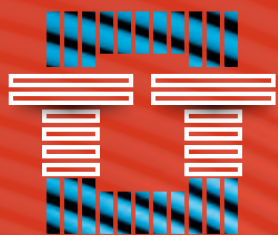


ISSUE 10

JANUARY/FEBRUARY 2021

transformer-technology.com

ISSN 2642-2689



TRANSFORMER TECHNOLOGY^{MAG}

Overheating & Creative Solutions Cooling

Transformers Are Cool - But Are They Really?

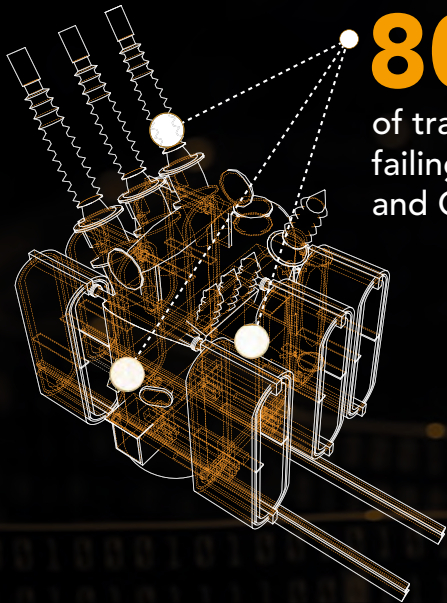
High-Performance Fans for Liquid-Cooled Transformers

The Power of Coatings - Keeping the World Connected



CAMLIN
POWER

CONNECTING DATA TO DECISIONS



80%+

of transformer failures are due to failings in the Bushings, Windings and OLTCs.

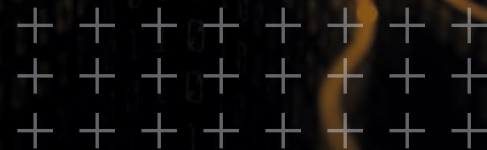
WHY IS DGA NOT ENOUGH?

Only by monitoring all components on the transformer can an accurate picture of transformer health be determined. The key benefit of online monitoring is the ability to detect anomalies under real operating conditions that otherwise would not be detected and then follow up with the best course of action.

WHY TOTAL TRANSFORMER MONITORING?

Build a complete picture of transformer health with TOTUS Transformer Monitoring. Integrating DGA, Partial Discharge (PD), Bushing Monitoring (BM), Through Fault Currents (TFC) and Transformer Analytics into a single system, TOTUS delivers an in-depth understanding of transformer health.

Data and insights are key to driving business critical decisions about assets. At Camlin we deliver that data through our TOTUS monitoring solution. We work with you to interpret this data and deliver insights that drive action. Our goal is to 'connect the dots', linking complex data sets with actionable information. This provides the complete picture you need to make informed decisions and optimise long-term transformer health.



25%+
Failure Rate



TAP CHANGER

What do we monitor?

- Temperatures
- Gases DGA
- Moisture in Oil
- Tap Position
- Motor Current

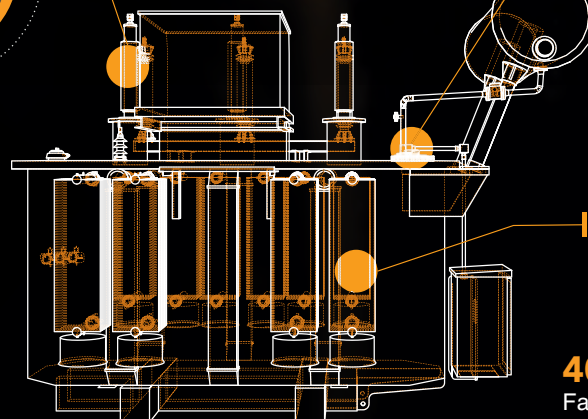
15%+
Failure Rate



BUSHING MONITORING

What do we monitor?

- PD
- Temperature
- Leakage Current Angle
- Leakage Current Amplitude
- Capacitance
- TanDelta/Power factor
- High Energy Events
- Load



40%+
Failure Rate



TRANSFORMER MAIN TANK

What do we monitor?

- DGA 5 & 9 Gas
- PD
- TFC
- Hot Spots
- Temperature
- Operating Condition Status
- Moisture in Oil
- High Energy Events
- Transformer Status/Levels
- Cooling System Status/Temperature

CIGRE TB642

SEARCHING FOR NEW CUSTOMERS?

LET THEM FIND YOU!

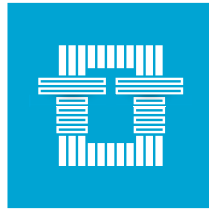
LOOKING FOR NEW MARKETS?

WE WILL SHOW YOU HOW.

Advertise with TT

and strengthen your presence
in the transformer market.





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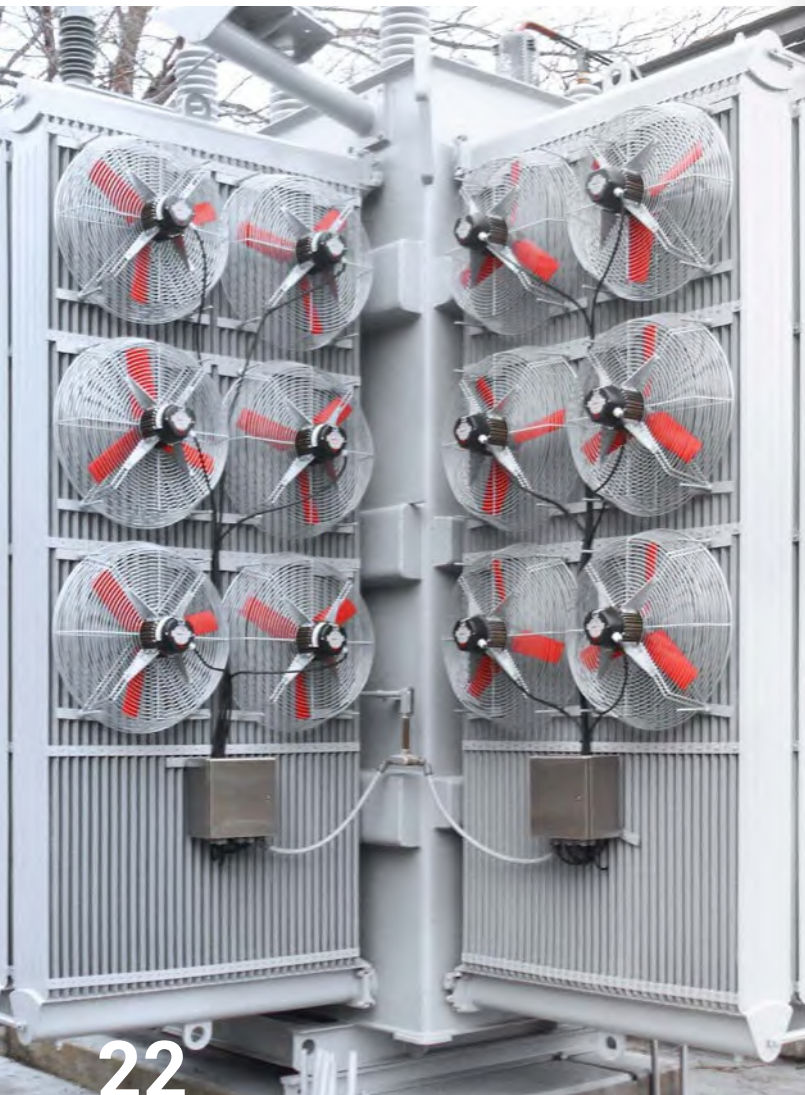
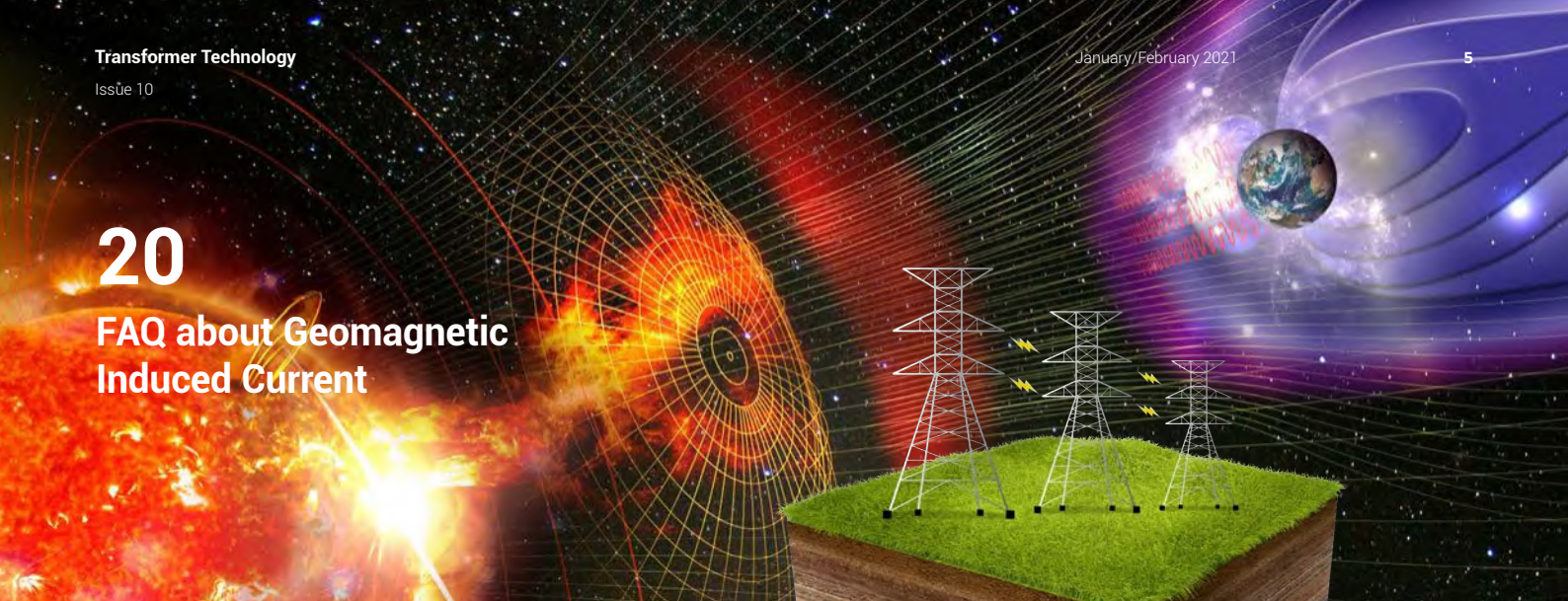
Transformers Are Cool – But Are They Really?

With transformers being a vital component of any electrical grid and their maintaining being of the utmost importance, we have to ask ourselves, how well are we managing the critical components of these transformers? This article focuses on the importance of the transformer cooling systems in its operation.



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FAQ about Geomagnetic Induced Current



22

It Isn't Rocket Science. Well, Actually...

When it comes to the cooling of transformers, there are a lot more factors to be considered than one would think. This article lays out a great case for decision making for specifying, repairing, upgrading or simply understanding cooling systems. While this article is heavily focused on fans, it is also a great primer on how to cool a transformer, so enjoy.



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High-Performance Fans for Liquid-Cooled Transformers



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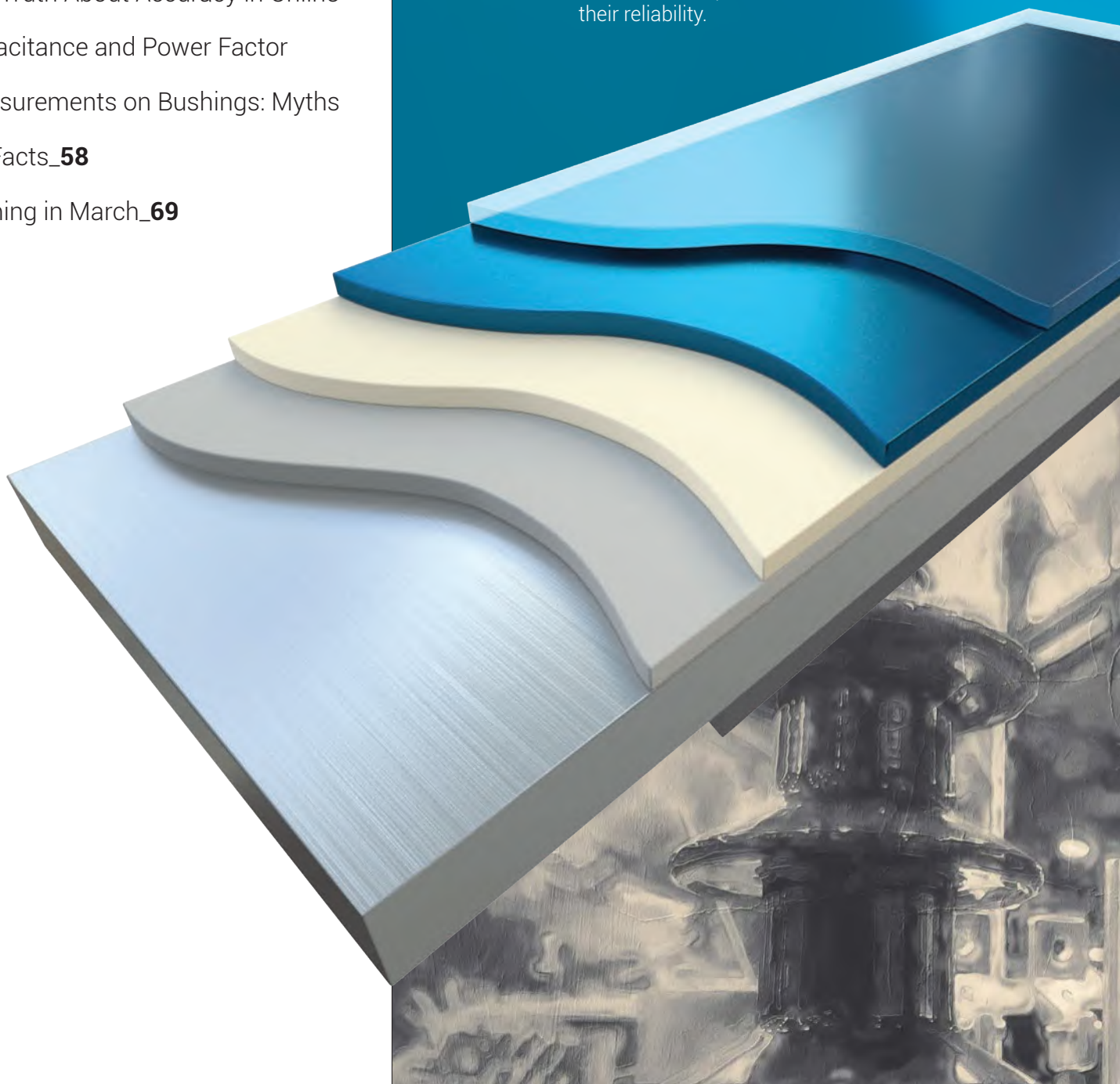
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The Power of Coatings – Keeping the World Connected

The design emphasis for transformers is typically focused on protecting its sensitive instrumentation, controls, and operation. Few consider how critical it is to protect the metals that house these vital components and ensure their reliability.





40

Twin Technologies Test Transformer Reliability

We can draw comparisons between the symbioses in fraternal twins to those prevalent in technologies used to monitor the health of electrical assets. This is especially true of ultrasound and infrared thermography; technologies that extend our human ability to hear and see.



48

Transformer Bushings – How to Detect Incipient Faults in an Early Stage?

Even a failing bushing which will not lead to a catastrophic failure can harm people due to burst porcelain insulators and broken fragments that can be catapulted through the air by the force of the breakdown arc. This article discusses the early detection of incipient bushing failures by using the knowledge of different failure mechanisms discussed previously.

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The Truth About Accuracy in Online Capacitance and Power Factor Measurements on Bushings: Myths vs. Facts

Most electrical utilities use limit criteria to replace bushings, however, it is widely unknown that the industry methods for online power factor and capacitance measurements do not always satisfy this criteria due to a number of factors that influence measurement accuracy. The focus of this article is to highlight these influences using theory and field observations and quantifying their effects on accuracy.

Impressum

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IMPRESSUM



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Transformer maintenance
and reliability
26 years industry
experience



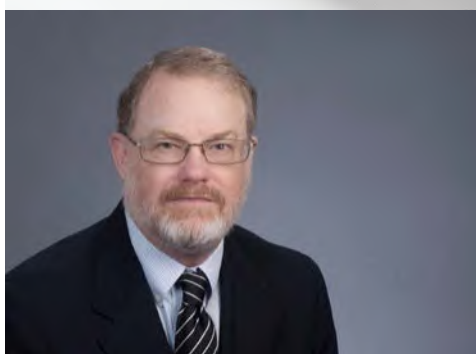
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ISSN 2642-2689 (Print)
ISSN 2642-2697 (Online)

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Curtus Duff
Power transformer design
4 years of experience

Dear Readers,

This letter is the start of something very different and important for Transformer Technology and our community of professionals. It is something that has been pressing on my mind for a long time now and can be summed up in one word:

Purpose!

What is the purpose of what you and I do, the purpose of what Transformer Technology (TT) is about, and why is it so critically important to our future?

Every organization, or person for that matter, must determine their purpose in order to succeed. Some call it True North, others their Vision or Charter. Regardless of what we call it, it is the engine of success that gives us two things – first, it gives us Direction, to know which of the myriad of directions we could take. And secondly, it gives us a defined Destination. Purpose is defined by both and purpose must be at the core of why and what we do.

What is the purpose of TT? When I was asked to become the Editor in Chief, something I had never done before, I had to determine what our purpose was and the folks at APC Media were very gracious in allowing me to do a bit of organizational consulting.

Our Purpose at TT was to create a North American focused magazine with the best transformer-centric technical content we could find. Very quickly we began to produce a quarterly magazine that did just that. Topics were broad and the goal of printing a high-quality publication was quickly achieved. But something was missing. We got our heads together and realized that the world was moving to a digital format rather than just a printed format, and we had to adjust our focus in order to meet those changes. We started that change in the fall of 2019 and then in 2020 Covid hit. Looking back, it would appear that we were lucky. We think we are blessed.

With that pivot we also realized that our community members accessed a lot of their technical content via video or webinars, so we began to build up our video content, adding a new staff member to manage the process.

We will produce **Tech Talks**, which are 8-to-10 minute video clips on technical topics answering questions from our Technical Advisory Board, Editorial Board or from TT Community members. In addition, our Allied Members will provide **Profiles** of their organization and area of expertise.



It is better to give than to receive” is an old and well tested saying, but we think it is better to do both – to be a life-long learner since no one is above learning, and to share what you know, what you have experienced, and how that can impact the next generation of learners.

Finally, we will begin curating a web series called **WebLinks**, which are non-commercial webinars created by members of the TT community to share knowledge, to inspire, to equip or educate.

Our direction was always clear, but our destination was too short-sighted, as is often the

case. We applied a Silhouette Planning Model, allowing us to refocus on our destination as we got closer to it, while maintaining clarity of direction. Who knows what the future might bring as we continue along our path that leads us to fulfilling our unique purpose.

Personally, my purpose was clear several years ago as the worlds of reliability and electric power began to merge. With the transformer being the “heart of the system”, I soon realized that my destination has changed, all the while maintaining the same direction. As I took on the role of President of the not-for-profit Electric Power Reliability Alliance, EPRA (I do love a good acronym), this year, I see how both roles align so well.

But I write this article to be more than about me. It is really a clarion call to professionals in the transformer, electric power, and/or reliability marketplace. Revisit your personal purpose. If your direction is to be a builder, helping create a body of knowledge based on your years or maybe even decades of experience, then the TT Community is for you. If your expertise expands beyond the transformer, then EPRA is a similarly focused membership organization you should explore.

If, on the other hand, you are relatively new to your career, then you are the professional we are aiming for, and since all of us need to be “life-long learners”, in a way, we are all still here to learn. “It is better to give than to receive” is an old and well tested saying, but we think it is better to do both, to be a life-long learner since no one is above learning, and to share what you know, what you have experienced, and how that can impact the next generation of learners.

We must become “givers” in a world where there are so many who need to be served. We must also become “takers”, in that all of the knowledge we share whether in a digital, themed, monthly magazine format or through audio and video, is content that you, the Transformer Technology Community, provide.

There is a scene in the movie *Jerry McGuire* where Tom Cruise says, help me to help you. While that seems a little bit of a cliché today, it really does embody what we are trying to accomplish at TT. But it might be better stated: Help us help us. And the best way to do that is to get engaged with the community.

Today communication is either viral or stagnant. In the media business, we create content that we believe is valuable to the community and we hope that you share that with your peers or your community. LinkedIn is a great way to connect with your connections, but there are so many other ways as well. Simply forwarding a link via email to your professional connections is a great way to support your profession.

As the magazine becomes a monthly, theme specific and content based digital publication, which adds tremendously to the Body of Knowledge, we want to address the changes in the way people consume content, and that is through audio (Podcasts and Interviews) and more increasingly through video. It is no wonder that Google bought YouTube, knowing video content will soon surpass written content for their audience.

As we revisited our purpose, one thing became clear, and Covid has both allowed us and caused us to make sure our purpose is clear and compelling to the community we serve: We must become givers in a world where there are so many who need to be served. We must also become takers, in that all of the knowledge we share whether in a digital, themed, monthly magazine format or through Audio and Video, is content that you, the Transformer Technology Community, provide.

We thank you for being part of our Purpose and would love to hear how we can support you as you realize your personal direction and destination.



Alan M Ross
CRL, CMRP
Editor in Chief
Transformer Technology
Curator of the Community
President of EPRA



Alan M Ross



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AND KNOWLEDGE
ARE IMPORTANT
TO US**

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about your area of business or expertise?**

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sharing in the transformer industry by
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studies, research results, or simply your
knowledgeable opinion on a topic of
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Transformers Are Cool – But Are They Really?

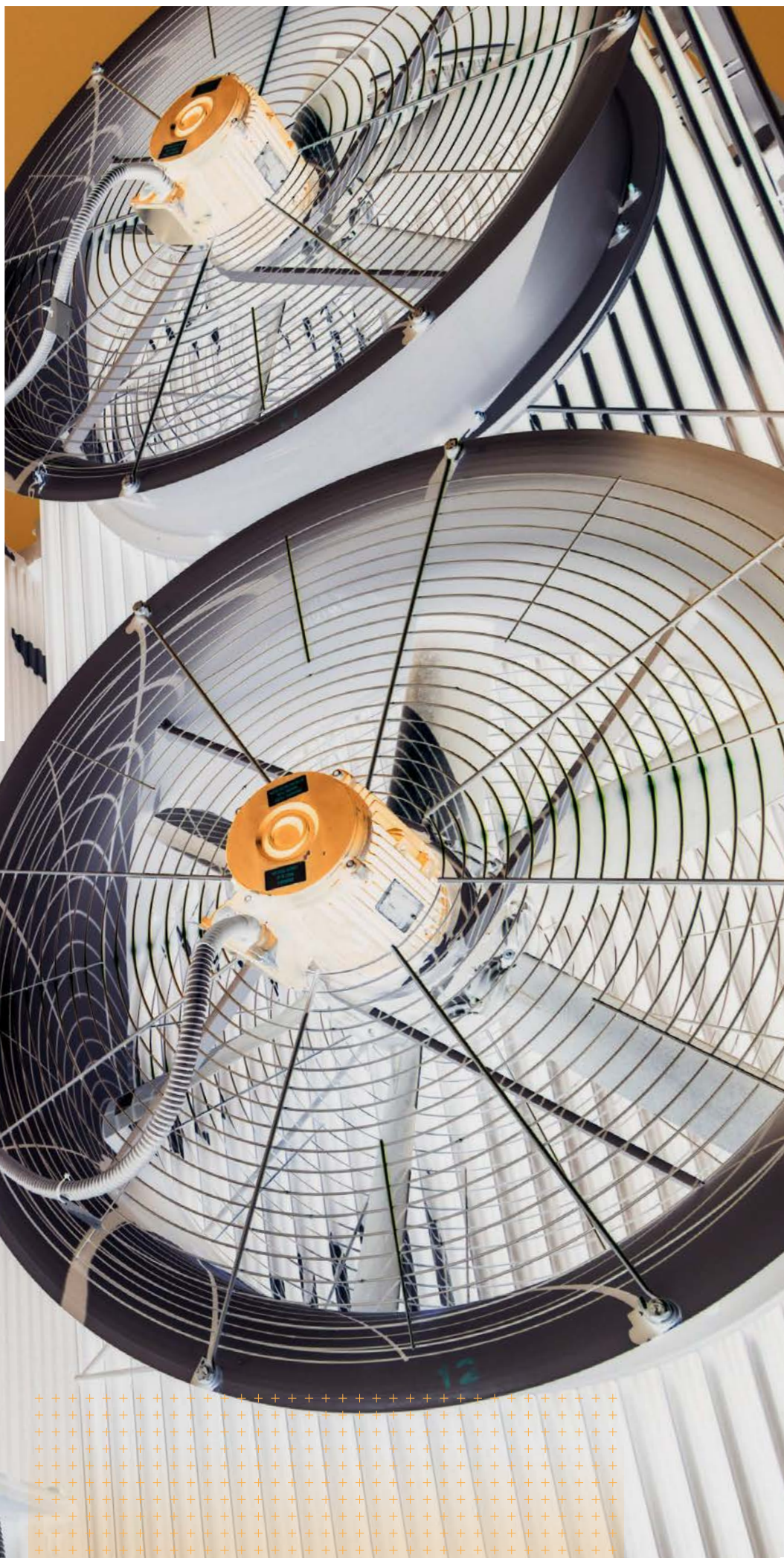
by **Kevin Riley**

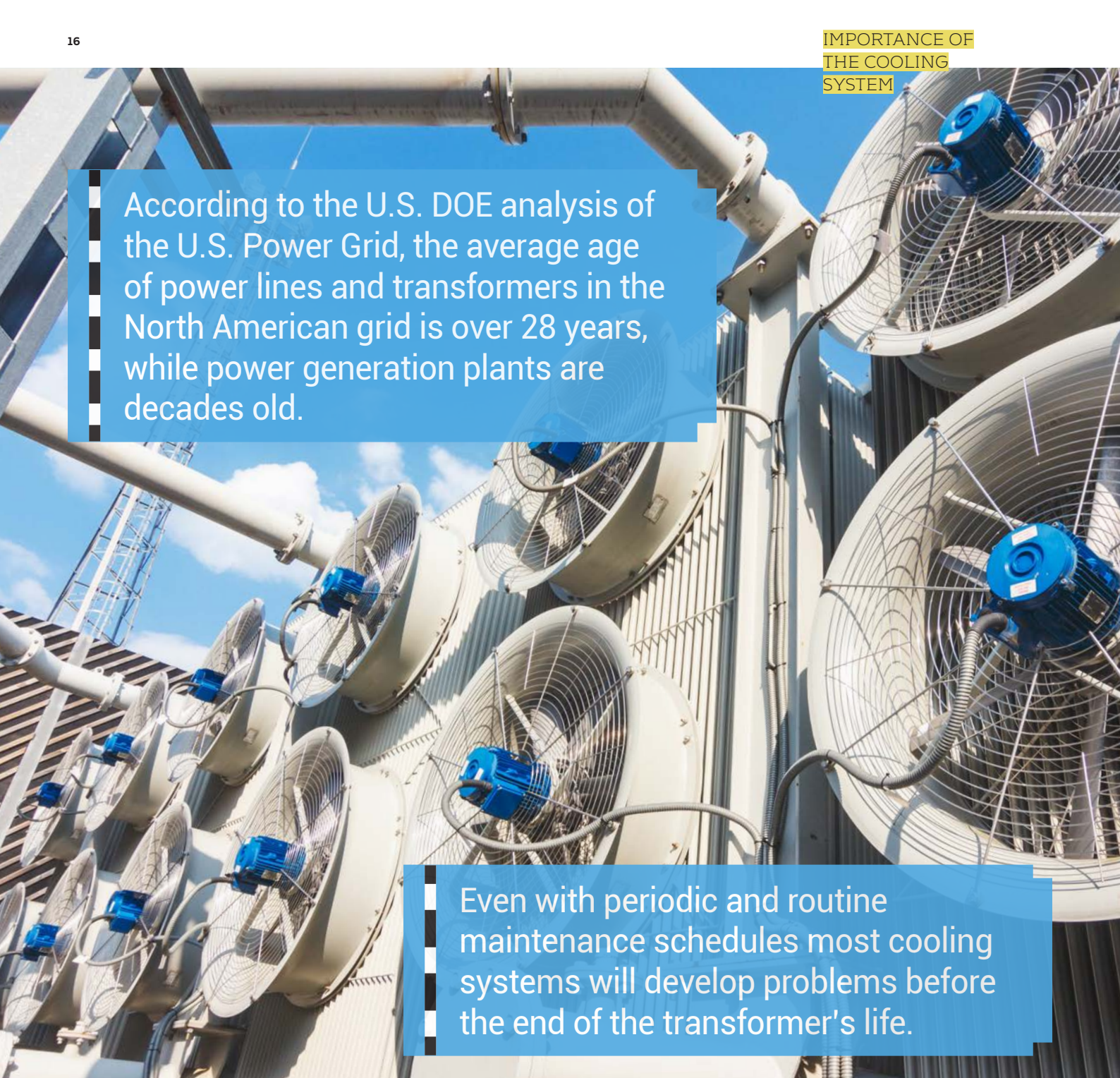
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With transformers being a vital component of any electrical grid and maintaining these assets being of the utmost importance, we have to ask ourselves, how well are we managing the critical components of these transformers?



Kevin Riley PE, CSSBB, holds a B.Sc. in Mechanical Engineering. He has been with Trantech Radiator Products for over 12 years and is the Product Development Manager. Kevin has worked in the heat exchanger industry for over 16 years within senior engineering and operations for a diverse range of products. He has also worked with customers for almost 20 years in the fleet, genset and T&D sectors. He currently works on cooling systems development and components with OEM and utility customers for new and replacement applications covering all types of transformers and equipment. Before beginning his career in the private sector with Caterpillar, Kevin served as a Special Warfare officer in the United States Navy where he worked on cooperative projects including VT Halter Marine's Mark V project as well as Northrop Grumman riverine projects.





According to the U.S. DOE analysis of the U.S. Power Grid, the average age of power lines and transformers in the North American grid is over 28 years, while power generation plants are decades old.

Even with periodic and routine maintenance schedules most cooling systems will develop problems before the end of the transformer's life.

Aging Grid

According to the U.S. DOE analysis of the U.S. Power Grid, the average age of power lines and transformers in the North American grid is over 28 years, while power generation plants are decades old [1]. Science News says that "The U.S. power grid in many cases is a 19th century system design operating under the stresses of a 21st century load and climate" [2]. The American Society of Civil Engineers (ASCE) said in its 2017 Infrastructure Report Card, which rated energy infrastructure at a D+, that "most electric transmission and distribution equipment were

constructed in the 1950s and 1960s with a 50-year life expectancy" [3]. With transformers being a vital component of any electrical grid and maintaining these assets being of the utmost importance, we have to ask ourselves, how well are we managing the critical components of these transformers?

Importance of the Transformer Cooling Systems

First, let's talk about cars and trucks. Most people perform routine maintenance on their automobile such as changing oil, air filters and giving it a wash and a rinse every

once in a while. What about your radiator and the cooling system? Most people do not know they have an issue with their cooling system until some type of an indicator alerts them that something is wrong, or they are left stranded on the side of the road with an overheated engine. The same or a similar type of cooling system technology is installed on most power transformers. In too many cases, they receive about the same amount of attention as the car that was left stranded from an overheated engine.

Now, let us talk about why we cool transformers to begin with.

Elevated temperatures accelerate aging of insulation paper. The life of a transformer is measured using the degree of polymerization (DP) of the insulating paper and aging, or the remaining life of a transformer is measured as the inverse of DP. Temperature affects lifetime, and this is given by the Arrhenius equation that shows that the life of a transformer is approximately reduced by 50% with every 8°C rise in temperature. High temperature also accelerates aging of insulating paper in the presence of moisture. The cooling system is one of the most important parts in the normal daily operation of a transformer, and, if it does not operate properly, it will reduce the life of the transformer. Without the cooling system operating properly, loading is limited (due to the fear of loss by overheating, causing irreversible damage to the insulation system paper and oil) and in the worst case, this may lead to the loss of the transformer. In cases of high loading over extended periods, it may become the most critical component for keeping the transformer operating. Even with periodic and routine maintenance schedules most cooling systems will develop problems before the end of the transformer's life.

Reasons for Cooling System Failures

Corrosion is the largest contributor to cooling system failures. Whether it is caused by outside atmospheric or internal anomalies such as high moisture levels, the corrosion process degrades the cooling system at an accelerated rate, compared to the transformer itself. Various forms of corrosion attack cooling systems, such as electrochemical and anaerobic corrosion. It is a known fact that saltwater accelerates corrosion at five times the rate of freshwater. Humid salt air corrodes at ten times the rate of average air at average humidity. Various other chemicals such as sulfides, chlorine and alkaline solutions will also accelerate corrosion. In today's grid, transformers are being moved frequently from one site to another. Some transformer cooling systems that were originally

designed for inland operation and have been moved to a coastal or industrial environment will begin to corrode at accelerated rates. In some cases, end users are misinformed about the ability of hot dip galvanized radiators and cooling products to resist corrosion in many environments, especially when fans are used directly in the

system is designed to cool and what the desired result needs to be for the end user with a new system. Many factors have to be taken into consideration when designing a new system, such as space requirements, current transformer performance, materials and coating requirements, desired cooling vs. load expectations, type of transformer fluid used, as

Corrosion is the largest contributor to cooling system failures.

cooling process. In many cases the corrosion rate is accelerated beyond the galvanic action of "self-healing", therefore allowing corrosion to attack the base substrate of the cooling system materials. The next largest contributor to cooling system failure or underperformance is high heat loads. These loads can be caused by steady temperature rise due to paper depolymerization, or intentionally increased loads on the transformers. Other factors, such as the increase of transformer harmonic with age, UV breakdown of coatings, and blocked or fouled heat exchange surfaces can also affect the efficiency of the cooling system.

Solutions and Options

Cooling system replacements or upgrades are generally transformer specific. In either case, it is essential to understand what the current

well as other details. Often, simply replacing the original equipment may not give the desired outcome needed. This is especially important when dealing with legacy transformers that have been relocated, or are operating at higher loads than historically seen since being placed in service. At times there are easy solutions for upgrading or adding capacity to transformers. Adding fans to an ONAN cooled system will increase cooling capacity while giving the asset owner an ONAN/ONAF cooling system transformer. Understanding the relationship between the heat exchanger design and performance, fan performance, fluid dynamics as well as other inputs such as ambient air and mass flow, are critical. On other occasions, upgrades may be more complicated, for example with directed flow transformers or when pumps are part of the cooling system.

ONAN

(O – liquid with flash point less than 300 degrees C)

(N – Natural Convection internally through cooling equipment and windings – generally means no pumps)

(A – Air)

(N – Externally, natural convection, generally means no fans)

ONAF

(O – liquid with flash point less than 300 degrees C)

(N – Natural Convection internally through cooling equipment and windings – generally means no pumps)

(A – Air)

(F – Externally, Forced Circulation – generally means adding fans)

Often, simply replacing the original equipment may not give the desired outcome needed.

Case Studies

Example 1

In this case, an ONAN transformer was experiencing higher loading than previously seen. This was one of the eight transformers located at various substations within the Kentucky Utilities (KU) network. In an effort to improve cooling capacities for extending life on these network transformers, KU decided to add fan cooling systems to each transformer. The scope was to model and design a fan cooling system including fan control cabinets that would connect to new temperature gauges. The system was modeled along with custom fabricated fan mounts and then installed. Cooling capacity was increased by an estimated 30%+ while making this an ONAN/ONAF method of cooling.

Transformer was retrofitted with a new ONAF cooling system including a fan control box and custom fan holder apparatuses (Figure 1).



Before



After

Figure 1. Cooling system upgrade on an LG&E and KU transformer: Before and after

Example 2

This is a case where manifold cooling systems using tubular radiators have reached their end of useful life. The transformer cooling system had developed leaks in the piping, pumps and tube assemblies. A new cooling package was developed, complete with a redesigned manifold system. After installation of the new cooling package, the customer observed an average of 9°C cooler operating temperatures. This system was installed as part of a complete life extension project for this Westinghouse 100 MVA transformer.

The project was repeated for the sister transformer within the same station (Figure 2).



Before



After

Figure 2. Replacement cooling systems on a Westinghouse 100 MVA transformer: Before and after

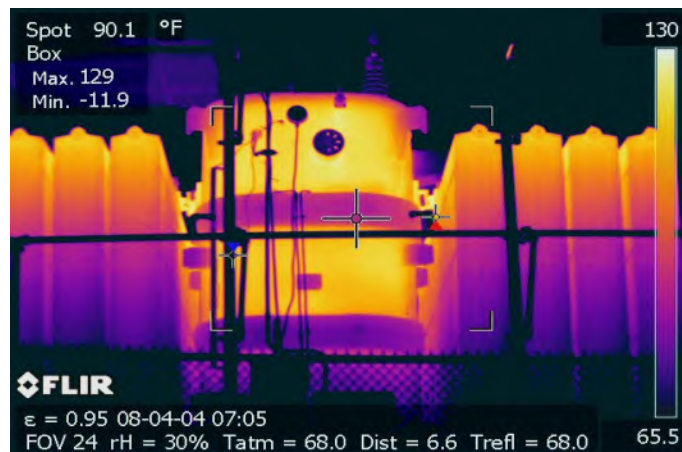
Example 3

In this case, a cooler was replaced with a bank of radiators at a copper mine. Due to the severe dusty environment, the coolers were frequently getting clogged, making the maintenance of the cooling system a nightmare. Again, with the help of the heat run test report, the appropriate size of a replacement radiator cooling system was designed (Figure 3).

At this site, the oil temperature was monitored with high temperature alarms. Prior to installation of the radiator cooling system the high temperature alarm system would trigger frequently but after the replacement there have been no such alarms. Note that the additional blowers were abandoned after the replacement.



Before



After

Figure 3. Replacement cooling system for the mining project: Before and after. Thermal scans after the installation of the new radiator package show improved cooling and operation.

Example 4

Here is another example of a cooling system type change. The key factors in the installation of a replacement cooling system were to:

- Increase cooling capacities to enhance the planned transformer life extension project by 15%
- Design a redundant system to assist in maintenance and provide critical fail-safe coverage
- Design a system in which the center of mass is closer to primary supports to help remediate subsidence.

Basically, the transformer and substation were sinking slightly year over year.

The cooling system was converted from an ON/ONAF/OFAF type to a primary OFAF type with redundancy. The center of mass was improved by 65% allowing the customer to have a system supported by the primary transformer pad rather than the transformer radiators in a cantilevered fashion. The weight of the system was reduced from nearly 30 tons to 5,3 tons (Figure 4).



Before: Original manifold assemblies



After: New fail-safe OFAF cooling system

Figure 4. Cooling system type change: Before and after

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FAQ

ABOUT GEOMAGNETIC INDUCED CURRENT

1

CME is ejected from the sun and carried by solar winds.

What causes Geomagnetic Induced Current (GIC)?

What are Geomagnetic Induced Currents (GICs)?

There are two kinds of solar activity that have the potential to disrupt our lives on earth: solar flares and coronal mass ejections (CMEs). Solar flares primarily impact communication and navigation systems while CMEs can impact the transmission grid.

Geomagnetic Induced Current (GIC) is the result of CMEs from the sun which interact with the earth's magnetosphere through a process called electromagnetic induction, resulting in rapidly changing magnetic fields as the magnetic particles move across the earth's surface.

Where do Geomagnetic Disturbances (GMD) occur?

- GMD events are just as likely to occur in the southern hemisphere as the northern hemisphere.
- Industry studies have identified that locations with latitudes above 45-50 degrees may be susceptible to GMD events.
- The probability of a GMD event increases based on the sunspot count, but GMD events can occur at any time during the solar cycle.

To better evaluate whether your transformers are at risk, read through the NERC standard TPL-007.

What is the effect of GIC on transformers?

The flow of GIC in transformers is the root cause of all GMD related power system problems:

- The magnitude of the GIC current and the associated DC offset is superimposed on the excitation current which forces the transformer into part cycle saturation.
- GIC can result in increased reactive power requirements and large harmonic currents during GMD events.
- The harmonics can result in tripping of VAR compensation devices at times when additional VARS are needed, most resulting in system disturbances and instability. Large GMD events are often associated with a variety system alarms.

2

Magnetic particles distributed across the Earth's surface cause a rapidly changing magnetic field.

3

The magnetic field interacts with the Earth's conductivity, resulting in ground voltage differences.

4

The flow of GIC is seen across transmission lines.



Are there any standards in place relating to GIC?

The increase in awareness of geomagnetic disturbance events has led to the creation of new standards in the U.S. including FERC order 830 which resulted in the creation of NERC standard TPL-007.

The standard establishes guidelines on planning for geomagnetic disturbances.

All transmission owners and generator owners with grounded wye connected transformers, operating with a high side voltage of 200 kV or greater, are subject to the requirements of TPL-007. The standard requires owners to perform an assessment of their assets and collect GIC data to validate system modelling of GIC flow during GMDs.

How do I monitor for GIC?

Geomagnetic Induced Current Sensors installed on the transformer neutral conductor have the following benefits:

- Split core design allows easy installation.
- Range of the sensor can be easily adjusted.
- Hall effect sensor provides excellent response time and is linear over the entire operating range.

Measure Harmonics and VAR loading with the E3 Transformer Monitor to:

- Measure and calculate current wave-form harmonics.
- Measure the DC offset in the current waveform during through faults and system disturbances.
- Measure the VAR requirements of the transformer.
- The monitor operates with the latest industry standards.



Learn more about Dynamic Ratings monitoring options at <https://dynamicratings.co/3mDhnFj>.

It Isn't Rocket Science. Well, Actually...

by **Laura Vandiver**

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It may not be actual rocket science, but proper transformer cooling is imperative and can become quite complicated, especially when dealing with transformer overheating and the thermal conditions surrounding it. Also, various cooling system designs and configurations, some of which have been discontinued or are in a dilapidated operating state, have further complicated things.



Laura L. Vandiver began her career in the energy sector with Advanced Power Systems in 2006 as an agent representing brands like Cooper Lighting Solutions, Cooper Power Systems (now Eaton's Cooper Power Systems), Salisbury, QEI, GE-ITI, and Digital, Federal Pacific, Huskie Tools, Nordic Fiberglass, and BMC in the Caribbean and Latin American markets. In 2010 she transferred to Paradox Corporation to help spearhead a new transformer cooling fan initiative. In 2014, Laura transitioned into a Business Development Manager position for the U.S. and Canadian territories. Today she continues her work to provide transformer cooling solutions and packages to utilities, industrials, service companies, repair shops, and transformer manufacturers worldwide.



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Many transformers currently in service were built with an over-capacity rating capability but are now more than 50 years old and operating past their intended service life.

Many transformers currently in service were built with an over-capacity rating capability but are now more than 50 years old and operating past their intended service life.

With an aging transformer fleet coupled with increased loads due to economic growth and advancement, routine maintenance and attention to the transformer's cooling system are critical. It is instrumental to extending the transformer's overall life and safety.

Excess transformer loading in liquid-filled transformers, which generates heat, can lead to avoidable catastrophic events like fire, unplanned outages and unnecessary aging of the asset. Though fire is rare in a properly maintained, inspected, and tested transformer; if catastrophe does strike, it is not only a safety issue but impacts the environment, and can tarnish the reputation of the utility, given that HSE (Health, Safety and Environment) issues are tremendously important for utilities of all sizes, from generation to distribution.

Many utility and maintenance managers consider cooling system upgrades to increase the load capacity in their liquid-filled transformers. And with capital funds and projects delayed due to the pandemic, reliability managers choose to add or replace existing cooling packages as a possible cost-effective solution if buying a new transformer is not an option [1].

It is always recommended to assess the overall thermal condition of the transformer, consult the original transformer manufacturer for the required cooling capacity and load information, and never overload the transformer, beyond the OEM rating. After proper inspection and testing of the transformer to determine the current condition, adding or upgrading existing transformer cooling fans to the radiator may prove to be a cost-effective solution to increase capacity. Along with that, transformer cooling fans tend to start to fail around the same time, so it may be beneficial to replace all fans once they start going out instead of only one at a time.



- Many utility and maintenance managers consider cooling system upgrades to increase the load capacity in their liquid-filled transformers.



Figure 1. Old and new transformer cooling fan

Types of Cooling

Transformer cooling is achieved in several ways.

Dry Type Transformer:

- AA:** Ventilated self-cooled
- AFA:** Ventilated forced air-cooled
- AA/FA:** Ventilated self-cooled forced air-cooled
- ANV:** Nonventilated self-cooled
- GA:** Sealed self-cooled

Liquid Filled Transformer:

First Letter – Insulating Medium

- O:** Mineral oil or synthetic insulating liquid with fire point of 300°C
- K:** Insulating liquid with fire point >300°C
- L:** Insulating liquid with no measurable fire point

Second Letter – Internal Cooling Medium

- N:** Natural circulation
- F:** Forced circulation
- D:** Forced directed circulation

Third Letter – External Cooling Medium

- A:** Air
- W:** Water

Fourth Letter – Circulating Method for External Cooling Medium

- N:** Natural circulation
- F:** Forced circulation

The code nomenclature for liquid filled transformers changed after the year 2000, moving from a two-letter code to a four-letter code to better articulate the cooling. Considering the classifications listed above, we will move forward speaking only about liquid-filled transformers with forced-air cooling using fans [2].

Transformer Cooling Fan Options

Another factor to consider when upgrading a transformer cooling fan package is what kind of cooling fan to choose. Many different types and manufacturers of cooling fans are available in the marketplace right now, ranging in price, performance, and durability. A key aspect to consider would be the environmental conditions in which the transformer cooling fan is exposed. For instance, a fan with non-corrosive characteristics would be well suited for wetter, more humid areas that experience accelerated weathering.

There are a couple of different types of transformer cooling fan designs. One would be a circulator type fan with a basket style cage, and another would be an axial style fan, sometimes referred to as a venturi

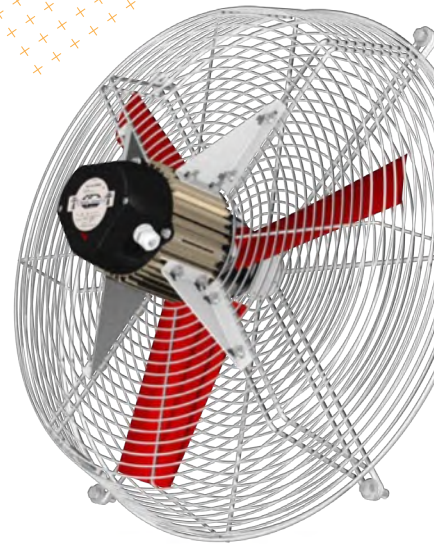


Figure 2a. Circulator Type



Figure 2b. Venturi Type

style fan with a tube or duct around the motor and impeller. Depending on the transformer design, both fans can be mounted on the side, top, or bottom of the radiator.

Another consideration would be the mounting configuration. There are three typical positions in which to mount cooling fans on the transformer. The most common mounting configurations are on the side of the radiator (horizontal airflow) and the bottom of the radiator (vertical airflow). Still, fans may also be mounted on the top of the radiator.

Choosing a Transformer Cooling Fan

Choosing a transformer cooling fan can be further complicated because it is hard to know the transformer's airflow requirement and the cooling capacity of the existing fan. It is always recommended to refer to the original transformer manufacturer to determine the required cooling, where the original transformer documents may hold some insight. Also, as noted earlier, it is recommended to inspect and test the transformer to determine the current condition.

Another factor that may complicate choosing an adequate cooling package is there is no transformer industry standard for measuring airflow. There are various ways to measure airflow in a fan. According to the Air Movement and Control Association (AMCA), the methods differ according to which type of fan you are testing. For instance, AMCA recommends using the AMCA 230

method to test circulator type fans as it measures for thrust, which is different from the testing method for a venturi style fan. At this time, each cooling fan manufacturer has its way of determining airflow, so it is hard to compare.

One way to find a comparable option is to match the transformer cooling fan's nameplate data and size as closely as possible. Some transformer cooling fan manufacturers have selection tools on their websites to help with this process. For instance, some of the information can be matched from the existing fan label. Although, please note, the existing fan nameplate may only reflect the performance data for the motor and not the entire fan.



Figure 4. Existing fan nameplate to replace

Absence of transformer industry standard for measuring airflow is another factor that may complicate choosing an adequate cooling package.



Figure 3a. Side mount airflow configuration



Figure 3b. Side mount fan tree configuration



Figure 3c. Bottom mount airflow configuration



Figure 3d. Bottom mount venturi configuration



Figure 3e. Top mount airflow configuration

Mounting Bracket Configurations

Another complicated aspect of replacing and upgrading a transformer cooling fan package is matching the mounting configurations. The transformer cooling fan cage's outer diameter and mounting footprint are essential when replacing or upgrading a cooling fan project. Once the footprint is set, a flush mounting kit, which generally consists of a threaded rod and brackets that affix in between the radiator fins and panels, can be used for side mount applications.



Figure 5a. Fan footprint



Figure 5b. Threaded rod

Some other side mount applications for transformer cooling fans include using a fan tree, baseplate mount, stand-off mount, and yoke mount. The latter three mount from the motor instead of the fan cage like the flush mount and fan tree mentioned earlier.

For bottom mount applications underneath the radiator, a header mount, j-bolt, or Unistrut kit can be used. The bottom mount applications typically mount from the cage but occasionally mount from the motor with a stand-off mount application.



Figure 6. Unistrut bottom mount configuration

Transformer Cooling Fan Cord Selection

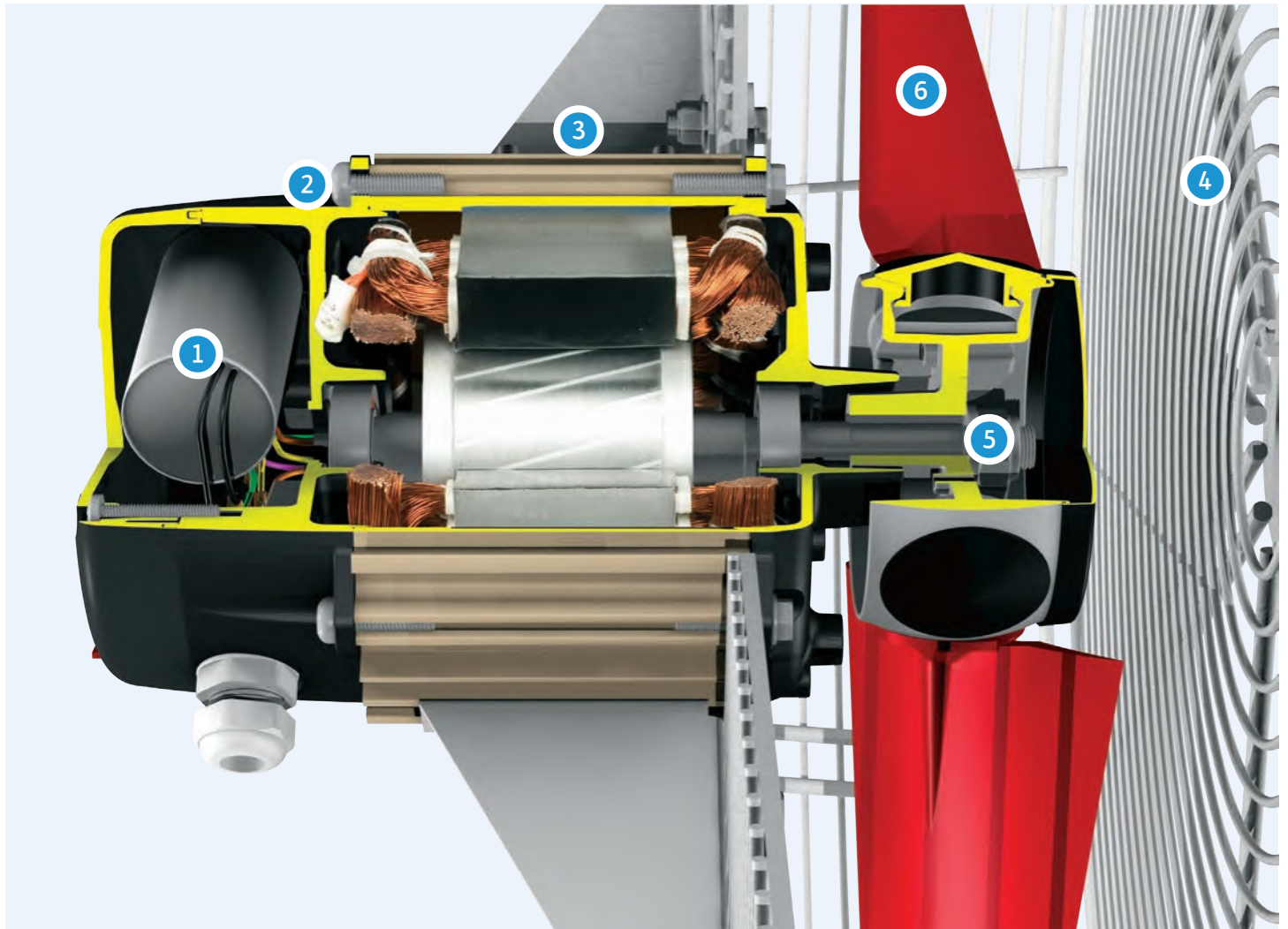
Upon choosing the perfect fan with the appropriate cooling characteristics, you will also need to select a power cable. There are a few different types of cords, for instance, quick disconnect (male and female connections) and hardwired. The quick disconnect cords typically come in lengths of 6 and 12 feet and are a plug and play application. A portion of the cord comes with either a male or female connector, and then there is a shorter cord often referred to as a "pigtail" or "whip" with the receiving connector. Usually, the female receiving connector is placed on the live side of the transformer instead of the male end. These connections offer a plug and play application as opposed to the hardwired. Some manufacturers offer these cords in a set, and some sell them separately, so make sure to verify before ordering. The hardwired cords usually come in lengths of 6, 8, and 12 feet as well but are easily customized. This cord is hardwired at the transformer cooling fan and then into the transformer side as well.

Summary

As stated earlier, transformer cooling may not be actual rocket science, but it certainly does feel like it sometimes. One notion remains constant; that aging transformer fleets with increased loads due to economic growth and advancement will require routine maintenance and attention to the transformer's cooling system, as mission critical. Choosing whether to upgrade and which cooling package is the most cost-effective and safe solution can be complicated. While the configurations can be taxing, there are professionals in the industry with years of experience in cooling and transformer manufacturing available to help assist in selecting the proper cooling system.

References

- [1] 1. Transformer Cooling System Improvements: Analysis and Recommendations, EPRI, Palo Alto, CA, 2005, 1010585
- [2] Power Transformers, A. (Ed.), "Types of Transformer Cooling," retrieved January 19, 2021, from <https://voltage-disturbance.com/power-engineering/types-of-transformer-cooling/>



- 1 Heavy Duty Class European Manufactured Capacitor
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Liquid-cooled transformers are ideal for handling high loads and are in growing demand to support the modernization of the power grid around the world. These liquid-cooled transformers are typically used for power generation, transmission and distribution applications and axial fans are an essential component for managing the thermal load. The airflow profile of an axial fan is ideal for dissipating waste heat to prevent damage associated with overheating and to ensure safe operation of these power transformers.

As an industry leader in ventilation and drive engineering, ebm-papst Inc. manufactures axial fans with either AC motors or innovative, highly efficient, Green Tech EC (electronically commutated) motors for demanding liquid-cooled transformers. The fans are reliable, quiet and energy-efficient. They are available as a complete solution including industry-leading HyBlade® impellers, innovative motors, grill guards, and venturi housings which further improve airflow performance. The fans can be mounted either horizontally or vertically, addressing customer-specific requirements with the level of quality and dependability customers have come to expect from ebm-papst.

AC Technology

Part of what makes ebm-papst fans unique is they are a complete packaged solution. They offer a portfolio of AC fans that serve as a drop-in replacement for existing transformer designs. Diameters range from 500 mm to 1,250 mm and are plug-and-play ready as a package.

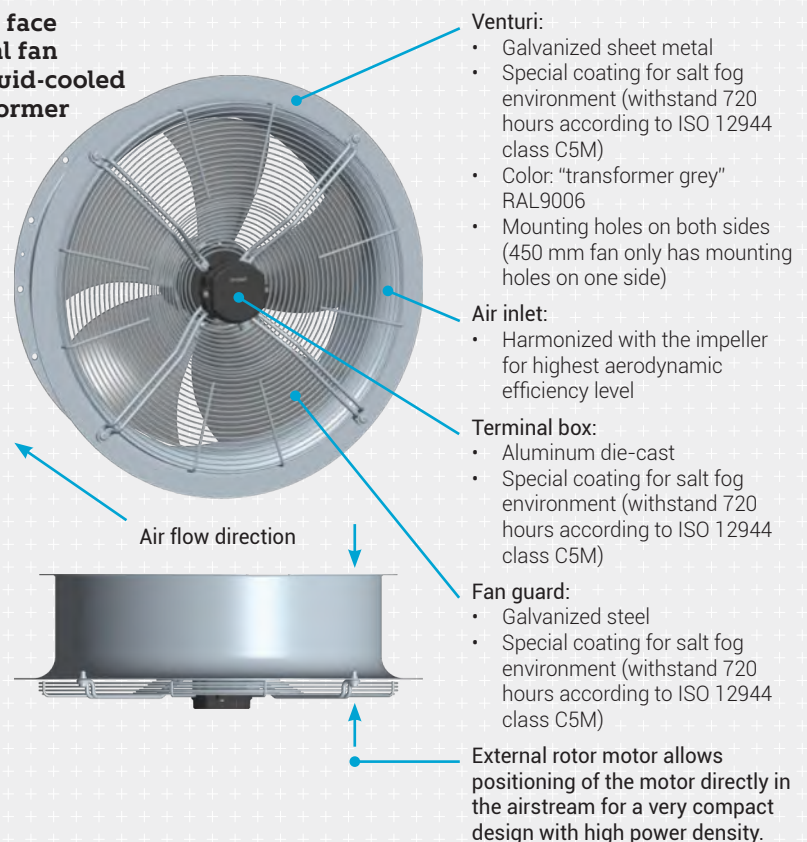
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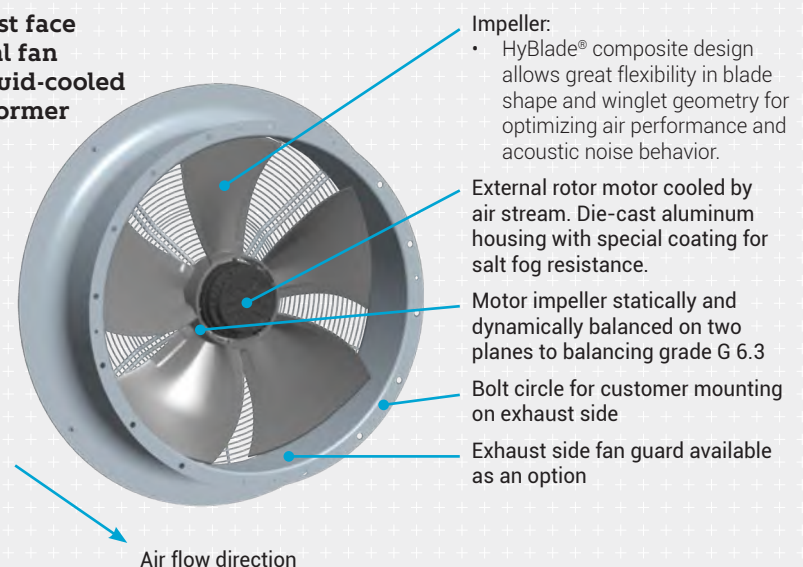
Axial fans mounted for vertical airflow on liquid-cooled transformers

ebm-papst's AC and high-performance Green Tech EC axial fans are complete, packaged solutions that satisfy the requirements of high-power, liquid-cooled transformers.

Intake face of axial fan for liquid-cooled transformer



Exhaust face of axial fan for liquid-cooled transformer



HyBlade® Impellers

HyBlade® impellers provide for weight reduction, noise reduction and significantly improve fan efficiency. They feature a strong aluminum core with an external sheath of fiberglass-reinforced plastic with a profiled blade geometry and winglets. The aerodynamically optimized plastic blade shape provides performance and noise benefits, while the corrosion-resistant aluminum core ensures a permanent connection with the rotor. The fan blades are UV-resistant, lightweight and built to last.

Balancing Quality

To prolong the life of the fan while ensuring consistency and reproducibility, ebm-papst dynamically balances its fans in two planes to quality grade level G 6.3 according to DIN ISO 1940.

The company's standard balance quality grade, G 6.3, allows for a vibration velocity of no more than 6.3 mm per second, which meets industry requirements for industrial fans, flywheels and aircraft gas turbine rotors. Should a higher balancing quality level be required, ebm-papst can dynamically balance fans to suit the needs of specific applications by request.

ebm-papst's EC motors operate well above efficiency requirements of super premium efficiency (IE4) motors, and they carry certifications for worldwide use.

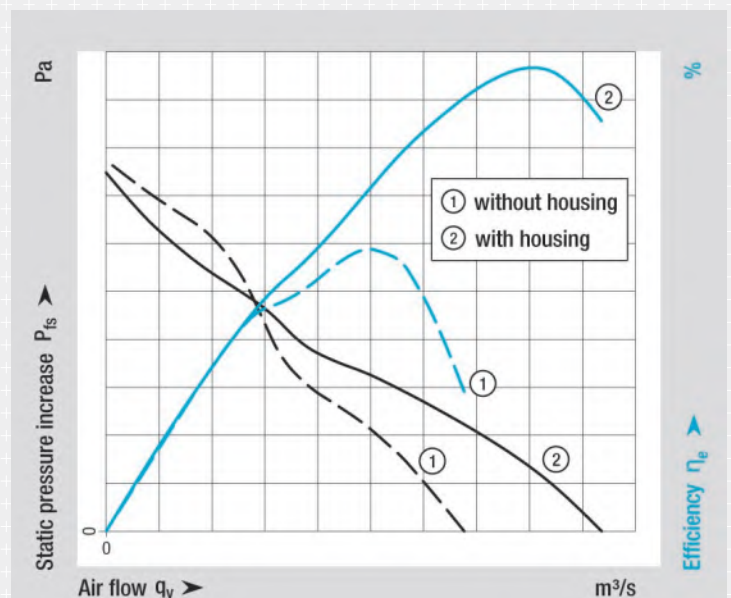
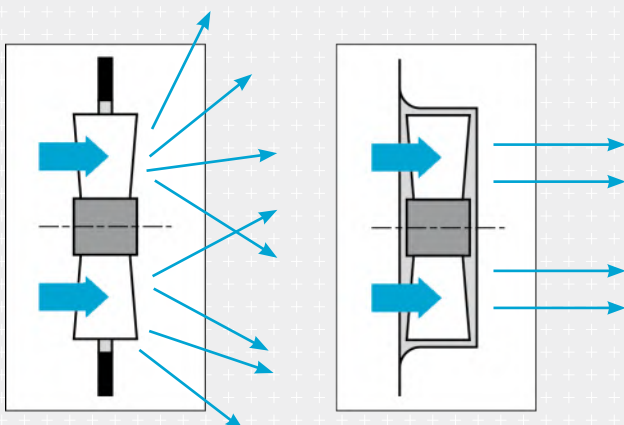
Venturi Housing

The rugged housing design consists of hot-dip galvanized sheet steel with a durable coating that is resistant to salt spray as per DIN EN ISO 12944, class C5M (color RAL 9006: transformer grey). The overall design has an IP55 rating for top protection against low-pressure water jets and dust. The housing also features an integrated venturi nozzle on the intake that improves airflow performance.

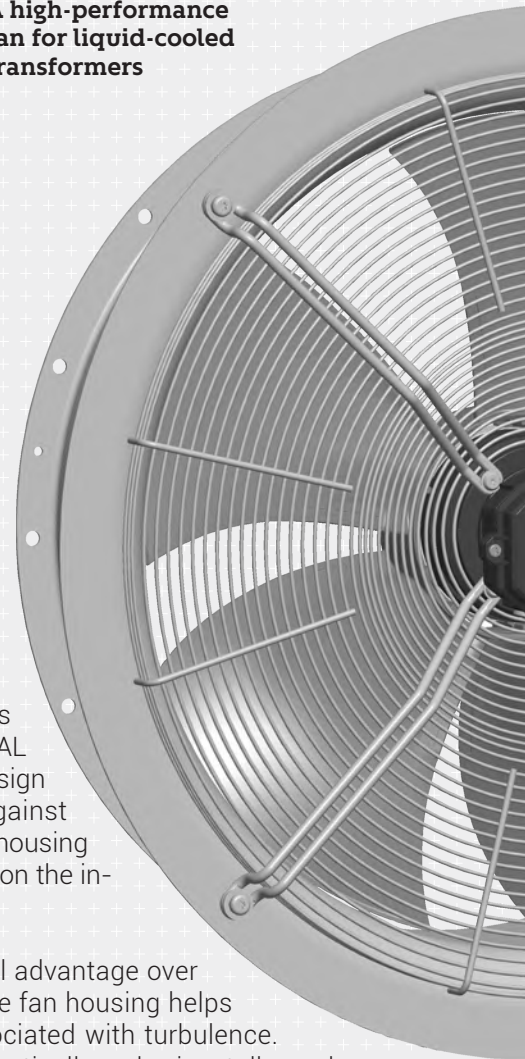
The venturi housing provides for a crucial advantage over fans operated with only a basket grill. The fan housing helps by reducing air performance losses associated with turbulence. The housed fans can also be installed vertically or horizontally, and may be mounted by either the intake or outlet side of the housing depending on the desired airflow direction. The fan housing also provides for easy handling and storage during transport.

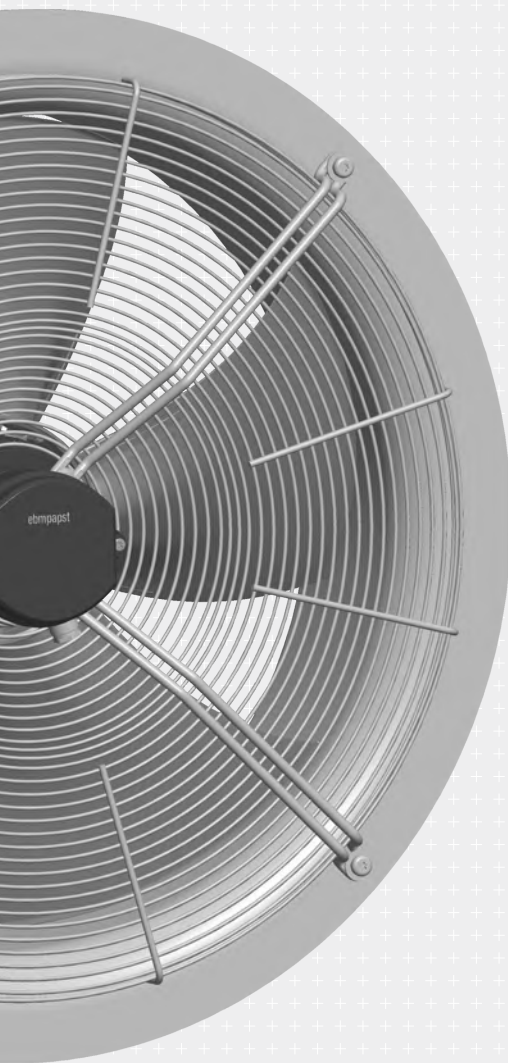
Installing the axial fans in a housing is a perfect way to significantly increase air performance.

The venturi housing improves air performance and increases system efficiency



A high-performance fan for liquid-cooled transformers





Green Tech EC Technology

In addition to traditional AC induction motor technology, ebm-papst offers highly efficient Green Tech EC motor technology, which addresses a gap in the liquid-cooled transformer market.

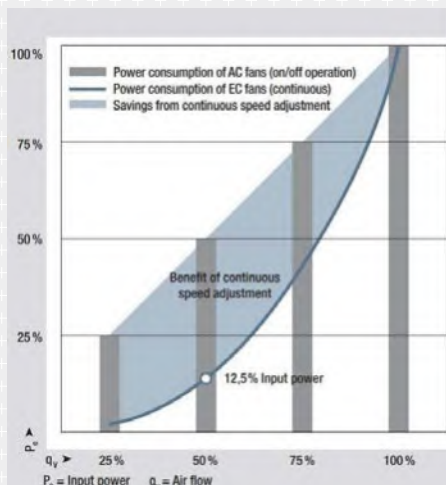
Green Tech EC motors are grid-powered, permanent magnet, synchronous motors with electronic commutation that are similar to brushless DC electric motors. An integrated electronics unit performs power conversion/inversion with frequency and amplitude modulation to provide precise adjustable speed control.

The EC fans are optimized for partial-load operation down to 10% of their rated speed. Continuously adjustable speed control is possible via open loop control using a 0 to 10 V DC analog input, pulse-width modulation (PWM) or Modbus RTU serial protocol.

ebm-papst Inc. transformer fans also feature external rotor motors, where the spinning rotor with permanent magnets is on the outside of the stator and coils. A fan using an external rotor motor with standard ferrite magnets can attain higher torques and levels of efficiency in a shorter package than an internal rotor motor of greater length using rare-earth magnets. The ability to attach the impeller directly to the rotor of the external rotor motor results in this space savings and allows the entire rotating assembly to be balanced in a single procedure.

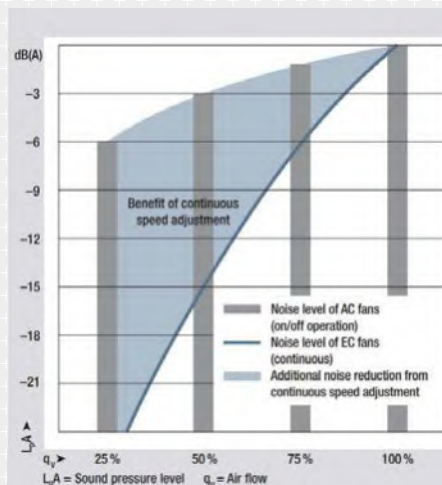
The EC motors operate well above efficiency requirements of super premium efficiency (IE4) motors. They carry certifications for worldwide use (e.g., UL, CSA, Eurasian Conformity, China Compulsory Certificate). Power supply requirements are 380 to 480 V AC, 50/60 Hz. ebm-papst Green Tech EC axial fans are universally deployable with simple commissioning. They are a dependable forced air cooling solution with air performance of up to 27,500 cfm.

Possible energy savings and noise reduction with continuous speed adjustment in part load operation



Reduced energy consumption

The bars show the power consumption of fans that are switched on stepwise as needed. Air performance is reduced by 50% when half of the fans are switched off. The blue line shows the power consumption of all fans with smooth speed adjustment at the required air flow (50% air flow = only 12.5% input power).



Lower noise generation

While switching off half the fans (50% decrease in air flow) only reduces noise generation by approx. 3 dB, a speed reduction resulting in 50% less air flow achieves an improvement of 15 dB.

Energy Savings and Noise Reduction

Transformers are increasingly used near residential areas, where strict requirements related to noise must be met. During peak demand times, all fans must typically run at rated speed to handle the thermal load of transformers working at full power. During off-peak times when cooling requirements drop, systems using conventional AC induction fans traditionally switch some of them off.

The fans which are still running continue to work at full power; this is not ideal for overall system efficiency or lifetime. This is where EC technology has a significant advantage.

Green Tech EC fans provide the more effective option of keeping all fans in operation at reduced speed while maintaining a high motor efficiency — even down to a fraction of the rated speed. Keeping all fans running results in a more uniform air flow through a transformer's radiators while still providing both a larger power reduction and a larger noise reduction than is achieved by on/off fan operation. Transformer hot spots created where fans are turned off are eliminated. Overall, it is a more economical system of operation that results in improved transformer and fan service life. The diagrams below illustrate the potential energy savings and noise reduction in comparison to on/off operation.

An added benefit to using an EC speed controllable fan is that fan selection may be made with the intention of having an air flow reserve should cooling demand exceed typical peak requirements (transformer overload) or to compensate for a failed fan. To avoid wasting power, the fans may be set below their rated speed during normal operation and only boosted to maximum speed for these atypical situations.

Rugged Design

ebm-papst fans have a long service life and are suitable for deployment in high salinity coastal areas. The incorporation of a hot-dip galvanized sheet-steel housing with a salt-spray resistant coating, UV-resistant composite blades and an extremely durable motor with an IP 55 rating provides for an extended service life even when subjected to harsh environments.

Liquid-Filled Transformer Market Requirements

Global Market Insights Inc. reports that the liquid-filled transformer market was valued over \$33 billion in 2017 and is set to witness the annual installation

of 600,000 units, with the anticipated market size to exceed \$45 billion by 2024. The adoption of distributed and renewable energy networks along with the subsequent upgrading of existing power networks will drive market value, while non-remote residential installations will force manufacturers to address noise requirements.

Conclusion

ebm-papst's AC and high-performance Green Tech EC axial fans are complete, packaged solutions that satisfy the requirements of high-power, liquid-cooled transformers. Innovative EC technology addresses a gap in the market place, fulfilling a need for noise reduction, extended service life and efficiency gains, while their AC fans are a drop-in replacement for existing transformer designs. ebm-papst can also devise customized solutions.



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ABOUT EBM PAPST INC.

ebm-papst is an innovator and market leader in ventilation and drive engineering technology. Our core competencies in motor technology, aerodynamics, and electronics make ebm-papst a much sought-after engineering partner in many industries. With around 20,000 products, we provide solutions to a wide range of markets including Air-conditioning and Ventilation, Appliance, Automotive, Commercial Refrigeration, Heating, Industrial, IT/Telecom, Lighting, Medical, Transportation and more. We have placed the highest emphasis on economy and ecology for many years. We believe the consistent further development of our highly-efficient GreenTech EC technology provides our customers with the best opportunities for the future in industrial digitization. With GreenIntelligence, ebm-papst already offers intelligent networked complete solutions that are unique anywhere in the world today and that secure our customers a decisive advantage.



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The Power of Coatings – Keeping the World Connected

by **Maria Lamorey**

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Many of us take electricity for granted. While we dread its absence during a power outage, most of us do not realize that there is performance-critical electrical equipment—typically fabricated from a variety of metals—that must withstand years of challenging outdoor conditions to support the flow, supply, and management of electricity. Transformers that have weak coating systems lead to failure, resulting in power outages. With many of us working from home, it is even more critical that we be able to charge our devices and computers so that we can stay connected to our jobs and families.

Current designs of transformers that are built today date back some 20 years and the coating specification could also be that old. This equipment has outdoor life expectancies that range from 25 to 30 years, with some lasting close to 50 years in extreme conditions and operating environments. The design emphasis for transformers is typically focused on protecting its sensitive instrumentation, controls, and operation. Few consider how critical it is to protect the metals that house these vital components and ensure their reliability.

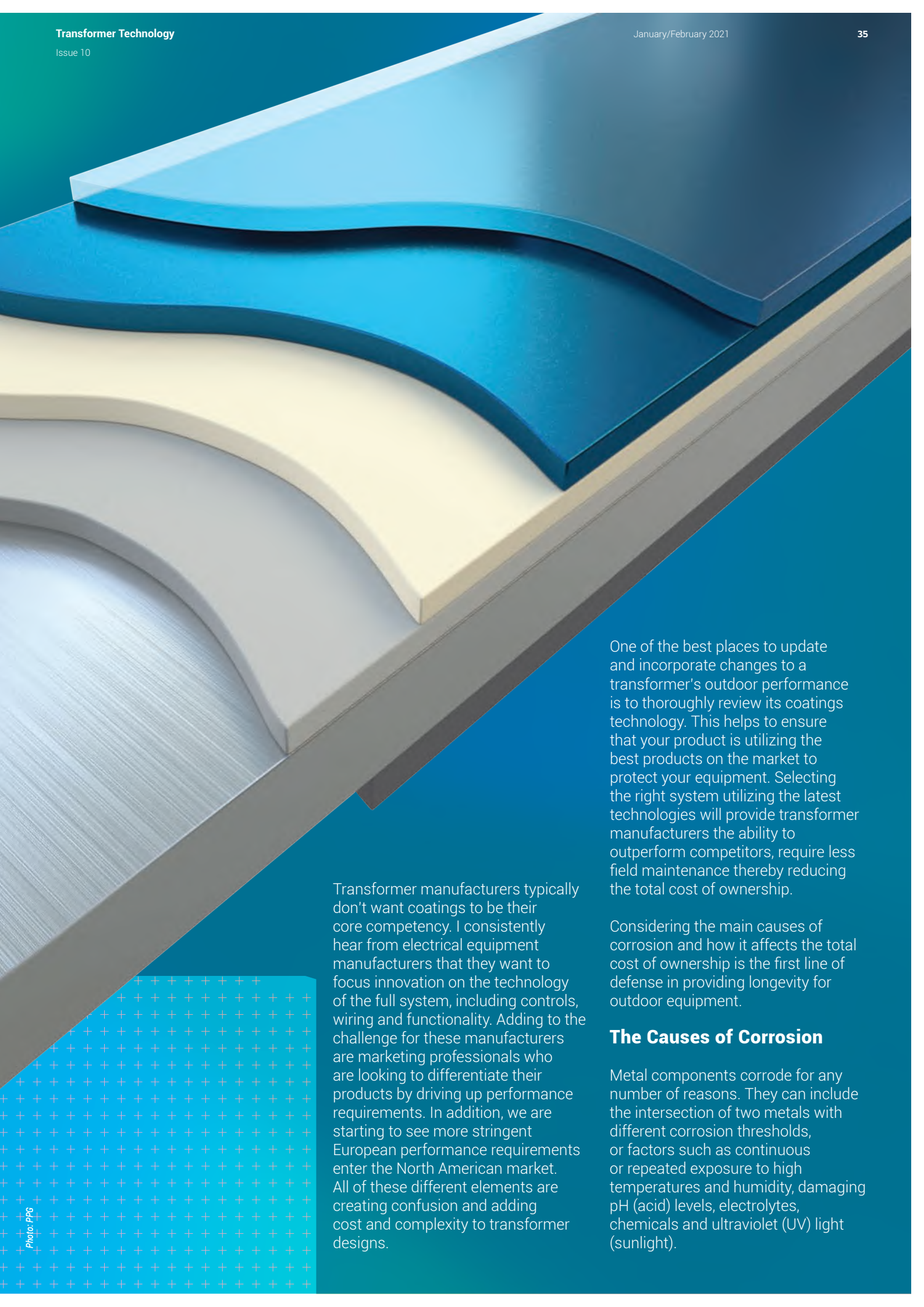
Unfortunately, when it comes to painting and protecting new equipment, many manufacturers combine old “cut-and-paste” paint specifications that date back 20 to 30 years with industry-standard regulatory requirements written by IEEE, UL, CSA, and ASTM.

In other cases, equipment manufacturers write their paint specs based solely on achieving a minimum industry standard or according to a specification written by their paint supplier. Paint manufacturers can further contribute to the problem by designing coatings systems that merely meet old specifications or achieve industry standards dictated by customers instead of featuring the latest technologies to provide better field performance.



Maria Lamorey is the PPG Commercial Manager for General Finishes. She has 20 years of experience in Industrial OEM Manufacturing. Prior to joining PPG, she worked with Alcoa for 8 years, transitioning into the electrical equipment industry, where she acquired a decade of experience while also becoming a certified instructor for a nationally PDH accredited course on material science in electrical equipment design. Maria has an MBA from the University of Pittsburgh and is an active member of the IEEE Transformers Committee and NEMA (National Electrical Manufacturers Association). She has been recognized for her growth in the electrical equipment market by the University of Pittsburgh Institute for Entrepreneurial Excellence, among others.

The design emphasis for transformers is typically focused on protecting its sensitive instrumentation, controls, and operation. Few consider how critical it is to protect the metals that house these vital components and ensure their reliability.



One of the best places to update and incorporate changes to a transformer's outdoor performance is to thoroughly review its coatings technology. This helps to ensure that your product is utilizing the best products on the market to protect your equipment. Selecting the right system utilizing the latest technologies will provide transformer manufacturers the ability to outperform competitors, require less field maintenance thereby reducing the total cost of ownership.

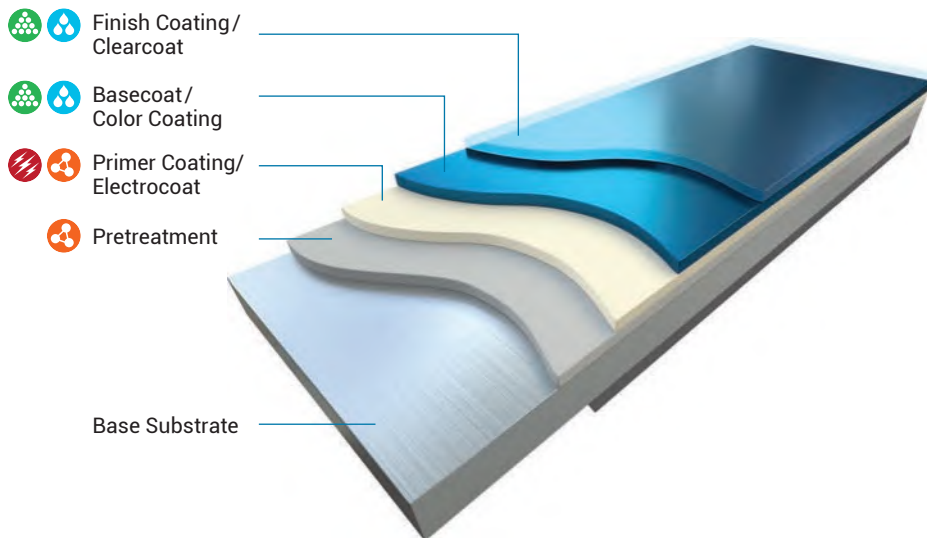
Considering the main causes of corrosion and how it affects the total cost of ownership is the first line of defense in providing longevity for outdoor equipment.

The Causes of Corrosion

Metal components corrode for any number of reasons. They can include the intersection of two metals with different corrosion thresholds, or factors such as continuous or repeated exposure to high temperatures and humidity, damaging pH (acid) levels, electrolytes, chemicals and ultraviolet (UV) light (sunlight).

Transformer manufacturers typically don't want coatings to be their core competency. I consistently hear from electrical equipment manufacturers that they want to focus innovation on the technology of the full system, including controls, wiring and functionality. Adding to the challenge for these manufacturers are marketing professionals who are looking to differentiate their products by driving up performance requirements. In addition, we are starting to see more stringent European performance requirements enter the North American market. All of these different elements are creating confusion and adding cost and complexity to transformer designs.

Multi-Stage Coating System



Considering the main causes of corrosion and how it affects the total cost of ownership is the first line of defense in providing longevity for outdoor equipment.

Building a great paint specification is critical to ensuring that electrical equipment manufacturers are capitalizing on the latest technology available to maximize the service life of their products.

The most effective way to select the right coatings for metal electrical equipment is a total system approach that considers and accounts for the following variables:

1. The composition of the metal substrate (cold-rolled steel, hot-rolled steel, stainless steel, galvanized metal, mixed-metal, etc.)
2. The types of lubricants and coolants used to fabricate the equipment
3. The materials selected to pretreat the metal substrate (zinc-, iron- or zirconium-based pretreatments)
4. The type of finish coat, including film build (coating thickness) and cure (baking time and temperature) requirements

Design Considerations

Another important criterion for selecting the right coating chemistry is the design of the finished part. For instance, components with sharp corners, recessed areas or intricate shapes can be finished with coatings that are formulated with high transfer

efficiencies. These specialized coatings are engineered specifically to maximize coverage on these types of parts.

Coatings manufacturers offer a variety of resin chemistries to improve resistance to corrosion and UV exposure, including epoxies, polyesters, urethanes and acrylics, as well as hybrid coatings, which incorporate a combination of resin chemistries. Each have their strengths and weaknesses.

For instance, epoxies are ideal for chemical resistance and mechanical properties, but are lacking in UV resistance and weatherability. Polyesters, urethanes and acrylics all offer exceptional weathering characteristics, but each offers a different benefit, such as great physical properties for polyesters; chip, scuff and mar resistance for urethanes; and superior surface appearance for acrylics.

Typical solutions for electrical equipment manufacturers include two-coat systems featuring a primer coat for corrosion protection and topcoat for

color, appearance and UV resistance. Other popular options include one-coat hybrid systems that combine a mixture of resin chemistries to provide an optimal balance of corrosion protection and UV resistance.

The Building Blocks of a Paint Specification

Building a great paint specification is critical to ensuring that electrical equipment manufacturers are capitalizing on the latest technology available to maximize the service life of their products.

If the goal of an electrical equipment manufacturer is to build next-generation components that exceed performance mandates, while protecting their brand reputation, paint specifications should be reviewed and updated regularly to ensure that they address the following criteria:

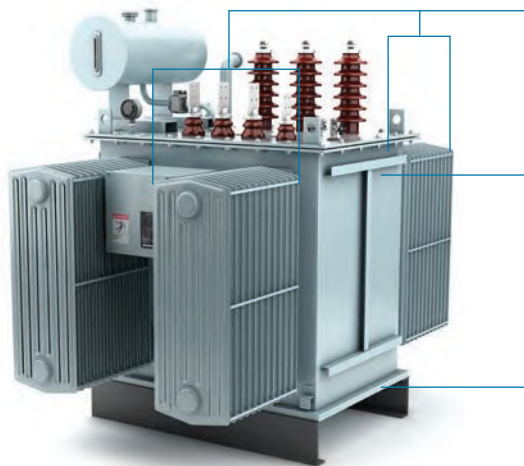
- **Scope of the product** – This section defines the products covered.
- **Substrate type** – This section details all the metals and non-

metal substrates incorporated into an electrical component or enclosure, including aluminum, cold-rolled steel, etc.

- **Paint type** – When declaring the type of paint to be used in a specification, electrical equipment producers should avoid using a specific paint manufacturer's product code. Codes can be ambiguous or difficult to find, as they often change or may be unique to a specific customer. Instead, detail the specific coatings technology the equipment demands (liquid, powder or electrocoat); then detail the resin chemistry of the desired coating (i.e., TGIC polyester, epoxy, urethane, etc.)
- **Substrate preparation and protection** – This section spells out substrate preparation details and methods. In addition to addressing the cleaning and removal of oils, lubes, and coolants left over from the fabrication process, the specification should also spell out chemical cleaning methods using alkaline, acid, or solvent-based products; and mechanical cleaning methods such as shot-blasting.
- **Color** – Establishing and maintaining a standard color can be challenging. It is important to detail an acceptable range of color variation and to have a proven and consistent method for determining that the color of a painted part falls within specification.
 - Pantone, RAL, Munsell, and ANSI are color-cataloging systems commonly used for these purposes, although some equipment manufacturers choose to create their own in-house standards. Maintaining color standards is a topic worthy of its own article, so it is best to work with a reputable paint manufacturer to understand the intricacies of creating a color standard and how to detail its parameters in the specification.
- **Gloss** – Like the color spec, the gloss range spec can have a big impact on a product's finished appearance. It is important to provide a specific gloss range in a paint specification, as variations in gloss can cause the same color on a piece of equipment to appear as different shades.
- **Texture** – This section defines the smoothness of the finish. In the electrical industry, some orange peel (minor paint dimpling) is considered preferable, as it tends to hide flaws and wears well over time. Even so, firm rules for texture types and variation should be written into the paint spec.
- **Cure** – This section establishes paint curing parameters for oven or air-drying paint.
- **Product handling and storage** – Manufacturers suggest specific rules for handling and storage in their product data sheets, including an acceptable range of temperature exposures and fixed expiration dates to ensure inventory is properly rotated.
- **Performance** – Regulatory standards such as UL or IEEE should be detailed in the paint specification. These standards are written to include a range of acceptable results for products undergoing laboratory-based performance tests, which have been agreed upon by the industry for their ability to mimic real-world performance environments.

Edge corrosion is one of the most common and most challenging issues transformer manufacturers encounter.

Pad-Mounted Transformer Coating Systems



Fins

-  Pretreatment and Engineered Products +
-  Powder Coatings OR  Electrocoat

Enclosure (Hybrid)

-  Pretreatment and Engineered Products  Electrocoat
-  Powder Coatings  Liquid Coatings

Pole-Mounted Transformer Coating Systems

Full System

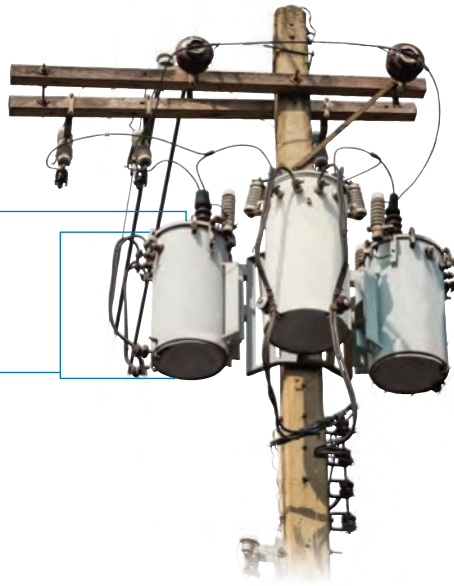
-  Pretreatment and Engineered Products

Tank Covers

-  Pretreatment and Engineered Products +
-  Powder Coatings OR  Liquid Coatings

Tanks (Hybrid)

-  Pretreatment and Engineered Products
-  Electrocoat
-  Powder Coatings
-  Liquid Coatings



Equipment Design Considerations in Reviewing the Latest Coating Technologies

Edge corrosion is one of the most common and most challenging issues transformer manufacturers encounter. Edges of equipment show wear and rust the fastest and are a transformer's greatest point of corrosion vulnerability.

What is edge corrosion? When parts are painted on the line, a visual inspection usually shows that the sharp edge appears to have coverage; however, during the heated cure time, coatings decrease in viscosity further liquefying the coating, which causes it to pull away from the sharp edge. This results in reduced film thickness and diminished corrosion protection.

Equipment design changes can be made to avoid this problem, but they can be costly. A better option is to select one of the state-of-the-art coatings that are specifically designed to provide edge corrosion. Some of these coatings also have high transfer technology built into their formulations, which helps to reduce waste during manufacturing. Selecting a state-of-the-art coating technology will:

- Provide superior corrosion resistance
- End in lower cost per square foot of painted metal
- Ensure color consistency across the equipment

Selecting the right coating using the latest technologies will greatly reduce the transformer overall cost of ownership by:

- Reducing warranty claims
- Extending product life cycle
- Reducing waste
- Saving energy related to equipment manufacturing

Summary and Suggestions

When creating a paint specification, it is critical to correlate a device's expected service environment and service life to the testing methodology that most rigorously replicates the performance challenges it will face. Not only will this help ensure that a product performs reliably throughout its lifetime; it may also lessen maintenance requirements for that device during its service life as well.

Equipment manufacturers should evaluate their paint specifications on a regular schedule to ensure that they always incorporate the most targeted

and technologically advanced coating systems and testing methodologies for a specific application.

Equipment manufacturers also should involve paint and pretreatment suppliers in the design process as early as possible, preferably with a proven coatings company that can offer both pretreatment and paint capabilities as an integrated package.

Integrated, full-service coatings suppliers typically have a deep understanding of the coatings process from start to finish, along with a wide range of products and resin chemistries that have been tested according to industry-standard criteria.

They also can act as a partner in identifying potential vulnerabilities to corrosion and help customers to select the right products to prevent it. Most integrated coatings suppliers also have dedicated lab resources, which enable them to recommend the best test methodologies to measure a product's potential service life. They also have complete testing services to verify lab results, identify probable reasons for a product failure, suggest potential solutions to correct a failure, and to troubleshoot general coatings-related production problems.

Giving you the edge in corrosion protection

Equipment manufacturers should evaluate their paint specifications on a regular schedule to ensure that they always incorporate the most targeted and technologically advanced coating systems and testing methodologies for a specific application.



PPG ENVIROCRON® Extreme Protection Edge powder coatings

Transformers and other performance-critical electrical equipment must withstand punishing outdoor conditions. Fins, sharp corners and other intricate parts are typically the first areas to fall victim to corrosion, costing the electrical industry billions of dollars a year.

That's why PPG developed *Envirocron* Extreme Protection Edge powder coating. This patent-pending breakthrough coating is ideal for laser-, fiber- and CO₂ plasma-cut sharp edges, louvers, blades and mesh, delivering protection where it's needed the most.



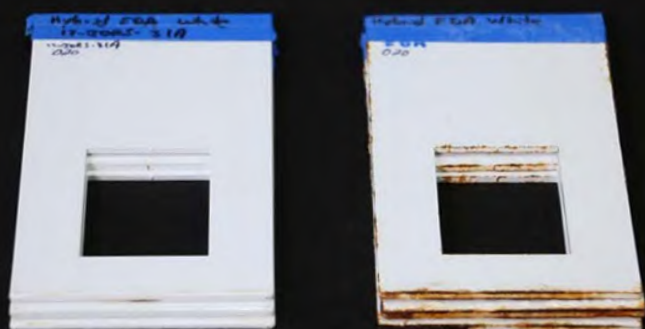
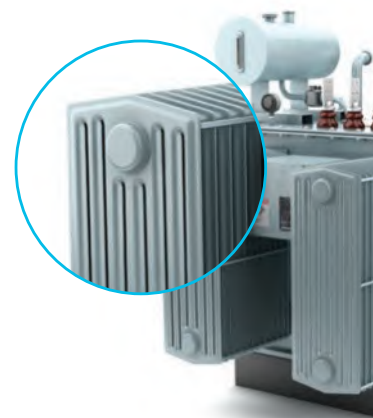
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High edge formula

Standard formula



Edge view, bottom high edge, top standard formula

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Twin Technologies Test Transformer Reliability

by **Allan Rienstra**

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WE CAN DRAW COMPARISONS BETWEEN THE SYMBIOSES IN FRATERNAL TWINS TO THOSE PREVALENT IN TECHNOLOGIES USED TO MONITOR THE HEALTH OF ELECTRICAL ASSETS. THIS IS ESPECIALLY TRUE OF ULTRASOUND AND INFRARED THERMOGRAPHY; TECHNOLOGIES THAT EXTEND OUR HUMAN ABILITY TO HEAR AND SEE.

Despite being spawned from the same DNA, there is no certainty that fraternal twins will look and behave the same. They might show different eye and hair color, they can have similar but not identical facial features, heights, and of course they can be the same, or opposite gender.

What is often the case, however, is the ways in which their personalities and characteristics complement each other. Some fraternal twins even make claim to having a mental connection — coined 'twin telepathy' — that allows them to share an uncommonly close mental bond with their sibling. Despite the lack of scientific evidence to support the existence of telepathy between twins, case studies demonstrating high levels of collaboration and cooperation are numerous.

We can draw comparisons between the symbioses in fraternal twins to those prevalent in technologies used to monitor the health of electrical assets. This is especially true of ultrasound and infrared thermography; technologies that extend our human ability to hear and see.

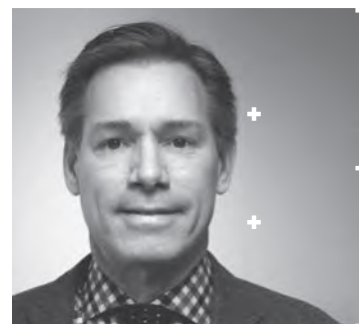
Ultrasound is a useful technology that extends the range of human hearing. It empowers inspectors to hear sounds they normally could not. Inspectors can use the information





The laser of this parabolic dish from SDT is pointing at the left phase of this 36 kV transformer while the inspector remains safely on the other side of the fence.

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++++++
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Allan Rienstra Some say I am passionate about ultrasound. They are not wrong, but not right either. I am passionate about helping people get the most from their investment in technologies that create safe workplaces, reduce unplanned downtime, and eliminate waste. Ultrasound just so happens to be *that* technology. There is so much we can do to create accident free, proactive, environmentally sustainable conditions in manufacturing. All we need to do is *care* and *hear more*. If you care like I do, join me and together let's make Earth Great Again!

gleaned from ultrasonic detectors to identify changes in normal operational parameters of critical assets. Moreover, they can do so in difficult, high-noise environments where the naked ear is useless. Properly trained technicians inspect, detect, measure, trend, and analyze ultrasound data so as to anticipate the need for maintenance intervention very early in the potential failure curve.

Infrared thermography is useful for detecting thermal anomalies not seen by the human eye. By displaying heat radiating from the surface of an object as a visual image, personnel with limited or no infrared experience can see patterns of temperature distribution from an asset. Using infrared in predictive and preventative maintenance is beneficial to electrical asset reliability. By locating potentially harmful abnormalities early, simple maintenance and repairs are carried out before damaging the equipment, or unplanned outages or catastrophic failure occur.

Ultrasound on its own hears many, but not all, symptoms of failure in electrical assets. Likewise, infrared thermography sees defects that produce heat, so long as that heat transmits to the surface of the asset. Inspectors using one of these technologies on its own can hope to tell a substantial story. But when

the two technologies are deployed together, expect a more complete and accurate accounting of the asset's condition.

Many electrical faults are the result of partial discharge which is defined as "a localized electrical discharge in an insulation system that does not completely bridge the electrodes." A discharge is described as either an "arc" or a "spark" and can be phase to phase, or phase to ground. Partial discharge is destructive to the conductor or insulator, and over time, will cause the component to fail. The integrity of insulation material is further damaged by corrosive gases like nitrous oxide. The time it takes for a system component to fail is related to system voltage, the shape of the void from phase to phase, ambient temperature, the condition of the insulation material, and environmental conditions such as pollution and humidity. The higher the voltage, the more destructive the partial discharge becomes.

One stage of partial discharge is termed "tracking." Tracking is difficult to detect since it doesn't produce heat. Like corona discharge and arcing, tracking exists only to seek a path to ground. Dirt, dust and moisture help tracking follow this path, which is why simple maintenance like cleaning is effective in prolonging the service life of electrical systems, Figure 1.



Figure 1.
An electrical service technician applies simple dry ice cleaning on a residential transformer.



Figure 2.
Tracking has begun to erode the enamel coating on this insulator. Moisture can impregnate and either super heat (arcing) or freeze. The insulative properties are failing and partial discharge will only worsen from here.

Ultrasonically, tracking begins with a low buzzing and crackling sound and builds in loudness until it reaches the point of flashover. For this brief moment there is heat, thus for an inspector relying solely on infrared,

timing is everything. After flashover, tracking quiets and cools. It is this repetitive, persistent build up in intensity and discharge that leads to insulation breakdown, and eventually the progression to more destructive arcing.

INSPECTORS USING ONE OF THESE TECHNOLOGIES ON ITS OWN CAN HOPE TO TELL A SUBSTANTIAL STORY. BUT WHEN THE TWO TECHNOLOGIES ARE DEPLOYED TOGETHER, EXPECT A MORE COMPLETE AND ACCURATE ACCOUNTING OF THE ASSET'S CONDITION.

The earlier an electrical fault is detected the less expensive it is to schedule and perform maintenance to mitigate risks. Early detection of an electrical fault can be the difference between a simple dusting and cleaning versus costly overhaul or even total repair/replacement.

Take for example one instance where a condition monitoring inspector, trained in both infrared and ultrasound disciplines, was tasked with inspecting a three-phase transformer in a steel mill. Had he relied on only infrared imaging data, he may have missed symptoms of an underlying issue that was progressing toward catastrophic failure.

Skip Young is a CAT 2 certified infrared thermographer as well as an SDT Level 1 ultrasound inspector. He was tasked to inspect electrical assets for a major steel manufacturer in Calvert City, Kentucky. Processing steel requires heavy duty electrical power systems. A single electrical component failure is all it takes to completely stop production, resulting in the loss of crucial time and money.

This inspector knew that electrical faults only generate heat once they've reached an advanced stage. Relying solely on infrared may have resulted in a missed diagnosis. Whenever conducting thermal scans, Young includes ultrasound as well. He knows that acoustic energy is generated at all stages of discharge and that by combining ultrasound and infrared scans there is less chance of a missed diagnosis.

Figure 2 displays an example of an electrical problem detected in its early stages with ultrasound. The insulator was damaged with tracking which indicates the presence of an equipment fault. When caught at an early stage, it can often be fixed with simple maintenance procedures.

Thermal images from several 161 kV to 13.8 kV step-down transformers were included in Young's report. The infrared image reveals no hot spots on the A phase bushings (Figure 3), but an ultrasound scan produced a sound file with obvious indications of early tracking.

Medium and high voltage switchgear poses great risk to inspectors. To mitigate the potential of an arc flash or arc blast incident when the panel is opened, ultrasound inspection first confirms the presence of any partial discharge sources.



This 6 kV transformer is inspected from the safe side of the fence for partial discharge, tracking, and destructive arcing.



Figure 3. Infrared did not discover any electrical anomalies; however, additional ultrasound scans revealed the onset of early stages of corona discharge.

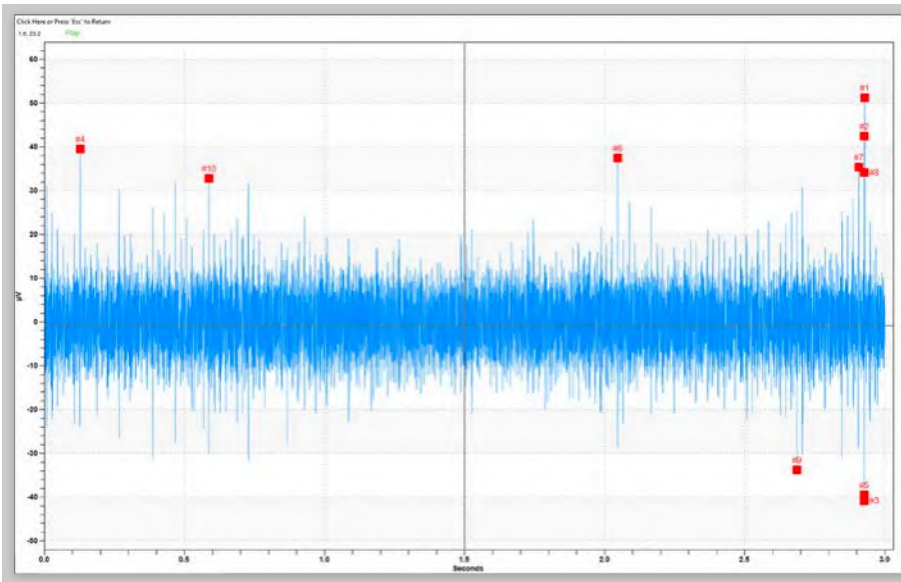


Figure 4.
Time waveform taken with SDT270 shows partial discharge activity classified as nuisance corona. Simple maintenance such as cleaning and tightening is required.



Figure 4 illustrates the time domain showing the build-up and release of the ionization discharge as it finds a path to ground. Ultrasonically, we hear the build-up and then a neutralization of the air surrounding the problem. Heat does not build up here until the situation progresses and there is sufficient flow or current to produce heat along the discharge path.

Figure 5 illustrates the spectrum domain from Young's ultrasonic data. There are two things to note

here. First, the repetition of 60 Hz events in the spectrum clearly reveals the presence of nuisance corona at the line frequency. Secondly, the short, abrupt bursts of energy in the timewave image, without the presence of heat, confirms there is tracking activity.

Similar tracking activity was discovered from the B and C phase bushings, while neither showed any signs of heat when scanned with an infrared camera.

Once the diagnosis was made on the suspect transformers, the decision to perform simple maintenance during the next planned outage was made. Since the problem was discovered at an early stage, the simple maintenance could be done on the terms of the maintenance crew rather than dictated by asset failure. This involved a cleaning and tightening of all connections on A, B, and C phase bushings.

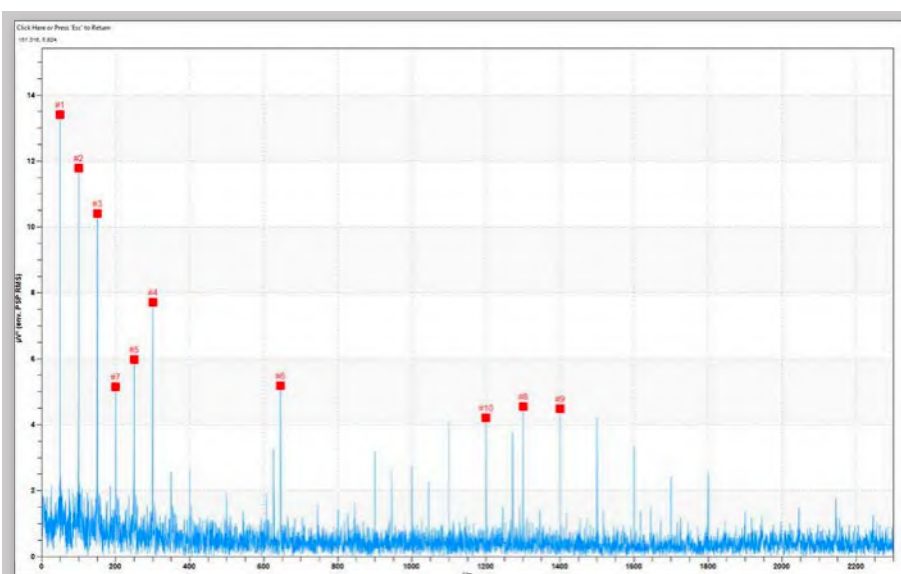
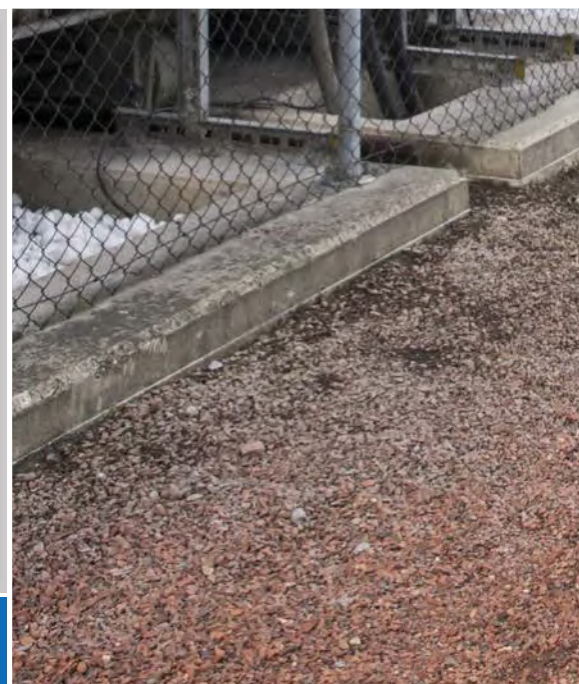


Figure 5.
The frequency view of the same ultrasound signal clearly shows 60 Hz line frequency. This is a classic example of nuisance corona.



A full-page photograph of a male worker in a blue uniform and yellow hard hat, wearing a headset and using a handheld ultrasound device. He is standing on a gravel path in a power substation, with high-voltage equipment and a building in the background. A semi-transparent grey box with a blue 'x' pattern and a '+' pattern contains text about maintaining distance when using ultrasound.

When measuring the dB level of partial discharge with ultrasound it is important to keep the distance between sensor and asset consistent.

JUST AS FRATERNAL TWINS ARE NOT IDENTICAL IN APPEARANCE, BUT SHARE A COMMON MENTAL LINK, SYNERGIES BETWEEN ULTRASOUND AND INFRARED TECHNOLOGIES ALLOW FOR A COOPERATION THAT CAN YIELD TREMENDOUS ADVANTAGES FOR ELECTRICAL ASSET RELIABILITY.

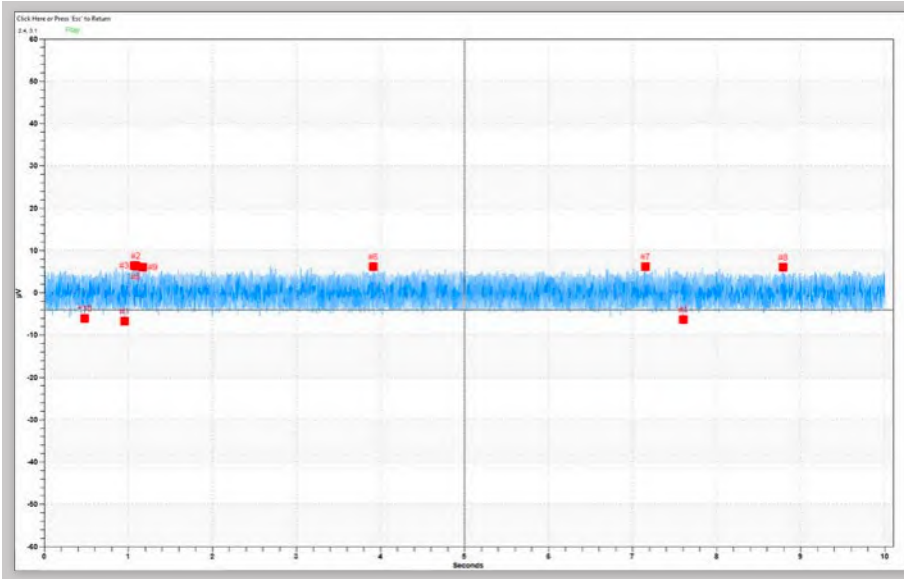


Figure 6.
Time waveform after simple maintenance shows a satisfactory drop in discharge activity.

Looking at the time signal in Figure 6 and the frequency signal in Figure 7, maintenance definitely improved the condition of the asset. Since tracking is a stage of partial discharge that does cause damage to connectors and insulators, it will be necessary for Young to continue his vigilant ultrasound scans moving forward.

Ultrasound and infrared deployed in tandem performed well on this transformer issue. Moreover, there is no reason why the pairing should not be considered a winner for observing



Ultrasound detectors equipped with parabolic sensors safely inspect 600 kV transmission and distribution lines for insulation-destroying corona discharge.

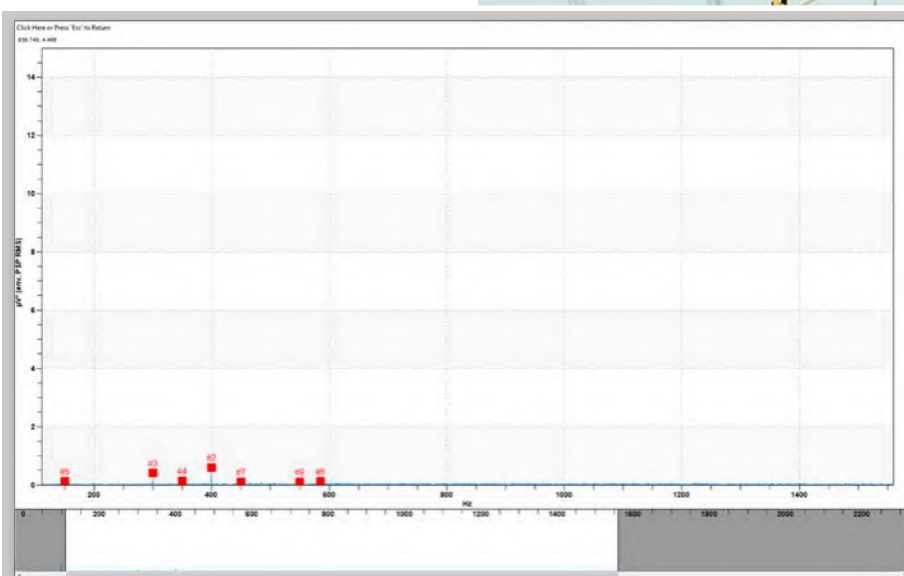


Figure 7.
Spectral view after simple maintenance confirms the system was restored to good working condition.

partial discharge on insulators, MCC panels and high voltage transmission and distribution lines.

There is no single manufacturer that organically developed both ultrasound and infrared. However, through merger and acquisition or inter-company partnerships, these technologies are, in some instances, born of the same 'parent'. Just as fraternal twins are not identical in appearance, but share a common mental link, synergies between ultrasound and infrared technologies allow for a cooperation that can yield tremendous advantages for electrical asset reliability.



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Transformer Bushings How to Detect Incipient Faults in an Early Stage?

by **Thomas Linn**

This article is the continuation of the [first article](#) in this series and continues to discuss the early detection of incipient bushing failures by using the knowledge of different failure mechanisms discussed previously.

Introduction

The condition of bushings can be accessed by different measurement techniques and online and offline approaches. Polarization-Depolarization Current (PDC) and the Frequency Domain Spectroscopy (FDS) measurements are offline measurements beside the common offline Power Factor measurements and can provide a good insight in respect to moisture ingress. Moisture ingress can easily get missed in "standard" offline tests, which will be explained later in this article.

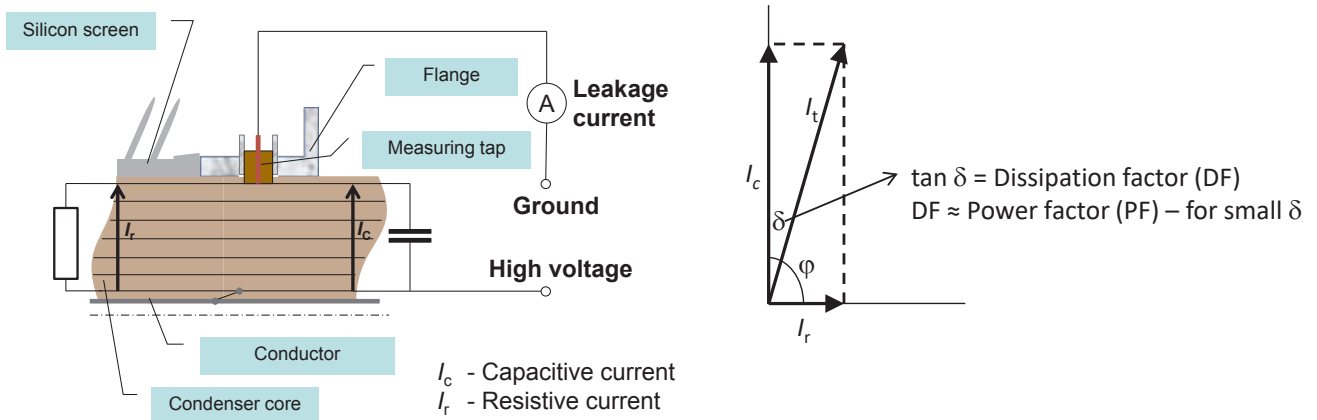
Removing bushings from the transformer during a planned outage to test them in a high voltage lab will allow conducting measurements at higher temperatures, which helps early detection of moisture.

Since offline methods demand de-energization of the transformer and mobilizing the workforce and equipment depending on the measurement to be taken, this can only be done periodically (yearly/bi-yearly, etc.), and critical faults developing between two consecutive measurement cycles can be missed. Online bushing monitoring can mitigate that risk.



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

Figure 1. Power factor / Dissipation factor



Incipient Fault Detection

Detection Parameters

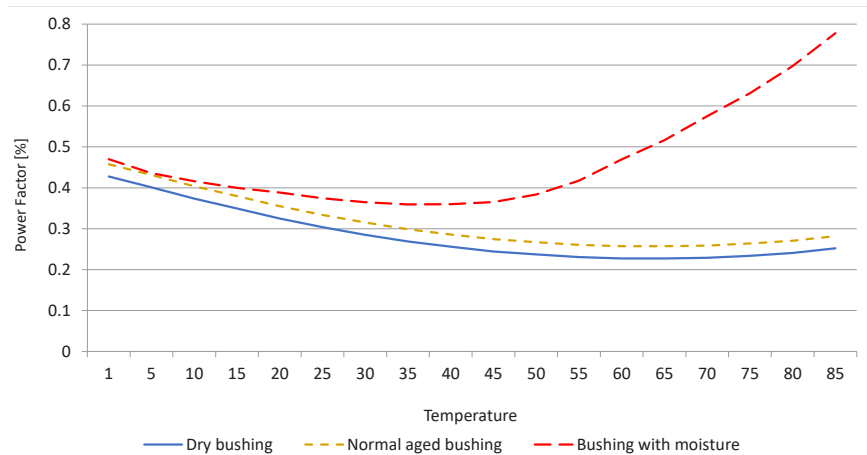
Power Factor/Dissipation Factor

The power factor, i.e. the dissipation factor reflects the condition of the insulation system and is the ratio of the resistive and capacitive part of the leakage current (see Figure 1). The formulas of the power factor and the dissipation factor can be seen in Figure 1. In the discussion below I only use the term power factor. Everything said about the power factor is valid for the dissipation factor as well.

In relation to temperature and frequency, the power factor is a non-linear parameter which can be used independently of temperature and frequency to assess bushing condition. The main influential parameter on the measurement is the moisture in the insulation. Various measurement methods will be discussed in this article.

Figure 1 shows the power factor over temperature at constant frequency for bushings with a different moisture content. Three important facts can be concluded from that graph. First, the higher the temperature, the clearer is the difference between a healthy, low moisture content bushing and a bushing with moisture ingress in an early stage. Second, at temperature below 40°C incipient moisture ingress causes only a slight increase of the power factor compared to a "dry" bushing, which can be easily missed. Third, the temperature compensation for "wet" bushings is not valid anymore (Figure 2).

Figure 2. Power factor / Temperature curve

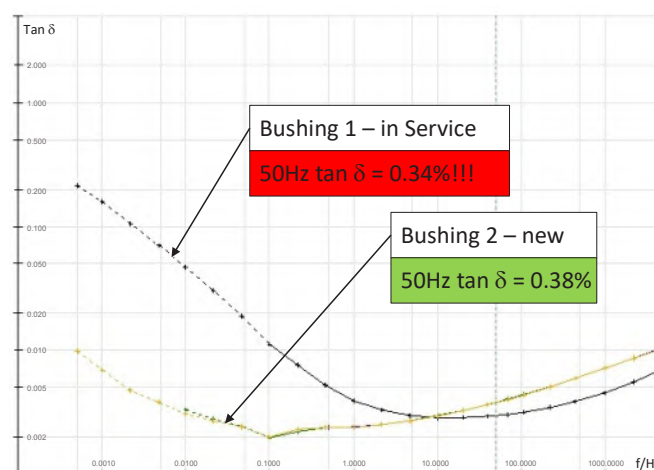


Power factor measurements over frequency, over a range of 10 Hz to 300 Hz, can bring little or no additional information for assessing bushing condition. Measuring Polarization-Depolarization Current (PDC) and Frequency Response Analyzes (FRA) for frequencies starting from 1 MHz is much more sensitive, especially for incipient moisture ingress.

FDS (Frequency Domain Spectroscopy) and PDC measurements are usually combined to shorten the measurement time.

Figure 3 shows the results for the measurements of two different bushings using the FDS/PDC method. The 50 Hz power factor values at ambient temperature did not show a

Figure 3. FDS/PDC measurement of dry and wet bushings [1]



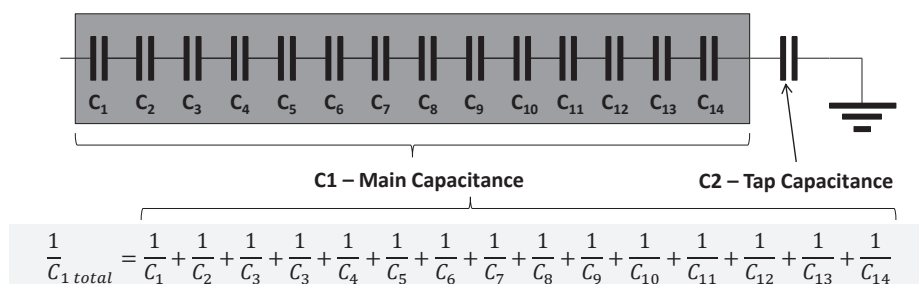
significant difference, but the FDS/PDC measurement did, and the 50 Hz measurement at higher temperature would show the difference as well. An incipient fault at an early stage can be missed by only assessing the power factor measured around network frequency and at ambient temperature. Finally, bushing 1 was taken out of service as moisture ingress was clearly detected.

Capacitance

Almost 100% of the leakage current is capacitive current and based on the capacitive layer design (Figure 4). If two aluminum layers are short circuit (partial breakdown), the total capacitance value will increase which will result in an increase in the leakage current as well.

If the number of layers is known, the percentage of capacitance increase can be converted into the number of layers involved in that partial breakdown. If, for example, a 550 kV bushing has around 60 to 70 capacitive layers, a partial breakdown between two layers will increase the capacitance by about 1.5% (which is equal to the increase of dielectric stress).

Figure 4. Bushing series capacitances



A 138 kV bushing with maybe 20 to 30 layers would see a 4% increase in capacitance. Therefore, the percentage increase of capacitance is the primary factor for the risk assessment.

Partial Discharge

Often the bushing tap is used to measure PD. The main bushing capacitance C_1 is acting as coupling capacitor and the PD measurement is based on IEC 60270 method. This principle is used during factory testing, re-testing in the factory, offline testing and online monitoring of bushings and transformers.

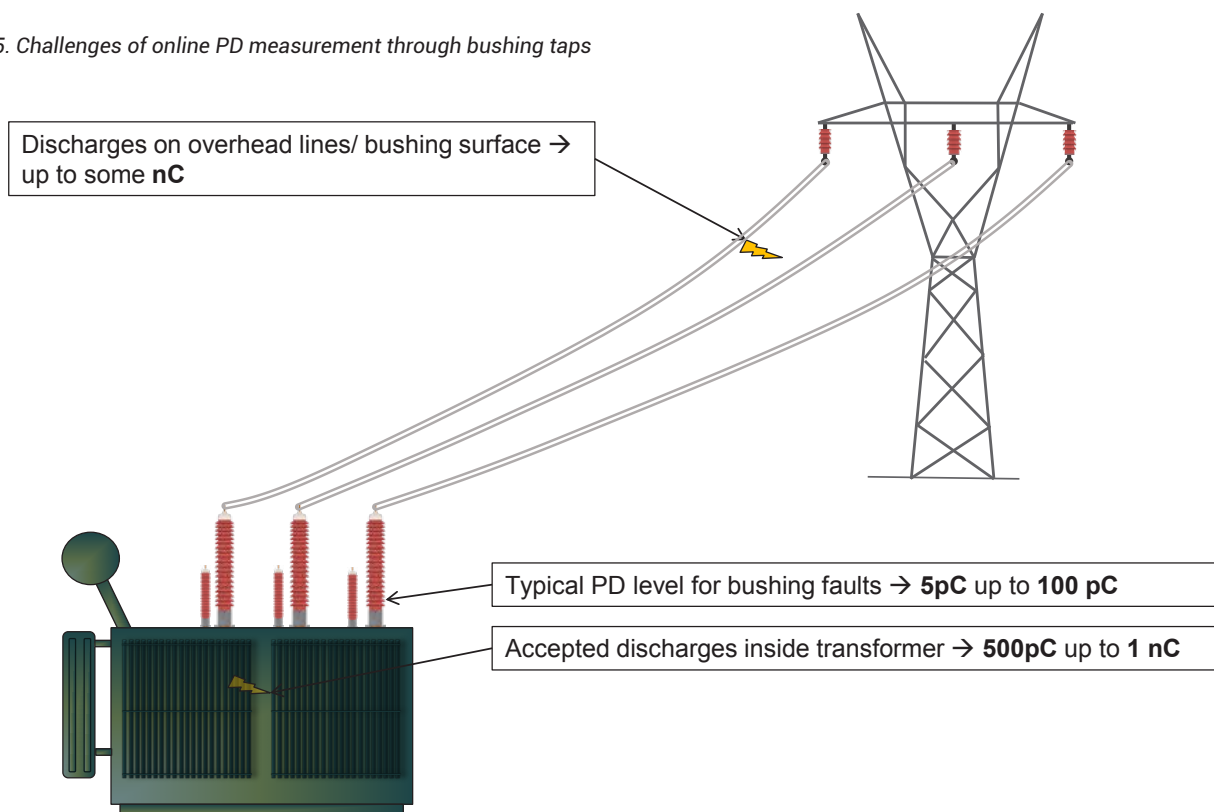
During factory or offline tests, external disturbances can be avoided by proper screening. On site it remains

difficult to identify the origin of the PD activity without further investigations.

Figure 5 shows the challenges for online PD monitoring conducted through bushing taps. The readings can easily be influenced by external disturbances or external PD. External corona discharges with several Nano Coulombs (nC) of magnitude can easily mask discharges originated from transformers or bushings.

Online PD monitoring through bushing taps usually cannot provide high confidence in the assessment results. A UHF sensor in the transformer close to the bushings can deliver better results when assessing the condition of transformers and bushings. Power factor and capacitance provide data that is reliable enough to make bushing health assessments.

Figure 5. Challenges of online PD measurement through bushing taps



Condition Assessment Approaches

Condition assessment techniques can be based on offline tests, online tests, and lab re-tests. Offline bushing tests are tests where an external voltage source is used while the transformer is offline. Lab re-tests are tests where the bushing will be removed from the transformer during an outage (planned or unplanned) and tested separately in a high voltage lab. Online tests or monitoring will be done while the bushings are in service.

Offline Testing

The frequency of offline testing of bushings depends mainly on the maintenance strategy. Usually new bushings will be tested for the first time after about 5 years (sometimes earlier, sometimes later, or never). As a good practice, further test cycles should be scheduled based on the bushing condition. For example, if there is an increase in the power factor or the capacitance detected, the measurement cycle should be shortened. Depending on the expected degree of degradation, it might be decided to have the next test after a year, half a year or even earlier. If the concept of periodic offline measurements is being followed, it is a good practice to have spare bushings available to be able to replace bushings in due time if needed. If no spare bushings are available, depending on the circumstances, network operators might be forced to put the transformer back into service with the critical bushing and the risk of a breakdown.

The advantage of offline measurements is that different tests can be carried out. The most common one is measuring the power factor and the capacitance with usually a 10 kV voltage source and a frequency different to the network frequency to avoid any influences of magnetic fields present in the substation environment. It is also common to conduct power factor measurements at different frequencies between 10 Hz to 400 Hz.

FDS/PDC measurement as discussed above have a higher sensitivity to early moisture ingress. Here the supply voltage is usually only 200 V

to 2 kV compared to conventional power factor measuring devices with 10 kV supply. The FDS/PDC measurement delivers low leakage currents, which makes it susceptible for disturbances. Further, the duration of such measurement per phase, assuming a combined FDS and PDC (below 0.1 Hz), is somewhere between 30 minutes and 1 hour 45 minutes, depending on the lowest frequency selected [2].

PD tests, which are mainly focused on transformers themselves, are sometimes carried out as well. For these tests, a transformer test trailer and extensive screening is necessary to carry out a conclusive PD measurement in the field, which translates to high costs and efforts.

A simple method to test the insulation of an OIP bushing is to take an oil sample and do the dissolved gas analysis in the lab. As the oil volume of an OIP bushing is comparably small, special attention need to be paid not to go below the minimum oil level.

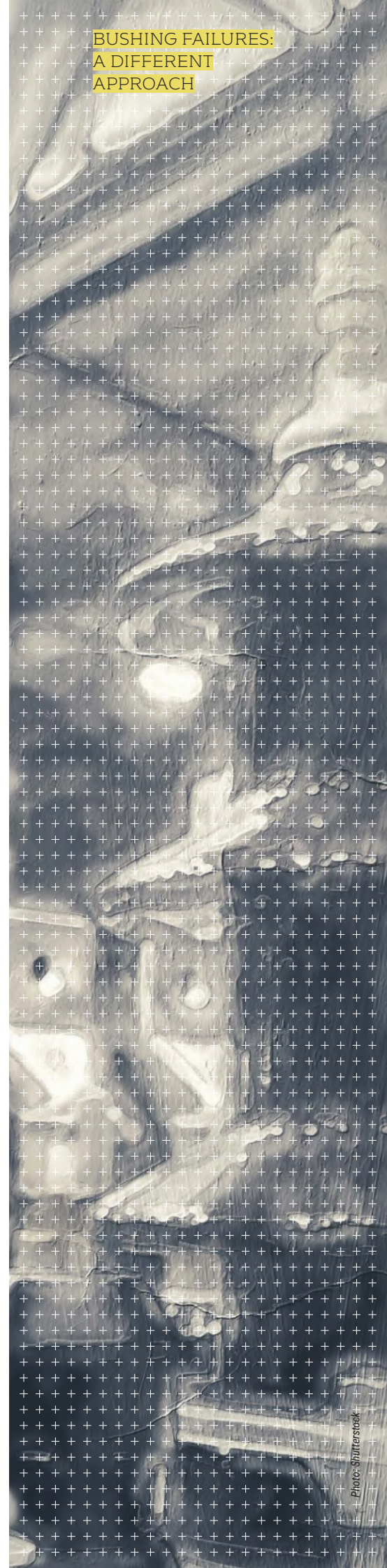
Offline tests are conducted at a certain point in time. A trending can be done in relation to previous measurements. Nevertheless, an accelerated fault development in-between two consecutive measurements will remain undetected and can lead to an unexpected catastrophic failure. Technical expertise for the execution of online tests must be built up within the organization or needs to be brought in for any single test.

HV Lab Re-testing

Lab re-tests of bushings from the field are an exception, but in fact a very powerful way for assessing their condition. The bushing must be removed from the transformer and brought to an HV test lab for testing before it is installed back to the transformer.

As part of a lab re-test, beside the power factor and capacitance measurements, a meaningful PD measurement concerning the bushing can be carried out. At a slightly increased power factor compared to factory values, specifically for RIP and OIP bushings, the bushing can be

BUSHING FAILURES: A DIFFERENT APPROACH



heated in an oven and tested again for a more accurate assessment (Figure 5). All other measurements can be applied in the same way as described in the chapter above.

Nevertheless, any degradation that might occur between two consecutive measurements can remain undetected, and catastrophic failures can occur. Further, the efforts and costs are higher for the removal and re-installation of the bushing. Additionally, an HV lab which has the capability to conduct such tests, must be within a suitable distance to the site considering limited outage durations.

Online Tests and Monitoring

Due to the limited accessibility of bushings in service, there are only a few different periodic online tests and measurements which can be done. These are infrared scans for high temperature areas which indicate overheating due to overload, bad contacts, low oil levels in bushings, etc. Further, surface discharges or excessive corona can be detected through ultraviolet cameras or through acoustic measurements or imaging (more advanced methods use microphone arrays). These methods can also be applied online, but they can only

cover a limited area of a substation. A solution which could cover a complete substation can be costly.

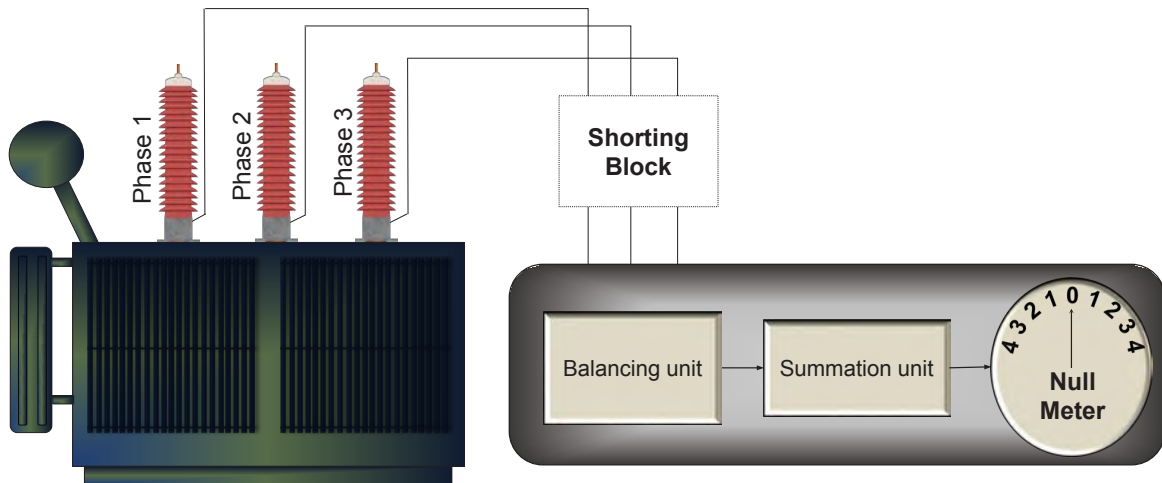
The most typical online applications are monitoring of the power factor and capacitance. Also, especially in South America (Brazil in particular), monitoring of the oil pressure inside OIP bushings is quite typical. In very few cases dissolved H_2 (hydrogen) in the insulation oil of OIP bushings is monitored.

The advantage of online tests and monitoring is that the bushing will be accessed under its operating conditions. As discussed above, different operating conditions can have a different influence on the health of a bushing. A combination of various stresses can occur. Therefore, online testing will provide the most accurate and in-time assessment of bushings in service. Additionally, the usage of online monitoring will allow a continuous recording and trending of the monitored data. Trending information is crucial for the detection of degradations in bushings. The speed of the development of the fault will give the reaction time for the rectification efforts. Online monitoring allows the operators to pull in internal or external expertise only if needed as the measurement results are already available.

Additionally, under high load conditions the bushing will also be heated. This allows measurement of the power factor at higher temperatures, which eases the detection of moisture in the same way as explained for offline lab re-tests.

The challenge is to strengthen the online monitoring equipment against disturbances. Also, especially for online monitoring systems, the equipment needs to be installed and commissioned by experts. Usually, a data network must be available to transfer the data to a remote assessment center or another point where the data will be collected and assessed by operators, maintenance crews, asset managers, etc.

Figure 6. Principle overview of the balanced current method



Online Monitoring Approaches

There are three different online bushing monitoring approaches and their combinations that are used today. PD monitoring through the bushing tap will not be further discussed considering it is mainly applied to detect the PD in the transformer itself. Likewise, capacitance monitoring, which is the simplest online bushing monitoring method, will not be discussed because it is seldomly used as standalone technique due to its limited ability to detect most of the incipient faults.

Balanced Current Method

The balanced current method, also known as the sum of currents method (Figure 6) is a frequently used method for bushing monitoring today. The assumption is that, under perfect circumstances, the sum of the leakage currents of the three bushings of different phases installed on the same transformer, under consideration of their phase angles, is zero. The perfect circumstances mean that for all phases the magnitudes of the voltage amplitudes are absolutely the same, and the phase shifts between the phases are exactly 120 degrees. Further, the bushings are considered to behave in the same way as their sister bushings on the same transformer.

In reality, electrical networks carry unbalanced load. Phase asymmetries regarding voltage magnitude of 1 to 1.5% and 0.2 degree in phase angle variations are very common for networks that are considered stable. Much higher asymmetries can be seen in more unstable networks.

The asymmetries change with load in a daily, seasonal and unpredictable manner. Changes in capacitance of a bushing (partial breakdowns) can still be detected accurately as the general fluctuations of the voltage magnitude across all three phases are lower compared to a critical partial breakdown.

A bigger challenge is the asymmetry in the phase angle. If the load asymmetry causes 0.2-degree phase difference, this will result in a deviation in the power factor measurement of about 0.35% (tangents of the 0.2 degree), which can cause a failure of more than 100%, assuming the power factor of a healthy OIP bushing is around 0.25%! Small power factor changes, caused by moisture ingress, cannot be detected with certainty or they can only be detected in a late stage of degradation.

Recent systems use self-learning methods which record the typical daily and seasonal behavior of the bushings to predict the load conditions. Nevertheless, the achievable accuracy

in terms of the power factor reading is limited. Further, the power factor is mostly displayed as a relative change compared to sister bushings. Using this method for single phase transformer is even more challenging and for a single bushing impossible.

Reference Method

Today, the balanced-current-based measuring systems also come combined with a reference method. Here the bushings of the outer phases are being compared with the middle phase bushing. As the bushings are still being compared to each other, the load asymmetry will cause the same variations in power factor as will the balanced current method described above.

The accuracy of the power factor and capacitance measurements can be increased by using a reference from the same phase. In the absence of a gas filled standard capacitor as used for offline measurement, existing voltage transformers from the same phase as the bushings can be used as reference. The output of voltage transformers (VT) is not load dependent. The principle of this method is to measure the phase shift between the bushing leakage current and the reference signal from a VT. The usage of existing equipment reduces the need of additional hardware. Figure 7 illustrates the principle of the reference method.

After the synchronized digitalization of both input signals, all signal processing will be done by software algorithms. Existing constant phase shifts caused by cabling and VTs must be compensated.

The major challenges are elimination

or limitation of noise, and availability of the stable reference source. In the absence of a VT or CVT as a reference, another bushing from the same phase, but from a sister transformer, can be used. Figure 8 shows a noisy signal before and after signal processing, while

Figure 9 illustrates another example of recorded raw data. Due to the relatively high amplitude, the signal from the reference source (blue curve) is almost not disturbed, while the signal coming from the bushing tap has a noise component of about 15 to 20%.

Figure 7. Principle of the reference signal method

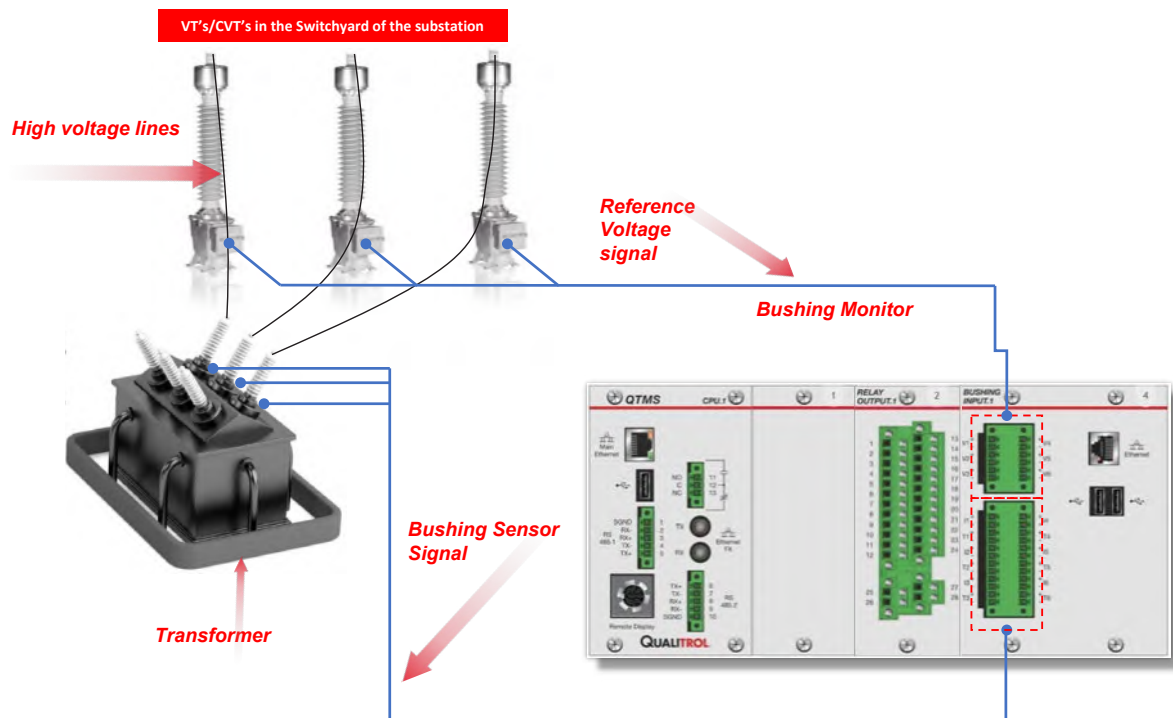


Figure 8. Example of effective noise elimination

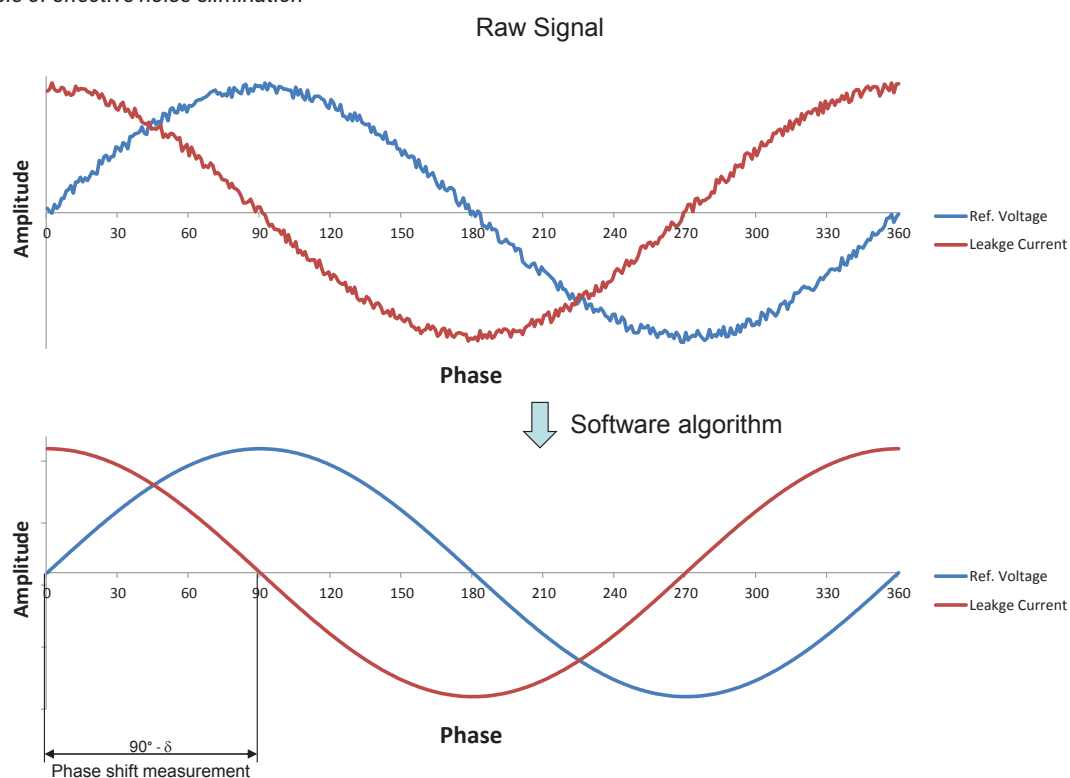
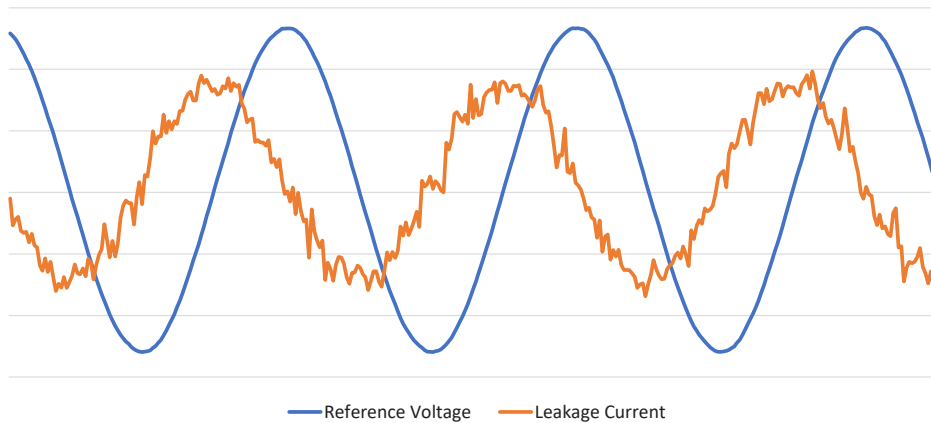


Figure 9. Raw data sample from site



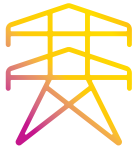
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Conclusion

Incipient faults must be detected early enough to avoid costly outages, injuries and environmental impacts. Offline tests provide a variety of methods for the assessment of bushings, but they might fall short in predicting critical conditions in service. Online monitoring can close that gap and is gaining more importance nowadays. Different bushing monitoring methods provide different accuracies. Common methods, for example those based on balanced current principles, have limitations due to the influence of the natural imbalance in the electrical networks.

By using a reference from the same phase, we can achieve higher accuracy and a better detection of incipient faults. Using independent reference sources for each bushing will also allow to have bushing monitoring systems for a single bushing only. Finally, the power factor result is a direct measurement and does not need a conversion from a relative value as for the balanced current method.



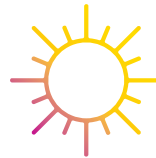
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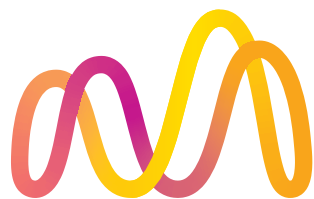
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The Truth About Accuracy in Online Capacitance and Power Factor Measurements on Bushings: Myths vs. Facts

by **Raja Kuppuswamy**

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A recent CIGRE survey shows that over two-thirds of the electrical utilities surveyed use limit criteria to replace bushings, which demands a measurement accuracy far better than the limit. However, it is widely unknown that the industry methods for online power factor and capacitance measurements do not always satisfy this because the accuracy is influenced by several factors that are beyond the realm of the instrument, including power quality, potential transformer usage related issues, practical constraints in implementation, and environmental effects. The focus of this article is to highlight these influences using theory and field observations and quantifying their effects on accuracy.

An overwhelming percentage of electric utilities surveyed by CIGRE use limit criteria to replace bushings, which demands a measurement accuracy far better than the limit.



Raja Kuppaswamy Ph.D., has been with the power industry for over 25 years. His experience includes high voltage power apparatus design, development of factory testing, and field diagnostic equipment. As a senior principal engineer at Dynamic Ratings Inc., he contributes to the development of diagnostics products for the power industry. He served as an invited member in CIGRE-A2 and IEC-TC42 technical committees in France (4y) and Switzerland (7y) as a technical expert on Partial Discharges. He has 15 inventions, five patents, and 120+ scientific publications as the first author.

Introduction

Continuous monitoring of condenser bushings using the signal tapped from their measuring taps is practiced using several methods. The most common is the sum-of-currents method. Additionally, reference (absolute values) or comparison (relative values) methods are increasingly being used because of their perceived higher accuracy.

A recent CIGRE survey [1] shows that over three-quarters of the electrical utilities surveyed use limit criteria of one-percent change in power-factor or a five-percent change in bushing capacitance to replace oil-impregnated-paper (OIP) bushings, or they use both. Two-thirds use the same limit criteria to reject resin-impregnated-paper (RIP) bushings.

When the merits of one measurement method over another

are discussed in the industry, the comparison is primarily restricted to how power quality factors like harmonics and system voltage fluctuations influence the measurement accuracy and are often based on subjective and anecdotal observations. There is hardly any discussion of other factors that significantly influence the measurement accuracy, probably due to the lack of awareness.

Therefore, an attempt is made to focus on the fundamentals of each measurement method, the factors that influence the measurement accuracy, and to use examples to estimate the reduction in accuracy due to these factors. Due to space limitations, the focus is on the measurement methods widely used in the industry and the dominant factors that influence measurement accuracy.

Concept of the Reference Signal Method

The concept of the reference signal method is shown in Figure 1. This method can be applied when a group of potential transformers (PTs) is available. The reference signal taken from the secondary side of the PT (V_S) is compared with the same phase leakage current (I_B) measured at the bushing measurement tap. The two signals must be time-synchronous to estimate the phase shift.

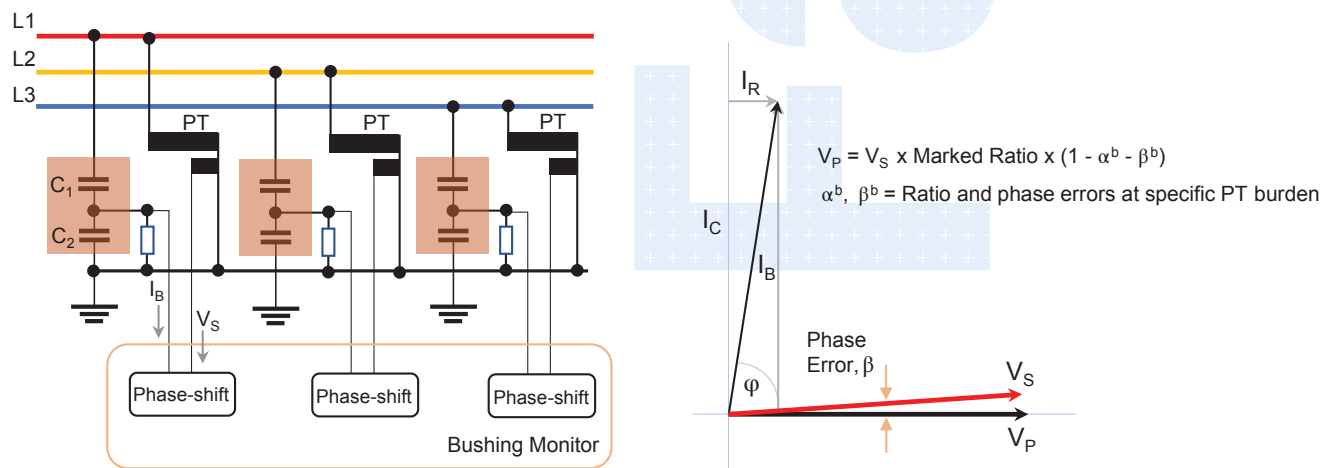


Figure 1. Bushing monitoring: Reference signal method

Power Factor Calculation

The power factor is the cosine of the angle between the V_P and I_B , where V_P is the primary side voltage on the PT. Since measuring instruments typically handle a few volts as input, V_S is used instead of V_P . This compromise results in a small phase shift or phase error (β) and a ratio error (α), as illustrated in Figure 1.

These errors are not fixed but depend on several factors, including the PT accuracy class, the length of the cable connected to the PT's secondary terminals, the temperature difference between the PT and the transformer tanks, and the additional burden on the PT caused by the bushing monitor.

The bushing power factor error can be approximated to $\cos(\beta_b)$, β_b is the phase-error at the specific PT burden.

As an example, according to IEEE C57.113, the maximum permitted phase error for PT of class 0.6 (standard metering) is 30 minutes or 0.5 degrees. A phase error of 0.5 degrees results in a power factor error of $\pm 0.9\%$. That is almost twice the factory acceptance test limit of $< 0.5\%$ for OIP bushings and closer to the 1% limit criteria used by a very large percentage of utilities surveyed by CIGRE to change OIP or RIP bushings [1]. When absolute limits are used to change bushings, an error of $\pm 0.9\%$ can cause a good bushing to be rejected and a bad bushing to be accepted.

The accuracy of the reference signal method is severely limited by the accuracy class of the PT used, wye or open-delta connection, long secondary cables, and temperature.

Capacitor Calculation

The capacitance C_B of an HV bushing is calculated using the equation 1.

$$\left\{ \frac{I_B}{2\pi \cdot f \cdot V_P} \right\} = \left\{ \frac{I_B}{2\pi \cdot f \cdot V_S \cdot \text{marked PT Ratio} \cdot (1 - \alpha^b - j\beta^b)} \right\} \quad (\text{Equation 1})$$

Where α^b, β^b = Ratio, and phase errors with the specific external burden.

As an example, according to IEC C57.113, the limits for ratio correction factor for PT of class 0.6 is between 1.006 and 0.994, which equates to a 1.2% error in C_B calculation. This is an acceptable error for both OIP and RIP bushings below 550 kV because the change in bushing C_1 capacitance due to a short in adjacent layers is above 1.2%.

A large percentage of utilities surveyed by CIGRE use +5% capacitance change from factory test values to change OIP or RIP bushings. An error of 1.2% can cause a good bushing to be rejected and a bad bushing to be accepted.

phases voltage reference is estimated from the remaining two phases where the PTs are available. The middle phase voltage is the vector sum of the voltages from the two outer phases. That means the magnitude and phase shift of the middle-phase reference voltage depend on the voltage and phase shift variations in the two outer phases. That introduces an additional error in power factor and capacitance calculations that varies dynamically with time.

Length of the PT Secondary Cable

If the cable from the PT secondary to the data-acquisition system input is very long, they may have sufficient impedance to introduce additional voltage drop and error. If it is of appreciable magnitude in percent of the secondary voltage, it will introduce other ratio and phase errors. The ratio and phase angle error may be calculated according to the vector diagram in Figure 3 and the equations 2 and 3.

Other Factors That Can Influence the Accuracy of Measurements

Potential Transformers Available Only in Two Phases

It is common in the United States to use PTs only in two phases, as shown in Figure 2. The missing middle

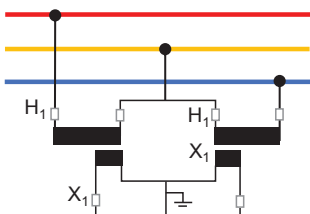


Figure 2. Open delta PT connection

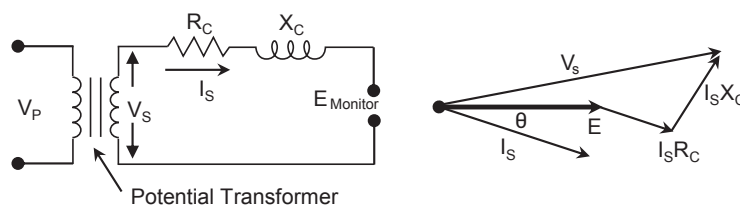


Figure 3. Equivalent circuit and phasor drawing

The percent ratio will be increased by the value in Equation 2, which must be added to the percent ratio of the PT to get the actual ratio.

$$\frac{I_s (R_C \cos \theta + X_C \sin \theta)}{V_s} \times 100 \text{ (Equation 2)}$$

The phase angle will be increased by the value in Equation 3, which must be algebraically added to the phase angle of the PT to get the actual phase angle.

$$\frac{I_s (R_C \sin \theta - X_C \cos \theta)}{V_s} \times 3438 \text{ minutes (Equation 3)}$$

The standard industry practice uses a coax cable of type RG58 [2] to run the PT's secondary voltage to the data-acquisition system. For example, let us estimate the different ratio and phase angle errors introduced by a 50 feet RG58 cable using only its dc resistance of 0.5 ohms and ignoring the inductance, which is negligible.

According to IEEE C57.113, the metering burden of 200 VA has a burden impedance of 72 ohms ($I_s = 1.67$ A). Considering only the resistive drop across the cable, per revised Equations 2 and 3, this translates to an additional ratio error of 0.7% and phase angle error of 0.4°. That causes an additional error of 0.69% on the power factor and 1.4% on the capacitance calculations.

The voltage drop across the secondary lead in percent of the secondary voltage is 0.7%. This value would violate the recommended total voltage drop in the secondary circuit, which must not exceed 0.1% for revenue metering.

PT Burden

The ratio and phase errors of the PT vary with the external burden value connected to the PT's secondary terminals. It is very common in the industry to operate PTs at burdens different from the ANSI or IEC calibrated values. Therefore, the ratio and phase error values at a random burden (α_b , β_b) necessary to correct the measured capacitance and power factor are unavailable to the user which may lead to unpredictable errors in the power factor and capacitance calculations.

The Temperature Difference Between Units

The reference signal method requires that the temperature inside the PT and the transformer tank is the same; otherwise, other errors in power factor and capacitance calculations will occur. Unfortunately, the temperature difference is unavoidable as PT operates at a fixed load, and the load on the transformer can fluctuate. During the transformer's operating range, the variation of capacitance for commonly used insulating materials in healthy bushings is between 0.03% and 0.05% per degree Celsius, and power factor variation is >0.1% per 20°C [1]. If the bushing is wet or aged, then the variations in capacitance and power factor with temperature are unpredictable.

Assuming the bushing is healthy and the relative temperature difference between the PT and the transformer tanks is 25°C, the capacitance and power factor changes are respectively >1% and >0.1%.

The summary of all the dominant influences on the accuracy is shown in Table 1. The total measurement error is a summation of the errors in columns 2 to 4, which can easily exceed 2%.

Concept of the Sum-of-currents Method

The concept of the sum-of-current method is shown as a block diagram in Figure 4. During commissioning, the indicator is balanced to zero. The balancing circuit's purpose is to balance out the minor variations in bushing capacitance and power factor, which can be present if they are of the same type and manufacturer. As the insulation ages, one bushing will eventually begin to age faster than the other two. The leakage current and the phase angle in one of the phases will also change, and the indicator will no longer read zero. The amplitude of the change reflects the severity of the problem, and the phase angles indicate which phase is experiencing the problem.

Diagnostic parameter	OIP & RIP bushing replacement limit per survey [1]	PT on all 3 phases (wye connection)	For PT with 50 ft secondary lead	The temperature difference between the PT & transformer tank
	[Col. 1]	[Col. 2]	[Col. 3]	[Col. 4]
Power-factor / Tan delta in %	> 1%	Min. ± 0.9%	0.70%	~0.3 to 0.5% / 10°C
Capacitance	> +5% of FAT	Min. ± 1.2%	1.40%	>0.1% / 20°C

Table 1. Summary of dominant influences on the reference signal method accuracy

Temperature difference of 25°C between the PT and the transformer tank causes a significant error in power factor measurements.

The change can be approximately represented by the Equation 4 under the assumption of a single defective phase.

$$\gamma = \frac{\Delta I}{I_0} \approx \sqrt{(\Delta \tan \delta)^2 + \left(\frac{\Delta C}{C_0}\right)^2} \quad (\text{Equation 4})$$

γ - parameter Gamma or imbalance

$\Delta \tan \delta$ - tangent delta change

$\Delta C/C_0$ - relative change in bushing capacitance

Equation 4 tracks relative changes in power factor and capacitor from a base value, typically their offline test values.

Influence of Voltage Unbalance

System voltage unbalance is one of the main contributors to the method accuracy. Voltage unbalance is a condition in which the three-phase voltages differ in amplitude or are displaced from their normal 120° phase relationship or both.

A variation in system voltage creates an unbalance and may be interpreted as capacitance or power factor change. Magnitude variation may be interpreted as capacitance change and phase shift changes as power factor.

Accounting for the influence of the voltage unbalance effects on the capacitance and power factor, Gamma's equation can be rewritten as Equation 5, assuming a change in one phase again.

$$\gamma = \frac{\Delta I}{I_0} \approx \sqrt{(\Delta \tan \delta + \Delta \phi)^2 + \left(\frac{\Delta C}{C_0} + \frac{\Delta V}{V_0}\right)^2} \quad (\text{Equation 5})$$

$\Delta \phi$ - change in phase shift

$\Delta V/V_0$ - relative change in system voltage

For changes in all phases, the equation must use vector summations. Gamma reacts only to asymmetric changes in the system voltage. All symmetric voltage changes will compensate each other (the same increase of all voltage magnitudes, for example, will not disturb the balance).

Therefore, the method's accuracy depends on the statistics of the asymmetric voltage variations in the location.

Field Study on the Effects of Voltage Unbalance

To study voltage unbalance effects, continuous measurements were performed at four locations across the United States for 6 to 8 weeks. At Location 1, three single-phase

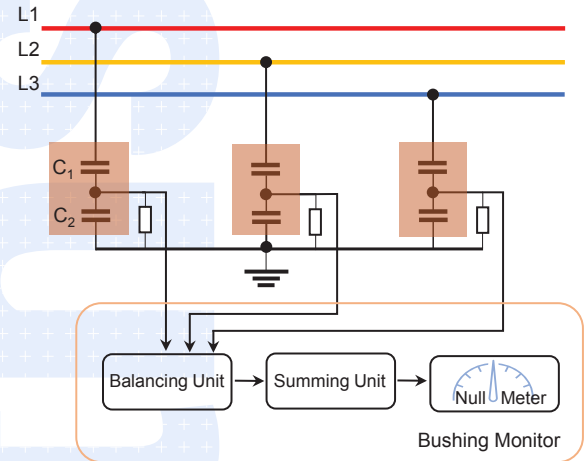


Figure 4. Bushing monitoring: Sum-of-currents method

transformers were in a three-phase bank with the bushing in each phase of different make and age. The initial power factor difference between the bushings was about ten percent. This example represents the worst-case scenario for any bushing monitoring method. At the remaining locations, the transformer type and bushing voltage ratings were chosen to represent normal configurations.

Table 2 is a statistical summary of the phase shifts estimated from units in four locations. Due to space limitations, the nameplate information of the transformers and bushings are not shown but can be found in [3].

During the field studies [2], the gamma value was <0.5% for Locations 2 to 4 and <0.8% for Location 1.

Estimating the Accuracy of Power Factor and Capacitance Measurements

Assuming the dataset follows the normal distribution, the mean plus two standard deviations represent 95th percentile values. 95th percentile for phase shift was <0.4°. This means 95% of data points are below 0.4°.

An exception was Location 1, a particular case where the unit was installed on a bank of three single-phase transformers where the make, model, and age of the bushings on all the three phases were different: for example, the bushing nameplate capacitance of phases A and C were 470 and 543 picofarads, respectively.

Field measurements across multiple U.S. sites reveal that errors in power factor and capacitance measurements due to asymmetric voltage variations are <1%.

	Unit #1 Loc. #1		Unit #2 Loc. #2		Unit #3 Loc. #3		Unit #4 Loc. #4	
Phase-pair	A - B	A - C	A - B	A - C	A - B	A - C	A - B	A - C
Average	0.10°	0.41°	-0.24°	-0.04°	-0.02°	-0.12°	-0.10°	-0.10°
Standard deviation	0.06°	0.06°	0.04°	0.04°	0.12°	0.11°	0.11°	0.10°

Table 2. Statistical summary of a field study on the effects of voltage unbalance

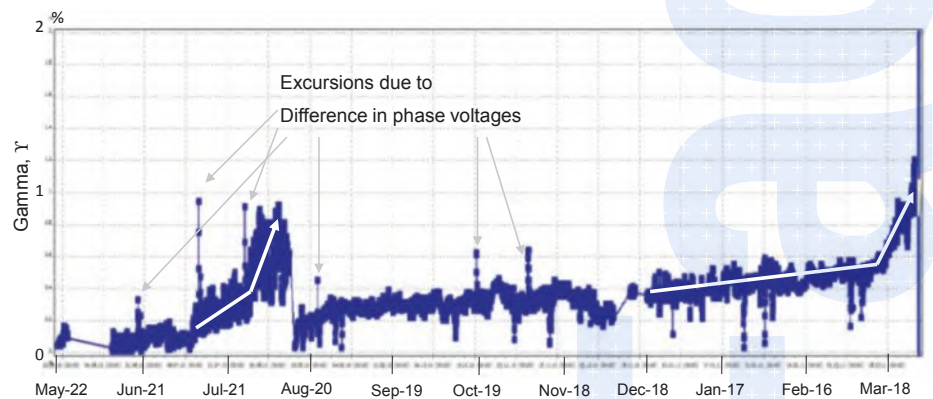


Figure 5. Illustration of the influence of system voltage fluctuations while monitoring a 230 kV bushing

A phase shift of 0.4° represents an error of $\pm 0.7\%$ in power factor calculation. If Location 1 is excluded, the phase shift drops to $<0.2^\circ$, and the error in power factor calculation reduces to $\pm 0.35\%$. That is well below the 1% limit used in the industry to replace OIP and RIP bushings.

During the field studies [2], the gamma value was $<0.5\%$ for Locations 2 to 4 and $<0.8\%$ for Location 1. 95th in Figure 5, which confirms this observation. During the entire 11-month period, the asymmetric changes in the system voltage were less than 0.85 ($\gamma < 1$).

For a hypothetical case of a purely capacitive type defect (short-circuited adjacent layers for capacitively graded bushings), Equation 5 can be rewritten as

$$\gamma^2 = 1 = \left(\frac{\Delta C}{C_0} + \frac{\Delta V}{V_0} \right) \quad (\text{Equation 6})$$

For $\Delta V/V_0$ of 0.01 or 1%, the relative change in bushing capacitance from

the initial value ($\Delta C/C_0$) is 1%. In other words, a one percent asymmetrical change in system voltage causes a one percent change in relative capacitance calculation. The results are summarized in Table 3.

Influence of Temperature

The temperature has minimal effect on the results because, on a three-phase transformer, all the bushings are affected nearly the same way by the heat source, which is the top oil of the transformer.

It is worth mentioning that when evaluating changes in the bushing power factor and capacitance, using the bushing nameplate values must be avoided. This applies to all online methods of bushing capacitance and power factor. Nameplate values are established during the factory acceptance testing of bushings with the bushings tested in a tank different from the transformer tank's size and geometry. A recent report published by HSP [4] reports a variation of 5% to 7% between the nameplate bushing

Diagnostic parameter	OIP & RIP Bushing replacement limit per [1]	All three bushings inside the same transformer tank	Influence of temperature
Power factor / Tan delta (%)	> 1%	± 0.70%	Negligible
Capacitance	> +5% of FAT	± 1.00%	Negligible

Table 3. Summary of dominant influences on sum-of-current method measurement accuracy

capacitance and the capacitance measured after the bushing was mounted on the transformer. This means it is more prudent to use offline capacitance test values from the bushing or transformer site commissioning report as a reference when diagnosing the bushing condition.

Comparison Method – Transformer to Transformer Comparison

This method can be applied when two twin transformers are close to each other and connected in parallel, as shown in Figure 6.

HV bushings installed on the same phase are compared against each other using the capacitive leakage currents, I_{A1} and I_{A2} , measured at their taps. Before starting the test, offline test values of power factor and capacitance must be available for all bushings.

Power Factor Calculation

At the start of the test, both bushings' online power factor is assumed to be the

same as their offline values, $\cos \phi'_1(\text{online}) = \cos \phi_1(\text{offline})$. It is worth mentioning that the bushing power factor depends heavily on temperature, and this assumption may not always be valid.

Next, the online power factor angles for the two bushings are estimated and the difference is established, as in Equation 7.

$$\Delta\theta = \phi'_2 - \phi'_1 \text{ (Equation 7)}$$

As the bushings are not identical, the angle $\Delta\theta$ will not be zero. Furthermore, if the two bushings age similarly, $\Delta\theta$ will remain constant. This means that if the rate of aging is the same for both bushings, aging effects cannot be detected.

The angle $\Delta\theta$ is calculated during the initial learning phase and is taken as a reference value. This value is compared with the online values determined throughout the lifetime of the bushings, $\Delta\theta'$. Considering that the power factor angles, ϕ'_1 and ϕ'_2 , get worse with time, we can state the following:

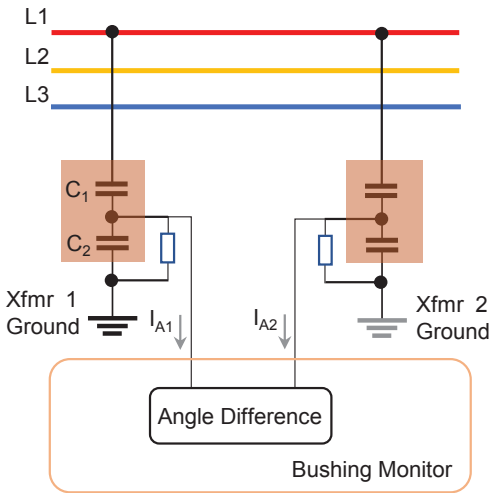


Figure 6. Bushing monitoring: Comparative signal method (two bushings in two separate tanks)

$\Delta\theta > \Delta\theta'$ - showing the degradation of the Bushing 1
 $\Delta\theta < \Delta\theta'$ - showing the degradation of the Bushing 2



The comparison method of bushing monitoring assumes that the online power factor and capacitance test values are the same as their offline values at the start of the test.

Capacitor Calculation

The capacitance of HV bushings is calculated with the Equations 8 and 9.

$$I_{A1} = 2 \cdot \pi \cdot f \cdot C_{A1 \text{ offline}} \cdot V_1 \equiv V_1 = \frac{I_{A1}}{2 \cdot \pi \cdot f \cdot C_{A1 \text{ offline}}} \quad (\text{Equation 8})$$

$$C_{A1 \text{ online}} = \frac{I_{A1}}{2 \cdot \pi \cdot f \cdot V_1} \quad (\text{Equation 9})$$

V_1 is the voltage on the terminals of the two-phase A bushings connected in parallel. $C_{A1 \text{ offline}}$ is the capacitance of the bushing A from transformer 1. Similarly, using Equations 8 and 9, the online capacitance values for all remaining bushings are calculated.

A change in the capacitive leakage currents measured at the taps indicates a change in the bushings' capacitance. The system voltage variations do not affect the

measurement since both bushings are affected in the same way by these variations. The bushings diagnosis is made based on the difference between the capacitance values determined in the offline and online mode, ΔC . This quantity (ΔC) must remain within certain limits.

Influence of the Ground Potential

The bushing monitor is usually mounted on one of the two twin

transformers, separately grounded, and the bushing monitor shares one of the grounds. If there is a difference in the grounding potential between the two transformer grounds, it will cause an additional noise current to flow, as shown in Figure 7, and can cause unpredictable phase errors.

The primary cause for the difference in the ground potential is the electromagnetic field interference from the overhead electric power lines that produce induced voltages on the metal structures like transformers. These are unavoidable and unstable situations that can change by the minute.

During monitoring a bank of three single-phase transformers, our field measurement shows that a typical difference in the ground potential between two transformer grounds is in the range of 100 mV to 300 mV. If the grounding is defective or electromagnetic interference is higher than usual due to the transformer's proximity to the overhead power lines, the differences can be higher. We had one such case on two 100 MVA autotransformers standing next to each other at a 230 kV substation (outside North America), where the difference was a little over a volt.

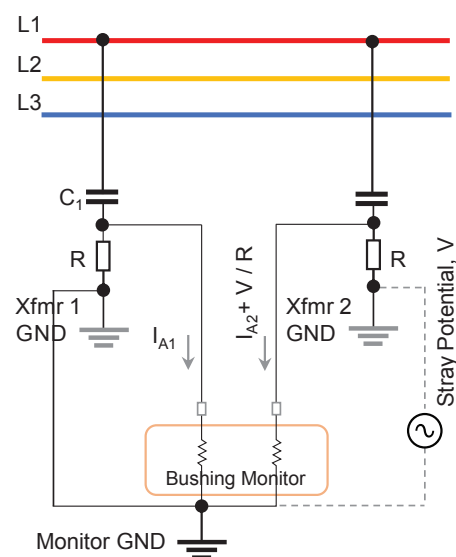


Figure 7. Influence of the ground potential

For a bushing C_1 capacitance of 500 pF, the terminal voltage of 345 kV, and sensor impedance of 2000 ohms, the noise current would be 0.3% of the test-tap current. According to Equation 9, this would result in an error of 0.3% in the capacitance measurements. Assuming that an amplitude change of 0.3% causes a phase shift of 0.3 degrees, the error in power factor measurements would be 0.5%.

Influence of Harmonics

In our discussions, odd harmonics alone are relevant as even harmonics only appear when there is no half-wave symmetry in the power frequency cycle. Harmonics affect all measurement methods, and the measurement accuracy is heavily dependent on the technology used in the instrument for suppressing them. That also applies to offline bushing power factor and capacitance measurements, and its measurement accuracy is also questionable.

The traditional definition of power factor, which holds only for a pure sine wave, is the cosine of the phase difference between fundamental frequencies of voltage and current and calculation based on the time

displacement of current and voltage waveforms. The actual power factor is the ratio of active power used and apparent power, and higher than the power factor calculated using the time displacement method. This underestimation of the power factor results in accuracy loss.

Capacitance calculation uses frequency (see Equation 1), typically estimated from the bushing leakage current waveform using the principle of zero cross detection, as illustrated in Figure 8.

Suppose the sine wave has several high-frequency harmonics. In this case there will be multiple zero crossings near the actual zero crossings of the AC signal, and the error in frequency calculation will directly influence the measurement accuracy.

Closing Notes

Over two-thirds of electrical utilities surveyed by CIGRE replace OIP and RIP bushings when their power factor exceeds an absolute limit of one percent. This demands a measurement accuracy below half a percent to avoid false positive or negative results.

The review of the three popular practices for the online bushing power factor and capacitance measurements shows that none of the three can guarantee accuracy under half a percent for all situations. Therefore, the industry must use alternate metrics to evaluate power factor changes in bushings.

The extent of the change in bushing C_1 capacitance reflects the number of short-circuited layers in the total number of grading layers in the bushing core. Most bushing manufacturers recommend at least a 3% change in the C_1 capacitance value from the factory acceptance test even to start an investigation. That demands a minimum measurement accuracy of $\pm 1.5\%$ in the bushing C_1 capacitance, and only some methods can meet this condition under certain situations. A study by HSP [4] reports that stray capacitance can significantly influence the bushing C_1 measurements, which must be accounted for when investigating the capacitance changes in a bushing.

Using a potential transformer in the reference signal method leads to additional loss in the measurement accuracy. In certain conditions, as elaborated in the article, the measurement accuracy can be even worse than with other methods.

The field measurements across multiple sites in the United States show that the system voltage variations between phases are less than one percent. Its effect on the accuracy of the power factor and capacitance measurements using the sum-of-currents method is within one percent. Even if these variations were to double, the accuracy is within the accuracy of the other methods.

In sum, multiple factors influence the accuracy of bushing capacitance and power factor measurements, and no discussed method has a specific advantage over another.

Our experience in monitoring RIP and RIS bushings shows that their time to failure is relatively shorter than that of OIP bushings after a

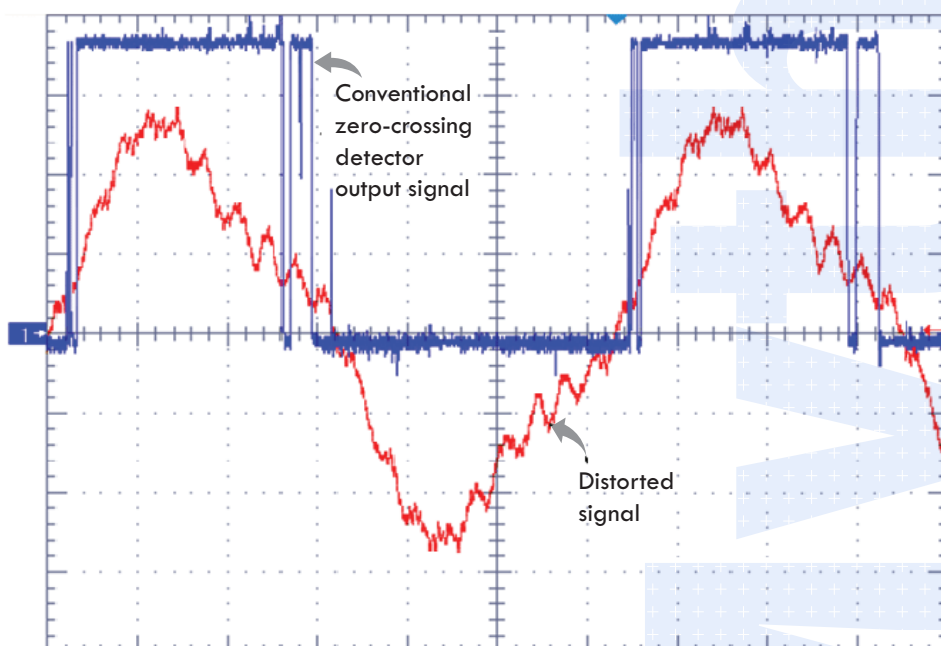
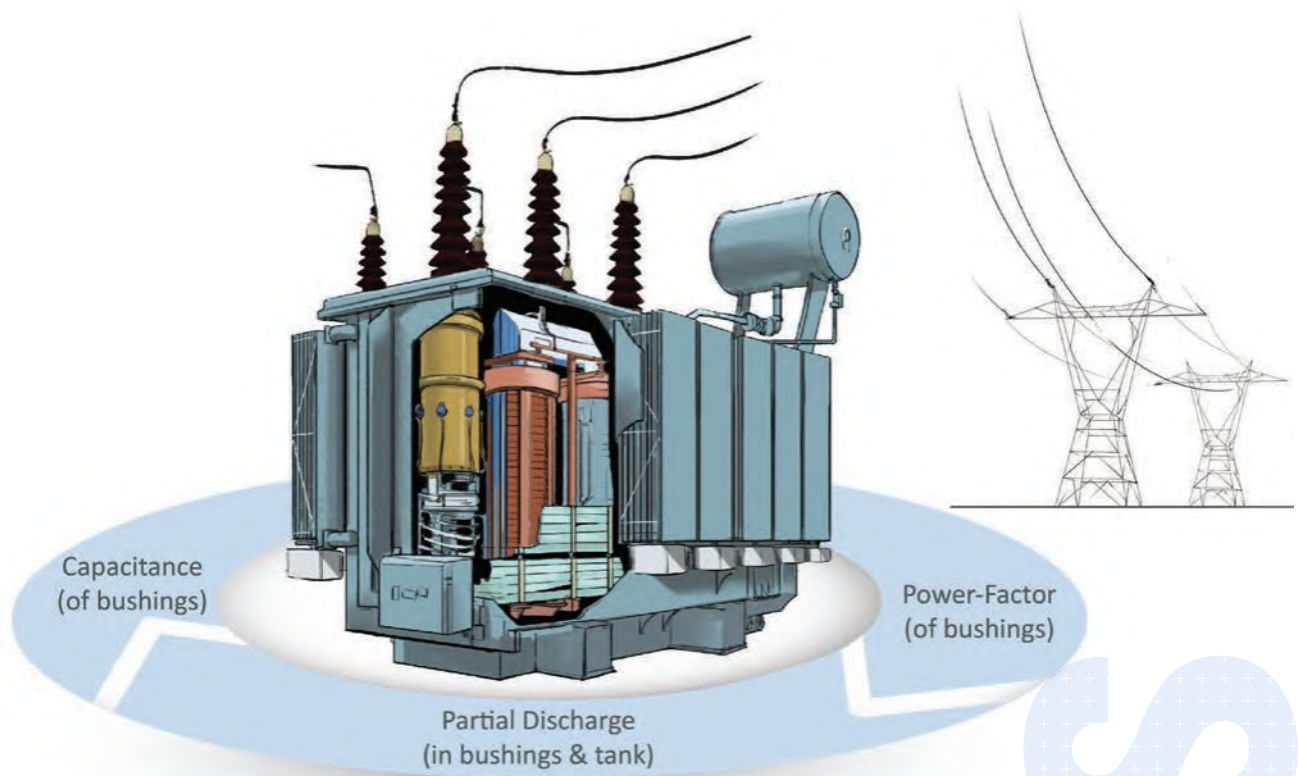


Figure 8. Influence of harmonics (used with a written permission from the authors [5])

measurable increase in C_1 capacitance has occurred. Therefore, it would be beneficial to invest in complementary techniques to monitor bushings. Also, our experience in monitoring bushings using the traditional partial discharge (PD) measurement method shows

that this method identifies developing problems in the bushing core relatively earlier than the bushing C_1 capacitance measurement method. A common misconception is that sensitive online PD measurements cannot be performed, and incorrectly based on

comparison to PD levels measured in the factory. Our experience in PD monitoring, having monitored over a thousand of bushings, reveals that defects inside bushings have PD amplitudes in hundredths and thousands of pico-coulombs.



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Multiple factors influence the accuracy of the bushing capacitance and power factor measurements, and no method has a specific advantage over any other. Therefore, it would be beneficial to invest in complementary techniques to monitor bushings.

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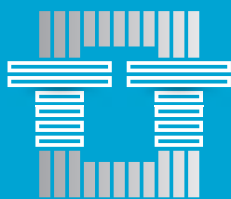
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