

With a continuous change in electricity demand, asset operators face a difficult challenge of predicting sudden changes in load cycle patterns. The increasing presence of electric vehicles introduces highly capacitive points in the grid, representing a major disturbance in the load cycles of each grid branch. The change in load cycle patterns occasionally requires loading transformers above their nameplate ratings. Exceeding these values can damage transformer windings and insulation. However, overloads are also necessary in emergency or contingency situations and are important to ensure a continuous supply of electric energy.

State of the Art

Motivation for Overloading Transformers

To ensure continuous power supply, overloading power transformers may be used as an emergency measure in different scenarios like natural and unnatural disasters that leave part of the grid inoperative, especially in critical areas.

Financial considerations can also be part of the decision to operate power transformers to their full potential. In this scenario, knowing the risks and impact on the transformer, especially after the unit is out of warranty, is key to successful operation [1].

Economic motivations can lead asset operators to overload transformers in an attempt to defer investments in new and more powerful transformers. This delay in investment is very significant considering the huge undertaking that is needed to restructure the entire power grid.

With the rate of migration to smart grid set-ups on an increase, overloading transformers will be more and more common since replacing each one of the power grid's transformers is too expensive.

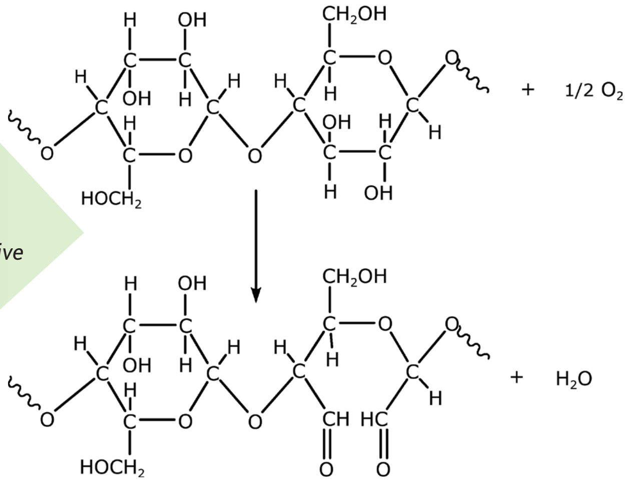


Figure 1. An example of oxidative degradation of cellulose [7]

The dynamic behavior of the energy flow as well as the rapid changes in smart grid configurations make overloading power transformers a much-needed scenario to support the evolution of this energy transition. However, when operating in overload conditions, it can be a challenging task to understand the risks and impact on the asset.

Overload Side Effects

Power transformer overloading usually results in conductor temperatures reaching levels above the nameplate rating, which can exponentially accelerate aging of the insulating material. Therefore, overloading should only be allowed with a good understanding of the risks and impact of the situation in order to prevent a potential collapse of the system [2-5]. Overloading in favorable environmental conditions, where the conductor current is higher than the nameplate thermal ratings, but due to lower ambient temperatures this limit is not reached, is an example of when overloading a transformer can be beneficial, preventing aggravated aging.

The exposure of insulating material to high temperatures is considered as one of the main factors for accelerated aging of power transformers [6]. However, there are other factors that impede a safe overload of transformers.

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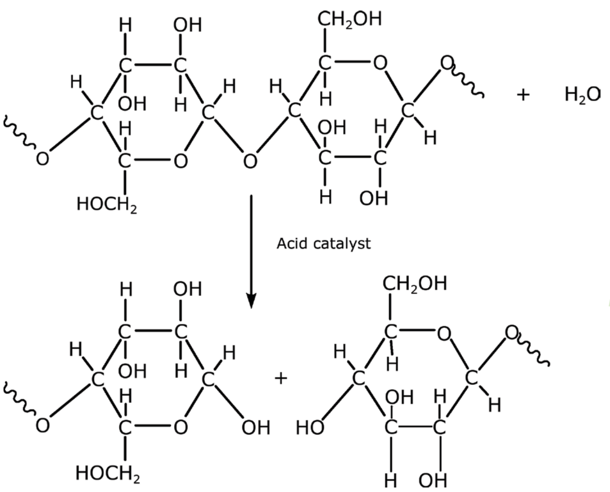


Figure 2. Cellulose hydrolytic degradation reaction [8]

Moisture and gas accumulation in the insulating materials, such as paper and oil, correlate with temperature change, reducing the dielectric strength of the materials.

Insulating paper is mostly composed of cellulose fibers bonded by hydrogen and Van-Der-Waals bonds. Paper naturally degrades over the transformer's operating life due to a variety of conditions the paper is subjected to. The main reactions responsible for paper degradation are oxidation, hydrolysis and pyrolysis of cellulose.

Oxidation is a reaction predominant at lower temperatures, when oxygen reacts with the glucose carbon rings, as shown in Figure 1, resulting in the release of carbon monoxide (CO), carbon dioxide (CO_2), water and two acid or aldehyde groups.

Hydrolysis of cellulose is a catalytical process related to water content, which can occur as a result of oxidation reactions as well as hydrolysis reactions themselves. These molecules react directly with the hydrogen bonds in the cellulose chain, leading to the breakdown of the glucose ring and the formation of two smaller acid groups, as shown in Figure 2. Due to the lower molecular weight, the absorption is easier, decreasing the dielectric strength of the insulating material. At temperatures close to 100°C, the rate of hydrolysis rises quickly due to a series of dehydration reactions, leading to the formation of a smaller compound and water.

Pyrolysis is a reaction that only depends on the system's temperature and results in gas components such as carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), water (H_2O), furan compounds and mud. During these reactions, the breakdown of cellulose chains leads to a decrease of the degree of polymerization, reducing several paper mechanical properties such as tensile strength, elongation and folding endurance. All these reactions have different catalysts, but they are all accelerated by heat as the temperature rises.

Water can be absorbed in cellulose amorphous structures, wall cell pores and polyose-lignin-gel. Cellulose fibers form microcapillaries, which contain insulating oil, gas residues and water. With low water content, the molecules are bonded with strong bonds; but when water content is higher, these molecules are bonded to the cellulose compound only with weak Van-Der-Waals bonds and capillary forces, as shown in Figure 3. This kind of water molecule is susceptible to evaporation like bubbles.

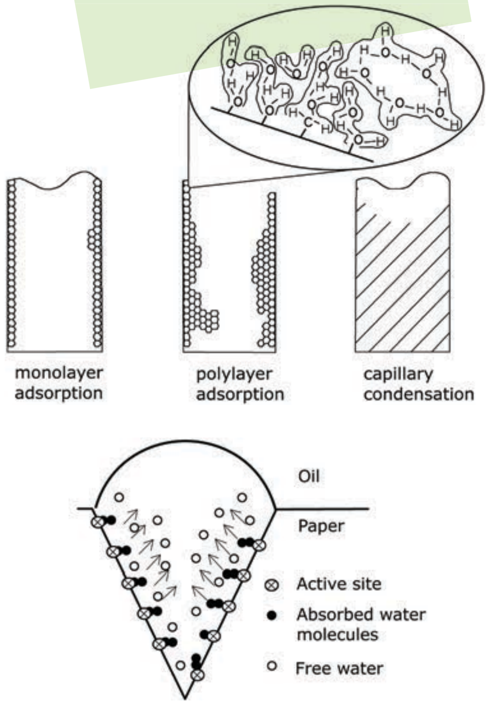
A rapid rise in temperature causes rapid evaporation of absorbed water, which in turn is followed by a rapid increase of vapor and gas pressure within the inner paper layers. This pressure can become so high that it presses out the oil from the microcapillaries of the paper insulation.

The issue with this sudden temperature rise is that the water migration from the insulating paper to the oil causes the local volume around the cellulose to quickly become saturated. The saturation limit of mineral oil is reported to be approximately 50 ppm [10]. Once the oil is saturated, bubbles of water will form.

Water content in the cellulose raises the internal pressure in a capillary, which presses out the bubble into the oil. This water content depends on the aging of the insulating paper as well as the microstructure, such as the diameter of capillaries and pores.

Oil quality constitutes an important factor in the inception temperature caused by its impact on surface tension. Aged oils have surface-active substances which decrease the surface tension, thus decreasing the inception temperature.

Figure 3. Bonds of water molecules in a microcapillary (top); bubble development in a pore (bottom) [9]



Bubble formation can lead to the insulation system failure as Garton and Krasucki concluded in their investigation on the effect of electric fields on water bubbles and its implications in regard to the dielectric failure of liquid insulation [11].

The research shows that an electrical field can distort the shape of a spherical bubble into the shape of a prolate spheroid in the direction of the field. When a bubble is sufficiently elongated it can cause the liquid insulation failure. However, this formation is usually located in areas of low electrical stress, and it is necessary to migrate to areas of higher stress for the reduction of dielectric strength to be significant [9].

At normal operating conditions, power transformers always generate gases; however, when abnormal conditions occur, there is an increase in generated gases. Mineral oil is composed by multiple hydrocarbon molecules, and its decomposition is based on the breakdown of carbon-hydrogen and carbon-carbon bonds. Thermal, partial discharge and arcing faults in the oil generate gaseous byproducts such as hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4) and ethane (C_2H_6). When cellulose material is involved, the faults generate hydrogen (H_2), methane (CH_4), carbon monoxide (CO) and carbon dioxide (CO_2), [12].

When oil temperature rises above certain values, as suggested in literature, this can also cause the oil to expand beyond the capacity of

Photo: Efacec

the transformer. This expansion can lead to an overflow of the oil and can subsequently lead to problems with the oil preservation system or even exposure of electrical components after the oil cools down [13, 14].

The expansion of conductor, insulating materials or structural components due to high temperatures may lead to deformations that can contribute to mechanical or dielectric failures [13, 14]. Operation at high temperatures may cause a reduction in mechanical strength for both conductors and structural insulators, which is of utmost importance during transient overcurrent periods where mechanical forces reach their peak.

Nowadays, there is a large number of transformers operating beyond their expected lifespan, and usually it is not wise to replace an asset that is still operational. Nevertheless, it is highly important to closely monitor these assets as the degradation of the quality of insulating materials means that the overloading regime can occur at lower temperatures than before. Over time, as moisture levels and dissolved gases increase [15], the oil quality tends to degrade, so the maximum allowable temperatures for transformer operation need to be lower in order to avoid gas bubble formation and transformer failure. With the decreased operating thermal range, the probability of critical situations occurring will be higher.

Conventional Overload Monitoring

The conventional approach to overload monitoring is based on a reactive strategy. After applying the necessary load to the transformer, temperatures and other parameters are monitored closely to ensure that the maximum values are not exceeded. This method has its disadvantages, such as high uncertainty as to how the transformer will operate, and a low control power to quickly reverse the temperatures that start rising too fast.

The temperature measurements are made using RTDs (Resistance Temperature Detectors), OTIs (Oil Temperature Indicators), WTIs (Winding Temperature Indicators) and they can also be made with fiber sensors, a practice that has become more popular practice since the mid-1980s.

RTDs are temperature sensors based on materials with accurate resistance/temperature relationship, i.e. the resistance changes per degree of temperature change.

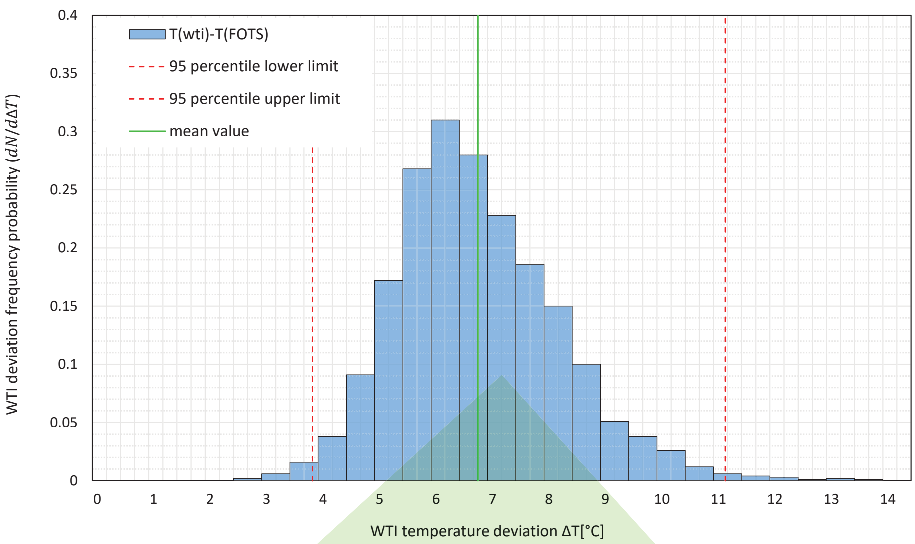


Figure 4. Relative frequency distribution of the WTI temperature deviation in relation to fiber optic temperature sensor measurements during the one-year period of transformer operation [17]

OTIs are based on the principles of gas thermal expansion by means of a sensing bulb. This sensing bulb is placed in an oil pocket on top of the transformer and connected to the remaining instrument by two capillary tubes. In the instrument housing the pointer is fixed with a steel carriage where mercury switches can be mounted for operation of fans and oil pumps as well as the high temperature alarm and circuit breaker trip.

WTIs have the same principle of operation as OTIs but additionally, for returning the winding temperature, they have a coil heating up the oil pocket where the sensing bulb is located. As the current flowing through the heating coil is proportional to the current on the transformer windings, the temperature measurements follow the load applied to the transformer.

Compared to fiber optic sensors, WTIs determine hot spot temperature as an approximation rather than making a direct measurement, which is a disadvantage. This is particularly noticeable in transient states, where WTIs yield significantly low values, especially in the case of short-term emergency loading [16]. A case study comparing measurements from a transformer equipped with a WTI and fiber optic temperature sensors showed an average of 7°C higher values for WTI simulated hot-spot values in comparison to the fiber optic temperature sensors measurements, as shown in Figure 4 [17]. From this case study it was concluded that in comparison to the fiber optic sensors, the WTI overestimates the actual hot-spot temperature, making it a conservative method of hot-spot temperature measurement.

This inaccuracy clearly indicates to asset operators that there is an uncertainty during overload which can outweigh the potential gains of taking this risk.

The use of fiber optic sensors, although allowing direct measurement of winding temperatures, has its own challenges, notably the location and number of the probes. Since there is a big thermal dispersion, even though local loss densities and oil circulation speeds are calculated, it requires a lot of knowledge (usually reserved for the manufacturer) to exactly determine the location of the hot-spot of the transformer.

Given this, on top of further developing of transformer thermal models, it is necessary for a minimum number of fiber optic sensors to best assess hot-spot determination and thermal model validation, being the highest temperature measured close enough to the actual hot-spot [18].

As a result of different types of faults occurring in the transformer – thermal, electrical or partial discharge, different gases are generated. Dissolved Gas Analysis (DGA) allows the identification of single faults or combinations of various ones, using detailed dissolved gas in oil composition information from chromatography. In a similar way, analyzing specific proportions between certain key gases can identify fault types. Detection of a large increase in hydrogen, ethylene and small amounts of acetylene indicate a thermal fault, since these gases are formed as a result of rising oil temperature. If this temperature rise affects cellulose, this will result in generation of carbon monoxide (CO), carbon dioxide (CO_2) and water vapor. A large increase in the quantities of acetylene (C_2H_2) can indicate current arcing. Low-intensity discharges, such as partial discharges, generate manly hydrogen (H_2), with decreasing levels of methane and trace quantities of acetylene. Increased intensity of the discharge will also see an increase in acetylene and ethylene values.

Oil analysis is currently not an exclusive offline operation, where an oil sample is taken from the transformer and analyzed in a laboratory. Online DGA monitors allow for an automated oil analysis with usually greater periodicity than laboratory analysis, detecting almost instantaneously any incipient failure that could be missed by regular oil samplings performed over longer periods of time [19]. Some devices can deliver laboratory grade results, which increases the level of confidence in relying on the monitor to manage the asset. A drawback to this confidence

Table 1. DGA example cases (concentrations in ppm) [19]

Fault	CH_4	C_2H_4	C_2H_2
PD	99	1	0
	9.9	0.1	0
D1	38	12	50
	3.8	1.2	5
D2	15	50	35
	1.5	5	3.5
T2	69	30	1
	6.9	3	0.1
T3	20	75	5
	2	7.5	0.5

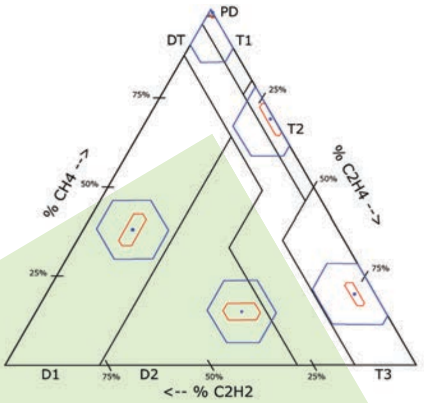


Figure 5. Duval Triangle with diagnostic uncertainty for cases from Table 1 [19]

is an analysis that will identify trends, but will lack the precision of measurements, differing by a significant margin from laboratory results. Accurate measurements are reflected in the incipient fault detection capability: the greater the inaccuracy of the measurements, the larger the uncertainty on fault diagnosis.

The Duval Triangle diagnosis method illustrates this problem, as shown in Figure 5, plotting the values from Table 1. For low-range gas concentrations, and fault types PD, T2 and D2, the uncertainty region overlaps multiple fault zones. For a more severe variation this can make the diagnostics unfeasible [19].

Recommended Approach

In order to mitigate the inherent risk of power transformer overload, it is wise to invest in the development of algorithms that simulate the thermal operation of transformers [20, 21]. In parallel with continuous monitoring and data collection, a dynamic simulation of the transformer thermal behavior should be made, based on internationally accepted thermal models, such as the one proposed in IEC 60076-7 [13] [20], where iteratively the applicable overload factors are determined in order to comply with the nameplate thermal limits.

Thermal Parameters

In order to simulate a real-life scenario as much as possible, it is extremely important to experimentally determine the thermal model parameters that define the behavior of the temperature evolution curves, such as oil and winding time constants and exponents. The use of engineering calculations and heat-run test measurements by means of oil temperature sensors and optical fiber sensors in windings enables a mathematical approximation of the thermal parameters to achieve temperature simulations that are as close to the real-life scenario

as possible, improving the results using standard parameters [13]. The thermal behavior of a transformer is directly related to its cooling, so the type of cooling plays an important role in the correct modeling of thermal evolution. A transformer with ONAN cooling tends to heat up faster than one with OFAF cooling. In other words, different cooling types have different thermal parameters, as the respective thermal evolution curves have unique characteristics.

Ambient Temperature

Ambient temperature, as the surrounding environment of the asset, represents the baseline which temperature variations refer to. The same temperature variations with different ambient temperatures constitute different operating scenarios, one of which may exceed the maximum limits while the other may remain in the safe operating range. Ambient temperature can be a very unstable parameter, depending on factors such as geographical location, time of day as well as physical environment where the transformer is installed. In order to simulate more realistic scenarios, the ambient temperature parameter should be supported by modeling algorithms that can make use of statistical models, historical data and, if possible, data from local weather stations. This way, scenarios where there is a big variation in ambient temperature, as, for example, an enclosed installation with poor ventilation, can include this increase in temperature when simulating the temperature evolution.

Load Factor

The load factors used in the simulation may, depending on the transformer's impact area, be in direct relation with the region's load diagram for planned overloads or scenarios that involve disabling part of the grid as well as other assets. By using a load factor that resembles the actual load, it is possible to more effectively assess the impact on the transformer as well as the real overload periods, as there is a possibility that overloading is only required during the peak time of the network.

Limit Temperatures

As the quality of the insulating materials degrades, the permissible limits that guarantee the protection of the asset change in relation to several factors such as moisture, dissolved gas in oil, etc. Thus, it is important to develop algorithms that take data from oil monitoring systems, such as DGA monitors, in order to calculate approximations of bubbling inception temperatures and failure. Data provided by laboratories, such as paper analysis which cannot be done by online monitoring, is important for condition assessment and estimation of the remaining life. With these approximations, the maximum operating temperatures are adjusted continuously during the transformer's lifetime, providing an operating range proportional to the asset's condition.

Considerations

Although the use of thermal models is of most interest for modeling the dynamic thermal behavior of the asset, it relies on a set of simplifications of the full complex model. These simplifications are made to facilitate computation and make this monitoring method usable. For certain transformers with special characteristics, these thermal models don't apply due to limitations of the simplifications and mathematical equations. Although this only occurs sporadically, it is a significant topic to consider, as it is important to study and validate the thermal models for each asset.

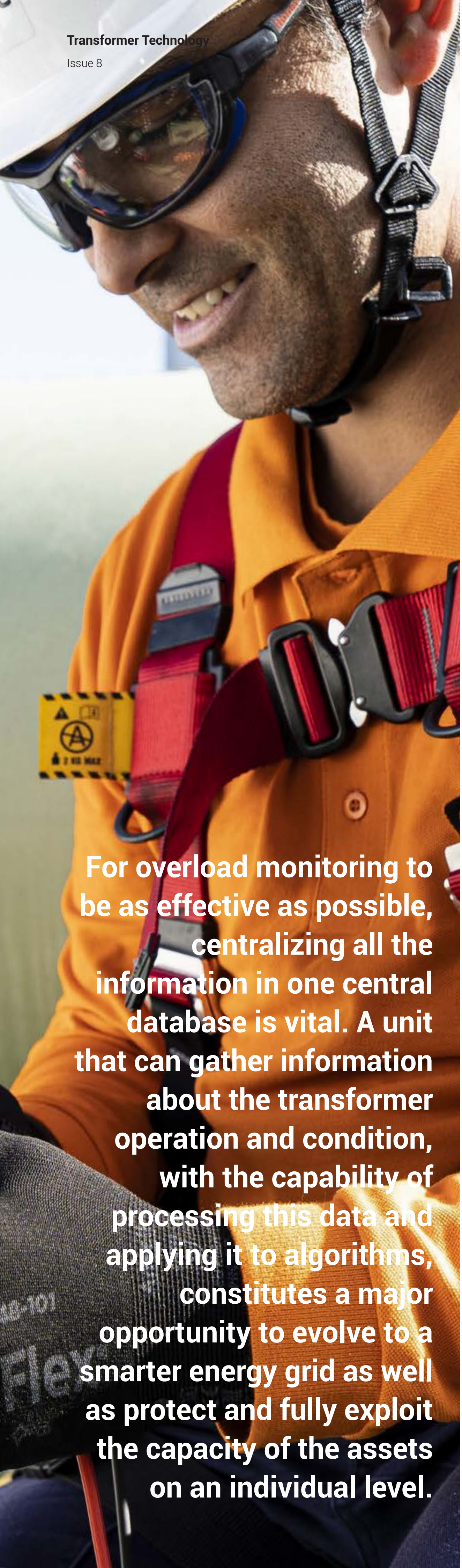
Advancements of computational power have made possible the real time use of more complex thermal models as well as the use of physical models that simulate the real behavior of material, such as oil flow. The possibility to increase the simulation complexity represents a major improvement in the reliability of transformer modeling.

Despite power transformers being the most efficient electrical devices, ranging from 95% to 98.5% in efficiency, power losses are a serious matter to consider when overloading a transformer, or even operate aged transformers. The benefits of overloading a transformer can quickly disappear with the increase of power losses. A lower transformer efficiency makes the overload gains only advantageous in contingency situations. From a financial point of view, overloading does not translate into optimal clear gains – namely, in order to meet electricity demand, due to losses, it is necessary to increase the applied load according to the efficiency gap. The transformer efficiency is at its maximum value when copper losses are equal to iron losses. Since the applied load is variable, following power demand, the optimal efficiency is not always achieved. When overloading, the same principle applies, but, at this operating range, the loss of life is greater than below nominal load. It is therefore of high importance to consider power losses when deciding whether to overload.

Digital Asset Management

Digital Asset Management makes it possible to supply electrical energy safely, with low maintenance costs and optimal exploitation of the active part of the transformer. By digitizing assets, various elements that make up the network are interconnected, creating an asset map that enables intelligent management based on a transparent view of its assets. Continuous monitoring and evaluation of transformer overload capability is a key element in smart grid asset management, ensuring greater control. The more information available for asset condition evaluation, the greater the entropy in data processing. Focusing on vital key points is of utmost importance for efficient asset health assessment. Transposing this into a fleet of assets, it is possible both to macro-manage as well as micro-manage in an organized and clear way. This flexibility enables us to adjust the grid operation to the dynamic load patterns regarding the rapid change in grid configurations, caused by the emergence of microgeneration as well as the rising electric mobility trend. Overloading power transformers is a very dangerous operation that can damage the asset and bring numerous problems to the network, and perhaps to the impact area. As the overload regime may become more desirable, it is of utmost importance to create an intelligent management network to fully understand the benefits and drawbacks of each decision over the asset fleet. Manufacturers have a vital role in pushing technology forward as they can develop management systems taking into consideration years of technical knowledge as well as develop better transformer designs based on the continuous monitoring data. Digital asset management is becoming one of the main pillars in the energy transition, as information is evolving into a more valuable resource than ever before.

Photo: Efacec



For overload monitoring to be as effective as possible, centralizing all the information in one central database is vital. A unit that can gather information about the transformer operation and condition, with the capability of processing this data and applying it to algorithms, constitutes a major opportunity to evolve to a smarter energy grid as well as protect and fully exploit the capacity of the assets on an individual level.

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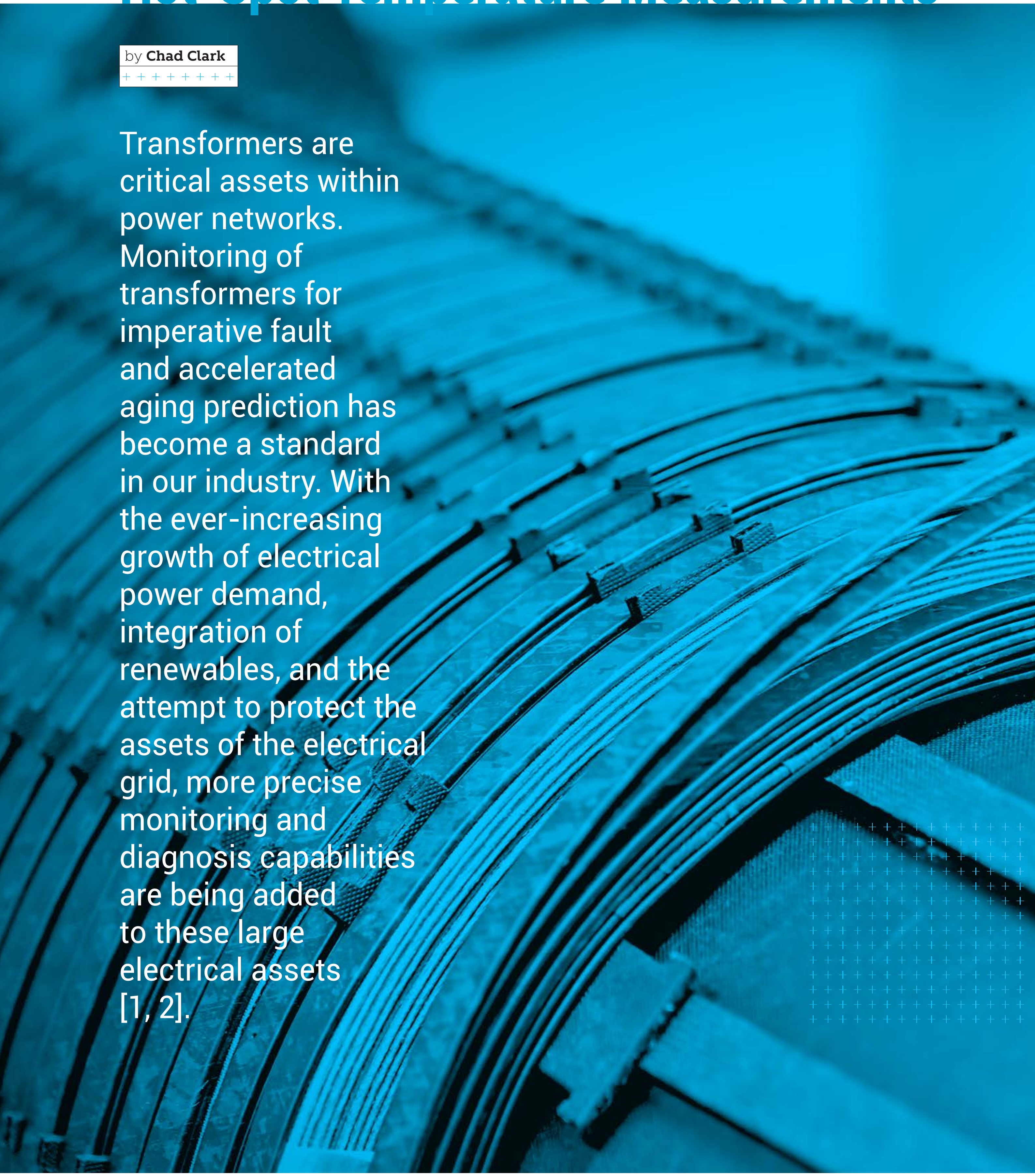
Immediate Benefits of Winding Direct Hot-Spot Temperature Measurements



by **Chad Clark**

Transformers are critical assets within power networks. Monitoring of transformers for imperative fault and accelerated aging prediction has become a standard in our industry. With the ever-increasing growth of electrical power demand, integration of renewables, and the attempt to protect the assets of the electrical grid, more precise monitoring and diagnosis capabilities are being added to these large electrical assets [1, 2].

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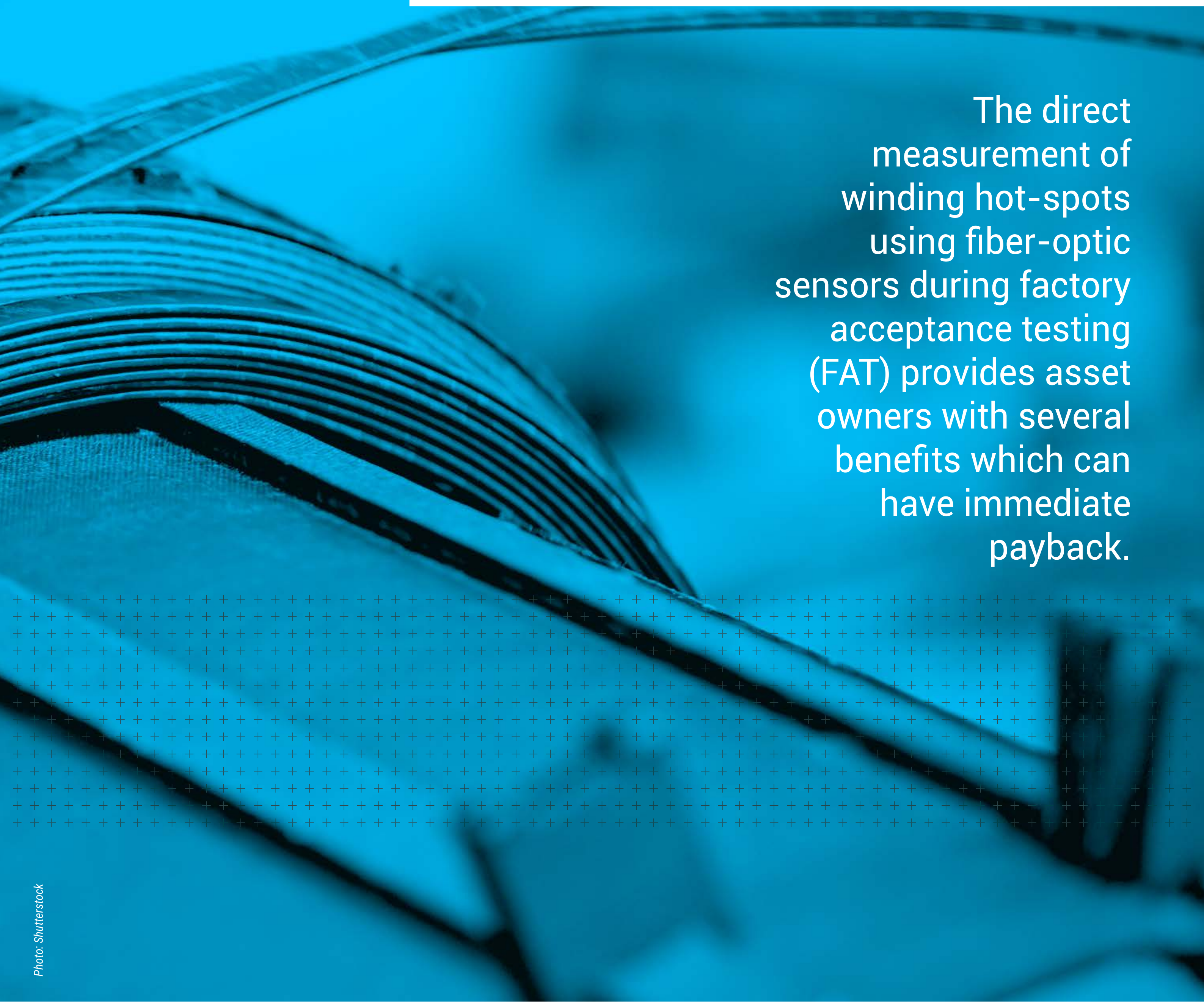
There is an evolution of monitoring strategy occurring right before our eyes. Monitoring systems are not only employed to ensure the asset lasts longer, but they are also being deployed to enable more efficient operations and business decisions. “Will this transformer last forty years” is being appended by questions such as, “Could we increase loading above the nameplate rating to meet short term demand increases?”, or “How will the transformer’s life expectancy be impacted by increased harmonics and/or distributed generation”. Having real data on which to make these assessments is crucial.

Transformer monitoring has many aspects to consider. Moisture, dissolved gases, magnetization current, partial discharge, bushing capacitance and power factor, OLTC loading, movement and contact care, load current, cooling operation, oil, tank and winding temperatures are the most well-known parameters to monitor. The proverbial “mountain of data” produced needs to be collected accurately, stored, filtered and analyzed into both fault conditions as well as health condition indices, to be managed by expert resources [3].

Evaluation of technologies and methodologies for moving from time-based to condition-based maintenance can take years to define and then implement [4]. In the meantime, simple steps can be taken to improve the quality of new transformers being introduced to the existing fleet.



The direct measurement of winding hot-spots using fiber-optic sensors during factory acceptance testing (FAT) provides asset owners with several benefits which can have immediate payback.

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Better to spend time on weeding out the problems at the beginning or you'll pay for it later. Installing fiber-optic sensors and relying on their data for temperature rise testing was a wise decision we made and we would never go back to not using them.

Quote from a Major Australian Transmission System Operator (TSO)

Here we propose one of those simple steps: *The direct measurement of winding hot-spots using fiber-optic sensors during factory acceptance testing (FAT) provides asset owners with several benefits that can have an immediate payback*. In short, even if the benefit of safely loading the transformer during service life and the long term benefits related to on-line real-time condition monitoring are excluded, the immediate benefits of installing these sensors can justify the investment.

You don't necessarily need a mountain of data to improve the safe-use and health of the transformer asset, just a select few smart data choices can sometimes suffice. Measuring winding hot-spot temperatures directly during temperature rise testing is one of those "smart data" choices.

Informative IEC 60076-2 Annex E

The application of winding direct hot-spot measurements using fiber-optic sensors has been around since the 1980s, with one of the pioneers being FISO's Nortech brand [5]. Today's state-of-the-art EasyGrid system utilizing IEC/ITU/TIA standard optical fiber is pictured in Figure 1 with the elements which are part of transformer (sensors, tank-wall plate, fiber-optic feedthroughs, and cover) along with the elements outside the tank (fiber-optic cable extensions and monitor) illustrated.

In 2011 IEC released an update to IEC 60076-2 "Temperature rise for liquid-immersed transformers" with a new Appendix E, "Application of optical fiber sensors for winding hot-spot measurements". Now recognized by authorities, this important publication by IEC changed the perception and future adoption rate significantly. Table 1 is an example of the recommended minimum number of sensors to be installed in different types of transformers depending on rated power, cooling system, and number of phases, according to IEC [6].

Immediate Return on Investment

One of the largest users of fiber-optic (FO) sensors today for direct hot-spot monitoring did not plan a detailed condition monitoring strategy and install sensors from the beginning with a completely defined health index grading program in place. Instead, they became a super-user quite by accident.

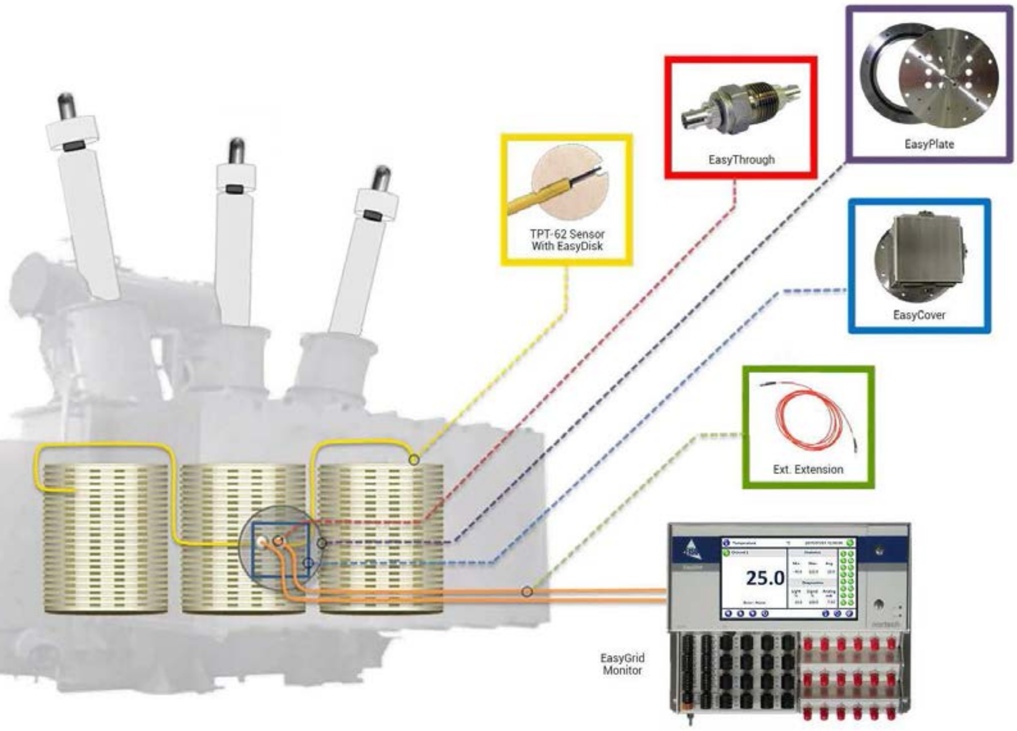

Figure 1. Complete winding direct hot-spot temperature monitoring system

Rated power MVA	Cooling system	Number and phases of installation				
		Total	On central phase		On each lateral phase	
			HV winding	LV winding	HV winding	LV winding
≥100	All system	8	2	2	1	1
From ≥ 20 to <100	ON... - OF..	6	1	1	1	1
	OD..	8	2	2	1	1

Table 1. Table E.1 from IEC 60076-2 Annex E defining minimum number of sensors based on transformer type

After the release of the new IEC 60076-2 standard this utility decided to install fiber-optic sensors as part of a Type Test of a new transformer design coming from a large multi-national transformer manufacturer. Temperature Rise test was conducted following IEEE PC57.12.90 and the results were surprising [7].

Temperatures were far higher than expected from the thermal modeling. After the first Type Test result, the utility requested that all transformers in a new order be fitted with FO sensors and data again acquired during the temperature rise test. When the results came in, all the transformers were well above the thermal model. What happened next is a matter of contract renegotiation and remains proprietary, but the result was the cost of sensor installation was paid back immediately through discounts provided for transformers which would not last 40+ years at the nameplate rated load.

After this experience, this asset owner required fiber-optic sensors to be installed on all new power transformers from all suppliers, and in the last few years has moved to continuous real-time monitoring on all transformers. This user case follows well the "Evolution of Adoption" that the typical user of fiber-optic temperature sensors experiences, see Figure 2.

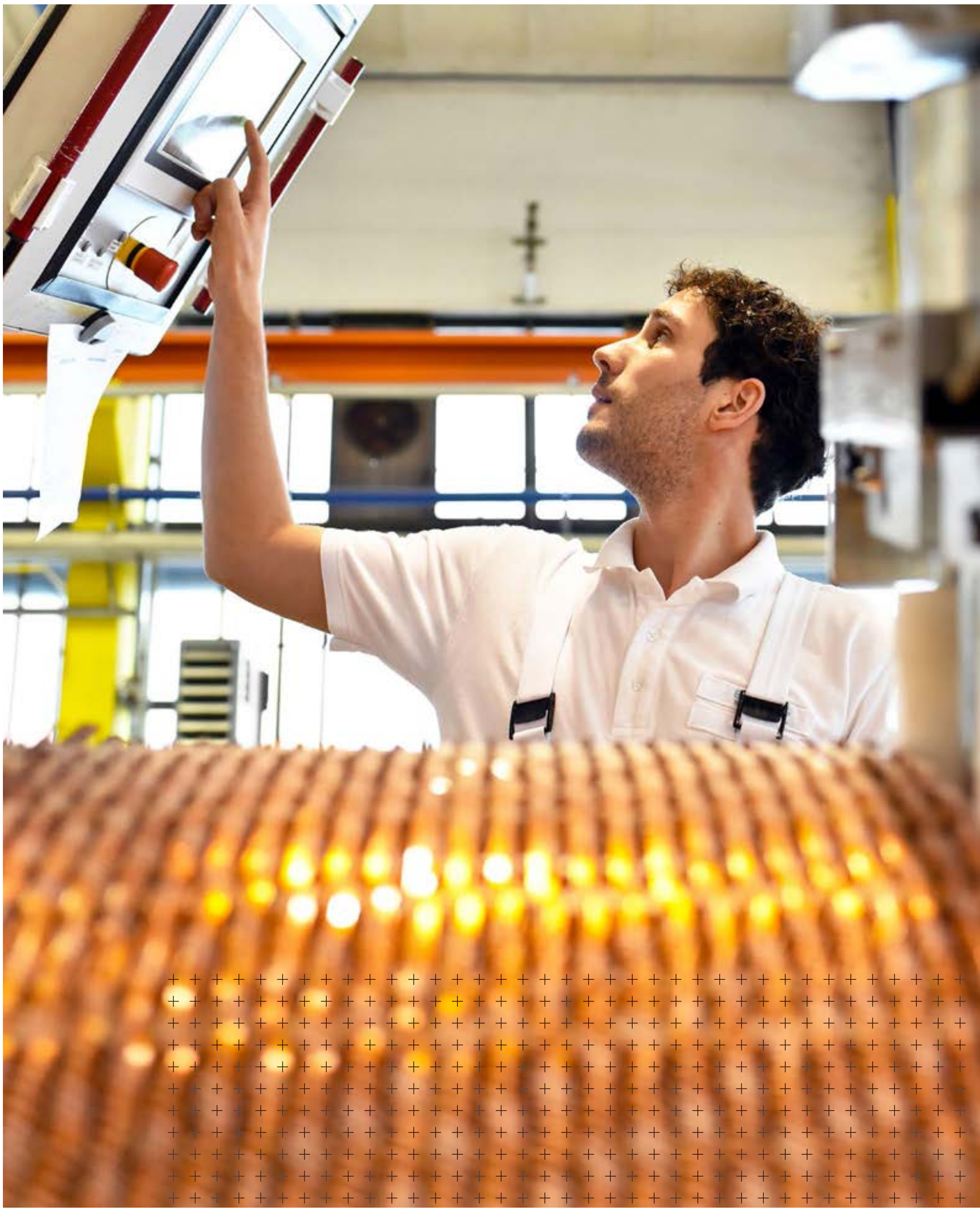

Figure 2. Evolution of adoption

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Temperature rise over the permissible limit (°C)	Compensation as a percent of total FOB price of the transformer
0-2.99	0%
3.00-4.99	3.00-4.99
5.00-6.99	10%
7.00-8.99	14.50%
9.00+	Right of refusal

Table 2. Compensation from temperature rise test results

Start with Type Testing

Type testing is an inexpensive means by which to assess the OEM manufacturer's design accuracy and in the case of winding temperatures to confirm the thermal model provided during the design review is accurate. IEEE standard 1538a-2015, "IEEE Guide for determination of maximum temperature rise for liquid immersed transformers" has detailed instructions on where and how many fiber-optic sensors to install on a transformer for this purpose.

With regards to the quote attributed earlier to a large Australian utility, the concept of "spending time at the beginning to avoid the problems later" has its origin from Type Testing. During Temperature Rise tests one of the sensors on the first transformer of a multiple transformer substation project was measuring 7°C hotter than expected at rated load. The traditional winding temperature indicator (WTI) which was to be used for control (alarming & cooling) showed a normal temperature. "That sensor is running a bit hot today" was the explanation from the transformer OEM. In this case the utility was not accepting the explanation and asked for the oil to be drained and the transformer to be investigated. This was not a small task, but the 7°C difference could not be explained and so the OEM reluctantly agreed.

The resulting investigation revealed that the outer surface on an oil duct used to direct flow at the bottom of the windings had delaminated. The delaminated material wedged itself in the oil flow and diverted the cooler oil away from a portion of the winding where one of the sensors had been installed. All the transformers on that order were drained and all were found to have the same delamination on the oil ducts causing the same type of blockage. The OEM changed the oil ducts to a new material, tests were redone, and the transformers subsequently passed.

If the Type Test had not been done with such accuracy, the original transformers would have been energized in the field and had a lifetime shorter than expected. Finding the design problem at the beginning avoided the financial loss associated with their early replacement, easily equivalent to a few hundred fiber-optic monitoring systems. That Australian Utility has since progressed to 100% Temperature Rise Quality Check during FAT using the data from the fiber-optic sensors.

Photo: Shutterstock

Our Ideal transformer includes direct hot-spot monitoring using fiber-optic sensors. The temperature tests done during FAT provide the beginning of life fingerprint against which to compare the on-line temperature data.

Senior Risk Consultant of a Major Commercial Property Insurer

100% Quality Check during FAT

Transformer design and material workmanship are major causes of transformer failures. Since an asset owner cannot be on-site the entire time a transformer is being manufactured, factory acceptance tests witnessed by the asset owner or contracted delegate are vital [8, 9].

What to do if the results are not as expected? Higher temperatures mean that either the transformer cannot be run at rated load, or if run at rated load the lifetime of the transformer will be reduced. Compensation for reduced life expectancy can be calculated and financial penalties can be assessed and pre-agreed contractually. An example of such a financial agreement is described in Table 2.

If a deviation of 3+ degrees is measured, then payback on the installed sensors is immediate. Further, after being installed and used in the factory test, the sensors could be made accessible for connection later on site. The temperature probes can be measured using a portable monitor before the transformer warranty period ends and compared to its beginning of life "fingerprint" performance. Having field-tested transformers enables a second opportunity for the transformer manufacturer quality check and more data by which the asset owner can base future transformer purchasing decisions. Are there some transformer OEMs that perform better or worse than others? Having real-time field data from the fiber-optic temperature sensors can help provide the answer.

Other Immediate Side Benefits

Although quality check of the transformer OEM is the key motivation for Type Test and 100% Temperature Rise QC adoption strategies there are other compelling technical and commercial benefits.

Benefit: Used to Correct Hot-Spot Simulators

Listing the deficiencies of traditional winding temperature indicators (WTI) is beyond the scope of this article, but for any user of these devices the process of calibrating them is seen as a bit of a dark art. Their precision is dependent wholly on parameters entered by the transformer OEM. Sources of error exist, such as the calculated value being dependent on ambient temperatures, due to changes in oil viscosity, and that variation is not considered in the model [10]. Further, the calculations made to estimate winding temperatures using this method are based on below rated load conditions, and in order to know the actual accuracy at above rated load requires further modeling and validation testing for that specific transformer class and design.

Some clever asset owners have taken to use the accurate fiber-optic probe measurements obtained during the temperature rise tests and use that to fine tune the thermodynamic model of the transformer in the WTI at the rated load condition. The real measurement from the fiber-optic sensors essentially corrects the WTI measurement at a critical temperature where cooling of the transformer is critical and the loading of the transformer needs to be managed closely.

Benefit: Recognized by Insurance Companies

The installation of fiber-optic temperature probes can result in a higher confidence level for the newly energized transformer. As a bonus, the sensors then provide the ability to monitor in future years to safely manage the loading and thus the life of the transformer. A multinational property insurer, covering over 100,000 power transformers worldwide, lists the fiber-optic direct hot-spot monitor as part of their ideal transformer.

Now that the immediate benefits are more clearly understood, the conversation inevitably turns to the cost of implementation.

Associated Costs

Pricing of systems can vary depending on the transformer, mainly due to the number of channels, length of cables, and monitor communications required. A rule of thumb is that the external monitoring components (external cables and monitor) are 50-60% of the total cost of the system. Therefore, asset owners can achieve the benefits of the fiber-optic sensor installation at less than half the cost they initially would have imagined. Table 3 compares the relative costs associated with each adoption strategy.

The concept of installing sensors without monitoring at the energized transformer site we refer to as "Dark Sensor" installations. Dark Sensors are one of the least guarded secrets of our industry, however, many end-users and asset owners are unaware of this strategy which is available at just 10-50% of the material costs related to continuous on-line monitoring.

Since fiber-optic sensors need to be installed in the windings at the time of manufacture, investing in the immediate benefits also comes with the ability to reap the long term benefits later. Consider the installed sensors as an "Insurance policy" which can be cashed in later.

The Insurance Policy

Consider the following cases which are likely to occur in the future, and which the existing fiber-optic sensors would then be utilized. As Figure 3 [11] helps illustrate, managing the temperatures of the hot-spots through dynamic loading and efficient cooling in order to avoid rapid loss of life is critical. Having real-time, accurate temperature data from fiber-optic sensors would be invaluable. Where on the dotted line of Figure 3 are your transformers?

New Regulations and Laws

As national energy policies evolve, new requirements can be introduced which require the understanding of how the transformer will fare under emergency loading conditions. What happens when one transformer fails and others have to carry a higher load?

Strategy / Parameter	Type Test	100% quality check during FAT	Monitoring pilot project	Continuous monitoring
Sensors installed?	12-30 on one transformer	All transformers	All transformers	All transformers
Monitor needed?	No	No	One transformer per site	All
Investment	10-15%	40-50%	60-70%	100%

Table 3. Cost of adoption

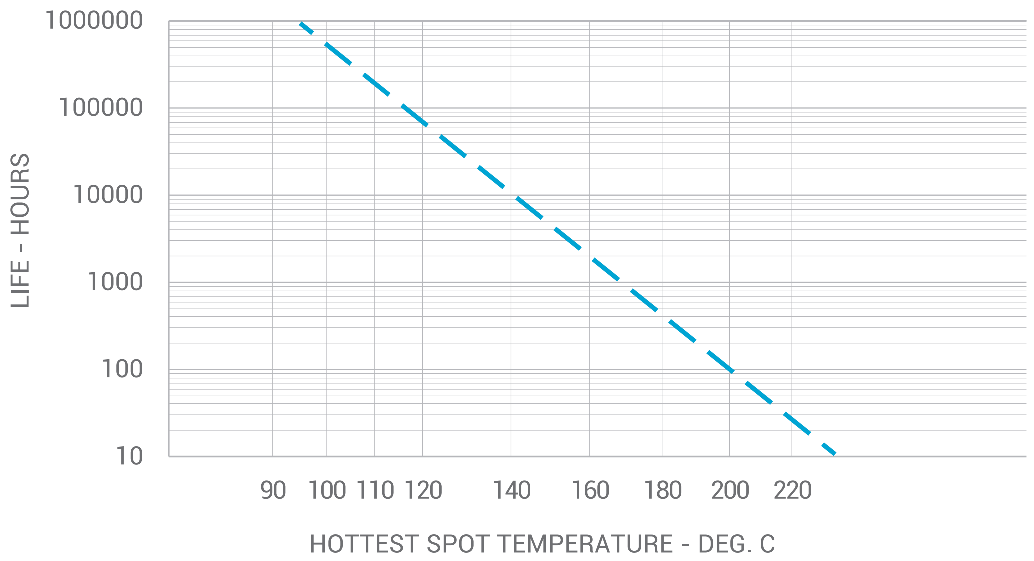

*Figure 3. A Transformer's life expectancy is dependent on winding hot-spot temperature [11]**
Minimum life expectancy curve for liquid-immersed distribution, power, and regulating transformers rated in accordance with Clause 5 IEEE Std C57.12.00-2015, at 65°C average winding rise, 80°C hottest-spot rise

The transformer previously running at just 55% may now need to run above 100% rated load. Ten, twenty, thirty years after first being energized can it do so *safely?*

Increasing Demand

Most transformers when put into service are not heavily loaded, perhaps only loaded to 40-60% of the nameplate value. This may last for 5 years or 15 years, but eventually the transformer can become heavily loaded and subject to stresses from overload or dynamic loading situations. As populations increase, space constraints occur, and/or economic realities change the situation can quickly become even more severe. In some countries today the electrical T&D networks run close or at maximum capacity. There are times when transformers in the network will be over rated load and the owner will want to efficiently cool, or reduce loading when the transformer temperature gets too hot. Catastrophic failures also need to be avoided. India is one country where managing overload conditions is the main driver for adoption.

Revenue Opportunity from Overcapacity

The economic benefit for owners to run their transformers over rated load for short periods of time to capture additional revenues can be calculated directly using only a few variables. Net yearly benefits of several hundreds of thousands of dollars can be realized with on-line monitoring, adding typically less than 1% to the cost of the transformer. In places like Australia and the United States this is one of the reasons why direct measurements and comprehensive monitoring systems are employed. Utilities can make better-informed decisions with the accurate data the real-time, direct temperature measurements provide.

The Age of Dark Sensors

The complexity of on-line condition monitoring coupled with the rigors of asset maintenance can paralyze an organization when evaluating new technologies for incorporation into their future plans. Long term benefits do need to be understood, but in the case of direct real-time hot-spot monitoring the immediate benefits provided during factory acceptance testing make their specification and installation into new power transformers a smart decision by owners of these assets.

The immediate benefits include:

- Identify design flaws and root out material and workmanship issues before acceptance from manufacturer
- Used as a basis on which to receive a pre-negotiated discount, or even reject entirely
- Used to correct the existing hot-spot indicators (WTI) which may still be used to control cooling
- Provide beginning-of-life performance "fingerprint" against which to compare energized transformers on-site before their warranty expires

Further, the medium and long-term benefits experienced from efficiently managing the load on a transformer due to increasing demand, economic benefit, or to comply with new regulations are non-debatable. *Transformers with fiber-optic sensors providing real-time accurate hot-spot temperature measurements will operate safer and last longer.*

Take a step back from the concept of condition-based asset maintenance for a moment and focus on the immediate benefits to your transformer fleet. The short-term benefits and the corresponding insurance policy for the future that direct hot-spot monitoring provides are clear. The installation of fiber-optic sensors into your power transformers for direct winding hot-spot temperature measurement could be your next bright idea [12].

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Oils & Fluids:

Better Solutions for a Changing World

Welcome to the future! In the next monthly issue of Transformer Technology we move to an important and ever-changing theme:

“Oils & Fluids: Better Solutions for a Changing World”

Every week between now and the curated digital issue, we will feature an article from a transformer technology professional based on this important theme. And if you think it will be limited to changes surrounding new fluids, natural and synthetic you would be partially correct.

While we want to make sure to update the TT Community on the advantages and benefits of natural and synthetic esters, we also want to address positive changes taking place with mineral oils. Our world demands changing approaches to current dilemmas and Transformer Technology is committed to bring you the latest solutions.

And we will also bring you great content on testing, maintenance and reliability features of existing fluids, and ways you can use the fluid to address the health of your transformers.

I am looking forward to advancing the Body of Knowledge in an area where we might think we know it all already. We don't!