Transformers

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MAGAZINE

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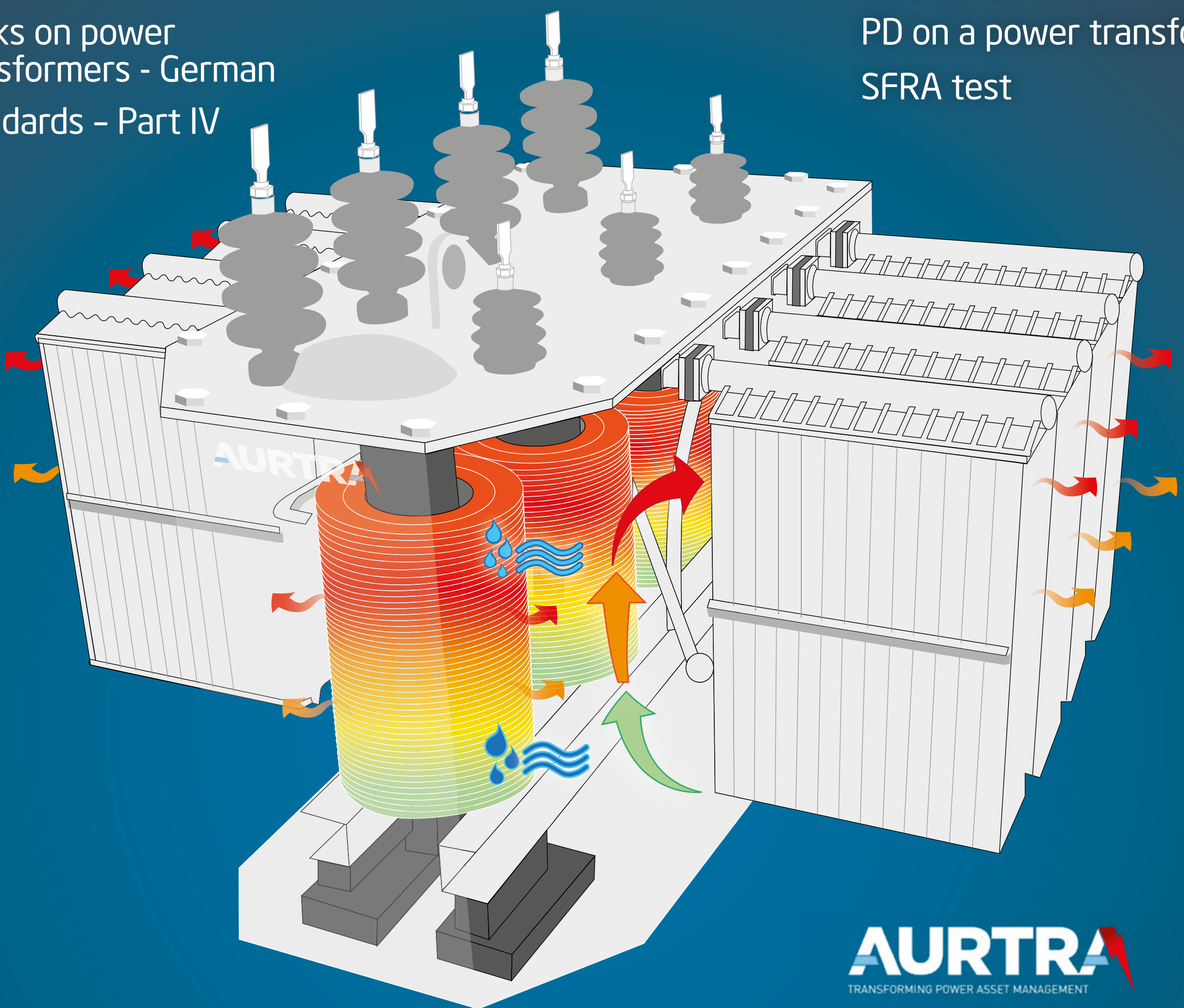

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Oweld's 40 years ▪ Transformer insulation risk and remaining life

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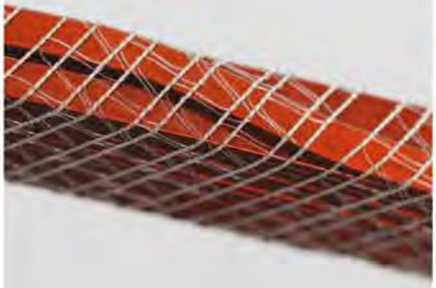
Insulated Rectangular Copper Conductors used in Windmills

Enamelled Round Wire Applications

- Auto Electricals
- Motors
- Consumer Durables
- Transformers
- Switchgears

Continuously Transposed Conductors



Insulated Rectangular Copper & Aluminium Conductors

Enamelled Round Wire Copper / Aluminium

CTC used in Transformers

Insulated Rectangular Conductor Applications

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- High Voltage Motors/Generators
- 765 Kv Transformers and Reactors
- 1200 Kv Transformers
- Traction Transformers
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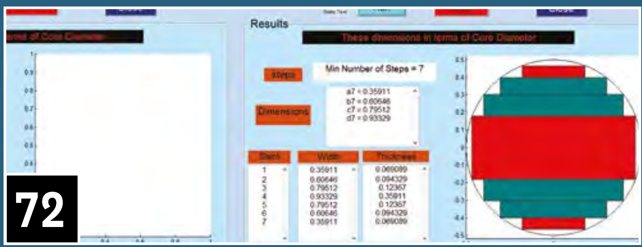

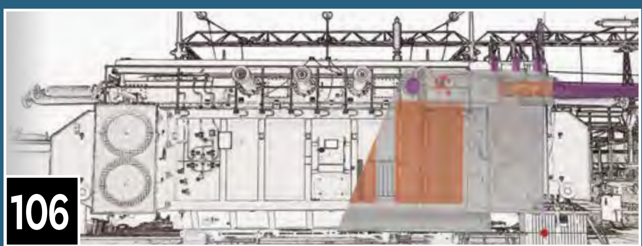

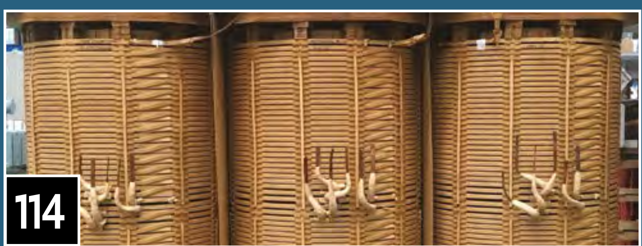

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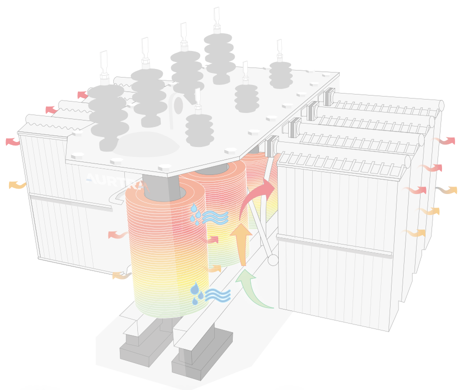


Dear Readers,

While writing this message nearing the end of 2020, I think back of the previous years in Transformers Magazine, when we frequently wrote of the market dynamics, upcoming changes, their impacts and risks for which we all needed to prepare ourselves, as well as of the best ways to get prepared for those changes and risks. First and foremost, we emphasized the importance of innovation and market communication.

Even so, only a year ago, it was very hard to imagine all the changes that have happened in the meantime. Those changes, to which we and our associates have often pointed out, could have easily caught us off-balance. Luckily, we started developing our innovation, by which I primarily mean Transformers Academy as well as other solutions, early enough to be prepared at the crucial moment not only to face our own challenges but also to respond to the challenges that our associates and customers have faced. The thing we always like to point out is that a great majority of these solutions has come to life with the support of our associates and key customers and much of the credit for everything we do goes to them.

If I had to sum up our most important results, I would first have to mention the launching and positioning of Transformers Academy as an outstanding e-learning and digital cooperation platform within our niche. In only a couple of months it hosted around 30 top quality sessions and we have recorded more than 7,300 registrations. A number of new high-quality programmes and some completely new opportunities are already being prepared.

We have had equally valuable achievements with our magazine, having published around 80 articles of exceptional quality, as well as an abundance of other material. The number of followers on our social networks has increased by about 25 %, the number of website visitors by approximately 30 %, average visit duration has increased by over 30 %, the number of newsletter subscribers by about 50 %, the number of page sessions by around 90 %, etc.

These growth rates were difficult to imagine a year ago and they have been the best indicator of how Transformers Magazine, Transformers Academy and Transformers Forum have jointly allowed for a unique synergy of innovation and market communication applicable to basically all company profiles on our market. These growth rates also play a significant role in reference to the materials that we publish, for they guarantee excellent visibility and a global reach. More importantly, the high ranking of our platforms has contributed to the high ranking of the material we publish, because they reflect the integrity and work ethics of all our associates, for which I am especially grateful, and I am very proud of them.

Finally, I wish to invite everyone who wants to be a part of this inclusive, ever-growing story to contact us. Here, you will have many opportunities for learning and development through subscription to the magazine and educational programmes of the academy, as well as for presentation of your solutions through articles in the magazine and academy e-lessons, but also an opportunity for innovation that we are always willing to support, so feel free to send your suggestions and ideas.

May you find this issue a useful and pleasurable read. I wish you all good health, happiness, and prosperity in 2021.

Mladen Banovic, Editor-in-Chief

NovAcec Services is a company offering installation, maintenance, repair and refurbishment for transformers and tap changers worldwide. As a total solution provider, NovAcec also delivers lifetime extension programs, training, spare parts and oil analysis.

VERONIQUE LANDRAIN

Managing Director at NovAcec Services

Veronique Landrain is the Managing Director of NovAcec Services S.A. Prior to that, she worked at Pauwels Trafo Services, holding various positions in the company from 2008. The company became CG Holdings Services in 2009 and from 2014 to 2020, Veronique Landrain held the position of General Manager.

She holds a master's degree in environmental science and in physical sciences from Universities in Belgium.

Re-branded experience

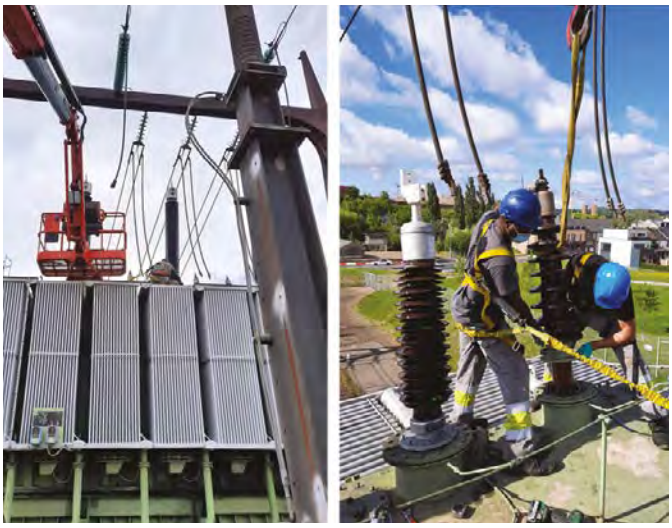
NovAcec Services is a transformer service company founded in March 2020, having acquired the business activities and the experienced team of the former CG Holdings Services division after bankruptcy of CG in Belgium. The company was created with the support of a Belgian industrial investment fund and Veronique Landrain as the managing director.

The history of the company goes all the way back to the 1980s, drawing its origin from the ACEC company and from the Pauwels Trafo Service company founded in 1986, which became CG Holdings Services in 2009. Hence, it is a succession of companies that has led the experienced service staff to NovAcec Services.

NovAcec Services employs about 35 employees, former experienced engineers and technicians from CG Holdings Services. It is important to note that we are able to offer our services all over the world and on all types and brands of transformers and tap changers.

One-stop shop for transformer services

NovAcec's main activities are services for transformers of up to 750 MVA and 400 kV that include installation and relocation, on-site preventive and corrective maintenance, repair works on-site and in our state-of-the-art repair shop of 3000 m2 in Charleroi, refurbishment, expertise, measurements and tests, lifetime extension programs for shell and core-type transformers, oil sampling and analysis, spare parts supply and trainings. Essentially, our team of experienced engineers and technicians offers the following services rela-



NovAcec's state-of-the-art value-added service and asset management solutions

Full retrofit of 400 kV transformer

NovAcec has exclusive access to drawings of ACEC, CG and Pauwels transformers manufactured in Belgium, which provides us a direct insight into technical details of these transformers, regardless of where they are installed

ted to transformers and tap changers:

- Installation, relocation and commissioning
- Expertise, oil analysis, tests and measurements
- Preventive and corrective maintenance
- Repair on site or in our repair shop (leak repair, active parts repair, replacement of accessories, painting, etc.)
- Oil treatment and oil refills
- Upgrade and replacement of tap changers and motor drive units
- Modification, manufacturing and installation of cable boxes
- Upgrade or replacement of cooling systems, replacement of HV, MV, LV bushings
- Lifetime extension programs for tap changers and transformers up to 400 kV
- Spare parts delivery
- On-demand trainings

Our repair shop, located in the south of Belgium (Charleroi), is equipped with a crane of 175 t capacity and a full equipped test bay, which allows us to repair all types of transformers, from distribution to power transformers up to 400 kV. This dedicated repair shop is particularly important when repair cannot be performed at a customer site, which is often the case when we need to intervene on active parts of transformers.

We can perform maintenance and repair, on site and in the repair shop, for all brands and not only for our main brands ACEC, Pauwels and CG. Since we now own the ACEC brand for transformers, we have access to drawings of all transformers manufactured in Charleroi and in Gent under the brand ACEC. Given that these transformers are still present on different markets, in Ireland, Belgium and in other countries, in Africa for instance, we continue to offer our services for this specific brand.

Also, in terms of brands, since we have acquired CG Holdings Services, we have negotiated to have an exclusive access to the drawings of CG and Pauwels transformers, which were manufactured in Belgium. This means that we can offer appropriate and accurate repair, maintenance and spare parts deliveries for these units to our customers all over the world. The fact that we have access to technical details means that we can precisely and rapidly define what has to be offered to the customers to satisfy their needs.

We also have a dedicated new oil analysis laboratory in the north of Belgium (Kontich). Decades of experience have showed us that having an own lab that can analyse the condition of the insulation oil of a transformer is critical for any transformer service providing company, not only to gain know-how to evaluate the status of the insulation and provide reliable con-

NovAcec repair shop – 3000 m^2 and 175 t crane

NovAcec lab for transformer oil analysis

ditional maintenance, but also to be able to keep the whole process of sampling-measuring-evaluating-intervening and saving a transformer in hand and react rapidly.

Our team of 35 people includes specialists with long-term experience in transformer business, services and operation. We have experts in our technical department with over 30 years of experience, which gives us potential for a large offer in the repair and maintenance business. Among other things, we are able to conduct studies for cooling systems and we also offer full retrofits of transformers, extending the lifetime of critical assets belonging to our customers. For example, we can inspect and re-tighten active parts of 400 kV shell type transformers and renew all critical accessories (bushings, cooling systems, etc.), allowing them to operate about 20 years longer than they usually would. This is all thanks to our technical department, as well as our experienced technicians.

Focus on our new oil analysis laboratory

Most clients primarily want sampling, a clear evaluation and report of the status of their transformer and oil, but most of all, they also like personal contact and background information when they have questions about the results.

We offer on-demand training sessions for any customer in need of specific training on transformers or OLTCs

In our new laboratory with brand new equipment, state-of-the-art techniques and engineers with over 30 years of experience, our customers get full service, ranging from sampling to evaluation and advice.

On account of our huge experience in transformer measurements and evaluations, we can guarantee high accuracy of results and evaluations and we can provide these services quickly at very competitive rates.

Most labs are experienced in measuring oil and DGA and use evaluations based on statistics and in line with standards, but they have seldom seen what actually happens inside a transformer. We, on the other hand, have both: more than 30 years of experience in measuring transformer oil and knowledge of transformer design, materials, weak points, etc. Due to our vast experience in transformer manufacturing, evaluation and services, we can use our knowledge of electrical and thermal phenomena in a transformer and their effects on oil, insulation and, eventually, gassing.

For more than 30 years, we have been correlating DGA results with actual faults inside a transformer and now we know what kind of DGA image an actual fault in a transformer can create. For this reason, we understand transformer failure modes very well.

Our task is to keep clients' transformers in good condition and intervene when this is jeopardised. We provide this service based on measurements and knowledge. For the lab, these measurements are a series of relevant measures of oil quality and DGA.

Today, DGA is the most powerful and most effective technique to perform a transformer's health check and determine the type of faults that can be expected. Clients sometimes ask for oil measurements without DGA, which is surprising. One has to bear in mind that oil measurements, such as breakdown voltage, tan delta, acidity and so forth, give you information on the status of the oil, but DGA shows the health status of a transformer. Both are equally important, and NovAcec Services is equipped to deliver both!

In our new laboratory with brand new equipment, state-of-the-art techniques and engineers with over 30 years of experience customers get full service, ranging from sampling to evaluation and advice

Since we use state-of-the-art techniques and equipment, we can provide reliable and accurate measurements.

Following an appropriate method for sampling is also critical to ensure accurate results. Therefore, NovAcec Services also offers on-site sampling by our specialists.

A DGA-measurement method of highest quality

There are different ways to get the gas out of the oil and inject it in a gas chromatograph. Most techniques are based on speed, numbers and general systems, using stripping or the so called "head-space method", in which only a limited part of the gas in the oil is used, and thus a poorer detection limit is achieved. NovAcec laboratory, on the contrary, uses the "full degassing method" where gases are nearly completely extracted from the oil and injected into a gas chromatograph. This results in significantly better (lower) detection levels than with other extraction methods. Low detection limits are important, especially in detecting incipient faults. Another important advantage of the full degassing method is that there is no need for calculations based on solubilities, like in the head-space method. This is very important when measuring insulation liquids other than mineral oil. For instance, one cannot simply measure esters correctly with the head-space coefficients for mineral oil. In general, measuring and evaluation of alternative insulation fluids that are becoming increasingly important in the transformer industry has to be done carefully, taking into account specific aspects of different fluids.

Since we have experience with nearly all modern insulation fluids, we perfectly understand their different advantages and disadvantages and how to evaluate them. It allows us to draw exact conclusions when evaluating measurements.

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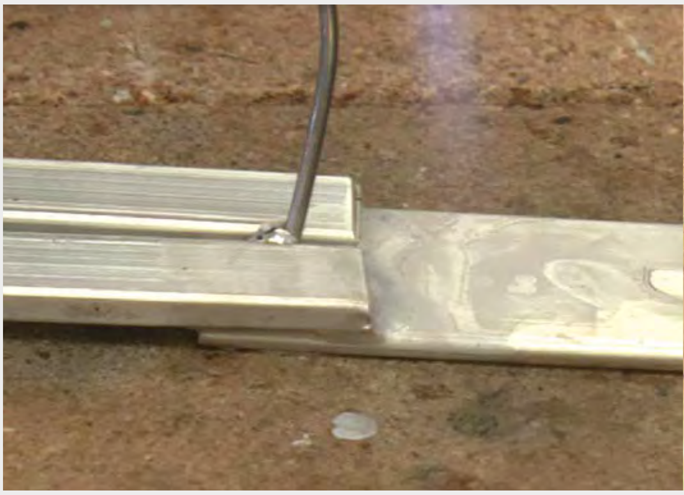
OXYWELD is an Italian company with 40 years of experience in the production of oxyhydrogen gas generators for brazing

40 years of oxyhydrogen gas generators with Oweld

OXYWELD, headquartered in the Italian province of Pordenone, is a company specialised in the production of oxyhydrogen gas generators for brazing. This is a special year because OWELD brand marks its 40th anniversary. By combining passion and innovation, the company has become an important player in this industry. In 1981, Enrico Andreetta, the founder of Oxyweld, set the goal of producing fire from water. The company, which started in a small garage in the town of Conegliano in the northeast of Italy, currently supports thousands of small to large companies in more than 75 countries.

"Oxyweld is extremely proud to be celebrating its 40th anniversary, a significant milestone that few companies manage to achieve nowadays", says Diego Andreetta, Sales Director. "We have overcome many challenges in the past, thanks to our tenacity and efficient strategy. It is particularly gratifying to celebrate this anniversary because the future of the industry looks particularly bright. The demand for environmentally friendly and safe technologies continues to grow, and Oxyweld is at the forefront, building new products and investing significant resources in the R&D".

Oxyweld's environmentally friendly brazing technologies transform water into oxyhydrogen gas and replace the conventional oxy-fuel cylinders



Oxyweld's environmentally friendly brazing technologies transform water into oxyhydrogen gas and replace the conventional oxy-fuel cylinders (i.e., the most common being oxy-acetylene, oxy-propane or oxy-natural gas). In the transformer industry, thanks to the flame properties, the system is specifically designed for the brazing of copper, brass, aluminium, bus bars, cables and wires ranging from small size up to large cross-sections. The same flame is also used to remove resin from the CTC (continuously transposed cable) in the power industry.

From the safety aspect, the system works at low pressure, below 0.5 bar, without storage gas because it is produced only on demand. Without optical radiation and toxic fumes from the flame, operators can work more efficiently and in a safer environment. In addition to that, Oweld products are adopted for the simplicity of usage and superior comfort in brazing, thanks to a light torch.

40 years and beyond

As history has proven decade after decade, Oweld's mission has always been to create products that combine the highest standards of brazing quality and reliability of equipment. The people at Oxyweld continuously pursue the philosophy of total quality management along the manufacturing process to guarantee the best product possible for the customers. The Andreetta family is working on significant reinforcement of ripe markets in Europe and the USA and on the expansion of its sales presence with strategic collaborations in new markets.

With a strong spirit of innovation and avenues of growth on the horizon, Oxyweld moves on to the future.

"This anniversary gives us more enthusiasm and a positive charge for the future. I would like to express thanks to all our internal collaborators, the global sales network, customers, stakeholders and friends for their continued commitment to Oxyweld. We hope to be able to share the celebration of our 40th anniversary with you throughout the year" concludes Diego Andreetta.

A preview of the new 40th-anniversary logo that will accompany Oxyweld throughout the year is available on oweld.com website. Below some pictures of Oweld equipment.

From the safety aspect, the system works at low pressure, below 0.5 bar, without storage gas because it is produced only on demand

ABSTRACT

Estimates of the future demand for transformers have been revaluated due to the global COVID-19 pandemic and related economic recession. The analyses have been made for generator transformers, transmission transformers and distribution transformers. Studies show that the electrical capacity installation growth is stable for the last 30 years despite the fluctuations in the global economies which leads to the conclusion that there will be no dramatic disruptions on the transformer markets.

KEYWORDS

COVID-19, GDP, installed capacity, prediction, transformer market

Steve AUBERTIN

Previous, pre-COVID-19 analyses and estimates projected the average yearly growth rate (CAGR) of the transformer's market to be 3.48 % up to 2028

Transformer demand from 2019 to 2029 and beyond

The impact of Covid-19 on future markets

The purpose of this analysis is to assess the future of the global market for transformers following the global pandemic that has swept the world since the start of 2020. Our original estimates were produced during the last quarter of 2019 and therefore pre-dated the pandemic. The scale and ferocity of the spread of the virus became clear during the first and second quarters of 2020, and the disruption to life worldwide is becoming clear. This has prompted a re-examination and a re-calibration of the future scenarios that were being proposed at the start of 2020.

Much has changed in the period between December 2019 and the fall of 2020 and the ramifications of those changes in a few short months will be present – at least for the next 10 years - if not longer.

Pre-Covid-19 the future demand for GSU (generator step-up) transformers was estimated to grow at 3.48 % through to 2028; details are shown in Table 1.

After GDP drop of 5 % on the worldwide level during 2020, The International Monetary Fund estimates recovery in 2021 and the growth of 4 %

These estimates produced in Q4 2019 need to be reviewed in order to estimate demands following the disrupted period and its impact on future growth. The generator step-up transformer demand differs from other transformers' utilities demand principally because it is capital expenditure-driven and closely linked with GDP growth, whereas the system and distribution transformer segments are disproportionately affected by operational expenditure in addition to capex. The change in the forecasts for these segments are discussed later in this article, but firstly it is logical to reset the GSU forecasts.

The original forecast CAGR for generating capacity from 2018 to 2028 was estimated to be 3.48 %. This took into account the relatively low growth rates in fossil and nuclear capacity and the high growth rates expected for renewable technologies. When computed to include the replacement of redundant plant during the forecast period and the power factor effect on generating MVA, we calculated that this would result in a total 10-year demand of 4,238 GVA of GSU capacity.

The International Monetary Fund has recently published a June 2020 update to the World Economic Outlook series of publications. This edition revised the projected growth and GDP forecasts from the earlier April edition downwards. The details by major regions are shown in Table 2.

Fig. 1 graphically illustrates the short-term forecasts.

Given that most generating plant development projects are planned several years ahead of commissioning and that GSU transformers are ordered over a year in advance of grid synchronisation on the face of it, the industry activity should be able to "bridge the gap". Projects in design or in construction phases may be subjected to delays caused by Covid-19 restrictions, but it looks as though GSU transformer demand may not be impacted too greatly. However, the future – and these forecasts – are far from certain and will depend on a number of factors, including speed of recovery, second or subsequent virus waves, government spending / debt, world commodity and oil prices, etc. The June review does explore some of these scenarios, and as a result, the recovery illustrated in Fig. 1 may be delayed but up to 3, 4 or 5 years into the future. In this case, the ability of the industry to "bridge the gap" will definitely be compromised to the point that if global electricity demand does not increase, the need for new generating capacity will also largely disappear.

On the basis that if we do not know what the future will be, let us look back to see if history can provide any valid indication that will help with the analysis. There have been many recessions, conflicts and periods of negative growth, but only a few during the period of time when electricity has been a major utility product. The 1914–1918 war and the Wall Street depression of the 1920s were globally devastating but probably too far back in time to shed light on the 21st centu-

Table 1. Forecast global capacity totals 2018 to 2028 by type GW

Capacity type	2018	2028	Increase in capacity GW	2028 % of total	CAGR %
Nuclear	360.4	395.4	35.0	4.1 %	0.93 %
Fossil	4,258.9	5,323.0	1,064.1	54.9 %	2.26 %
Hydro	1,123.2	1,383.5	260.3	14.3 %	2.11 %
Renewable	1,147.3	2,593.9	1,446.7	26.8 %	8.50 %
Of which:					
Wind	505.3	1,064.5	559.2	11.0 %	7.7 %
Solar	466.2	1,294.2	828.0	13.3 %	10.8 %
Biomass	131.8	214.8	83.0	2.2 %	5.0 %
Total additional capacity	**6,889.8**	**9,695.9**	**2,806.1**	**100.0 %**	**3.48 %**

Table 2. GDP estimates 2017 to 2021

Real GDP estimates and forecasts 2017 to 2021					
(Percent change from previous year)	**2017**	**2018**	**2019e**	**2020f**	**2021f**
World	3.3	3.0	2.4	-5.2	4.2
Advanced economies	2.5	2.1	1.6	-7.0	3.9
United States	2.4	2.9	2.3	-6.1	4.0
Euro Area	2.5	1.9	1.2	-9.1	4.5
Japan	2.2	0.3	0.7	-6.1	2.5
Emerging market & developing economies	4.5	4.3	3.5	-2.5	4.6
East Asia and Pacific	6.5	6.3	5.9	0.5	6.6
China	6.8	6.6	6.1	1.0	6.9
Europe and Central Asia	4.1	3.3	2.2	-4.7	3.6
Latin America and the Caribbean	1.9	1.7	0.8	-7.2	2.8
Middle East and North Africa	1.1	0.9	-0.2	-4.2	2.3
South Asia	6.5	6.5	4.7	-2.7	2.8
Sub-Saharan Africa	2.6	2.6	2.2	-2.8	3.1

Source World Bank

ry. Similarly, the 1973 oil crisis, whilst it did result in a reassessment of fuel strategy in many countries, it happened at a time when the total global GDP was less than 25 % of the current USA total today and happened well before China became the major global financial power that it now is. So, the nearest comparison from which we might learn is the 2008 financial crash that, albeit for very different reasons, constitutes a similarly sudden and globally devastating event.

Fig. 2 shows the year-on-year growth in global GDP and the growth of the global

Based on the data for the 2008 recession, we can see that the global capacity installation continues to grow even during the period of the negative GDP growth

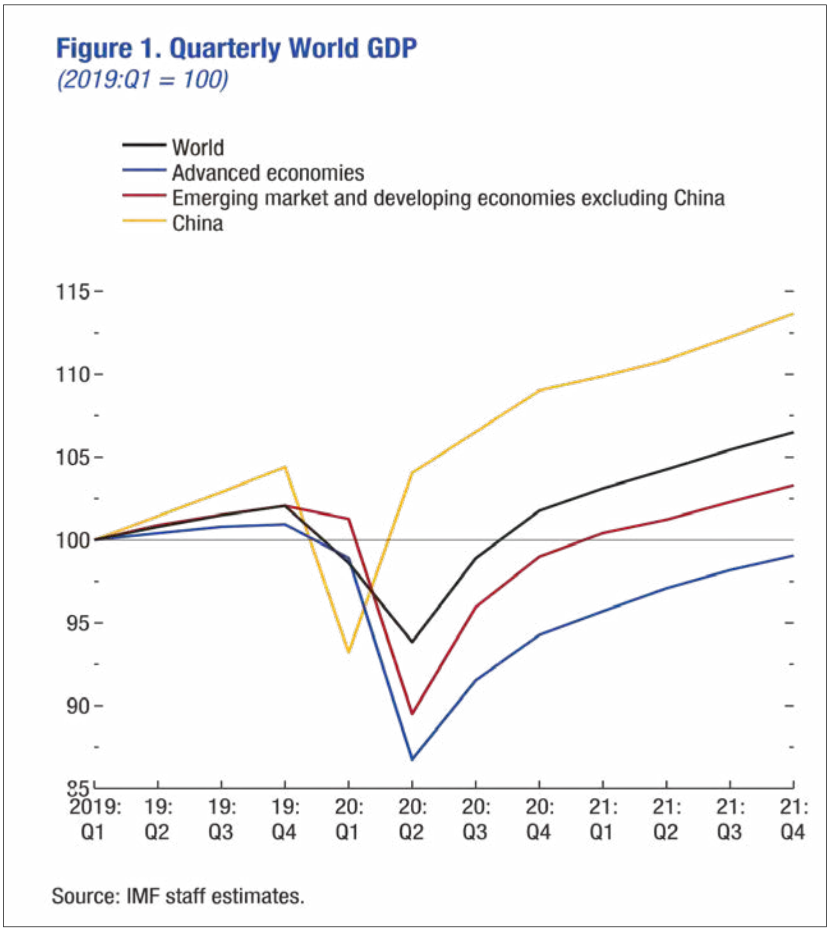


Figure 1. Quarterly world GDP by IMF

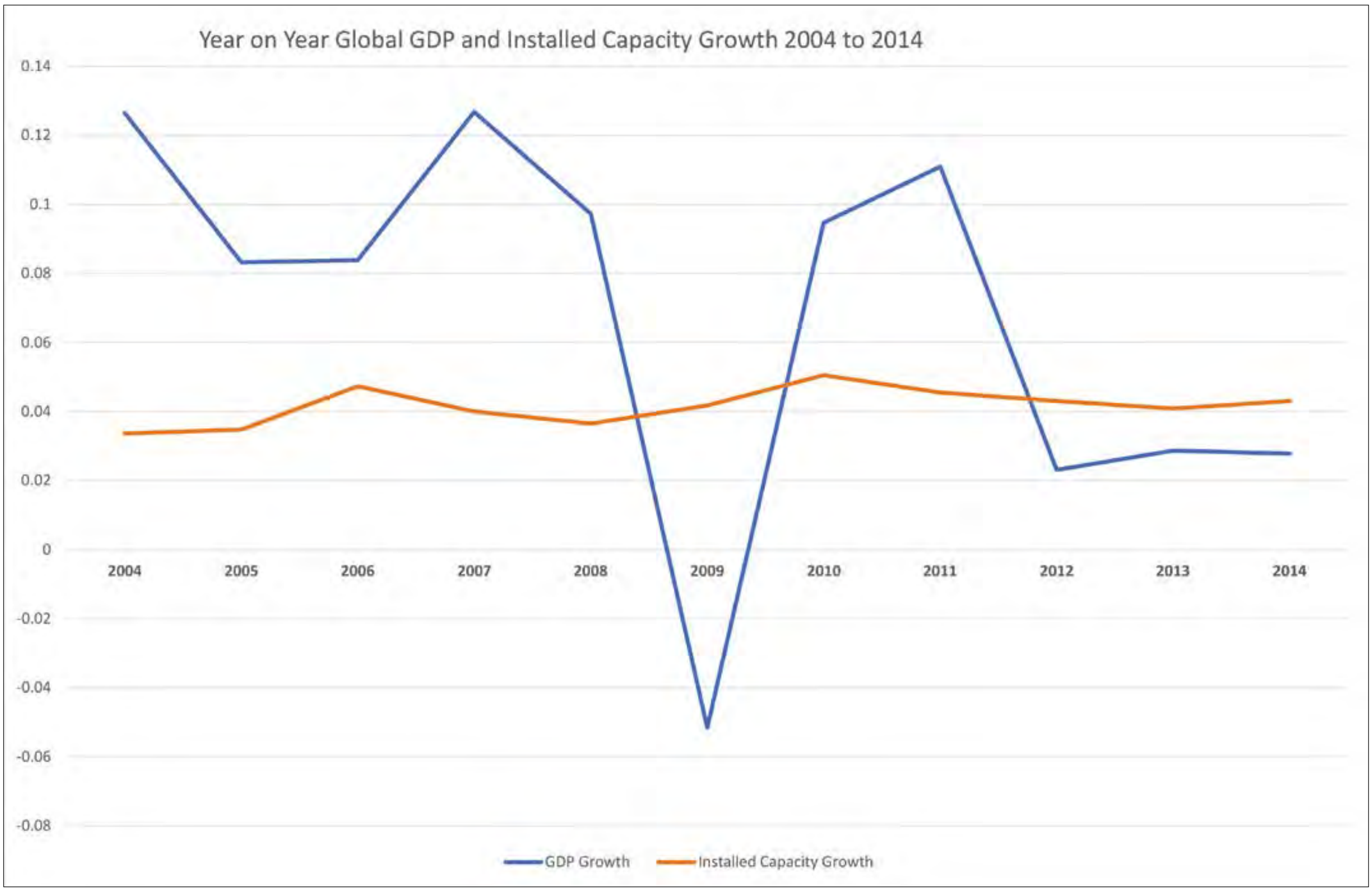


Figure 2. Global GDP & installed capacity growth rate comparison from 2004 to 2014

The global growth of the installed capacities is stable during the last 30 years and has a rate between 1 % and 5 %

installed generating capacity for the period from 2004 to 2014.

The chart in Fig. 2 shows the fall in GDP growth, which started in 2008 and then more dramatically to -5.2 % in 2009. There was a bounce back in 2010 and 2011 but then reduced to a little over 2 % in the following years. Interestingly, the global installed generating capacity continued to grow at over 4 % each year from 2008 through to 2010 when it breached the 5 % level and then remained above 4 % for the remainder of the period to 2014 (for the recorder continued above 4 % until 2018). The recovery of the world's financial system took nearly a decade, and some would say that it has still not fully recovered 12 years later.

It is important to see if this trend is long- or short-term because it may be expected that there will be non-related peaks and troughs in both series. The chart in Fig. 3 provides a comparison over a longer time frame from 1980 to 2019.

The chart covers a period of nearly 30 years, and it can be seen that the more extreme peaks and troughs that occur in global GDP growth are not reflected in the installed generating capacity rates over the same period. In fact, the rate of growth in global installed capacity has remained relatively stable, growing between 1 % and 5 % for the last 30 years. It must be borne in mind that this is installed capacity growth and it does not include replacement plant; a segment which will also be growing in line with the increases in installed capacity – starting at levels thirty years prior to 1980 (see earlier columns for the rationale of replacement rates).

It is fair to conclude, without going into a more detailed examination of the factors that will impact the post-Covid world, that short of the decimation of the global population, or total economic stagnation, the global installed capacity is likely to continue to grow at between 1 % and 5 % for the next 20 to 30 years.

The overall growth rate proposed in January 2020 of 3.48 % between 2018 and 2028 is likely to be valid with respect to the GSU transformer segment of the market. In the immediate short-term period from 2018 to 2023, the growth is almost set in stone due to the long-term nature of the contracts and development projects. At most, there may be a percent below that level. The period from 2023 to 2025 should hold up to the original estimate, but again it may be slightly impacted by decisions deferred during the first half of 2020. However, the effects of government spending on infrastructure projects in order to stimulate economies should ensure that the period from 2023 to 2028 will exceed the current estimates and overall the growth rate of 3.48 % between 2018 and 2028 still looks to be valid. There will, of course, be variations between countries and regions which will mean that manufacturers will need to be quick on their feet to identify opportunities.

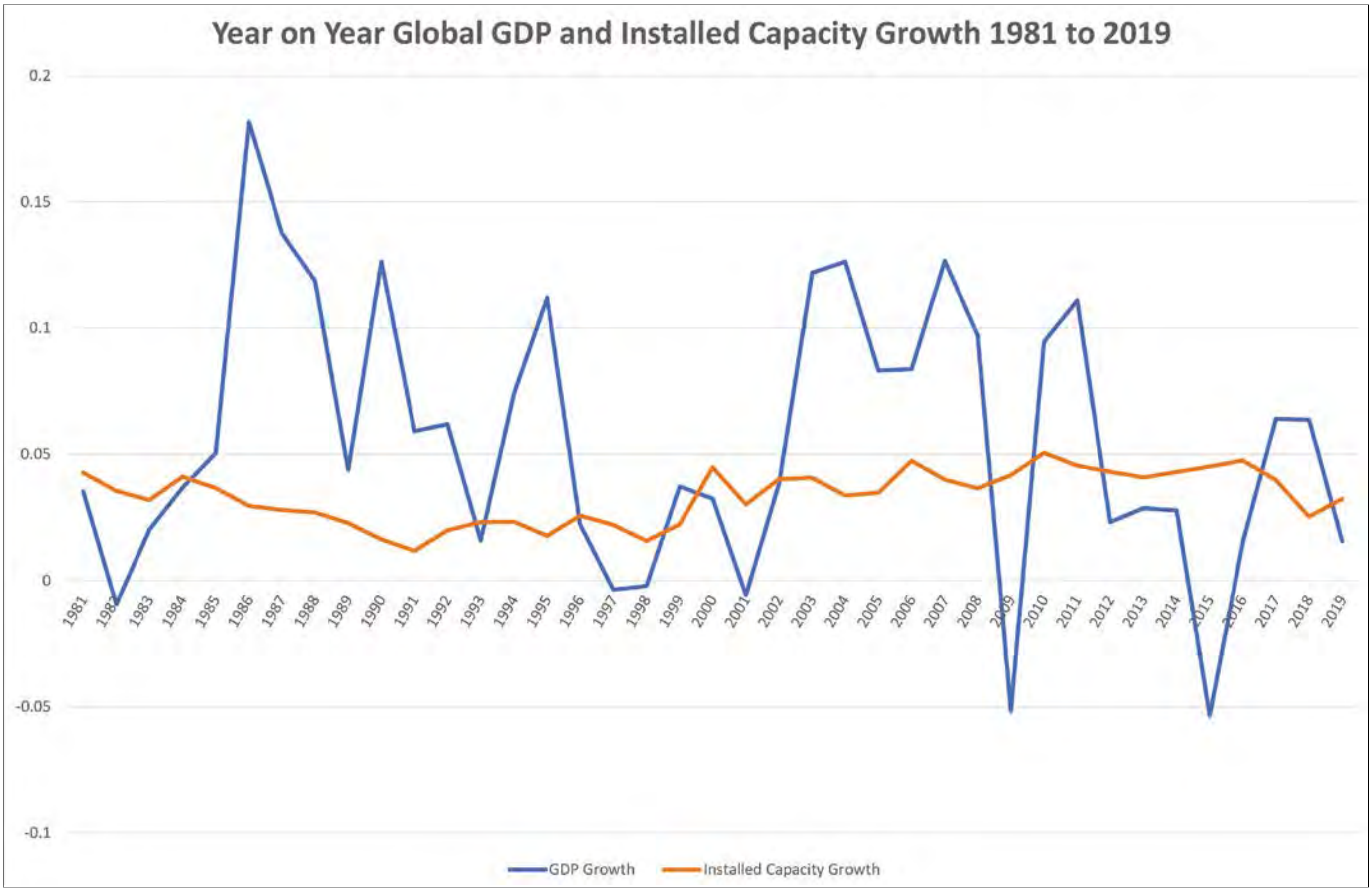


Figure 3. Global GDP & installed capacity growth rate long term comparison from 1981 to 2019

Transmission system transformers

The drivers impacting on the system transformer market are different from the GSU segment. As noted earlier, transmission network development is a mixture of capital expenditure (capex) and operational expenditure (opex). The critical difference between the two is that it is easier for utility companies to quickly cut back on opex than capex and in times of hardship that is what they do. This segment covers a broad range of transformers from the very largest auto-transformers measured in the 100's of MVA down to 10 or 20 MVA (depending on the definition used in each country). There is another factor unique to this segment of the transformer industry; it is also extremely sensitive to industrial investment.

This combination of drivers means that demand is likely to be suppressed, particularly in the more industrialised regions immediately following the pandemic, but it is equally likely to spring back in the medium term supported by infrastructure development. On this basis, it is estimated that the growth rate between

The overall growth rate proposed in January 2020 of 3.48 % between 2018 and 2028 is likely to be valid with respect to the GSU transformer segment of the market

Table 3. Transmission system transformer growth rates from 2019 to 2029

Transmission system transformer growth rates		
Region	**CAGR 2019 to 2024**	**CAGR 2024 to 2029**
Europe	1.12 %	1.48 %
FSU	1.62 %	2.36 %
Asia	4.10 %	5.15 %
S & C America	1.96 %	2.83 %
N America	0.94 %	1.87 %
ROW	2.07 %	2.77 %
World	**2.83 %**	**3.84 %**

It is estimated that the growth rate of the transmission system transformers market between 2019 and 2024 will be 2.83 % CAGR, and it will increase to 3.84 % between 2024 and 2029

2019 and 2024 will be 2.83 % CAGR and it will increase to 3.84 % between 2024 and 2029.

As a result of these suppressed growth rates this global market segment which was worth US$15.7 billion in 2019 will reach just over US$18 billion in 2024 and US$21.8 billion in 2029 (all values in 2019 US$).

Distribution transformers

Of the three, this segment is the most at risk from sudden economic shock. The supply of distribution transformers is principally a commodity business, and orders are often placed on a call-off basis from stock. The market is driven to a lesser extent by grid development in "new installations" or predominantly by maintenance and replacement of existing networks.

In the period post-Covid-19, the demand for distribution transformers is likely to be disproportionately depressed, for many reasons. Labour shortages, the need to reduce utility opex, depressed industrial demand, depressed consumer demand, de-stocking, reduced house building, lack of consumer mobility will all be negative drivers on this segment of the transformer market.

Table 4. Distribution transformer growth rates from 2019 to 2029

Distribution transformer growth rates		
Region	**CAGR 2019 to 2024**	**CAGR 2024 to 2029**
Europe	0.49 %	1.02 %
FSU	1.42 %	1.91 %
Asia	3.09 %	3.87 %
S & C America	1.82 %	1.91 %
N America	0.49 %	0.97 %
ROW	1.91 %	2.32 %
Total	**2.10 %**	**2.80 %**

Summary

Estimates for the transformer market that were produced at the start of 2020 – essentially pre-Covid-19 are shown in the table below compared with revised estimated as at Q4 2020.

The effects of the analysis shown in Table 5 result in a reduction of US$2.5 billion by 2024 and US$4.0 billion by 2029; this represents a reduction of 5 % and 6.5 % respectively.

The change in the overall composition of the market in terms of the type of transformer in 2019 and 2029 are as shown in Table 6 and Table 7.

Table 5. Global transformer market estimates pre- and post-Covid-19 from 2019 to 2029

Global transformer market estimates pre- and post-Covid-19 – Values US$ M					
	Base year	**Original estimate**	**Revised estimate**	**Original estimate**	**Revised estimate**
Region	2019	2024	2024	2029	2029
Europe	5,803.6	6,315.9	6,082.6	6,800.4	6,479.8
FSU	1,632.8	1,840.0	1,780.1	2,047.5	1,975.6
Asia	21,842.5	28,082.5	26,385.6	35,944.5	33,023.1
S & C America	1,911.0	2,170.0	2,116.9	2,472.7	2,390.2
N America	6,696.3	7,298.7	6,991.1	7,852.3	7,503.0
ROW	4,340.3	5,026.8	4,843.8	5,748.6	5,499.0
Total	**42,226.4**	**50,733.9**	**48,200.0**	**60,866.1**	**56,870.7**

Table 6. Global transformer market by type by region 2019

Global transformer market by type by region 2019				
	% Generator	**% Transmission**	**% Distribution**	**Total**
Europe	19.23 %	34.38 %	46.38 %	100.00 %
FSU	26.37 %	28.56 %	45.07 %	100.00 %
Asia	17.95 %	37.60 %	44.45 %	100.00 %
S & C America	25.74 %	38.48 %	35.78 %	100.00 %
N America	15.24 %	40.72 %	44.04 %	100.00 %
ROW	24.55 %	36.37 %	39.08 %	100.00 %
Total	**19.05 %**	**37.22 %**	**43.73 %**	**100.00 %**

Table 7. Global transformer market by type by region 2029

Global transformer market by type by region 2029				
	% Generator	**% Transmission**	**% Distribution**	**Total**
Europe	20.2 %	35.0 %	44.8 %	100.00 %
FSU	27.3 %	28.7 %	43.9 %	100.00 %
Asia	19.6 %	39.1 %	41.4 %	100.00 %
S & C America	26.6 %	39.0 %	34.4 %	100.00 %
N America	16.0 %	41.8 %	42.3 %	100.00 %
ROW	25.5 %	36.5 %	38.0 %	100.00 %
Total	**20.3 %**	**38.4 %**	**41.4 %**	**100.00 %**

Although the distribution transformer market is at most risk, the estimated growth rate of between 2019 and 2024 will be 2.10 % CAGR, with the increase to 2.80 % between 2024 and 2029

The changes do not look that dramatic but because the markets are so large in value terms even a small percentage change equates to millions of dollars reduction in the market and the message is particularly hard for the distribution transformer sector; however, at least the growth is measured in positive rather than negative percentages – albeit only just in some regions.

Author

Steve Aubertin is the Managing Director of Goulden Reports and following a first career in electrical engineering has spent the last 30 years researching and reporting on the global market for electrical products in both published and in the form of tailored research for specific clients.

Geographically, we are covering the area where i-DE operates in Spain, taking care of power transformers from 10 MVA up to 450 MVA, and voltage ratings ranging from 30 kV to 400 kV

Transformer Team (from left to right): Julian Montero, Andrés Aguado, Diego Lumbreras

We are using diverse test equipment to carry out measurements such as Insulation Resistance (IR), Sweep Frequency Response Analysis (SFRA) and Dielectric Frequency Response (DFR)

JULIAN MONTERO

Head of Predictive and Corrective Maintenance for Power Transformers

Victor Lozano, Sales & Application Engineer for OMICRON Spain talked to Julian Montero from i-DE, Spanish distribution system operator, part of IBERDROLA Group, one of the largest power utilities worldwide, about their power transformer maintenance and testing program.

Julian Montero has been responsible for the area of predictive and corrective maintenance within the Power Transformers standardization and maintenance department at I-DE (Group Iberdrola) since 2014. Previously he worked as a project engineer at Elecnor, Gamesa and Iberdrola Engineering, always related to the development of new HV lines and substations in Spain and Brazil.

Dear Mr. Montero, can you briefly explain your role at Iberdrola?

Our work within i-DE is related to the area of maintenance and standardization of Power Transformers. Internally, our group is called NMTP (Spanish acronym standing for Power Transformers Maintenance and Standardization).

This specialized group consists of ten people, divided into three main areas. The first team is responsible for the standardization of new transformers; then we have a team focused on transportation and relocation of transformers; and, finally, a team responsible for maintenance policies, which also leads any significant corrective maintenance. These three areas are coordinated, obviously.

Geographically, we are covering the area where i-DE operates in Spain, taking care of power transformers from 10 MVA up to 450 MVA, and voltage ratings ranging from 30 kV to 400 kV.

In addition to the people mentioned above, there are nine fieldwork teams assigned to the regional operation and maintenance units in five regions, making up a total of 24 people. These fieldwork teams check the proper operation of OLTCs (On Load Tap Changers) and perform electrical testing of the power transformers defined in both predictive and corrective maintenance programs.

What are the most important tools that you are using for these tasks?

We are using diverse test equipment to carry out measurements such as Insulation Resistance (IR), Sweep Frequency Response Analysis (SFRA) and Dielectric Frequency Response (DFR) in order to evaluate the moisture content within the transformer. The main device that we use is the CPC 100, which we use to perform most of the tests.

Currently, there is a total of eleven CPC 100 in service, nine of which are assigned to the regional maintenance units and two are assigned to the NMTP department. We are not using the CPC 100 as an individual unit but combined with CP TD1 to measure capacitance and dissipation factor, and CP SB1 to minimize the connection time and to automate the tests controlling the OLTC. So, our eleven test sets are composed of CPC 100, CP

When a possible problem is detected, it is important to compare the results to the previous tests on the same power transformer, in order to discard a potential endemic parameter of the power transformer

TD1 and CP SB1, plus all the necessary accessories, such as cables and clamps.

What do you mainly use the CPC 100 for?

Our group uses this piece of equipment exclusively for electrical testing and diagnosis of power transformers, although other departments in Iberdrola may use it also for other tasks, such as testing current transformers.

Which tests do you usually perform when testing a power transformer, and how often?

Our maintenance range is based on our own technical manual, which is adapted to the characteristics of each family of power transformers. We currently have more than 2000 power transformers in service, so it is necessary to adapt the maintenance range to what is really needed for each of them.

The predictive maintenance frequency is based on the type of OLTC that every power transformer has. Our Technical Manual indicates that the complete range of electrical tests has to be performed when the OLTC is maintained. This should happen, as specified by the OLTC manufacturer, every three to six years, or, in the case of the new vacuum OLTC, after performing 300,000 operations. In this case, we define a time interval of six years for electrical testing for this type of OLTC.

This maintenance and electrical testing programs are complemented by annual physical-chemical analysis and DGA of the power transformer oil.

Overall, about 400 OLTC maintenances with their corresponding electrical tests, 2000 oil analysis and 2000 DGA analysis are carried out every year.

What electrical tests do you perform?

The type of tests depends on the reason we carry them out. We can distinguish several reasons to conduct these tests: commissioning, predictive maintenance, after oil treatment, and tests after an incident.

In the commissioning tests, we carry out a complete battery of electrical tests: insulation resistance, turns ratio, winding resistance, capacitance and dissipation factor both in the power transformer and in the bushings, no-load current (excitation current) and short-circuit impedance. We also include DFR and SFRA, and we complete these tests with the oil analysis, both physical-chemical and DGA. These chemical and electrical tests will serve as a fingerprint for comparison and trending analysis in subsequent maintenance tests.

If we talk about predictive maintenance, we perform capacitance and dissipation factor at windings and bushings, applying voltage sweep and frequency sweep. Then we measure static and dynamic winding resistance and the turns ratio.

If the tests are performed after an oil treatment, we do the same tests as for the predictive maintenance routine but including a more comprehensive oil analysis.

Finally, after an incident, we measure the capacitance and the dissipation factor on windings, the static and the dynamic winding resistance, the turns ratio, the frequency response of stray losses and the no-load current.

When test results hint at a possible problem, what do you do?

When a possible problem is detected, it is important to compare the results to the previous tests on the same power transformer, in order to discard a potential endemic parameter of the power transformer. For example, we may have a tangent delta of the windings with a rather high value of around 1 %. However, if the tests of the last 15 years have always shown a similar value without evolving, then we do not consider this value to be worrying, but rather a characteristic of the power transformer, normally a constructive characteristic. On the other hand, an increasing value over time would indicate a deterioration in the element being measured. One clear example is the dissipation factor over the frequency in the bushings, where deviations of the values are a symptom of accelerated deterioration. This is especially true for OIP type bushings, in our experience. Here the deterioration can lead to the explosion of the bushing and consequently to the loss of the power transformer and potentially to a dangerous accident.

In these cases, the measurements are usually repeated to confirm the results. An oil sample is also taken to perform a DGA. If the second electrical measurement and the gases confirm the first results, the power transformer is taken out of service. Based on our experience, in more than 95 % of the cases, the DGA confirms the results of the electrical tests.

Why did you choose the CPC 100?

When we decided that we wanted to replace our former test equipment, the CPC 100 was the only instrument that could perform several types of tests. Previously, we had one device for each of the electrical tests. Also, we saw that the CPC 100 had the potential to add more tests in the future without changing the equipment, but simply by adding or updating software. This has been confirmed over time and has been the case, for instance, for the frequency and the voltage sweep for the capacitance and dissipation factor measurement, but also for the dynamic resistance measurement. Another nice feature introduced lately is the possibility to use the Primary Test Manager (PTM) software for other tests with other test devices such as FRANEO 800 and DIRANA.

What do you like most about it?

In our specific case, in addition to the fact that the CPC 100 is technologically advanced, we must emphasize at this point the excellent technical support that we receive from OMICRON, which is fundamental in order to take full advantage of this piece of equipment.

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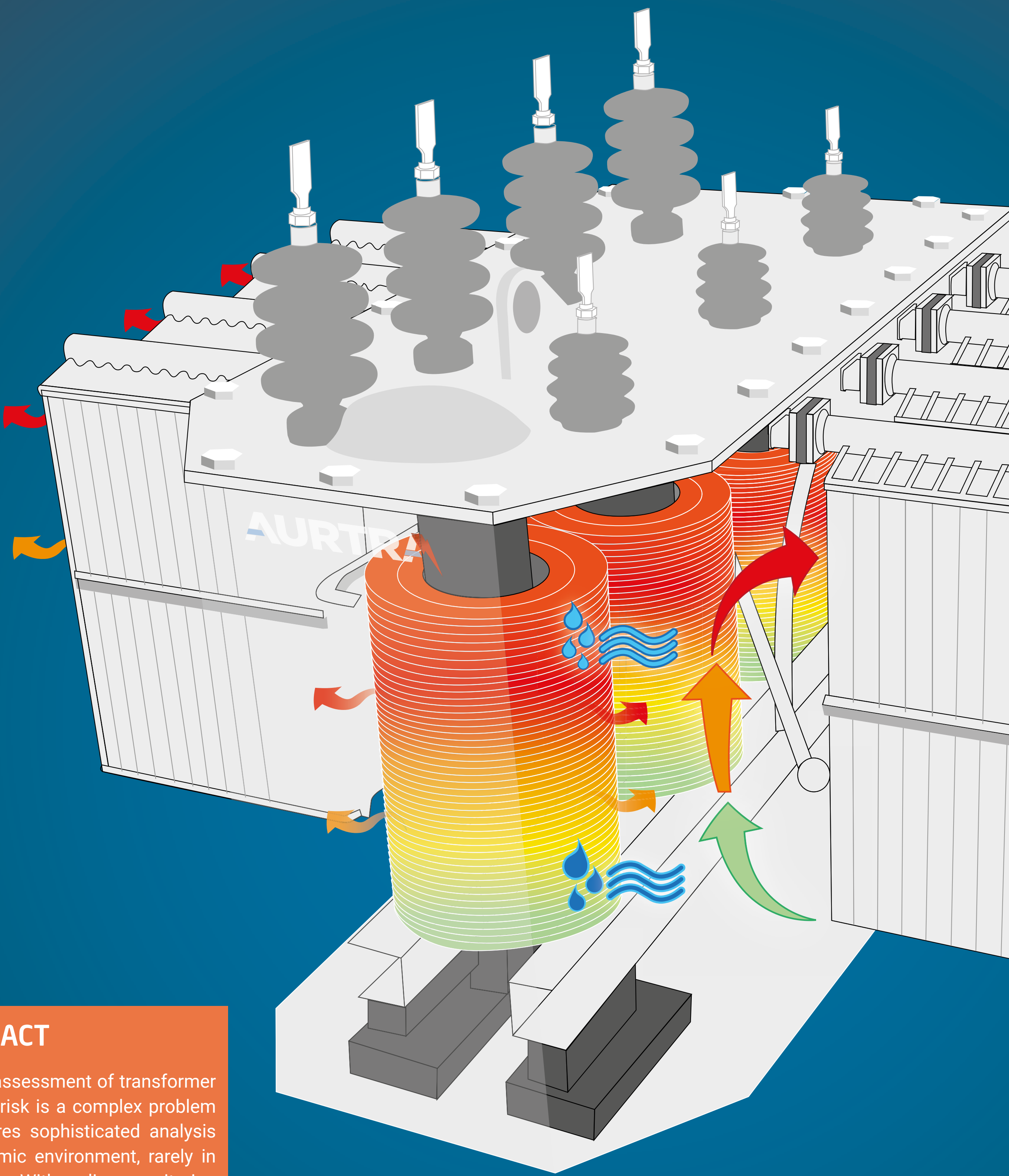


ABSTRACT

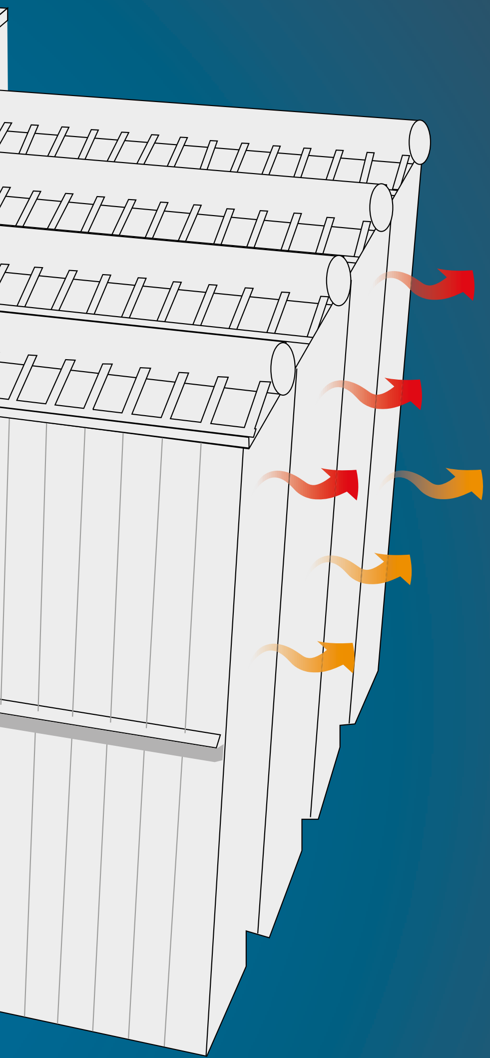
Accurate assessment of transformer insulation risk is a complex problem that requires sophisticated analysis of a dynamic environment, rarely in equilibrium. With online monitoring and an understanding of the detailed relationship between temperature and water activity in both the paper and oil, a complete and useful automated assessment is possible.

KEYWORDS

aging, condition monitoring, depolymerisation, insulation, moisture

Moisture and temperature are the biggest drivers of irreversible transformer aging

Like the complex excitation and loading of an electrical power system, equilibrium is rarely achieved



Accurate determination of transformer insulation risk and remaining life

Introduction to insulation breakdown

Moisture and temperature are the biggest drivers of irreversible transformer aging. The critical issue is that temperature causes polymer chains in the paper to break down. At start-of-life, the paper insulation within a transformer consists of long intertwined cellulose chains, which make it structurally strong, tough and durable to resist mechanical and electrical stresses.

Over time, chemical breakdown of these chains ultimately makes the paper mechanically weak, brittle and unable to withstand normal operating stress. This stress is caused mainly by heating cycles and transient electrical forces. Cracks and breaks become more probable and the risk of electrical breakdown and structural instability increases. Eventually, the structural strength of the paper and pressboard cannot withstand the mechanical stress, and the electrical insulation role it plays is compromised, resulting in a failure of the transformer. Moisture exacerbates this ageing effect. For example, perfectly dry Kraft paper (< 0.5 % moisture and medium oxygen [1]) operated at 80 degrees will last > 20 years before it is critically damaged. Add 2 % moisture and the usable life left falls to 3 years. Add 4 % moisture and it falls to just over one year.

Measuring temperature and moisture

Measuring the temperature of a transformer is relatively easy, in comparison with measuring the water content of the paper. For example, sensors can be located throughout the transformer winding. Alternatively, close estimates can be made from measuring the top oil temperature as it exits the core or enters the radiator.

On the other hand, assessing the water content is much more difficult. Precision requires sampling the paper, which is not possible without removing the transformer from service. Using the measurements from the oil is far more difficult. Water Content of Oil (WCO) vs Water Content of Paper (WCP) relationships have been developed and refined for decades by some of the best practitioners and researchers. Unfortunately, these methods remain prone to serious error for fundamental reasons discussed below.

The diffusion phenomenon

Moisture in transformers is mostly contained in the paper. WCP is measured as a percentage (or parts per 100). WCO is measured in parts per million, ppm. Take the example of a modest size transformer, which may have 1000 kg of paper and 3000 litres of oil. At 3 % WCP, this equates to 30 kg total of moisture in paper. At 3 % WCP, the WCO at normal operating temperatures will be between 10 and 50 ppm, which equates to a maximum of 150 ml of total water in the oil. As a useful rule, 95 % of the moisture in a transformer is in the paper.

The balance between the moisture in the paper and the moisture in the oil is a simple molecular diffusion phenomenon. Effectively, when there is a difference in water pressures across a boundary, water molecules will move from the area of higher pressure to lower pressure. This mathematical theory was developed by Adolf Fick in 1855 (specifically Fick's second law). The pressure of the water in a material divided by the pressure above liquid water, at the same temperature, is by definition the relative saturation or water activity (a_w) [2]. Therefore, the water activity difference across a boundary is in fact the driving force for diffusion (as the denominator is constant). Further, when the water activity in each of the materials either side of a boundary are equal, no diffusion occurs. This is when the materials are in equilibrium.

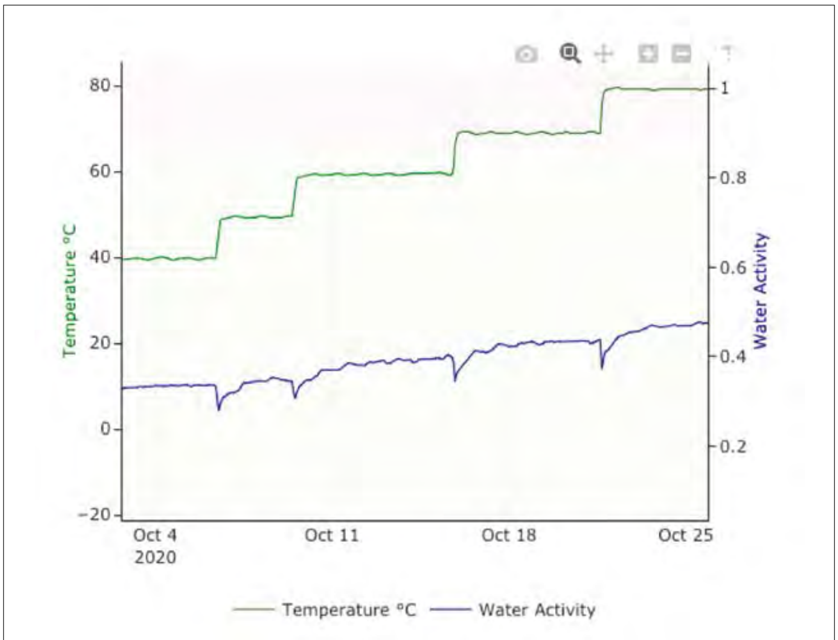


Figure 1. Water activity response to 10 °C temperature steps using 4 % wet Kraft paper in an oil bath

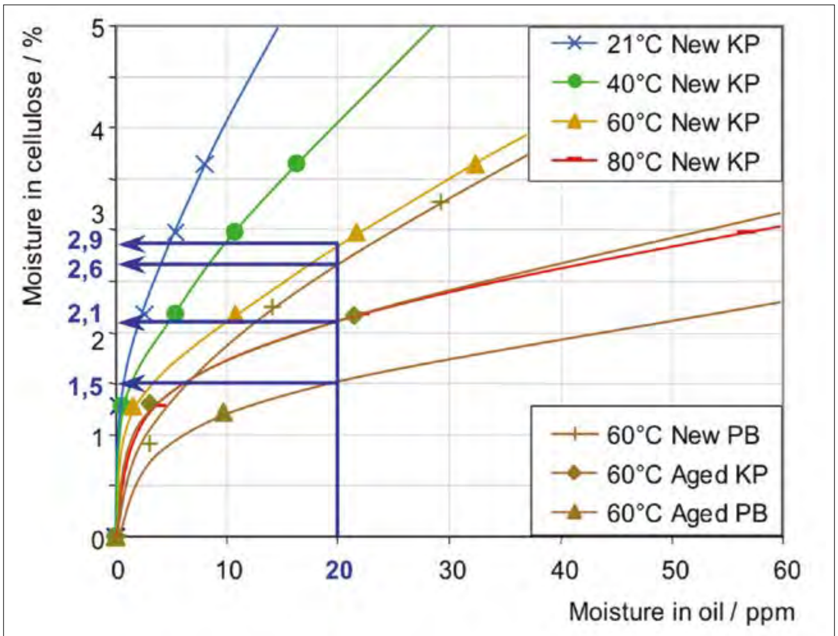


Figure 2. Example chart showing changes in moisture saturation of old and new pressboard [3]

As most of the moisture in a transformer is within the paper, only a very small amount of the total moisture in the paper needs to migrate to the oil to completely saturate it. In essence, the paper controls the moisture seen in the oil, not the other way round. If the paper's water activity is greater than the water activity in the oil, then moisture will move out of the paper and raise the water activity in the oil to match. Very little moisture is needed to move out of the paper to achieve this - much less than is needed to materially change the water content of the paper.

So, when in equilibrium (i.e., when water migration across the boundary between the oil and the paper stops), then the water content of the oil will be a direct indication of the water content of the paper, as their water activity will be the same. Unfortunately, equilibrium rarely occurs in an active transformer due to its oscillating load, plus there are further complicating factors to consider.

A complex relationship

Some of the complex issues to consider when analysing moisture in a transformer include:

1. The relationship between WCO and water activity is complicated and highly dependent on the type, age, pollutants, and additives within the oil. As a result, relating WCO to water activity in the oil around the paper is problematic.
2. The relationship between water activity and water content within the paper is dependent on paper quali-

ties including paper type, degree of polymerisation (DP), manufacturing process and surface finishes.

3. Water activity in the oil decreases with temperature (for constant water content in ppm), but actually increases with temperature in paper (water becomes more active in paper as the temperature increases), so any equilibrium is short-lived and highly dynamic in an operating transformer.
4. Hot paper holds much less moisture than cold paper at the same a_w, so as the oil circulates in an operating transformer, it is passing layers of paper with differing water content at different temperatures and at different states of equilibrium, generating a complex set of moisture movements.
5. Diffusion as a result of differences in water activity across the paper / oil interface increases with temperature. This means that in hot areas moisture equilibrium is achieved quickly (in terms of hours), but in cold areas it is very slow (days or weeks).
6. In summary, the assessment of water in the paper in a functioning transformer where the load and ambient temperatures are continuously changing is very complicated.

Aurtra HealthSense automates this complex dynamic WCP analysis using data from the low cost HealthSense Sensor

Dynamic moisture movement

To better understand moisture movement in a transformer, it is useful to consider it in terms of a moisture pump. Moisture in the hot (top) sections of the transformer is highly mobile in comparison with the cold sections (as explained previously, the diffusion rate increases with temperature). Changes in the top temperature, pump moisture into the oil or draw moisture out of the oil much more quickly than cold areas. As a result, when an "at-equilibrium" transformer's top temperature increases, the water activity of the paper at the hot top will respond accordingly (and increase) and moisture will quickly begin to diffuse out of hot paper in an attempt to reach equilibrium with the hot oil (where water activity will have fallen with the increase in temperature). See Fig. 1 showing a test of wet Kraft paper in an oil bath exposed to sudden temperature changes and the resulting effect on water activity.

When that "changing a_w oil" circulates down to the cold sections, its higher moisture level will be out of equilibrium with the colder areas of the transformer (where temperature does not change greatly as it is close to ambient).

Diffusion at the lower bottom temperatures is slow in comparison, so this non-equilibrium state lasts a relatively long time, until the colder sections absorb the extra moisture. As the moisture is absorbed into the cold sections, the hot sections release more moisture until a new equilibrium point is found. If the tempera-

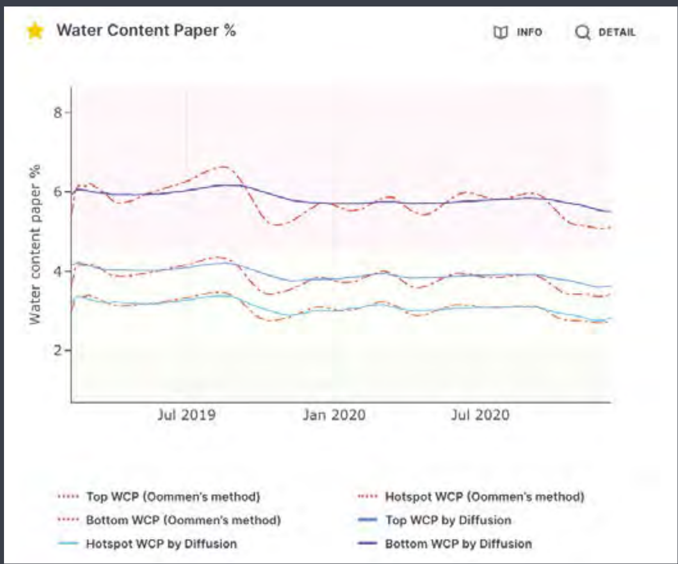
Figure 3. Aurtra HealthSense Sensor installed in top fill valve

With Aurtra HealthSense, these complex analyses are immediately available to assess, track and forecast the insulation state and life left across the transformer fleet

ture of the top sections falls before equilibrium is reached, the reverse process starts immediately, and the oil moisture content remains continuously out of balance with either the hot or cold areas.

Like the complex excitation and loading of an electrical power system, equilibrium is rarely achieved. Understanding the state of the transformer (moisture levels at different locations) from a single sporadic "oil-test" observation is therefore like trying to understand the dynamic state of a power system using a single point measurement. You know something, but not quite what.

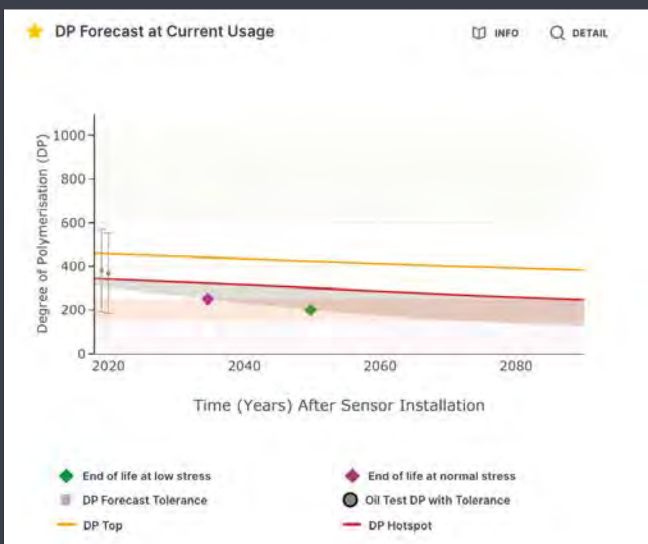
WATER CONTENT OF PAPER



Greater WCP accuracy is achieved using a dynamic model

Figure 4. Aurtra HealthSense Water Content of Paper Analysis

DP DETERMINATION AND FORECAST



Forecast DP and life left. Correlate oil test results.

Figure 5. Aurtra HealthSense DP Analysis and Forecast

Online monitoring is key to accuracy

Water content of the oil is a function of the oil's ability to hold moisture at the specific a_w and is driven by the a_w and WCP of the hottest paper in the transformer. Importantly, a_w is the driving parameter not WCO. Measuring WCO therefore provides an indication of the a_w in the hot areas but it is complicated by the oil's characteristics and the dynamic state of the pumping process. Averaging over time helps to remove the effects of the dynamic processes, but this requires continuous monitoring, not spot observations. Systems that directly measure the a_w, together with the top temperatures, provide a much greater level of accuracy in WCP estimation and therefore consequential calculations such as paper age and life left.

Unfortunately, the ability of the paper to hold moisture at a given a_w is also complicated by the paper age (DP). As paper ages (DP decreases), its ability to hold moisture reduces. Moisture is absorbed by new paper primarily as a surface layer within the inter- and intra-fibre spaces attracted by the oxygen within the polymer chain. Layers of moisture build on top of this surface layer with decreasing stability to generate the complete moisture absorption capability of the material. As the paper ages, the chains are broken down and the water attachment sites, inter- and intra-fibre spaces destroyed. Fig. 2 shows the relationship between typical new and aged Kraft and PB paper.

Complex computational problem solved

To complete a detailed and accurate assessment of the moisture profile of a transformer, the age profile of the transformer at top, bottom and hotspot must therefore also be considered in the calculations. This is a difficult computational process which can only be done by means of an iterative solution using an observation-matching algorithm.

Observations of a_w need to be made together with temperature at a sufficient rate to observe the dynamic characteristics of the temperature profile (Nyquist rate). With this information, plus an understanding of the age of the paper at different locations, and the detailed relationship between temperature and a_w in both paper and the oil, it is possible to conduct a complete and useful assessment.

Aurtra HealthSense automates this complex dynamic WCP analysis using data from the low cost HealthSense Sensor (Fig. 3), which measures multiple temperatures, water activity, vibration and RF signals that indicate partial discharge.

Fig. 4 is a HealthSense screenshot example of an automated WCP analysis. As indicated, the analysis considers different diffusion characteristics of the paper at top, bottom and hotspot.

With an accurate, dynamic analysis of WCP, DP Forecast and Life Left can be calculated based on current load profiles as shown in Fig. 5. Scenario forecasts of insulation aging with changing load profiles can also be easily modelled by the dashboard user.

With Aurtra HealthSense, these complex analyses are immediately available to assess, track and forecast the insulation state and life left across the transformer fleet. Insulation failure risk rankings enable the asset manager to engineer data-driven life extension and risk-reduction maintenance strategies (Fig. 6), as well as optimise aged transformer replacement programs (Fig. 7).

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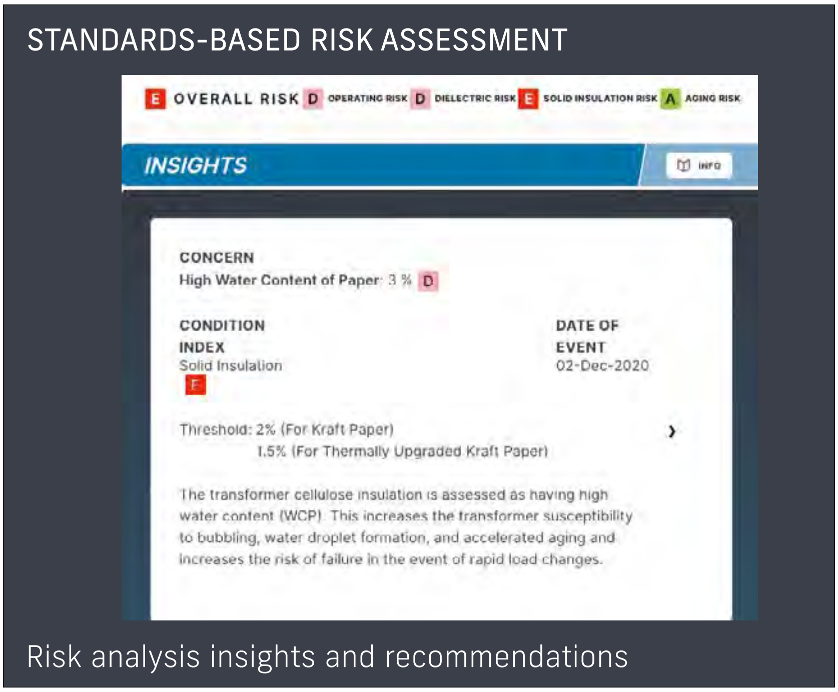

Figure 6. Aurtra HealthSense Insights

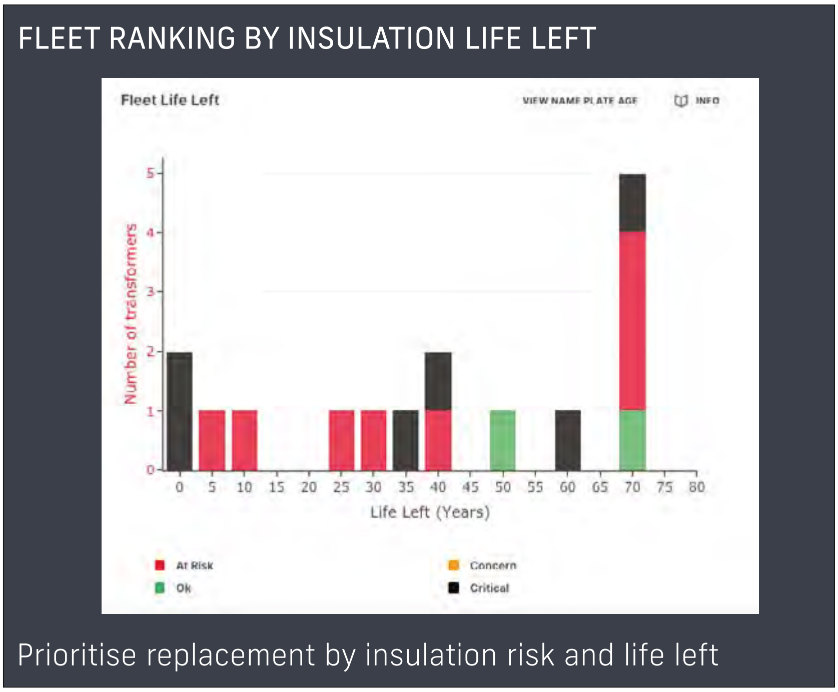

Figure 7. Aurtra HealthSense Fleet Life Left

Author

Richard Harris, PhD

CTO & Founder of Aurtra Pty Ltd. Aurtra is an Australian company focused on providing innovative solutions in asset condition monitoring and assessment to the electricity market. Dr Harris is an experienced technology entrepreneur, having founded a number of successful companies in the telecommunications and high voltage electronics fields. He is the holder of numerous patents and an Adjunct Professor with the Queensland University School of Information Technology and Electrical Engineering.

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Despite its ups and downs, the overall GCC transformers market is still a large demand centre for both power and distribution transformers

ABSTRACT

GCC market has been having its ups and downs in the last few years. What used to be one of the most attractive T&D equipment markets might be losing its high place in the eyes of international manufacturers. A big part of it has to do with the region's dependency on oil revenues, which, in the last few years, have not been stable, owing to the lower oil prices. Infrastructure consumption has reduced significantly over the years with austerity measures in place. In addition to this, the overall geopolitical situation in the Middle-East region has had its toll on the GCC markets, making it difficult for international manufacturers to do business in the rest of the region using GCC countries as a regional base.

KEYWORDS

COVID-19, distribution transformers, future trends, GCC, Gulf countries, market overview, power transformers

GCC transformers market

Is the region still an attractive market for manufacturers?

GCC market has been having its ups and downs in the last few years. What used to be one of the most attractive T&D equipment markets might be losing its high place in the eyes of international manufacturers. A big part of it has to do with the region's dependency on oil revenues, which have not been stable in the

last few years owing to lower oil prices. Infrastructure consumption has reduced significantly over the years with austerity measures in place. In addition to this, the overall geopolitical situation in the Middle East region has taken its toll on the GCC markets, making it difficult for international manufacturers to do business in the rest of the region using GCC countries as a regional base.

Changes in the regional market

The situation is expected to ease up a little with infrastructure projects coming back online again in lieu of the mega projects in the region. Against the backdrop of these developments, it is important to note that GCC market has been undergoing the following changes.

Local content requirements

Countries in the GCC, especially Saudi Arabia, are trying to encourage foreign companies to participate actively in the

Local distribution transformer suppliers are leading the market, whereas, due to limited power transformer manufacturing, foreign players with no local manufacturing hold a higher share of the market

Current megaprojects, coupled with large power generation projects in UAE, Oman, Saudi Arabia, and some petrochemical projects will contribute to a stable transformers demand at least for the next few years

local economy. Frameworks like Saudization, vision 2030 local content, and UAE's ADLC / ICV have been in place encouraging local production.

Manufacturers operating in the region now need to have local production, local partnerships, and local workforce to be able to do business in the region. And this is true not only for utilities but also for the state-owned oil and gas companies like Saudi Aramco, ADNOC, and Kuwait Petroleum, which are also large buyers of transformers. These programs do not necessarily mean that foreign businesses with no local presence cannot do business in these countries. It means they have a disadvantage in bid evaluations ranging from 10 % upwards in the score.

Companies must rethink their approach in terms of local content if they want to continue having a presence in the region. Today it practically means that in the transformers business, local distribution transformer suppliers are leading the market, whereas, due to limited power transformer manufacturing, foreign players with no local manufacturing have a higher share of the market as well.

Funding problems due to oil prices

Unstable oil and gas prices play a huge role in infrastructure development. Starting in 2015, oil prices have been significantly lower due to decreased oil revenues and hence lower investments. More recently, the Russia – OPEC+ agreement has been signed, leading to a slight improvement in the prices, but overall revenues remain low. This has impacted the regional investments in the power grid sector too, with even large buyers such as the Saudi electric company not placing orders as large as before.

Infrastructure projects reviving slowly

Despite the oil prices fluctuating, there is an increasing focus from the Gulf states to create alternate sources of revenue in addition to oil, which will lead to infrastructure consumption. However, this is primarily due to mega projects like NEOM, King Abdullah Economic City, Expo 2020, and other large initiatives to promote the tourism and services sector in the region. These megaprojects, coupled with large power generation projects in UAE, Oman, Saudi Arabia, and some petrochemical projects (e.g., ADNOC-OMV-ENI) will contribute to a stable

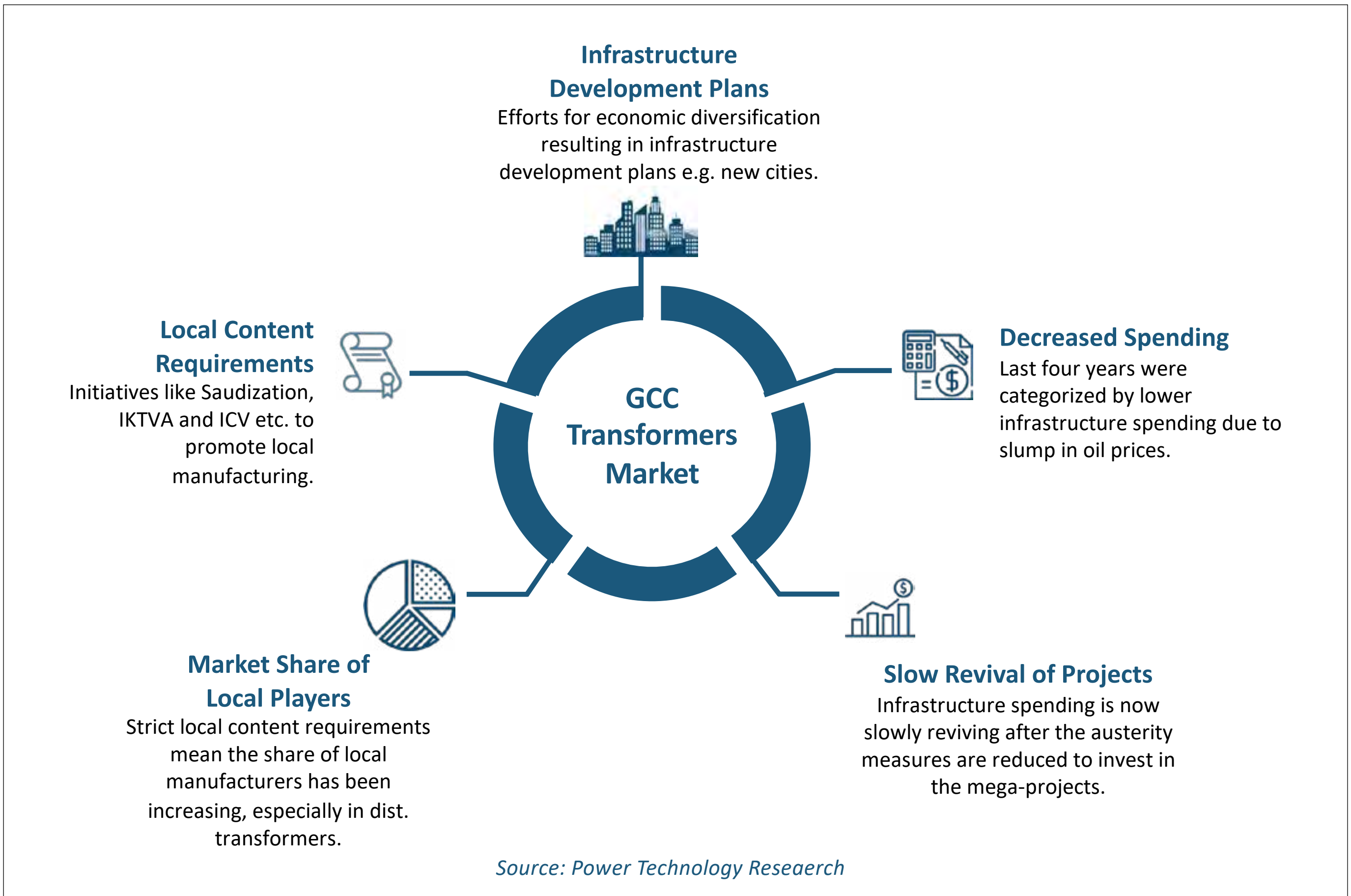

Figure 1. GCC transformers market specifics [1-2]

transformers demand at least in the next few years.

GCC transformers market specifics

Market size

Despite its ups and downs, the overall GCC transformers market is still a large demand centre for both power and distribution transformers. In 2019, the total demand for transformers in the region reached around $1.17 B. A big portion of this demand came from power generations and infrastructure segments, followed by oil and gas. Contrary to the usual, in 2019, UAE was the largest transformer market with Saudi Arabia as the close second followed by Oman.

However, looking at the last 5 years (2016 – 2020) the market was led by Saudi Arabia followed by UAE, Qatar, Oman, Kuwait, and Bahrain, respectively.

Table 1. GCC transformers market - country market ranking by size [1-2]

Country ranking by market size (2016 – 2020)	
1.	Saudi Arabia
2.	UAE
3.	Qatar
4.	Oman
5.	Kuwait
6.	Bahrain

Supply - side: Key players

In GCC, the transformers market from a supplier category can be segmented into power and distribution transformers. A major chunk of distribution transformers market is served by local manufacturers, especially in Saudi Arabia or by foreign manufacturers with local manufacturing or local partnerships. However, the picture is quite different for power transformers. Limited local manufacturing (e.g., SPTC in Saudi Arabia) means the market is dominated by foreign suppliers.

The overall GCC transformers market is still a large demand centre for both power and distribution transformers with the total demand for transformers in the region reaching around $1.17 B in 2019

Tables 2 and 3 show the top five distribution transformer and power transformer suppliers in the GCC region in the order of their market position.

Table 2. Distribution transformer supplier positioning (GCC) [2]

Distribution transformers	
1.	Hitachi ABB Power Grids
2.	Saudi Transformers Company (STC)
3.	Alfanar
4.	Siemens
5.	Schneider Electric
6.	Bahrain

Table 3. Power transformer supplier positioning (GCC) [1]

Power transformers	
1.	Hyundai HI
2.	Hyosung
3.	Hitachi ABB Power Grids
4.	Siemens
5.	SPTC

Key drivers of demand in the GCC market

Looking at the main drivers of the market, the following are the three main drivers of transformer demand in the region:

1. The efforts towards diversification of the economy to increase non-oil revenues are one of the big reasons for investment in the infrastructure. This leads to new transformers demand from commercial and industrial projects.
2. Power generation projects to cater to the regional electricity demand along with large renewable development plans are also a big contributor to the GCC transformers market.
3. Large projects in the petrochemical sector, e.g., Duqm Refinery and Petrochemical complex in Oman, and ADNOC-OMV-ENI Joint Venture Refinery in Ruwais, are also contributing to the transformers demand leading to a growth in the transformers market.

Saudi Arabia's transformers market

Focusing on the largest market in the GCC region, Saudi Arabia is still one of the highly attractive markets not only in GCC but also in the MENA region, too. Moving forward, it is expected to still stay the largest demand centre for transformers. Major drivers of growth are:

- High tech NEOM City, Qiddiya entertainment city (worth $8 B), and the Red Sea project are some of the large infrastructure projects planned under

The key drivers of transformer demand are infrastructure projects, power generation projects, and large projects in the petrochemical sector

Saudi Arabian policy is to give 10 % advantage to the local product manufacturers compared to foreign manufacturers in order to encourage the local production and suppliers

Vision 2030 economic diversification program which will drive the market of transformers in the Kingdom.

- Historically, Saudi Arabia has relied on crude oil to fuel its electricity needs, but with the Kingdom's plans to move from its dependence on oil resources, for the first time in the history of KSA, large renewable energy projects are planned under Vision 2030 to achieve 27.3 GW of clean energy by 2024, which will, in turn, lead to transformers demand.
- To accommodate this injection of power into the system, a lot of greenfield investments are planned by Saudi Electric Company (SEC) to expand T&D infrastructure in the future years.

Another important element of the Saudi Arabian market is the local content guidelines. Saudi Arabia has some of the strictest local content requirements in the region to encourage foreign companies to participate actively in the development of local economy and workforce (Saudization) in addition to the Kingdom's goal of promoting local companies into becoming regional entities. The Kingdom's Vision 2030 program goal is to localise 70 % of the procurement and services by 2021. Looking at the two major transformers buyers in the country for their specific local content programs:

Saudi Aramco

In 2015, the world's largest oil company introduced the IKTVA (In Kingdom Total Value Add) programme promoting localisation. According to this program, in addition to the technical compliance and low cost, IKTVA score will also be a deciding factor in evaluating suppliers.

Saudi Electric Company (SEC)

In addition to having a pre-approved list of suppliers, SEC incorporates local content in bid evaluation. During bid evaluation, among the qualifying suppliers based on technical features, locally produced products are given a 10 % advantage compared to foreign products, favouring the evaluation for local suppliers.

COVID-19 impact and beyond

COVID-19 situation has adversely affected the GCC market in two ways. First, the demand for transformers was decreased, especially in Q2, with demand shifting to Q4 and onwards. Second, disruption in the supply chain as it has been difficult for local manufacturers to import raw materials and components on time, resulting in longer lead times and fulfilment delays. The situation has eased up a little as the main component / raw material supply factories in China and India are slowly coming back online operating on higher capacity. Local projects are also coming back online with order in-take becoming better. However, despite this short-term recovery from COVID-19's effect, the big question remains: Would GCC still be an attractive market in the future as it used to be, beyond the current megaprojects?

With local content requirements increasing in time, the geopolitical situation is changing, foreign manufacturers, especially those in the west, are reluctant to heavily invest in the power grid business in the region. A little promise of returns from the rest of the MENA region might not be enough for the manufacturers to consider the region as the base for a larger market, maybe for software solutions business.

Today, however, there is still a decent demand to be fulfilled in the region for the next couple of years. Moving forward, the success of these mega projects in shifting the dependence of the GCC economy on oil revenues will decide how attractive the market is for both local and foreign manufacturers.

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Despite recent recoveries, COVID-19 has negatively influenced the market and supply chains, but the question that remains is, will the GCC still be an attractive market in the future as it used to be before?

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Transformer design and manufacturing for natural ester fluids

VTC Engineering Department

Introduction

One of the most important and expensive equipment in a transmission and distribution network is a transformer. The main function of a transformer is to transform the energy and power at the most economical voltage, where the proper electrical and thermal design of the transformer is of great importance. Transformers are filled with fluids for dielectric and thermal purposes. Petroleum-based oil has been used as a fluid for fulfilling the dielectric and thermal requirement for over 100 years. Petroleum-based oil (mineral oil) is not a biodegradable fluid, and this has led to the development of environmentally friendly ester insulating fluid for electrical power applications. The high fire point of ester fluid reduces the risk for transformers installed close to a building or people or even for indoor applications. Though biodegradable and fire-resistant, ester has a higher viscosity than mineral oil, which is a challenge for the transformer designer and manufacturers.

Ester FR3 is a fire-resistant fluid created from edible seed oil and food-grade performance-enhancing additives that make it biodegradable and environmentally friendly

VTC/GTC team has successfully designed and tested a 150 MVA transformer insulated with natural ester Envirotemp™ FR3™ fluid, one of the largest FR3 insulated transformers built in the USA. Our team has built and tested units up to 750 kVp Basic Insulation Level. Envirotemp™ FR3™ is a product of Cargill.

Properties of natural esters

Virginia Transformer has developed Envirotemp™ FR3™ ester-filled transformers for biodegradable applications as well as for indoor applications based on customer requirements. Ester FR3 is a fire-resistant fluid created from edible seed oil and food-grade performance-enhancing additives. It does not contain any petroleum, halogens or silicones. It is tinted green in colour, and a has fire point of 360 °C and flash point of 330 °C. Natural esters can hold a higher amount of water than mineral oil. Due to this property, the water content in newly received oil can be 200 mg/kg as per IEEE. Table 2 of the standard [4] provides acceptable values for ester fluids. The moisture is bonded to the oil molecule and does not affect the insulation. Also, the power factor of 1 % in ester is equivalent to 0.5 % in mineral oil. The viscosity of the fluid is 4 times that of mineral oil for the operating temperature of 80 °C, shown in Fig. 1.

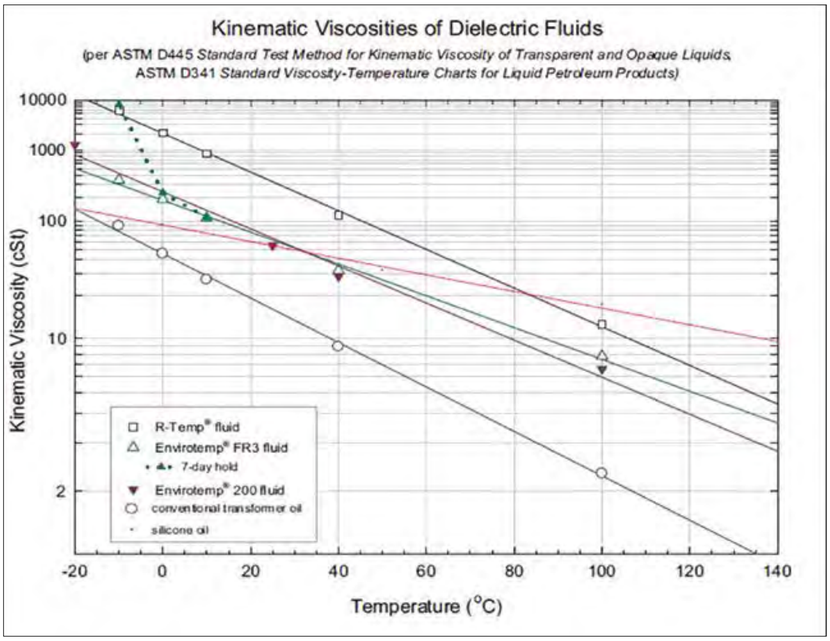

Figure 1. The viscosity of different fluids

Table 1. Comparison of properties

Material	Property	Mineral oil	Natural Ester
Oil	Dielectric constant	2.2	3.2
	Viscosity	3.5 cSt	12 cSt
Paper	Dielectric constant	3.2	3.4
Low-density pressboard	Dielectric constant	4.4	4.6
High-density pressboard	Dielectric constant	4.4	4.6
Moulded Pressboard	Dielectric constant	3.5	4

Design

Designing a transformer using natural ester requires a fundamental understanding of the fluid's electrical, thermal and physical properties. Electrical properties such as breakdown strength and discharge ignition of the liquid under power frequency and lightning impulse condition play an immense role in the electrical design of the transformer. The fluid properties which govern the design are tabulated below.

Electrical design

Dielectric performance of the ester fluid is different than what is understood for the mineral oil fluids. Based on the literature available in various technical forums, it is indicated that ester fluid performance is poorer for the field around sharp electrodes (highly non-uniform fields). The transformer has many surfaces / edges which are not perfectly smooth and can cause field gradient to rise and go beyond the limit. Traditionally transformers are designed with stress limited in the oil duct around electrodes, as oil carries the high stresses due to material property. Weidmann has published the partial discharge inception limit of oil ducts for different configurations for mineral oil years back, and this has been followed by the industry around the world [5].

There are no such partial discharge inception curves available for the ester fluid due to the newness of the fluid, and research is still going on to predict the breakdown values less than 1 % probability. For a typical insulation arrangement, field distribution is shown in Fig. 2. Field distribution of

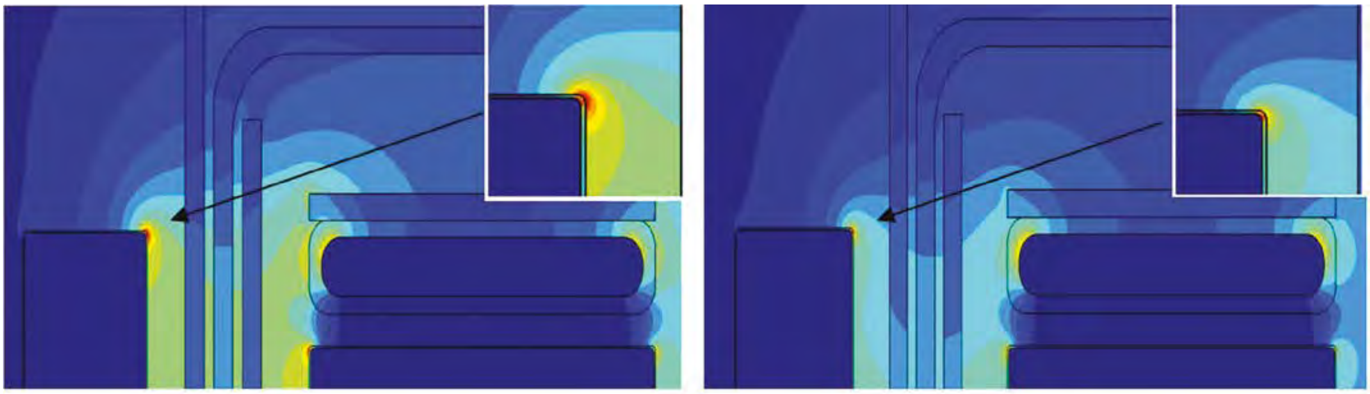

Figure 2. Field distribution for mineral oil (left) and ester (right)

a transformer filled with ester fluid shows a higher concentration of the field in solid insulation compared to liquid insulation for FR3. A concentrated field has a higher possibility of initiating discharges in ester fluid. Therefore, low voltage winding corners need to be secured with additional reinforcements for the protection against corner stresses. Moulded insulation parts are required based on the voltage severity requirement to improve the creepage withstand from HV to LV.. The ester designs require more stringent verification using a numerical FEM analysis.

The design and manufacturing processes should work together for the transformer to produce an acceptable partial discharge level with ester fluid. Ester fluid behaviour with different electrode shapes applicable to the transformer has 15–30 % lower dielectric for the impulse withstand. In general, due to the difference in permittivity, the stress in ester fluid is by 5–7 % lower, and stress in solid insulation is higher in ester fluid by up to 37 % (approximately) than in mineral oil. For a typical medium power transformer gap between the HV and LV winding, the electrical stress distribution is shown above in Fig. 3.

Due to a stress shift from the liquid to solid insulation, the stress in high voltage leads can be challenging for the stress control. Radial insulation on the lead shall be evaluated by a trade-off between electrical and thermal requirement. Comparison

Field distribution of a transformer filled with ester fluid shows a higher concentration of the field in solid insulation compared to liquid insulation

Due to the difference in permittivity, the stress in ester fluid is by 5–7 % lower, and stress in solid insulation is higher in ester fluid by up to 37 % (approximately) than in mineral oil

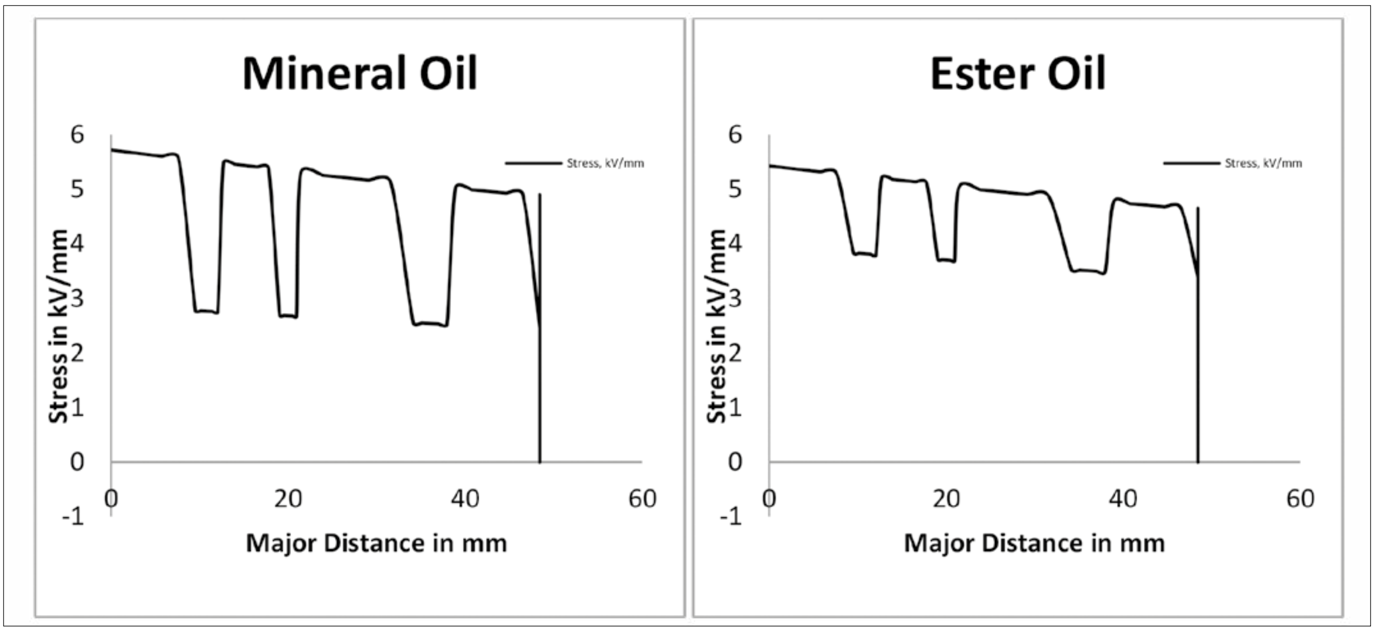

Figure 3. Comparison of the electric field between windings

Table 2. Comparison of stresses for high voltage lead

BIL class (kVp)	Mineral Oil (kV/mm)		Ester (kV/mm)	
	Stress on solid insulation	Stress on fluid insulation	Stress on solid insulation	Stress on fluid insulation
550	5.8	4.02	7.87	3.74
650	5.92	4.41	8.07	4.13
750	6.5	4.48	8.81	4.17

The viscosity of ester fluid is almost 4 times that of the mineral oil for 80 °C temperature and approximately 40 °C temperature difference brings the viscosity of the natural ester close to the mineral oil

of the lead stress for insulated lead to the ground plane for mineral oil and ester fluid is given in the table below.

Thermal design

The viscosity of ester fluid is almost 4 times that of the mineral oil for 80 °C temperature. The viscosity of the fluid introduces complexity in the thermal performance of the transformer even though paper degradation is not compromised. IEEE limit [3] for the hot-spot rise is 80 °C for 65 °C winding rise transformer. To meet the thermal performance radiators and fans need to be selected based on a thermal calculation considering flow resistance and tested the performance of the units already built. Special design radiators and number of plates need to be adopted for catering to the ester fluid requirement. Oil ducts closer to the winding need to be selected by analysis for the oil to flow in the narrow room available close to the winding. Duct size needs to be selected to meet the thermal and dielectric requirements.

Manufacturing and processing

FR3 fluid received in the plant is to be tested for dielectric breakdown voltage (BDV) as per IEEE Std C57.147 [4]. Dedicated storage tanks have to be cleaned every time new oil is filled required in all facilities to keep it free from residual fluids and moisture. Storage tanks are to be kept under a positive pressure of nitrogen. FR3 fluid is recommended to be stored indoor and dedicated oil hoses, and pumps are to be used. Separate in-house processes are to be maintained for the oil received in totes and in tankers.

Approximately 40 °C temperature difference brings the viscosity close to mineral oil for the natural ester. Oil filling is recommended to be done within the temperature range of 60–80 °C and in vacuum to improve the impregnation process. Settling time after oil filling is roughly doubled compared to the mineral oil for the oil temperatures of 60–70 °C.

Conclusion

VTC/GTC understands the properties of ester fluids and has been building hundreds of transformers with FR3 fluid from the early 2000s. We have dedicated equipment in the shop for storage and processing requirements, design rules, and process guidelines for each plant based on the plant capacity to cater to the needs of the customers requiring ester fluids.

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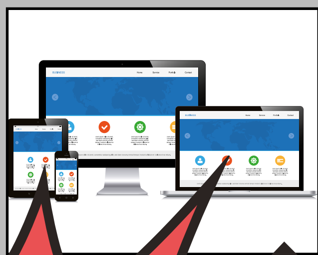

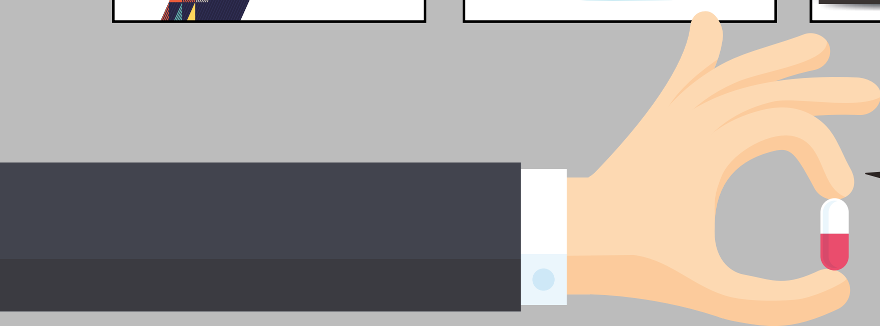

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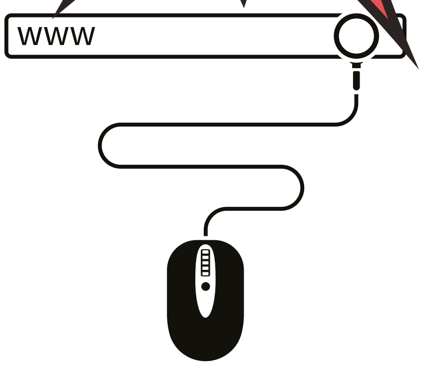

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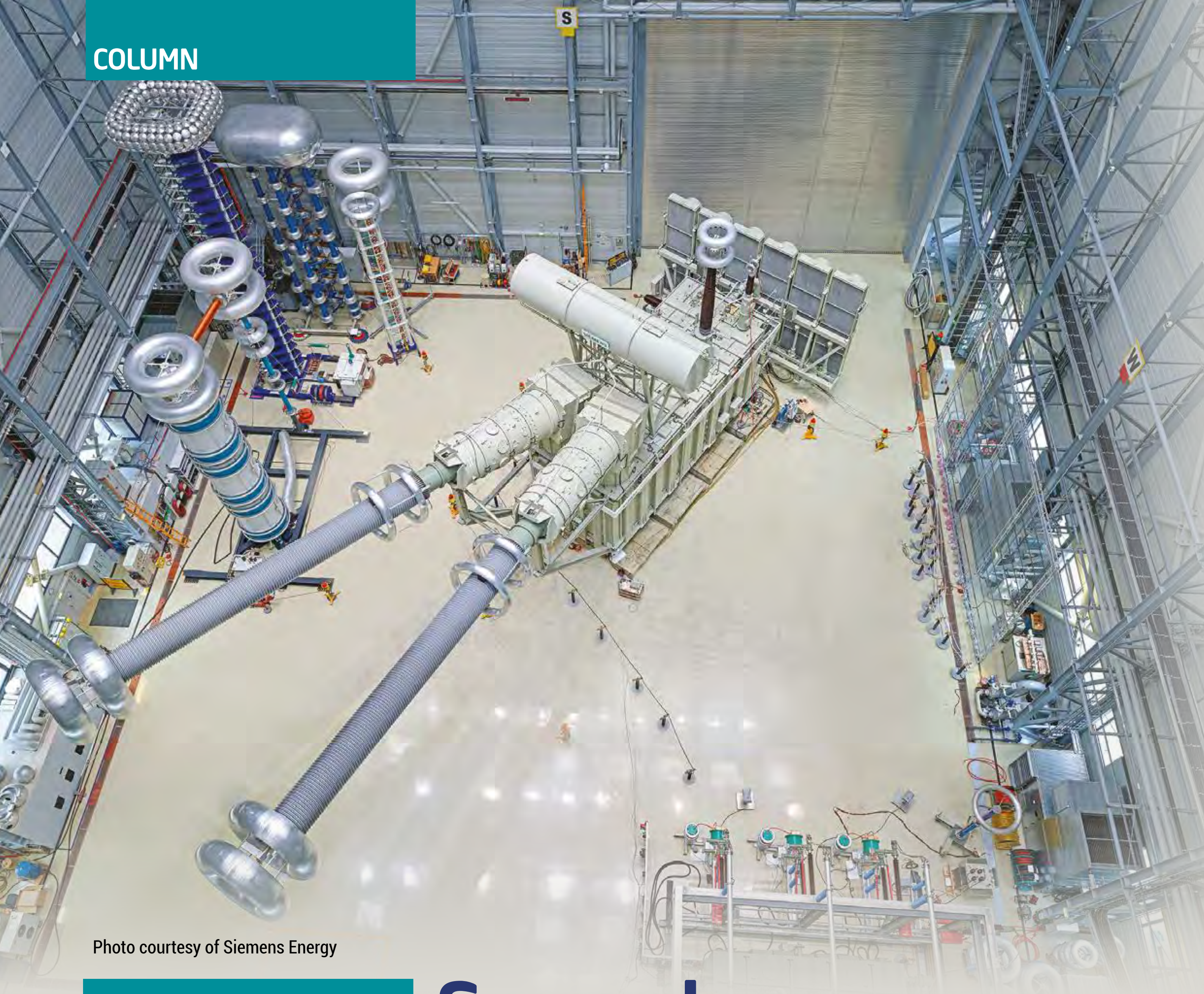

Photo courtesy of Siemens Energy

ABSTRACT

Nowadays, the huge demand for long-distance UHVDC transportation prompts research on the super large capacity converter transformer. Especially in China, UHVDC projects are widely built and put into use. This article reviews the history of converter transformer research and introduces details in the design of the converter transformer. The recent advances in the fundamental study of converter transformers such as partial discharge, space charge, and material performance test are also introduced in the article. In the end, this article summarizes the application status of the converter transformer in China and looks forward to its future prospects.

KEYWORDS

bushing; converter transformer; partial discharge; space charge

Super large capacity converter transformer

1. Introduction

Driven by the growing prosperity of fast-growing developing economies, the demand for energy will continue to grow in the future. In order to cope with the challenge of climate change, clean energy is more preferred in the world. Therefore, with the continuous development of the social economy, the proportion of electric energy in terminal energy consumption and the demand for electric energy are increasing. According to the forecast of the International Energy Agency (IEA) [1], the share of electricity in terminal energy consumption may exceed that of oil by 2040, which is currently less than half of oil. Electricity demand will also increase by 70 %, with more than 50 % of the demand growth coming from China and India.

Column by the University Transformer Research Alliance (UTRA) www.university-transformer-research.com

MANCHESTER 1824 The University of Manchester · The University of Queensland Australia · Tsinghua University 1911 · University of Stuttgart Germany · Xi'an Jiaotong University 1896

How to transport clean energy such as wind, water, and other clean energy to the economic development with strong demand is the current research focus of the researchers. Especially in China, a country with a vast territory and unbalanced regional development, the energy transmission distance may exceed 1000 km, so the power transmission with large capacity and long-distance has become a necessary choice. However, the transmission capacity of the existing AC power grid is reaching its limit, and the loss of energy in ultra-long-distance AC system is also uneconomical. The huge demand for energy consumption and optimal allocation of resources promotes the rapid development of long-distance, low loss UHVDC (ultra-high voltage direct current) transmission technology. The UHV converter transformer connects the AC power grid and converter valve hall, which is an important component of UHV AC / DC conversion. Converter transformer accounts for 43 % of the total investment of the converter station, which is the highest technical level, highest value, and most core equipment in ± 800 kV DC transmission project.

For a very long power transmission, UHVDC technology has become beneficial compared to conventional AC power transmission systems in terms of stability and losses

2. The development history

In the 19th century's debate about AC and DC, the AC system won out. However, with the development of power electronics, HVDC transmission technology has become popular because of its high system stability and low line loss. In 1954, the world's first commercial HVDC transmission project undertaken by ABB was put into operation in Sweden. In the 1970s, Siemens began to develop a high voltage converter transformer. Since then, ABB and Siemens have been industry leaders in the design and construction of converter transformers. They provided converter transformers for the first two ± 800 kV UHVDC transmission projects in the world (Xiangjiaba-Shanghai project and Yunnan-Guangdong project) and made a breakthrough in the ± 1100 kV UHV converter transformer.

Beside ABB and Siemens, Chinese researchers have also made great progress in the converter transformer due to the rapid development in the UHVDC transmission project. In 1989, China imported foreign technologies and built the first HVDC transmission project, the Gezhouba-Shanghai project. With the Lingbao back-to-back project in 2005, China had fully mastered the ± 500 kV converter transformer design and manufacturing process. In 2010, by importing high technology converter transformers, China built the world's most advanced ± 800 kV DC transmission project, Yunnan-Guangdong project, and Xiangjiaba-Shanghai project. By 2013, China was able to design and manufacture ± 800 kV converter transformers independently, but still needed to make breakthroughs in some key component supporting technologies. In 2017, the Belo Monte project in Brazil undertaken by State Grid Corporation of China was put into operation, marking that China's UHV converter technology entered into the global market. In 2018, China produced the world's first 1100 kV converter transformer and applied it to the Fuchangji-Guquan UHVDC transmission project. Up to now, there have been 15 UHVDC transmission projects in operation in China, and more than 50 converter transformers in a single

Figure 1. Wind and solar power

UHV converter transformer is subject to complex stress, including long-term AC / DC superimposed electric field, high harmonic voltage, serious DC magnetic bias, lightning, and switching overvoltage

project. China is the only country in the world releasing large-scale commercial application of UHV transmission technology and has ranked at the forefront of the world in the converter transformer design, manufacturing, operation, and maintenance technology.

3. The design of the UHVDC converter transformer

As one of the core components of the UHVDC transmission project, the UHV converter transformer has played an unreplaceable role in the system. For example, it can realize voltage conversion and AC / DC electrical isolation, restrain DC fault current, weaken overvoltage of AC system invading DC system, and reduce harmonics injected into the AC system by the converter. Therefore, the UHV converter transformer is subject to complex stress, including a long-term AC / DC superimposed electric field, high harmonic voltage, serious DC magnetic bias, lightning, and switching overvoltage. The electric, magnetic, and thermal environments inside the transformer are harsh, and the design requirements are high.

3.1 Insulation design

As the electrical isolation between the AC system and converter, all energy will flow between the AC system and the DC system through the converter transformer. Moreover, its ultra-high voltage level requires the converter transformer to have a higher insulation level, which means that the converter transformer has a larger physical volume. However, due to the transportation limits, the size is limited for the converter transformer, which often needs to be transported as a whole unit. Moreover, the size of the converter transformer is not linear with its insulation level. Too much insulation margin will lead to a rapid increase in the cost, which is uneconomical. Therefore, insulation design is an important issue in the UHV converter transformer.

The converter transformer must bear both AC voltage and DC voltage under normal working conditions. When the power flow reverses, the DC voltage it bears will also reverse in polarity [2]. It has been proved that the most complex and difficult challenges in the insulation design of converter transformer are how to design the converter transformer insulation to withstand the action of AC / DC composed electric field for a long time, and the DC step voltage such as polarity reversal.

Under AC voltage, the electric field distribution in the insulation structure of the converter transformer is determined by the dielectric constant. Due to a small difference in dielectric constant between insulating oil and paperboard, the electric field distribution is relatively uniform. The resistivity of paperboard is much higher than that of insulating oil, so the electric field is mainly distributed in paperboard under DC voltage. Therefore, compared with the power transformer, the main insulation of the converter transformer uses more paperboard to form a "thin insulating board – narrow oil gap" insulation structure.

However, it should be noted that the resistivity of insulating materials varies over a wide range affected by temperature, humidity, and electric field strength. At the same time, it is difficult to process the large-size insulation paperboard and insulation molding used in the UHV converter transformer, and the finished products are dispersive. In order to solve these problems, changes in dielectric parameters of different types of insulating parts from different sources and with different specifications under different conditions are measured. The measurement is used to realize the accurate calculation of insulation margin under the special working condition of ± 800 kV converter transformer. Furthermore, by optimizing the oil gap at the end, the insulation distance can be reduced. In this way, the compact design of the main insulation structure of ± 800 kV converter transformer is realized.

3.2 Electric field control of outlet device

The converter transformer's valve side outlet device is the key insulation structure connecting the valve-side winding lead of the converter transformer and DC high voltage bushing. At present, there are mainly two types of valve-side outlet devices in the market. One is an open structure designed by ABB, which adopts a simple multi-layer straight paperboard cylinder, uncovered electrode, and insulation shield against axial flashover. This structure is used together with an oil-paper bushing without a porcelain sleeve, and the structure of the field is relatively simple. The other is a closed structure designed by Siemens, which uses a multi-layer special-shaped paper cylinder and an insulated covered electrode, which is used together with a resin-impregnated paper bushing.

The valve-side outlet device works under harsh working conditions of high AC/ DC composite voltage, large current, and long-term vibration. The space is limited, and the electric field is especially concentrated. It is difficult to control the field strength. Therefore, the number, shape, and position of insulated paper cylinders need to be carefully designed according to the calculation results of the electric field distribution.

In addition, the valve-side outlet device can be independently placed outside and inside the tank. When the valve-side outlet device is placed independently outside the tank, it can reduce the transportation size of the converter transformer. However, due to its large weight, large volume, and complex interfaces, the assembly is very difficult. Therefore, it is easy to cause damage to the devices during the test and assembly process. When the valve-side outlet device is placed inside the tank, the field installation can be simplified, and the risk is reduced. But it is difficult to arrange the valve-side lead in the tank with a very limited space, which requires a lot of calculation, analysis, and optimization of the design.

In addition to adopting the insulation barrier with an equipotential profile to reduce the field strength along the surface, Chinese manufacturers have also adopted a split type for the insulation structure outside the barrier, and the insulation of each split is overlapped by steps from inside to outside. Moreover, they conducted the insulation margin test of the 1:1 valve-side outlet device. Based on the test results, they proposed a design of "pin-free" in the high field strength areas and developed a built-in valve-side outlet device.

3.3 Temperature rise control and loss

The ageing of insulation material is closely related to temperature, so the thermal design of the converter transformer is very important for its life. Compared with a power transformer, the converter transformer bears a lot of harmonic power and serious DC magnetic biasing, which leads to a serious magnetic leakage and increased loss. However, the converter transformer has a compact structure and complex oil circuit. So, when the oil resistance of the cooling channel is increased, the temperature rise control is very difficult.

Compared with the power transformer, the main insulation of the converter transformer uses more paperboard to form a "thin insulating board – narrow oil gap" insulation structure

Therefore, the converter transformer's key point of temperature rise control is to accurately control the heating caused by the leakage flux of structural parts, winding ends, and magnetic shunt. A lobe-type magnetic shield could be adopted to control the whole flux leakage of a large capacity converter transformer. And the copper plate is set on the inner wall of the tank to reduce the leakage flux into the tank. In addition, the tap lead of the voltage regulating winding of the large capacity converter transformer will produce a strong magnetic leakage field. The diamagnetism of the copper compensation ring on the core surface can greatly reduce the eddy current loss on the core structure. In addition, using the structure of a reverse spiral double-layer voltage regulating coil, the magnetic leakage flux can be counteracted in the reverse direction in order to weaken the heating of structural parts and reduce the temperature rise.

In terms of heat dissipation, the ODAF cooling mode is often used in large capacity converter transformers. This cooling method has a high oil flow rate and good cooling capability, but the welding slag and other metal particles produced by the metal oil guide box may easily enter the device body through the oil path, causing potential safety hazards. At the same time, the oil flow guiding structure must be reasonably designed to avoid serious oil flow electrification and local oil flow dead

Figure 2. Core and coils of oil impregnated transformer

The converter transformer's valve side outlet is the key insulation structure connecting the valve side winding lead of the converter transformer and DC high voltage bushing

angle leading to temperature rising out of control. Chinese manufacturers have designed a horseshoe-shaped oil guide device to improve heat dissipation capacity.

But even with various measures, precise control of the transformer temperature rise is still a difficult problem. This is because the temperature of the hottest part of the hottest coil affects the thermal life of the transformer. Unfortunately, the hot spot temperature cannot be directly measured. Moreover, the oil flow control inside the transformer is not simple. The existing calculation software is actually based on a simplified and idealized model, which has a large uncertainty. Reliability of the calculation results can only be verified with a test. Therefore, it is of great significance for the converter transformer design to accurately calculate the loss of the converter transformer and conduct a reasonable temperature rise test.

3.4 Manufacturing process

A UHV converter transformer is not only the heart of a complex system but also a huge and complex system itself. The ± 800 kV converter transformer contains more than 30000 parts and components with a weight of more than 500 tons. The assembly and manufacturing process involves more than 100000 operations. Most of these operations need to be done manually by experienced technicians.

Because the converter transformer plays a key role, it requires high reliability. The manufacture, installation, and debugging of the converter transformer are the key to avoid any fault. Therefore, requirements of the manufacturing environment and processing quality of the converter transformer are very strict.

For example, installation of the bushing is a major difficulty in the assembly process of the converter transformer. Due to the transportation problem, the high-voltage bushing of the UHV converter is transported separately from the converter body. Therefore, the bushing will undergo several assembly and disassembly processes from the moment of being manufactured in the converter plant until put into service. Once the insulating paper of the outlet device is knocked, it is easy to cause damage to the outlet device. Even if the outlet device is not damaged, the damage to the insulation paper is also a safety risk to reliable operation of the converter transformer in the following period. Therefore, it is necessary to precisely guide and control the bushing, which weighs several tons and needs to smoothly

Figure 3. Manufacture of transformers – winding copper wire

enter more than 10 meters into the outlet device.

Another example is the winding process of a coil. In the converter operation process, the coil is affected by the electric force. Especially in the case of a short circuit, the current passing through the coil is far beyond the rated current. The axial force and radial force on the coil will greatly increase, even deforming the winding. Therefore, the radial direction of the coil should be tightly wound. The axial height and radial dimension of the coil not only affect the coil assembly and its body but also affect the impedance value of the whole converter. After the coil is wound, it is necessary to dry it and impregnate with oil. This requires a correct process and reasonable pressure control to minimize axial and radial deformation.

In fact, for the huge and complex equipment such as a UHV converter transformer, it is necessary to have a complete set of production process and quality control methods in the whole process of converter transformer manufacturing, such as coil winding, core stacking, tank welding, and body assembly, so as to form high-end power equipment manufacturing capacity.

3.5 Bushings

The bushing of the converter transformer is a device that leads the internal winding out of the tank. The converter transformer connects AC and DC power systems, and the insulation bushing is also divided into grid-side bushing and valve-side bushing. The valve-side bushing of the converter transformer is an important piece of equipment to realize the electrical connection between the UHV converter transformer and valve tower. It is the core component that causes most of the manufacturing difficulties in the UHV converter transformers.

According to the insulation structure, the valve-side bushing can be divided into oil-impregnated paper gas-filled bushing, resin-impregnated paper gas-filled bushing, resin-impregnated paper foam-filled bushing, and dry-type resin-impregnated paper bushing. The head end of the bushing is provided with a grading ring, which is connected to the DC system terminal. The end of the bushing goes deep into the outlet device, which is connected with the winding lead. The capacitor core inside the bushing body is composed of an electrode plate and insulating dielectric, which is the place where the electric field is concentrated, especially the edge area of the electrode plate in the core.

A ± 800 kV converter transformer is a very complex system that contains more than 30000 parts and components with a weight of more than 500 tons

Compared with AC bushing, the influence of temperature should be especially considered in the valve-side bushing design. This is because the valve-side bushing needs to withstand AC / DC composite voltage. The DC voltage component mainly distributes according to the resistivity. However, the resistivity value is greatly affected by temperature, which is different from the dielectric constant. This leads to a fact that the electric field distribution of a bushing is different from that of isothermal state in the traditional design due to the radial temperature gradient distribution of the bushing. In addition to considering the influence of temperature distribution on the electric field, temperature distribution, especially hot spot temperature, is very important for the bushing's safe operation. Especially for the resin-impregnated paper bushing, an overheat trace near the plug-in structure is usually the starting point of an internal failure of the bushing from the analysis results of the failed bushing disassembly.

In terms of the current market share, the oil-impregnated paper gas-filled bushing is widely used and has good operation stability. However, the oil-contained valve-side bushing and ascending flange pass through a fireproof wall of the valve hall and directly connect with the valve tower. In case of a fire, the fire can easily develop in the valve hall through the casing, which will cause the equipment in the valve hall to catch fire. To reduce the fire risk, researchers have been paying more and more attention to the resin-impregnated paper bushing in the recent years.

4. Fundamental research

As a large-scale precision instrument of the UHV transmission line, it is necessary to have a clearer understanding of the fault mechanism of the converter transformer before the equipment is put into operation. Therefore, many scholars have carried out a lot of fundamental research on the insulation coordination, electric field calculation, and insulation breakdown of the converter transformer.

Liu Zehong and others of State Grid Corporation of China have studied ± 800 kV UHVDC transmission in China and pointed out that UHVDC transmission project must be designed according to higher reliability requirements in the main wiring, equipment parameter selection, overload capacity, filter design, arrester setting, and external insulation design. Wang Jian and others of TBEA Shenyang Transformer Co., Ltd. Have put forward improvement methods for DC magnetic bias in the converter transformer, which has effectively reduced the harm of DC magnetic bias current to the transformer. Mi Chuanlong and others of China West Electric Co., Ltd. Have put forward a harmonic equivalent circuit of the converter transformer with additional resistance, so as to better simulate the influence of harmonic frequency and harmonic voltage distortion rate on the no-load loss of the converter transformer, in order to guide the loss measurement of the converter transformer field test.

The valve-side bushing (DC-side bushing) is the core component causing most of the manufacturing difficulties in the UHV converter transformer

Figure 4. Power transformer bushing

4.1 Partial discharge

According to the data on converter transformer fault released by the CIGRE working group, the fault rate of the converter transformer is about twice that of an ordinary power transformer, and the insulation accident of a converter transformer accounts for about 50 %. A partial discharge is one of the main reasons for insulation failure, and it is also an important indicator to reflect the degree of electrical ageing of the insulation.

In order to avoid discharge caused by a concentration of the local field strength, the electric field is barely uniform in transformers. However, in the actual operation process, a partial discharge is caused by the concentration of partial electric field due to mechanical deformation and insulation ageing of oil-paper insulation. When a partial discharge occurs at the junction of the metal oil paperboard, or when the discharge occurs near the paperboard and damages the paperboard, the partial discharge will develop along the paperboard and become the surface partial discharge [3].

Although partial discharge generally does not cause penetrating breakdown of the insulation, it can cause partial damage to dielectric (especially organic dielectric). If partial discharge exists for a long time, it will lead to insulation deterioration or even breakdown under certain conditions, and serious accidents may occur. Therefore, through a partial discharge test of the transformer, it is possible to monitor the insulation condition of the equipment and promptly detect problems related to manufacturing and installation time.

Chinese scholars have done a lot of research on partial discharge characteristics of the converter transformer. Lu Licheng and others of State Grid Corporation of China have discovered that the starting voltage of partial discharge is related to different voltage components in different models. In the plate-plate electrode model, only when the DC component increases to a certain extent can a partial discharge in the oil be directly caused. Li Chengrong et al. of North China Electric Power University have adopted different methods to diagnose and analyze the relevant data in the process of partial discharge. And the discharge process is divided into the initial stage, development stage, and near breakdown stage.

4.2 Space Charge

When the converter transformer is in operation, the DC electric field component will make the oil-paper insulation accumulate space charge when its valve-side winding bears AC and DC superimposed electric field. Space charge accumulates in the insulation medium, strengthening the local electric field, which may cause early insulation damage, and accelerate the ageing of the insulation medium [4].

It is generally believed that the space charge in the polymer is mainly composed of two parts. Some of them are the carriers injected into the electrode and transportable carriers. The other is due to the ionization and migration of inorganic or organic impurities in the medium under the influence of voltage, which is the main factor when the electric field is low. Simultaneously, as the charge injects, charge trapping is de-trapping, which causes a recombination. The energy transfer and release are accompanied by charge trapping and de-trapping, which will destroy the microstructure of the oil-paper insulation. At the same time, the complex electric field, high temperature, and mechanical stress can also aggravate the charge accumulation effect in the oil-paper insulation and cause irreversible damage.

Space charge accumulates in the insulation medium, strengthening the local electric field, which may cause early insulation damage, and accelerate the ageing of the insulation medium

The interface between the multi-layer oil-paper insulation structure accumulates the interface charge more easily than the dielectric itself [5]. The charge density at the interface is much greater than that in the dielectric. Under special working conditions such as polarity reversion, the speed of charge dissipation at the interface is slower than that of an applied electric field. An electric field generated by the interface charge and polarity inversion is overlapped with the applied electric field, which results in a distortion of the electric field in the oil-paper insulation. It can cause partial discharge, even flashover, and insulation breakdown along the surface.

Through a large amount of experimental data, the researchers have gained a certain understanding of space charge's characteristics and mechanisms. We have found that the space charge accumulation rate and dissipation rate of double-layer media are lower than that of single-layer media. The effect of DC pre-voltage on the local discharge of the oil-paper insulation is also studied. It has been found that the starting and extinguishing voltage of oil-paper insulation decreases gradually with the increase of DC pre-voltage amplitude.

4.3 Material performance test

The insulation materials of the converter transformer are composite insulation materials composed of insulating oil and insulating paper. Transformer oil is a kind of insulation material that plays the role of insulation, cooling, and arc extinguishing in the converter transformer. At the same time, it needs to be combined with insulating paper to form a better insulating oil-paper insulation media.

Under a long exposure to high temperature and electromagnetic field, the oil in the converter transformer is easy to undergo a metathetical reaction, which generates a new chemical composition the oil ageing. Experiments show that oxidized oil absorbs moisture more easily and deteriorates more quickly after moisture exposure.

Figure 5. Dissolved Gas Analysis Test (DGA) for transformer oil

Insulating paper is another key insulation material in the oil-paper insulation. The affinity between paper and water is better than that of oil and water, so paper generally absorbs water from oil. The presence of water can severely reduce the electrical and mechanical strength of the insulation and accelerate the ageing and failure of the insulation.

The ageing of oil-paper insulation of the transformer is an irreversible chemical reaction process. The research on the chemical diagnosis of the ageing condition of oil-paper insulation is relatively mature[6], which mainly includes micro-water analysis, dissolved gas analysis in oil, insulating paper polymerization degree test, and analysis of furfural content in oil.

Qi Bo et al. of North China Electric Power University have observed the electric field of the overlapping structure of oil-paper insulation by the Kerr effect. Li Peng et al. of the China Academy of Electrical Sciences have studied the electric field characteristics in different sizes of oil-paper insulation in the case of polarity inversion. Liu Dongsheng et al. of Baoding Tianwei Electric Power Company detected latent faults in transformers through a dissolved gas analysis in oil and gave a corresponding treatment suggestion.

5. The application and future development prospects in China

China is a vast country, but the energy center is located in the western inland area, far away from the economic center of the eastern coastal area. The demand for super large capacity energy transportation has led to a rapid development of UHVDC transmission technology in China. At present, 15 UHVDC transmission projects have been built in China, among which the Changji-Guquan ± 1100 kV project is the UHV project with the highest voltage level, the longest transmission line, the most advanced technology, and the largest transmission capacity in the world. Chinese enterprises have accumulated sufficient experience in the construction, operation, and maintenance of UHVDC projects. At the same time, the ± 800 kV converter transformer production process system with independent intellectual property rights has been established, and the manufacturing capacity of high-end power equipment has been formed.

At present, 15 UHVDC transmission projects have been built in China, among which the Changji-Guquan ± 1100 kV project is the UHV project with the highest voltage level

In the future, with the continuous development of clean energy, the scale of offshore wind power will be expanded. However, the equipment is easy to corrode and rust in the humid and high salinity environment at sea, affecting the quality and stability of the wind power equipment. In addition, the offshore transformer is bulky and inconvenient to replace and maintain. Moreover, once it is corroded and damaged, the internal transformer oil will leak, easily causing environmental pollution. How to improve the reliability of the transformer and find more economical and environment-friendly insulation materials still needs further development. Finally, how to further optimize the insulation structure of the converter transformer, improve its reliability, and reduce the occurrence of faults is also an important topic.

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Transformer assessment using health index – Part II

Sensitivity analysis and critical discussion

ABSTRACT

Health Index (HI) is a very popular asset management tool. Several methods have been used to determine the transformer HI using the popular "scoring" and "weighting" method, which are now extended / improved using fuzzy logic, regression neural network, support vectors machine, etc. However, not much

Bhaba DAS, Luiz CHEIM

Tiered "scoring" and "weighting" method is introduced as an attempt to fix the issue of misdetection of the malfunctioning transformer as healthy using the HI method

work has been documented on the sensitivity analysis of the "scoring" and "weighting" method. This paper presents a critical review of the "scoring" and "weighting" method by performing sensitivity analysis which shows the masking of issue(s) using this approach. The need for a risk of a failure-based approach based on non-linear scoring is discussed.

KEYWORDS

asset management, condition assessment, fault tree analysis, health index, risk of failure

It is difficult to get the scoring and weighting correct; there is no standard to adhere to, and all the weighting factors differ depending on the expert assessment

3.3 Pitfalls of modified "scoring" and "weighting" approach

The pitfalls of this modified "scoring" and "weighting" approach is very evident. The new scoring model is listed in Table 11, and the rating codes are listed in Table 12.

Assuming the transformer has a perfect DGA, excellent oil quality, good thermal scan profile, good load profile, etc., but there is an issue with the foundation and / or anchorage of the transformer, from the visual inspection, a rating of E with score = 0 is decided.

Table 11. Health index scoring model [23]

#	Condition criteria	K	Rating	HIF
1	DGA	10	A, B, C, D, E	4, 3, 2, 1, 0
2	Load history	10	A, B, C, D, E	4, 3, 2, 1, 0
3	Power factor	10	A, B, C, D, E	4, 3, 2, 1, 0
4	Infrared	10	A, B, C, D, E	4, 3, 2, 1, 0
5	Oil quality	6	A, B, C, D, E	4, 3, 2, 1, 0
6	Overall condition	8	A, B, C, D, E	4, 3, 2, 1, 0
7	Visual inspection	10	A, B, C, D, E	4, 3, 2, 1, 0
8	Turns ratio	5	A, B, C, D, E	4, 3, 2, 1, 0
9	Leakage reactance	8	A, B, C, D, E	4, 3, 2, 1, 0
10	Winding resistance	6	A, B, C, D, E	4, 3, 2, 1, 0
11	Core-to-ground	2	A, B, C, D, E	4, 3, 2, 1, 0
12	Bushing condition	5	A, B, C, D, E	4, 3, 2, 1, 0
13	DGA of LTC	6	A, B, C, D, E	4, 3, 2, 1, 0
14	LTC oil quality	3	A, B, C, D, E	4, 3, 2, 1, 0
15	LTC condition	5	A, B, C, D, E	4, 3, 2, 1, 0

Table 12. Visual inspection rating codes

Rating code	Description
A (Score = 4)	Good, normal operation
B (Score = 3)	Acceptable, 1 - 2 items have a problem
C (Score = 2)	Caution, 3 items have a problem
D (Score = 1)	Poor, 4 items have problem
E (Score = 0)	Very poor, more than 4 items have a problem

The overall health index is calculated as 93.3, which represents a very healthy score. However, foundation issues may result in the failure of both Class 1 and Class 2 components, as follows:

1) Class 1:

- Failure of transformer internal parts
- Relative movement of the transformer and the radiator leading to oil leaks
- Failure of the structural support system for the conservator
- Failure of the pipe connection between the conservator and transformer tank, which may result in an oil spill, etc.

2) Class 2:

- Inertial loads on bushings due to tilting and subsequent bushing failure
- Failure of the lightning arrester and tertiary bushing, which require full replacement due to limited flexibility of bus support structures.

3.4 Tiered "scoring" and "weighting" approach

In [24], a tiered "scoring" and "weighting" was introduced. Tier 1 served as the base to determine the presence of faults (DGA), the quality of the insulating oil (OQF), degradation insulation paper (furan), as well as physical and operating performance of the transformers. Tier 2 is applied if Tier 1 tests classify a transformer having HI < 55 (poor / very poor). Tier 2 involves the diagnostics of transformer turns ratio, winding resistance, tan delta, excitation current and insulation resistance, and polarisation index measurements. Tier 3 will then be performed if Tier 2 tests again classify the condition of a transformer as poor / very poor. Tier 3 involves advanced diagnostic tests such as FRA and partial discharge (PD) measurement. Each parameter has been assigned to a certain weighting factor and scores as listed in Table 14.

With the worst ranking for thermography and physical condition, TH1 = 60. This classifies as "fair" with the recommendation to either maintain or revise the frequency of tests to a six-month interval. Whether this is adequate or not, is for experts to decide. There is a correlation between DGA, load, bad thermography, etc., and this may cause the parameters to violate the limits before the six-month interval. Until such correlations are adequately addressed in any model, the conventional time frame for retesting in six-months' time needs to be questioned.

There is no risk of failure associated with this transformer with bad "thermography" and "physical condition". Similarly, in [25,26] a HI model was developed that combined transformer test data: dielectric and thermal conditions (DGA, furan), mechanical conditions (sweep frequency response analysis), oil condition, and non-transformer dependent data, such as lightning frequency, substation layout, and external events.

Any of the above will result in transformer failure, and it is difficult to get the weighting correct. Several permutations and combinations that need to be carried out make this "scoring" and "weighting" method difficult. Additionally, there is no standard to adhere to, and all the weighting factors differ depending on the expert assessment. This shows that HI based models are not modelled on reliability centred maintenance (RCM) approach. RCM always ensures the following:

- Transformer functionality is always maintained.
- Every individual component of a transformer maintains its functionalities to maintain the overall transformer functionality.

Drawback of HI method is the false estimation of the healthy transformer in the case when most of the failure mode scores are good, and only one or two failure mode scores are bad; the overall score will mask the issue associated with the faulty system

Table 13. Transformer health index with a very poor visual inspection

Rating code	Overall HI
HIF_7 (visual inspection) = 0	93.3

- Identification of different failure modes and prioritisation of failures.
- Identification and prioritisation of maintenance / refurbishment or replacement to control failure modes.

3.5 Limitations of using health index

3.5.1 Masking of failure modes

The sensitivity analysis study clearly demonstrated that the overall assessment score masks a bad failure mode. As shown, when most of the failure mode scores are good, and only one or two failure mode scores are worse, the overall assessment will mask the issue associated with the worse failure mode. An option is to decouple failure modes or use the worst-case scoring in the overall assessment.

3.5.2 Data quality

The quality of health assessment ultimately depends on incoming data quality - be it the accuracy of data or completeness of data. Sometimes the DGA data for the main tank is available whereas from the OLTC compartment it is not available. It is paramount to understand what it means not to have data or below-par data. It is essential to understand the questions below:

- Is the new incoming data "normal"? What is "normal"?
- Is the new data a statistical outlier?
- Why is it important to know if it is an outlier?
- Does the sensor output make sense at all?
- Is there a trend? Is there a sudden trend? How critical or significant is the trend?
- What is the reliability of the incoming data?

3.5.3 "What next" scenario

Health index does not provide any indication on the urgency of follow up action

Table 14. Tiered "scoring" and "weighting" approach

Condition indicator	Weighting factor	Ranking	Amplified ranking	Total
DGA	1.2	3	20	24
OQA	1.2	3	20	24
FFA	1.2	3	20	24
Thermography	0.6	0	-20	-12
Physical/op condition	0.4	0	-20	-8
Age	0.4	3	20	8
			Tier 1 total (TH1)	60

Health index does not provide any indication on the urgency of follow-up action for transformers with poor scores, nor does it provide any indication of what should be done next

for transformers with poor scores, nor does it provide any indication of what should be done next. Whether the transformer needs to be replaced, repaired or refurbished is not answered.

3.5.4 No associated risk

There is no risk associated with the failure of the transformer with a HI score = 100. There is a need to address this concern. The question on "what if a transformer with good HI score fails" is not answered by "scoring" and "weighting" method.

4. The requirement of a new approach

The new approach / alternative to HI based asset management strategy should be based on the following:

- Decoupled failure mode analysis - probabilistic fault tree-based analysis [29]
- Inclusion of the probability of failure and risk associated with failure
- Inclusion of replacement or repair / refurbishment scoring based on economics [30].

The CIGRÉ Working Group A2.49 [28] published the laid down general guidelines for transformer assessment index development, including the use of on-line monitors. A detailed summary and advantages / disadvantages of aggregation methods used to calculate HI has been listed. These methods include:

- Weighted sum
- Sum of non-linear scores
- Worst case
- Statistical regression
- Artificial intelligence

Detailed tables are provided for condition assessment of different factors, such as:

- Dielectric condition assessment - core assessment, winding insulation
- Thermal condition assessment
- Mechanical condition assessment
- Bushing condition assessment
- Cable box assessment
- OLTC assessment
- Cooler / radiator condition assessment
- Oil (mineral / natural ester / synthetic ester) assessment.

The scoring matrix developed by the working group has six levels - Level A (minimal signs of deterioration) to Level E (very poor condition), with Level F (denoting de-energise as soon as possible) not used for scoring but for immediate action. Each level is colour coded for easy visualisation. The basic steps to develop the transformer assessment index (TAI) are listed below [28]:

1. Determine the purpose of the TAI
2. Identify the failure modes to be included in the TAI
3. Determine how each failure mode will be assessed
4. Design a calibrated system for categorising failure modes (scoring matrix)
5. Calculate a TAI score for each transformer.

Fig. 2 shows the scoring assessment sheet for this new method. In [28], the scoring for replacement or repair / refur-

	Replacement Index				
		Refurbishment Index			
	Replacement of TX	Maintenance Index			
Analysis Summary	Active Part	OLTC	Bushing	Dielectric Fluid	Cooling system
Main Tank DGA (1-4)	D				
Main Tank Oil (1-3)	A			A	
Furan -DP (1-4)	D				
Corrosive Sulfur (0,50)	A				
LTC DGA (1-4)		A			
LTC Oil (1-3)		A			
Doble Test (1-3)	A				
Bushings (1-3)			A		
Arresters (1-3)			A		
Cooling System History (1-3)					A
IR Scan History (1-3)					A
Main History (1-4)					C
Loading (1-3)					C
Fault Duration Multiplier (1, 10, 25)					A
Substation 3 - T1	A2.49 Summation + Colour Score			12 Pink	

Figure 2. TAI scoring method [31]

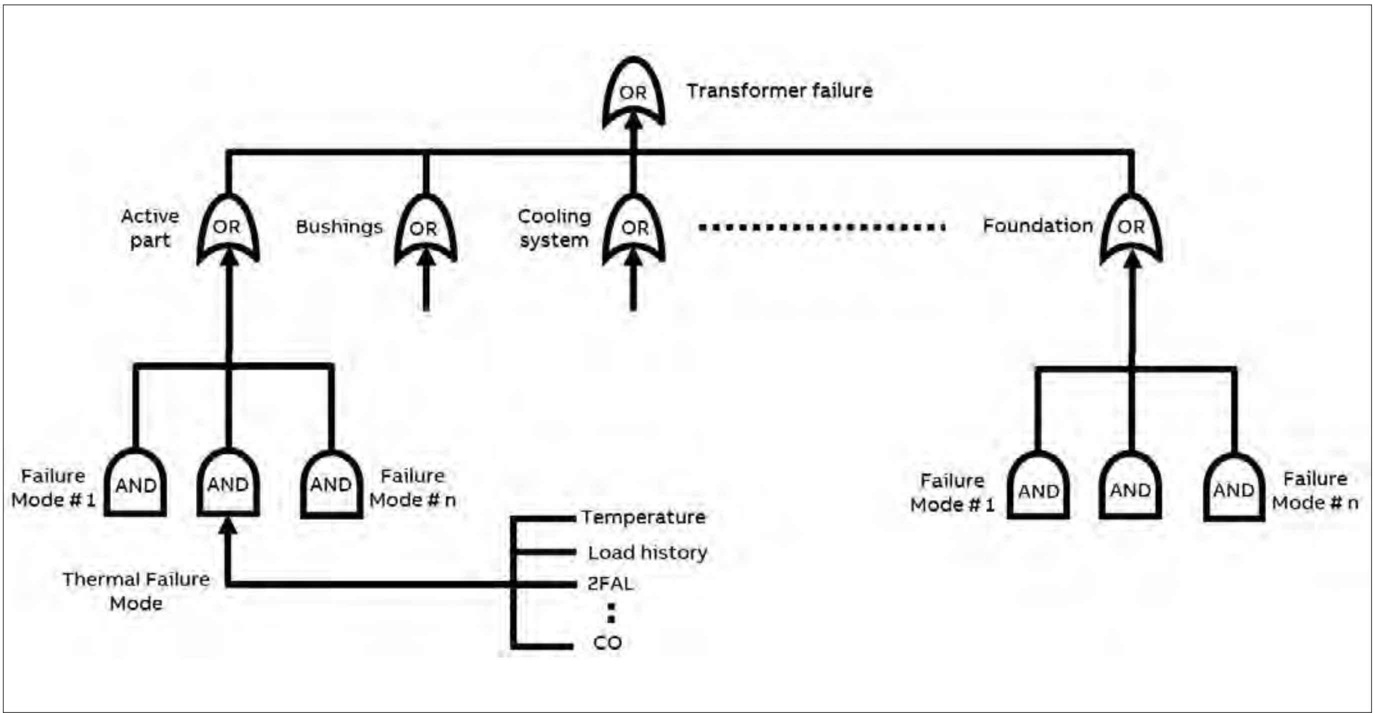

Figure 3. Illustration of fault tree-based assessment method

bishment has been introduced. The idea behind introducing this is as mentioned by CIGRÉ Working Group A2.49:

1. "High moisture content is not a driver for replacement, as the moisture can generally be removed as part of a refurbishment. However, a transformer will not be considered for refurbishment if the paper is already significantly degraded (high furans). Similarly, transformers with high levels of partial discharge or arcing will not be considered for refurbishment as it is unlikely that these problems can be easily corrected during the refurbishment process".

2. "Bushings can be replaced as part of either the repair or refurbishment process. However, as replacing bushings can be expensive if identical bushings are not available, defective bushings are also one of the drivers for replacement."

However, both the above can be achieved with the associated cost – be in repair / refurbishment in workshop or possibility to replace bushings by having the right match & engineering support from the factory. Thus, the cost of replacement or repair / refurbishment must be part of any new approach.

In [27-29], a decoupled failure mode approach based on the RCM philosophy was presented (Fig. 3). The procedure developed selects those failure modes for each of the components and brings to the "analysis matrix" those operational parameters that play a role in that specific failure mode. It is very important to note that parameters that are not correlated or those that do not contribute to a given failure mode are not analysed together with those directly associated with a failure mode.

As an example, a bushing may fail due to several reasons such as design and manufacturing issues, storage, maintenance and operations, external causes, etc. In order to be properly assessed, each of these possible failures may require different data inputs, such as:

- Bushing installation date
- Bushing power factor and capacitance
- Bushing reference power factor and capacitance as per manufacturer
- Bushing voltage class
- Bushing construction type
- Bushing inspection results - hot spots, cracked, oil, oil leak?
- Bushing maintenance date.

After all major components and their failure modes are duly evaluated, a global associated probability of failure (POF) score is produced out of the individual scores of each component. This score is mapped in a criticality index matrix, designed to map the POF score against the importance of the unit. This model also incorporates the "expert system" within the fault tree-based assessment method. One such example is the data

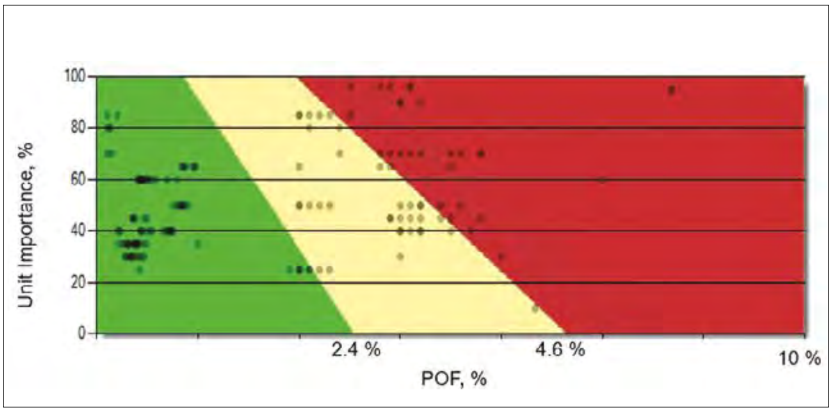

Figure 4. Criticality index matrix - Risk-based POF mapping

As an alternative to traditional HI score method, there are several different modelling techniques proposed such as TAI scoring method and fault tree-based assessment method

quality check and management by employing statistical packages within the model. As data is generated every few minutes / hours from technology deployed within a smart grid, such as online DGA equipment or other online devices, assessment of data quality by manual methods becomes tedious. Statistical packages, such as outlier identification, box plots, piecewise linear approximation, normal data distribution, etc., are inbuilt in this model to automatically process data and perform data quality checks. The "expert system" raises flags for either causes or components responsible for the causes. Based on the causes or components, replacement or refurbishment scores are calculated.

Conclusion

The paper has presented a critical review of the limitations of weighting and scoring concept of the transformer health indexing. This approach fails to maintain the functionality of the transformer as a whole system and fails to identify individual components which are required for maintaining the overall transformer functionality. Limitations of the traditional health index system are clearly demonstrated. The need for a new index which is based on the philosophy of reliability centred maintenance is clearly identified. A discussion on future assessment model is presented, which addresses problems of the traditional health index system.

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A statistical approach for the calculation of DGA limits may seem simple, however, it is not straightforward and easy to calculate a 90 % statistical limit, for example

ABSTRACT

DGA plays a vital role in the diagnostics and maintenance of the transformers. It is a multidisciplinary and complex field that is not easy to master. That is the reason why this article is oriented to explaining the learning and understanding the process associated with DGA.

KEYWORDS

basics, DGA, diagnostics, gasses, oil, principles

Basic principles of DGA - Part II

Learning, using, and creating your own view on DGA

Limits values for DGA tests and results

The exact specification for DGA is something that all transformer users, managers, specific DGA software manufactures, online devices producers, and all the industry are looking for. For other oil test types, it is a usual behaviour to refer the measured value to the relevant limit from the corresponding guide or standard. Having limits like for dissipation factor or oil acidity does not work for DGA. It is probably the key obstacle for DGA manual or software-based diagnosis. The hard challenge here becomes selecting values that represent the specific equipment in the light of new developments and knowledge, and also considering the maintenance policy of the transformer owner. Adopting the published and already processed value is an excellent stage for the initial learning process for DGA interpretation. Using such general limits or normal or cut-off values may lead to substantial pricey consequences.

In this essential aspect, a new version of IEEE C57.107 [9] published the 90 % approach of limits value, shown in Table 1.

This approach was previously presented in CIGRÉ WG on DGA [11] and is a significant step forward to improve the uniqueness of the DGA limits values.

The readers will be able to understand and exercise this statistical approach for DGA limits. Even if it may seem simple to calculate a 90 % statistical limit, it is not a straightforward statistical calculation. The ones who need to compute are demanded to select different options from the primary and extensive database to the specific 90 % limits. Of course, the challenge is inversely proportional to the size of the database. The constrains of data securities imply minimum size databases, and therefore more extensive efforts to develop such kind of limits.

The countenance of these difficulties also comes into view from the new CIGRÉ WG approach, as shown in Table 2. The selected values for two options of database size emphasise the importance of these selections and the meaning of the relation between the database size and the 90 % computed value.

An additional important factor that CIGRÉ BT 771 introduces and the emphases is the fault severity and gas apparition. Here again, the unimportance of hydrogen is notable from Table 3. This gas appears in a minority of cases, and even then, it indicates non-severe faults.

Table 1. Dissolved gas concentrations [9]

Status	Table 1- Dissolved gas concentration limits [µL / L (ppm)]							
	Hydrogen H_2	Methane CH_4	Acetylene C_2H_2	Ethylene C_2H_4	Ethane C_2H_6	Carbon monoxide CO	Carbon Dioxide CO_2	TDCG*
Condition 1	100	120	1	50	65	350	2500	720
Condition 2	101-700	121-400	2-9	51-100	66-100	351-570	2500-4000	721-1920
Condition 3	701-1800	401-1000	10-35	101-200	101-150	571-1400	4001-10000	1921-4630
Condition 4	>1800	>1000	>35	>200	>150	>1400	>10000	>4630

Note 1 - Table 1 assumes that no previous tests on the transformer for dissolved gas analysis have been made, or that no recent history exists. If a previous analysis exists, it should be reviewed to determine if the situation is stable or unstable. Refer to 6.5.2 for appropriate action(s) to be taken.
Note 2 - An ASTM round-robin indicated variability in gas analysis between labs. This should be considered when having gas analysis made by different labs.
• TDCG – total dissolved combustion gas

Table 2. Typical values of gas concentrations in the database of the WG and IEC 60599 [12]

Database of WG47 Typical values in ppm	Number of DGA results	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
All results	337,805	118	85	111	56	5	700	6300
Only last results	85,059	21	55	54	48	2	730	6660
IEC 60599 (No OLTC)	N/A	50-150	30-130	60-280	20-90	2-20	400-600	3800-14,000

The laboratory DGA tests are usually the preferred choice compared to an online DGA device since its efficiency and capabilities, in most cases, are superior to the best available DGA online monitor

From this, Table 3 shows it is evident that the same gas may be sourced from different insulating materials, liquid (oil) and cellulose, and may indicate various phenomena with totally different severity. In addition to the different materials, the location of gas sources inside the transformer may also have a significant impact on the accurate diagnosis.

The readers will be able to realise and discern among those options.

CIGRÉ Technical Brochure 783 describes the effectiveness of the number of gases for the online detector device related to fault capability detection. Table 4 shows the relevant table from this brochure.

Evidently, the costs of the online monitors highly depend on the number of the gases detected, and therefore to the capability to detect the transformer internal faults. The efficiency and capabilities for offline DGA in a specialised laboratory are, in most cases, superior to the best available DGA online monitor. In many circumstances, the laboratory DGA tests are the preferred choice, not just because of their substantial low cost compared to an online DGA device. Some users unjustifiably abandon all offline DGA performed in a monitored lab after installing an online DGA device.

The comparison of performance DGA in laboratories versus online DGA is also elaborated in the last CIGRÉ brochure. Table 5 presents the developments in DGA analytical performances by those two options in the previous 20 years.

In the last two decades, most of the laboratories have switched to a much hastier DGA method, but with lower accuracy, repeatability, and dependability on much more factors. The influence of switching

Table 3. Fault severity by CIGRÉ 771 [12]

Fault :	**In paper**		**In oil**	
Type:	Main products formed	Severity	Main products formed	Severity
D2	C, C_2H_2	Very High	C_2H_2, C	Very High
D2				Moderate
T3	C, C_2H_4,		C_2H_4, C	
T2	C, CH_4	High	CH_4	Low
T1, O	C_2H_6 , CO	Moderate	C_2H_6	Very low
Corona PD	H_2	Low	H_2	
S, T<200°C Aging	CO_2, Furans, alcohols, Low DP's of paper	Very low		

Table 4. Effectiveness of measured gas in oils correlated to fault detection capability [13]

Application	Type of monitor	Gases Measured	Faults Possible to identify	Faults not Possible to identify
Fault Diagnostic	M8 (M9)	H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2, O_2, (N_2)	-all 10 faults in Table 2.2 at an early stage	- none
	M6 , M(7)	H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, (CO_2)		-Faults in the paper very often are not detected correctly with CO only with M6, M5 and M2
	M5	H_2, CH_4, C_2H_4, C_2H_2, CO	-the 6 basic faults only	-the 5 sub-types of faults
	M3	CH_4, C_2H_4, C_2H_2		
Fault Detection	M2	H_2, CO	-none of the 10 faults can be identified	-may not detect faults D1, D2 in their early stages, only in their late, sometimes catastrophic stages.
	M1	H_2		
	M1*	Composite reading of H_2 and others gases		

Table 5a. The accuracies of DGA methods through the methods and ages [13]

	Average accuracy of labs in % at:		Number of inaccurate labs in % at:	
Method	> 100 ppm	< 8 ppm	> 100 ppm	< 8 ppm
A – Partial degassing	12	18	17	0
B – Stripping	19	65	60	63
C – Headspace	28	51	75	42
IEC Spec	15	30	CH4	Low

Accuracy of laboratories using gas extractions methods: A - Partial degassing, B - Stripping, C- Headspace

Table 5b. The accuracies of DGA online monitors through the ages [13]

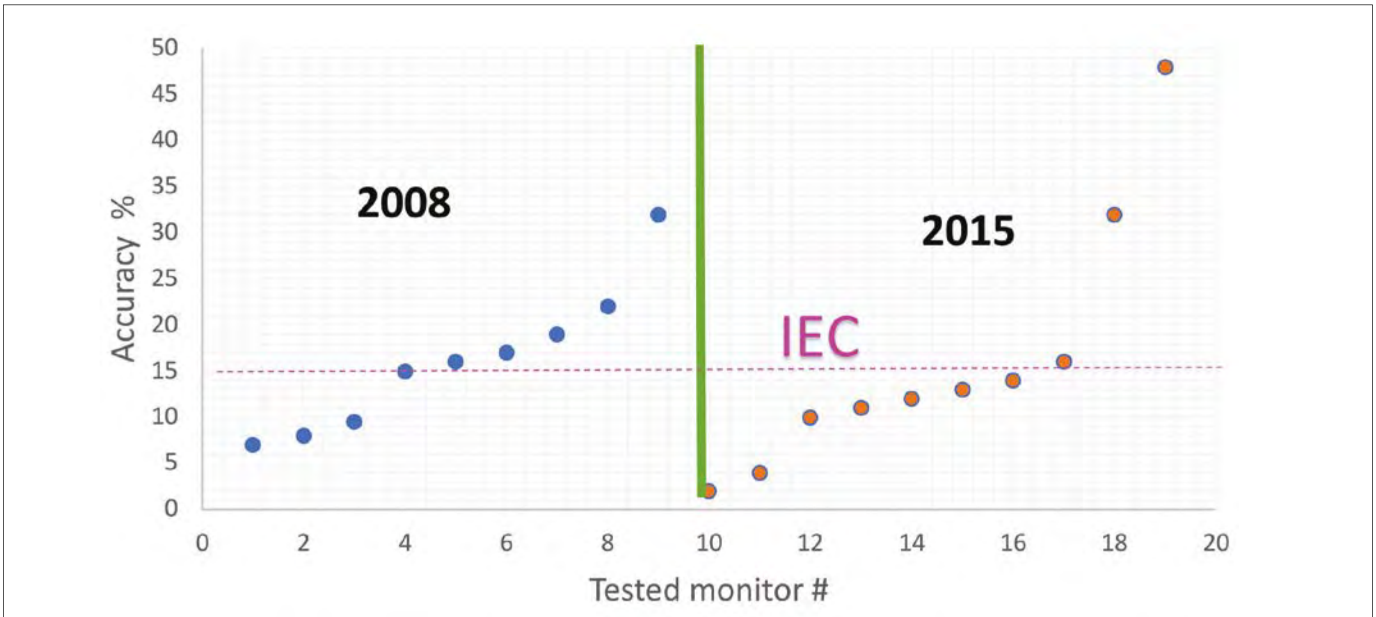

Table 6. Early DGA diagnosis method based on the gas ratio [14]

DGA diagnosis by Mueller, Schliesing, Soldner (MSS)					
Ratio range	C_2H_4/C_2H_2	H_2/CH_4	C_2H_4/C_2H_6	C_2H_4/C_3H_6	CO_2/CO
< 0.3	0	0	0	0	1
0.3 to < 1.0	1	0	0	1	1
1.0 to < 3.0	1	1	1	2	1
3.0 to < 10.0	2	2	1	3	0
10 ≥	2	3	1	3	2
Diagnosis	**Number of sequences**				
Normal ageing of insulant	0	0	0	0	0
Discharge of high energy	2	1	1	2/3	1
Discharge of low energy	2	2	1	2/3	1
Partial discharge with high energy	1	3	0	n.i	0
Partial discharge with low energy	0	3	0	n.i	0
Local overheating up to 300 °C	0	0	0	1	2
Local overheating from 300 °C to 1000 °C	0	0	1	2	2
Local overheating and discharge	1	0	1	2/3	2
Local overheating and discharge partial	1	1	1	2	2
Local overheating up to 300 °C	0	3	1	2	2

There may be inconsistencies of various DGA interpretation and diagnosis methods, which is the reason why the same diagnosis methods are ranked differently by different experts in terms of success

from a vacuum-based approach to the famous headspace is shown in Table 5a by taking into consideration that method A was the popular method 20 years ago and is almost absent in 2020. If one is interested in increasing the DGA performance and reliability, one should use a more sensible and accurate way. Assuredly, the readers will understand better and be able to select the best option, concerning the budget and expected performances.

As displayed in Table 5b, the analytical performances of online devices were considerably improved due to massive investments in this market niche. The demands of such devices express the importance of power transformer continuous operation along with intense activities for critical market research done by CIGRÉ DGA Working Groups in the last decades.

Offline DGA performed in specialised laboratories remains a valuable tool in the transformer maintenance portfolio. The analytical performance and reliability of a DGA test in a lab remain superior versus most of the online devices.

The following paragraphs will focus on overall description of DGA.

The DGA begins from the test priorities and sets the test intervals for each transformer through the bidding process or selecting the proper locations for the tests. It is finalised by correct diagnosis and internal inspection if needed. All those stages will be elaborated through the DGA articles.

Table 7. A comparison of two studies of DGA diagnoses accuracies [19, 20]

Diagnose method	Rogers	Key gas	Duval	IEC
Successful prediction in % by Ref 19 *	23-50	45-100	50-100	23-82
Successful prediction in % by Ref 20	76.24	85.15	91.09	69.31

*Different faults possess different successful prediction values

A variety of many diagnosis schemes is presented briefly. Table 6 shows one of the early gas ratio approaches. The pros and cons for the diagnosis techniques will be described in the following articles as well.

The consistencies of DGA also do not diagnose a consensus. Different experts or software are not evaluating equally the DGA diagnosis outputs. This means that the same diagnosis methods are ranked differently by different experts in terms of success, correctly revealing the incipient failure. Table 7 shows a comparison of two studies of DGA diagnosis accuracies. The following articles will explain the reasons for those discrepancies along with more studies of this subject. The readers will understand the basics of those differences and the adequate modality to select the proper diagnosis and even to develop their own.

How to become a DGA expert?

Probably the main reason for the discrepancy of the importance of DGA for all transformer operations and the contemporary level of uncertainty level of the DGA methodology, emerge from the knowledge divergence between oil chemists and power transformer electrical engineers.

Every reader of these materials possesses unique and valuable information on DGA and / or related aspects. Active reading will permit sharing the information, merging knowledge, and resolving the uncertainty from many different points of views. These articles will emphasise the chemical for a better balance of the light and explain it better to non-chemist readers. There is a general awareness that in 2020 the virtual media is already saturated with webinars and literature on this subject and the potential readers and attendees have to select very carefully the ones they should invest their time and expenses. This article offers some necessary information that may be a proper basis for reading further similar articles, or attending classes on this topic, and of course, getting a better understanding of any commercials offers.

DGA is a multidisciplinary field and to become an expert on DGA, it is required to dig deep and study all available DGA related materials, literature, and other sources of information

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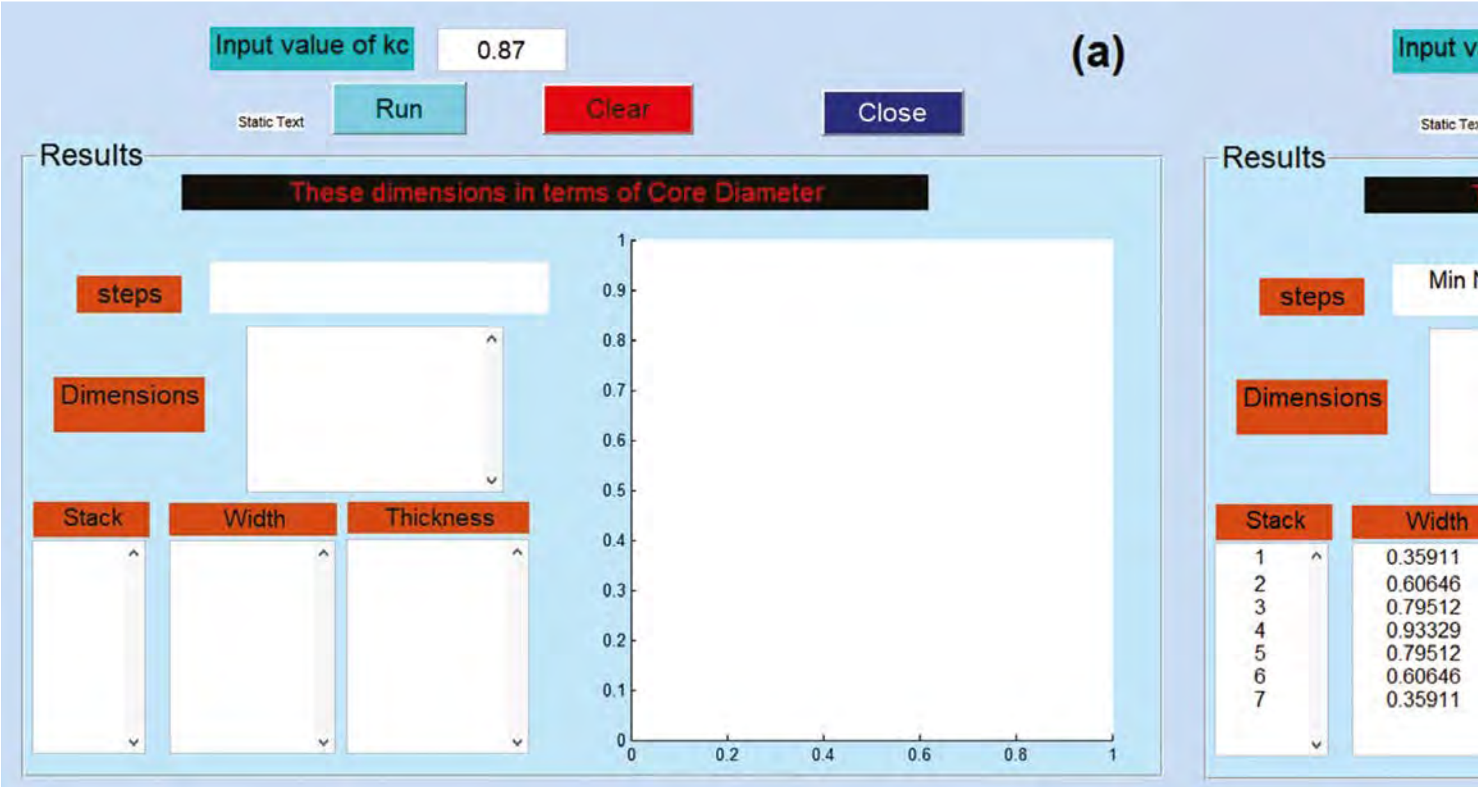


ABSTRACT

It is known that the deployment of highly efficient power transformers is crucial for the minimization of overall network losses. Hence, the curriculum of an elective senior-level course was developed for Cairo University students. This curriculum was developed by industrially experienced faculty members to mimic typical tasks encountered by power transformer manufacturers. In addition to classical methodologies, the course offers students hands-on experience in relevant finite-element analysis tools and newly introduced artificial intelligence techniques. Examples of student-developed design software packages are given. It is evident that linking the course content to actual real-life industrial scenarios results in outstanding student performance.

KEYWORDS

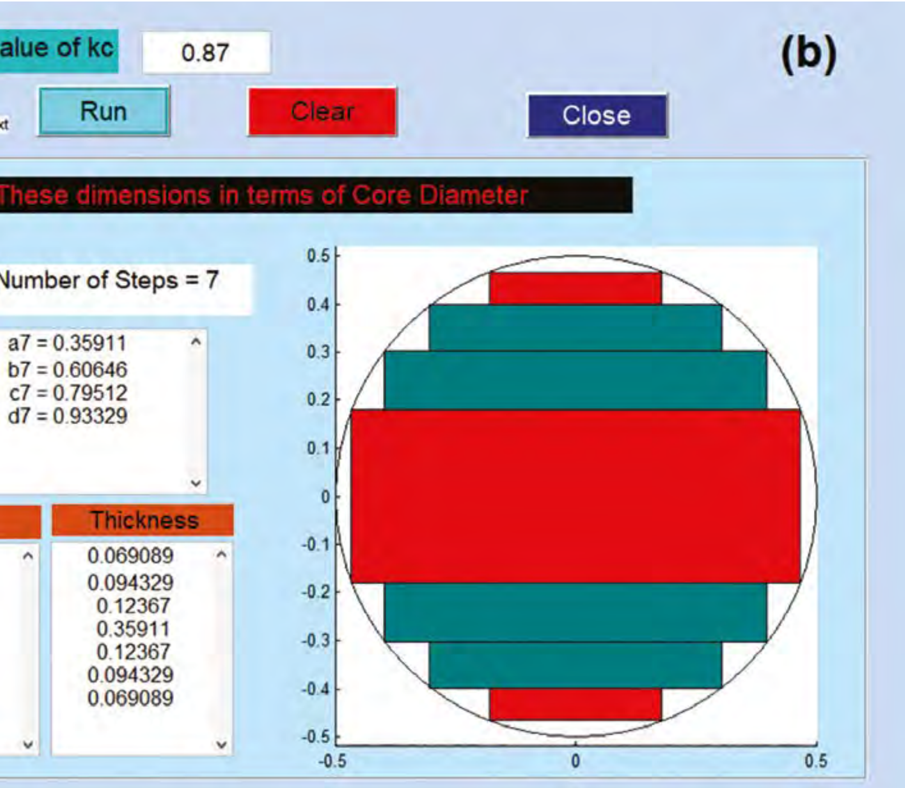
artificial intelligence techniques, computer-aided design, design optimization, transformer design methodologies

Computer-aided transformer design capacity building

A sample industry-oriented senior level university course

1. Introduction

Power transformers are considered among the most important components in any power network. Obviously, deployment of highly efficient power transformer units is indispensable for minimization of overall network losses. While most of the relevant power engineering curricula focus on power transformer operation and maintenance technicalities, availability of design methodologies know-how is crucial to fulfilling national and regional transformer manufacturers' job needs as well as to support efforts aiming at boosting the value added in national industries. Within the aforementioned context, a curriculum of an elective senior-level course was developed a few years ago for Cairo University Power Engineering students. Unlike traditional courses covering the same topic, the curriculum was developed by industrially experienced faculty members to mimic typical tasks encountered in design and research and development (R&D) offices of power transformer manufacturers. It should be mentioned that, in addition to power transformer design methodologies, the aforementioned course is entitled: "Computer-Aided De-



Availability of design methodologies know-how is crucial to fulfilling transformer manufacturers' job needs as well as to support efforts aiming at boosting the value added in national industries

sign (CAD) of Electrical Machines" and also exposing students to design methodologies related to fractional horse-power (HP) induction motors (i.e., ratings less or equal to 1 HP) [1]. The unique nature of the course curriculum and teaching strategies with regards to power transformers design mechanism are discussed in the following sections.

2. Course objectives and teaching methodologies

The main objectives of the course under consideration are:

- to make students acquainted with the materials and theories related to specifications-oriented transformers design,
- to give students hands-on experience with some CAD tools currently used at R&D and / or design offices of power transformer manufacturers (see, for example, [2, 3]),
- to introduce students to typical optimization and / or cost reduction challenges encountered by manufacturers. It should be mentioned here that optimization reduces to minimum both the construction and running costs which are usually achieved by fulfilling the required design specifications yet competing pricewise in sales tenders.

In other words, the course objectives tend to help potential power transformer design engineers acquire necessary technical capacity relevant to the industry as well as to give them a flavour of what design challenges should be expected in real life.

2.1 Specifications-oriented power transformers design approach

In real-life situations, whether a sophisticated Finite Element Analysis (FEA) transformer design software tool or a simplistic analytical design approach is adopted, the main challenge is to identify the detailed design specifics that would result in fulfilling a set of required specifications at the minimum possible cost (refer, for instance, to [4, 5]). Obviously, the trade-off for using a simplistic analytical design approach is the involvement of safety factors to guarantee fulfilment of the required specifications at the expense of uncertainty in achieving the minimum cost design. Nevertheless, such analytical approach could yield a very good initial design details for more sophisticated transformer design software tools in addition to offering a fast high-level assessment of how design details may change as a result of a variation of certain design parameters, such as specific losses of utilized steel sheets.

Aside from covering all basics related to power transformer materials, the theory of operation and effect of the properties of every single component on the operation performance [1], a recently compiled specifications-oriented design methodology is mainly adopted [6]. According to this methodology, the main specification requirements may be directly correlated to four main design parameters. More specifically, the Volt-Ampere Rating (S), the overall ohmic Copper Losses (Pcu), the ohmic No Load Losses (Pnl), and the ohmic Reactance per Phase (X) may be correlated to the Window Height (Hw), the Limb Diameter (D), the maximum Core Flux Density (Bc), and the average conductors' Current Density (J) in accordance with the following equations:

$$S = C_1 f_1(J, Bc, D, Hw) \quad (1)$$
$$Pcu = C_2 f_2(J, D, Hw) \quad (2)$$
$$Pnl = C_3 f_3(Bc, D, Hw) \quad (3)$$
$$X = C_4 f_4(J, D, Hw) \quad (4)$$

It is extremely important to give students hands-on experience with some CAD tools currently used at R&D and / or design offices of power transformer manufacturers

In the era of the fourth industrial revolution and its far-reaching consequences it is extremely important to expose students to non-traditional artificial intelligence (AI) transformer design techniques

In (1)-(4), C_1, C_2, C_3 and C_4 represent equation constants which take into account other design parameters such as: frequency, voltages, winding connections, window space factor, steel core stacking factor, conductor resistivity, copper and steel densities and specific core losses (please refer to [6]).

Obviously, several approaches may be taken to solve the above four equations to directly meet the main operating specifications. More specifically, equations may be solved simultaneously or iteratively to offer a very good initial detailed design guess. There is no doubt that a solid technical background of design limitations is required to sort out non-realistic solutions that may be a consequence of unachievable specifications requirements. Examples of such non-realistic solutions may include a maximum core flux density (*Bc)* exceeding the saturation range of the utilized steel core magnetization curve and / or practical current density of copper windings. It should be stated that once the four unknowns are determined, all other design specifics, such as the number of turns and winding cross-sections, may be calculated from other parameter inter-relations.

2.2 Hands-on experience with different CAD tools relevant to transformer design

A considerable percentage of the course work grade was related to the development of friendly software packages equipped with graphical user interfaces (GUI) that would support real-life activities carried out in transformer manufacturer design and / or R&D divisions.

Typical programming assignments included the development of software packages offering fast design support based on the previously discussed specifications-oriented analytical approach. Other examples involved optimization techniques to maximize gross core cross-sectional area within a given winding inner diameter.

Students were also exposed to free student version two-dimensional (2D) FEA packages [2, 3]. This was especially important to give them a head start in comprehending mathematical basics and limitations of such packages as well as to introduce them to how more sophisticated FEA packages may be well utilized within power transformer manufacturer plants to further refine preliminary design details that lead to the ultimate minimization of production material and, consequently, cost. It should be stated here that some assignments focused on using the FEA packages in the assessment and visualization of stray fields leading to eddy current losses in winding top and bottom edges, something hard to convey without such tools. Such FEA assignments focused on demonstrating that minimization of the previously mentioned losses related to the transformer window height to width ratio.

Given the implications of the Fourth Industrial Revolution [7], it was also extremely important to expose students to non-traditional artificial intelligence (AI) design techniques. In line with this mandate, feedforward artificial neural networks (FFANN) were introduced, and means of training and usage were covered. Some assignments involved using an FFANN with inputs and outputs conforming to the eight variables given in equations (1)-(4) to recommend design details for a given set of required specifications [8]. Obviously, this was possible by training the same FFANN using a set of top-quality power transformers having different specifications and with known design details.

2.3 Sample assignments and student work

In addition to a total of 45 contact hour lectures, and 15 contact hour tutorials, 112 students registered in the Spring 2020 semester were subdivided into 22 different groups. It should be mentioned that the course topic proved to be appealing to students interests since the registered students represented 70 % of the total final year students despite the fact that two other elective courses were offered. Different mini projects were assigned to the student groups, where more than one group was assigned the same project. This was especially important to highlight the possibility of adopting different optimization logic and / or design methodologies to achieve the same ultimate goal. All mini projects involved the development of a software tool equipped with a user-friendly GUI. A very brief listing of some of those mini projects, which had to be accomplished within a month duration, is given below:

- Development of a software package that can maximize the transformer core cross-sectional area for 5, 7 and 9 step steel lamination stacks,
- Development of a software package capable of identifying the minimum number of lamination stacks required to achieve a certain required stacking factor,
- Getting acquainted with a free student version of a 2D electromagnetic FEA package to construct an energized power transformer having specific dimensions and use the package to identify eddy current losses in winding edges as well as to plot leakage flux and flux density distribution at central parts of the core limbs,
- Development of a transformer design FFANN capable of identifying design details corresponding to the required specifications, provided that these specifications fall within extreme specification values of a given set of 20 different transformers used for the neural network (NN) training purposes,
- Development of a transformer design software package based on the taught specifications-oriented analytical methodologies.

Clearly and as previously stated, such mini projects were carefully chosen to give the students a flavour of what they might encounter in case they join a transformer manufacturer design and / or R&D office.

An example of the delivered student mini projects is shown in the cover figure where the number of core steel stacks and their dimensions relative to the winding inner diameter is calculated to achieve a given stacking factor. This package involved both a GUI and an optimization routine. The figure clearly highlights the input data in the image (a). Once the "RUN" button is clicked, detailed dimensions are calculated and given, as shown in the image (b). It should be mentioned that this tool has been developed to fulfil assignment requirements for a group of 3 students.

An alternative for steel stacking is shown in Fig. 1. where the number of stacks, inner winding diameter in addition to the dimensions of the steel laminations are identified. The developed student mini-project software tool then computes the stacking factor, dimensions of the various steel stacks in addition to the wasted steel laminations as a result of a mismatch between the lamination and stack dimensions. Once more, Fig. 1.a highlights the input. Once the "CALCULATE" button is clicked, detailed dimensions are calculated as in Fig. 1.c, as per the dimensioning scheme of Fig. 1.b. It should be stated that this tool has been developed by a group comprised of 5 students.

Another example is shown in Fig. 2, where a non-iterative software tool equipped with a GUI was developed to automate the analytical specifications-oriented transformer design approach. In Fig. 2.a., symbols *Kc*, *SW* and *CFe* represent the stacking factor, the window space factor and a constant correlating the steel sheets losses per kg weight as per the expression $CfeBc^2$, respectively. Once the "CALCULATE" button is clicked, design details are computed as shown in Fig. 2.b. In this figure, *Ww*, *Hw*, *N1*, *N2*, *A1*, *A2*, *I1* and *I2* represent the window width, the window height, primary winding number of turns, secondary winding number of turns, primary winding cross-section, secondary winding cross-section, primary current, and the secondary current respectively. Moreover, *R*, *Rc* and *Xm* represent the equivalent winding resistance per phase, equivalent core loss resistance per phase, and the magnetizing reactance per phase, respectively, all referred to the high voltage side. Please note that the tool also offers an insight into how the quality of steel laminations would affect the overall design details through the shown curves demonstrated once the "PLOT" button is clicked. It should be mentioned that development of this tool was assigned to a different group of 6 students enrolled in the course.

Within the course, students are developing software packages for the transformer-related mini-project, which include a GUI and a solution using advanced computational techniques such as optimization

Alternatively, Fig. 3 demonstrates a different iterative software tool equipped with a GUI which was developed to automate the analytical specifications-oriented transformer design approach. The required design specifications are entered as shown in Fig. 3.a. Once the "CALCULATE" button is clicked, design details are given as shown in Fig. 3.b. This design tool and its GUI was developed by yet another group comprised of 6 students.

Overall, it was clear that linking the course content and assignment requirements to actual real-life industrial scenarios has resulted in boosting student motivation and the will to deliver high-quality work. This is indeed in the very best interest of both the students within their future job search efforts as well as for power transformer manufacturers in search of new qualified and talented manpower.

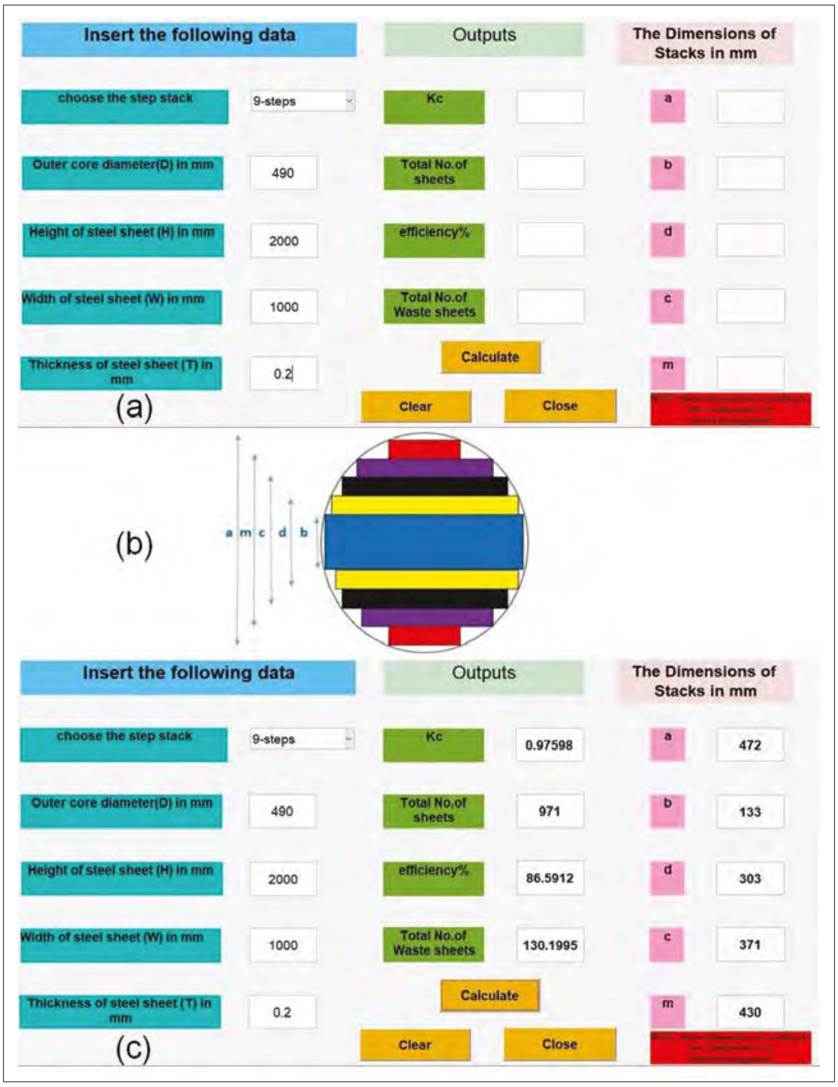


Figure 1. A delivered student mini-project where, given the number of stacking steps, the inner diameter of windings and steel lamination dimensions (a), the tool identifies the steel stack dimensions as identified in (b) in addition to the stacking factor and wasted steel laminations (c).

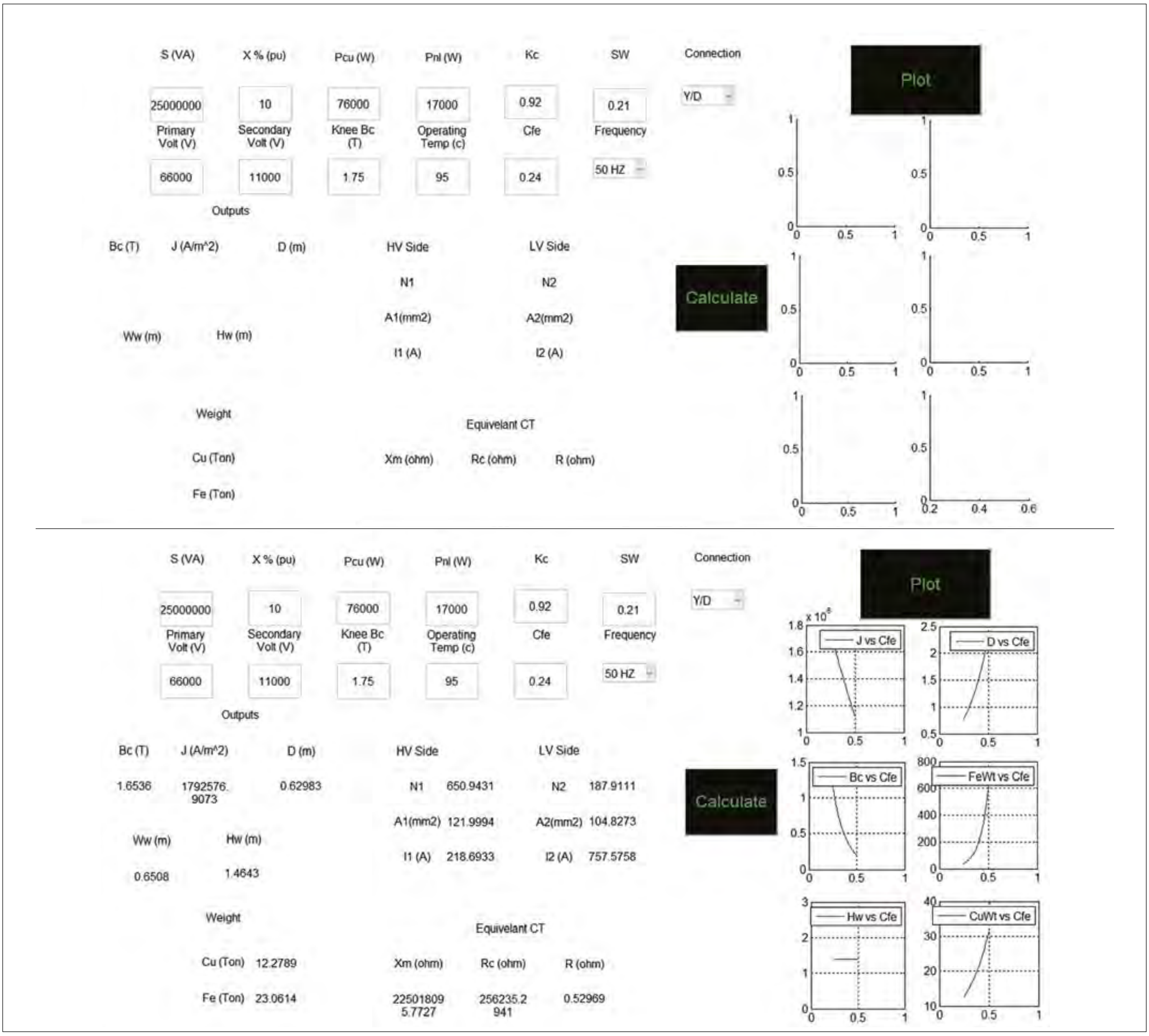


Figure 2. Non-iterative automation of the analytical specifications-oriented transformer design approach where, for a set of required specifications as shown in (a), it is possible to obtain detailed design details in addition to an account of how the quality of steel sheets material could affect those details (b).

Conclusion

This article has highlighted the need for developing transformer design curricula reflecting real-life industrial design challenges. On a quest for these capacity-building efforts, hands-on knowledge transfer related to electromagnetic software packages and newly introduced artificial intelligence approaches is a must. Outstanding mini projects developed by the students suggest that adopting the aforementioned curricula results in boosting the students' motivation. Tertiary and / or tap changers windings are also planned in future versions of the course. The author would like to conclude this article by acknowledging the great work of all 112 students who enrolled in the reported Spring 2020 course (of which sample design tools have been reported in this article) as well as the support of Dr. H. Hassan and Eng. A. Abbas who participated in the teaching efforts.

Expect outstanding work from students as a result of being motivated by linking the course content and assignment requirements to actual real-life industrial scenarios

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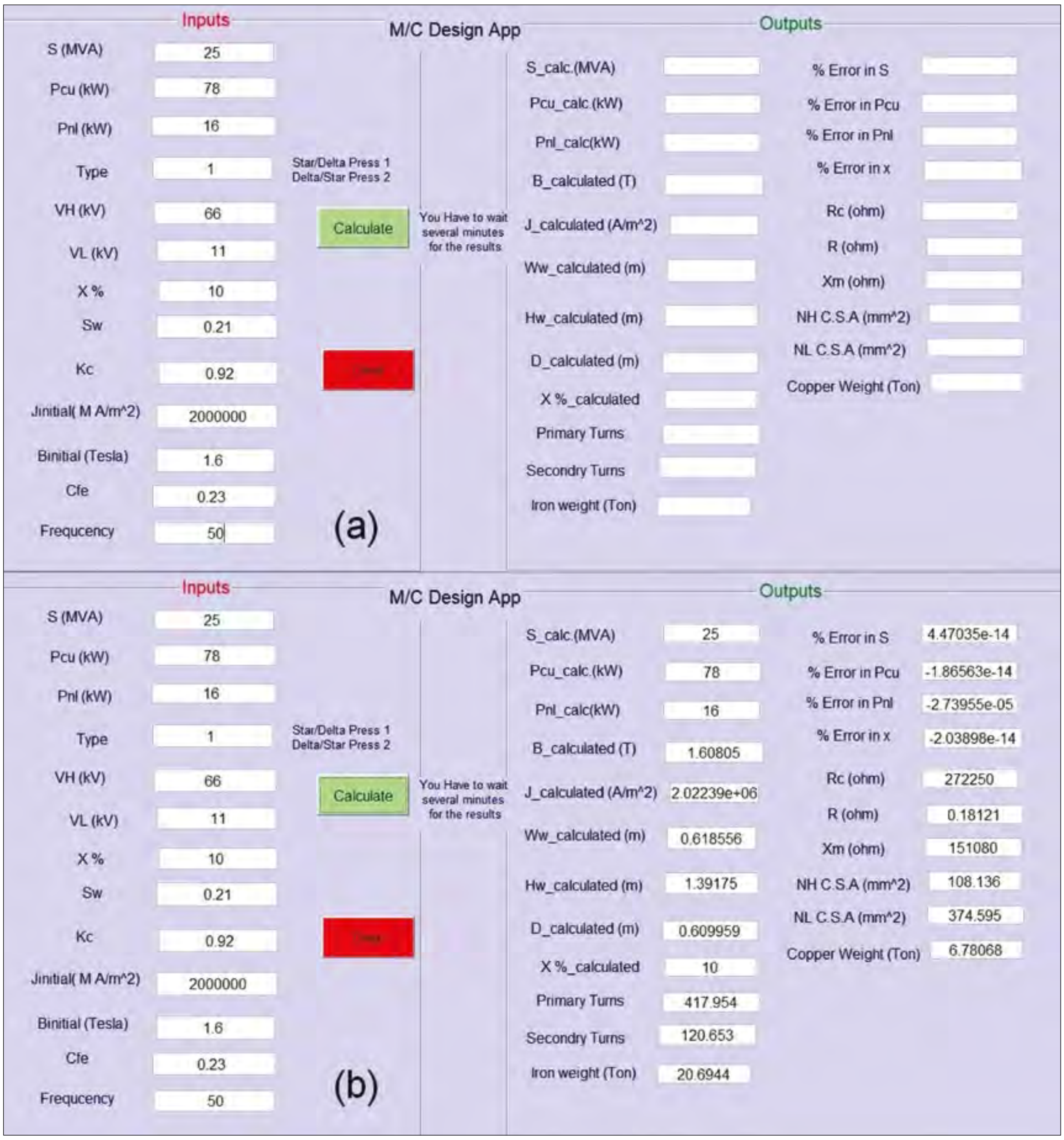
Figure 3. Iterative automation of the analytical specifications-oriented transformer design approach where, for a set of required specifications as shown in (a), it is possible to obtain detailed design details in addition to an account of how the quality of steel sheets material could affect those details (b).



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Standards relevant to transformers – Part IV

BSI has more than 100 years of history in covering standards for transformers which make them pioneers in the field

ABSTRACT

Last three parts of this series covered the evolution of Standards / Technical Brochures related to Power Transformers under IEC, IEEE and CIGRE and listed current standards issued by them. Now we see the evolution of transformer standards in Britain and the current position of European Standards (EN) on Transformers.

KEYWORDS

standards, transformers, BSI, BESA, CENELEC

> **First tentative British standard exclusively for transformers was issued in 1917 as Specification No. 72 'Electrical Performance of Transformers for Power and Lighting'**

BSI – British standards institution

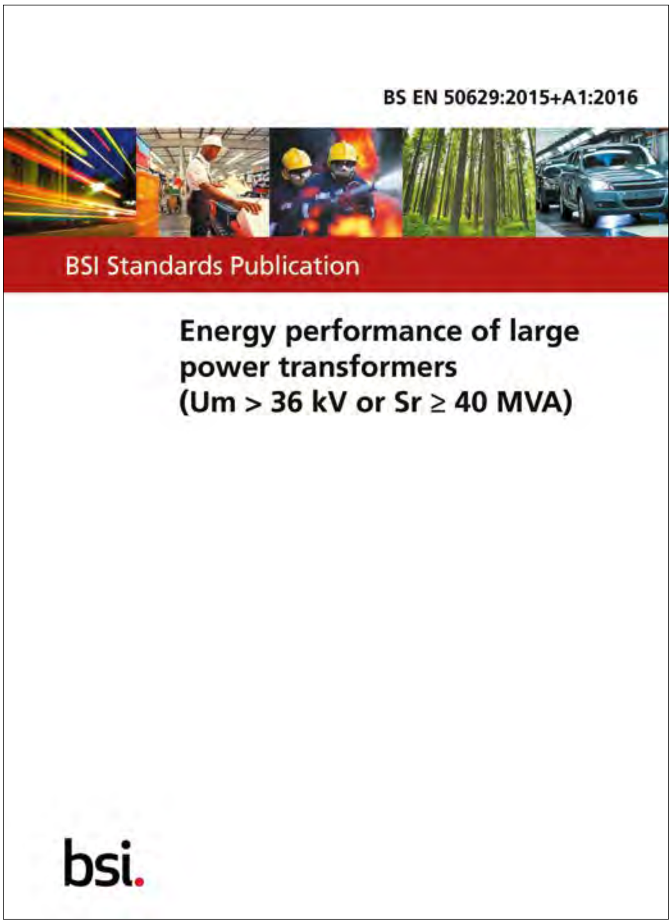
Work on engineering standards started in Britain in 1901 on the initiative of the British Engineering Standards Committee under Sir John Wolfe Barry KCB (the engineer who designed London's famous Tower Bridge). Later, the electrical section committee was constituted under Sir John Snell. British Engineering Standards Association (BESA) issued the "Standardization Rules for Electrical Machinery" during the first decade of the 20th century. A tentative standard exclusively for transformers was issued in 1917 as Specification No. 72 'Electrical Performance of Transformers for Power and Lighting'. A further tentative standard for Transformer oil was issued in 1923 and this was reproduced in full in the first edition of The J & P Transformer Book, published in 1925 [1].

First standards for transformers and oil were issued in 1927 with numbers BSS: 171 "British Standard Specifications for the Electrical Performance of Transformers for Power and Lighting" & BSS: 148 "British Standard Specifications for Insulating Oils for Electrical Purposes (excluding cables)". In the fourth edition of The J & P Transformer Book, published in 1928 [2], these two standards were reproduced in full, under the permission of BESA. In the above book, we can find the first national standards on transformers, as in use 90 years back. These two standards, along with the Code of Practice CP 1010 'Transformer Loading Guide' were widely referred to and used in Britain and its colonies for the next half a century, undergoing several revisions. Later, these British Standards were replaced by individual national standards or IEC standards, as the colonies became independent countries. In 1961, there were nearly 40 British standards relevant to power and distribution transformers.

CENELEC - European committee for electrotechnical standardization

CENELEC (French: *Comité Européen de Normalisation Électrotechnique*) is the European Committee for Electrotechnical Standardization and is responsible for standardization in the electrotechnical engineering field [3]. CENELEC prepares voluntary standards that facilitate trade between countries, create new markets, cut compliance costs and support the development of a Single European Market.

Designated as European Standards Organization by the European Commission, CENELEC is a non-profit technical organization set up under Belgian law. It was created in 1973 as



a result of the merger of two previous European organizations: CENELCOM and CENEL.

CENELEC concentrates most of its work on two major deliverables: the European Standard (EN) and the Harmonization Document (HD). These two documents are referred to commonly as "standards" and must be implemented in all CENELEC member countries, who must also withdraw any conflicting standards.

There are a few differences in the implementation process of the ENs and HDs. Basically, the EN must be transposed as it is, not adding or deleting anything. The process for the HDs is a bit more flexible. It is the technical content that must be transposed, no matter the wording or how many documents are made of it. In addition to these two major deliverables, CENELEC also produces and approves documents with a different objective and target.

European Standards (ENs) are based on a consensus, which reflects the economic and social interests of 34 CENELEC member countries channelled through their National Electrotechnical Committees (NCs).

The technical committee responsible for the formulation of EN Power Transformer Standards is CLC/TC 14, and EN Bushing Standards is CLC/TC 36 A. Standards published by these committees are listed below.

Designated as European Standards Organization by the European Commission, CENELEC is a non-profit technical organization set up under Belgian law

CENELEC prepares voluntary standards that facilitate trade between countries, create new markets, cut compliance costs and support the development of a Single European Market

Table 1. EN Standards on Transformers

Serial No.	Standard Number	Title
1	**HD 538.1 S1:1992/AC:2011** (pr=23795)	Three-phase dry-type distribution transformers 50 Hz, from 100 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV - Part 1: General requirements and requirements for transformers with highest voltage for equipment not exceeding 24 kV
2	**EN 50195:1996** (pr=5740)	Code of practice for the safe use of fully enclosed askarel-filled electrical equipment
3	**EN 50216-1:2002** (pr=4783)	Power transformer and reactor fittings - Part 1: General
4	**EN 50216-2:2002** (pr=216)	Power transformer and reactor fittings - Part 2: Gas and oil actuated relay for liquid immersed transformers and reactors with conservator
5	**EN 50216-2:2002/A1:2002** (pr=14853)	Power transformer and reactor fittings - Part 2: Gas and oil actuated relay for liquid immersed transformers and reactors with conservator
6	**EN 50216-3:2002** (pr=5601)	Power transformer and reactor fittings - Part 3: Protective relay for hermetically sealed liquid-immersed transformers and reactors without gaseous cushion
7	**EN 50216-3:2002/A2:2006** (pr=20479)	Power transformer and reactor fittings - Part 3: Protective relay for hermetically sealed liquid-immersed transformers and reactors without gaseous cushion
8	**EN 50216-4:2015** (pr=22810)	Power transformer and reactor fittings - Part 4: Basic accessories (earthing terminal, drain and filling devices, thermometer pocket, wheel assembly)
9	**EN 50216-5:2002/A2:2005/ corrigendum Oct. 2006** (pr=26210)	Power transformer and reactor fittings - Part 5: Liquid level, pressure and flow indicators, pressure relief devices and dehydrating breathers
10	**EN 50216-5:2002** (pr=11501)	Power transformer and reactor fittings - Part 5: Liquid level, pressure and flow indicators, pressure relief devices and dehydrating breathers
11	**EN 50216-5:2002/A2:2005** (pr=14950)	Power transformer and reactor fittings - Part 5: Liquid level, pressure and flow indicators, pressure relief devices and dehydrating breathers
12	**EN 50216-5:2002/A3:2006** (pr=20506)	Power transformer and reactor fittings - Part 5: Liquid level, pressure and flow indicators, pressure relief devices and dehydrating breathers
13	**EN 50216-6:2002** (pr=7656)	Power transformer and reactor fittings - Part 6: Cooling equipment - Removable radiators for oil-immersed transformers

Serial No.	Standard Number	Title
14	**EN 50216-7:2002** (pr=4784)	Power transformer and reactor fittings - Part 7: Electric pumps for transformer oil
15	**EN 50216-8:2005** (pr=14952)	Power transformer and reactor fittings - Part 8: Butterfly valves for insulating liquid circuits
16	**EN 50216-9:2009** (pr=15198)	Power transformer and reactor fittings - Part 9: Oil-to-water heat exchangers
17	**EN 50216-10:2009** (pr=15199)	Power transformer and reactor fittings - Part 10: Oil-to-air heat exchangers
18	**EN 50216-11:2008** (pr=20505)	Power transformer and reactor fittings - Part 11: Oil and winding temperature indicators
19	**EN 50216-12:2011** (pr=20478)	Power transformer and reactor fittings - Part 12: Fans
20	**EN 50225:1996** (pr=5741)	Code of practice for the safe use of fully enclosed oil-filled electrical equipment which may be contaminated with PCBs
21	**EN 50299-1:2014** (pr=24705)	Oil-immersed cable connection assemblies for transformers and reactors having highest voltage for equipment Um from 72,5 kV to 550 kV - Part 1: Fluid-filled cable terminations
22	**EN 50299-2:2014** (pr=24706)	Oil-immersed cable connection assemblies for transformers and reactors having highest voltage for equipment Um from 72,5 kV to 550 kV - Part 2: Dry-type cable terminations
23	**CLC/TR 50453:2007/ corrigendum Dec. 2007** (pr=26124)	Evaluation of electromagnetic fields around power transformers
24	**CLC/TR 50453:2007** pr=16657)	Evaluation of electromagnetic fields around power transformers
25	**CLC/TR 50462:2008** (pr=15968)	Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors
26	**EN 50464-2-1:2007** (pr=14815)	Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2 500 kVA with highest voltage for equipment not exceeding 36 kV - Part 2-1: Distribution transformers with cable boxes on the high-voltage and/or low-voltage side - General requirements
27	**EN 50464-2-2:2007** (pr=14816)	Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2 500 kVA with highest voltage for equipment not exceeding 36 kV - Part 2-2: Distribution transformers with cable boxes on the high-voltage and / or low-voltage side - Cable boxes type 1 for use on distribution transformers meeting the requirements of EN 50464-2-1
28	**EN 50464-2-3:2007** (pr=14817)	Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2 500 kVA with highest voltage for equipment not exceeding 36 kV - Part 2-3: Distribution transformers with cable boxes on the high-voltage and / or low-voltage side - Cable boxes type 2 for use on distribution transformers meeting the requirements of EN 50464-2-1
29	**EN 50588-1:2017** (pr=64220)	Medium power transformers 50 Hz, with highest voltage for equipment not exceeding 36 kV - Part 1: General requirements
30	**EN 50588-2:2018** (pr=65066)	Medium power transformers 50 Hz, with highest voltage for equipment not exceeding 36 kV - Part 2: Transformers with cable boxes on the high-voltage and / or low-voltage side - General requirements for transformers with rated power less than or equal to 3 150 kVA
31	**EN 50588-3:2018** (pr=65067)	Medium power transformers 50 Hz, with highest voltage for equipment not exceeding 36 kV - Part 3: Transformers with cable boxes on the high-voltage and / or low-voltage side - Cable boxes type 1 for use on transformers meeting the requirements of EN 50588-2
32	**EN 50588-4:2018** (pr=65069)	Medium power transformers 50 Hz, with highest voltage for equipment not exceeding 36 kV - Part 4: Transformers with cable boxes on the high-voltage and / or low-voltage side - Cable boxes type 2 for use on transformers meeting the requirements of EN 50588-2
33	**EN 50629:2015** (pr=25005)	Energy performance of large power transformers (Um > 36 kV or Sr ≥ 40 MVA)
34	**EN 50629:2015/A1:2016** (pr=60895)	Energy performance of large power transformers (Um > 36 kV or Sr ≥ 40 MVA)
35	**EN 50629:2015/A2:2018** (pr=64553)	Energy performance of large power transformers (Um > 36 kV or Sr ≥ 40 MVA)
36	**EN 50708-1-1:2020** (pr=69509)	Power transformers - Additional European requirements: Part 1-1: Common part - General requirements

Serial No.	Standard Number	Title
37	**EN 50708-2-1:2020** (pr=69510)	Power transformers - Additional European requirements: Part 2-1 Medium power transformer - General requirements
38	**EN 50708-3-1:2020** (pr=69511)	Power transformers - Additional European requirements: Part 3-1 Large power transformer - General requirements
39	**EN 60076-1:2011** (pr=22467)	Power transformers - Part 1: General
40	**EN 60076-2:2011** (pr=22468)	Power transformers - Part 2: Temperature rise for liquid-immersed transformers
41	**EN 60076-3:2013** (pr=24097)	Power transformers - Part 3: Insulation levels, dielectric tests and external clearances in air
42	**EN 60076-3:2013/A1:2018** (pr=64726)	Power transformers - Part 3: Insulation levels, dielectric tests and external clearances in air
43	**EN 60076-4:2002** (pr=14207)	Power transformers - Part 4: Guide to the lightning impulse and switching impulse testing - Power transformers and reactors
44	**EN 60076-5:2006** (pr=16426)	Power transformers - Part 5: Ability to withstand short-circuit
45	**EN 60076-6:2008** (pr=20669)	Power transformers - Part 6: Reactors
46	**EN 60076-10:2016** (pr=25043)	Power transformers - Part 10: Determination of sound levels
47	**EN IEC 60076-11:2018/ AC:2019-06** (pr=69410)	Power transformers - Part 11: Dry-type transformers
48	**EN 60076-11:2004** (pr=15242)	Power transformers - Part 11: Dry-type transformers
49	**EN IEC 60076-11:2018** (pr=63478)	Power transformers - Part 11: Dry-type transformers
50	**EN 60076-13:2006** (pr=16727)	Power transformers - Part 13: Self-protected liquid-filled transformers
51	**EN 60076-14:2013** (pr=24171)	Power transformers - Part 14: Liquid-immersed power transformers using high-temperature insulation materials
52	**EN 60076-16:2011** (pr=22613)	Power transformers - Part 16: Transformers for wind turbines applications
53	**EN 60076-18:2012** (pr=23523)	Power transformers - Part 18: Measurement of frequency response
54	**EN 60076-19:2015** (pr=58616)	Power transformers - Part 19: Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors
55	**EN IEC 60076-22-1:2019** (pr=63125)	Power transformers - Part 22-1: Power transformer and reactor fittings – Protective devices
56	**EN IEC 60076-22-2:2019** (pr=63126)	Power transformers - Part 22-2: Power transformer and reactor fittings - Removable radiators
57	**EN IEC 60076-22-3:2019** (pr=63127)	Power transformers - Part 22-3: Power transformer and reactor fittings - Insulating liquid to air heat exchangers
58	**EN IEC 60076-22-4:2019** (pr=63128)	Power transformers - Part 22-4: Power transformer and reactor fittings - Insulating liquid to water heat exchangers
59	**EN IEC 60076-22-7:2020** (pr=67592)	Power transformers - Part 22-7: Power transformer and reactor fittings - Accessories and fittings
60	**EN IEC 60076-24:2020** (pr=66214)	Power transformers - Part 24: Specification of voltage regulating distribution transformers (VRDT)
61	**EN 60214-1:2014** (pr=24779)	Tap-changers - Part 1: Performance requirements and test methods
62	**EN 61378-1:2011** (pr=22426)	Convertor transformers - Part 1: Transformers for industrial applications
63	**EN 61378-2:2001** (pr=13165)	Convertor transformers - Part 2: Transformers for HVDC applications

Pr = Project number

Table 2. EN Standards on Bushings

Serial No.	Standard Number	Title
1	**EN 50180-1-2015** (pr=23286)	Bushings above 1 KV to 52 kV 250A-3.15 kA for liquid filled transformers –Part 1: General requirements for bushings
2	**EN 50180-2-2015** (pr=25234)	Bushings above 1 KV to 52 kV 250A-3.15 kA for liquid filled transformers- Part 2: Requirements for bushing components
3	**EN 50180-3-2015** (pr=25235)	Bushings above 1 KV to 52 kV 250A-3.15 kA for liquid filled transformers- Part 3: Requirements for bushing fixations
4	**EN 50180-3:2015/A1:2017** (pr=61704)	Bushings above 1 KV to 52 kV 250A-3.15 kA for liquid filled transformers- Part 3: Requirements for bushing fixations
5	**EN 50181-2010** (pr=21119)	Plug-in-type bushings above 1 kV -52 kV 250A-2.5 kA for equipment other than liquid filled transformers
6	**EN 50243-2002** (pr=7135)	Outdoor bushings for 24 & 36 KV, 5kA & 8 kA
7	**EN 50299-2002**	Oil-immersed cable connection assemblies for transformers and reactors having voltage for equipment Um 72.5 kV – 550 kV
8	**EN 50336-2002** (pr=6219)	Bushings for transformer and reactor cable boxes not exceeding 36 kV
9	**EN 50386-2010** (pr=21708)	Bushings up to 1 kV and from 250 A to 5 kA, for liquid filled transformers
10	**EN 50386:2010/A1:2013** (pr=23287)	Bushings up to 1 kV and from 250 A to 5 kA, for liquid filled transformers
11	**EN 50387-2002** (pr=14940)	Bus bar Bushings up to 1 kV, 1.25 kA – 5 kA, for liquid filled transformers
12	**CLC/TS 50458:2006** (pr=3760)	Capacitance graded outdoor bushing 52 kV up to 420 kV for oil immersed transformers
13	**EN 50673:2019** (pr=63364)	Plug-in type bushings for 72,5 kV with 630 A and 1,250 A for electrical equipment
14	**EN 60137:2017/AC:2018-08** (pr=67231)	Insulated bushings for alternating voltages above 1,000 V
15	**EN 60137:2017** (pr=62435)	Insulated bushings for alternating voltages above 1,000 V
16	**EN IEC/IEEE 65700-19-03: 2018/AC:2019-03** (pr=69149)	Bushings for DC application
17	**EN IEC/IEEE 65700-19-03:2018** (pr=64163)	Bushings for DC application

***Note**: Standards having IEC number designation after EN are adopted from IEC by CENELEC without modification as per IEC/CENELEC agreement.*

Conclusion

Transformer engineers frequently refer to national standards during the selection, manufacture, operation and maintenance of transformers. It is hoped the list of National Standards on Power Transformers covered in this column will help engineers to appreciate the extent of standards available today for their work connected with transformers. Historical evolution of these standard bodies and BSI/CENELEC is covered till it reached present levels. With the march of Industrial Revolution 4.0, transformers will get connected with more and more new horizons like power electronics, artificial intelligence, machine learning, big data, sensors and digitalization. Power engineers working on standardization committees for transformers will have to reflect these new developments in future revisions of standards.

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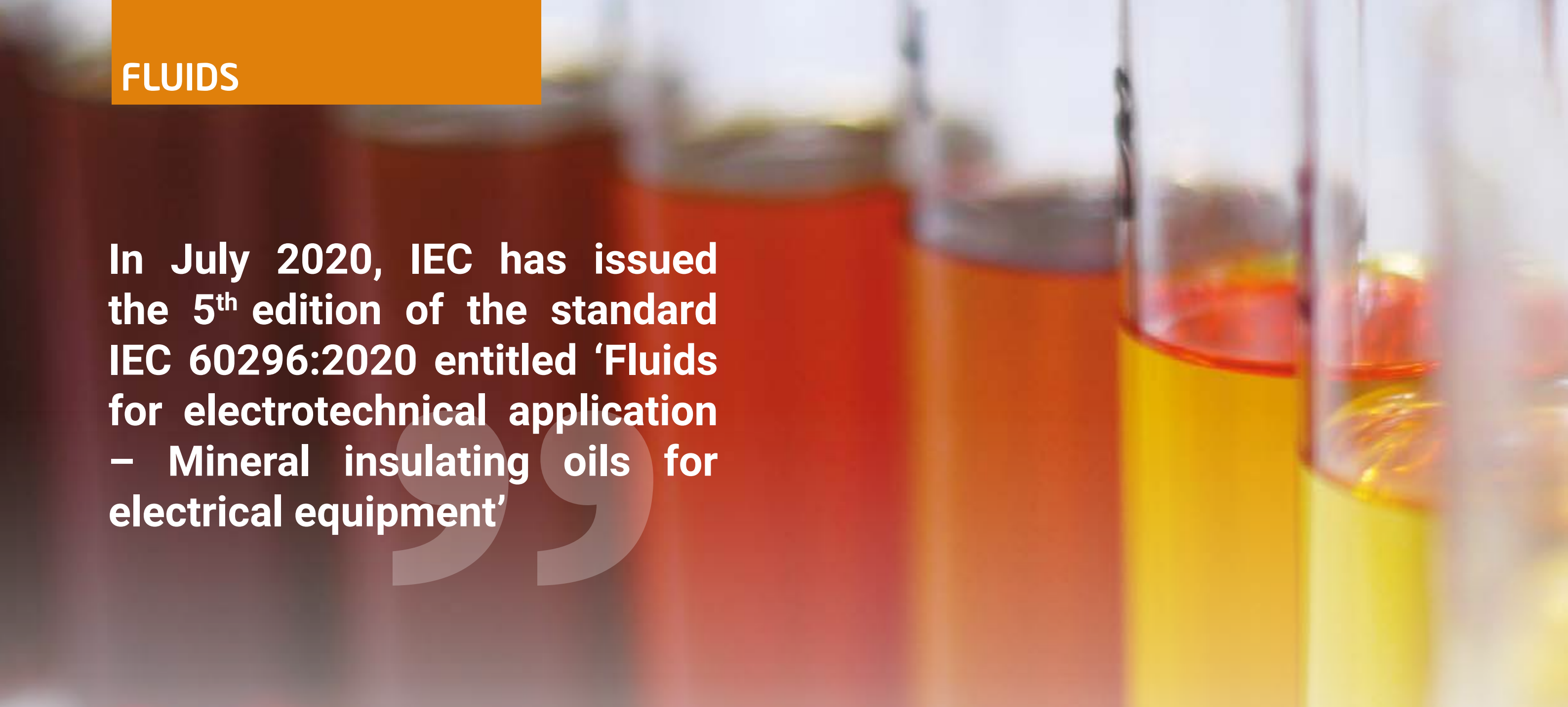
P. Ramachandran started his career in transformer industry in 1966 at TELK, Kerala, a Hitachi Joint venture, in India. He worked with ABB India during 1999-2020. He has more than 50 years of experience in the design and engineering of power products including power transformers, bushings, and tap-changers. He received Bachelor of Science Degree in Electrical Engineering from the University of Kerala, India, and Master of Business Administration Degree from Cochin University, India. He is a Fellow of Institution of Engineers (India), and he represented India in CIGRE Study Committee A2 for transformers during 2002 – 2010.



In July 2020, IEC has issued the 5th edition of the standard IEC 60296:2020 entitled ‘Fluids for electrotechnical application – Mineral insulating oils for electrical equipment’

IEC 60296 (Ed. 5) – a standard for classification of mineral insulating oil on performance and not on the origin

1. Introduction

TIn July 2020, the 5th edition of IEC 60296 has been published (Fig. 1). The title of the standard is as follows: Fluids for electrotechnical applications – Mineral insulating oils for electrical equipment.

ABSTRACT

The revision of the standard IEC 60296, Ed. 4.0 resulting in IEC 60296, Ed. 5.0 had three main aims: to set up a standard based on the performance of mineral insulating oil and not on the origin, to distinguish between good and bad mineral insulating oils, and to protect the user providing adequate testing parameters. In addition, there are several exciting news and changes in the new version of the standard compared to the previous versions.

KEYWORDS

classification, mineral insulating oils, performance

IEC 60296 is one of the oldest (first edition 1969) and most developed specifications on insulating liquids. The developing on the oil market and the environmental issues require high knowledge from the users and more possibilities to assure the right quality of a certain brand.

2. History

The FDIS (Final Draft International Standard) of the standard IEC62701 *Rerefined and reclaimed mineral insulating oils for transformers and switchgear* was approved in September 2013. Part of the industry saw discrimination of reprocessed oils in respect of unused ones. SMB (Standardization Management Board) withdrew IEC 62701.

SMB instructed TC 10 (Technical committee Fluids for Electrotechnical Application) to revise IEC 60296 so that it becomes a standard for mineral insulating oils irrespective of their source. The standard shall include requirements for declaration of the provenance of the oils without bias to the origin. The user / purchaser may then make any preference declared in their purchasing process.

As a consequence, MT 38 has been established in TC 10 with the following task – to revise IEC 60296 so that it becomes a standard for mineral insulating oils, irrespective of their source.

Mrs. Ivanka Atanasova-Höhlein has been nominated as MT 38 convenor.

In this article, the convenor presents her personal point of view on IEC 60296 5th edition. Some of the points are not new. Nevertheless, they will be mentioned in order to elucidate their meaning. New items will be explicitly marked.

For the first time we have a standard which is based only on performance, not on the origin. Nevertheless, it must be clear that the described properties are those that have turned out to be important in the course of time. A standard reflects the state-of-the-art practices and is adaptive in case of damages and accidents caused by the material described. Raw materials such as crude oil and specially processed oil such as transformer oil are short resources and must be economically used. This is not just a temporary statement but substantial necessity for mankind survival. Present methods for oil processing have been developed using adsorption methods, such as the ones in the case of reclaiming (regeneration), and mild hydrogenation, as in case of re-refined oils. Chemical engineering and technology are further developing and able to rejuvenate already aged transformer oils. The properties of such oils shall not differ from those of unused transformer oils.

3. Classification in classes for labelling (New, Part 5.1.4 of IEC 60296)

Regarding labelling mineral insulating oils can be:

Unused mineral oil (V for „virgin")

- Mineral insulating oil, obtained by refining, modifying and / or blending petroleum products and other hydrocarbons (e.g., from gas source); such oil has not been used in, nor has it been in contact with electrical equipment or other equipment not required for manufacture, storage, or transport

Recycled mineral oil (R)

- Mineral oil previously used in electrical equipment that has been subjected to re-refining or reclaiming (regeneration) after removal from the electrical equipment
- It is important that in its „first life" the oil has been used for the same purposes and also that the reprocessing takes part after removal from the electrical equipment. This is important since an oil reprocessing within equipment will also be influenced by the other materials experienced the ageing.

Recycled mineral oils are:

- Reclaimed (regenerated) – recycled mineral insulating oil subjected to chemical and physical processing to reduce soluble and insoluble contaminants

A new standard IEC 60296 (Ed. 5) reflects the state-of-the-art practices and is adaptive in case of damages and accidents caused by the material described

- Re-refined – recycled mineral insulating oil, subjected to a process similar to that used for the production of unused mineral oil

Both oil groups unused and recycled can be uninhibited (U), trace inhibited (T), or inhibited (I). The classification is based on the quantity of the oxidation inhibitor, which is defined as di-t-butyl-p-cresol (DBPC) or di-t-butyl-phenol (DBP).

4. Classification in classes for application (Part 5.1.1 of IEC 60296)

According to IEC 60296 (Ed. 5), there are two classes for application:

- Transformer oils (T)
- Low-temperature switchgear oils (S)

5. Classification on performance – Two types – A and B (New, Part 5.1.1. of IEC 60296)

Within the transformer oils, two groups of oils are defined: Type A (Table 1) and Type B (Table 2).

- Type A insulating oils are fully inhibited (I) and deliver higher oxidation stability than Type B.
- Type B insulating oils can be uninhibited (U), trace inhibited (T), or fully inhibited (I), deliver good resistance to oil degradation, and provide good oxidation stability.

In Table 1 and Table 2, the most important functional properties are listed. These are the properties where limit values are necessary and available.

IEC 60296

Edition 5.0 2020-06

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Fluids for electrotechnical applications – Mineral insulating oils for electrical equipment

Fluides pour applications électrotechniques – Huiles minérales isolantes pour matériel électrique

INTERNATIONAL ELECTROTECHNICAL COMMISSION

COMMISSION ELECTROTECHNIQUE INTERNATIONALE

ICS 29.040.10

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Figure 1. Screenshot from the IEC website

Table 1 – General specifications, Type A (fully inhibited high-grade oils)

Property	Test method	Limits	
		Transformer oil	Low-temperature switchgear oils
1 – Function			
Viscosity at 40 °C	ISO 3104 a or ASTM D7042	Max. 12 mm^2/s	Max. 3,5 mm^2/s
Viscosity at –30 °C [b]	ISO 3104 a or ASTM D7042	Max. 1800 mm^2/s	–
Viscosity at –40 °C [c]	IEC 61868	–	Max. 400 mm^2/s
Pour point	ISO 3016	Max. – 40 °C	Max. – 60 °C
Water content	IEC 60814	Max. 30 mg/kg [d] / 40 mg/kg [e]	
Breakdown voltage	IEC 60156	Min. 30 kV / 70 kV [f]	
Density at 20 °C	ISO 12185 a or ISO 3675 or ASTM D7042	Max. 895 kg/m^3	
DDF at 90 °C	IEC 60247 a or IEC 61620	Max. 0,005	
2 – Refining / stability			
Colour	ISO 2049	L0,5 (less than 0,5)	
Appearance	–	Clear, free from sediment and suspended matter	
Acidity	IEC 62021-2 a or IEC 62021-1	Max. 0,01 mg KOH/g	
Interfacial tension	IEC 62961 a or ASTM D971	Min. 43 mN/m	
Total sulphur content	ISO 14596 a or ISO 8754	Max. 0,05 %	
Corrosive sulphur	DIN 51353	Not corrosive	
Potentially corrosive sulphur	IEC 62535	Not corrosive	
DBDS	IEC 62697-1	Not detectable (< 5 mg/kg)	
Inhibitors of IEC 60666	IEC 60666	(I) Inhibited oil: 0,08 % to 0,40 %	
Metal passivator additives of IEC 60666	IEC 60666	Not detectable (< 5 mg/kg), or as agreed upon with the purchaser	
Other additives		See [g]	
2-furfural and related compounds content	IEC 61198	Not detectable (< 0,05 mg/kg) for each individual compound	
Stray gassing under thermo-oxidative stress	Procedure oil saturated with air in the presence of copper	Non stray gassing:	
		< 50 µl/l of hydrogen (H_2) and < 50 µl/l methane CH_4) and < 50 µl/l ethane (C_2H_6)	
3 – Performance			
Oxidation stability	IEC 61125: Test duration (I) Inhibited oil: 500 h	For oils with other antioxidant additives and metal passivator additives	
– Total acidity [h]	4.8.4 of IEC 61125:2018	Max. 0,3 mg KOH/g	
– Sludge [h]	4.8.1 of IEC 61125:2018	Max. 0,05 %	
– DDF at 90 °C [h]	4.8.5 of IEC 61125:2018	Max. 0,050	
4 – Health, safety and environment (HSE) i			
Flash point	ISO 2719	Min. 135 °C	Min. 100 °C
PCA content [j]	IP 346	< 3 %	
PCB content	IEC 61619	Not detectable (< 2 mg/kg)	

[a] Reference method
[b] This is the standard LCSET for a transformer oil and can be modified depending on the climatic condition of each country. Pour point should be minimum 10 °C below LCSET.
[c] Standard LCSET for low temperature switchgear oil
[d] For bulk supply
[e] For delivery in drums and IBC
[f] After laboratory treatment
[g] The supplier shall declare the chemical family and function of all additives, and the concentrations in the cases of inhibitors, antioxidants and passivators.
[h] At the end of oxidation stability tests
[i] In some countries there can be additional requirements, e.g., REACH in the EU.
[j] Some individual PAH compounds can be determined by EN 16143.

Table 2. General specifications, Type B (uninhibited and inhibited standard grade oils)

Property	Test method	Limits	
		Transformer oil	Low-temperature switchgear oils
1 – Function			
Viscosity at 40 °C	ISO 3104 [a] or ASTM D7042	Max. 12 mm^2/s	Max. 3,5 mm^2/s
Viscosity at –30 °C [b]	ISO 3104 [a] or ASTM D7042	Max. 1,800 mm^2/s	–
Viscosity at –40 °C [c]	IEC 61868	–	Max. 400 mm^2/s
Pour point	ISO 3016	Max. –40 °C	Max. – 60 °C
Water content	IEC 60814	Max. 30 mg/kg [d] / 40 mg/kg [e]	
Breakdown voltage	IEC 60156	Min. 30 kV/70 kV [f]	
Density at 20 °C	ISO 12185 [a] or ISO 3675 or ASTM D7042	Max. 895 kg/m^3	
DDF at 90 °C	IEC 60247 [a] or IEC 61620	Max. 0,005	
2 – Refining / stability			
Colour	ISO 2049	Max. 1,5	
Appearance	–	Clear, free from sediment and suspended matter	
Acidity	IEC 62021-2 [a] or 62021-1	Max. 0,01 mg KOH/g	
Interfacial tension	IEC 62961 [a] or ASTM D971	Min. 40 mN/m	
Corrosive sulphur	DIN 51353	Not corrosive	
Potentially corrosive sulphur	IEC 62535	Not corrosive	
DBDS	IEC 62697-1	Not detectable (< 5 mg/kg)	
Inhibitors of IEC 60666	IEC 60666	Uninhibited (U): not detectable (< 0,01 %) Trace inhibited (T): ≥ 0,01 < 0,08 % Inhibited oil (I): 0,08 % to 0,40 %	
Metal passivator additives of IEC 60666	IEC 60666	Not detectable (< 5 mg/kg), or as agreed upon with the purchaser	
Other additives		See [g]	
2-furfural and related compounds content	IEC 61198	Not detectable (< 0,05 mg/kg) for each individual compound[h]	
3 – Performance			
Oxidation stability	IEC 61125 Test duration [i] (U) Uninhibited oil: 164 h (T) Trace inhibited oil: 332 h (I) Inhibited oil: 500 h	FFor oils with other antioxidant additives and metal passivator additives	
– Total acidity [j]	4.8.4 of IEC 61125:2018	max. 1,2 mg KOH/g	
– Sludge [j]	4.8.1 of IEC 61125:2018	max. 0,8 %	
– DDF at 90 °C [j]	4.8.5 of IEC 61125:2018	max. 0,500	
4 – Health, safety and environment (HSE)[k]			
Flash point	ISO 2719	Min. 135 °C	Min. 100 °C
PCA content[l]	IP 346	< 3 %	
PCB content	IEC 61619	Not detectable (< 2 mg/kg)	

- Stray gassing under thermo-oxidative stress is not included as a normative test for Type-B mineral oils, because there has been insufficient data to determine the appropriate limits. The requirement for a stray gassing test, as well as the limit values, if stipulated, can be negotiated between the user and supplier.

[a] Reference method

[b] This is the standard LCSET for a transformer oil and can be modified depending on the climatic condition of each country. Pour point should be minimum 10 °C below LCSET.

[c] Standard LCSET for low temperature switchgear oil

[d] For bulk supply

[e] For delivery in drums and IBC

[f] After laboratory treatment

[g] The supplier shall declare the function and chemical family of all additives and the concentrations in the cases of inhibitors antioxidants and passivators.

[h] In agreement with the customer, oils with a higher furfural content can be delivered, when these values do not jeopardise the application.

[i] In some countries there can be lower requirements for oxidation stability.

[j] At the end of oxidation stability tests

[k] In some countries there can be additional requirements, e.g., REACH in the EU.

[l] Some individual PAH compounds can be determined by EN 16143.

Table 3. Meaning of the identifying letter codes in the ordering designation of mineral oil according to IEC 60296

First letter = equipment	**T** – transformer	**S** – switchgear	
Second letter = declaration	**V** – unused (virgin)	**R** – recycled	
Third letter = type	**A** – specification type A	**B** – specification type B	
Fourth letter = antioxidant	**I** – inhibited	**U** – uninhibited	**T** – trace inhibited

Example 1. For order for inhibited high grade recycled oil for transformers: **TRAI**.
Example 2. For order for uninhibited unused oil for transformers: **TVBU**.
Example 3. For order for inhibited high-grade unused oil for switchgear: **SVAI**.
Example 4. For order for trace inhibited recycled oil for switchgear: **SRBT**.

The standard is applicable to specifications and test methods for unused and off-site recycled mineral insulating oils in the delivered state

6. Coding matrix (New, Part 5.1.4. of IEC 60296)

Since there are several possibilities – unused and recycled oils, transformer and switchgear oils, uninhibited, trace inhibited, inhibited – they can be summarised as shown in Table 3. This table also reflects the labelling and ordering designation.

The ordering designation shall follow the order: Equipment / Declaration / Type / Antioxidant.

In case of non-standard specification, e.g., for lowest cold start energising temperature (LCSET), pour point etc., this shall be declared separately.

7. Lowest cold start energising temperature (LCSET) (Revised, Part 6.1. of IEC 60296)

LCSET shall be – 30 °C unless otherwise specified. If a different LCSET is specified it shall be chosen from the values shown in Table 4.

8. New properties for the mineral insulating oils group A – Stray gassing (New, Annex A of IEC 60296)

Stray gassing under thermo-oxidative stress (usually called stray gassing), describes the development of gases in an insulating liquid in-service under temperatures considered usual for normal operating conditions [3], due to its constituents and not connected to an internal fault in the electrical equipment. Various kinds of gassing have been observed, for example producing hydrogen, methane, ethane, or a combination of these gases. Stray gassing is accelerated by oxygen content and copper availability as well as by the temperature. Nevertheless, it has been observed both in open breathing and sealed equipment.

Stray gassing can be caused by different reasons, such as refining or additives. The definition used in IEC 60296 for stray gassing does not include the influence of incompatible materials on the gassing of oil. In reality, however, outgassing of paints or some types of cross-linked polyethylene (XLPE), as well as other incompatible materials, can contribute to gas formation not related to internal faults. The method used in this document and described in Annex A does not consider this, since the compatibility of materials is a responsibility of the equipment manufacturer.

Dissolved gas analysis (DGA) was developed long ago as a tool recognising faulty conditions in liquid insulated electrical equipment. The most common evaluation schemes, however, may not distinguish between this kind of stray gassing and certain kinds of fault and therefore can lead to misinterpretation.

It is, therefore, useful to have a method characterising the stray gassing behaviour (under thermo-oxidative stress) of a certain oil. In practice, gas due to stray gassing only has not been proven to be harmful to the equipment, and it usually levels off with time. The proposed method provides useful information to help users differentiate between genuine fault conditions in electrical equipment and stray gassing due to thermo-oxidative stress. This characterisation should be considered when users select oil for equipment so that it forms part of the supporting information when DGA is done.

The method used in this document is described in Annex A of IEC 60296 (Ed. 5). It implements a temperature of 105 °C, which is the highest permissible top oil temperature at normal cyclic loading according to IEC 60076-7 [3] for the duration of 48 h (it has been shown that longer incubation times do not increase the significance of results) in the presence of copper (copper enhances the radical formation and is a metal used for the windings in the majority of electrical equipment).

The incubation at 105 °C can be carried out with air or nitrogen saturated oil with and without the presence of copper. Testing under all these conditions can be beneficial for qualifying a new oil.

The results of the round robin test (RRT) showed that the most severe condition for gas formation is under air saturated oil in the presence of copper. The limits reported in Table 1 are based on the testing under this condition.

9. Miscibility and compatibility (New, Part 5.3. of IEC 60296)

According to IEC 60296 (Ed. 5), mineral oils are generally considered miscible and compatible if the characteristics of their mixture are not less favourable than those of the worst individual oil.

Table 4 . Maximum viscosity and pour point of mineral insulating oil

Application	LCSET °C	Maximum viscosity mm^2/s	Maximum pour point °C
Transformer	0	1,800	− 10
Transformer	− 20	1,800	− 30
Transformer	− 30	1,800	− 40
Transformer low ambient temperature application	− 40	2,500[a]	− 50
Low ambient temperature switchgear	− 40	400[a]	− 60
[a] for low ambient temperature applications; in other cases, the value shall be discussed between the user and manufacturer			

All mineral insulating oils are physically miscible with each other and are considered to result, after homogenisation, in a single homogeneous phase and without precipitation of insoluble substances, or formation of turbidity. The mixture, however, can show different properties from the original oils, for example, density, viscosity, total sulphur content, oxidation stability, or stray gassing.

Mineral insulating oils of the same class and type, the same group, same LCSET, and containing the same types of additives are considered to be compatible with each other in mixtures up to 10 % with no need for additional testing.

If oils of a different class, type, group, LCSET, or type of additives are mixed, the resulting mixture shall be classified and tested according to Table 1 and Table 2.

10. General properties

Of course, there are further mineral oil properties, which can be of importance, but no general limit values exist. These properties are summarised in Chapter 7 of IEC 60296 (Ed. 5). Such general properties are, e.g., electrostatic charging tendency (ECT), gassing tendency, thermal properties, aromatic content, lubricating properties, particle content, etc. In case limit values are necessary for the correct functioning of a certain type of equipment, these values must be clarified and negotiated between customer and manufacturer.

11. Transformer oil equivalents (informative, new, Annex D of IEC 60296)

For all known oil parameters there are standards for measuring as well as in the ASTM and in the IEC world. Some of them deliver the same values, and some of them do not. It is sometimes difficult for a user to carry out an evaluation and comparison between results achieved with different standards.

Annex D is the first attempt to provide guidance on standard measuring procedure equivalents, based on equivalency of results.

12. Conclusion

With the items listed above, IEC 60296 (Ed. 5) gives better answers to the industry and also addresses environmental and sustainability requirements.

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[2] TOR-WG D1.70, *Functional properties of modern insulating liquids for transformers and similar electrical equipment,* https://www.cigre.org/userfiles/files/News/2018/TOR_WG_D1_70_Functional_properties_of_modern_insulating_liquids_for_transformers_and_similar_electrical_equipment.pdf, current 4 September 2020

[3] IEC 60076-7, *Power Transformers. Part 7: Loading Guide for mineral oil immersed power transformers*, Ed. 2.0, 2018

Within the transformer insulating oils, two new groups are defined – Type A and Type B – based on their performance

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ABSTRACT

German literature on power transformers is covered from 1888 (first book on transformers published anywhere, just three years after patenting transformers), up to most recent publications issued in 2019. The purpose of the compilation of published books on power transformers is to give a historical summary on the topic, which may also be useful to other specialists in their research.

KEYWORDS

calculation, construction, design, DIN, historical development, power transformers, testing, VDE

Books on power transformers in German – Part II

A bibliography 1920 – 1951

1920

W. Demuth et al., *Die Materialprüfung der Isolierstoffe der Elektrotechnik* (The testing of electrical engineering insulation materials), Springer, Berlin, Pages IX+149, 1920

F. Kotschi, *Der Transformator bei tiefen Temperaturen, Arbeit zur Erlangung der Würde eines Doktoringenieurs* (The transformer at low ambient temperatures, thesis for doctoral degree), self-publishing, Pages 68, 1920 [26, 27]

Vitaly GURIN, P. RAMACHANDRAN

By the beginning of the 20th century, transformer technology reached a relatively high level of development for that time. Lots of different topics were analysed and published

H. Kyser, *Die elektrische Kraftubertragung, Band 1, Die Motoren, Umformer und Transformatoren* (The electric power transmission, Volume 1, The motors, converters and transformers), Springer, Berlin, Pages 416, 1920; Ed. 2.0, Pages 548, 1923; Ed. 3.0, Pages 544, 1930

F. Raskop, *Der Katechismus für die Ankerwickelei* (The Catechism for anchor winding), Meusser, Berlin, Pages VIII+145, 1920; Ed. 2.0, 1922; Ed. 3.0, 1929; Ed. 4.0, M. Krayn, Berlin, Pages 224, 1933; Ed. 5.0, Pages VII+241, 1937; Ed. 6.0, Pages XII+287, 1941; Ed. 8.0, De Gruyter, Berlin, Pages XII+299, 1944; Ed. 10.0, Pages XI+416, 1951 and Reprint 2019; Ed. 11.0, Pages 472, 1953; Ed. 12.0, Pages 516, 1957; Ed. 13.0, Pages 616, 1964; Ed. 14.0, 1967 and Reprint 2019; Ed. 15.0, Pages 503, 1976 [28, 29]

This book has survived 15 editions and a few reprints. At first it was a guide for manufacturing windings for electrical machines and transformers. Then the book was repeatedly expanded in the direction of increasing the volume of repairs, adding faults, testing, and monitoring. At the same time, the title of the book was changed, and its coverage naturally expanded. In the bibliography, we have combined all available publications under the popular short historical name *The Catechism for anchor winding*. Other books by the author are indicated in the bibliography for 1929, 1938 and 1948.

1921

Milan Vidmar, *Die Transformatoren* (The transformers), Springer, Berlin, Pages 702, 1921; Ed. 2.0, Pages 751,1925; Ed. 3.0, Birkhäuser, Basel, Pages 630, 1956

In this book, a famous engineer, scientist and chess player, Prof. Milan Widmar (1885–1962), outlines the basics of designing and constructing power transformers. The fundamental principles presented in it remain valid even today, despite the development of the theory, great progress in the properties of materials, technology, growth in ultimate power and voltage classes, and automation of the design process. The book has withstood many editions and has been translated into many languages. Other books by the author are indicated in the bibliography for 1927, 1928, 1935, 1940 and 1945.

In 1921, Prof. Milan Widmar published a book Die Transformatoren which treat design and construction of power transformers. Presented fundamental principles remain valid even today

F. Unger, M. Kloss, *Konstruktien der Dinamomaschinen und Transformatoren* (Constructions of dynamo machines and transformers), Fifth section p. 361-434 in book: Starkstromtechnik Pocketbook for Electrotechniker, Vol. I by E. v. Rziha and J. Seidener, Wilchelm Ernst & Sohn, Ed. 5.0, Berlin, Pages 892, 1921.

1922

J. Fischer-Hinnen, *Theoretisches und praktisches Lehrbuch für Elektrotechniker. Mit besonderer Berücksichtigung der Berechnung und Prüfung von Maschinen und Transformatoren* (Theoretical and practical textbook for electrical engineers. With special attention to the calculation and testing of machines and transformers), Raustein, Zürich, Pages 550, 1922

Walter Spath, *Über Durchschlagseigenschaften von Transformatorenölen. Inauguraldissertation.* (About electric breakdown properties of transformer oils. Inaugural Dissertation.), Springer, Jena, Pages 347, 1922

1923

VDE, *Regeln für die Bewertung und Prüfung von Transformatoren (R.E.T. 1923)* (Rules for the evaluation and testing of transformers (R.E.T. 1923)), Ed. 1.0, Springer, Berlin, Pages 23, 1923

1924

A. von Königslöw, *Transformatoren und asynchrone Drehstrommotoren, Ihre Wirkungsweise und Berechnung (=Bibliothek der gesamten Technik 308)* (Transformers and asynchronous three-phase motors, their mode of operation and calculation (=General technology library 308)), M. Janecke, Leipzig, Pages 172, 1924

1925

Egon Eichwald, *Mineralöle (=Technische Fortschrittsberichte Bd. 40)* (Mineral oils (= Technical progress reports Vol. 40)), Steinkopf, Dresden, Pages 151, 1925

1926

Conrad Aron, *Der Transformator* (The Transformer), Wilhelm Herbst Verlag, Pages 118, 1926

1927

AEG, *Anweisung zur Behandlung der Transformatoren* (Instructions on how to handle the transformers), Verlag AEG, Pages 67, 1927

Heinrich Keller, *Zur Kenntnis von Transformatorenöl. Dissertation. (Transformer oil. A Dissertation.)*, Munich, Pages 41, 1927 [30, 31]

Normen der Elektrotechnik für Maschinen, Transformatoren, Apparate, DIN Taschenbuch 7 (Electrical engineering standards for machines, transformers, apparatus, DIN Taschenbuch 7), VDE, Beuth-Verlag, Berlin, Pages 133, 1927; Ed. 2.0, Pages 139, 1928

Wilchelm Schafer, *Transformatoren, Goschen Collection No. 952* (Transformers, Goschen Collection No. 952), Walter de Gruyter & Co., Berlin - Leipzig, Pages 114, 1927; Ed. 2.0, Berlin, 1949; Ed.3.0, 1957; Ed. 4.0, 1962

Milan Vidmar, *Die Transformatoren im Betrib* (The transformers in operation), Springer, Berlin, Pages 310, 1927

Rudolf Wotruba, *Der ein- und mehrphasige Wechselstrom: Einführung in das Studium der Transformatoren und Wechselstrommaschinen* (Single and multi-phase alternating current: Introduction to the study of transformers and alternating current machines), Oldenbourg, Munich and Berlin, Pages 86, 1927 [32]

1928

Gustav Haberland, *Elektrotechnische Lehrhefte IV, Transformatoren und Wechselstrommaschinen* (Electrotechnical instruction book IV, Transformers and AC machines), M. Janecke, Leipzig, Pages 174, 1928; Pages 191, 1944; Ed. 8.0, Fachbuchverlag, Leipzig, Pages 206, 1950

Siemens-Schuckert Preislisten Band M 2 Maschinen und Zubehör Transformatoren (Siemens-Schuckert price lists volume M 2 machines and accessories for transformers), Self-published printing and art publishing Haberland, Leipzig, Pages over 300, circa 1928-1936

Milan Vidmar, *Wirkungsweise elektrischer Maschinen* (Mode of operation of electrical machines), Springer, Berlin, Pages 223, 1928

Rudolf Wotruba, Adalbert Stifter, *Die Transformatoren, Theorie, Aufbau und Berechnung* (The transformers, theory, structure and calculation), De Gruyter Oldenbourg-Verlag, Munich-Berlin, Pages 203, 1928 [33, 34]

1929

Dr. G. Brion, *Die elektrische Meßtechnik II: Die Messungen an elektrischen*

Figure 1. Milan Vidmar, Die Transformatoren im Betrib

Maschinen, Transformatoren und Gleichrichtern (The electrical measurement technology II: The measurements on electrical machines, transformers and rectifiers), de Gruyter & Co., Berlin, Pages 120, 1929

Friz Raskop, *Die Instandsetzungen an elektrischen Maschinen und Transformatoren, insbesondere die Herstellung von Ankerwicklungen und Transformatorenwicklungen* (The repair of electrical machines and transformers, especially the manufacture of armature windings and transformer windings), Ed.4.0, Meusser, Berlin, Pages 342, 1929

E. Roller, H. Pricks, *Schulversuche zur Elektrizitätslehre mit dem zerlegbaren Transformator und Zusatzteilen* (School trials on electricity with the dismantled transformer and additional parts), Verlag Physikalische Werkstätten AG, Goettingen, Pages 111, 1929 [35]

1930

Georg Dettmar, *Erläuterungen zu den Regeln für die Bewertung und Prüfung von elektrischen Maschinen R.E.M. / 1930, Transformatoren R.E.T. / 1930 und Maschinen und Transformatoren auf Bahn- und anderen Fahrzeugen R.E.B./1930 sowie zu den Normalen Anschlußbedingungen und den Normalen Klemmen-Bezeichnungen* (Explanations of the rules for the assessment and testing of electrical machines R.E.M. / 1930, transformers R.E.T. / 1930 and machines and transformers on trains and other vehicles R.E.B. / 1930 as well as the normal connection conditions and the normal terminal designations), Springer, Berlin, Pages 406, 1930 [36]

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Rudolf Richter, *Elektrische Maschinen, 3. Band: Die Transformatoren* (Electrical machines, volume 3: the transformers), Springer, Berlin, Pages 321, 1932; Ed.2.0, Birkhäuser, Basel-Stuttgart, Pages 352, 1954; Ed. 3.0, Springer Basel AG, Pages 321, 1963

Before his death, E. ARNOLD (see the year 1902-1904 in our bibliography above), suggested RUDOLF RICHTER (1877-1957) to become the leader of TH Karlsruhe. On 1 October 1912, at the age of 35, R. Richter took up the position of full professor and director of TH, and showed himself to be a worthy successor to his great predecessor, working until 1947. During 1924-1950, he published 5 volumes of his book *Electrical machines, volume 3: The transformers*, which was first published in 1932, and gained international popularity by competing with the works of M. Vidmar.

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Figure 2. Der praktische Transformatorenbau, Walter Kehse

The purpose of the compilation of published books on power transformers is to give a historical summary on the topic, which may also be useful to other specialists in their research

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Written in aid of technicians involved in the maintenance of electric equipment

Absorption index of insulation at end of service life – Part I

Old-aged transformers equipped with silica gel air breather

ABSTRACT

Absorption Index (AI) remains valid for old-aged unsealed transformers as a simple and effective method of non-destructive control insulation. The reasons for AI decrease within transformer operation are insulation moistening and contamination. Seven gradation levels of the insulation condition and algorithm of the operating procedures are proposed depending on the value of the measured AI and its variation in time. Along with AI, it is recommended to measure the polarisation index (PI) and the PI-2 (R_{600}/R_{15} ratio).

KEYWORDS

absorption index, cellulose insulation, insulation resistance, moisture, polarization index

Introduction

Transformers are the most important and most expensive equipment at a substation, and their failure leads to severe problems in the power supply. The purpose of preventive testing is to determine a runaway for the condition of the complex system of the transformer insulation from the initial state (at the factory and installation site), and upfront detection of the defects occurred. Preventive measures are based on the systematic inspections, and they allow to keep the equipment in operation state by means of cost-effective way, reducing the risk of permanent damage and potential failure, assisting the companies in avoiding major and costly repairs, and extending the service life of old-aged transformers.

Transformer fleets in all countries are ageing. With insufficient maintenance, a transformer older than 40 years can accelerate failure due to deterioration of the insulation condition (primarily due to its moisture and pollution). A middle-aged transformer may fail earlier, because its safety margin is substantially less, due to the fact that its design has been optimised for the limited service life of 25 years, according to GOST [1], Russian technical standard.

A significant number of old-aged unsealed USSR-made power and distribution transformers (in accordance with GOST) are in operation in the power systems and electric networks of Eastern Europe and a number of countries in Asia, Africa, and South America. Excessive moistening and contamination of these transformers are their main problems, since moisture and dirt at operating voltage, and even more so in case of the voltage increase, accelerate the insulation ageing. The combination of electrical voltage and insulation deterioration over time leads to the fatality of the transformer.

Measurement of insulation resistance (IR) at 15 and 60 seconds (IR_{15} and IR_{60}) is the routine factory test, according to GOST. These values are specified in the certificate of each transformer. The operating manuals require regular (once per year) measurements of these values. During establishing these requirements, it was believed that using the trend of IR_{15} and IR_{60} decrease, it is possible to evaluate the degree of insulation moisture content of the transformer in operation. In addition to moistening, the experience has shown that these values are also affected by insulation contamination.

The article provides consideration of some real-life examples of old transformers manufactured by Zaporozhye Transformer Plant ZTZ and Moscow Electrozavod MEZ. The numerous measurements of IR_{15} and IR_{60} at the site in post-Soviet countries, in Bulgaria, Czech Republic, Slovakia, Macedonia, Serbia, and India, were conducted by the author personally, or under his guidance.

The article goal is to describe the absorption index as the criterion for evaluation of insulation condition and for the provision of simple, practical recommendations for maintenance staff of old-aged transformers based on the test results.

With insufficient maintenance, a transformer can deteriorate rapidly due to worsening of the insulation condition, which occurs primarily due to the moisture and pollution

1. Determination of absorption index AI

For more than 100 years, insulation resistance measurement using the Megger is the simplest and the most reasonable method for evaluation of a transformer and other electrical equipment insulation condition. At applying DC voltage to the transformer insulation, the transient phenomena consist of three main components:

- Charging current of the geometric capacitance of the measured section of transformer insulation; this current drops from maximum to zero within a few seconds.
- Absorption current due to the displacement of the molecular charges in the insulation. This transient current decays much slower (up to about 30 minutes).
- Insulation conduction current.

Absorption and conduction currents depend up on insulation moisture content and its contamination. They also change with a number of defects in the bushings and / or tap changers. Net current consists of the sum of these three components. Ohm's law calculated insulation resistance is used for diagnostics. The absolute value of IR_{60} (IR test) and the resistance ratios measured at 15, 30, 60, and 600 seconds are used to assess the insulation state, shown in Table 1.

For more than 100 years, insulation resistance measurement using Megger test is the simplest and the most reasonable method for evaluation of a transformer and other electrical equipment insulation condition

Table 1. Criteria for assessing the status of insulation of transformers

Ratio	Name	Abbreviation	Practice
IR_{60} / IR_{15}	Absorption index	AI, AI test	GOST
IR_{60} / IR_{30}	Dielectric absorption ratio	DAR	Testing of the electrical machines
IR_{600} / IR_{60}	Polarisation index	PI, PI test	IEEE [2]

In the late 1940s and early 1950s, Soviet specialists in the transformer field were discussing the suitable criterion for evaluation of the transformer insulation moisture content which led to the definition of the AI

2. From the history of the application of AI

In the late 1940s and early 1950s, Soviet specialists in the transformer field (A. K. Ashryatov, S. A. Gorodetsky, A. I. Sapozhniyov, N. P. Fufurin, and others) held a comprehensive discussion regarding which criterion is more suitable and sufficient for evaluation of the transformer insulation moisture content during installation and operation. The following methods were considered: the capacitance ratio at 2 and 50 Hz (C_2 / C_{50}), t he dielectric loss tangent (tan delta), AI, IR_{60}, the capacitance ratio in the hot and cold state. As a result, the criteria C_2 / C_{50} and AI were selected and included in the manuals. Gorodetsky [3] has proposed the permissible AI value of at least 1.3 at a temperature of 20 °C. Criteria C_2 / C_{50} and AI ≥ 1.3 over the next two decades have been successfully applied in practice. Then C_2 / C_{50} went into oblivion.

The requirement to measure AI remained unchanged, but the fate and fortunes of AI have proved to be challenging. The standard AI = 1.3 was later transferred to SEV 5266 standard (developed by the former German Democratic Republic) [4]. However, in the mid 1960s, due to a supply of 220 – 500 kV transformers to India and Egypt, ZTZ introduced more advanced drying methods and initiated the transformer filling with new high-quality oils (T-750, T-1150, obtained by hydrocracking GK [5, 6]). At the same time, it turned out that on frequent occasions, AI value became less than 1.3 just upon dispatch from the factory. In particular, this led to formal problems during the commissioning of 500 kV transformers at Aswan Hydroelectric Power Plant. To overcome the problem, ZTZ removed the standard value of AI ≥ 1.3 from installation instruction of the power transformers [7], so that AI was devaluated.

At the same time, the experience of servicing Soviet transformers in different countries and the personal experience of the author showed that this was a wrong decision, and it is very useful to know the acceptable AI values for practice.

In Russia and Ukraine, AI standard value = 1.3 is still maintained at 10 – 30 °C temperature as the criterion for the permissible start-up of the transformers up to 35 kV inclusive, rated for power less than 10 MVA [8]. This requirement is outdated (see Annex 1), and it needs to be revised.

Since 1995, the new method for evaluation of transformer insulation moisture content by means of measurement of insulation capacitance and tan δ depending on the frequency ranged from a few millihertz (0.1 – 10 mHz) up to 1 kHz (dielectric frequency response test (DFRT) [9]), has been introduced. Maintenance practice of the transformers does not always need such a complex method. As applied to old-aged transformers, DFRT method cannot replace AI method, also due to the fact that, as a rule, there is no basis for comparison of DFR, because such measurements have not been previously performed. DFRT is still not widespread in the distribution networks, especially because another new and relatively expensive device is required to carry out the measurements, and interpretation of DFRT results is much more complicated compared to AI.

It is recommended to measure AI immediately after the transformer shut down, while its temperature does not differ by more than 5 °C from the previous measurements

3. Preparation and measurement of AI

It is recommended to measure AI immediately after the transformer shutdown (but after the measurement of no-load losses at the reduced voltage for the transformer manufactured in USSR, or after the excitation current test for the transformer manufactured by others, with recording the transformer temperature). If transformer temperature during measurements differs by more than 5 °C from the previous measurements (usually a year back), repeat the measurements on the transformer during its cooling at temperature differing by no more than 5 °C.

All bushings, including neutral, should be disconnected from the network, including disconnection of the copper bus bars from the HV neutral and / or LV bushings.

Example of the impact of support insulation of a piece of copper busbar connected to HV neutral

Unit transformer 01BAT10 (410 MVA 420 / 20 kV manufactured by AREVA, Turkey, 2007) in the Thermal Power Plant (TPP) AES Galabovo [10], Bulgaria, November 2012, transformer temperature was 17 °C. Initially, AI in the scheme HV - (LV + GND) was measured as 1.09. After the disconnection of a piece of the busbar, AI = 1.38.

Each winding should be short-circuited directly on the bushings' studs. The jumpers for short-circuiting should be made using short bare conductors and maximally distanced from the tank and other grounded transformer elements.

The weather conditions should be without precipitation and fog, and the bushings should be dry and clean.

Measurements carried out on the transformers rated for 110 kV, and higher may be affected by electromagnetic and electrostatic interferences. It is important to be sure in the safety of the transformer tank grounding and to ensure the grounding of adjacent de-energised substation equipment to prevent the floating potential.

Measurements should be carried out with unconditional observance of the instructions for devices and safety precautions. In order to remove the residual charge of the transformer windings (caused by the disconnection of the transformer or by previous tests) before starting the measurement, the winding should be short-circuited to ground for 2 - 5 minutes, and after measurement, it is to be grounded for a time period not less than the measurement interval.

One example of a principal scheme of the measurement circuit AI test is shown in Fig. 1. In the article, the author considers the AI values in these schemes precisely, since the insulating distance between the windings (HV - LV) contains the most solid insulation, and the distance (HV - tank) is mainly filled with oil. Therefore, these distances are the most informative for assessing the condition of a transformer. Other schemes are shown in Annex 2.

The minimum scope of the measurements, their sequence, measurement circuits, and test voltage should be similar to previous measurements. Based on the measurement results, it is proposed to create a graph of the dependence of AI on time, starting from factory tests, in order to better understand the trends in insulation, as shown in Fig. 2.

If there is a significant decrease in AI (read more about in the second part of the article), it is necessary to perform more measurements and to change the value of the test voltage (0.5, 1, 2.5, 5 kV, but not exceeding the rated voltage of the winding). New devices allow testing at 10 kV. For good insulation, AI will not be affected by the voltage test. And for poor insulation, this dependence will serve as additional information about the condition of the transformer. It is important to consider the effect of temperature on the measurement results (that will be shown in Chapter 6).

AI measurements are carried out periodically as part of the transformer diagnostics, in case of unsatisfactory results of oil analysis and / or dissolved gas analysis (DGA), and after those events that could cause the transformer insulation deterioration. By comparing the test data obtained after the failure with the results of the previous tests, it is possible to assume the nature of the transformer failure.

If there is a significant decrease in AI, it is necessary to perform more measurements and to change the value of the test voltage

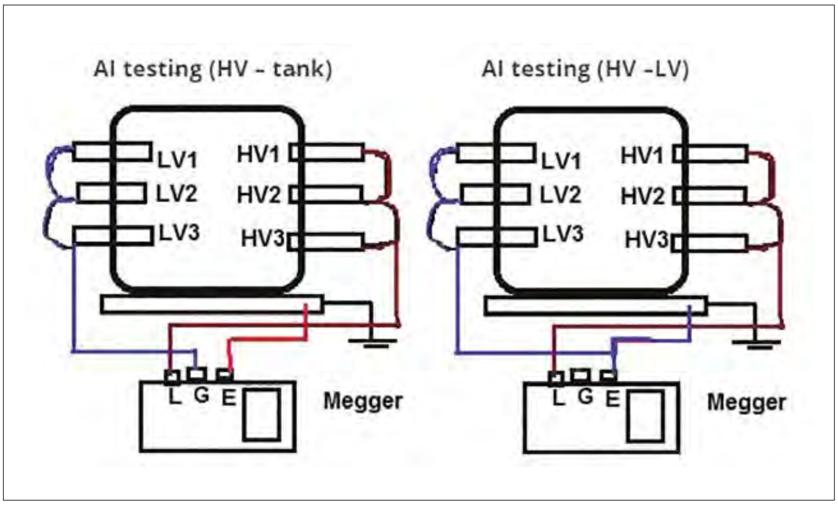

Figure 1. Connection diagram for AI in a double winding transformer (HV - tank and HV – LV)

4. Moisture content, contamination, and AI

The transformer insulation is a combination of transformer oil and oil-impregnated solid cellulose insulation (insulation paper, cylinders between windings and other barriers, angle rings, clamping plate and spacer blocks). The moisture content of dry solid insulation upon dispatch from the transformer factory manufactured in accordance with GOST, does not exceed 0.2 - 0.5 % [9]. Typical AI values for dry and clean insulation of new transformer are specified in Annex 1.

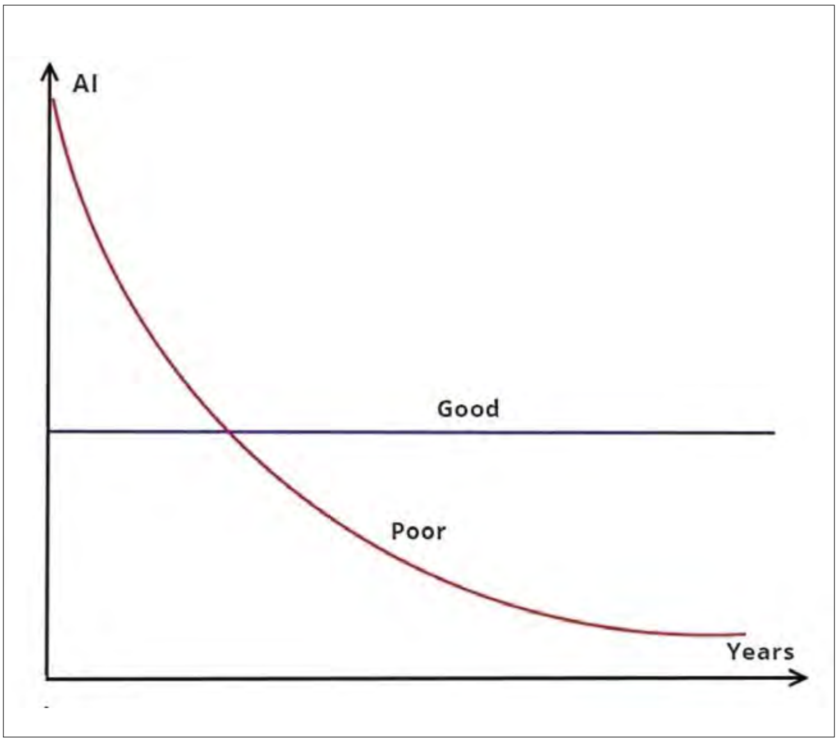

Figure 2. Change in AI over time (schematically)

By comparing the test data obtained after the failure with the results of the previous tests, it is possible to assume the nature of the transformer failure

Within long-term operation, the insulation condition is deteriorated inevitably. The transformer solid insulation is moistened up to 1.5–4.5 % [11] due to breathing and water absorption from wet air entering via air breather, or water ingress due to improper tank sealing. Water in the tank is also generated due to paper ageing. Solid cellulose insulation and wooden structural elements accumulate the bulk of the water. Oil is only a means of water transfer, in the case of oil ageing, its ability to dissolve water increases [12]. The insulation of old-aged transformers is also deteriorating due to inevitable contamination by polar oil ageing products and mechanical impurities, including the conductive ones. Therefore, for the LV - HV circuit, lower AI values are often observed compared to AI in the HV - LV circuit. The example is shown in Fig. 3. This can be explained by the fact that the total surface of the lower part of the LV bushings and wires from the bushings to the winding is several times larger than the similar surface on the HV side. More contaminants accumulate on a larger surface, and when a voltage test is applied to LV bushings, the absorption processes are stronger, and the measured value off AI is correspondingly less than when voltage is applied to the HV. This hypothesis needs additional verification. In practice, for comparison, it is required to use the scheme (HV - LV or LV - HV) that was in the previous test.

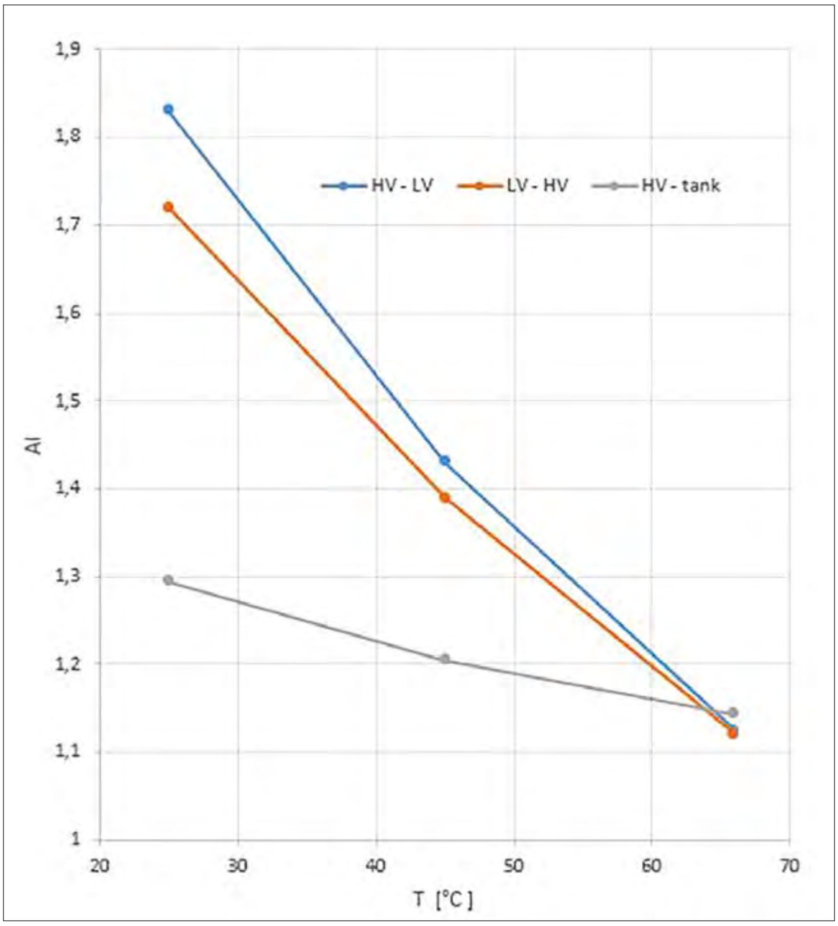

Figure 3. AI (HV - tank and HV – LV) difference of AI in the circuits HV – LV and LV – HV and temperature-dependence of AI. Autotransformer AT201 (200 MVA 220 / 121 / 36 kV) Dobrudja Substation, Bulgaria, manufactured by ZTZ in 1974. AT diagnostics was carried out in September 1996. Insulation resistance was measured at 2.5 kV. Before the shutdown of AT, the moisture content in oil was 36 ppm at 40 % load. The moisture content of solid insulation was 2.5 % (calculated)

Since 1992, under the supervision of the author, more than half of the 110 – 750 kV power transformers in Bulgaria have been surveyed. On 156 transformers equipped with silica gel air breather, a complete diagnosis was performed (under load and after decommissioning). It emerged that 80 % of the transformers that have operated for 20 years had the moistened solid insulation (2 % or more). 70 % of the transformers there had contaminated oil (often number 5 - dark colour) and required oil regeneration or replacement. Half of the transformers equipped with an on-load tap changer (OLTC) had moistened the insulating parts of the diverter switches. The rubber gaskets in major transformers lost their elasticity and did not provide oil sealing of the transformer tank, including the gaskets at the upper part of the bushings, in dehydrating filter breathers in the conservators. Ingress of water into the transformer was through the gaskets damaged. There were transformers with the poor condition of air breathers and dehydrating filter breathers; in some cases, silica gel was not processed before its filling into the air breathers and the dehydrating filter breathers [13, 14].

The moisture content of the insulation of an unsealed transformer depends on the mode of its load and the transformer service period. According to old Soviet rules, it was required to carry out the first overhaul of a power transformer with opening the active part, with the replacement of rubber seals and insulation drying to remove moisture at the first 6 years after the transformer installation. Then the interval to repair was increased in a consistent manner up to 8, 10 and 12 years [15]. This was justified by operating experience, each time confirming the transformer reliability. The next following major repairs (overhauls) are carried out when necessitated, depending on the transformer condition which is evaluated by the results of the diagnostics. The methods used in the past for drying transformers in the field are described in [7, 11]. Then varieties of the oil spray method were developed, one of which was used by the author in Bulgaria [16].

The author's data is the confirmation of the correctness of the previously established time period until the first overhaul. As shown in Fig. 4, even for almost 100 % round-the-clock and year-round loaded transformers, the value of AI is gradually decreased with deceleration during the periods between the repairs. In the example considered, in 1980, AI values at measurements of HV - (LV + GND) and LV - (HV + GND) were 1.33 and 1.25 respectively, and over 7 years they decreased to 1.13 and 1.12, respectively. Between the end of 1982 and the end of 1988, no AI measurements were made. In 1988, the overhaul was carried out with the transformer drying, after which AI value increased to 1.38 and 1.48.

During operation, AI value is significantly decreased for inter-winding distances due to the accumulation of moisture in the solid insulation. Table 2 contains AI measurement results at 2.5 kV for the transformer with doubled concentric HV winding (LV wining is located between HV winding concentres). The transformer was commissioned in 1965. It is shown in Table 2 that within 22 years of operation, the significant decrease of AI value is in LV-HV distance (from 2.27 up to 1.11), despite the two performed repairs of the transformer with insulation drying within this period of time.

The transformer solid insulation can be moistened up to 1.5 – 4.5 % due to breathing and water absorption from wet air entering via air breather, or water ingress due to improper tank sealing

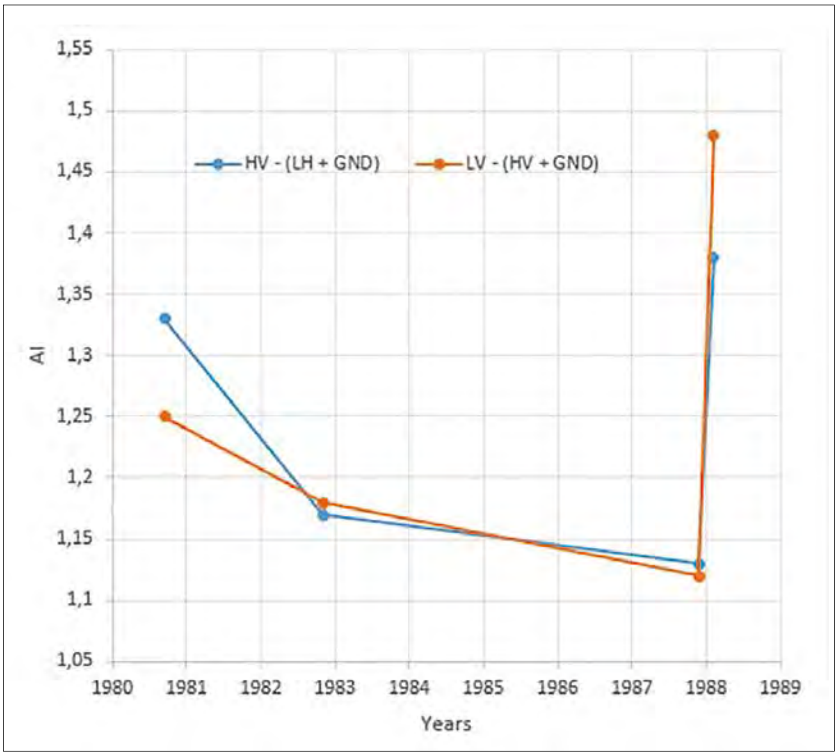

Figure 4. Variation of insulation AI of unit transformer 2GT (60 MVA 121 / 10.5 kV) TPP Neyveli, India, within 1980 – 1988, manufactured by MEZ in 1962

Table 2. Unit transformer T-8 (200 MVA 342 / 15.75 kV) Nevinnomysskaya TPP, Russia, manufactured by ZTZ in 1964

Year	1972			1994		
Transformer temperature	35 °C			45 °C		
Test	R_{15}, MΩ	R_{60}, MΩ	AI	R_{15}, MΩ	R_{60}, MΩ	AI
HV - (LV + GND)	460	900	1,96	220	250	1,14
LV - (HV + GND)	550	950	1,73	260	290	1,12
(HV + LV) - GND	720	980	1,36	350	400	1,14
LV - tank	1700	2080	1,22	1100	1300	1,18
LV - HV	770	1750	2,27	350	390	1,11
HV - tank	1150	1850	1,61	540	610	1,13

During operation, AI value is significantly decreased for inter-winding distances due to the accumulation of moisture in the solid insulation

Another example of AI value at 2.5 kV decrease within the operating period is shown in Table 3.

It contains the comparison of AI values measured at the transformer dispatch from the factory and after 30 years of operation of another unit transformer of the same state district power plant. In both cases, the measurements were carried out at 2.5 kV. Within 30 years, AI value at HV - tank distance has been almost the same because AI in this distance is determined by oil, which was replaced during the transformer repair in 1989. But AI value of HV - LV distance has sharply decreased over 30 years (from 3.51 to 1.22), which is to be explained by moistening of solid insulation, and this indicates the low efficiency of the field repairs.

As follows from Tables 2 and 3, after approximately 30 years of operation of both transformers, AI value in the distance LV - HV of the transformer T-7, was higher (AI = 1.22) than the value of the transformer T-8 (AI = 1.11). This is due to the presence of solid insulation in this distance of the transformer T-7 (rated for 110 kV), and therefore, the amount of moisture is much less than in T-8 (330 kV): in T-7 there are only 2 cylindrical barriers against 6 cylinders in the T-8.

In case of inadequate maintenance of air breathers (untimely replacement of silica gel when its colour changes, insufficient oil level) and of dehydrating filter breathers, moisture content of insulation is accelerated. If AI tests are carried out rarely and irregularly (it is related to distribution transformers), then evaluation of the hazard rate of insulation moisturising will be constrained.

In the case of sealed transformers, the insulation moisturising from the atmosphere is excluded, and during normal operation, moisture is generated only due to paper ageing. The moisture content, in that case, should not reach 0.5-0.75 %, even after many years of operation [11]. In such transformers, the AI test will be useful in case inappropriate sealing is suspected.

Annex 1. Summary of the factory tests of new transformers

Measurements of AI carried on for 484 transformers manufactured by ZTZ rated for voltage 35-750 kV, and capacity from 10 to 630 MVA, filled with new oil type GK or Nynas have been analysed. Circuits HV – (LV + GND), LV – (HV + GND) and (HV + LV) – GND have been considered. It turned out that AI values are in the range 1.17–2.75, and statistically, these values are dependent in a minor way on the transformer parameters (power and voltage class).

The average values AI for LV – (HV + GND) are higher than for HV – (LV + GND) (1.79 versus 1.45), which is to be explained by the lump of solid insulation adjacent LV windings if compared to HV windings. At the dispatch from the factory, more than one third of the transformers have AI value less than 1.3.

With temperature increase, the AI value of new transformers is practically the same. But if the transformer is filled with old TKp oil, then AI value decreases significantly depending on the temperature, and this is evidently for the distance HV-tank. Once again this confirms the fact that at a distance of HV – tank, the main role is played by oil, and that TKp oil gives higher AI values than GK and Nynas.

Annex 2. Other possible test connections of transformers for AI test

Two-winding transformer:
1. LV - tank
2. HV – (LV + GND)
3. LV – (HV + GND)
4. (HV + LV) – GND

Three-winding transformer:
1. LV – tank
2. TV – tank
3. HV – TV
4. LV – TV
5. HV – (LV + TV + GND)
6. LV – (HV + TV + GND)
7. TV – (HV + LV + GND)
8. (HV + LV) – (TV + GND)
9. (HV + TV) – (LV + GND)
10. (LV + TV) – (HV + GND)
11. (HV + LV + TV) - tank

Table 3. Unit transformer T-7 (200 MVA121/15.75 kV) Nevinnomysskaya TPP, Russia. T manufactured by ZTZ in 1965

Year	1965	1994
Transformer temperature	46 °C	34 °C
Test site	Plant	TPP
LV - HV	3,51	1,22
HV - tank	1,33	1,35

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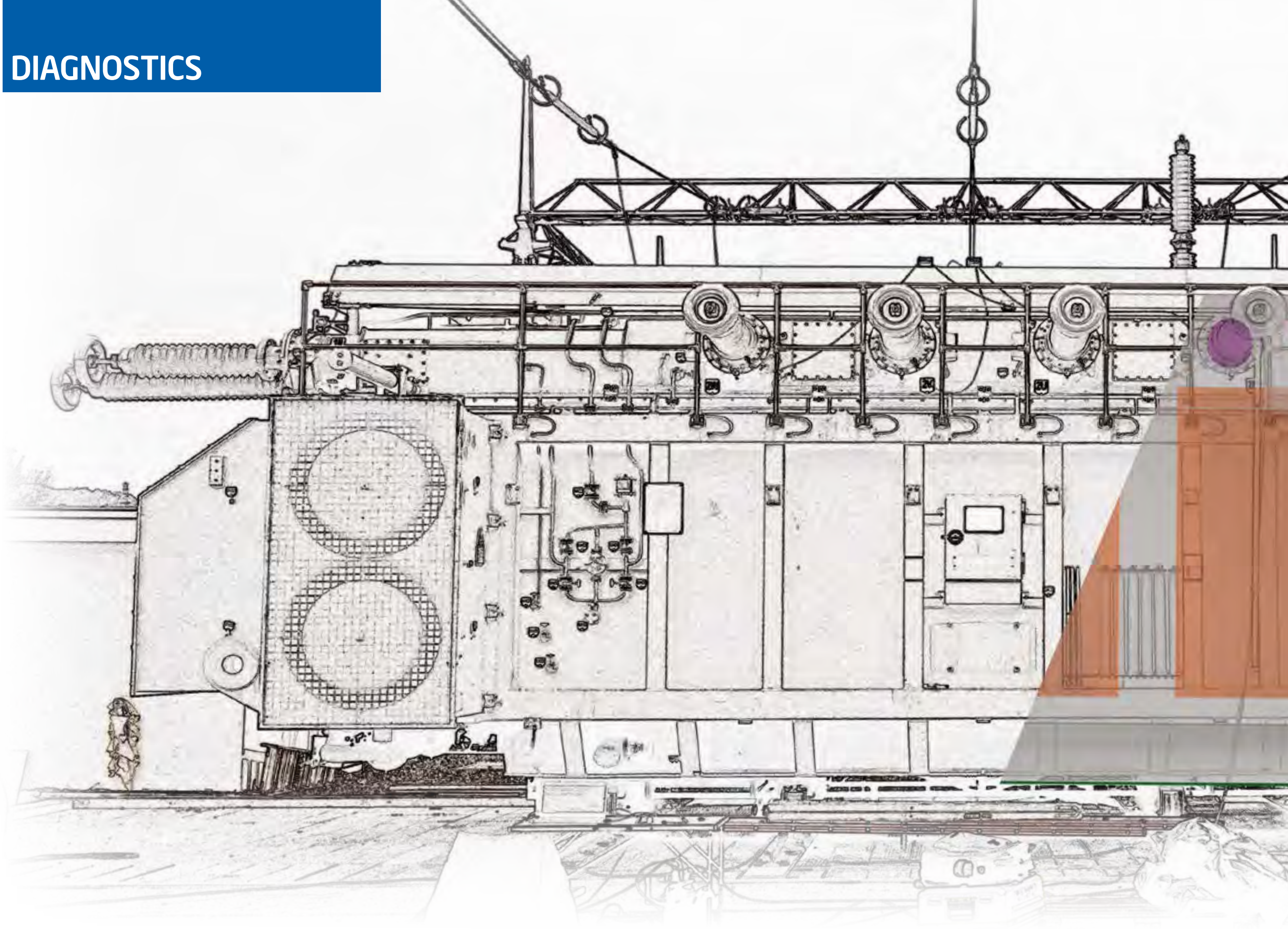


Measurement, localisation, and monitoring of partial discharges on a power transformer

ABSTRACT

A partial discharge measurement is a sensitive tool to assess the insulation integrity of a high voltage apparatus. This article discusses measurements, localisation and monitoring of partial discharges on a power transformer after transportation.

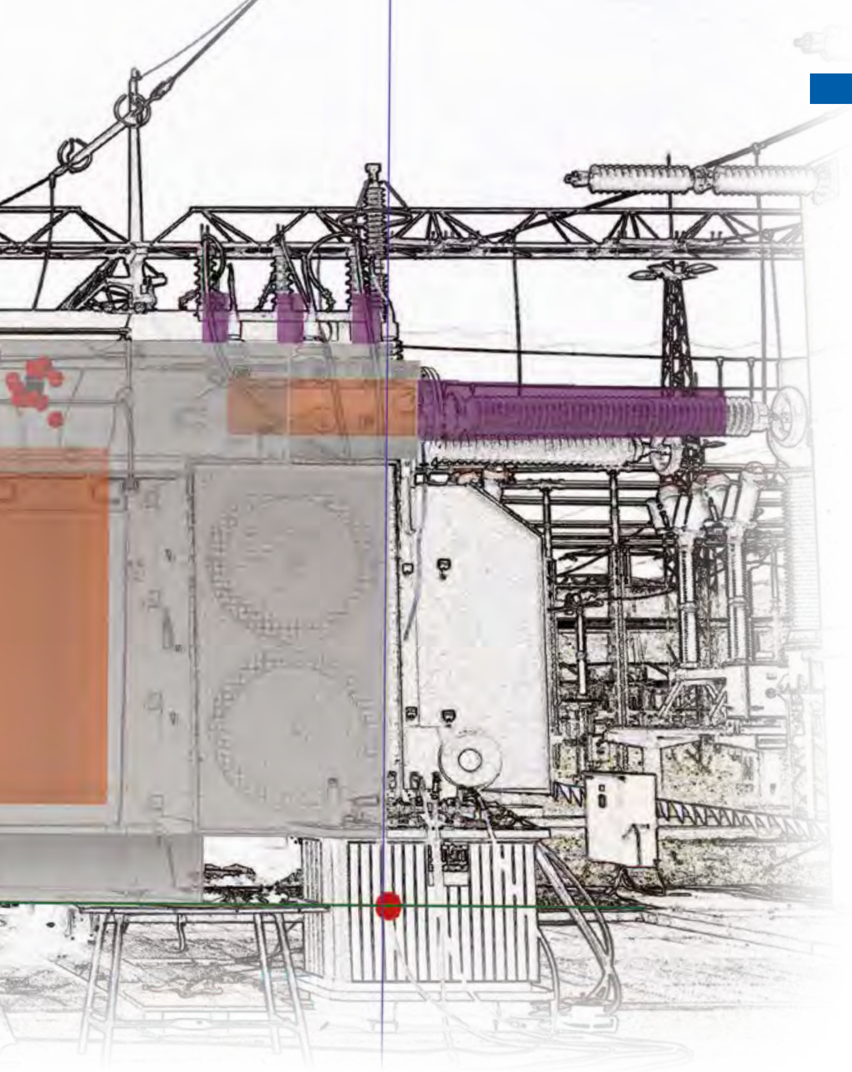
KEYWORDS

measurement, monitoring, partial discharges (PD), PD localisation, transformer, trending

Introduction

Power transformers, a vital element of the electrical grid, are subjected to different levels of electrical, thermal, mechanical, and chemical stress during service. To ensure reliable and safe operation, it is critical to continuously assess the ageing of the system insulation during a transformer's life cycle. Partial discharge (PD) measurements are a non-destructive tool which allows for measurement, assessment, and localisation of weak spots in complex insulation systems. PD measurements on power transformers are typically carried out during the manufacturing process as a part of quality assurance, after onsite installation, and are used as a tool for condition-based maintenance for matured assets.

PD is a local electrical breakdown of a weak region within the electrical insulation system, resulting in fast current impulses. These electrical signals are often accompanied by other physical effects, such as pressure waves, electromagnetic signals, chemical effects or optical effects [1]. PD measurements of the different effects using conventional and unconventional tools and combining the findings will lead to a more meaningful assessment.



PD is a local electrical breakdown of a weak region within the electrical insulation system, resulting in a fast burst of the current impulses

Case study – PD measurement on a 300 MVA oil-filled transformer

The high-voltage (HV) bushings of the 220 kV and the 110 kV windings had to be disassembled for transportation of a 300 MVA transformer. After mounting the bushings at the new substation, the bushing domes had to be refilled with oil. Due to the horizontal-oriented bushings, this had to be done very carefully to avoid gas bubbles. To ensure a proper filling, partial discharge (PD) measurements have been performed.

Fig. 1 shows the 300 MVA transformer with the horizontal 220 kV and 110 kV bushings and a small step-up transformer with 24 / 0.4 kV for exciting the 300 MVA transformer with a diesel-powered generator.

Electrical PD measurement

The test setup was performed in accordance with IEC 60270 [2], simultaneously decoupling the PD and AC signals at the measuring taps of all 220 kV and 110 kV bushings. Fig. 2 shows the setup of the MPD 800 PD detection instrument at the 220 kV bushings 1U and 1V. The signals of both bushing taps can be directly connected to one MPD 800 detector without using an additional coupling device. Fig. 3 shows the overall PD test setup.

A calibration signal was injected into all bushings, enabling for determination of a cross-coupling matrix. In addition to the conventional PD calibration from HV to ground, a recording was also performed while injecting the calibrating signal into the measuring tap of the bushing to simulate a fault directly at the bushing tap [1].

The ambient noise level was less than 10 pC at 0.5 x Un using a centre frequency of 400 kHz and measuring bandwidth of 600 kHz. Even below the nominal voltage, partial discharges up to 2 nC could be detected at the measuring point 1U.

Figure 1. View of the 300 MVA transformer

Figure 2. Setup for PD measurements on phases 1U and 1V

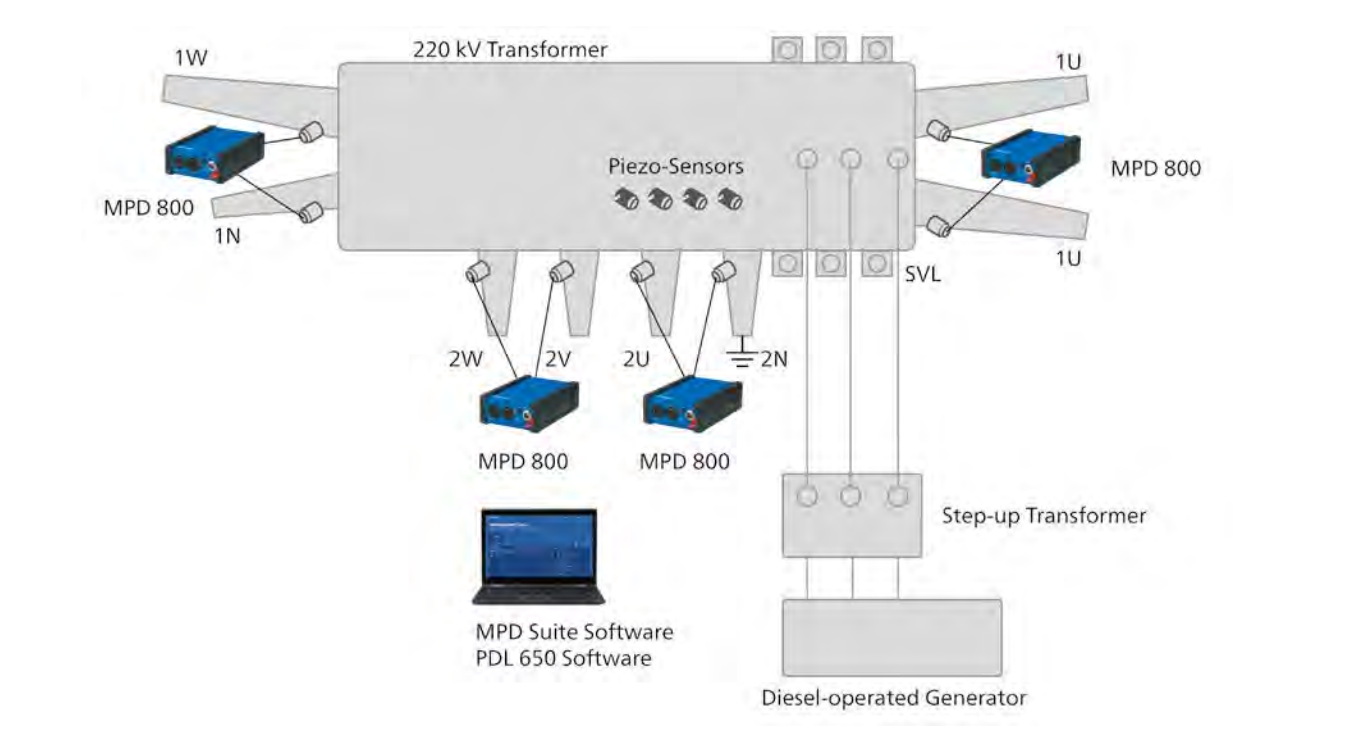


Figure 3. Setup for the PD measurements

A case study of the PD measurement has been performed on 220/110 kV, 300 MVA oil-filled transformer in accordance with IEC 60270 standard

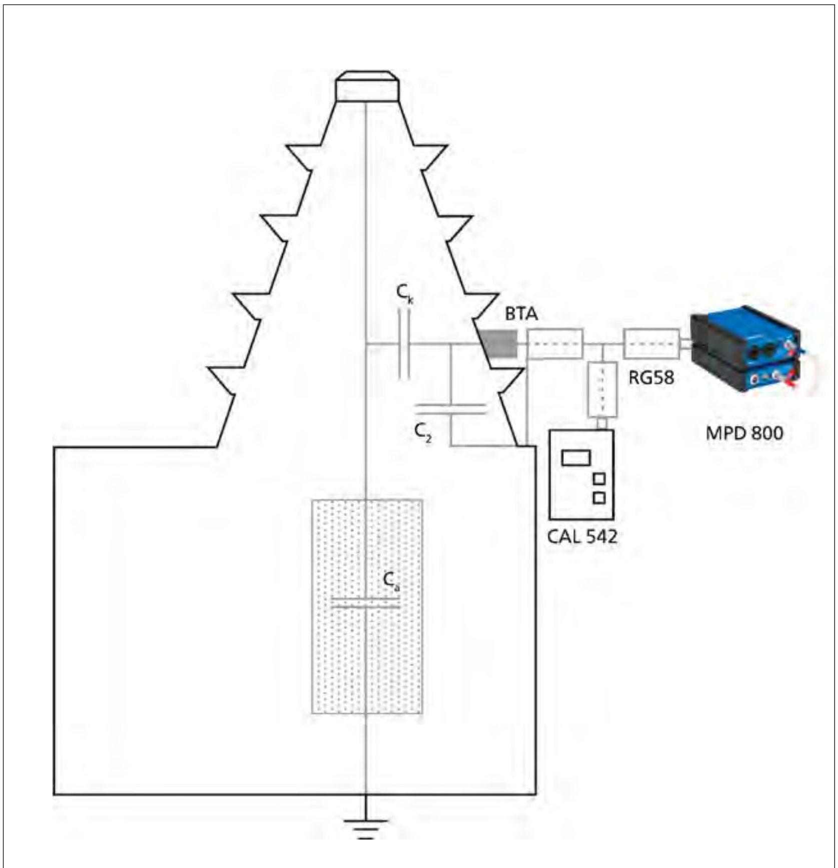


Figure 4. Artificial impulse injected directly at the bushing tap

Comparing the charge values of the calibration cross-coupling matrix with the cross-coupling of the real PD activity indicated that the origin of the PD event was physically close to the measuring point 1U.

The MPD Suite software allowed the test engineers to draw a trigger window in the PRPD pattern. Only PD impulses occurring in the selected phase and amplitude area will trigger the scope and FFT view. This tool allows easy comparison of the unfiltered high-frequency signals. Comparing the time signal and frequency spectrum of the signal directly injected at the bushing tap with the actual PD signal showing high similarities of their rise time and oscillation as well as resonances in the frequency spectrum. The frequency spectrum of the conventional calibration, where long cables had to be used, did not match.

Acoustic PD measurement and localisation

The localisation of PD sources is performed by means of differences in the runtime of the acoustic signal between the fault location and multiple acoustic emission (AE) sensors. Possible fault locations are calculated from the signal runtimes, using the speed of sound and the known geometrical positions of the sensors on the tank wall.

MPD 800 was used for PD measurement together with MPD Suite software for visualisation of the PRPD patterns

The MPD 800 PRPD window trigger also provides an electrical or optical output signal which can trigger an acoustical localisation system. With this method, the delay time to the different piezo sensors can be measured absolutely referred to the electrical triggered PD impulse. This enables the use of averaging functions, which can result in a significantly improved signal-to-noise ratio. Fig. 7 shows the measured acoustic signals of the piezo sensors and the impact of averaging. The acoustic localisation was performed with eight piezo sensors installed in the area of phase 1U.

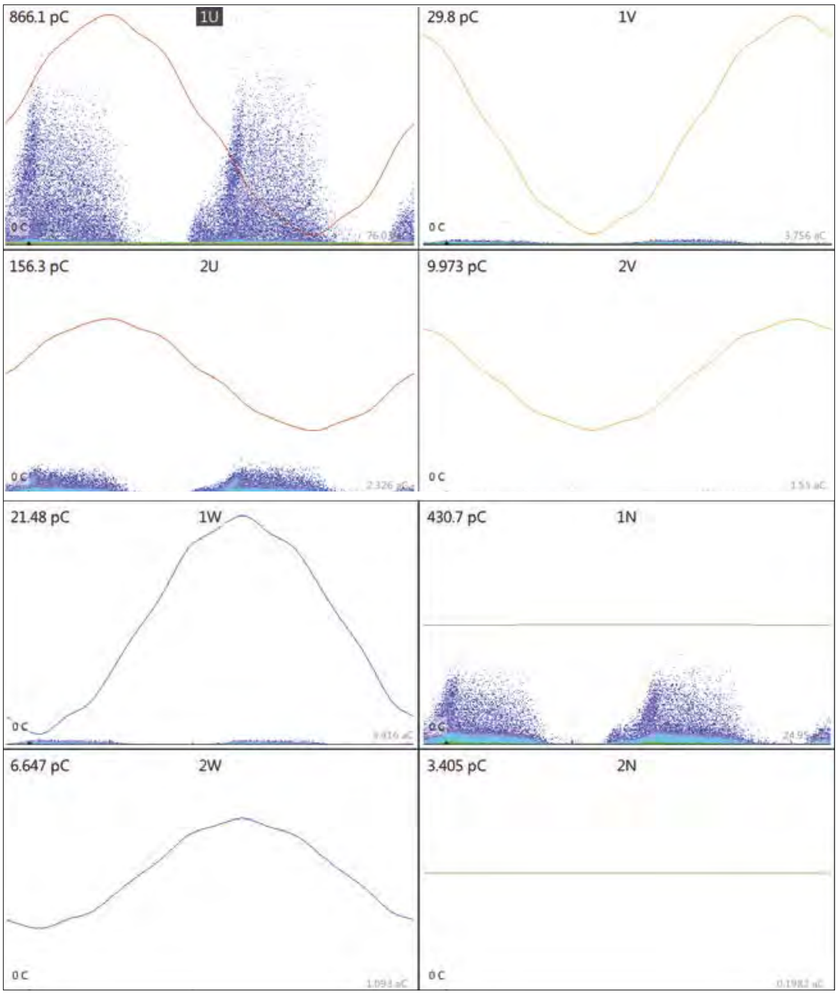


Figure 5. Phase Resolved PD (PRPD) pattern obtained at all measuring points at 0.8 x Un, linear view

The triangulated fault position, as well as the acoustic signal of the internal partial discharges, is shown in Fig. 9 and Fig. 10.

The location is close to the high-voltage exit lead of the 220 kV winding of phase 1U.

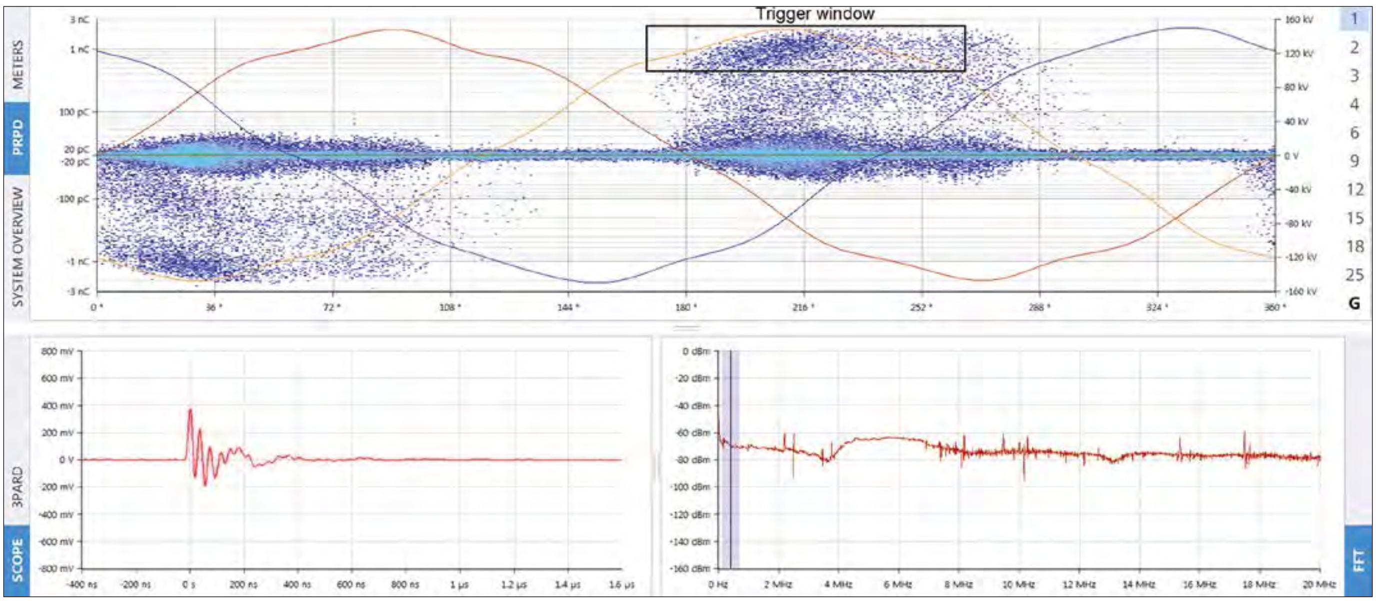


Figure 6. MPD Suite software; logarithmic-bipolar view of the PRPD pattern at 1U, the trigger window and corresponding time and frequency signal

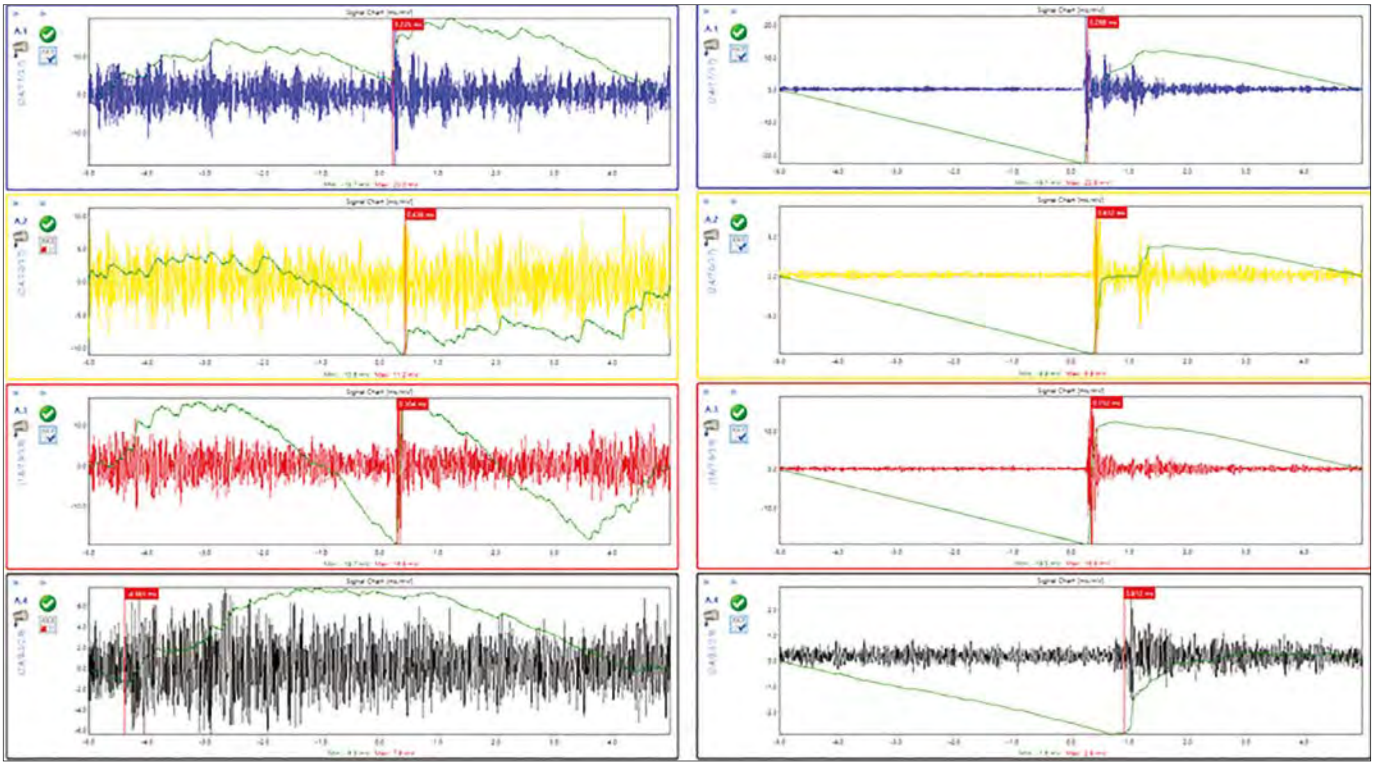


Figure 7. Acoustic signals without averaging (left) and the averaging of 100 events (right) using the electrical signal as the trigger

> **Localisation of the PD activity is determined by triangulating the delay times between the acoustics signals from piezo sensors and electrical signals triggered by the PD impulses**

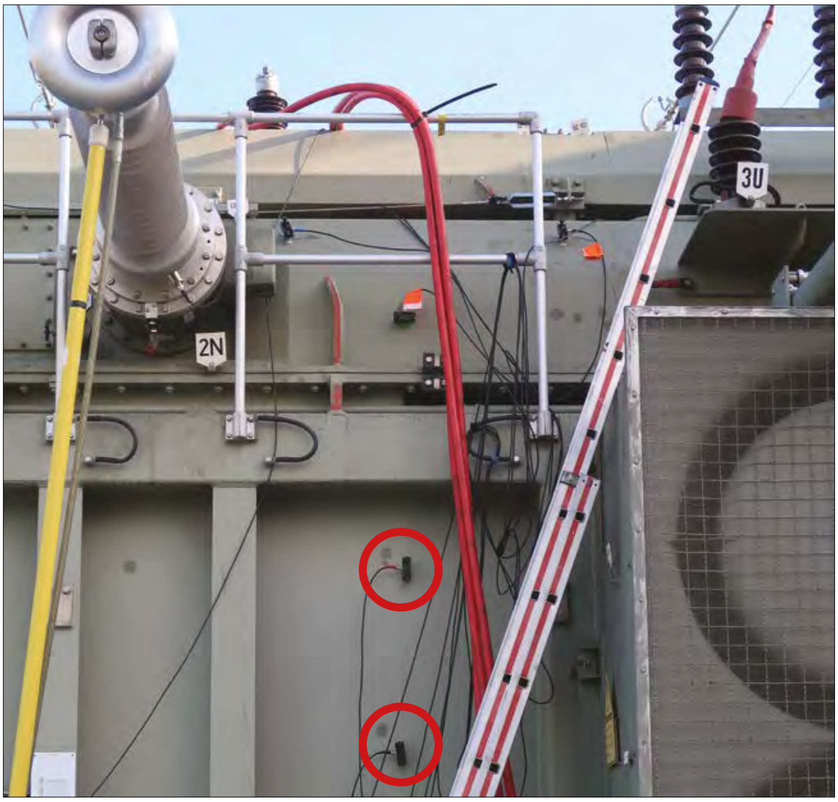


Figure 8. Installation of piezo sensors

Electrical PD Trending and Monitoring

Findings of the off-line PD measurement and localisation were discussed with the transformer manufacturer. The fault location, PD behaviour and the fact that it cannot be repaired onsite led to the decision that the unit could be re-energised while the PD activity and dissolved gasses are carefully monitored in the insulation oil of the transformer.

The transformer was then therefore equipped with bushing adapters at the bushing taps of all 220 kV bushings. The MONTESTO 200 PD monitoring and trending device used can be remotely controlled, and it communicates with the control centre in case PD warning levels are exceeded.

Audible corona discharge was active in the substation thus the measuring frequency was tuned to 2.2 MHz – a frequency range where the internal discharges dominated and external disturbances were minimised. The discharge level of the internal PD activity at Phase 1U was stable for the first weeks of operation but then started to continuously increase over a period of one month. Fig. 12 shows the increasing trend of the apparent charge measured on Phase 1U.

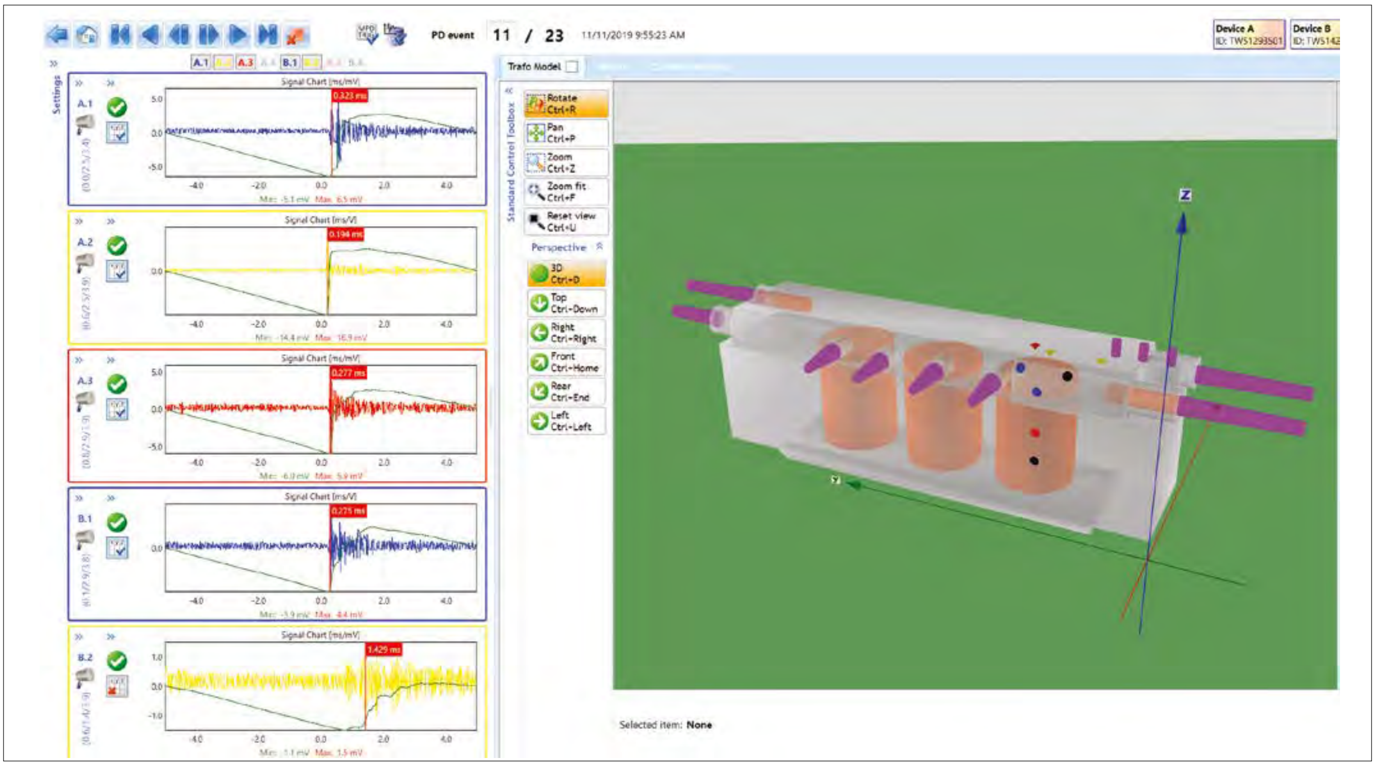


Figure 9. Acoustic signals of piezo sensors

The MONTESTO 200 PD monitoring and trending device used can be remotely controlled, and it communicates with the control centre in case PD warning levels are exceeded.

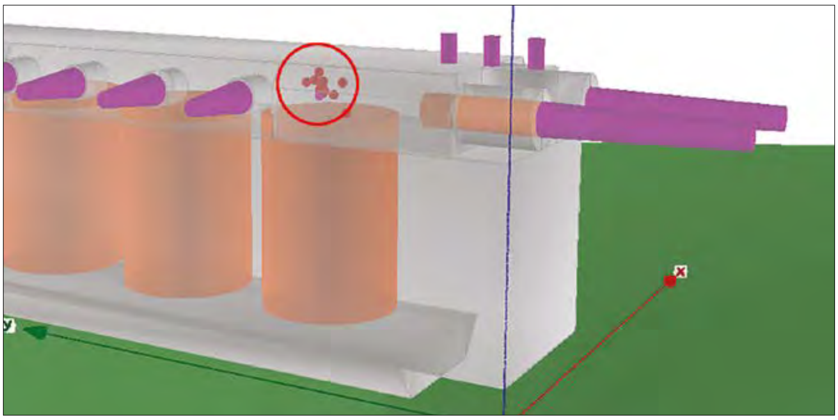


Figure 10. Location of PD at the high voltage exit of phase 1U

In addition to the known PD activity at Phase 1U, a second pattern developed over 3 months, which started with approximately 100 pC and stabilised at 2 nC. The discharge pattern can be assigned to Phase 1V and shows high similarities to the phenomena obtained at 1U. The development of the PRPD pattern as well as the 3PARD diagram, is shown in Fig. 13. Fig. 14 shows the development of the 3PARD filtered PRPD pattern obtained at Phase 1V.

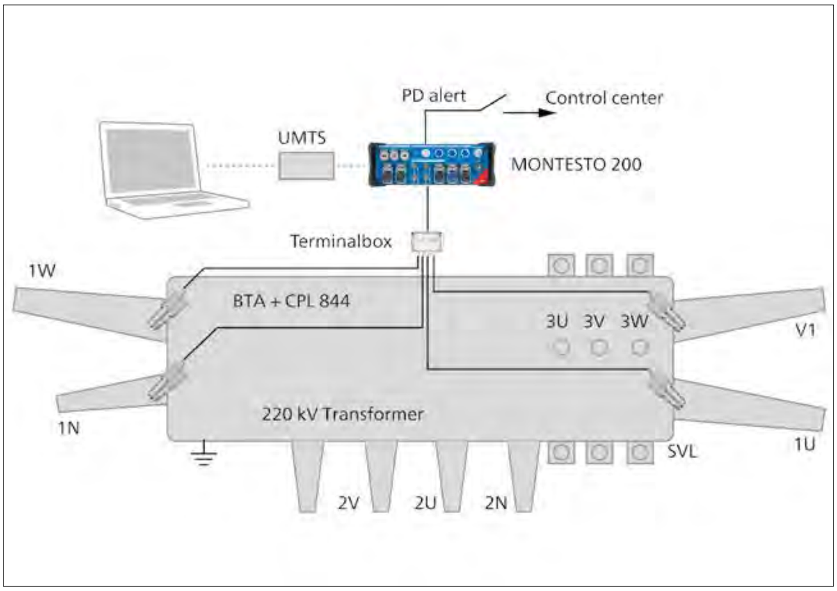


Figure 11. Complete setup of the PD monitoring and trending system

A local defect inside a solid insulation part does not necessarily lead to an increase of dissolved gases

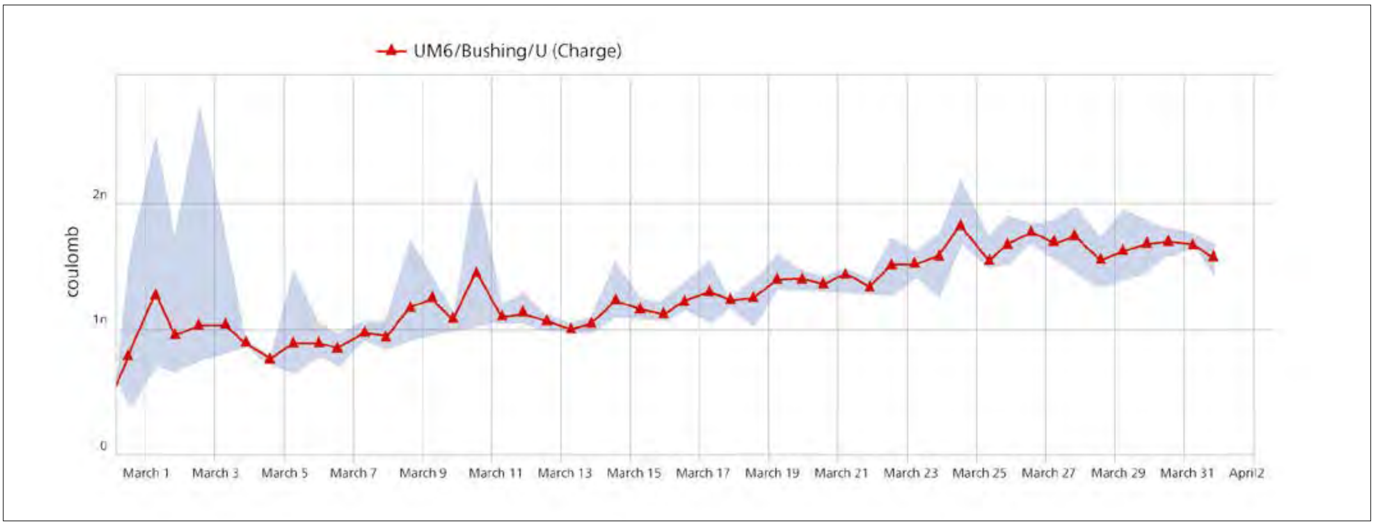


Figure 12. Increasing PD trend on Phase 1U

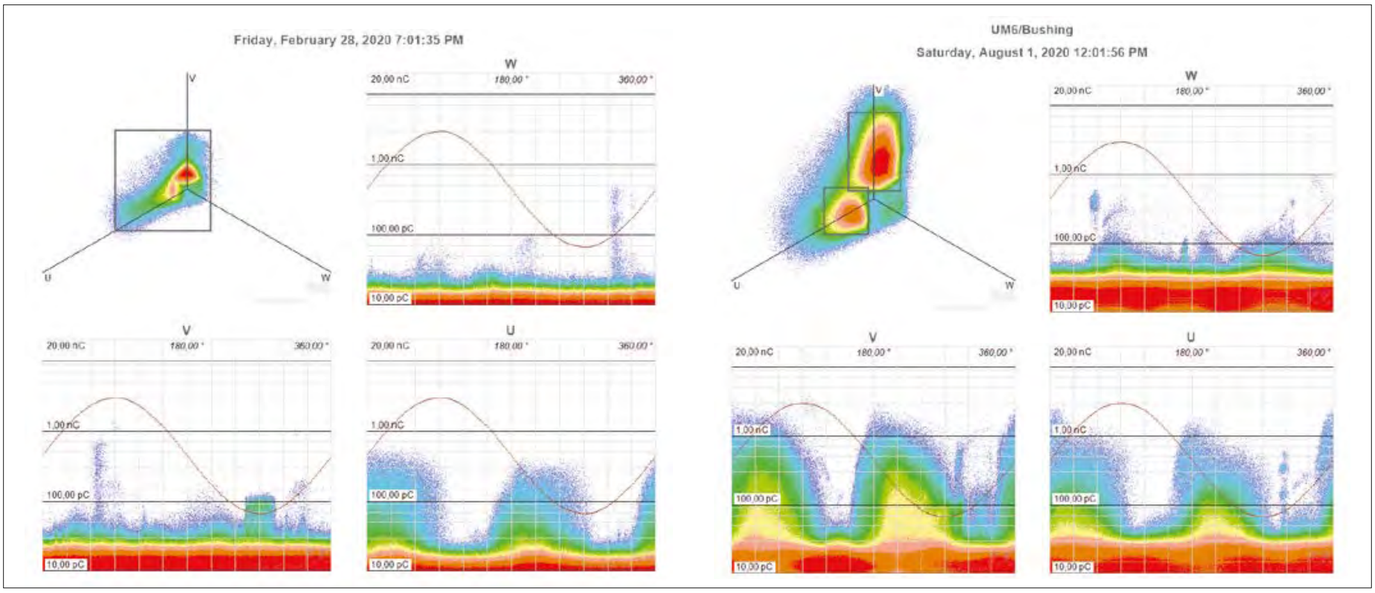


Figure 13. Development of PD activity over a five-month period, logarithmic view

Dissolved Gas Analysis (DGA)

The DGA results before and after the transportation did not indicate any failure or PD activity. Hydrogen slightly increased during operation, but the overall amount of dissolved gases were below typical values, thus no reliable assessment could be performed [4]. A local defect inside a solid insulation part does not necessarily lead to an increase of dissolved gases.

Conclusion

In this article, the importance of electrical PD measurement, localisation, monitoring and trending is discussed. Onsite PD measurements on liquid-filled transformers are often only triggered by DGA results. The case study on the 300 MVA transformer highlights that an electrical PD measurement and trending can be more sensitive and instantaneously compared to the analysis of dissolved gases in the oil. Analysing the unfiltered signals in time and frequency domain as well as performing acoustical PD locali-

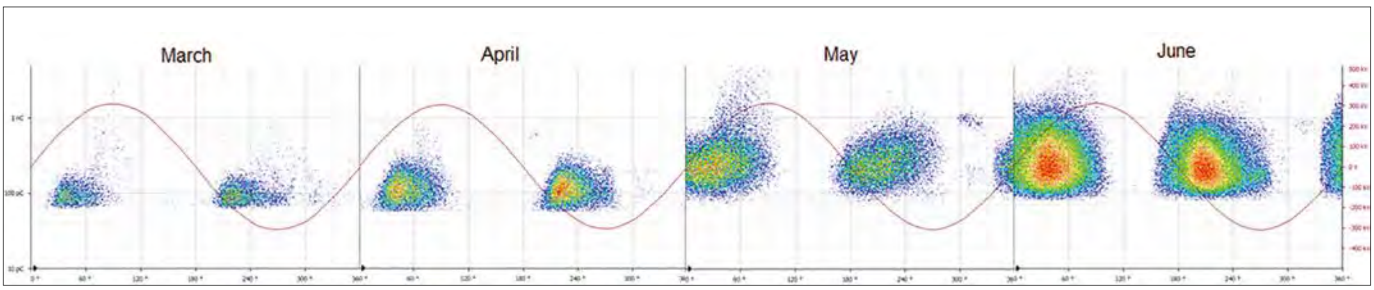


Figure 14. 3PARD filtered PRPD pattern and development of the pattern obtained during Phase 1V

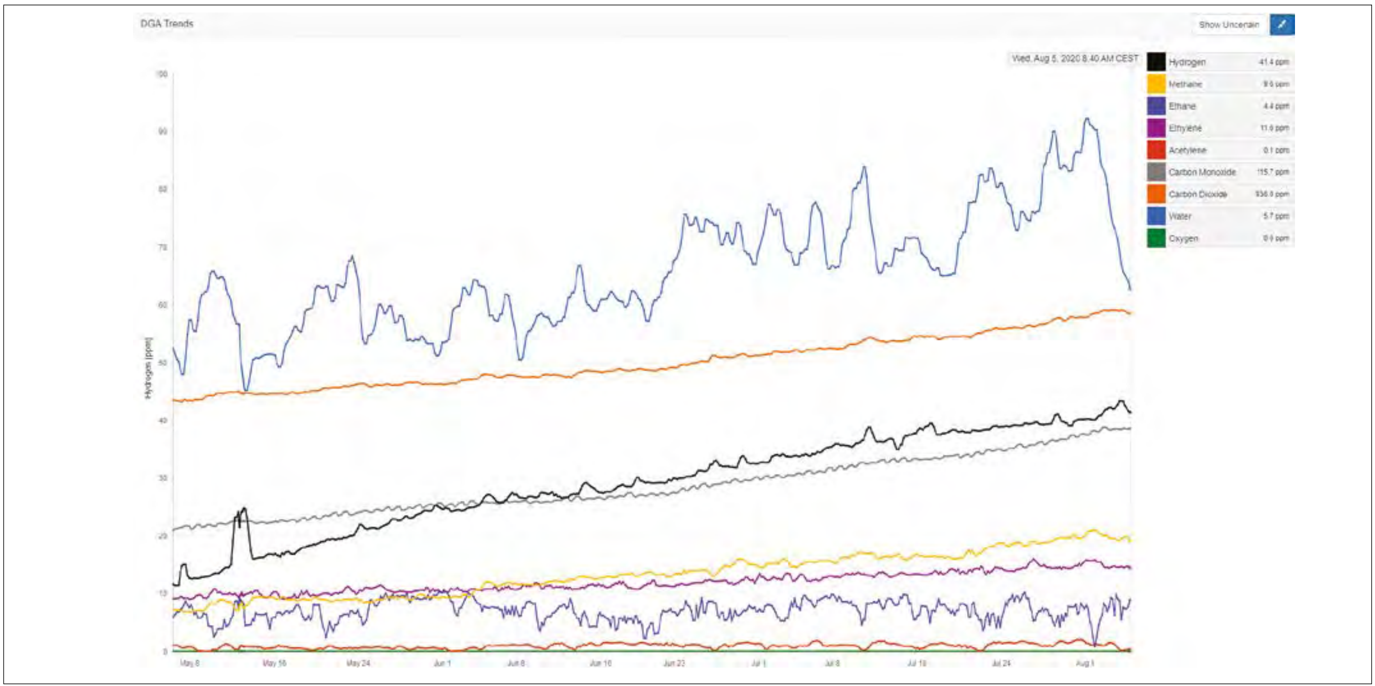


Figure 15. DGA trend over a three-month period

The case study on the 300 MVA transformer highlights that an electrical PD measurement and trending can be more sensitive and instantaneously compared to the analysis of dissolved gases in the oil

sation with three or more piezo sensors can provide valuable information when it comes to localisation, interpretation and risk assessment. The transformer, with active but stable discharges in two phases, remains online and is further monitored.

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SFRA ratio test on transformers

A simple diagnostic test to identify winding with shorted turns

ABSTRACT

SFRA test is a powerful and sensitive method for assessing the mechanical and electrical integrity of the transformer core/coil assembly. The two most commonly used tests are open- and short-circuit tests. Both are used for testing the complex network of inductances, capacitances and electrical resistances and, frequently, have no difficulties in detecting the presence of an electrical fault with the shorted turn(s). Since windings are electromagnetically coupled, the SFRA trace obtained from one of the windings may be affected by the electrical fault on a different winding. Identifying which winding has the problem is a challenging task. This paper describes the experience with six units, where the faulty winding (if any) was identified by employing an inductive inter-winding SFRA setup. We elected to refer to this test as "SFRA ratio" test.

KEYWORDS

data analysis, detecting fault winding, diagnostics, SFRA ratio, shorted turns

1. Introduction

The objective of a traditional voltage ratio test is to verify the proper number of turns, internal connections and to serve as a benchmark to assess possible future damage, e.g., shorted turn(s). While theoretically, a change in the voltage ratio data should point to the winding with a shorted turn(s), in practice, it may not paint a clear picture. To address that, an inductive inter-winding SFRA (Sweep Frequency Response Analysis) setup was employed. It offers a frequency scanning from low frequency (e.g., < 200 Hz), where the ratio of the induced voltages is closely proportional to the turns ratio. Therefore, the direction of the deviation in the aforementioned SFRA trace segment points to a winding hosting the defect. The following discussion describes the basics of the test, along with the results of several field investigations.

With a simple calculation of the deviation between traces, SFRA Ratio identifies the winding sheltering the shorted turns

2. Basic concept

Fig. 1 shows a basic setup of a SFRA ratio test, which employs connections for the inductive inter-winding SFRA test. In that, the high-voltage winding is excited by the test voltage applied between the red lead and ground, and the secondary voltage is measured between the black lead and ground. Let us recall the expression for the SFRA magnitude in dB:

$$20\log\left(\frac{V_2}{V_1}\right) = dB \quad (1)$$

From (1), the ratio of voltages is:

$$SFRA\ Ratio = \frac{V_1}{V_2} = 10^{\frac{dB}{20}} \quad (2)$$

Obviously, the relevant ratio data can be obtained in a frequency range where the ratio of voltages corresponds to the ratio of turns. To that end, for the units tested, the SFRA ratio remained constant at frequencies < 200 Hz. The difference between the SFRA traces can be useful in detecting / confirming the presence of the defect (3):

$$\Delta_{25\ Hz} = \frac{Max(R_1, R_2, R_3) - Min(R_1, R_2, R_3)}{Average(R_1, R_2, R_3)} \quad (3)$$

In (3), $\boldsymbol{R_1}$, $\boldsymbol{R_2}$, $\boldsymbol{R_3}$ are SFRA ratio values obtained from the traces of each phase. To identify which winding has a shorted turn, the trace deviation in that segment is examined. If the turn is shorted in the low-voltage winding, the trace segment will move upwards (towards a higher ratio value) and move downwards (towards a lower value) if the shorted turn is located in the high-voltage winding. A comparison can be made either with the previous data or with other phases. Furthermore, the nameplate (NP) voltage ratio can be compared with the SFRA ratio taken near the power frequency to avoid potential interference. The latter allows verifying that the SFRA ratio test setup is correct. Given the wealth of experience gained with traditional voltage ratio tests, it seems practical to continue relying on the traditional voltage ratio test in all situations. The SFRA ratio comes into play when an electrical defect is detected (by any of the tests), and there is a need to identify / confirm the faulty winding. In that, the SFRA ratio test offers a more visible indication of the defective winding.

Combining standard SFRA tests with SFRA ratio enhances diagnostics of shorted turns

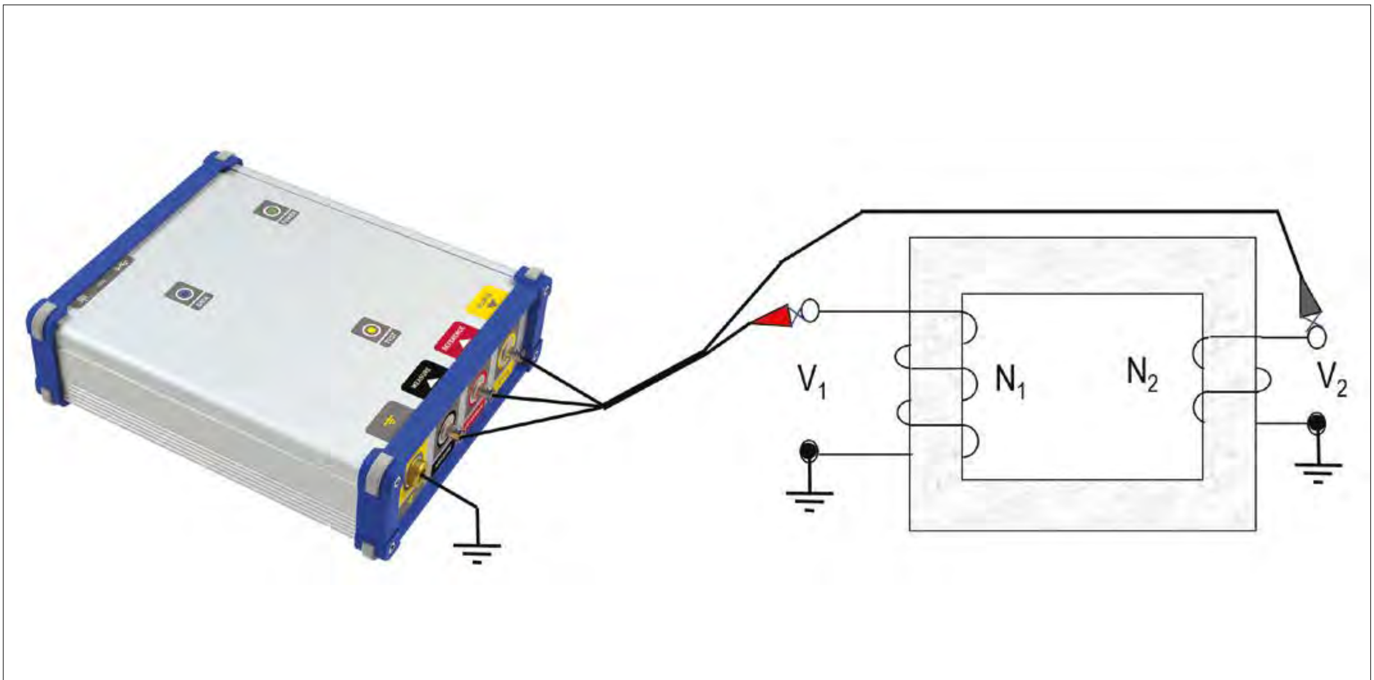
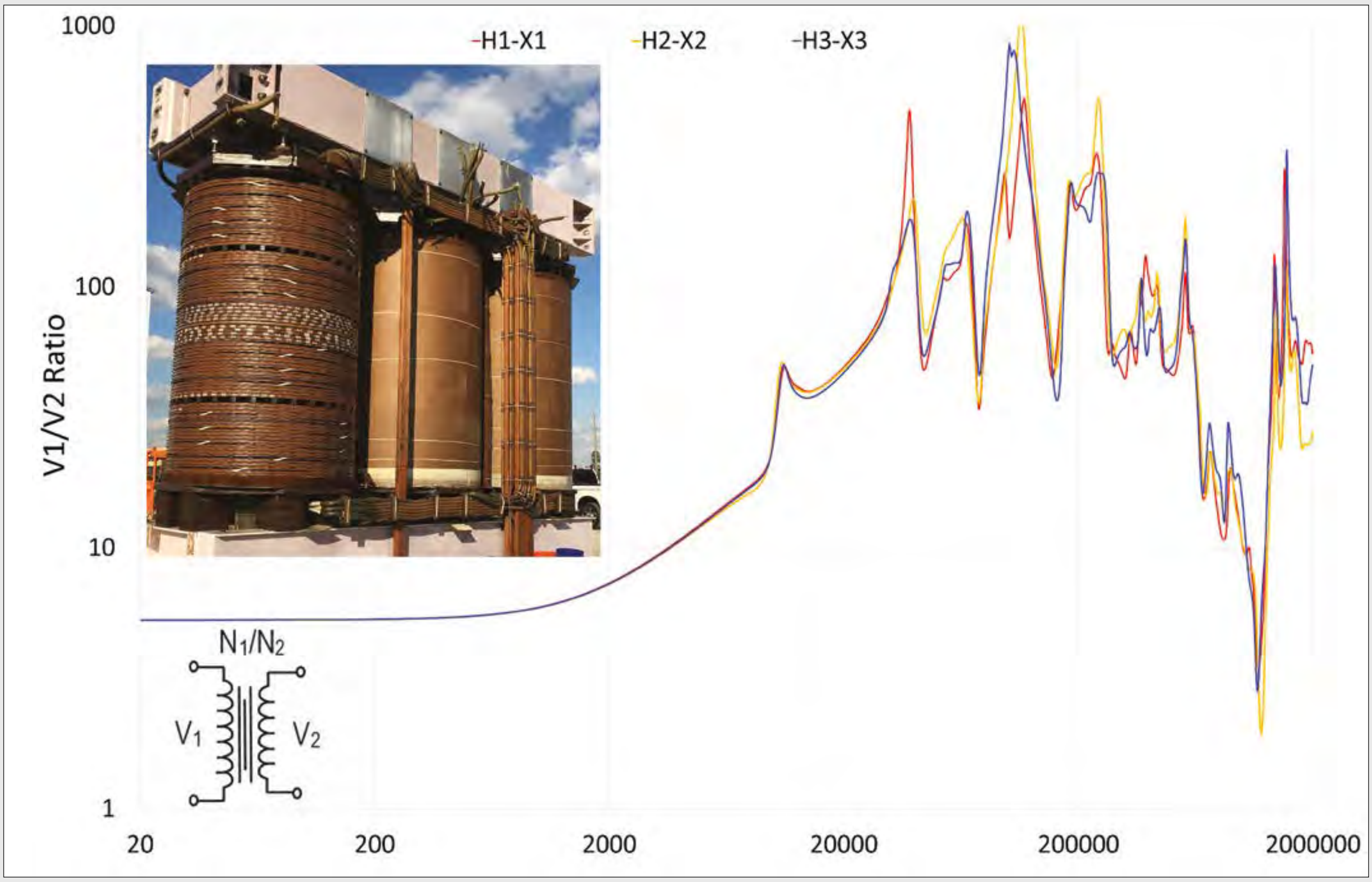


Figure 1. Basic setup for SFRA ratio test



An interesting observation is that with a higher frequency range the SFRA ratio seems to behave in a way similar to the traditional open circuit and short circuit tests

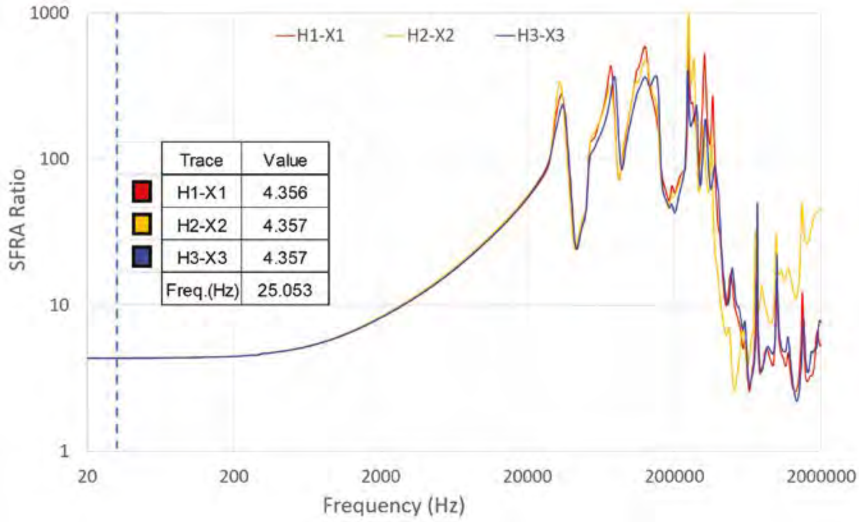
3. Experience

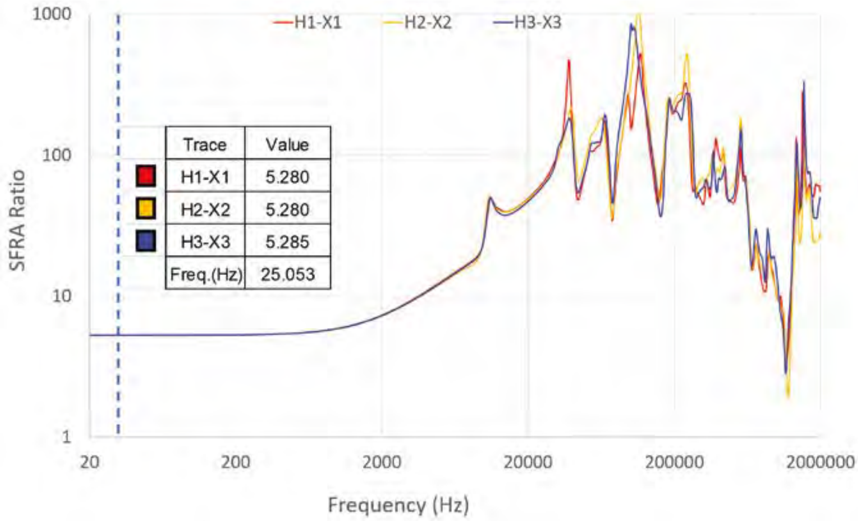
Six transformers in different conditions were used to demonstrate the SFRA ratio application. These units have different winding configurations with conditions varying between good and with a fault such as shorted turns in either the primary or secondary winding, as summarized in Table 1. The analyses of the test results are summarized in Table 2.

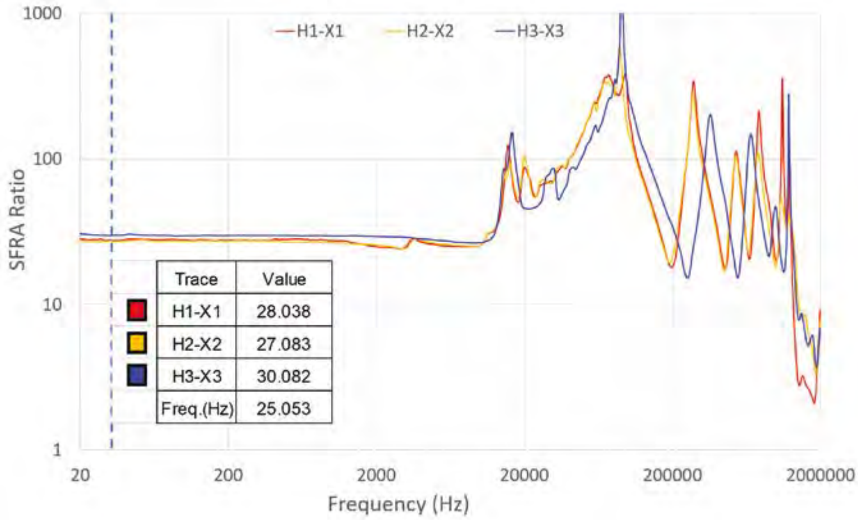
Table 1. Transformers tested

Unit #	Condition	Winding	Manufacturer	MVA and voltage at tested tap position
1	Good	Dyn1 -2012	Electric Power Service	12.5 MVA, 34.5 / 13.8 kV
2	Good	YNd1 -1962	General Electric	40 MVA, 120.75 / 13.2 kV
3	Fault on LV	YNd1-1989	Westinghouse	41.6 MVA, 120.75 / 13.2 kV
4	Fault on LV	Dyn1-1970	Moloney Electric	18 MVA, 115.5 / 13.2 kV
5	Fault on HV	YNd1-1998	Ferranti Packard	300 MVA, 241.5 / 20 kV
6	Fault on LV	YNa0d1-1971 H-X	McGraw-Edison	33 MVA, 230 / 99.4 kV
	Fault on TV	H-Y		230 / 44 kV
	Fault on LV, TV	X-Y		99 / 44 kV

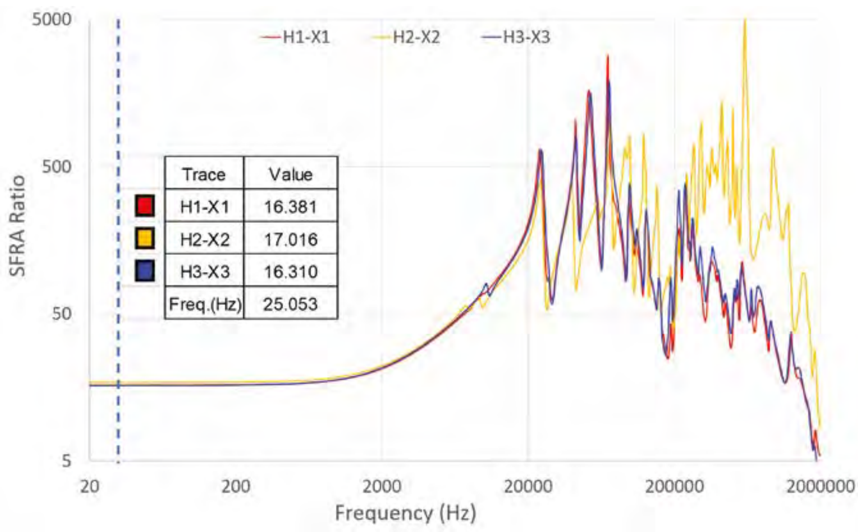
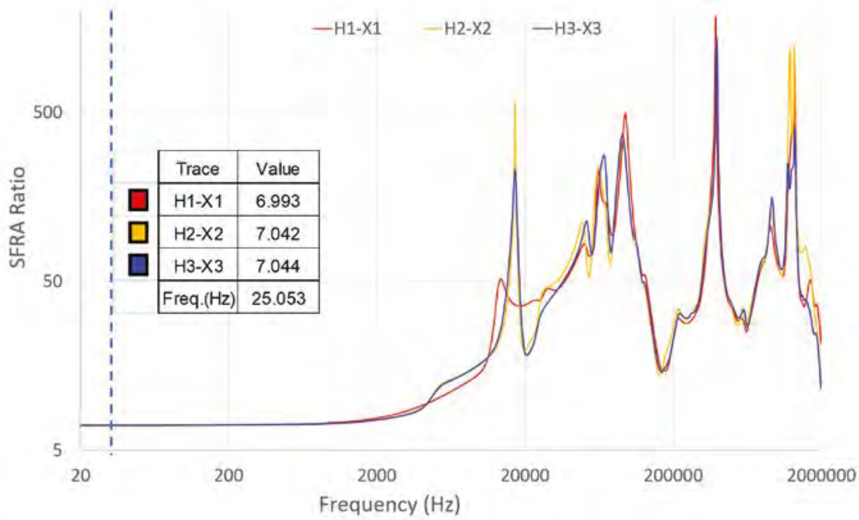
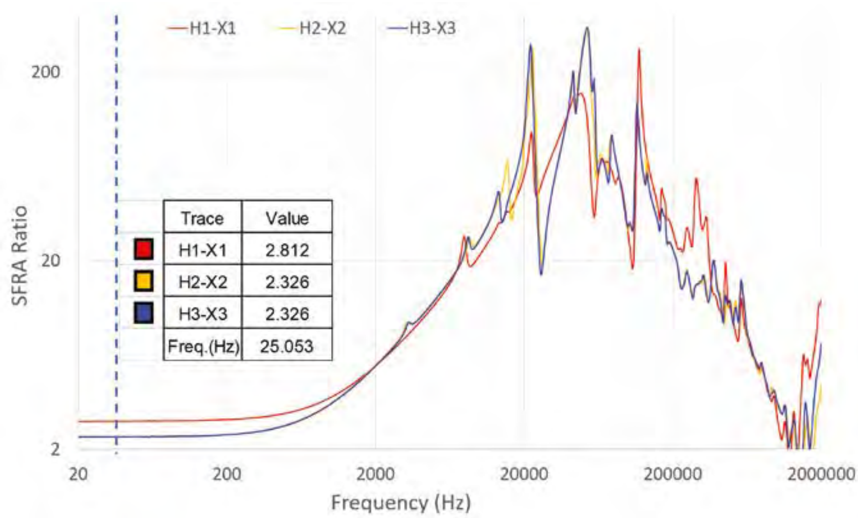
Table 2. Data review

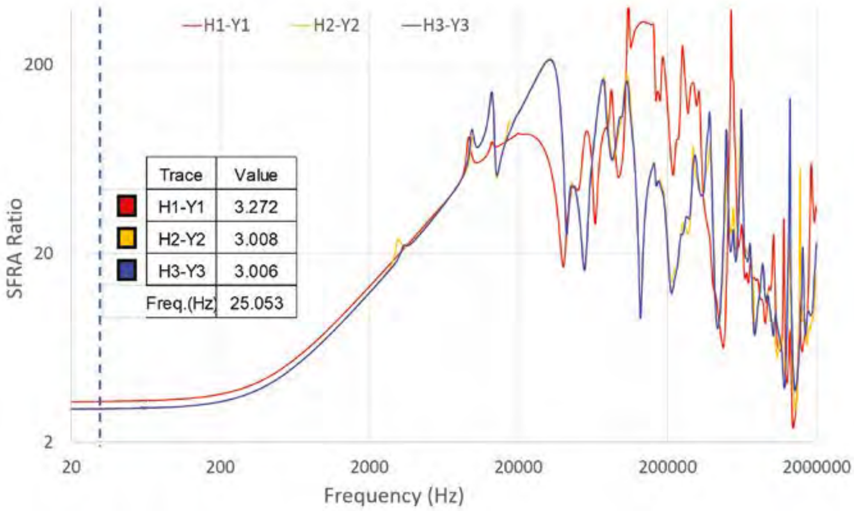
<table>
<tr><th>SFRA ratio data</th><th>Observations</th></tr>
<tr><td>


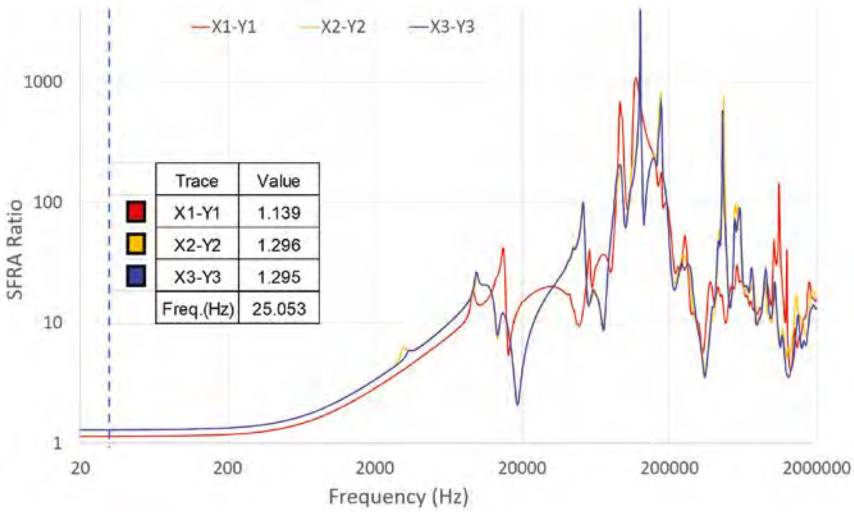
</td><td>
1) Δ25Hz = 0.023 %
2) SFRA ratio is reasonably close to NP ratio. The expected Δ25Hz is within ± 0.5 %.
3) No fault detected
</td></tr>
<tr><td>


</td><td>
1) Δ25 Hz = 0.095 %
2) SFRA ratio is reasonably close to NP ratio.
3) No fault detected
</td></tr>
<tr><td>


</td><td>
1) Δ25 Hz = 10.56 %
2) SFRA ratio values on each phase drastically deviate from the NP ratio.
3) H3-X3 trace is higher than traces of the other two phases, indicating that fault is present in phase 3 of X winding.
</td></tr>
</table>

<table>
<tr><th>SFRA ratio data</th><th>Observations</th></tr>
<tr><td>
</td><td>1) Δ25 Hz = 4.26 %
2) SFRA ratio values deviate from the NP ratio.
3) H2-X2 trace is higher than traces for the other two phases, indicating that fault is present in the phase 2 of X winding.</td></tr>
<tr><td>
</td><td>1) Δ25 Hz = 0.72 %
2) SFRA ratio is reasonably close to NP ratio.
3) H1-X1 trace is lower than traces of the other two phases, indicating that fault is present in the phase 1 of H winding.</td></tr>
<tr><td>
</td><td>1) Δ25 Hz = 19.52 %
2) SFRA ratio in phase 1 significantly deviates from both the NP and SFRA ratio values in other phases.
3) H1-X1 trace is higher than the traces of the other two phases, indicating that fault is present in the phase 1 of X winding.</td></tr>
</table>

<table>
<tr><th>SFRA ratio data</th><th>Observations</th></tr>
<tr><td>


</td><td>
1) Δ25 Hz = 8.61 %
2) SFRA ratio in phase 1 significantly deviates from both the NP and SFRA ratio values in other phases.
3) H1-Y1 trace is higher than traces of the other two phases, indicating that fault is present in the phase 1 of Y winding.
</td></tr>
<tr><td>


</td><td>
1) Δ25 Hz = 12.62 %
2) SFRA ratio in phase 1 deviates from both the NP and SFRA ratio values in other phases.
3) X1-Y1 trace is lower than traces of the other two phases, indicating that fault is present in the phase 1 of X winding. This suggests that X winding has a higher percentage of shorted turns than Y winding.
</td></tr>
</table>

Conclusion

In summary, the reported experience shows that in tested transformers, the SFRA ratio test was successful in both, detecting the presence of the shorted turns as well as identifying the winding that has the fault. As the analysis guideline, the maximum deviation among phases near 25 Hz (Δ25Hz) should be within ± 0.5 %, Another interesting observation has to do with a higher frequency range where the SFRA ratio seems to behave in a way similar to the traditional open circuit and short circuit tests, i.e., dominated by the interactions within/between the windings as well as with surrounding components. More studies are required to validate this observation and to establish a practical diagnostic.

The experience shows that the SFRA ratio test was successful in both, detecting the presence of the shorted turns as well as identifying the winding that has the fault

Author

Long Pong works as a Senior Principal Engineer in the Client Service Department at Doble Engineering Company. He has amassed over 30 years of experience in the power utility industry and has published numerous technical papers pertaining to condition assessment, troubleshooting and new test techniques of electrical power apparatus. Before joining Doble in 2000, he was employed at Alcan-Énergie Électrique and Hydro-Quebec. He is an IEEE member, a registered professional engineer in North Carolina and obtained a Bachelor of Electrical Engineering from École Polytechnique de Montreal, Quebec, Canada, in 1988.

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