



TRANSFORMER TECHNOLOGY^{MAG}

TRANSFORMER TECHNOLOGY^{MAG}

new Technology Changing the Heart of Power Systems

High Temperature Insulation Systems:
An Option for Resilient Transformers

Interview with
Jon Trout, FirstEnergy

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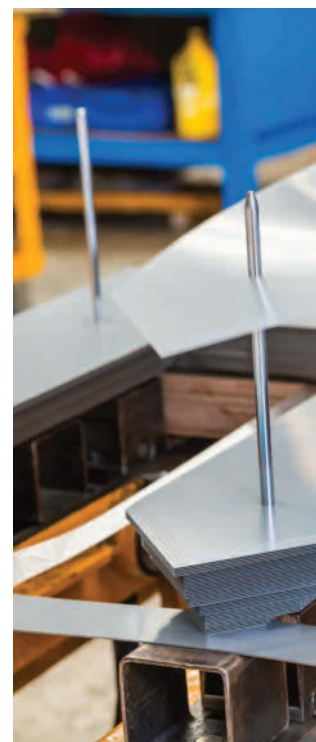
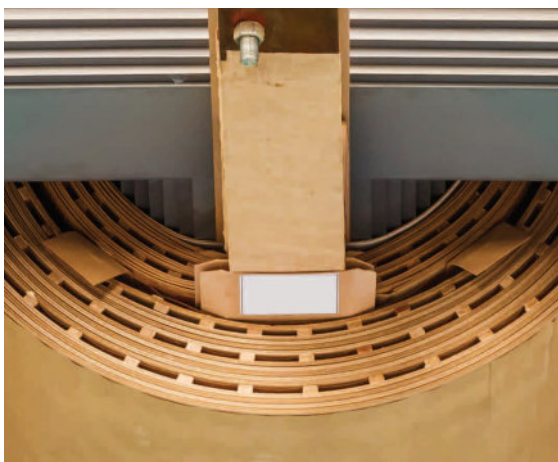
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Jon Trout is Manager of Transmission Design for FirstEnergy, who has experienced many changes in the world of transformer technology over the years. In this interview we were curious to find out what changes he considers to be the most important.

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Don't move one step forward with new loads that save money or improve capabilities, and then one step backward with outages and transformer failures. New Transformer Technology includes being aware of the new problems associated with new high-tech loads; and understanding how they can impact the life of a transformer. By Gabe Paoletti





28 Transformer Resiliency

Richard P Marek reviews the latest developments and trends towards highly moveable large power transformers designed to improve grid resiliency.



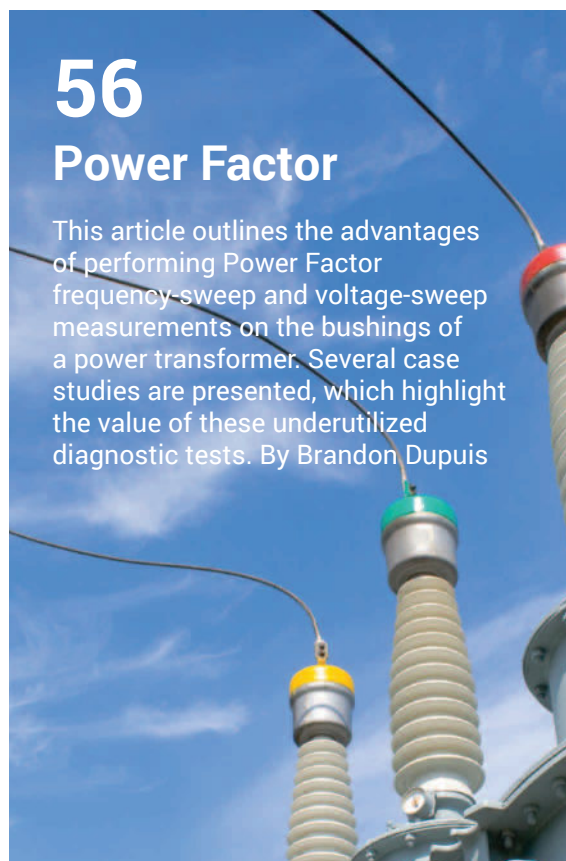
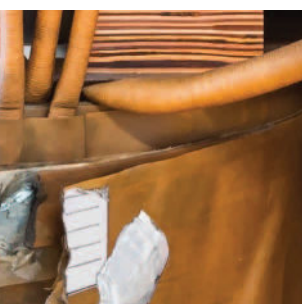
48 Natural Esters

Natural ester fluids have been around for more than a century. Recently more environmental pressure has emphasized the need for an environmentally safe dielectric fluid to replace mineral oils. Modifications to improve electrical properties and oxidation stability made this possible.
By Corné Dames



40 Dielectric Response

Diego Robalino and Roberts Neimanis provide a short summary of IEEE's publication IEEE C57.161-2018 – "Guide for Dielectric Frequency Response Test", a needed document for a non-intrusive and non-destructive testing method that has been used in the field for over twenty years to better understand the complex condition of the insulation system of power and distribution transformers.



56 Power Factor

This article outlines the advantages of performing Power Factor frequency-sweep and voltage-sweep measurements on the bushings of a power transformer. Several case studies are presented, which highlight the value of these underutilized diagnostic tests. By Brandon Dupuis

Dear Readers,

When I was first offered to become the Editor in Chief, three thoughts came to mind immediately: First was, why me, did everyone else turn it down? The second was the reason for the first; my passion for transformers was less about their technical nature than it was about their reliability. As the Vice President of Reliability for one of the North American leading companies in transformer maintenance, oil testing, training and field service, that has been my primary focus, not on their technology.

But the third and perhaps most important objection was: why? Why did we need a magazine called Transformer Technology? It was the answer to that last question that made the difference - a realization that we need a North and South American focused publication that would bring the best and the brightest together, as readers, as contributors, as advertisers. You have before you, I am proud to say, our first issue, focused on new technology or adaptations and updates of older technology for transformers.

The authors have been tremendously gracious to share their knowledge and expertise without having a previous issue as a template. That is an accomplishment in and of itself. Their willingness to trust and to meet the deadlines and submit to an editing process still in development, has been something I will personally remember and treasure. Excellence is one of my most important personal challenges and something they achieved in our first issue.

There were two important aims that we defined before embarking on this project. The first was that we would produce a magazine, both digital and print, a daily news feed and an interactive website distinguished by excellence. We have a team handling the heavy lifting when it comes to the actual articles from drafts to layout and print, and they are a delight to work with. And my own personal champion, Rachel Linke, has been tremendous in keeping me and our contributors organized and on track. Thank you all for your commitment to excellence as well. Also, a great thank you to Dale Bissonette and all the people at SDMyers, who have sponsored my journey into the world of transformers and transformer technology and reliability for nigh on a decade now. Without their support, none of this would have been possible.

The second was that we created a learning arc, where we could approach transformer technology in a cohesive and logical manner, rather than cobbling together a bunch of articles, most of which did not relate to each other, just to be the

filler for advertising. As you can see, this first issue is all about "New" Transformer Technology and we barely scratched the surface. Rest assured this theme will be repeated from time to time as we see the need for publishing changes and updates. The June issue will be themed "The Revolution in Dry Type Transformers" given the many changes taking place in that segment of the industry. Future issues in September and December will focus on "Testing and Monitoring Best Practices" and "Critical Failure Modes and Prevention", respectively.

Recently, I had a chance to attend or review several major conferences and/or exhibitions, which, by the way, will be one of our goals at Transformer Technology - keeping you up to date with events or conferences related to or affecting transformers. The first event was the bi-annual IEEE PES Conference in Denver last year and the second was DistribuTECH, which was held this year in New Orleans. What amazed me most about both events was how much digital technology, software and Artificial Intelligence (AI) or Machine Learning (ML) seemed to be the rage. Will any of these changes in the marketplace impact transformer technology in the future? You can be certain they will and we will be there, reporting on what is new and relevant.

That leads me to a commitment: Just because something is new does not mean it is useful or relevant. At a recent Reliability Conference, I coined the term UIoT or the Useful Internet of Things. That was in the midst of a full day of short presentations devoted to AI and ML from the perspective of reliability. With over 30 presenters, it became hard to separate the wheat from the chaff. How much of what is coming will be needed or useful? Our hope is to sift through the chaff and bring you only the wheat as it relates to transformer technology.

As an engineer, I like to look at things from the perspective of a problem to be solved, and most engineers I know are the same way. We were drawn to engineering by the need to know and the desire to solve problems. Electrical, mechanical, chemical or any engineering discipline for that matter all have as the core the desire to know and to understand. Most engineers are lifelong learners and the writers in this issue are great examples of that. I expect you'll hear from them again in these pages. I commit to you, our readers, that we will strive to be a great source of new knowledge, while building on the existing body of knowledge that has stood the test of time. We will also face the challenge of a changing of the guard as boomers retire and a new

generation takes their place. I looked at legacy knowledge in an article that I wrote for NETA, where I asked,



What if much of that legacy knowledge isn't worth passing on in the first place? What if things have changed - and are changing - so rapidly in our field of electrical system reliability that much of that legacy knowledge is outdated, or even worse, what if it is flat out wrong? Would we want to make sure the next generation learned it?

We want to make Transformer Technology an honoring of the past and a gateway to the future, where all generations can learn from each other and a place where we are building a Body of Knowledge (BoK) of old and new. If you are like me, lifelong learning is also your passion, then welcome to Transformer Technology. Personally, I will strive to meet the high expectations we have of ourselves and I challenge you to become part of our future by sharing your wisdom and experiences when it comes to transformer technology.

You can contact me at alan.ross@transformer-technology.com. I'd love to hear from you about our editorial content.

Thank you,

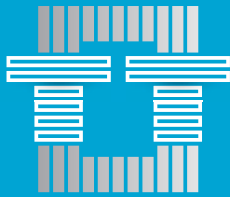
Alan M Ross
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Magazine



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Impressum

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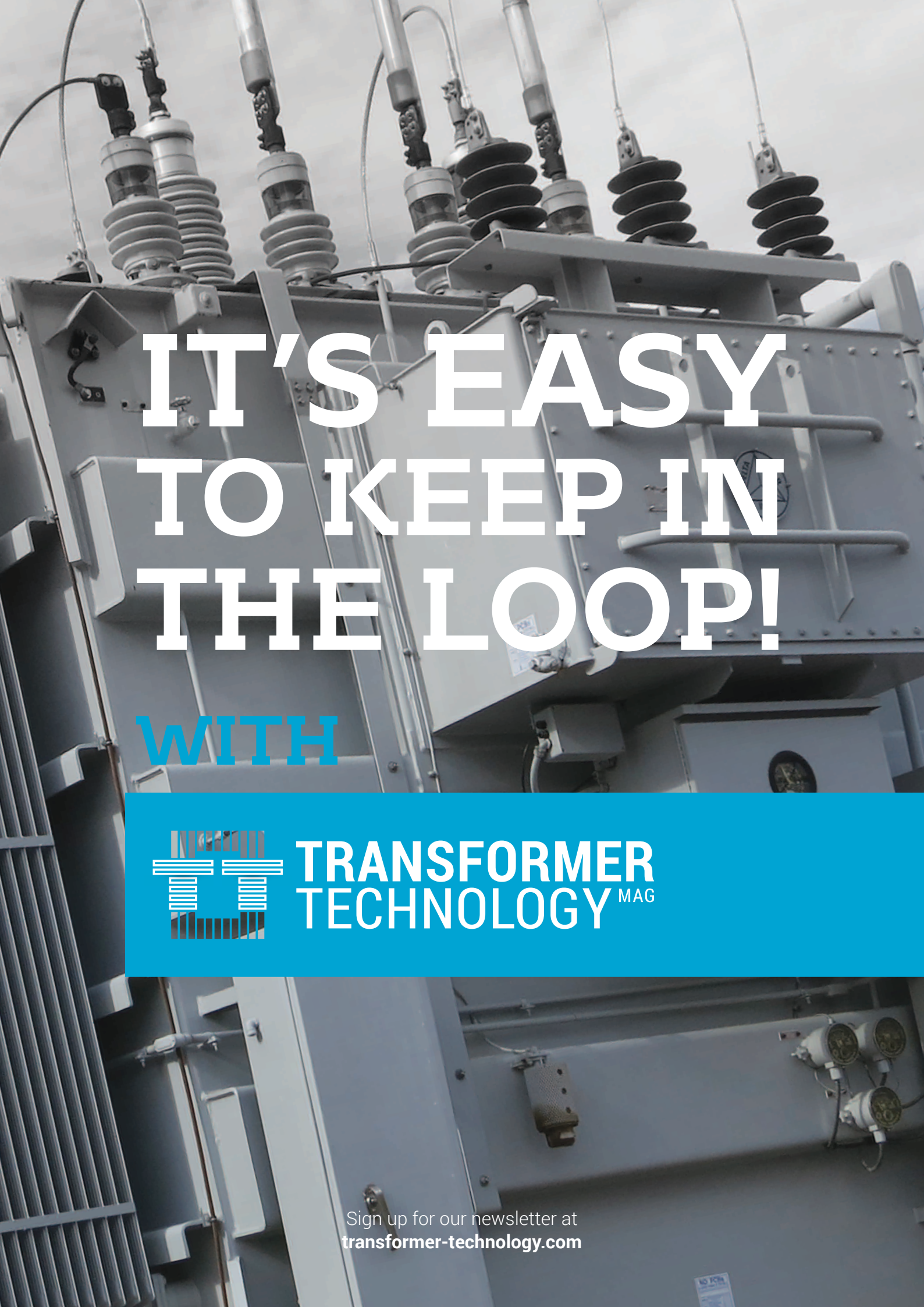
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At a Glance

China pursuing a goal to build a giant supergrid

The State Grid Corporation of China (SGCC) is building the world's first 1,100 kV transmission line, a project that has grown into a more ambitious goal to stitch together the electricity systems of neighboring nations into transcontinental "supergrids" capable of exchanging energy across borders and oceans.

Once the government-owned utility completes the project this year, the new 1,100 kV line will stretch from the Xinjiang region in the northwest to Anhui in the east, connecting power plants deep in the interior of the country to cities near the coast.

The transmission line will be capable of delivering the output of 12 large power plants over nearly 2,000 miles (3,200 kilometers), sending 50% more electricity 600 miles further than anything that's ever been built.

The world's largest utility has collaborated closely with foreign transmission technology companies, including ABB and Siemens, but it has also assimilated the expertise of its partners and began developing its own technology, including high-voltage transformers as well as lines that can function at very high altitudes.

At the end of last year, China had poured at least \$57 billion into the projects, according to Bloomberg New Energy Finance.

Last September China's National Energy Administration said that it will sign off on 12 new ultra-high-voltage projects by the end of 2019.

Source: MIT Technology Review

Latest technology at work, first 800 kV transformer tested for one of India's largest HVDC projects

India's transformer manufacturer BHEL Bhopal inaugurated the first of several 800 kV HVDC power transformers manufactured for POWERGRID's prestigious 6,000 MW Raigarh Pugalur project.

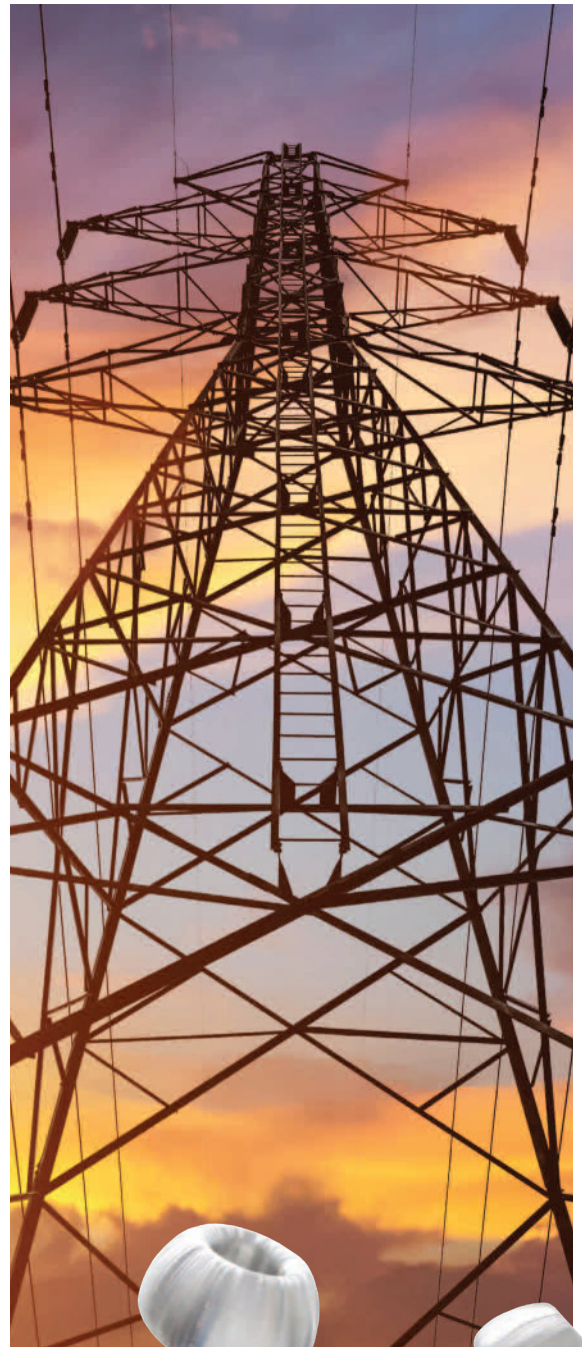
The 800 kV HVDC transformer boasting the latest technology and developed in collaboration with ABB has been successfully type tested at BHEL Bhopal's manufacturing facility, reports Daily Pioneer.

For this project, BHEL Bhopal in partnership with ABB will supply eight units of 295.1 MVA, 765 kV HVDC transformers.

The 6000 MW ± 800 kV Raigarh-Pugalur HVDC project is one of India's largest projects implemented by the central transmission utility POWERGRID Corporation of India Limited.

The 1,830-kilometer link will be among the longest in the world.

Source: Daily Pioneer; Photo: ABB





Siemens successfully tests first 345 kV natural ester-filled power transformer for a hydro project in USA

Siemens has successfully short-circuit tested a natural ester-filled power transformer at the KEMA test facility in the Netherlands, one of 14 eco-friendly transformers manufactured to replace 50-year-old generator transformers in a hydropower plant in the U.S.

To meet the customer's specific requirements for this project, the Siemens transformer plant in Linz, Austria designed 14 natural ester-filled power transformers. They are rated at 125 MVA and have output voltages of either 345 or 230 kV. One of these transformer units has now been successfully tested at the KEMA test facility in the Netherlands and has passed type and routine tests, including a severe short-circuit test.

For Siemens, this single-phase generator-step-up transformer represents three milestones. It is the first 345 kV natural ester-filled generator step-up transformer worldwide, the first 345 kV natural ester-filled power transformer tested at the KEMA test facility and the first 345 kV natural ester-filled power transformer successfully tested for a project in the USA.

"Sustainability is important to Siemens and its customers, but foremost to the society in general. This triple milestone is yet another proof that Siemens Transmission Products is always striving to break new grounds together with our customers", comments Dr. Beatrix Natter, CEO of Siemens Transmission Products.

Source: Siemens; Photo: www.siemens.com/press

German TSOs plan to invest \$38-41b in power grids by 2030

The four German power transmission system operators (TSOs) recently published draft development plans announcing total estimated investments of \$38-41 billion (€34-36 billion).

The investment plans go through 2030 and 2035 and assume that the DC-1, DC-3 and DC-5 HVDC transmission lines are built, including \$6.7 billion for the startup of the network, reports Enerdata.

According to the draft plan, German TSOs intend to build 3,800 km of new lines, including around 2,600 km of HVDC lines and around 1,200 km of AC lines. They also plan to reinforce between 7,600 km and 8,500 km of existing cables.

Around 330 km of cross-border connections to Belgium, Denmark, Norway and Sweden should be built, with a total transmission capacity of 8 GW.

Nearly 2,800 km of offshore lines could be developed by 2030 (3,700 km by 2035), with a planned network capacity ranging from 7.4 GW in 2030 to 11.4 GW in 2035. In that case, total investments would near \$18 billion by 2030 and \$28 billion by 2035.

Source: Enerdata

Innovative transformer technology for offshore wind applications

ABB's specifically designed transformers for offshore wind applications will be installed in the WindFloat Atlantic windfarm in 2019, a project of MHI Vestas Offshore Wind, a joint venture between Vestas Wind Systems A/S and Mitsubishi Heavy Industries (MHI).

The WindSTAR transformers are extra resilient against strong vibrations and extreme and sudden movements encountered in locations such as towers of floating wind farms and offshore platforms, while keeping them compact and light weight, according to the manufacturer.

The 8.4 MW wind turbines at the WindFloat Atlantic windfarm off the coast of Portugal will be 623 feet tall to blade tip, more than double the height of the Statue of Liberty. They will be the world's largest and most powerful wind turbines ever installed on a floating foundation.

Source: ABB



Omicron launches new solution for online partial Discharge assessments

Omicron has launched a new solution that combines on-line partial discharge (PD) measurement and temporary PD monitoring capabilities into one portable system.

MONTESTO 200 is a portable, two-in-one solution that enables both on-line partial discharge (PD) measurements and temporary on-line PD monitoring on various medium-voltage and high-voltage electrical assets under load, designed for use both indoors and outdoors.

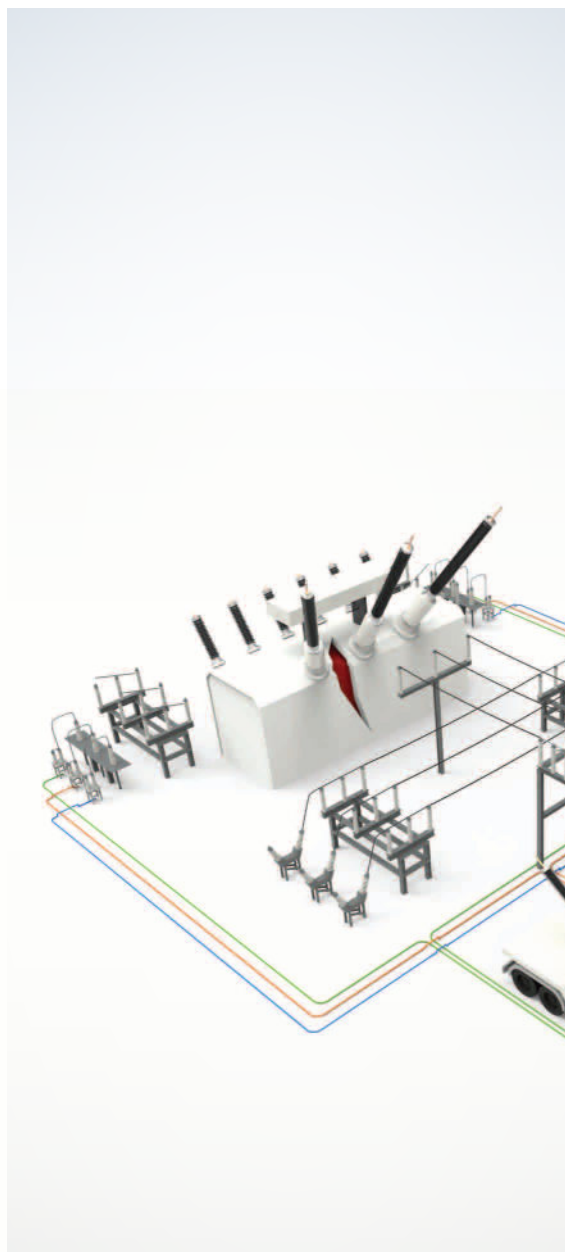
"On-line PD measurements and monitoring are performed while the asset is in service under regular operating conditions. They enable you to trend the impact that variable loads, temperature and vibration have on insulation condition over time to predict the risk of failure and plan maintenance accordingly," said MONTESTO product leader Andreas Cobet.

Three primary features of the new solution include versatility, ease of set-up and user-friendly software.

"Asset manufacturers, service companies, as well as maintenance teams at utilities and industrial sites will appreciate the versatility of MONTESTO 200. For example, the system can be used to clarify asset insulation issues during warranty periods and to periodically check the insulation condition during an asset's service life. MONTESTO 200 will also help users to observe assets at risk over extended periods of time and to plan maintenance and investments based on asset condition," added MONTESTO product manager Frank Zokoll.

Source, Photo: Omicron





Siemens introduces on-demand mobile resilience transformer leasing for fast outage response

Siemens is introducing the company's first U.S. offering that allows utilities and generation owners to lease a PRETACT® Plug & Play GSU Resilience Transformer when needed for outage or emergency response. With this on-demand access, asset owners can quickly replace an out-of-service transformer across several voltage ratings and configurations to restore power quickly for customers.

"Traditionally, replacing a conventional power transformer can take several weeks or months, leaving the power supply incredibly vulnerable to outages and interruptions," said Wade Lauer, Vice President of Siemens Transmission Products, in the U.S. "This innovative offering now provides asset owners the opportunity to quickly lease this critical equipment locally for quick installation, resulting in a more secure and reliable power supply."

The GSU Resilience Transformer is easy to load and ship and its plug and play bushings allow for an extremely short installation time. The transformer is also designed with environmentally-friendly synthetic ester fluid so it can be installed near water or sensitive areas.

Source: Siemens; Photo: www.siemens.com/press



Clair Claiborne selected as Top Scientist of the Year by the International Association of Top Professionals

Clair Claiborne, Consulting Materials Scientist for Claiborne Consultants LLC, was just recently selected as Top Scientist of the Year by the International Association of Top Professionals (IAOTP) for his outstanding leadership and dedication to the Materials Science industry.

With over four decades of professional experience in materials science, Dr. Claiborne has had a repertoire of prior roles including Fellow of the ASTM International and Vice Chair Natural Esters Task Force for IEEE Transformers Committee.

One of Dr. Claiborne's biggest achievements was the invention of BIOTEMP, a biodegradable vegetable oil used to deliver high performance power transformer insulation. BIOTEMP offers significant environmental, fire safety and operational advantages over mineral oil and other alternative insulating fluids. Dr. Claiborne and Dr. T.V. Oommen (deceased) are duly noted for the invention.

Source: PRDistribution; Photo: Claiborne Consultants LLC

Next generation transformer cooling system monitor

MESSKO offers new technology for monitoring the transformer cooling circuit which helps ensure operational reliability of transformers and is vital in extending the transformer's service life, according to the manufacturer.

The new solution, MESSKO MFLOC 2.0 flow indicator, helps an operator know if an error has occurred within this cooling circuit and prevent overheating within the transformer.

To enable monitoring, a specially designed, spoon-shaped paddle made of fiberglass-reinforced plastic is placed in the cooling circuit as a flow detector. MESSKO optimized the design based on new computer simulation possibilities and internal and external laboratories, using test scenarios, thoroughly checked the functionality and reliability of paddle return after pump shut-off.

The patented magnetic coupling translates the paddle movement into rotational movement of the indicator in the display area. This means that the flow indicator can immediately and reliably detect and signal any possible pump failure.

Among the features the solution offers:

- Robust and weather-resistant aluminum housing
- Available in C4H and CX
- The paddle is made of a polyamide copolymer with 50% glass fiber that has been proven in applications in the Reinhausen Group
- A single variant for all pipe diameters, flow directions and speeds
- Can be used in various coolants (oil, water, alternative coolants)

According to the manufacturer, the new flow indicator guarantees that the cooling circuit will be completely sealed and ensures reliable function even in turbulent (non-laminar) flows.

Source, Photo: MR



M&I Materials opens new production facility in India

M&I Materials has opened its ester transformer fluid manufacturing plant and laboratory near Mumbai, India, from where it will supply MIDEI ester fluids for utilities and transformer manufacturers across the country.

The operation, based in Maharashtra, is the result of a new strategic alliance with ACME Synthetic Chemicals and will help Indian utilities and OEMs to deliver safer, greener transformers and substations. Ester transformer fluids have a much higher fire point than the conventional transformer fluid – mineral oil – and are far more environmentally friendly. The company has had a presence in India, providing product and technical support, for almost a decade.

With a locally manufactured product, Indian utilities will have direct access to a flexible and responsive supplier, meaning less dependence on imports for this key transformer component. As a biodegradable alternative to mineral oil, the availability of MIDEI fluids across India marks another step forward in creating a sustainable electricity grid for the future. In addition, the M&I Materials investment in local manufacturing is a clear endorsement of the Indian Government's "Make in India" initiative.

Source: MIDEI





NYPA's transformer asset health system receives EPRI Technology Transfer Award

The New York Power Authority (NYPA) was recognized for its first-of-its-kind transformer asset health system that helps to predict failures in electricity generation transformers before they occur with a Technology Transfer Award from the Electric Power Research Institute (EPRI), NYPA announced in the press release.

The annual industry awards recognize industry leaders and innovators who demonstrate excellence in innovation through the application of research and development in the utility industry.

"This cutting-edge digital innovation has significantly improved our ability to assess the health of our critical assets and predict any potential failures before they cause disruption," said Gil C. Quiniones, NYPA's president and CEO. "Utilities need informed data to use in their decision-making processes and we at NYPA are so pleased to receive this recognition from an influential national and international energy research organization like EPRI."

In the early stages of the development of this asset management system, NYPA worked with EPRI to further understand dissolved gas analysis monitoring and how it can be used to detect transformer issues. NYPA then began using on-line sampling of gases together with a first of a kind asset health system to monitor its fleet of transformers and indicate any needs for maintenance, replacement or repair.

Source, Photo: NYPA

ABB to support the increasing digitalization of substations

ABB and Intel signed a formal agreement to collaborate on the marketing and selling of next-generation distribution automation systems and products for protection and control in utility and industrial applications.

The aim of the strategy is a single, centralized, software-driven device with extensive application coverage.

At the core of the agreement is ABB Ability smart substation control and protection for electrical systems, SSC600, powered by Intel Xeon processors.

SSC600 centralizes all protection and control functionality in a single, IEC 61850-compliant device at the substation level to reduce network complexity and support optimal, lifelong asset management for the digital substation. It helps utilities make the change to a more digital environment, allowing protection and control of a wide variety of applications in real time.

Source, Photo: ABB



Chinese steel works implements new transformer drying technology to prevent premature failure of transformers

Alongside increased winding and oil temperatures, the moisture content in the oil is one of the most critical factors that can massively shorten the service life of a transformer. This is what a Chinese steel works experienced first-hand, when moisture levels triggered early warnings. Using the MR EXPIOTECH MMS Moisture Management System, they were able to reduce the moisture content and prevent their transformers from failing prematurely.

The steel works had operated three 22,000 kVA/35 kV furnace transformers for more than five years without regular maintenance or diagnostic measurements. In the fall of 2018, oil analyses were finally carried out, showing that the moisture and acetylene contents in the oil of all three power transformers significantly exceeded the relevant standards. This caused their dielectric strength to drop, triggering early warning signals on two of the transformers.

During the maintenance of these two transformers, it was determined that a lot of water had collected on the bottom of the transformer tank, that the iron core was rusty, and that the insulation resistance to ground was too low.

To reduce the moisture content effectively and thus avoid damage to the transformer, the operator used a special drying method – an innovative technology from MR. The new MR EXPIOTECH Moisture Management System was put to use for the first time in China, removing 4.3 L of water from the paper over an extended period during continuing operation.

Source, Photo: MR



EPRI forms European subsidiary

The Electric Power Research Institute (EPRI) is forming a new business entity, EPRI Europe Limited, to expand its collaborative research and development programs in Europe.

Headquartered in Dublin, Ireland, EPRI Europe will enable EPRI to participate in consortiums for research projects in Europe that align with EPRI and industry research priorities and roadmaps. By broadening European engagement with this research, Europe's technology and thought leaders can work with EPRI to enhance collaborative energy and environment research for EPRI members and energy sector stakeholders around the world.

EPRI's established relationships with Irish researchers and its focus on technical innovation with Irish electric utilities were important factors in EPRI's decision to establish EPRI Europe in Dublin. "EPRI considers Ireland a center for electricity sector innovation and testing for utility systems, making it an ideal setting for European R&D collaboration," said Mike Howard EPRI President and CEO. "Likewise, Europe has emerged as a pivotal testing ground for the broader integration of energy systems overall into what EPRI calls The Integrated Energy Network."

Source: EPRI





Delta-X Research Named 2019 Company of the Year for Asset Management Solution Providers

Delta-X Research has been named the number one Asset Management Solution Provider of 2019 by Utilities Tech Outlook Magazine.

Delta-X Research offers market leading software for managing and interpreting test and monitor data for high-voltage equipment such as the large power transformers found in electrical substations. In particular, the company provides expert analysis of insulating fluid test data, including dissolved gas analysis, that can indicate if equipment is experiencing a fault or requires other maintenance.

Delta-X Research's main product is used by over half of the largest utilities in the USA and Canada.

"We are excited and grateful to have our company acknowledged in this way," says John Brett, President & CEO of Delta-X Research. "Our customers tell us that Reliability-based DGA, combined with some of the other analytics we've developed, represents one of the major advancements in the area of DGA analysis that they have recently seen.

After investigation, our customers confirmed fewer false negatives and fewer false positives using Reliability-based DGA, and each one of those avoided errors has saved our customers from financial losses, power outages, and, most importantly, a potentially dangerous catastrophic failure occurring without warning."

Source: Delta-X Research

Delta Star Field Service obtains California electrical contractor's license

Delta Star Field Service has attained a California electrical contractor's license.

Obtaining the license will enable the company to better service their growing customer base, Delta Star said in a press statement.

Delta Star is a North American transformer manufacturer, with a long history of providing full-service packages including installation, processing, and standard maintenance.

In addition to field service, the company offers specialized sourcing of transformer replacement parts.

Source, Photo: Delta Star

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Coming Events



IEEE PES GTD Asia
March 19-23, 2019
BANGKOK, THAILAND



IEEE Transformers Committee - Spring Meeting
March 24 - 28, 2019
ANAHEIM, CALIFORNIA



CWIEME Shanghai
March 26-28, 2019
SHANGHAI, CHINA



HANNOVER MESSE
April 1-5, 2019
HANNOVER, GERMANY



86th International Conference of Doble Clients
April 7-12, 2019
BOSTON, MASSACHUSETTS



CWEXPO 2019
May 8-10, 2019
SHENZHEN, CHINA



CWIEME BERLIN
May 21-23, 2019
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Jon Trout

Manager of Transmission Design
FirstEnergy

Interview with **Jon Trout**





“

Manufacturers optimize their designs to smaller and smaller margins. That optimization impacts how the transformer gets built, how much safety margin is involved, and how much additional material is in the transformer.

Jon Trout's current role is Manager – Transmission Design for FirstEnergy, responsible for the Transmission Design activities in the Akron, OH office. Jon's previous experience at FirstEnergy included significant experience with Transformer specification and purchasing. Jon also has experience at SD Myers, working with industrial applications on Transformer Life Cycle analysis, including condition assessments, online DGA monitoring and transformer electrical testing.

Jon Trout is Manager of Transmission Design for FirstEnergy, an electric utility headquartered in Akron, Ohio. FirstEnergy is involved in distribution, transmission, and generation of electric power. Trout previously worked with transformer manufacturers to supply FirstEnergy with reliable electric power system equipment. He has experienced many changes in the world of transformer technology over the years, and we were curious to find out what changes he considers to be the most important. Alan Ross spoke with Trout about what changes he's seen so far in terms of design, manufacturing, and application, and how those changes might affect resiliency and reliability in years to come.

Transformer Technology: What is the most significant transformer design and manufacturing change you have seen in your career?

Jon Trout: The increase in the accuracy of our design techniques has really changed the way transformers are manufactured and built. Transformer design continues to advance, and the technology around analyzing the various aspects of the transformer continue to improve. Manufacturers optimize their designs to smaller and smaller margins. That optimization impacts how the transformer gets built, how much safety margin is involved, and how much additional material is in the transformer.

TT How will technology change either for transformers or substations in the future, and what does that mean in terms of operation and maintenance of transformers and substations?

JT I would love to tell you the future, but I don't fully know what it's going to be. But it is going to be interesting to see how the optimized designs perform over time, and what that means for reliability and for maintenance. Exactly what that looks like, though, I don't really know. But I'm curious to see.

TT You have probably seen more transformer manufacturing in your career so far than most of us in the transformer business will see in a lifetime. When you evaluate buying a new transformer, what is your process?

JT There's a lot of very capable people out there who've seen a lot more than me, but I have seen quite a few. The process that I go

through when I'm evaluating a manufacturer is to look at the different aspects of their design process and their manufacturing process. When I'm evaluating a plant, I'm looking to see how they control the flow of material through the plant, how they handle transformer windings, how the material is handled, and make observations on the press board and wire. Cleanliness is very important. What sort of set up is there to maintain the cleanliness of the windings? Because the contamination of the windings can be a big problem, and maintaining good cleanliness around the winding room is very important.

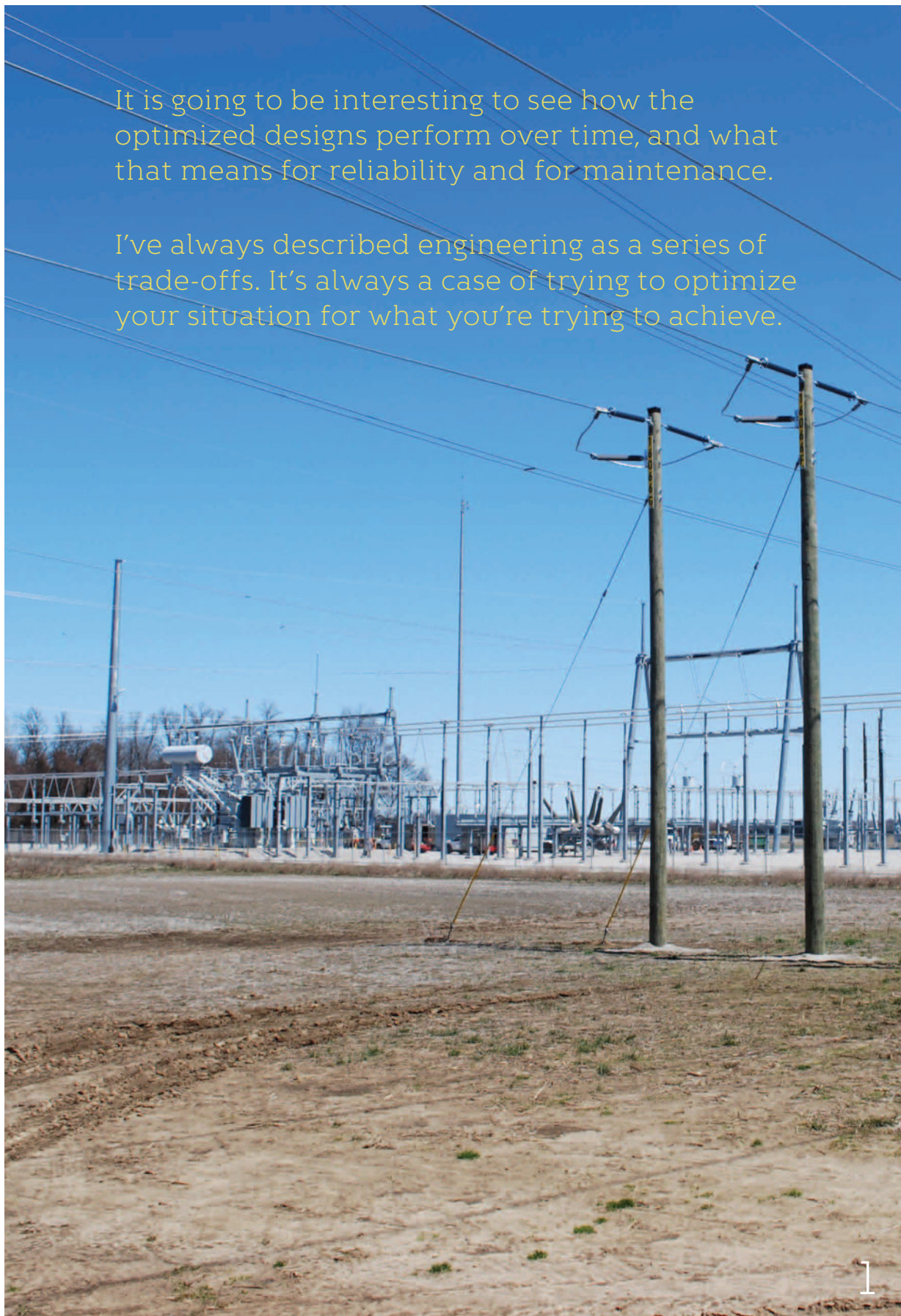
I look for how they maintain the other areas of manufacturing too. There might be dirtier processes like welding, or steel cutting, and I need to see how they keep the contamination generated by those processes away from the windings. Then I ask how they maintain dryness and maintain the moisture content in the winding of the core and coil assembly, and what different drying processes they use to maintain those levels of moisture. I also consider the testing facilities, because once they build the transformer they have to be able to test it to the applicable standards. Do they have sufficient test equipment? Do they have knowledge of the testing standards?

I also look to see how integrated the engineering is with production, because having the engineer readily available to answer questions about the design can be very beneficial to eliminate issues in the future.

There's a lot more that goes into it, but that's a high-level overview of how I'd evaluate a manufacturer.

It is going to be interesting to see how the optimized designs perform over time, and what that means for reliability and for maintenance.

I've always described engineering as a series of trade-offs. It's always a case of trying to optimize your situation for what you're trying to achieve.



1) FirstEnergy nearing completion of transmission project to support Northern Ohio.

Sometimes older units have a little more resiliency, in that they could be used in applications that they were never intentionally designed for.

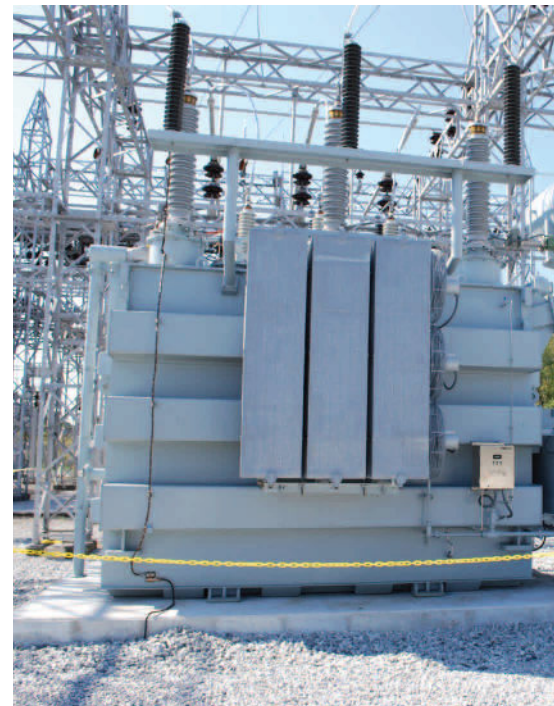


2) FirstEnergy's grid modernization program in Pennsylvania.

3) In 2016 FirstEnergy completed work on a new transmission substation to help support shale gas industry in West Virginia.



FirstEnergy



TT You mentioned that reduced margins are an aspect of new transformer designs. We've seen an 840 MVA utility transformer being replaced by a 950 MVA utility transformer, with the new transformer weighing in at five tons lighter than the old transformer. That's a lot of this margin that you talk about! When you consider the build of today's

transformers versus the ones that are already 30 or 50 years old, what do you think the impact of that will be, in terms of resiliency and reliability?

JT I've always described engineering as a series of trade-offs. It's always a case of trying to optimize your situation for what you're trying to achieve. Manufacturers and utilities and the owners of these transformers are all playing that balancing act of how to optimize the situation. Utilities and transformer owners have financial constraints around the available resources they have to acquire the equipment that they need. Likewise, manufacturers have constraints around their resources of what materials they can purchase. So everyone is looking to optimize the situation.

I think that we're going to find that the designs that are being put out now will be adequate and

perfectly capable for the applications to which they're being applied. Sometimes older units have a little more resiliency, in that they could be used in applications that they were never intentionally designed for. That flexibility may not be there any longer, where you could apply a unit in an application that it wasn't initially designed for and it would function adequately. Now we might have a little more of a challenge if we try to follow that same process.

TT Gassing is probably the number one test in the utility industry. What transformer gassing issues cause you immediate concern?

JT Gassing is an excellent indicator of potential problems. Sometimes the gassing is in a situation where you need to be able to trend the information to see what's happening. I have some experience working alongside a steel manufacturer, helping them evaluate the conditions of their transformers based on some online gas monitoring, and we were able to watch some units over the course of time that were gassing. By observing trends, however, we could see that the gassing was steady over time, which meant there was no apparent incipient fault happening.

One particular unit had a significant spike of gassing at a very specific time, and that unit then settled back down there very little gassing over the next few months. And if you don't know what you're looking for, you may see a spike like that and overreact, or maybe under react to a gassing situation that seems under control when you haven't seen the spikes. It's a challenge in the industry that everyone's trying to get their hands around. But we've got a lot of experience in the industry, and it's ever-evolving. There's always new challenges and new opportunities to understand the condition of transformers based on the gassing and other oil quality tests.

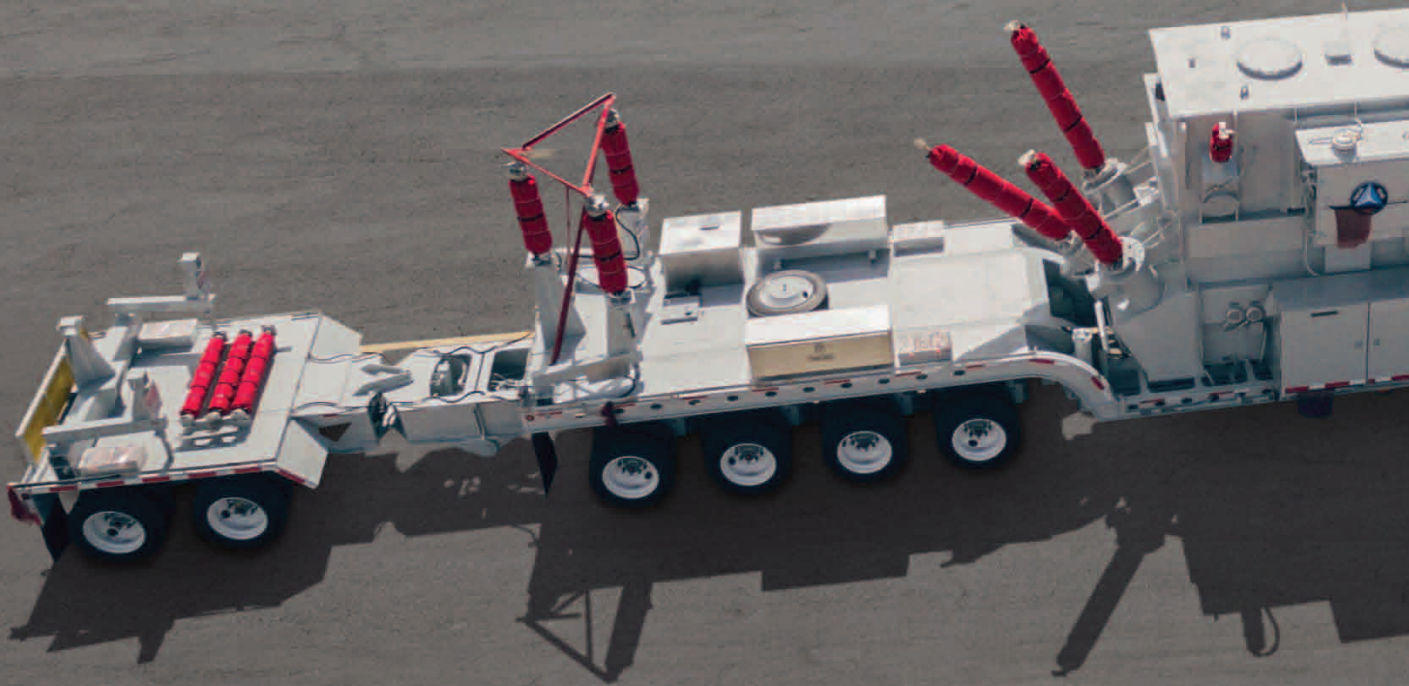
4) FirstEnergy invested about \$371 million in 2017 on distribution and transmission infrastructure projects to help enhance reliability for customers in the Ohio Edison service territory. Major projects included building new substations and transmission lines, installing equipment in existing substations, adding remote control equipment on circuits, and the inspection and replacement of utility poles.



High Temperature Insulation Systems: An Option for Resilient Transformers

by **Richard P Marek**

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Richard P Marek received his BSEE from Purdue University and has been employed with DuPont since 1998. His previous work experience includes a total of 28 years as a transformer design engineer. He is a senior life member of IEEE where he has been active in the Transformers Committee since 1982 and he was chairman/convenor of the high temperature liquid immersed transformer standards IEEE C57.154 and IEC 60076-14. He is also an IEC TC14 delegate for the US TAG.

For many years, utilities have used mobile transformers or complete mobile substations to mitigate outage risks in their smaller capacity substations. These fast deployable units have offered the advantages of quick availability of replacement equipment. They are mobile, compact, lightweight, and versatile, generally covering multiple voltage ratings. Designed to match the regional road weight limits, they can be installed and operating in a very short time. Now, this same concept is being applied to large power applications.

This article reviews the latest developments and trends towards highly moveable large power

transformers designed to improve grid resiliency. Using advanced insulation systems allows innovative design techniques that result in smaller size and lower weight transformers. Initially developed specifically for mobile transformers and substations, the hybrid insulation system has evolved to allow much larger units to be transported more easily and rapidly to areas with emergency situations. **Among various design methods for reducing the size and weight of power transformers, high temperature insulation systems offer a key tool.**

Many modern design techniques and state-of-the-art optimal technical



Using advanced insulation systems allows innovative design techniques that result in smaller size and lower weight transformers.

solutions have already driven designs to be smaller and more compact. However, the use of high temperature materials and insulation systems allows a step change in the ability to make designs significantly more compact, compared to so-called “conventional” designs, based on cellulose insulation and mineral oil. In order to reach maximum size reduction, new insulation components must also be developed using high temperature materials.

For many years standards development has played a major role in expanding high temperature liquid immersed transformer applications. In 1997, IEEE Standard 1276 – “Guide for the

Application of High-Temperature Insulation Materials in Liquid-Immersed Power Transformers” [1] was published after this working group first published a thorough background paper in 1994 titled “Background Information on High-temperature Insulation for Liquid-Immersed Power Transformers” [2]. In 2008, the development of a document was begun by IEEE: IEEE Standard C57.154 – “Standard for the Design, Testing, and Application of Liquid-Immersed Distribution, Power, and Regulating Transformers Using High-Temperature Insulation Systems and Operating at Elevated Temperatures” [3], which was published in 2012.

This document introduced many key definitions necessary to describe new insulation systems which are defined by temperature class rather than by specific combinations of solid materials in a liquid. These concepts were patterned after the insulation system approach to motors and dry type transformers which has worked well for many years.

Among various design methods for reducing the size and weight of power transformers, high temperature insulation systems offer a key tool.

Hybrid insulation system, one of these key definitions, uses mineral oil and high temperature materials throughout the transformer on the windings, but only limited to the hottest areas. Typically, the conductor insulation and the radial and axial spacers separating the coil windings are high temperature materials. Conventional cellulose-based insulation is used in all other areas, such as cylinders and angle rings that operate at conventional temperatures. While mineral oil is restricted to a 65°C temperature rise, other liquids may also be used in a hybrid application at higher temperatures, as long as the temperature capability of the cellulose is not exceeded. for the use of DFR technology and interpretation of transformer's insulation dielectric response in the frequency domain.

Unlike the hybrid insulation systems, the high temperature insulation system consists of

mostly high temperature solid insulation materials for all insulation components and an insulating liquid operating at high temperature. Clamping plates, cylinders, tubes, angle rings, molded lead exits, snouts, spacer blocks, caps and stress rings are all made from high temperature materials. Currently some of these insulation components do not yet exist in high temperature material for power transformers. However, prototypes have already been developed for some of these fabricated parts to facilitate the development of ultra-compact transformers for resilient systems. For example, new insulation parts to be available in aramid material could include wet formed 3-dimensional components and large laminated clamping rings.

Mobile units have been built in US since the 1950s. Over the years, the size (MVA) and voltages have increased and the protection and trailer designs have become more

refined. Aramid insulation started to be used to reduce the size and weight by increasing the operating temperature. Some of these units are built as simple mobile transformers, equipped with surge arresters. Others are complete substations with all the typical accessories such as lightning arresters and switchgear. They are capable of completely replacing a small substation, especially in rural areas. High temperature insulation systems are commonly used in mobile transformers to allow higher winding temperatures. Aramid insulation is commonly used for conductor insulation and for pressboard parts exposed to temperatures that would exceed the thermal capability of cellulose based components.

In 2012, ABB partnering with the U.S. Department of Homeland Security (DHS), the Electric Power Research Institute (EPRI) and CenterPoint Energy, delivered three modular transformers from its St. Louis facility to a substation in Texas within 20 hours, in an emergency drill [4]. These "spare" transformers, designed with aramid high



temperature insulation, were shipped and were fully energized in less than a week.

From a design standpoint, the transformer, called the RecX, had to meet numerous installation requirements, including storage and transportation specifications that required a small footprint and light weight to ship on standard trucks. Building on ABB's mobile transformer expertise, they chose a high temperature hybrid insulation system to reduce both size and weight. Alone or in hybrid solutions with cellulosic pressboard, insulation systems based on aramid maintain excellent electrical, thermal and mechanical characteristics over a transformer's service life. Reduced aging, high resistance to shrinkage and compression, combined with the excellent dynamic mechanical strength of aramid paper and board, all help ensure that coil structures will remain tight and are able to withstand short-circuit forces, even after years of service. The RecX 200 MVA prototype bank of single phase units were designed to replace a 600 MVA, 345/138 kV autotransformer. The RecX design

principle was to make the units modular, transportable and quick to install. The challenge was to reduce the transformer's size and weight to less than 59,000 kg. The final design actually weighs in at less than 57,200 kg and is small enough to be shipped by truck, while maintaining its performance and reliability.

A similar fast-deployable transformer concept was developed in another ABB project in Spain. In this case, three 250 MVA, 400 kV units with multiple voltage ratings on the LV side were built using a shell type construction. The design evaluation showed significant weight and size reduction was possible by using a hybrid insulation system in the transformer windings. The new unit with hybrid insulation not only achieved a base rate increase of 25% compared to the installed unit (250 MVA vs. 200 MVA), but it represented a more than double base rate increase, compared to the maximum rating of the conventional cellulose mineral oil unit (250 MVA vs. only 117 MVA).

A new step of innovation was reached when SIEMENS delivered

resiliency units to the New York City utility in 2016 for its network. These units will act as emergency replacements in case of unplanned outages, such as those caused by hurricanes or may also be used for planned outages. Normally, failure of one of these large transformers causes many issues including:

- Long lead times for new transformers (up to 14 months)
- Multiple spares needed for various rated transmission transformers
- Shipping and logistic issues
- On-site assembly that can take weeks and is weather dependent

As it was demonstrated in January 2017, the mobile resilience transformers allowed the utility to respond to these events, where multiple transformers may be impacted and normal spares or system redundancy may not be able to address the issues. SIEMENS provided six transportable resilience transformers to help replace units within days rather than weeks in times of outages due to extreme weather or other major events. The new transformers are highly optimized for weight and dimension through advanced design and



New insulation parts to be available in aramid material could include wet formed three-dimensional components and large laminated clamping rings.

environmentally-friendly synthetic ester liquid technology. The use of a hybrid insulation system in combination with the synthetic ester enabled this remarkable performance. This solution is aimed at quickly restoring power to the areas served by the unavailable transformers within one to three days, compared to the weeks it may take to transport and install normal available spare units. In cases where utilities do not have existing spare units, it may take twelve to fourteen months for new units to be procured, shipped and installed.

The concept of ultra-compact large power transformers operating with high temperature insulation systems is now under evaluation, but not only for grid resiliency emergency applications. The concept could be of benefit for upgrading existing space constrained substations, as well.

The main drivers for the innovation are:

- Need to replace and upgrade aging transformers within physical station space constraints
- Need for higher capacity to meet load growth
- Desire for sustainable solutions – environmentally friendly insulating liquid
- Use of high temperature insulation system for higher output and compact size

As shown in the above examples, the high temperature insulation systems can be important in the design of compact, transportable and fast-deployable large power transformers. Transformers with reduced size can then bring various benefits to power utilities in selected installations and improve the resiliency of the overall system, since they can be deployed faster using conventional trucks.

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New Loads, New Problems:

Why Harmonics Destroy Transformers

by **Gabe Paoletti, P.E.**
+ + + + + + + + + +

+ Don't move one step forward with new
+ loads that save money or improve
+ capabilities, and then one step backward
+ with outages and transformer failures.
+ New Transformer Technology includes
+ being aware of the new problems
+ associated with new high-tech loads;
+ and understanding how they can impact
+ the life of a transformer.



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Gabe Paoletti has applied his 40-plus years of electrical power distribution experience to support the electrical power industry by providing professional engineering services to increase system reliability, resiliency, equipment life extension, personal safety, power system personnel training, failure and root-cause analysis, feasibility studies, quality systems and new solution creation. He is a Registered Professional Engineer in New York, Pennsylvania and Delaware and has authored and presented numerous technical publications for IEEE and other organizations. He received his BSEE in Electrical Engineering at Drexel University in 1976 (Magna Cum Laude), and an MBA from Rutgers in 2009 (Summa Cum Laude). Mr. Paoletti has also been on the forefront of many power system innovations and was awarded the IEEE Engineer of the Year Award for 2009 (Northern New Jersey Chapter) for new product and service innovation which improved the efficient distribution of electrical power. He currently provides services such as failure analysis, project engineering, owners representative and engineering and feasibility studies, with his company Paoletti Engineering PLLC.

Being involved in root-cause failure evaluations and harmonic studies provides a history of practical experience related to why harmonics destroy transformers. New Transformer Technology includes being aware of the new problems associated with new loads; and understanding how they can impact the life of a transformer.

Some examples of new loads, which are implemented for very good reasons are: adjustable speed drives and/or electronic ballasts both resulting in reduced electrical power demand and the associated cost savings; improving the capabilities by installing new data processing equipment in office buildings, industrial sites and institutions. When these new loads are being planned, it is imperative that harmonics be reviewed.

There has been substantial research and publications regarding the effects of harmonics on transformers. While harmonics can be linked to overloading neutral conductors and causing nuisance tripping of circuit breakers, we're focusing on the impact of harmonics on transformers. This background has been extracted from an excellent article by C. Sankaran [1].

Harmonics

Some loads cause the current to vary disproportionately with the voltage during each half cycle. These loads are classified as nonlinear loads, and the current and voltage have waveforms that are non-sinusoidal, containing distortions, whereby the 60 Hz waveform has numerous additional

waveforms superimposed upon it, creating multiple frequencies within the normal 60 Hz sine wave. The multiple frequencies are harmonics of the fundamental frequency.

Examples of nonlinear loads are uninterruptable power supplies (UPSs), adjustable speed drives, battery chargers, electronic ballasts, variable frequency drives, and switching mode power supplies (normally used in computer loads and other data processing equipment). As nonlinear currents flow through a facility's electrical system and the distribution-transmission lines, additional voltage distortions are produced due to the impedance associated with the electrical network. Thus, as electrical power is generated, distributed and utilized, voltage and current waveform distortions are produced.

Power systems designed to function at the fundamental frequency, which is 60 Hz in the United States, are prone to unsatisfactory operation and, at times, failure when subjected to voltages and currents that contain substantial harmonic frequency elements. Very often, the operation of electrical equipment may seem normal, but under a certain combination of conditions, the impact of harmonics is enhanced, with damaging results.

As previously discussed, changes to a system that will lead to the potential of failure due to harmonics could include installation of variable frequency drives, electronic ballasts, power factor improvement capacitors, arc furnaces, or the addition or removal of large motors.



Eddy Currents

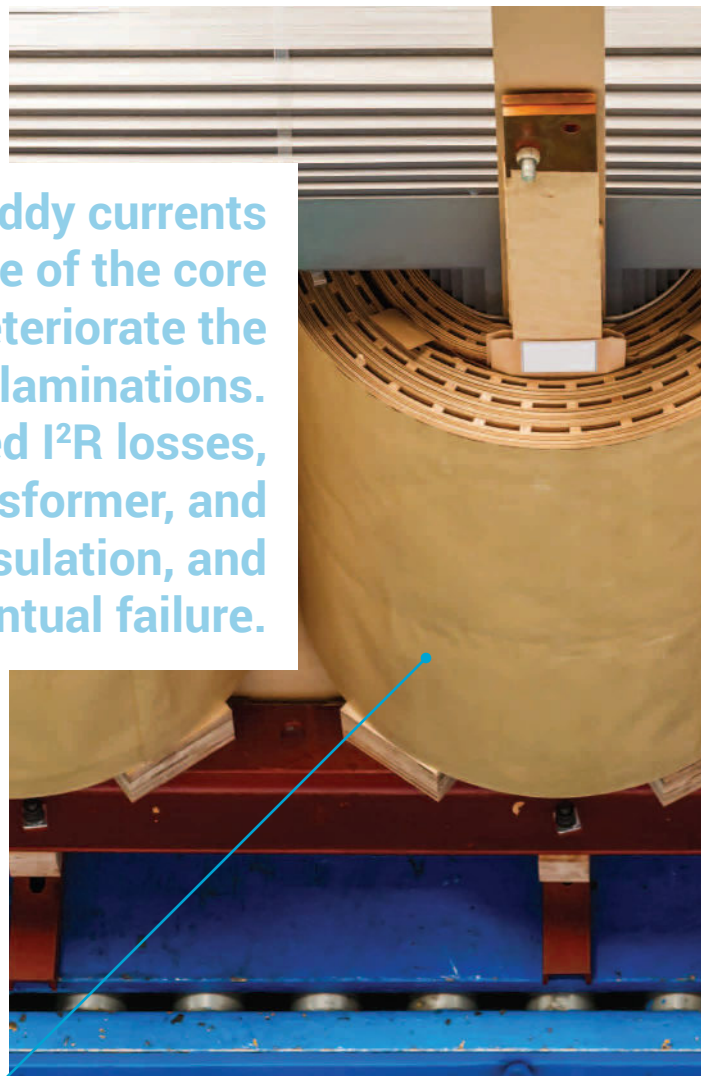
Application of non-sinusoidal excitation voltages to transformers increase the iron losses in the magnetic core of the transformer in much the same way as in a motor. A more serious effect of harmonic loads served by transformers is due to an increase in winding eddy current losses. Eddy currents are circulating currents in the conductors induced by the sweeping action of the leakage magnetic field on the conductors. Eddy current concentrations are higher at the ends of the transformer windings

due to the crowding effect of the leakage magnetic fields at the coil extremities. **The eddy current losses increase as the square of the current in the conductor and the square of its frequency.** The increase in transformer eddy current loss due to harmonics has a significant effect on the operating temperature of the transformer. Transformers that are required to supply power to nonlinear loads must be de-rated based on the percentages of harmonic components in the load current and the rated winding eddy current loss.

The resultant increase in eddy currents increases the operating temperature of the core iron, which in turn begins to deteriorate the insulation between the core iron laminations. This leads to greatly increased I^2R losses, beyond the design limits of the transformer, and overheating of the actual winding insulation. Once the winding insulation allows the energized copper winding to contact the grounded core-iron, an internal failure will result. This process is illustrated in Figure 1.

The harmonic related increase in eddy currents increases the operating temperature of the core iron, which in turn begins to deteriorate the insulation between the core iron laminations.

This leads to greatly increased I^2R losses, beyond the design limits of the transformer, and overheating of the actual winding insulation, and eventual failure.



The insulation between the laminations is deteriorated and damaged.

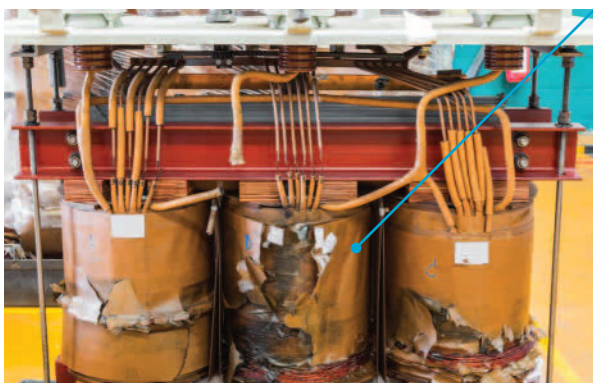


Figure 1. Pathway from harmonics to transformer failure



Figure 2. 5-Why analysis of harmonics related transformer failure



As previously stated, the eddy current losses increase as the square of the current in the conductor and the square of its frequency; therefore, with higher and higher harmonics, this heating is further increased.

When looking at a transformer, it appears that the high and low voltage winding are wrapped around a solid iron core; but, if you look more closely, you'll see that the "solid" iron core is made up of a series of thin laminations, usually of silicon steel, and these thin

laminations are insulated from each other with an insulating coating that is applied to both sides of the thin metal laminations. The purpose of insulating the laminations is to limit the heating effect of eddy currents during normal operation.

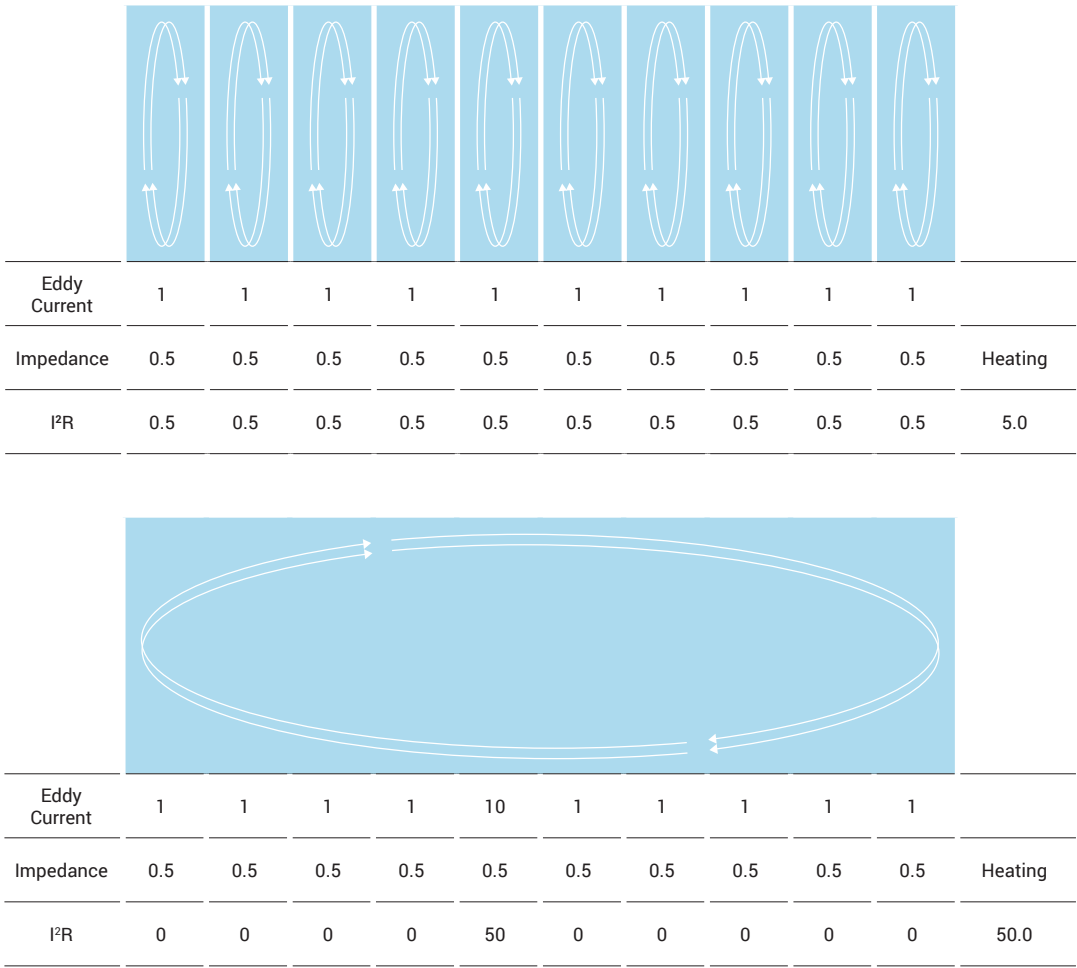
Even without taking into account the increased heating effect of the harmonic's higher frequencies, Figure 3 clearly illustrates the effect on the I^2R , heating losses that occur within the core-iron as the insulation between the laminations is deteriorated and damaged.

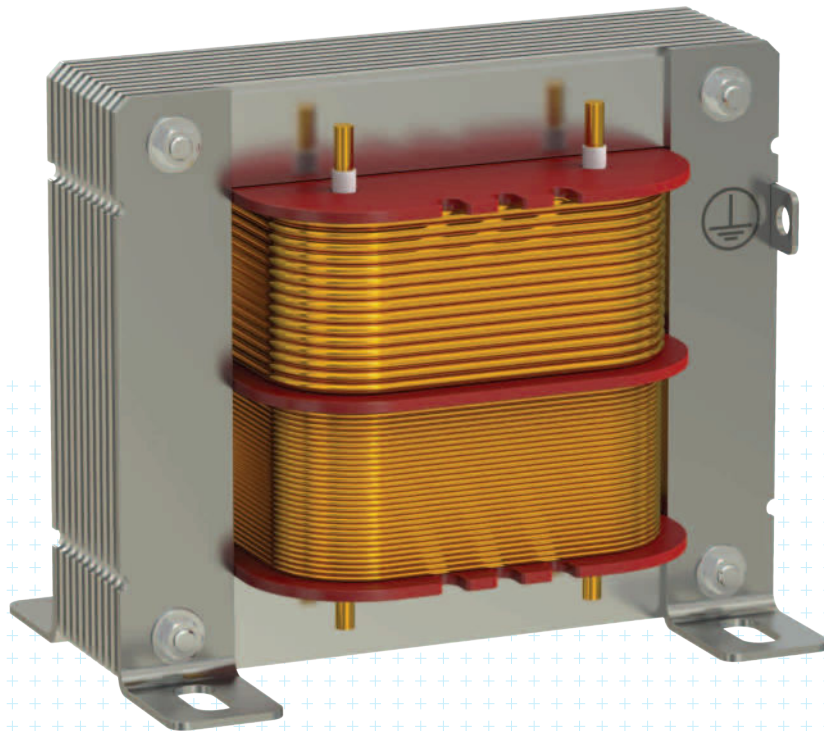
Many end-users are familiar with protection for transformer voltage surges, therefore they do apply transient voltage surge suppression and/or lightning arrestors, but many do not fully address the potential high harmonic currents of new, or added, computer loads or solid-state drive systems.

In the second illustration, we have the same 10 amperes of eddy currents, but now the insulation membrane between the iron core laminations has been deteriorated and damaged to the point that all ten sections of the iron core are in contact with each other. As shown, the total heating effect has increased from 5.0 watts to 50.0 watts, or a 900% increase heating.

This increased heating effect, which does not include the added effect of the increased frequency associated with harmonics will overheat the primary and/or secondary winding insulation, resulting in a transformer internal winding failure.

Figure 3. Illustrative effect of deteriorated iron-core lamination insulation failure





Solutions

Many end-users are familiar with protection for voltage surges, therefore they do apply transient voltage surge suppression and/or lightning arrestors, but many do not fully address the potential high harmonic currents of new, or added, computer loads or solid-state drive systems.

The first step when redesigning or altering your current power distribution system to support new power loads is to model your electrical system to simulate the harmonics from the new loads. It is also highly recommended to measure the actual current harmonics that exists, and after the new loads are installed, to then again measure the actual current harmonics.

If the changes are being made to an existing power distribution system, you can cautiously add the new loads and then immediately obtain the harmonic measurements resulting from these new loads. A transformer supplying these new loads will hopefully not fail within days of the new loads being installed.

Once the level of harmonics is determined, you should disconnect them from the transformer and determine your next steps.

A solution can be to install harmonic filtering or reconfiguring transformers connections to allow for cancellation of harmonics, or changing the transformer to accommodate the harmonics.

Another option to support long-term diagnostics is to install a permanent harmonics meter. Should you have a transformer failure, and you have not applied the types of new loads discussed above, then a review of harmonics should be part of the root-cause analysis. As an example, IEEE standard 519-1992 [2] states the total harmonic distortion (THD) of the voltage waveform provided by the utility cannot exceed 3% of the ideal sine wave. To ensure that harmonics are not generated by the utility, you would obtain this measurement at the point of common coupling (PCC). This is where the utility and facility wiring meet (usually at the meter box). If the voltage distortion exceeds 3%, the utility should provide some form of mitigation to correct the problem.

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Dielectric Frequency Response:

A New IEEE Guide for Field Test on Power and Distribution Transformers

by **Diego Robalino**
and **Roberts Neimanis**





Diego Robalino currently works for Megger as Principal Engineer, where he specializes in the diagnosis of complex electrical testing procedures. While doing research in power system optimization with a focus on aging equipment at Tennessee Technological University, Robalino received his electrical engineering PhD from that institution. Robalino has over 20 years of involvement in the electrical engineering profession with management responsibilities in the power systems, oil and gas, and research arenas. He is a Senior Member of the IEEE, member of the IEEE/PES transformers main committee and a certified Project Management Professional with the PMI. He is an active member of the IEEE/DEIS Electrical Insulation Conference. Author and co-author of multiple technical articles related to power, distribution and instrument transformer condition assessment.

Since the invention of the transformer, the design, quality and efficiency of this magnificent machine has been improved thanks to the development of electromagnetic materials, computer design algorithms, insulation materials, cooling systems, structural design, etc. Nowadays, a vast number of transformers operate worldwide aiming to provide reliable and safe operation under the most cumbersome environmental and operational conditions.

Even though the materials, design and manufacturing processes have improved, the most common insulation system is a combination of liquid insulation, cellulose and impregnated in oil cellulose. These components of the overall insulation system go through an inevitable aging process that leads to the end of the service life of power and distribution transformers. One can expand this statement into other components with similar insulation construction such as bushings and instrument transformer with oil-impregnated paper insulation.

The Institute of Electrical and Electronic Engineers (IEEE) Standards Association approved the publication of IEEE C57.161-2018 – “Guide for Dielectric Frequency Response Test”. The work was developed within the IEEE Transformers Committee and the Dielectrics Sub-committee. A needed document for a non-intrusive and

non-destructive testing method to better understand the condition of the insulation system of power and distribution transformers.

Introduction

During the last two decades, other technical references presented the development of DFR (Dielectric Frequency Response) a.k.a. Frequency Domain Spectroscopy (FDS), aiming specifically to its application for power and distribution transformers with oil-impregnated paper insulation. CIGRE Technical Brochures 254, 414 and 445 as well as IEEE Std. C57.152 addressed the importance, the research carried out and the benefits of the method as applied to power and distribution transformers.

In the IEEE Transformer Committee, a Task Force was initially formed to recommend (or not) the need to develop a guide describing the application of DFR on oil-impregnated transformers. From the initial step of forming the Task Force to the publication of the guide, the contribution and participation of specialists, end-users, testing equipment manufacturers, transformer manufacturers and academia made possible the production of a practical and comprehensive guide for the use of DFR technology and interpretation of transformer's insulation dielectric response in the frequency domain.

In 1996, WaBtech AB in Sweden brings to the market the first portable device for DFR test in the field.

Dr. Peter Werelius and Bjorn Bengtsson introduced IDA (Insulation Diagnostics Analyzer) mainly for cable and transformer testing.

DFR References

As mentioned previously, since the beginning of the use of insulation materials, a method to determine an acceptable condition for its use in electrical applications was required. The dielectric response of any insulation material can be obtained in the time domain or in the frequency domain. Time domain dielectric response has been in place for over 100 years and the typical "Insulation Resistance" test became, by far, the easiest and most practical approach to understand the condition of the solid insulation.

The practical application of DFR in the field generated the interest in the industry and international organizations took lead on the investigation of this "new technology" revolutionizing the testing practices in the field.

In 2002, CIGRE developed the Technical Brochure 254 – "Dielectric Response Methods for Diagnostics of Power Transformers". This report from the Task Force (TF) D1.01.09 focused on three dielectric response techniques:

- Return Voltage Measurements (RVM)
- Dielectric Spectroscopy in Time Domain (PDC)
- Dielectric Frequency Domain Spectroscopy (FDS)

To summarize the text of this document, the TF concluded that all three methods reflect the same fundamental polarization and conduction phenomena in transformer insulation and that the definition of moisture in the solid insulation by time domain and

frequency domain responses required mathematical modelling and good understanding of dielectric properties of the insulation system components.

In 2010, CIGRE continued the work and published the Technical Brochure 414 – "Dielectric Response Diagnoses for Transformer Windings". In this document, CIGRE combines the practical experience acquired with the mathematical modelling approach to determine best testing practices. The document covers the fundamentals of the X-Y model, measurement configurations, test performance and maybe the most important part, case studies and comparative analysis using Karl Fisher Titration (KFT) to validate the moisture estimation

in the solid insulation by dielectric response methods.

Considering the great acceptance of the technology in the field, the CIGRE Working Group (WG) A2.34 incorporates dielectric response methods in time and frequency domain in section 5.1.3 in the Technical Brochure 454 published in 2011. Dielectric response methods are included as "Special or Advanced Measurements". DFR or FDS is an advanced testing technique used in the field to determine the water content in the solid cellulose insulation of oil-paper insulation, insulation failures, and contamination of insulation. Moisture content in the solid insulation derived from field testing, mathematical modelling and data base source is compared against limits given for dry, moderately wet and extremely wet insulation given in IEC 60422. As a reminder, IEC 60422 states that the determination of the water content in the paper of a transformer by the measurement of the water in oil has been frequently described, but practical results are often not in line with the theoretical predictions. All calculations and correlations of the water content in oil and the water content in the oil/paper-system depend on the equilibrium state between the insulating oil and the oil/paper system and vice versa.

The complex impedance of the dielectric system is measured at different frequencies and the dielectric response is finally plotted as percentage dissipation factor, permittivity or capacitance as a function of frequency.

Nevertheless, around the mid-1900s, the frequency domain response was greatly studied and the definition of dielectric losses at power or line frequency (50/60 Hz) turned to be a great success for transformer manufacturers, end-users and testing service companies. Nevertheless, technology evolved and with that, electronic components and control devices opened the door to a wider band frequency spectrum to analyze different insulation materials.

In 1996, WaBtech AB in Sweden brings to the market the first portable device for DFR test in the field. Dr. Peter Werelius and Bjorn Bengtsson introduced IDA (Insulation Diagnostics Analyzer) mainly for cable and transformer testing.



In the North American world, the IEEE Transformer Committee revised the document IEEE 62 Part 1 – “Guide for Diagnostic Field Testing of Electric Power Apparatus – Oil filled Power Transformers, Regulators, and Reactors”. One of the fundamental reasons to revise this document was the application of new testing techniques not described in this document and considered important for the current requirements of manufacturers and end-users especially in the field. It is interesting to notice that IEEE 62 (R2005) provided in section 6.3.12 two tables with general guidelines for interpreting data expressed in percent saturation of water in oil and in percent moisture by dry weight of paper.

The work carried out by the IEEE transformer committee ended up with the publication in 2013 of the IEEE Std. C57.152 – “Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators and Reactors”. The amount of information put together in this document is difficult to describe in just a few lines, but this guide added the Informative ANNEX G introducing to the IEEE references the Dielectric Frequency Response Method. Annex G provides a brief description of the DFR method and its interpretation for oil-paper insulation systems in power transformers. Enough about history. Let us focus now on the recently published guide for DFR testing.





IEEE Guide for Dielectric Frequency Response Test

The continuous work of IEEE and its members is well reflected in the guide for dielectric frequency response test applicable for liquid-immersed transformers. The guide includes a thorough description of the DFR method, a comparative analysis between line-frequency power factor and the dielectric response in a wide frequency spectrum, recommendations for instrumentation, procedures for performing the tests, and guidelines for interpretation of the data. The application of DFR allows testing in factory and in the field.

After a general overview, Section 4 introduces the DFR method. DFR is a non-intrusive and non-destructive off-line testing technique performed in the frequency domain to determine the moisture content of the transformer's solid insulation and the conductivity of the liquid insulation. This paragraph covers one very important characteristic of the dielectric response; it can discriminate between the effect of moisture or contamination in the liquid or solid insulation.

In Section 4, some important facts are described. First, DFR as any other dielectric response method depends on the unique dielectric properties of the material, the electric field and the



DIELECTRIC
RESPONSE

temperature of the specimen at the time of the test. Second, DFR follows the same measurement principle as line – frequency power factor test, but the excitation signal applied by DFR instruments varies frequency in the range from 1 kHz down to 1 mHz (typical range at 20°C). The complex impedance of the dielectric system is measured at different frequencies and the dielectric response is finally plotted as percentage dissipation factor, permittivity or capacitance as a function of frequency.

After a clear understanding of the behavior of the materials under an alternating excitation signal in a wide frequency spectrum, different factors affecting the dielectric response are described. One of the most important factors to take into account is the presence of EMI in the surrounding test area.



The modelling algorithm requires specific information to evaluate the condition of the insulation system. The normally fixed information is:

- Liquid Insulation relative permittivity ϵ_r
- Thermal activation energy for solid and liquid insulation
- Temperature of the insulation under test

The outcome of the test will provide:

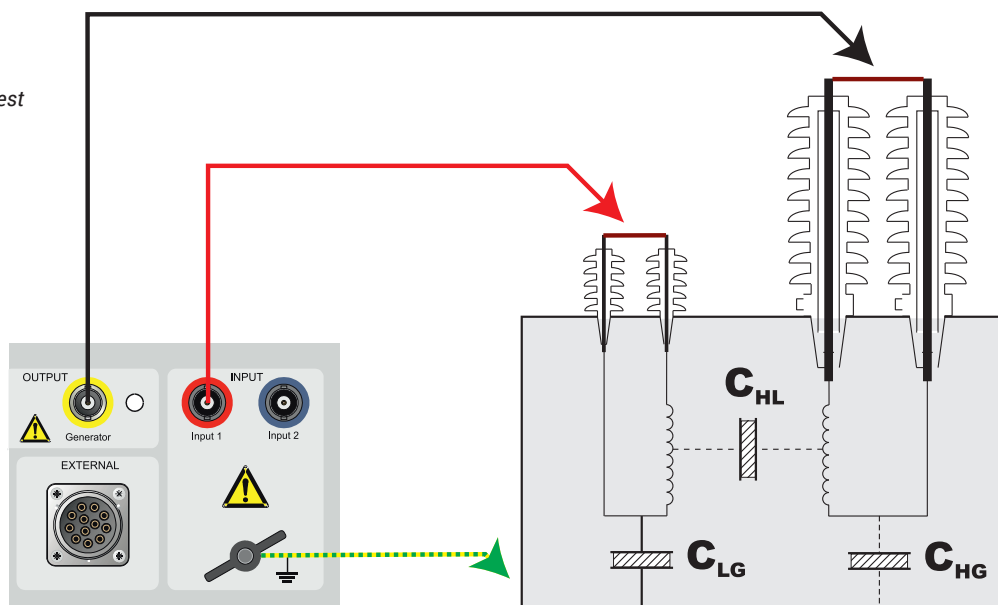
- Liquid insulation conductivity (σ)
- Moisture in solid insulation (m)

Besides the modelling part, it is important to understand that the test is performed in the field following the same instrument-to-object hook up principles as those used for power factor / dissipation factor testing at line frequency. Figure 1 shows the hook up diagram of the DFR test set to a commonly used two-winding transformer.

Section 5 provides the best practices and configurations to perform the test in the field.

As any other electrical test, the very first recommendations are related to safety. For many readers, safety is not just a best practice but also a life style. Therefore, local and federal regulations required to perform the test as well as safety instructions provided by the test set manufacturer must be followed. One more advantage of DFR is that the test involves a LV excitation signal typically $\leq 140 \text{ V}_{\text{RMS}}$.

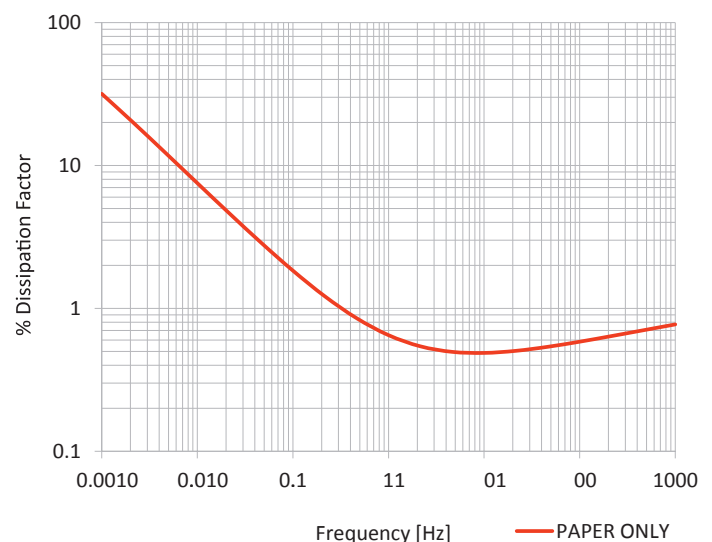
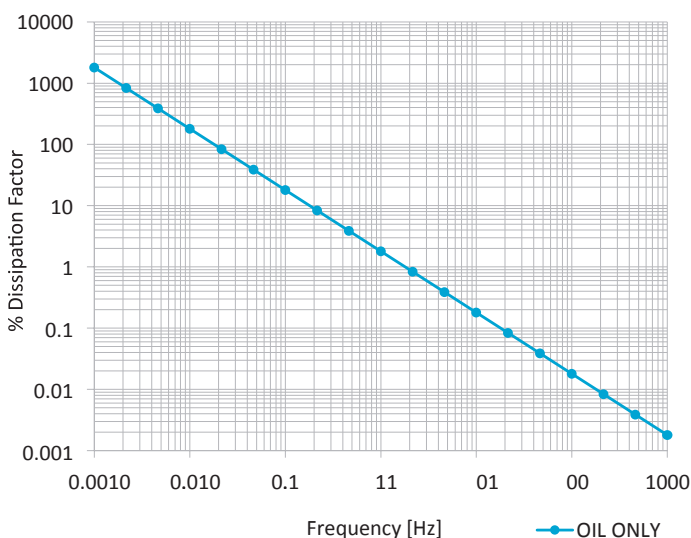
Figure 1. Hook up diagram between a DFR test set and a two-winding transformer





In the field, working conditions might not be optimal. Section 5 provides guidelines to minimize the effect of external factors on the test performance as well as the measurement configurations. At this stage, the reader should be aware that the most accurate estimation of moisture in the solid insulation is related to the test between windings in a UST (ungrounded specimen test) test mode. In a two-winding transformer, the capacitance of interest is the inter-winding insulation between high and low voltage windings represented in Figure 1 as C_{HL} . Other insulation systems, between high voltage winding and ground (C_H) or between the low voltage winding and ground (C_L) are susceptible to the influence of bushings and sometimes other components inside the transformer such as tap changers. Nevertheless, the GST measurements are often taken to identify non-typical responses related to contamination or degradation of the insulation system.

Figure 2. DFR of mineral oil (left);
DFR of paper only (right)



Section 6 provides the guidelines to generate the test report, including an example of the report.

Maybe the most important part of the guide is without a doubt Section 7 – Measurement Analysis and Interpretation. In this section, the guide provides the differences between the dielectric response of liquid and solid insulation graphically represented in Figure 2. The liquid insulation dielectric properties can be described by a simple parallel RC-circuit, the capacitance representing the liquid permittivity and the resistance the liquid conductivity. The dielectric properties of solid insulation are more complex, both capacitance and losses vary with frequency in a manner that cannot be described by a simple parallel or series RC-circuit.

After a clear understanding of the behavior of the materials under an alternating excitation signal in a wide frequency spectrum, different factors affecting the dielectric response are described. One of the most important factors to take into account is the presence of EMI in the surrounding test area.

Overcome the effect of noise (EMI) on the measurement signal, the use of a voltage amplifier is considered as optional in the field, especially for low capacitance specimens and tests at temperatures close to zero degrees Celsius.

The Annexes included in the document cover:

- A. Dielectric Frequency Response Analysis – Theory and validation
- B. Non-moisture related factors influencing the DFR measurements
- C. Examples of typical measurement challenges
- D. Bibliography

Closing Note

This article is a brief summary of a well-developed document provided by IEEE and its members. Authors consider imperative for asset managers, utility operators, transformer manufacturers and testing service providers to acquire this document and follow the guidelines given. The article is co-authored by Dr. Roberts Neimanis, Product Manager at Megger Sweden.

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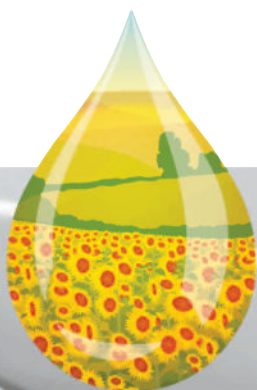
New Developments in
Natural Ester Fluids:

Modification by Addition of Nanoparticles Applied in Electrical Transformers

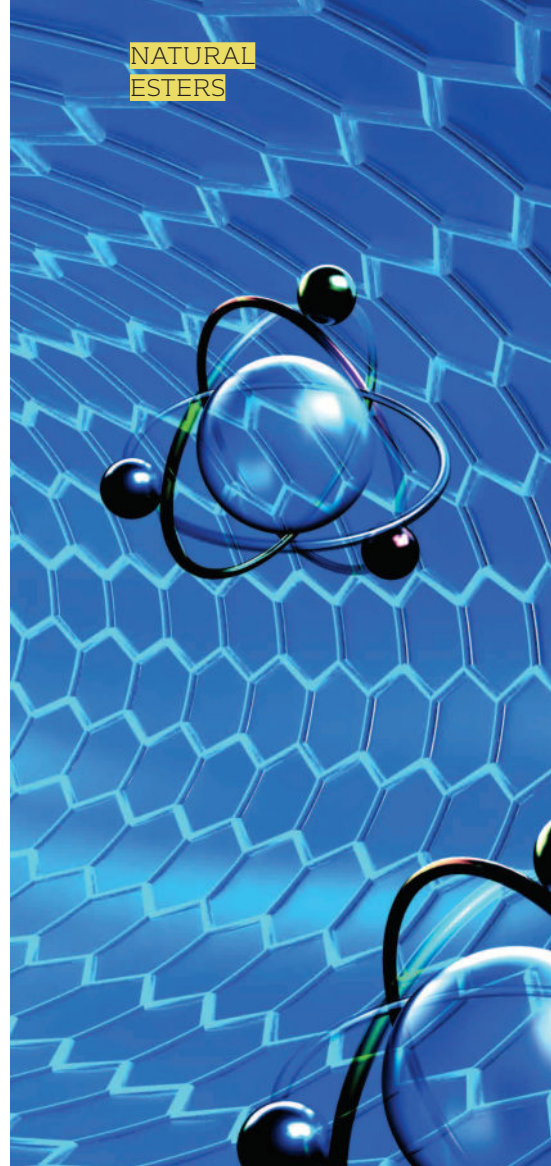
by **Corné Dames**

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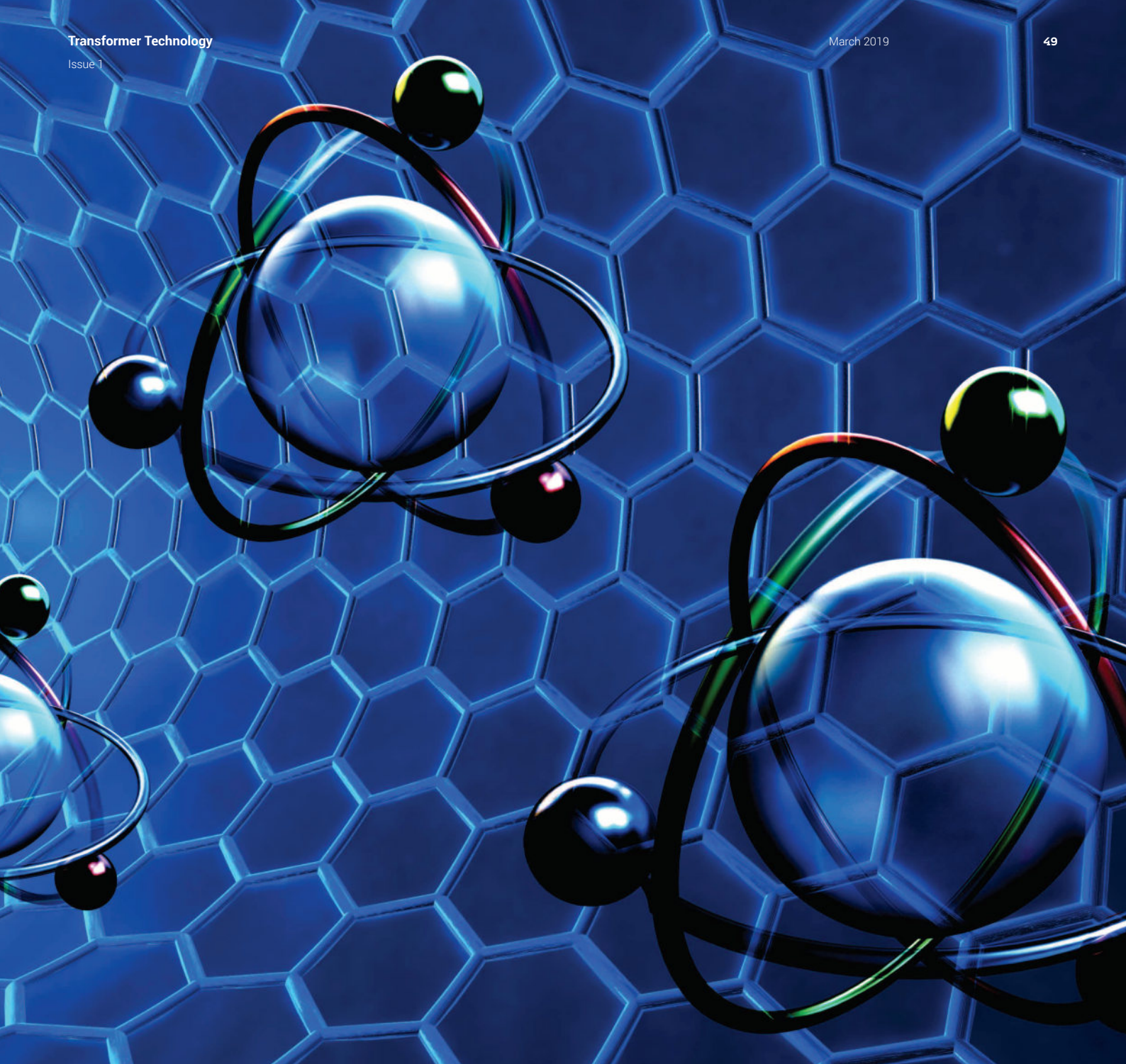
The main advantage of natural esters is the possibility of using domestic raw materials with a relatively low price and suitable properties, which include biodegradability.



NATURAL
ESTERS



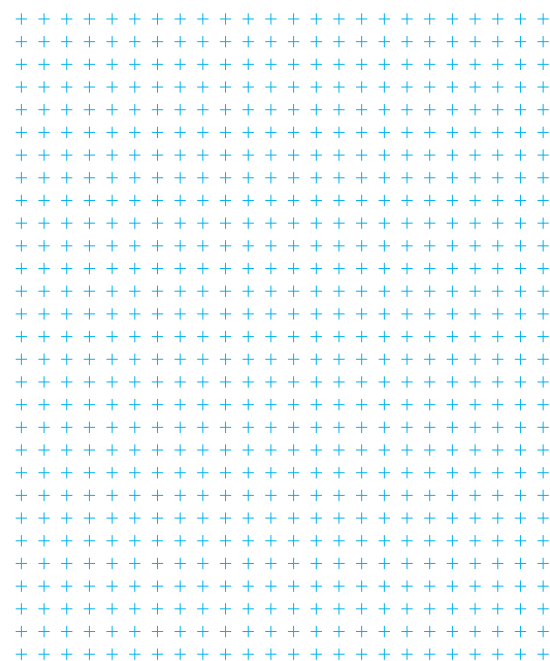
Corné Dames is the Managing Director of Independent Transformer Consultants, always striving to keep on top of new developments and research. She has expertise as Laboratory Manager in the analysis of transformer oils and as diagnostician identifying problem areas in transformers, as well as profiling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



New insulating liquid materials development is guided by multiple factors such as environmental requirements and other safety and economic considerations. Therefore, transformer manufacturers have to consider new specifications related to these new requirements.

The vegetable-oil based transformer fluids are increasingly replacing mineral oil-based products in the marketplace. These oils are successful because they perform better in various aspects than mineral oil products and they provide definite environmental and safety gains.

However, some modifications to natural esters are needed to make them more competitive as an insulating fluid. By filtration, nanoparticles addition and oxidation stabilisers added, these natural ester fluids display the necessary characteristics to compete with mineral oils as a replacement for dielectric fluid as part of the transformer insulating systems.



Advantages of Natural Esters

By adding nanoparticles to the natural ester fluids there should be an improvement to the key electrical properties of the fluid.

There are a significant number of advantages that natural esters have as dielectric fluid in transformers:

- Better environmental and health profile than conventional mineral oil
- High bio-degradability, thus leading to easier oil spill management solutions
- Higher flash and fire points that assist in overall safety which can result in lower substation upgrade costs.
- Interactions between the fluid and cellulose have been identified to extend insulation life
- 95% bio-based, providing a very high degree of sustainability
- A unique ability to absorb moisture contained in aging paper that can extend insulation life by a factor of as much as five
- Helping, chemically, to prevent long cellulose paper molecules from scission (i.e. aging) when exposed to heat
- Increased overloading capability and longer transformer insulation life
- Lower lifecycle costs and better utilization of assets
- Coming from renewable resources makes them recyclable and reusable
- Lower gassing tendency under electrical stresses and better resistance to sludge formation
- Due to their viscosity and ability to polymerise when thin layers are exposed to warmth and air flow, they do not spread along the surface and into subsurface soil in the case of spillage



In general, vegetable oil is fully miscible with traditionally used mineral oils, so it can be used to refill existing transformers. Additionally, corrosive sulphur is not present in natural esters. Considering their fire point is much higher than that of mineral oil, natural esters are a **much safer choice for areas where a) there is a risk of human life, b) there are high down time costs, c) there is difficult evacuation of surrounding areas, and d) where transformer replacement time and cost are posing a problem.**

Esters have a lower calorific value than mineral oil, providing less energy units per weight than mineral oil in the event of a fire. The by-products of ester fluid combustion are water, carbon monoxide and carbon dioxide which are less toxic than the carbon, nitrogen and sulphur oxides produced by mineral oil fire.

Disadvantages of Natural Esters

While the list of advantages above is significant, there are some disadvantages to the use of natural esters. Oxidation stability is the greatest concern. The natural ester is the most susceptible to oxidation, more so than all the available oils. Therefore **the exposure to oxygen and moisture should be kept at a minimum.**

The following characteristics are preventing natural esters from being deployed as an entirely technically acceptable replacement for mineral oils:

- Higher viscosity
- High pour point
- Higher permittivity
- Low oxidation stability
- No legislative path and test methods
- Durability problems in short high voltage impulse resistance

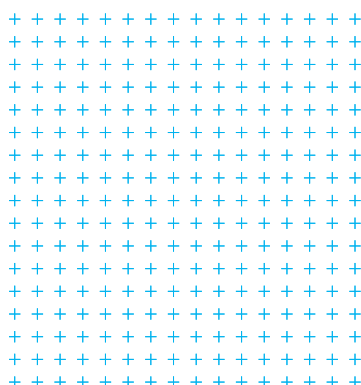
Assessment of Natural Esters for Further Development of Their Electrical Properties

Two types of natural esters have been identified for industrial application – rapeseed (*Brassica napus*) and sunflower (*Helianthus Annuus*) oil. However, the high number of poly and mono unsaturated fatty acids keeps the oil in a liquid state, even in lower temperatures, but makes it prone to oxidation. When AC stress voltage is applied, the sunflower oil exhibits a higher rate of deterioration. **The behavior of both natural esters under elevated temperature (25°C up to 140°C) is similar, with no conclusive differences. The value for volume resistivity for rapeseed is better than that of sunflower oil.**

There is no fully implemented legislative guidelines for the use of natural esters in transformers so far, but some properties are given in IEC 62770:2013 - "Fluids for Electrotechnical Applications – Unused Natural Esters for Transformers and Similar Electrical Equipment" [1]. The values for the individual parameters are mentioned in the middle column of Tables 4 and 5 in [1].

It is obvious that these oils could not fully comply with the requirements of Standard IEC 62770 [1] without modifications. These oils could not meet the values for some key parameters e.g. Breakdown Voltage (BDV), Acid number, water content and dissipation factor $\tan \delta$. Therefore, adjusting the insulating liquid for the desired purpose was needed. The vegetable oil needed to be passed through a column filled with a suitable sorbent and the addition of an oxidation inhibitor at the corresponding concentration. The modified rapeseed passed the test of oxidative stability (TOS) according to method C in standard IEC 61125 [2]. The TOS is based on the exposure of an oil sample by oxidation with the presence of copper, and eventually other materials. Changes in the measured parameters of the electrical insulating liquid are monitored before and after exposure.

Titanium Dioxide with a silica surface treatment (SFT TiO₂) has the maximum positive effect on breakdown voltage.



Preparation of Electro-insulating Ester Fluid

By filtering the oil for a 24-hour cycle through a composite pulp filter the acid number comes down to acceptable values. Furthermore, an oxidation inhibitor, di-butyl-para-cresol (DBPC), is added to the oil. Sunflower oil has a slightly better oxidation stability than rapeseed oil, however if a phenolic type antioxidant is added, the stability of rapeseed oil is higher. The final concentration in oil was set to 0.5 wt%, as this was identified as the optimum level.

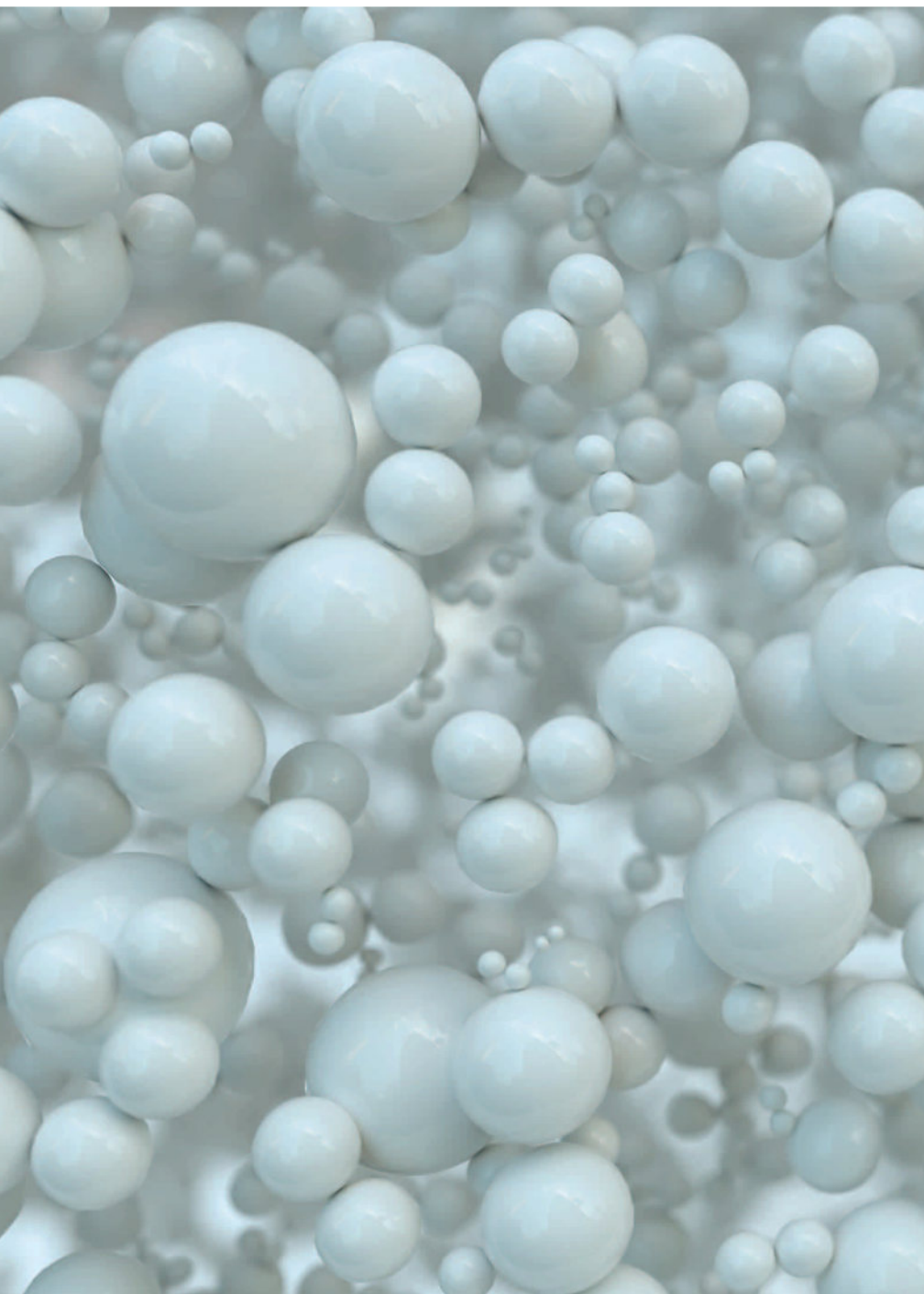
The electro-insulating liquid from rapeseed oil that has undergone the described methods of treatment was found ready for direct use in hermetic, distribution transformers and was patented under utility number CZ 29982. It was found that the modified natural esters resulting from the aforesaid treatment fully complies with the requirements of IEC 62770 [1]. The main advantage is the possibility of using domestic raw materials with a relatively low price and suitable properties, which include biodegradability.

This oil is safe for use in distribution transformers, especially around water sources and protected natural areas.

Improving the Electrical properties

As per above results, it is now clear that the electro-insulating liquid resulting from the modification treatment has electrical properties that comply with IEC 62770 [1]. **We can further improve the electro-insulating properties of the liquid by addition of nanofillers.**

By adding nanoparticles to the natural ester oils there should be an improvement to the key electrical properties of the fluid. It should increase the flashover/breakdown voltage and dissipation factor for the fluid. By adding nanoparticles to the fluid system, it will suppress the development of an electrical charge in the liquid after an electrical potential is applied.



Nanofiller Oxide	Purity (%)	Primary Particles size (nm)	Variation	Surface Treatment	
TiO ₂	>96% TiO ₂	20	Hydrophilic UV resistive	SiO ₂	
	<4% SiO ₂				
TiO ₂	99+	20			
Al ₂ O ₃ y	99,97	20-30			
Al ₂ O ₃ y	99,99	10			
SiO ₂	>98 SiO ₂	20	Hydrophilic Lipophilic	(3-Aminopropyl) Triethoxysilan	
	<2 (3-Aminopropyl)				
	Triethoxysilan				
SiO ₂	99+	20	Hydrophilic		
ZnO	>98 ZnO	30	Hydrophilic Lipophilic	(3-Aminopropyl) Triethoxysilan	
	<2 (3-Aminopropyl)				
	Triethoxysilan				
ZnO	99+	20			
ZnO	99+	30			

Table 1. Overview of the selected nanoparticles to modify the new oil properties

An increase in the value of flashover/breakdown voltage is achieved as well as improved electrical properties by addition of the nanoparticles as this spreads the discharge path. The overall chemical and physical parameters of the oil are preserved even after addition of the nanoparticles.

Four nanoparticles were selected for addition to the natural esters to improve the electrical properties; which was done in review of experiments that have been conducted on mineral oils. These nanoparticles were the selected nanoparticles TiO₂, Al₂O₃, SiO₂, ZnO. Table 1 gives an overview of the selected nanoparticles.

The selection was made based on several criteria. The first is the type of nanoparticle, the second the material purity and particle size in nm, the third is the surface treatment (ST). The surface treatment is known to have a significant influence on the incorporation of the particles into the fluid system.



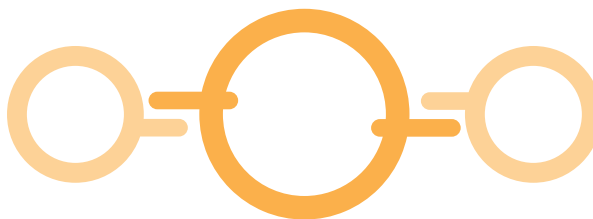
Results and Outcome Discussion on the Tests

Titanium Dioxide with a silica surface treatment (SFT TiO_2) has the maximum positive effect on breakdown voltage, and well at 0.25 wt%. The increase in breakdown voltage was approximately 20 kV, from 60 kV average to 80 kV average. The other nanoparticles were also added in the other tests, one type of nanoparticle ranging in concentration and particle size. The best results were achieved by the addition of titanium dioxide and well for the 20 nm size, 0.25 wt% concentration.

The increase in breakdown voltage and volume resistivity by addition of the Titanium Dioxide nanofiller at concentrations of 0.25 wt% can be explained by the creation of surface charges on the particle. These charges act against the outer electric field in the fluid, and thus the local electrical field is lowered and electron cascades from the electrode are shifted toward a higher voltage. Some studies claim that nanoparticles distributed polymers could create a "fence" effect and make the growing path of the electrical tree twist and turn like a "Z" shape, so that more energy would be consumed and therefore not available in the electrical system anymore [3].

Due to the more complicated path of pre-breakdown channels in dielectric fluids with nanoparticles, more energy is consumed and leads to the improvement of BDV, increased shallow trap density in the liquid. The shallow traps convert fast electrons to slow electrons by a trapping and de-trapping process. The hydrophilic surface can bind the water absorbed in the liquid this is in direct correlation to the type of surface treatment the nanoparticles has been subjected to. The nanofiller concentration is also an important factor, if the concentration is too high the interaction layers on the particle surfaces overlap and this will have a negative effect on the BDV.

Titanium dioxide molecule



The particle is usually covered by 5-10 H_2O molecules tightly bound to its surface, and they may absorb additional water from the oil, in which case the conductive paths may be created [4]. However, there are many variables that might contribute in minor part to changes in breakdown voltage behavior (e.g. size, specific surface area, morphology, viscosity, moisture, etc.) [5].

The dissipation factor, $\tan \delta$, was improved by the addition of ST TiO_2 . The dissipation factor increases for concentrations higher than 0.25 wt%.

Points of Caution When Using Uninhibited, Untreated Natural Ester Fluids

Due to lack of oxidative stability it is recommended that the natural ester oils would only be used in hermetically sealed transformer units. The higher viscosity might cause an increase in operating temperature of transformer units, thus a design alteration needs to be done for successful long-term operation of the transformer without damage. Saturation of the cellulose pressboard system in the transformer might take longer due to the higher viscosity and higher permeability of the natural esters. Currently, there are no reliable standard test methods for analytical determination of electrical faults that might be developing in the transformer system. No fault gases or critical concentrations of individual gases has been identified. There is still a long way to go on the analytical side to get to the level of reliability testing needed for the assured infrastructure reliability needed in electrical reticulation.

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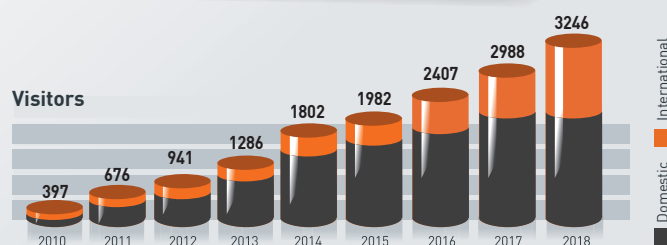
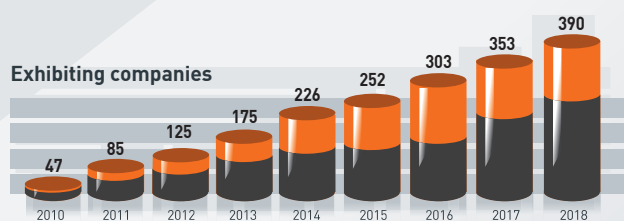
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Production staff	10%
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Head of R&D	7%
R&D staff	8%
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President/CEO/Vice president	6%
Other top management	3%
Head of Purchasing and sourcing	12%
Purchasing and sourcing staff	6%
Other staff	7%

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The Value of Performing Power Factor Sweep Measurements on Bushings

by **Brandon Dupuis**

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Brandon Dupuis joined OMICRON electronics Corp in 2013 and presently holds the position of Regional Application Specialist for transformer testing. Brandon's focus is currently on standard and advanced electrical diagnostics for power transformers and circuit breakers. He is a well-known OMICRON instructor teaching electrical transformer diagnostic testing theory, application, and test result analysis. Brandon received a BSEE from the University of Maine.

The Power Factor measurement is highly sensitive to the test-environment. For example, it is sensitive to moisture on the surfaces of the bushings during the time of the test, to the test connections, and to the test specimen's earth-ground connection; therefore, a simple tool that allows a user to better detect a “bad” (i.e. invalid) Power Factor measurement is useful.

Introduction

The Power Factor measurement has long been accepted as an invaluable tool for identifying insulation defects such as aging, deterioration, moisture ingress, and localized failures involving the winding and bushing insulation of a power transformer. Historically, Power Factor measurements have been performed at a single test-frequency (typically 60 Hz) and at a single test-voltage (typically 10 kV); however, modern test instruments can perform Power Factor measurements at several different test-frequencies and at several different test-voltages with minimal additional time and effort.

Based on experience, performing Power Factor frequency-sweep and voltage-sweep measurements can help identify and confirm:

- Compromised insulation
- User-error
- Influences of the test environment

Power Factor sweep measurements help the industry:

- Better assess the condition of an insulation system
- Determine whether a given Power Factor measurement is even valid

Although Power Factor sweep measurements can be performed when testing the overall winding insulation of a power transformer, this paper focuses on the benefits of applying sweep measurements to the C1 insulation of bushings. While Power Factor sweep measurements are not the silver bullet of Power Factor testing, they can be beneficial for the maintenance testing industry.

Who Can Benefit from Performing Power Factor Sweep Measurements?

The Power Factor measurement is highly sensitive and is one of the most challenging transformer tests to “get right”. In many cases, a questionable Power Factor measurement is not caused by compromised insulation, but is due to either user-error or the influence of the test environment.

The Test Equipment Operator

Although it is difficult for the user to determine whether a Power Factor measurement at one test-voltage and one test-frequency is valid, invalid measurements often become obvious when the Power Factor sweep measurements are performed and analyzed. Therefore, the test equipment operator should use Power Factor sweep measurements as a tool to quickly identify and correct invalid measurements, before they leave the job site with incorrect test results.

The Engineer

In most cases, a test equipment operator performs the Power Factor measurement in the field and distributes a test report to an engineer, who assesses the test results in the office. Based on the results, the engineer is responsible for assessing the condition of the insulation system to determine the appropriate course of action.

However, an engineer who has the Power Factor sweep results in-hand can better identify invalid measurements, which helps prevent an incorrect condition assessment.

It is widely known that the best way to assess a Power Factor measurement is to compare the most recent measurement to a series of previous baseline measurements that were obtained at consistent test-intervals. However, many asset owners do not have a collection of reliable baseline test results for their transformer fleet, which makes assessing the condition of an insulation system and determining the appropriate course of action a challenge.

Power Factor Sweep Test Analysis

The analysis of the voltage-sweep and frequency-sweep measurements is performed visually. The Power Factor measurements are plotted versus the applied test-voltage and versus the applied test-frequency, and the condition of the insulation is assessed based on the shape of the plots (aka, the traces).



Although this paper focuses on applying Power Factor sweep measurements to the C1 insulation system of bushings, the same analysis strategies are valid for assessing Power Factor sweep measurements performed on the overall winding insulation of a power transformer.

In general, the analysis involves determining whether the shape of a trace is normal or abnormal. If either of the sweep measurements produces an abnormal trace, and the measurements are valid, then the insulation system should be investigated and/or tested more frequently in the future.

The Power Factor Voltage-Sweep Test (aka the Voltage Tip-Up Test)

Performing a Power Factor measurement at multiple test-voltages helps identify compromised insulation as well as invalid Power Factor measurements.

At a minimum, an oil-and-paper insulation system should be tested at two test-voltages (e.g. 2 kV and 10 kV). In most cases, a Power Factor measurement performed on bushing insulation should not be voltage sensitive. Therefore, regardless of the applied test-voltage, the measured Power Factor value should be the same.

If the measured Power Factor values obtained from testing the same insulation system at two different test-voltages are not reasonably similar, then the measurement

is questionable and should be investigated. To investigate further, the Power Factor measurement can be repeated at four or five different test-voltages (e.g. 2 kV, 4 kV, 6 kV, 8 kV, and 10 kV) to establish a definitive pattern.

When a Power Factor measurement is invalid, it often becomes voltage sensitive. Therefore, a Power Factor measurement at two different test-voltages – first at a relatively low test-voltage (e.g. 1 kV or 2 kV) and then at a relatively high test-voltage (e.g. 10 kV) – can detect invalid measurements better than a single Power Factor measurement at one test-voltage.

When the insulation of a bushing begins to deteriorate, the C1 Power Factor measurement for that bushing often becomes voltage sensitive. Therefore, at a minimum, a bushing C1 Power Factor measurement should be performed at two different test-voltages (e.g. 2 kV and 10 kV). If the Power Factor value obtained at the two test-voltages is not reasonably similar, then the C1 insulation of the bushing is typically deemed questionable. Remember, however, that a few bushing types may produce C1 Power Factor measurements that are slightly voltage sensitive even when the C1 insulation system of the bushing is healthy.

The Power Factor Frequency-Sweep Test

Performing a Power Factor measurement at multiple test-frequencies helps to identify compromised insulation and invalid measurements. The Power Factor frequency-sweep test involves performing Power Factor measurements at a series of various test-frequencies (e.g. 15 Hz, 30 Hz, 45 Hz, 60 Hz, 150 Hz, 200 Hz, 300 Hz, and 400 Hz).

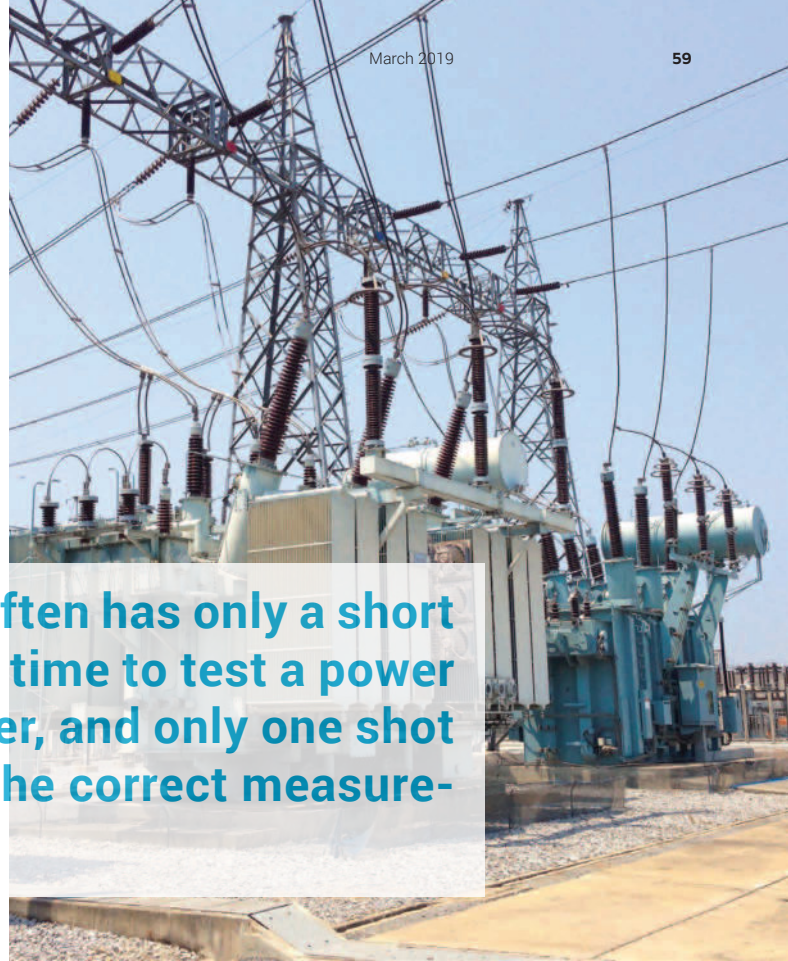
The general guidelines used to assess a frequency-sweep trace are as follows:

The user often has only a short window of time to test a power transformer, and only one shot to obtain the correct measurements.

- In general, if an oil-and-paper insulation system is healthy, the measured Power Factor value increases versus frequency. In other words, the frequency-sweep trace climbs uphill versus frequency.
- As an oil-and-paper insulation system deteriorates, the frequency-sweep trace typically becomes flat, or worse, decreases versus frequency. If the trace decreases versus frequency throughout all or most of the frequency-sweep, then the insulation system is typically considered questionable and is either investigated further and/or tested more frequently in the future.
- Another characteristic of compromised insulation is a distinct fishhook shape in the lower frequency range of the sweep (i.e. at frequencies below 60 Hz). If this occurs, then the insulation system is typically considered questionable and is investigated further and/or tested more frequently in the future.
- One advantage of performing Power Factor frequency-sweep measurements on the C1

insulation system of a bushing is that, in most cases, a bushing mounted on a power transformer has two or three similar-unit bushings that can be tested and compared to each other. In general, Power Factor sweep measurements should behave similarly when comparing similar-unit bushings. Ideally, the traces for similar-unit bushings overlay or overlap when plotted against each other. Most important, the shape of the frequency-sweep traces should be reasonably similar when comparing similar-unit bushings. If the shape of the trace of one bushing is dissimilar relative to the shape of the traces of the other similar-unit bushings, then the dissimilar bushing should be investigated further and/or tested more frequently in the future.

The C1 Power Factor frequency-sweep measurements for three sister-unit bushings are provided in Figure 1. Notice that the shape of the traces is similar when comparing the similar-unit bushings, and in all the traces in Figure 1, the measured power factor increases versus frequency (from left to right). This is typically indicative of healthy insulation.



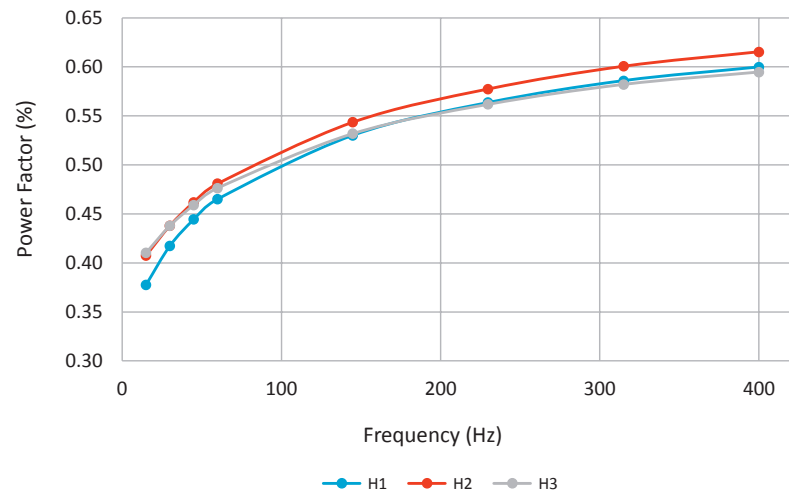


Figure 1. Acceptable C1 Power Factor frequency-sweep traces



Invalid Power Factor measurements that go undetected are a significant waste of a company's resources.

CASE STUDIES

Several case studies involving Power Factor sweep measurements helped identify both compromised insulation and invalid measurements and demonstrated the value of performing Power Factor sweep tests on the C1 insulation of a bushing.

Fortunately, Power Factor sweep measurements can be used to better assess the condition of an insulation system at a given point in time, especially when there are no historical test results for comparison.

Case Study #1:
Haefely 115 kV Bushings

The first case involves Power Factor measurements that were performed on three Haefely 115 kV bushings (specified in Table 1), see Figure 2.

Table 1.

Haefely 115 kV bushings (2000)				
	2 kV PF	10 kV PF	10 kV PF – 2 kV PF	Nameplate Power Factor
H1	0.34%	0.34%	0.00%	0.38%
H2	0.32%	0.32%	0.00%	0.37%
H3	0.38%	0.41%	0.03%	0.35%

Note: the measured capacitance for each bushing compared well to its respective nameplate value

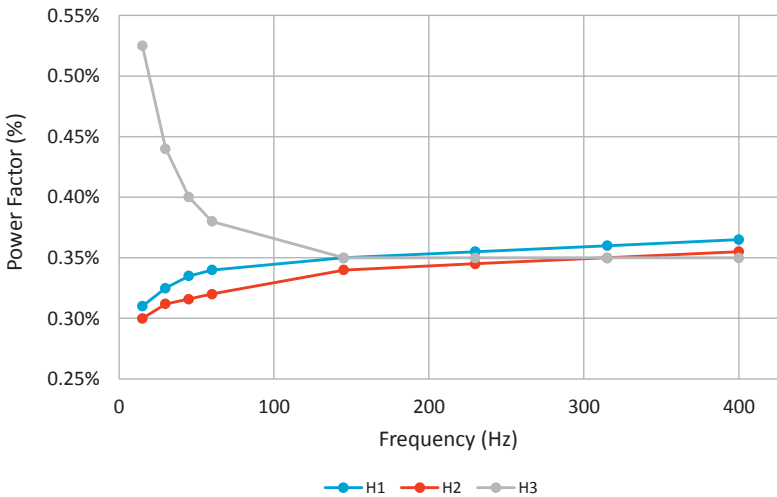


Figure 2. C1 Power Factor results for three Haefely 115 kV bushings

Based on the results in Figure 2, the 10 kV Power Factor for H3 is higher than its nameplate value, whereas the 10 kV Power Factor for the other two bushings is below their respective nameplate values. Notice that the 2 kV and 10 kV Power Factor measurements for the H3 bushing are dissimilar. In contrast, the 2 kV and 10 kV Power Factor measurements for the H1 and H2 bushings are reasonably similar, which further suggests that the H3 measurements are abnormal.

When comparing the Power Factor frequency-sweep traces among similar-unit bushings, the shape of the traces should be reasonably similar. Clearly, the shape of the H3 trace is dissimilar relative to the traces of the other two bushings. Moreover, the H3 trace decreases versus frequency and has the distinctive fish-hook in the lower frequency range; this is typically indicative of compromised insulation.

Interestingly, the 10 kV Power Factor for H3 is below 1.5 to 2 times its nameplate value, which the industry generally considers to be acceptable. However, the H3 bushing is clearly behaving differently than the other two similar bushings, which is cause for concern. This case demonstrates that Power Factor sweep measurements are more sensitive to compromised insulation than conventional 10 kV Power Factor measurement. The H3 bushing should be flagged as the weak link among the three bushings, and if returned to service, should be tested more frequently to gauge the severity of the situation.

Case Study #2:
Lapp POC Series 2 115 kV Bushings

The second case involves Power Factor measurements performed on three Lapp POC Series 2 115 kV bushings (specified in Table 2), see Figure 3.

Table 2.

Lapp POC Series 2 115 kV Bushings (1998)				
	2 kV PF	10 kV PF	10 kV PF – 2 kV PF	Nameplate Power Factor
H1	0.27%	0.28%	0.01%	0.25%
H2	0.25%	0.25%	0.00%	0.25%
H3	0.66%	0.76%	0.10%	0.24%

Note: The measured capacitance for each bushing compared well to its respective nameplate value.

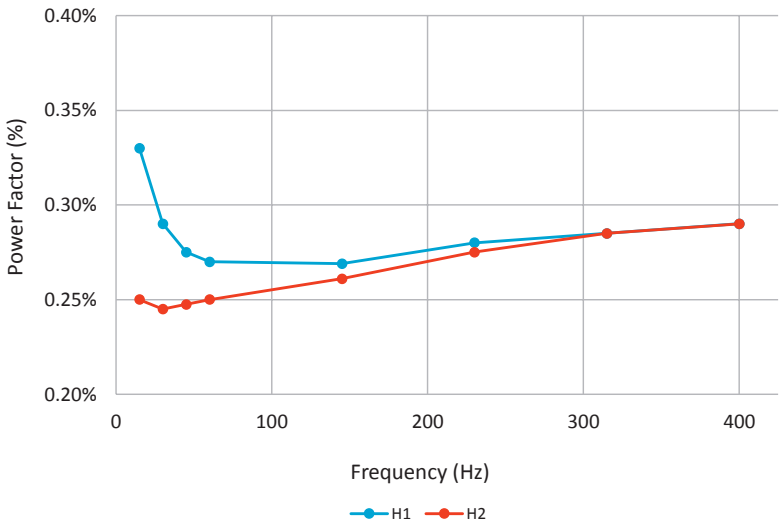


Figure 3. C1 Power Factor results for three Lapp POC Series 2 115 kV bushings

The Power Factor frequency-sweep trace for the H3 bushing is not plotted because its 10 kV Power Factor value is three times its nameplate value, which is already enough to condemn the H3 bushing. In other words, the Power Factor frequency-sweep trace for the H3 bushing only confirms what we already know. Additionally, the 2 kV and 10 kV Power Factor values for the H3 bushing differ significantly – further evidence to condemn the H3 bushing.

Based on the results in Figure 3, the 10 kV Power Factor value for H1 is higher than its nameplate value, whereas the 10 kV Power Factor value for the H2 bushing is the same as its nameplate value. Additionally, the frequency-sweep trace for the H1 bushing is clearly dissimilar relative to the frequency-sweep trace for the H2 bushing. The H1 trace decreases versus frequency and has developed the distinctive fish-hook in the low-frequency range – typically indicative of compromised insulation. Although the 10 kV Power Factor for H1 is well below 1.5 to 2 times its nameplate value, the H1 bushing is clearly behaving differently than the H2 bushing. As a result, the H1 bushing should be tested more frequently to gauge the severity of the situation.

Case Study #3:
Westinghouse Electric Type S 37 kV Bushings

The third case involves Power Factor measurements performed on three Westinghouse Electric Type-S 37 kV bushings (specified in Table 3). The Power Factor measurements are summarized in Figure 4.

This case provides an example of three sister-unit bushings that produced three completely different Power Factor frequency-sweep traces. The Power Factor frequency-sweep trace for the H1 bushing is a typical example of a trace produced by a healthy bushing, whereas the Power Factor frequency-sweep trace for the H2 bushing is a typical example of a trace produced by a questionable bushing. However, the Power Factor frequency-sweep trace for the H3 bushing is an example of an abnormal or non-typical frequency-sweep trace, which warrants concern.

Table 3.

Westinghouse Electric Type S 37 kV Bushings						
	2 kV PF	10 kV PF	10 kV PF – 2 kV PF	Nameplate Power Factor	Measured Capacitance	Measured Capacitance
H1	0.60%	0.58%	-0.02%	0.65%	169 pF	182 pF
H2	0.79%	0.78%	-0.01%	0.72%	184 pF	197 pF
H3	0.69%	0.69%	0.00%	0.66%	203 pF	198 pF

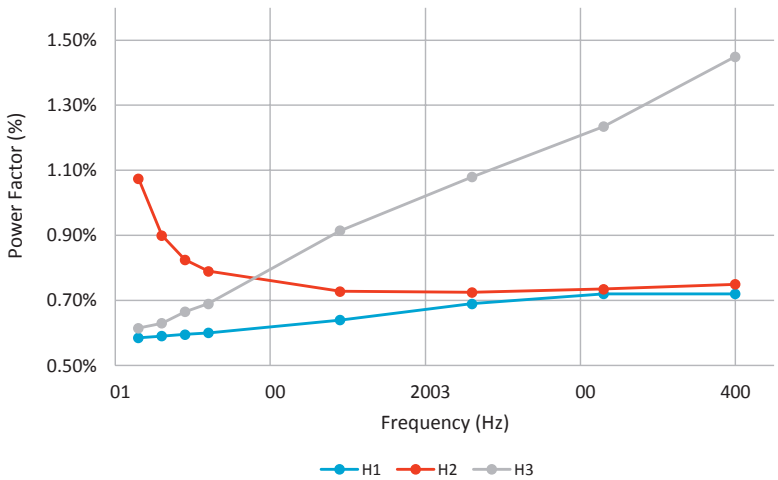


Figure 4. C1 Power Factor results for three Westinghouse Type-S 37 kV bushings

Based on experience, there appears to be a bushing insulation failure mode where the measured capacitance (pF) value of the bushing is dissimilar different relative to its nameplate value and to the other sister-unit bushings. For this type of insulation failure, in addition to the measured capacitance (pF) value being different than expected, the Power Factor frequency-sweep trace becomes more-or-less linear and exhibits a steep incline from left-to-right (as demonstrated by the H3 bushing in Figure 4).

Interestingly, the H1 and H2 bushings tested with capacitance values well below their respective nameplate values; the capacitance value of the H3 bushing is above its nameplate value. If the measurements provided in Figure 4 can be verified, then the insulation system of the H3 bushing is behaving abnormally, and if returned to service, it should be tested more frequently to gauge the severity of the situation.

Case Study #4:
Lapp POC 138 kV Bushings

This case involves Power Factor measurements performed on three Lapp POC 138 kV bushings (specified in Table 4), see Figure 5.

Table 4.

Lapp POC 138 kV Bushings (1998)				
	2 kV PF	10 kV PF	10 kV PF – 2 kV PF	Nameplate Power Factor
H1	0.34%	0.36%	0.02%	0.29%
H2	0.52%	0.24%	-0.28%	0.23%
H3	0.34%	0.35%	0.01%	0.23%

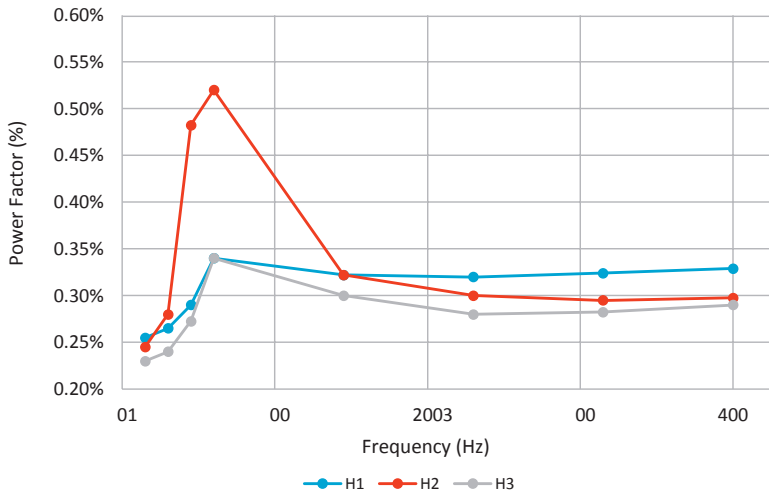


Figure 5. C1 Power Factor results for three Lapp POC 138 kV bushings

Based on the results in Figure 5, the Power Factor values for all three bushings are higher than their respective nameplate values. Notice that the Power Factor measurement for the H2 bushing is clearly voltage sensitive. Furthermore, the Power Factor frequency-sweep traces for the three bushings are erratic and jagged. In general, jagged Power Factor frequency-sweep traces are indicative of invalid Power Factor measurements. Regardless of whether an insulation system is healthy or compromised, its Power Factor frequency-sweep trace should be smooth.

By analyzing only the 10 kV Power Factor measurements, it is not obvious that the Power Factor measurements for the three bushings are invalid; however, the voltage and frequency-sweep test results make it obvious that the Power Factor measurements are invalid. In this case, the customer determined that the primary-side bushing terminals were not short-circuited together when the C1 Power Factor measurements were performed; this identified the cause of the abnormal Power Factor measurements.

Conclusion

With both the voltage and frequency-sweep measurements on hand, invalid measurements are easier to identify. The equipment operator can use the sweep measurements to quickly identify and correct invalid measurements in the field before the transformer is placed back into service. The engineer can use the sweep measurements to identify invalid Power Factor measurements, especially when they must rely on the data provided within a test report. Finally, Power Factor sweep measurements help to accurately assess the condition of a bushing’s insulation system. This helps the asset owner choose the best course of action.

References
[1] IEEE Std. C57.152-2013, IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors.

Additional Information
For more information and Case Studies regarding the Power Factor Sweep Tests, please email a request for my extended paper titled “The Value of Performing Power Factor Sweep Measurements on Bushings”.



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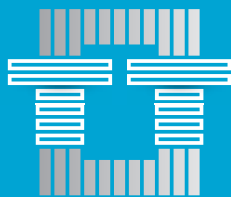
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