Transformers

VOL 1 ISSUE 3 OCTOBER 2014 MAGAZINE

Power transformer protection – an outline

Transformers with low degree of polymerisation of paper

Tank depressurisation

Fire testing for transformer pit fire protection

Low voltage single-phase excitation for power transformers

INTERVIEW with Dr. Michael Krüger

INTERVIEW with Mr. Lars Martinsson

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POWER TRANSFORMER LIFE CARLOS GAMEZ

TRENDS IN POWER TRANSFORMER FAILURE ANALYSIS WALLACE BINDER

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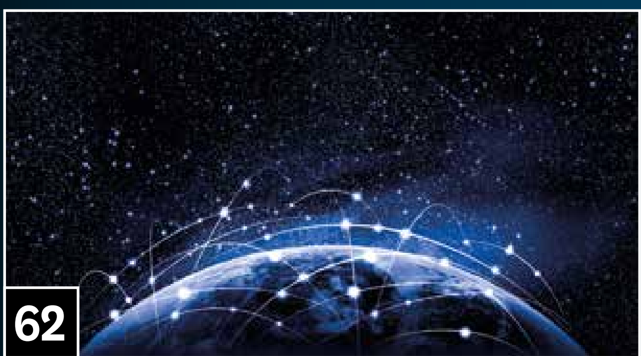

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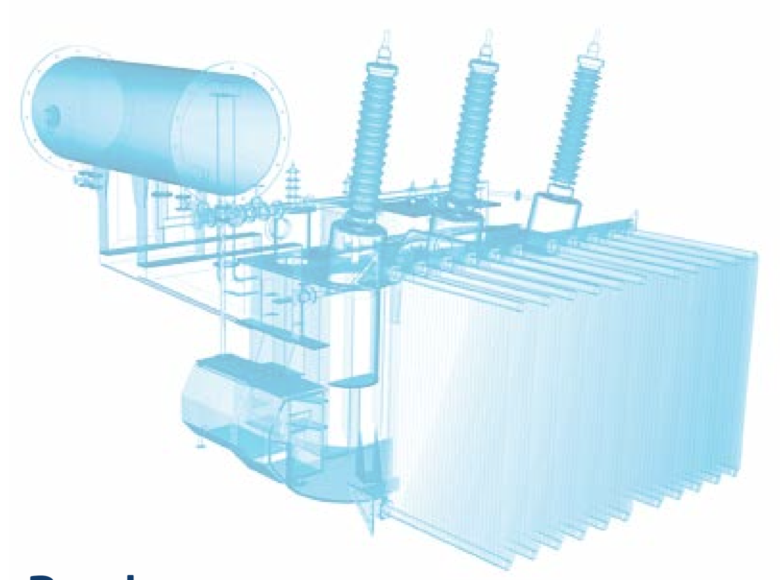


Dear Readers,

Again Transformers Magazine brings you a wide range of technical articles and two columns.

In his column Carlos Gamez reviews the most important factors that determine a transformer's longevity and explores which actions a transformer owner, operator and maintainer can take in order to manage and, as much as possible, extend the life of the important and expensive assets.

Omar Ahmed and Anne Goj analyse the activation of two mechanical depressurisation devices, the transformer protector and the pressure relief valve during an internal arc on a 400 MVA three phase transformer. Authors performed computational simulations to study the dynamic pressure evolution and static pressure build up inside the tank.

Michel Duval presents challenging findings regarding the widely accepted criterion for end of life for paper insulation of paper DP of 200 being too high, and that it could be decreased to about 100 or even lower. In this way, the life of transformers could be extended by several years without increasing their risk of failure due to the mechanical condition of paper, thus significantly reducing capital investment costs needed for their replacement.

Wallace Binder's column 'Trends in transformer failure analysis' reports on recent progress on standardisation projects, describes some failures which have evolved recently, and identifies many things that are not found in the IEEE Guide for Failure Analysis.

In his article Talha Ali Qasmi demonstrates different protection schemes and protective devices used to protect transformers, their need and importance to disconnect the transformer from the grid as quickly as possible because the damage is proportional to the fault time.

Johan Lindström and Michael Försth describe fire safety issues related to pits for collection of oil in the event of an oil leak from a transformer. Pits are conventionally filled with rocks. There is, however, no well defined test method that quantifies the fire performance. Authors presented a test with test results for an alternative system with profile planks instead of rocks.

Zhan Yangang introduces the readers to another auxiliary judgment method for core type transformer - low voltage single-phase excitation, explaining how to perform the test and what should be done to achieve the correct results.

I hope you will find something interesting in this issue and that reading it will be a pleasurable experience.

Mladen Banovic, Editor in Chief

Global transformer market to reach $48.3 billion in 2019

USA: BCC Research announced new report Global Market for Transformers.

The market is expected to grow to $48.3 billion by 2019, with a five-year CAGR of 7.3%. The Asia-Pacific market is the fastest-growing region and is moving at a significant 8.1% CAGR, reports Broadway World. The Asia-Pacific market is expected to surge to $21.1 billion by 2019 due to increasing use of the region as a hub for Western markets to outsource the manufacture of their transformers. The European and North American markets are projected to grow at a healthy CAGR of 7.2% and 5%, respectively. *Source: Broadway World*

ABB, Alstom & Siemens dominate distribution transformer market

Ireland, Dublin: Research and Markets has announced the addition of the ‚Global Distribution Transformer Market 2014-2018‘ report to their offering.

Acording to the report, the global distribution transformer market will grow at a CAGR of 5.30% to 2018.

One of the major trends emerging in this market is increase in power generation and distribution capacity as the demand for power is on the rise especially in developing countries such as China, India, Russia, and Brazil, reports Business Wire.

The report also states that the market faces fluctuating raw material prices. Key vendors mentioned are ABB, Alstom and Siemens. *Source: Business Wire*

Transformer Association predicts brights future for transformer manufacturing in Americas

The Transformer Association's President, James Tabbi predicts growth for transformer manufacturing in North America, thanks to favorable domestic economic conditions, coupled with rising labour and freight costs in Asia.

„During the late nineties and 2000s, the trend was to offshore. We saw a huge decline in the manufacturing of electronic transformers domestically in the US." Tabbi says. "But over the last year or so there's been a lot of talk about re-shoring. Much of that is to Mexico and Central America but a significant amount has been right here in the US."

"Some companies shifted, not only the high volume work, but their complete operations to Asia and are perhaps now starting to feel this wasn't such a good choice. For the mid-to-low volume, higher complexity work, it often makes sense to manufacture domestically." Tabbi affirms.

Source: CWIEME

The Latin American traction transformer market is expected to reach $64.3 million by 2018

USA: MicroMarket Monitor has published report for the Latin American traction transformer market.

The market was valued at $51.7 million in 2013, and is expected to reach $64.3 million by 2018, at a CAGR of 4.4% from 2013 to 2018, reports Micromarket Monitor.

The market covers AC traction transformer and DC traction transformer and is segmented into solid state transformer (SST) and other products. The market based on models include electric multiple unit (EMU), electric locomotive, high speed train, and tram. The market is further segmented and forecast based on types, comprising rectifier transformer, tap changing transformer, and tapped transformer.

Tapped transformer dominated the market with highest revenue in 2013 ($48.3 million) as they were being used in locomotives and high speed trains due to their higher power rating. *Source: Micromarket Monitor*

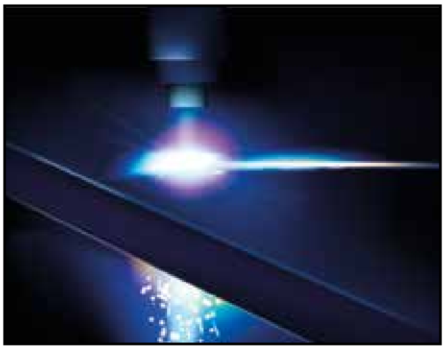
SGB-SMIT to launch €7.7 million ($10.3 million) takeover bid for Retrasib

Germany, Regensburg: SGB-SMIT has announced it will launch a takeover bid for 100% of the Retrasib Sibiu shares - Romanian power transformers producer.

According to the Bucharest Stock Exchange, the value of the offer will be €7.7 million ($10.3 million), reports Romania Insider.

SGB-SMIT reached an agreement with the main shareholders of Retrasib, Calin and Octavian Bozoianu, to buy their shares for a minimum price of €0.0768 per share. They hold 55.4% of the company and will get €4.3 million ($5.7 million).

Retrasib which is the main power transformers manufacturer in Romania, had a turnover of €9.86 million ($13.2 million) and a €470,000 ($626,980) net profit in 2013. *Source: Romania Insider*



Fraunhofer IWS develops new laser processing for electrical steel

Germany, Dresden: The Fraunhofer Institute for Material and Beam Technology IWS is developing new laser processing in order to reduce hysteresis loss in electrical steel.

„By heating selected areas of the material, it is possible to reduce the size of the domains with the same magnetic orientation, which in turn alters the magnetic structure of the steel.“ says Dr. Andreas Wetzig from the Fraunhofer Institute for Material and Beam Technology IWS.

„We have developed a means of deflecting the laser beam that allows the distance between the paths to be controlled flexibly and adapted to different parameters.“ reports Wetzig. The researchers make use of galvanometer scanners which consist of galvanometer driven mirrors attached to one end used to deflect the laser beam.

The researchers have also recently started working with a new type of solid-state laser: the fiber laser. The optimised process is currently being implemented by the first commercial customer. *Source: Phys Org*

Intertek launches TransoilCHECK - a global transformer oil testing service

United Kingdom, London: Intertek, a provider of services to a wide range of industries around the world, is launching TransoilCHECK.

It is a new global service testing transformer insulating oils and related liquids in transformers, other electrical devices, and power-grid infrastructure.

TransoilCHECK provides transformer oil analysis services to owners and operators in identifying potential transformer component failures. With a single point of contact for all transformer oil testing requirements, power generation and distribution operators are able to access Intertek's testing, consultancy advice, and test result interpretation. *Source: Intertek*

Rea Magnet Wire to launch new products - Nanoshield wire and MagneFlex

USA, Indiana: Rea Magnet Wire will soon launch Nanoshield aimed at the electrical and electronics industries. The company will also present MagneFlex® for customers in the transformer industry.

Nanoshield magnet wire is a three-coat system, consisting of a base coat of THEIC-modified polyester, a nano-particle shield coat and a polyamide-imide top coat. The smaller microstructure of the Nanoshield enamel allows particles to move as the wire is stretched and flexed.

For customers in the transformer industry, Rea Magnet Wire offers MagneFlex®, an advanced polymer-based magnet wire coating on an aluminum conductor. Rea Magnet Wire also offers CTC, a specialised multi-conductor cable, to customers in the transformer industry. *Source: CWIEME*

Courtesy of A-Line E.D.S.

Power Transformer

Part 3: Life management and extension

ABSTRACT

This article closes the *Transformer Life* series by looking at various ways that a transformer owner can extend the life of their investment.

From the initial stages of specifying and purchasing a transformer to the management of the transformer throughout its useful life, we explore which options have the best cost to benefit ratio and why.

KEYWORDS

power transformer, life, asset management, condition assessment, life extension, paper, insulation, cellulose

HOW LONG IS A TRANSFORMER SUPPOSED TO LAST?

In the first article in this series we defined what life means for a power transformer. In the second article we looked at the factors that most influence a power transformer's life.

In this, the third and last, article of this series we explore what options we have to manage and, as far as possible, extend the life of these important assets in your system.

Before we delve into what you can do to extend the life of a transformer, we need to agree on how long it is supposed to last.

As we have discussed, the life of a particular transformer depends on many factors, some of which are unpredictable in nature. In most circumstances there is not enough information to accurately predict the remaining life of a particular unit with any significant confidence. Current national and international standards and publications [1],[2],[3] and [4] favour the definition of life in "per unit" terms.

However, enough statistical data might be available in a particular system to be able to ascertain an estimated "average" life for a transformer in that system. In my own experience an average life of 35 to 40 years is a reasonable number to be expected for transformers manufactured before the 90s and working under nominal conditions with some transformers, in very isolated cases, reaching into the 70 to 100 years of age mark [5].

So, if a transformer is to last 40 or more years of active service, what can you do

> **So, if a transformer is to last 40 or more years of active service, what can you do to give it the best chances to do so?**

Life

to give it the best chances to do so?

THE LIFE CYCLE VIEW OF LIFE EXTENSION

We might be tempted to think of the term *life extension* as something that is executed towards the end of the life of the asset in an attempt to extend its life.

In my opinion this would be a very short-sighted view of the topic. In my view, life extension starts before the transformer is even manufactured. A holistic view of the complete life cycle of the unit will allow making the right decisions and putting the appropriate measures in place at every step of the way, from purchasing to disposal of the asset.

Just as with our own life and health, the most effective way of preventing a premature death is with prevention more than remediation. In the case of transformers this is not only logical, but considerably less costly.

On a dollar (or the applicable currency used in your country) per year of service of a particular asset, investing in prevention is almost always the wisest decision.

In the remaining sections of this article I will lay out what I think are the most important actions you can take to maximise the benefit that you get for your investment.

SPECIFYING AND PURCHASING

A good start in life leads to a good performing transformer during operation. By investing the time and resources in correctly specifying and sourcing the transformer most suitable for your application, you will save an incredible amount of money in the long run and a lot of headaches to your operations and maintenance team.

A properly documented specification that adequately reflects your needs is essential to ensure that you are getting the right asset for the intended function. In many instances I have seen asset owners and buyers contempt with buying transformers that merely stick to the existing standards. While standards should be the starting point of any specification, they are certainly not sufficient in most cases. In my opinion, standards are just the bare minimum that a transformer should comply with. By their very nature, standards cannot cater for the specific requirements that you might have in your specific operational context and circumstances.

Buying a transformer that simply meets the standards is like buying a car only specifying that you want it with an engine, a body and four wheels. Well, maybe I am exaggerating a little bit, but my point is that you are likely to require certain characteristics in your transformers that are not listed or spelled out in the standards and that you will need to be explicit about when requesting a new unit. Things like specific types of bushing terminals, connection boxes, control wiring and protective devices are but a few of the elements of your transformer design that you might want to stipulate to ensure compatibility with your environment.

A well crafted specification will also allow you to compare apples to apples when evaluating offers from various manufacturers. The best way to avoid unexpected outcomes is to be explicit about what you want.

MANUFACTURING

You have now ordered a new unit with a proper specification and from a manufacturer you feel comfortable with. Well, the next step is building the transformer.

> **Life extension starts before the transformer is even manufactured**

A good manufacturer is made up of many small details that add up to a properly built and good quality finished transformer. From the quality of the raw materials, to the expertise and skill of the people manufacturing these machines, to the attention to detail on every step of the manufacturing process, it all counts.

The process of building a transformer is complex and hand-labour intensive where a lot of things can go wrong. In fact, almost always something will not go exactly as planned. In essence you will want to associate with a manufacturer that is not shy in acknowledging and correcting the issues that will inevitably arise during the manufacturing process. When I was working as a service engineer for a transformer factory, a client once told me that he measured the manufacturer's quality not only by the number of issues they had but also by how they responded to them.

In the realm of client to manufacturer relations each company will have its own preference in how these are handled and I do not intend to give you an opinion one way or the other. Some customers prefer a pre-approval process to select the manufacturer or manufacturers with whom they plan to establish a long term relationship. Others prefer to witness key milestones at the factory during the manufacturing process like tanking or final testing.

My point is simply that it is in your best interest to ensure that you have a mechanism to guarantee that the manufacturing quality of your transformer is adequate and the final product fulfils with your expectations.

INSTALLATION AND COMMISSIONING

Most power transformers of a certain size and above are like flat-packed furniture - some assembly is required.

The level of assembly required varies with the size and manufacturer of the transformer. In some cases it is only necessary to fit a few of the components like radiators and conservator tank and then "top up" the oil. In other cases a full assembly is required that finishes with the vacuum dry-out and hot oil-fill process.

> **Buying a transformer that simply meets the standards is like buying a car only specifying that you want it with an engine, a body and four wheels**

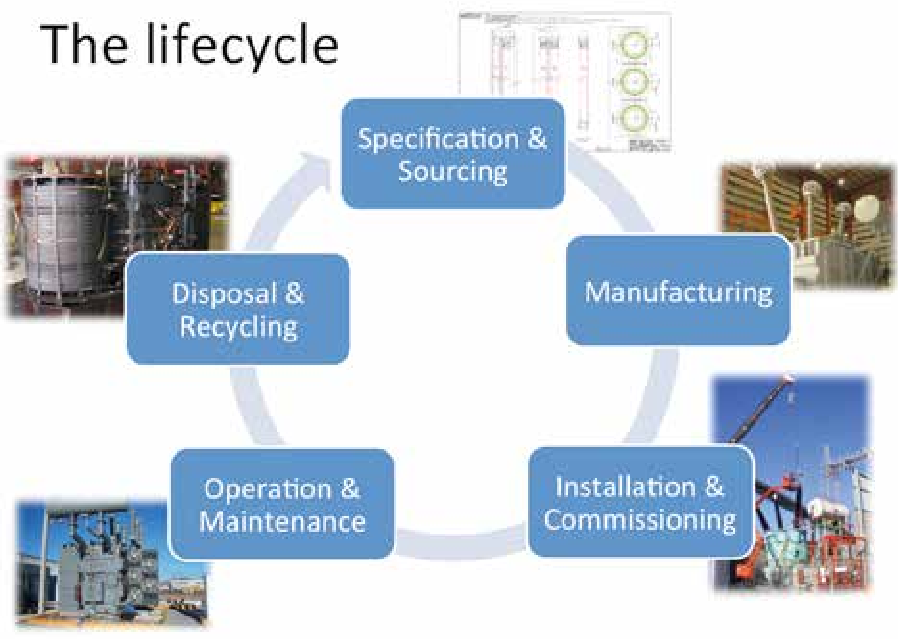


Figure 1: Typical transformer life cycle

In any case, executing the assembly procedure according to the manufacturer's recommendations will not only insure the unit is put together properly but also ensure your warranty is in full effect by the time the unit is placed in service. There are many factors that need to be taken care of during the final field assembly of the unit. You would want to ensure that a qualified team of techni-

Figure 3: Good quality coils are essential to ensure the longevity of your transformer

Figure 2: Different environments require different specifications

It is in your best interest to ensure that you have a mechanism to guarantee that the manufacturing quality of your transformer is adequate and the final product fulfils with your expectations

cians perform this assembly. Investing in the right service provider at this stage will increase your chances to avoid issues like oil leaks or any other type of assembly related malfunctions after energising the transformer.

It is at this stage in the life of a transformer that the initial moisture level in the insulation system is established. It might be tempting to take shortcuts in this process. Sometimes the dry-out might take days to bring down the moisture to acceptable levels (typically 0.5% by dry weight). But if you remember from the second article in this series, water is one of the main catalysts that accelerate the ageing processes of the solid insulation of the transformer. Saving a few days or even a few hours of work at this stage has the potential to reduce the life by years in the long run. The economy is simply not there unless you want to operate your plant on a very short term basis.

OPERATION AND MAINTENANCE

Since this stage in the life of a transformer is the longest (or at least it is supposed to be) much of your attention and day-to-day efforts will be spent in maintaining the unit in an adequate condition.

If I attempted to summarise what I think you should focus your preventive maintenance efforts on during this period, I would point out the following:

- Keep the transformer dry. As we have mentioned a few times already, water is one of the main ageing accelerating factors. In order to keep the transformer dry, you would want to ensure that there are no oil leaks (if oil can come out, moisture can come in). You will want to make sure that whatever the oil preservation system is, it is operating as the design intended. If silica gels are used, they should be dry and with enough capacity to dry the air that the transformer breathes. If diaphragms are used to separate the oil in the conservator tank from the ambient air, you want to make sure they are in good condition and free of ruptures. If automatic nitrogen equipment is used, it should be kept in good working order, with sufficient nitrogen in the supply and with the regulating system always ensuring the adequate positive pressure in the nitrogen chamber. In summary, ensure that water does not find its way into the coils of the unit.

- Keep the oxygen to a minimum. Similar to the point above, you would want to minimise the exposure of the oil to oxygen which obviously accelerates the oxidation processes in the transformer. The same recommendations given above to keep the water out of the unit are applicable to keep the oxygen out, although in some cases, like a conservator tank without diaphragm, it is not always possible.

- Ensure nominal operating conditions. As we also talked about, temperature plays a major role in the ageing processes. The unit is designed to operate within a certain temperature range and the more you can do to keep it within that range, the better chances you are giving the unit for a long useful life. Situations like overloading are sometimes unavoidable and in these cases, there are clear guidelines available in the technical literature to allow you to estimate the impact of overloading in the life of a particular transformer. On maintenance basis, you can help by ensuring that the cooling system is operating adequately and that the top oil or

Saving a few hours or even a few days of work at the initial stage has the potential to reduce the life by years in the long run

winding hot spot temperature has not reached alarm levels. If you find that this has happened, you need to investigate the root cause so you can address it as soon as possible.

Now, what if you are not the person that has watched the transformer its entire life and you just got handed over a fleet of old transformers to maintain? (Hard to imagine right?). In this case you are in corrective maintenance territory and the best course of action, in my opinion, would be:

- Establish the condition of each unit in your fleet. You have many tools at your disposal for this purpose. Try to gather as much information as possible on each unit and establish an effective information storage and retrieval mechanism. Include oil analysis history and any other test and inspection performed on each transformer. This information will allow you to establish a preliminary condition ranking for each asset in the fleet.

- Once the above has been established, you will have a clearer idea of which units are priorities and which units can wait.

- Depending on the state of each unit, a number of actions can be taken in order to ameliorate the current condition or remove some of the agents that might be causing the accelerated ageing.

- The oil can be processed to remove water and acids, which contribute to the ageing processes.

- If any, more serious, failure modes are suspected, these need to be addressed on a case by case basis until you have satisfied the risk management policies of your company and you are aware of the situation of each unit.

Last but not least, an adequate condition monitoring programme is essential to give you as much reaction time as possible if a failure mode starts to affect any particular transformer.

The condition monitoring method most commonly used is oil sampling and analysis. The analysis of the oil is a well established technique that allows the early detection of incipient failures in the transformers.

A suitable condition monitoring strategy will minimise the probability of unexpected failures occurring and therefore minimise the overall operational risk of your transformer fleet.

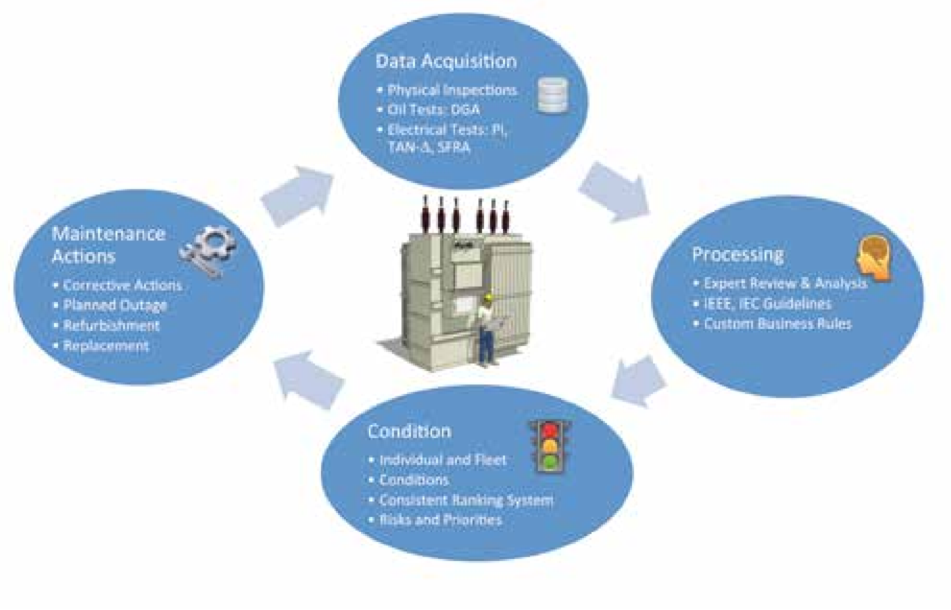


Figure 4: Example of a condition monitoring and maintenance programme

CONCLUSION

This brings this article series to a conclusion. Through the series we discussed some of the concepts that help to understand what transformer life is, what determines its duration and what actions you can take to extend it as much as possible. The topics covered in this series are vast and I have inevitably had to reduce them to their fundamental concepts. I hope that in doing so I have not made them unintelligible, boring or too simplistic.

For the readers who are interested, there is plenty of literature to consult to become acquainted in depth with each of the subjects covered here.

Our industry is a specialised one and it is a great privilege to have the opportunity to communicate some of my experiences and ideas to my colleagues and friends around the world.

I now will start thinking about an interesting topic for the next article. I hope that you have enjoyed reading this series as much as I have enjoyed writing it.

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Preventive maintenance efforts should be focused on keeping the transformer dry, keeping the oxygen to a minimum, and ensuring nominal operating conditions.

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Author

After graduating in Electrical and Mechanical Engineering in 1996, Carlos started working as a Transformer Design Engineer at PROLEC-GE, the biggest transformer factory for General Electric on the American continent.

Over the course of the following years, he gained expertise working in various roles such as Product Development, Manufacturing Improvements, Technology and Software Development, Field Engineering and Customer Service.

In early 2007, Carlos was seconded by General Electric to move to Perth, WA to start up the Transformer Division to provide field and workshop maintenance and repair services to customers across Australia.

Having fulfilled this mission, in early 2011, Carlos accepted a Principal Consultant position with Assetivity, a consultancy firm leader in Asset Management.

In early 2013, he moved to TxMonitor, part of MM Group Holdings, where he currently works as a Principal Consultant and Product Manager in developing innovative solutions for the electrical asset management industry using both his technical and business acumen.

30 Years of Experience in Power Transformer Testing and Diagnostics

Interview with Dr. Michael Krüger, OMICRON electronics GmbH

TM: Mr. Krüger, thank you for your time and interview. I am sure it is not easy for you at the moment as you are attending the CIGRE 2014 conference in Paris. How do you see this conference?

MK: Well, you must know, the CIGRE takes place only every 2 years. It is one of the most important central conferences in the field of high voltage electricity which leading experts and decision makers attend regularly. First of all, I expect, of course, some interesting conversations, new contacts and drivers for the future. I am currently working in five different CIGRE working groups on the topic of transformers. And some of these working groups use the conference's off-peak times to meet and discuss concepts and ideas for the future. That's another important reason for me to attend this conference.

TM: What do you think are the major things that came out of this year's conference?

MK: A striking number of papers in this year's agenda deal with the 'Health Index for Power Transformer'. This is obviously an important topic of current interest and it is also interesting for me - one of my working groups has the same focus.

TM: How did you become a member of the CIGRE and what benefits do you see in being a member?

MK: I became a member of CIGRE through the working group A2.26 'Mechanical Condition Assessment of Transformer Windings using Frequency Response Analysis' (FRA). If you work in such a working group, it is usual to be a personal member of CIGRE. The publications they produce, especially the brochures, are really useful. Every working group aims to put together a brochure on their topic. If the working group has the right members, including leading experts, their experience and expertise is influential in producing brochures of a high professional standard. Members can download the brochures and many other trade publications from www.e-cigre.org free of charge.

For example, the working group A2.26 published the FRA brochure 342 in 2008, whose findings formed the basis for the new IEC norm 60076-18 established in 2012. The standardisation of the FRA method has resulted in becoming mandatory when carrying out final testing of transformers in the factory.

TM: You have been working in the power supply industry for a long time now. Looking back, what has changed the most over that time?

MK: I have been in the industry for 35 years and the biggest changes have been brought about by the arrival of computers as well as better calculation methods of electric equipment and above all, by new electronic measurement procedures which were previously unimaginable. Meanwhile, there is an increasing change from time-based to condition-based testing and permanent online monitoring. This is exciting for working on new approaches and, thus developing new test systems.

TM: Could you give an example?

MK: Sure. Have a look at partial discharge (PD) measurements. It is something that has been around for many years. I carried out my first PD measurement in 1977 with a SIEMENS radio interference voltage (RIV) measuring device. If I compare that with our MPD 600 and its software today, they are worlds apart. Especially considering that you can now make sensitive PD measurements even in areas with high electromagnetic interference as you might find in a substation.

Monitoring systems have undergone a lot of changes too and are used more and more. That also affects diagnostics measuring on site. Offline diagnostic measurements are now often only carried out when the monitoring systems show abnormal readings.

For example, through a DGA (dissolved gas analysis) system, we were able to detect raised hydrogen levels in a transformer. This often indicates a presence of PD. At the same time, the PD monitoring system also allowed us to detect and confirm strong PD activities around 2 bushings. To investigate further, a PD localisation was carried out with our PDL 650. We were able to locate the faults. Therefore, we could also reduce repair costs as we directly knew where to attempt for repairs.

TM: Looking back, what was the most interesting case/measurement you dealt with in your career?

MK: To be honest, I was just lucky that I came across so many exciting jobs. I can't actually bring any particular job to mind. In my life, I have tested a lot of different electrical assets. First it was GIS switchgear systems, then instrument transformers, then high voltage cables and at OMICRON, it was transformers, rotating machines and other equipment. The broad experience certainly stands in my favour these days. A lot of problems and phenomena repeat themselves. For example, sonic runtime measurements to detect faults in cables and transformers, to recognise patterns in PD faults, etc.

TM: This explains generating ideas on new approaches for carrying out electrical measurements. Tell us more about how you implement newly generated ideas into real testing devices?

MK: Those sorts of ideas aren't conceived sitting at a desk. You only actually get an inspiration like that from customer visits and by really listening to customers and their unsolved problems. If you're in the business for so many years, you're sometimes more likely to have an idea about how to solve a particular problem. Experience and gut instinct help you to better judge whether a solution promises success or not.

What I find really important are practical attempts that can quickly show you whether a new method of measuring is doable or not. I often find that making an attempt with a simplified test assembly gets me further in half a day than long theoretical calculations. A good basic education and a solid theoretical knowledge is needed, otherwise you'll proceed without a plan and get frustrated. At OMICRON, 'innovate with passion' stands for the development philosophy as well as for a clear expectation about the results. It's great to have such an environment with the time and the possibility for trying out new things.

TM: Tell us how long have you been with OMICRON and how have you contributed with your work?

MK: I was very lucky to start at OMICRON in 1999, and then had the opportunity to help to build up a second business area for OMICRON. At that time, OMICRON was already very well established in testing technology for protection relays. With my knowledge and experience I was able to help develop testing and measuring technology for transformers and other „primary" electrical equipment. This was the birth of the CPC 100, a multifunctional primary test system for electrical diagnosis. For the time being, we have two business units. The first one is for secondary testing technology and measuring equipment that also deals with testing communication technology in power stations and substations. The second business unit focuses on technology used for testing and diagnosis of primary electrical equipment like transformers, rotating machines, instrument transformers, GIS switching stations, circuit breakers and more.

TM: How have you managed to develop new testing methods over the years?

MK: I'll give you an example. The CPC 100 device was an important step in the right direction for us. Thanks to the amplifier technology used, we were able to develop new testing methods. Measuring the dissipation factor in a wide frequency range helps to assess the insulation condition, for example detect whether the cellulose or the oil is contaminated by moisture. This method is now established and recognised. It's surely a good sign when your competition copies you.

TM: I see you really enjoy working there. Where does it come from?

MK: Well, that's easy to say. During these 15 years, I have been able to work really independently, being accountable to myself. I was able to offer and realise a lot of ideas. It has been incredibly fun to see how everyone works together and how one idea has formed the basis of a new business unit. This business unit increased more and more and many other test systems followed. Today that makes up a substantial part of the company's entire success. For a number of years now, I have been increasingly focused on the application of our diagnostic devices, which I enjoyed a lot. OMICRON employs many young people. It's nice to be able to pass on my knowledge. Especially when they value the knowledge and it is fostered by the company.

TM: How is OMICRON different as a global player in comparison with its competitors?

MK: Apart from the high quality of our devices, our own applications expertise in primary testing has always been and remains very important. I currently see it as my most important task to further build on and develop the team's expertise as well as their applications experience. This expertise, a strong commitment and the best possible customer support in using our devices clearly sets us apart from our competition. We offer our customers worldwide 24/7 support and a large customer area on our website, where customers can download all of the latest software versions or interesting papers and applications notes free of charge. In addition, a special user forum is provided, where customers can post and discuss current testing issues.

TM: How do you achieve customer satisfaction?

MK: Expertise and support are not really enough. It is also important to us that the customer gets the best out of our equipment. Sometimes that means additional training or even guiding them through their first measurements. Customers should not only understand how to work with their test device, but also get a comprehensive knowledge about the measurement and application. In the end, they should also be able to assess the results alone and correctly.

In the meantime, almost not a single day goes by without OMICRON training taking place somewhere in the world. It is really important for establishing a relationship with a customer. We also host workshops and conferences both to pass on our knowledge and also to create a platform where our customers can meet with us as well as external experts to exchange their experiences. Another big area for us is taking part in relevant conferences and seminars that are not organised by OMICRON. I might have said it before, but taking part in the CIGRE and its working groups is also important. Thanks to our constant contact with the leading experts, we have by now built up a fantastic network of knowledge providers. Our customers also benefit from this network. For example, when evaluating results from measurements, we can also bring foreign experts in and get their opinion. This helps us in supporting customers and in responding best to their needs.

TM: What advice would you give to future electrical technicians?

MK: I think the most important thing that makes a good technician is curiosity and a desire to understand and further develop technology. When developing something, in most cases, there are setbacks. It doesn't just work out on the first go as you expect it to. A good technician doesn't give up at that point. It is important to learn from our failures and then try to achieve the goal through different means. Of course, a solid professional training is a fundamental requirement for being a successful technician. You also have to know how to listen and have the ambition to solve problems with your own, new ideas. For me, breaking new ground is like the first ascent on a mountain that is really hard to climb.

TM: What's coming up for you in the following months?

MK: I will be giving talks at many international conferences. Besides that, I am currently working on a new test system that should reduce the total weight of conventional devices by 90%. That is really exciting!

Mr. Krüger, thank you for your time and for agreeing to take part in this interview.

__Michael Krüger__ is Principal Engineer with OMICRON electronics GmbH in Klaus, Austria.

He studied electrical engineering at RWTH in Aachen and at the University of Kaiserslautern. He graduated with a PhD in electrical engineering at the Technical University of Vienna in 1990. Michael Krüger has more than 35 years experience in high voltage testing and measuring equipment. He has published a lot of papers about electrical measurement on high voltage equipment and holds more than 15 patents. He is a member of VDE, Cigre and IEEE and works in several working groups of OEVE, IEC and Cigre.

He is actively involved not only in the development of worldwide standard testing methods but also in OMICRON test sets. Through his extensive experience, great expertise and professional knowledge, he delivers valuable insights to the market.

Tank depressurisation

ABSTRACT

This paper analyses the activation of two mechanical depressurisation devices, the transformer protector (TP), a leading example of a fast tank depressurisation technique (FTDT) and the pressure relief valve (PRV) during an internal arc on a transformer installed at the JSC RusHydro Boguchanskaya Hydro Power Plant, located in Krasnoyarsk Krai, Russia. The incident occurred on a 400 MVA three phase transformer on the 3rd May, 2013. Using all the available data, including SCADA records, dissolved gas analysis and voltage/current measurements, computational simulations were performed to study the dynamic pressure evolution and static pressure build up inside the tank. Simulation results on tank protections were analysed in the context of general arcing events. This incident demonstrates that the first dynamic pressure peak due to the arc quickly activates the FTDT, while the PRV activates with static pressure only.

KEYWORDS

tank depressurisation, transformer protector, pressure relief valve, computational fluid dynamics (CFD)

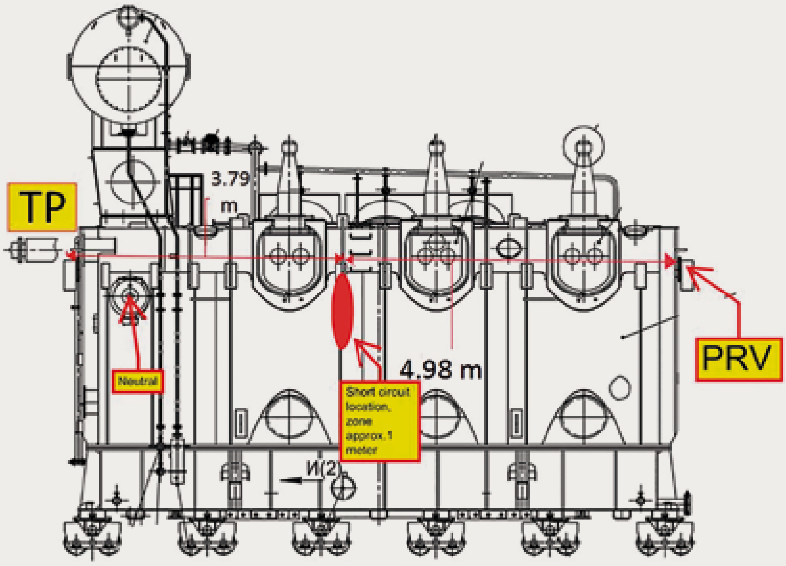
Successful operation during short circuit on a 400 MVA transformer during operation and comparison of parameters recorded during transformer internal arcing event with computational simulations

Introduction

On the 3rd May, 2013, a fault occurred on a transformer installed at the JSC RusHydro Boguchanskaya Hydro Power Plant, located in Krasnoyarsk Krai, Russia. The incident occurred on phase B of the transformer T2 which is a three-phase transformer manufactured on the 26th June, 2008, and in operation since the 11th May, 2012.

T2 has a nominal capacity of 400 MVA but was operating at 360 MVA. A schematic of the transformer can be observed in Figure 1. Transformer T2 was equipped with a TP and a PRV. During the investigation, it was observed that the transformer differential protection, the Buchholz relay, the PRV, and the TP were activated.

> During the investigation, it was observed that the transformer differential protection, the Buchholz relay, the pressure relief valve and the transformer protector were activated



Analysis of the event

A) SCADA

According to the SCADA data in Table 1, the transformer differential protection registered a signal at 19:08:57.110 through a warning associated with its 220 kV windings. However, the transformer protector activation signal was first registered 27 ms prior. Because the TP activation must succeed the fault, the fault is estimated to be at 19:08:57.078, roughly 5 ms prior to the TP activation. Therefore, the transformer differential protection signal was registered 32 ms after the estimated fault origin. The PRV activation signal was detected 71 ms after the estimated fault origin. Finally, the circuit breaker fully open signal was detected 97 ms after the estimated fault origin.

Due to some contradictory data between the oscillograph voltage and current measurements and the SCADA described in the 'Short circuit energy' section of this paper, we have doubts regarding the ability of the SCADA to timely follow all events.

Table 1: SCADA list of events

Time	Events	Pressure Calibration	Time after estimated short circuit origin (milliseconds)
19:08:57.078	Estimated Short Circuit Origin (Currently Under Investigation)		0
19:08:57.083	**TRANSFORMER PROTECTOR ACTIVATION**	**1.2 bar Atmospheric, 17.63 psi**	**5**
19:08:57.110	Transformer Differential Protection		32
19:08:57.149	Pressure Relief Valve Operation	0.8 bar Atmospheric, 11.75 psi	71
19:08:57.175	Circuit Breaker Fully Open		97

Observed failure traces helped to locate the short circuit in the B phase of the high voltage windings. The arc length was estimated by the transformer manufacturer to be 1 m long by locating burnt sections of the windings

B) Short circuit location

The short circuit location was identified, among other factors, by burnt cardboard insulation (Figure 2) as being associated with the B phase of the high voltage windings (Figure 3). The arc length was estimated by the transformer manufacturer to be 1 m long by locating burnt sections of the windings.

Figure 2: Burnt cardboard insulation

Figure 3: Location of short circuit

Dissolved gas analysis

In Table 2, we see the dissolved gas analysis for the transformer T2. Using the data associated with the date 03.05.13, we may characterise the fault.
The DGA suggests that the arc may be classified as D2, which corresponds to a high energy arcing event. Because the lines do not strictly intersect, further validation would be useful. An alternative classification system, known as the Rogers' Ratio, is defined in an IEEE standard, shown in Table 3 [1].

Based on Tables 2 and 3, we determine the following gas ratios:

$$\frac{C_2H_2}{C_2H_4} = R_2 = 0.8326 \qquad \frac{CH_4}{H_2} = R_1 = 0.6089 \qquad \frac{C_2H_4}{C_2H_6} = R_3 = 5.241 \quad (1)$$

Table 2: Dissolved gas analysis for transformer T2

Analysis date	H2 Hydrogen	CH4 Methane	C2H4 Ethene	C2H6 Ethane	C2H2 Ethyne	CO2 Carbon Dioxide	CO Carbonic Monoxide	O2 Oxygen	N2 Nitrogen	Total gas content
Boundary Concentration %	0,01	0,01	0,01	0,005	0,001	0,2	0,05			2
28.1.2013	0,00024	0,00004	0,00002	0,00003	Absent	0,0066	0,0028	0,0147	0,3204	0,34
3.5.2013	0,0777	0,04731	0,0873	0,00818	0,07269	0,0132	0,0161	0,0901	1,749	2,16
Relative Concentration	6,96	4,24	8,49	1,62	68,26	0,02	0,26			
V Relative % Month	9880	36176	133592	8316		31	147	157	137	

Gas Concentration %

Table 3: Rogers' Ratio interpretation method

Case	C2H2/C2H4 (R2)	CH4/H2 (R1)	C2H4/C2H6 (R3)	Suggested Diagnosis
0	R2 < 0.01	R1 < 0.1	R3 < 1.0	Normal
1	R2 >= 1.0	0.01 <= R1 < 0.5	R3 >= 1.0	Low Energy Discharge
2	0.06 <= R2 < 3.0	0.01 <= R1 < 1.0	R3 >= 2.0	High Energy Discharge
3	R2 < 0.01	R1 > 1.0	R3 < 1.0	Low Temperature Thermal
4	R2 < 0.10	R1 > 1.0	1.0 <= R3 < 4.0	Thermal < 973 K
5	R2 < 0.2	R1 > 1.0	R3 >= 4.0	Thermal > 973 K

Interpretation of dissolved gases by Rogers Ratio method and Duval triangle indicated a high energy arcing event

Using Table 3, we may characterise the fault as a high energy arcing event. The IEEE standard defines arcing temperatures as being between 700 K and 1800 K. The confirmation from the Duval algorithm suggests that the temperature is near or in excess of 1800 K, Figure 4.

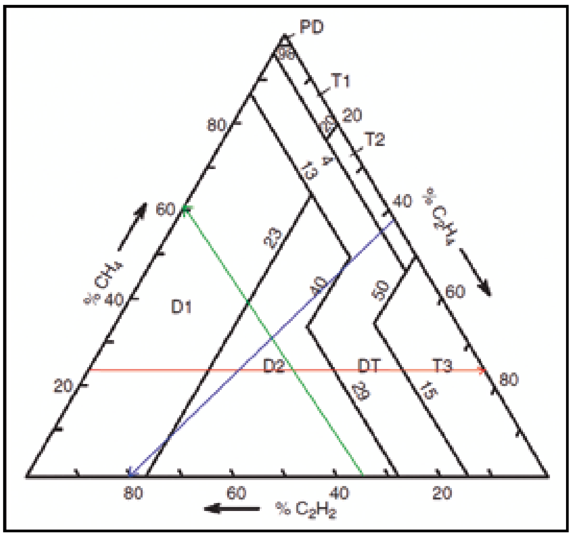


Figure 4: Duval triangle for dissolved gas analysis

Short circuit energy

The arc energy is defined in terms of the voltage (U), current (I), and time (t) as follows:

$$E = \int_0^T UIdt \qquad (2)$$

In Figure 5 we see the electrical measurements taken 2 ms prior to the short circuit. This information will be used as it is the closest set of measurements acquired to the fault.

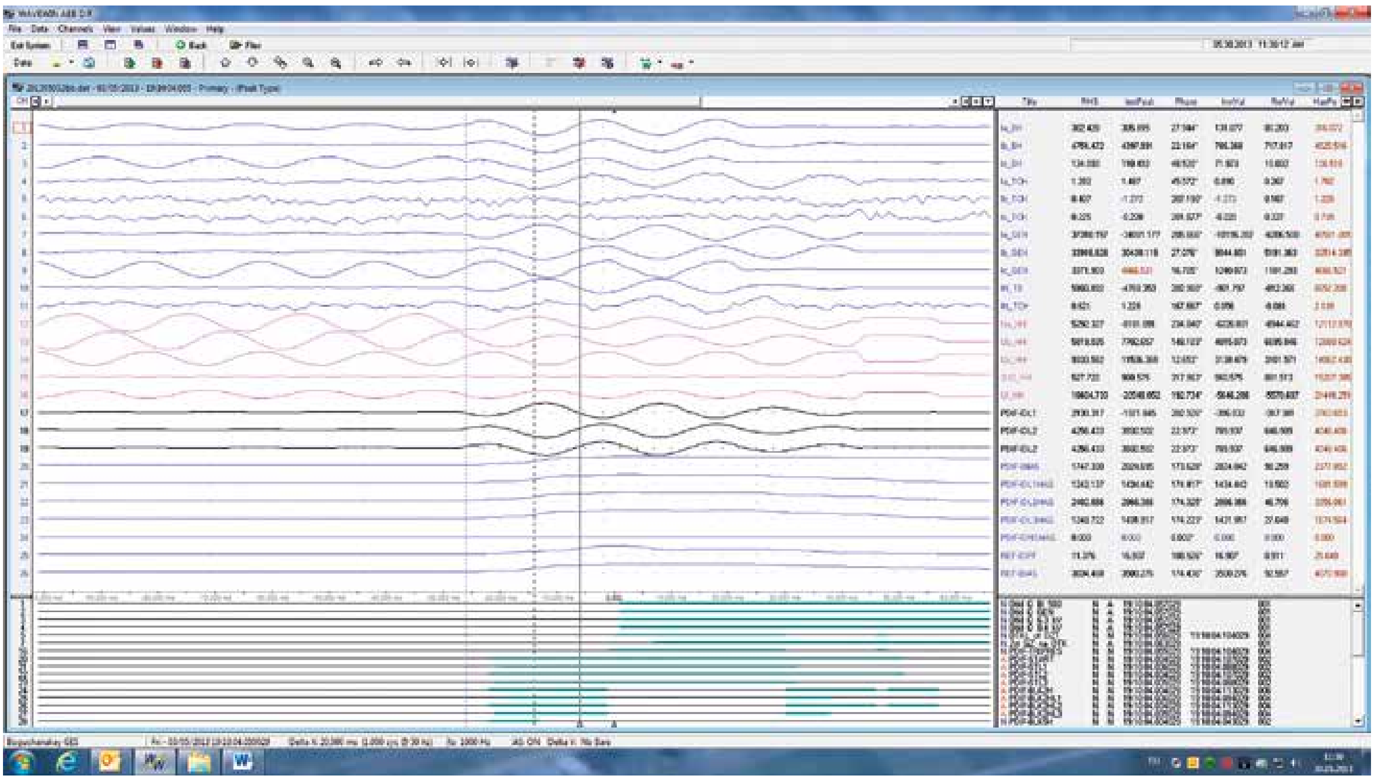


Figure 5: Display of electrical measurements during 2 ms prior to the short circuit

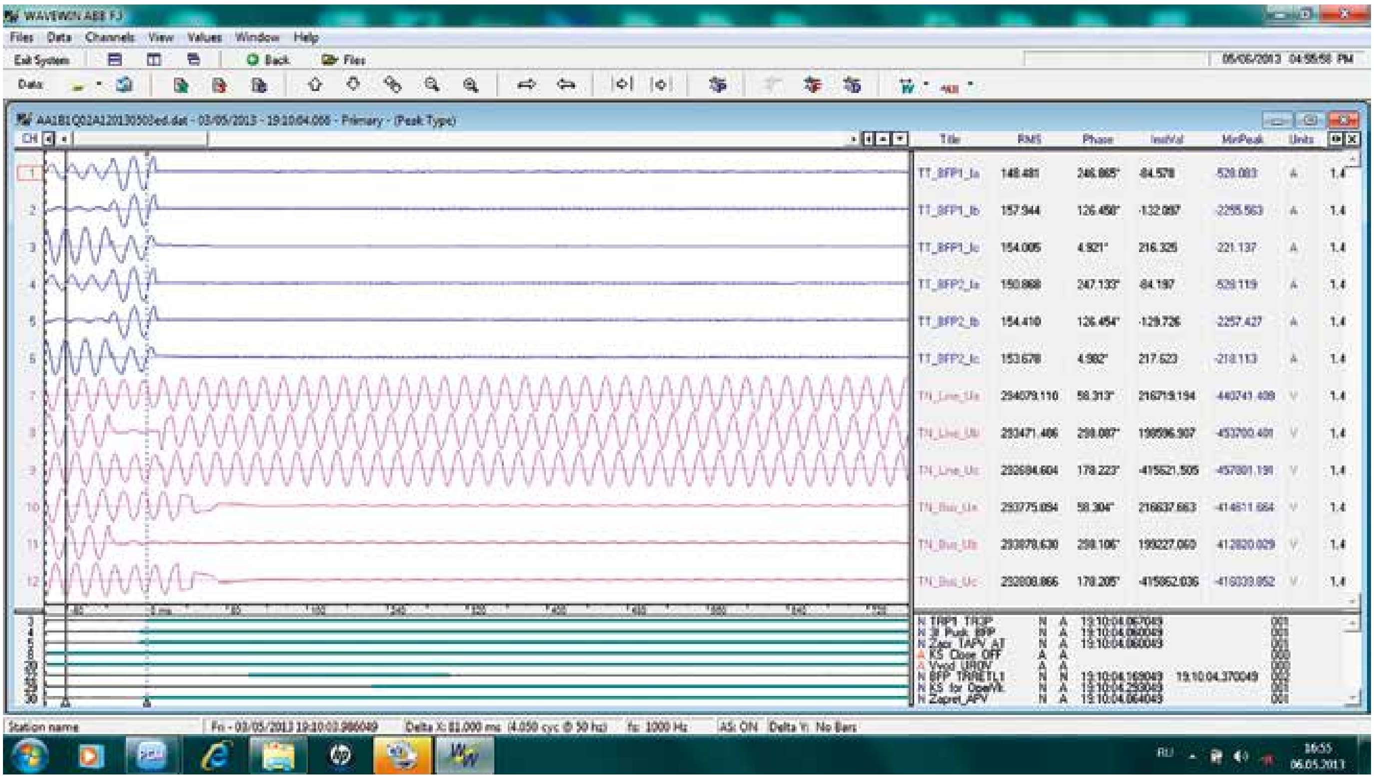


Figure 6: Display of electrical measurements in the short circuit

From this figure, the high voltage phase B current peak, Ib_BH, is 4.526 kA. From information provided by the transformer manufacturer, the maximum current on phase B is 4.492 kA. For the purposes of this paper, the short circuit current is assumed to be 4.5 kA. However, we are also interested in the voltage across the short circuit. These measurements include information on the low voltage side, Ub_HH, but not on the high voltage side.

One measured potential difference related to phase B of the high voltage windings is 31 kV. It is uncertain across which two points this potential is measured but let us assume that the two points correspond to the two terminals of the short circuit. Two possible situations are that it represents an RMS value or a maximum amplitude. If we assume that it is a maximum amplitude, the arc voltage is roughly 31 kV.

If this value is an RMS value instead, it can be assumed that the voltage across the short circuit is $31\sqrt{2}$ kV = 43.84 kV. Another set of measured potential differences is in Figure 6, where a line voltage associated with phase B has a maximum amplitude of 45.37 kV. This is consistent with the interpretation of the value being an RMS voltage. Let us therefore average these two values: 44.6 kV.

In this paper, we will consider both values, 31 kV and 44.6 kV. We remark that an empirical measure for the arc voltage in terms of arc length has been proposed [2]. This is shown in Figure 7.

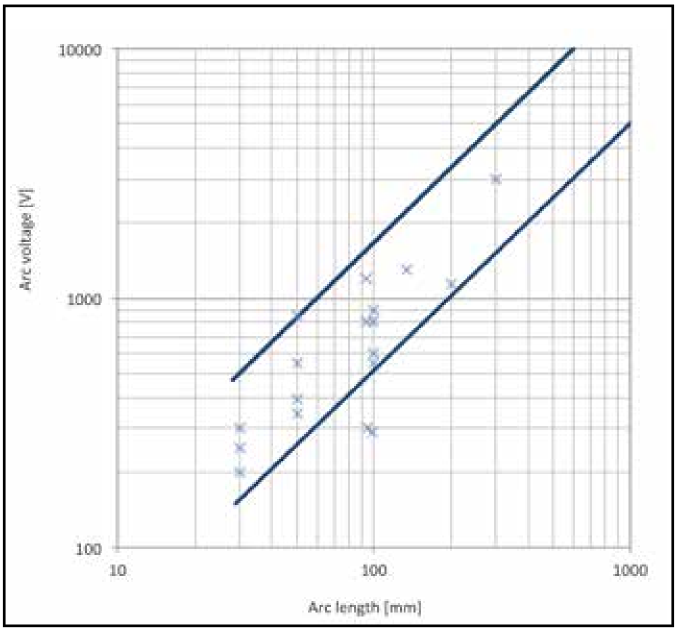


Figure 7: Relation between arc voltage and arc length

> **Data from SCADA system show the arc duration of 97 ms and oscillographs of the voltage and current measurements show the arc duration of 65 ms. The oscillograph data is considered much more reliable, hence the estimated arc duration was 65 ms**

Kawamura uses the upper bound as the more appropriate estimate for the arc voltage. For an arc clearance of 1 m, this implies a voltage of up to 16.66 kV. This is within the same order of magnitude of our values, however more consistent with the 31 kV value.

The SCADA is the electrical output detailing diagnostic events for the transformer. In Table 1 we see a subset of the SCADA data pertaining to critical events. Using this data, we identify the arc duration, the difference between the circuit breaker fully open signal and the estimated fault origin to be roughly 97 ms long. However, the oscillograph of the voltage and current measurements indicate that the arc duration is 65 ms. Because the sampling frequency of the SCADA will be of much lower resolution than the sampling frequency of the oscillograph data, the oscillograph data is considered much more reliable. Therefore, we will use the 65 ms figure to represent the duration of the arc.

We will assume that the stated values for the peak amplitudes of the arc current and voltage are constant across this arc duration and that the voltage and current oscillate at a 50 Hz frequency (f).

The AC current and voltage can be described as proportional to sin $(2\pi f t + \varphi)$, where φ is the phase. It is difficult to determine the precise phase of the voltage and current at the beginning of the arc. This paper assumes that both the current and voltage start at a phase of 0.1 radians (therefore, approximately 10% of its maximum value). Using equation 2:

$$E = I_{\max} U_{\max} \int_0^T |\sin(2\pi f t + \phi)|^2 dt \tag{3}$$

Defining: $T = 65$ ms, $f = 50$ Hz, $\varphi = 0.1$, $I_{max} = 4.5$ kA, $U_{max} = 31$ kV, we arrive at the following arc energy:

$$E_{\text{low}} = 4.578 \text{ MJ} \tag{4}$$

Alternatively, defining: $U_{max} = 44.6$ kV, we have the following value for the arc energy:

$$E_{\text{high}} = 6.586 \text{ MJ} \tag{5}$$

The arc energy may be somewhat larger or smaller than these values, depending on the phase of the current and voltage. We will use the higher energy of 6.586 MJ for all presented simulations as it is the worst case scenario, therefore the most problematic.

Generated gas volume

One paper uses a simplified set of reactions: as oil breaks down, H atoms CH_3 radicals recombine to produce gases such as H_2, C_2H_2, CH_4, and C_2H_4, given a gas temperature T [3]. The simplified model is shown in equations 6-8

$$H + H \rightarrow H_2 \tag{6}$$

$$CH_3 + H \rightarrow \frac{1}{18}(23H_2 + 7C_2H_2 + 2CH_4 + C_2H_4) \quad if\ T \leq 1500K \tag{7}$$

$$CH_3 + H \rightarrow C + 2H_2 \quad if\ T \geq 1500K \tag{8}$$

> **The arc energy was estimated by two methods as 4.578 MJ and 6.586 MJ. As the worst case scenario, the higher value was used in simulations**

At the CEPEL laboratory an experimental test campaign was performed on a series of transformers subject to internal arcs (11). These experiments have determined the following dependence for the relationship between the arc energy and generated gas volume:

$$V = \left(0.44 \ln\left(\frac{E}{\text{J}} + 5474.3\right) - 3.8\right) \text{m}^3 \tag{9}$$

Specifically, a 6.586 MJ arc produces a gas volume of 3.11 m^3 at standard temperature and pressure.

Rupture disc aperture

The top layer of the rupture disc is open at roughly 90% the maximum cross section, Figure 8. This result is consistent with a strong arc.

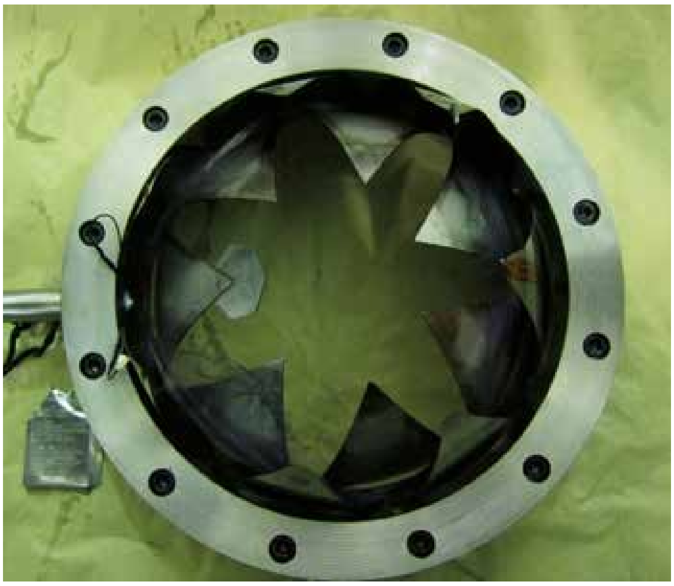


Figure 8: Rupture disc of the transformer protector

Computational fluid dynamics (CFD) simulation background

We are interested in modeling the propagation of pressure waves in transformer oil when subject to internal arcing events. Such phenomena are modeled as a 3D compressible two-phase flow, using a set of partial differential equations based on a 5 equation model developed in [4] and described in equations 10a - 10e. These equations represent the conservation of mass (ρ), momentum (ρv), and energy (E), as well as the advection of the volume fraction (α) for each phase. Source terms relating to gravity (g), viscosity (μ), and heat conduction (T) are added in the conservation equations to adhere to physical constraints.

> **The propagation of pressure waves in transformer oil when subjected to internal arcing events was simulated by computational fluid dynamics**

$$\frac{\partial \alpha_1}{\partial t} + \vec{u}.\vec{\nabla}\alpha_1 = 0 \quad (10a)$$

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho\vec{u}) = 0 \quad (10b)$$

$$\frac{\partial \alpha_1 \rho}{\partial t} + \mathrm{div}(\alpha_1 \rho \vec{u}) = 0 \quad (10c)$$

$$\frac{\partial \rho\vec{u}}{\partial t} + div(\rho\vec{u} \otimes \vec{u} + P) = \Phi_g^u + \Phi_\mu^u \quad (10d)$$

$$\frac{\partial E}{\partial t} + div\big((E + P)\vec{u}\big) = \Phi_g^E + \Phi_\mu^E + \Phi_T^E + \dot{E} \quad (10e)$$

This model was selected to accurately depict the pressure wave propagation inside liquids and gases. A finite volume algorithm is adopted to transform the system of differential equations into algebraic equations. The fluxes across cell boundaries are determined by the Godunov Riemann solver. The volumes are defined by an unstructured 3D mesh to allow a precise description of complex geometries such as transformer tanks.

The experimental test by CEPEL was simulated in order to verify the mathematical model developed for arc-induced dynamic pressure peak within transformers [5].

Originally developed and presented, HYCTEP (**HY**drodynamic **C**ode for **T**ransformer **E**xplosion **P**revention) is implemented as a hydrodynamic numerical tool for computational fluid simulations [6]. The mesh used to discretise the transformer geometry has up to 139,794 tetrahedral elements, and is shown in Figure 9.

The transformer oil and its vapour are represented as a stiffened gas fitted to the mineral oil dodecane (Table 4).

Included on the geometry are a TP and a PRV. The TP DC is 300 mm in diameter, and the PRV 150 mm. The PRV is set to open at 0.8 bars above atmospheric pressure, and the TP rupture disc opens at 1.2 bars above atmospheric pressure.

The arc parameters used in the simulation are listed in Table 5 and energy is injected using HYCTEP's arc model 4, which guarantees that the total power input is determined by the product of the voltage and current throughout the arc region.

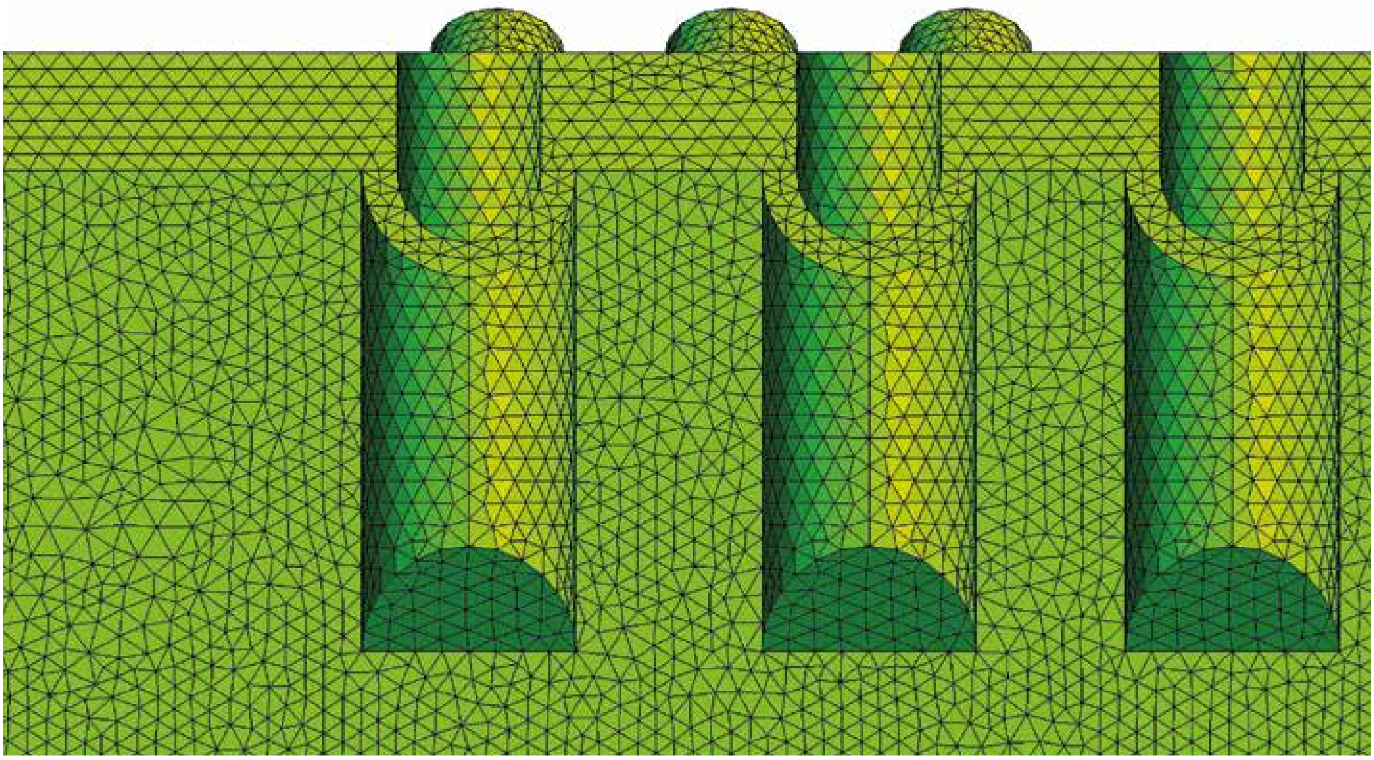


Figure 9: Transformer model in the hydrodynamic numerical tool for computational fluid simulations

Table 4: Fluid parameters for usage in simulations

	p_∞ (Pa)	C_p (J kg^{-1} K^{-1})	C_v (J kg^{-1} K^{-1})	γ	q (J kg^{-1})	q' (J kg^{-1}K^{-1})
liquid	4×10^8	2534	1077	2,35	-755×10^3	0
vapour	0	2005	1956	1,025	-237×10^3	-24×10^3

> **For the case of the transformer with both a transformer protector and a pressure relief valve, the average tank pressure first drops below the approximate static withstand limit of the tank (2.2 bars) after 125 ms**

Table 5: Arc parameters

Max Current	Max volatge	Duration	Phase
4.5 kA	44.6 kV	65 ms	0.1

The simulations were run for up to 900 ms with a time step of 10^{-6} s. Four cases were run:

1) The actual case where transformer T2 has both TP and PRV
2) T2 only has a TP
3) T2 only has a PRV
4) T2 is completely sealed

CFD simulation results

In Figure 10 the average tank pressure is visualised for the four simulated cases in the case of arc energy of 6.586 MJ. It can be observed that for both cases with a TP, the tank is rapidly depressurised. For the case of T2 with both a TP and a PRV, the average tank pressure first drops below the approximate static withstand limit of the tank (2.2 bars) after 125 ms.

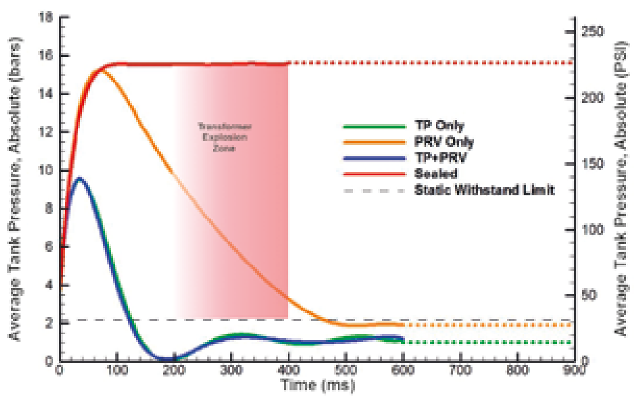


Figure 10: Average tank pressure for simulated cases with the arc energy of 6.586 MJ

In contrast, for the case with only a PRV, the average tank pressure does not drop below the static withstand limit until 461 ms, a duration more than three times as long as the case including the TP.

With neither a TP nor PRV, the average tank pressure approaches a steady state of roughly 15.6 bars, more than seven times the static withstand limit.

In Figure 11 we see the pressure evolution under the three most distinct cases. This figure reinforces our observations for Figure 10. The transformer with a TP only is safely below the static withstand limit by 150 ms in contrast to the case of the transformer with only a PRV and particularly the sealed tank.

Conclusion

A fault was identified in transformer T2, with a 400 MW capacity at the Boguchanskaya HPP, equipped with a TP. No permanent damage to the tank was observed.

Due to the dissolved gas analysis, the fault was identified as a high energy arcing event through the insulation. From observations of the current and voltage data, the energy of the short circuit is approximately 6.586 MJ.

Using this knowledge, we attempted to model the sequence of events through a CFD simulation. This in-house simulation tool is designed to model pressure wave propagation in a two phase compressible media. Observing burnt areas of the insulation allowed us to approximate the spatial extent of the arc. Using a schematic of the transformer, a mesh was generated to discretise the geometry.

Four simulation cases were run: 1. transformer T2 with both a TP and a PRV, 2. T2 with only a TP, 3. T2 with only a PRV, and 4. a completely sealed T2. The two cases including a TP behaved similar although the tank with both the TP and PRV depressurised below the static withstand limit by 125 ms. In contrast, the case with only a PRV did not depressurise below the static withstand limit until 461 ms. The sealed tank reaches a steady state of 15.6 bars, likely leading to a rupture.

We observe that the first dynamic pressure peak due to the arc quickly activates the TP while a sustained pressure for a duration roughly 14 times longer is necessary to open the PRV, which therefore activates with static pressure only.

We may conclude that the inclusion of the TP allowed the tank to depressurise very quickly, saving the transformer from explosion. This conclusion has been attested by RusHydro through a TP Successful Activation Certificate [7].

> **With neither a transformer protector nor pressure relief valve, the average tank pressure approaches a steady state of roughly 15.6 bars, more than seven times the static withstand limit likely leading to a rupture**

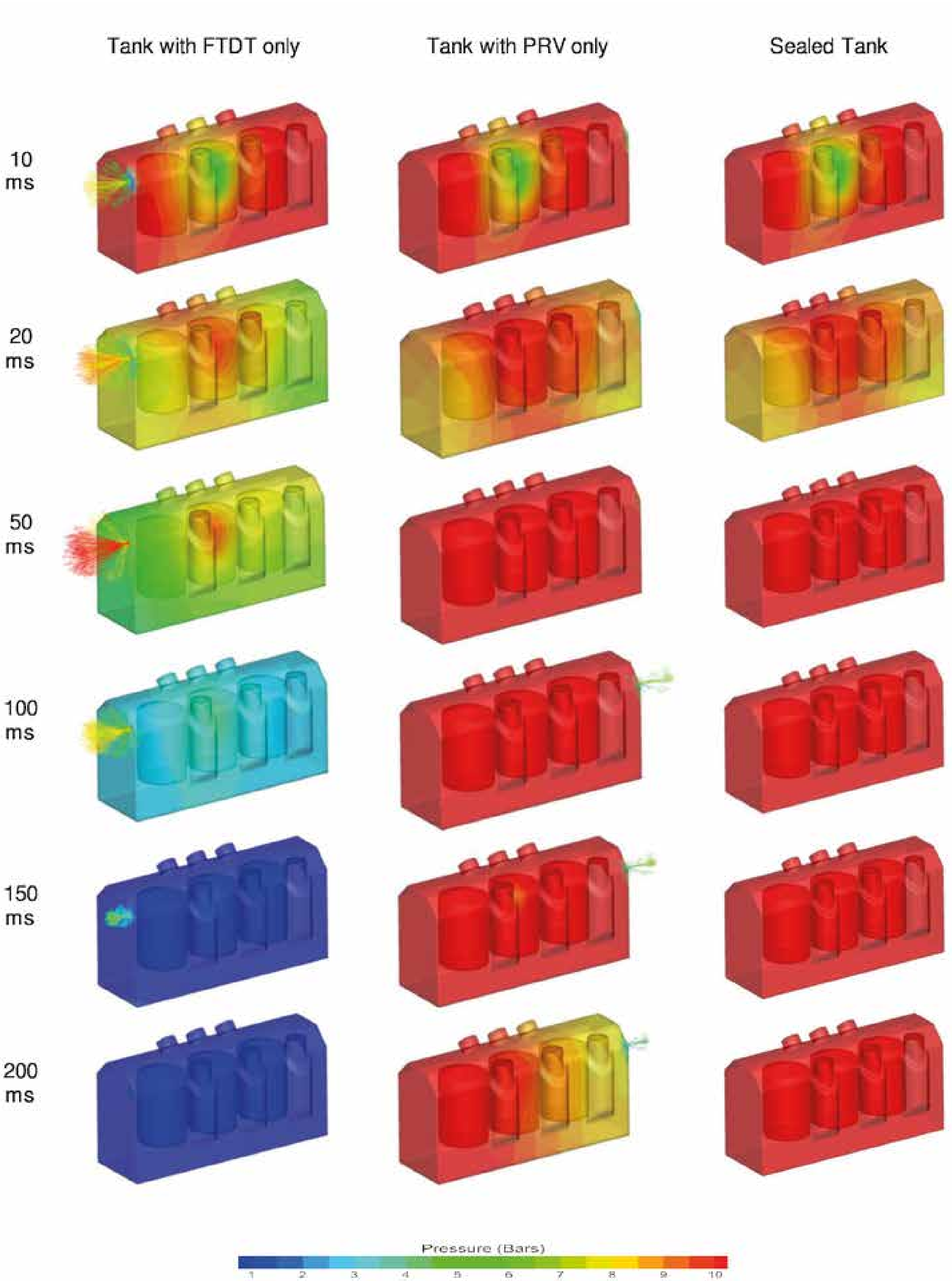


Figure 11: Pressure evolution in three most distinct cases

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Authors

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Courtesy of A-Line E.D.S.

Transformers with low degree of polymerisation of paper

ABSTRACT

Present observations indicate that the life of transformers with a degree of polymerisation of paper of 200 could be extended by several years without increasing their risk of failure due to the mechanical condition of paper, thus significantly reducing capital investment costs needed for their replacement.

KEYWORDS

power transformers, low degree of polymerisation (DP) of paper

Introduction

Abnormal faults are the main cause of failure of transformers in service as a result of transformer design (e.g., hot spots), manufacture (e.g., loose bolts), operation (through faults, overloading) or poor maintenance (e.g., high moisture, oxidised oil, leaking gaskets, corrosion, etc). Most electrical and thermal faults can be detected by dissolved gas analysis (DGA) in oil.

Paper insulation also slowly degrades during the life of transformers, more or less rapidly depending on their operating/loading conditions.
Owners of transformers with degraded paper are faced with a technical and financial dilemma:
- if they do not replace these transformers early enough, they risk unplanned failures, the cost of which may be very high, largely exceeding the cost of the transformer itself.
- if they replace them too early, even though they could still operate satisfactorily for several more years, this will markedly increase their capital investment costs.
Deciding on the optimum time to replace transformers with degraded paper depends very much on a correct evaluation of their risk of failure at various stages of paper degradation. Presently there is no agreement among transformer experts on this issue.

Abnormal faults are the main cause of failure of transformers in service. A DP of 200 is presently considered the lowest value acceptable in operating transformers in the industry

Degree of polymerisation of paper

The extent of paper degradation is represented by the degree of polymerisation or DP of paper.

New insulating paper has typically a DP of 1100 and a high tensile strength. This high initial tensile strength is needed to run insulating paper on the winding machines used to wrap it under tension around conductors without tearing it.

In transformers in service, DP decreases more or less rapidly, depending mainly on temperatures in the transformers and on other factors such as moisture, oxygen content and acidity of oil. The more degraded the paper is, the lower is its DP.

A DP of 200 is presently considered in the industry as the lowest value acceptable in transformers in service. It corresponds arbitrarily to paper having lost 60% of its initial tensile strength measured in the laboratory [1]. It has been assumed since the 1970s that below a DP of 200 paper is not able to withstand any more of the mechanical forces occurring in transformers, therefore that the transformers are going to fail imminently and have reached their 'end-of-life.' Another popular statement is that 'the life of the transformer is the life of paper.'

The accuracy of these assumptions and statements, however, has never really been demonstrated in transformers in service.

Determination of DP of paper

DP of paper can be determined:
- either by direct measurement on paper samples taken from transformers removed from service (e.g., in the bottom, middle and top of windings), paper samples are dissolved in a solvent and the viscosity of the solu-

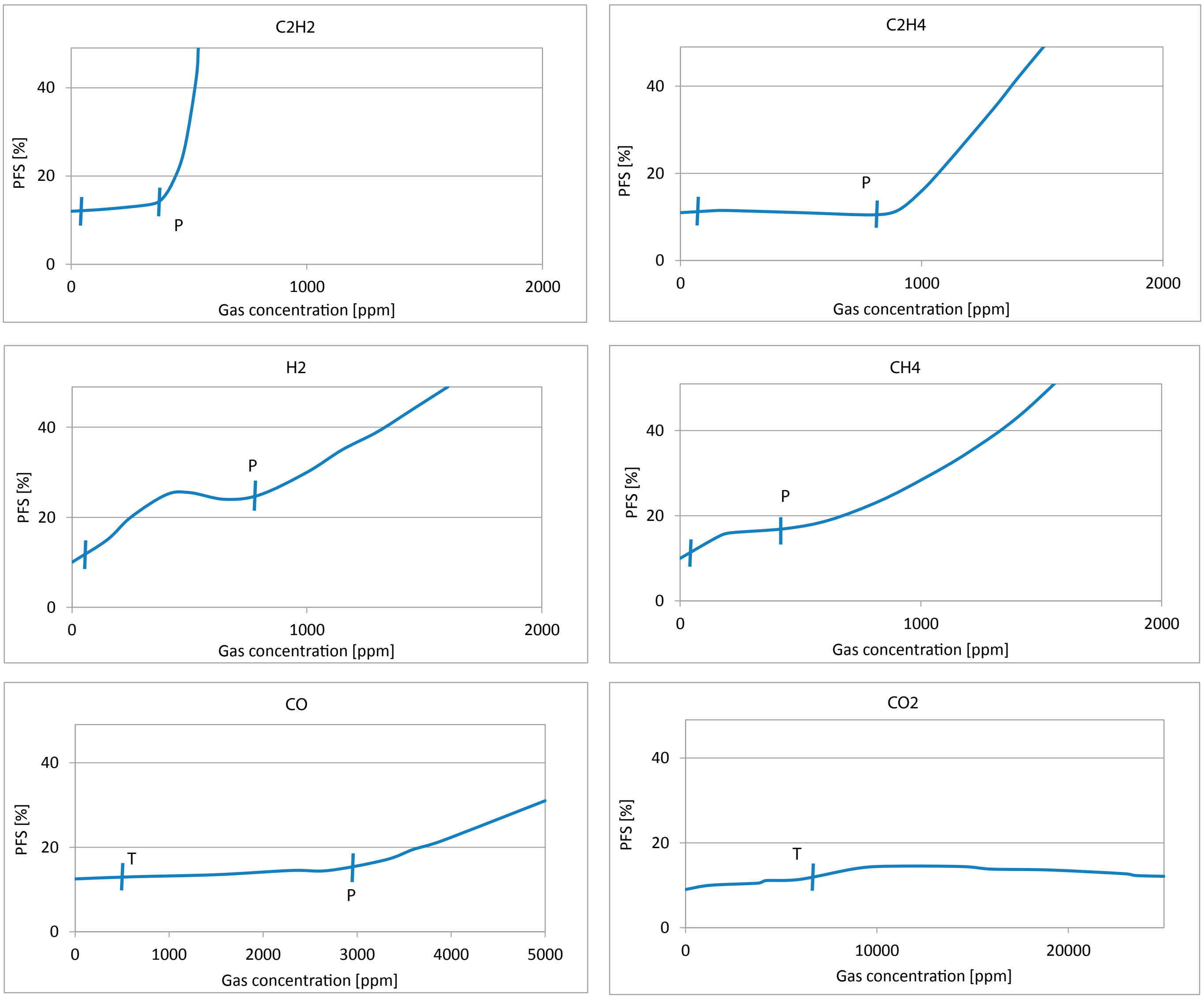

Figure 1: Probability of failure in service (PFS) vs. gas concentration

A large number of cases (more than 55) of transformers with DPs between 250 and 75 has been reported and still operating normally without failure. So far, no transformer failures due to mechanical failure of paper at low DPs have been reported

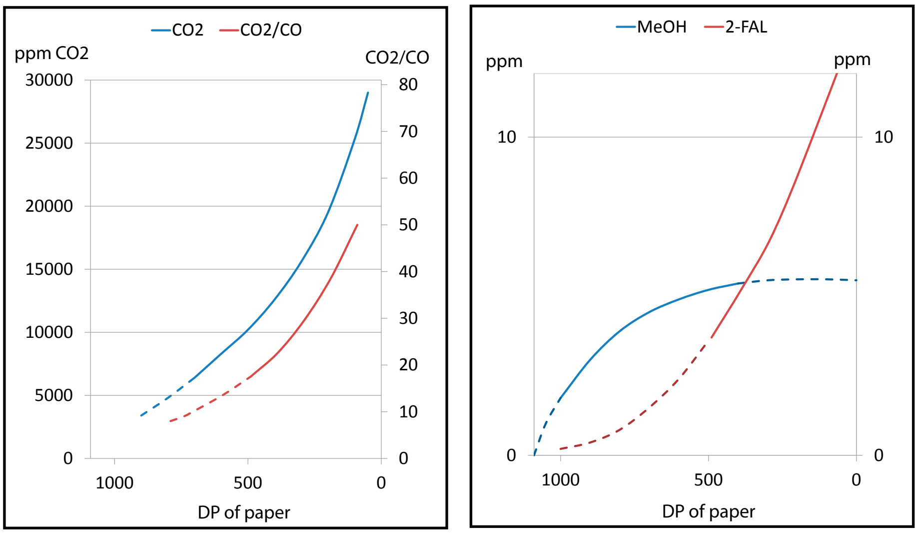

Figure 2: Typical correlations between DP of paper, CO2, CO2/CO, 2-FAL and MeOH

Table 1: Cases of transformers with low DPs of paper

DP	Company	Date	Number of Transformers	Comments
150-220	NTPC (IN)	2006-2013	5	No failure on account of low DP
87	Alliant (US)	2009	1	No failure
	HQ (CA)	2010	Several	Has never seen a failure because of low DPs
	EDF (FR)	2010	Several	Has never seen a failure because of low DPs
150	ERDF (FR)	2011	1	Survived external short circuits, transport
140	FKH (CH)	2011	1	No failure due this low DP in windings
100	TjH2b	2011	Several	No failure
<200	VPDiagnose (SW)	2011	Several	No failure
100-250	Hydro One (CA)	2011	25	5 failed, but for other reasons (high moisture, rusting, leaks
100	NL	2012	1	No failure
75	Transfo Services (FR)	2012	1	No failure (2-FAL = 13 ppm)
<100	Ameren (US)	2013	1	No failure (2-FAL = 14 ppm)
280	Sonelgaz	2013	3 +	Moved several timeswithout reclamping
150	Austr/ NZ	2013	Several	No failure
250	EDF (FR)	2013	1	Failure occurred in paper with DP 400/ 600, not 250
200	EIMV (SL)	2013	1	No failure
<100?	NZ	2013	1	Darkened paper, no failure, 10,845 ppm CO_2
170	HQ (CA)	2014	At least 1	No failure
175	EDF (FR)	2014	1	Dielectric failure of overheated paper, not due to the low DP
145	Elma (IT)	2014	2	No failure (in Congo)

tion measured. The higher the viscosity, the longer the cellulose chains, the higher the DP and the mechanically stronger the paper. This, however, requires paper samples to be fully soluble in the solvent, otherwise measurements will falsely indicate a lower viscosity, lower DP and paper mechanically weaker than in reality.

- or by indirect measurement of paper degradation products in transformer oil:
- furans, using different models of DP vs furans content available in the literature.
- methanol [2].
- CO2 and CO2/CO ratio [3].

Risk of failure of transformers with low DPs of paper

It has been shown [4, 5] that even at very high concentrations of CO_2 the risk of failure of transformers in service is very low (Figure 1) in the absence of abnormal faults indicated by DGA.

It has also been shown [6] that there is a strong correlation between high values of CO_2, CO_2/CO ratios and furans and low DPs of paper. The typical curves of Figure 2 indicate the general trends observed. In practice, there is often a large dispersion of individual values around these curves. Figure 2 shows that CO_2 and furans (2-FAL) are more sensitive than methanol (MeOH) to detect DPs < 400.

Since the risk of failure at high concentrations of CO_2 is very low, the risk of failure at low DPs is also likely very low. This is supported by a large number of reported cases (> 55) of transformers with DPs between 250 and 75 and still operating normally without failure. These cases have been compiled for CIGRE WG47 and are indicated in Table 1. Most DP values in Table 1 were measured directly with paper samples and from high values of furans. When paper samples were taken from different places in the transformer, only those with the lowest DPs are given in the Table 1. In the 4 cases where DPs were only estimated from furans, the models used were not indicated.

In the few cases from Table 1 that failed, transformer failure was not due to mechanical failure of paper but to other reasons (dielectric failure of paper, high humidity, corrosion, etc). So far, no transformer failures due to mechanical failure of paper at low DPs have been reported.

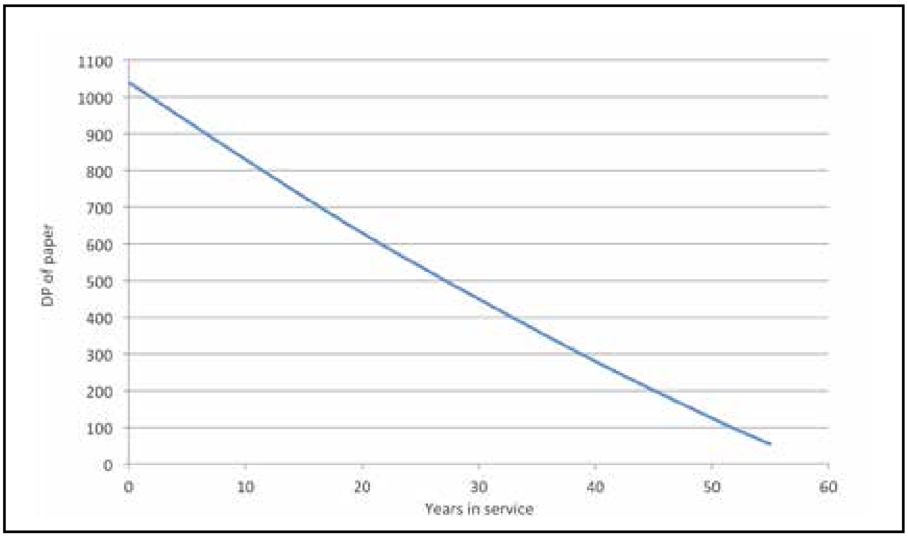

Figure 3: Typical decrease of DP of paper vs years in service (utility transformer)

Table 1 indicates that the risk of failure of transformers with DPs between 250 and 75 is quite low, even when subjected to external short circuits or transported (otherwise the transformers would have failed), and not very high as generally mentioned. Using a DP limit of 100 or 75 would therefore be more realistic than the present 200.

Based on this limit of 100 or 75 and on typical curves of decrease of DP vs. years in service (Figure 3), the life of transformers with a DP of 200 could be extended by 6 to 8 years for utility transformers, and 3 to 4 years for industrials, with no significant increase in their risk of failure due to the mechanical condition of paper in the absence of abnormal faults indicated by DGA.

The horizontal scale in Figure 3 will vary depending on transformer operating conditions and for industrial transformers.

Behaviour of paper with low DPs in transformers

Table 1 indirectly indicates that paper with DPs between 250 and 75 still provides adequate mechanical and insulating barrier between winding turns. Also, that paper between turns is not submitted to strong tensile forces but rather to compression forces, even when submitted to external short circuits (as also observed at ABB US).

No significant decrease in clamping pressure on windings has been observed at low DPs of paper, indicating that the decrease in thickness of paper at low DPs is more than compensated by the increase in thickness due to higher moisture in degraded paper.

Paper with a DP of 200 to 30 has the visual aspect of paper but turns brown to dark (Cargill US [7]). For instance, in Figure 4, paper has a DP of 270 on HV turns and

Figure 4: Example of paper with low DPs

Based on the limit of 100 or 75 and on typical curves of decrease of DP vs. years in service, the life of transformers with a DP of 200 could be extended by 6 to 8 years for utility transformers, and 3 to 4 years for industrials, with no significant increase in their risk of failure

Figure 5: Example of transformer coil with degraded paper

170 on LV turns. Other examples of transformers with degraded paper operating without failure are indicated in Figures 5 to 7.

Paper with a DP < 30 is black and cracks into pieces or powder impregnated with oil acting as a binder. Such paper, composed of very short cellulose fibres, provides mechanical barrier between turns only as long as oil is not removed from it by transformer treatments such as vapour phase drying or de-sludging with hot oil spray.

In some cases, paper with a low apparent DP has been observed to be surprisingly difficult to cut from windings, possibly because of cross-linking reactions between short fibres and degradation products of cellulose (the main component of paper), which become insoluble in the solvent used for DP measurements in the laboratory. This phenomenon is under investigation in Algeria.

Conclusion

– Based on present observations, transformers with DPs of paper between 250 and 75 and with no abnormal faults indicated by DGA still operate normally without failure, even when subjected to external short circuits and transported.

– A DP limit of 100 could therefore be more realistic than the present limit of 200.

– This would allow the life of utility transformers with a DP of 200 by several (~ 6) years to be extended and would significantly reduce capital investment costs for companies having to renew their fleets of transformers based on DP criteria.

– Transformers with DPs > 250 are still far from their end of life and do not need to be replaced.

– In case of transformers with very low DPs of paper it is preferable not to remove the oil and not to use vapour phase drying, since oil acts as a binder.

– This article represents only the point of view of its author.

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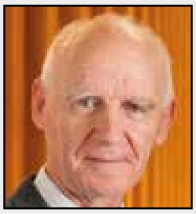
Figure 6: Example of transformer turns with degraded paper

Figure 7: Example of cooked paper

Author



Dr Michel Duval obtained a B.Sc. and PhD. in chemical engineering in 1966 and 1970, and has worked for IREQ (Hydro-Quebec, Canada) since 1970. He has made significant contributions in 3 mains fields of R&D: dissolved gas-in-oil analysis (DGA), electrical insulating materials and lithium-polymer batteries.

In the field of DGA, Dr Duval is well known for his «Triangle method» of DGA interpretation, used worldwide. He has developed the use of gas-in-oil standards and participated in the development of the «Hydran» on-line monitor for hydrogen in oil. Dr Duval has established the levels of gas formation observed in various types of electrical equipment. He has been the Convenor of numerous IEC and CIGRE working groups and the principal author of several IEC international standards and CIGRE Technical Brochures on DGA. He is also very active in several IEEE working groups.

Dr Duval holds 16 patents and is the author of more than 100 scientific papers and standards. He is a Fellow at the Chemical Institute of Canada, a Life Fellow of IEEE, and the recipient of IEC and CIGRE Awards and of the IEEE Herman Halperin Electric Transmission and Distribution Award for 2012.

Trends in Power Transformer Failure Analysis

ABSTRACT

Part three of this series on *Trends in transformer failure analysis* will report on some recent progress on standards body projects that were described in the first issue. It will describe some failures which have evolved recently. It will also identify many things that are not found in the IEEE Guide for Failure Analysis and describe the reasons why they are not included.

KEYWORDS

power transformer, failure analysis, failure reporting, failure investigation

Recent development in failure analysis and reporting

In my first article on the subject of failure analysis [1], I described work underway in the IEEE/PES Transformers Committee to revise the IEEE C57.125 *Guide for failure investigation, analysis, and reporting for power transformers and shunt reactors* [2] and parallel work in CIGRE WG A2.45 *Transformer failure investigation and postmortem analysis.* What I neglected to mention is the IEEE effort included incorporating the process by which any entity can establish a database of a population of similar transformers, determine the differences and statistically come to some conclusion about how the population was behaving. The original work on developing the database was titled IEEE C57.117 *Guide for reporting failure data for power transformers and shunt reactors on electric utility power systems* [3]. We have merged the rules for statistical analysis, the appropriate definitions, and the suggested forms which we hope will become a part of the data describing the transformer so that its identity and pertinent rating information can be entered into a database. An Electrical Power Research Institute (EPRI) project took that effort to the pilot stage but the effort died for lack of funding or lack of interest. Fortunately, another U.S. company has stepped up to host a database for clients who wish to participate and have sufficient interest to proceed. Each participating company's data has been converted into a "standard format" and the queries are developed to calculate various failure rates of interest to the group. The host is currently updating everyone's 2013 data; adding in

Courtesy of A-Line E.D.S.

failures that occurred during the year plus adding in newly installed transformers and noting transformers that were retired so that the database maintains accurate population data.

The CIGRE A2.45 Working Group has met six times, the latest meeting being August 2014 in Paris. Their early meeting minutes recognised the C57.125-1991 as state of the art. We share some common interests although we are not actively coordinating the work between the two groups. The A2.45 WG is making progress toward a brochure which, based only on my reading of their minutes, appears it will address many of the same issues that are addressed in the IEEE Guide.

I am happy to report that as of this writing, the effort by the IEEE/PES Working Group has progressed to ballot of a final draft of PC57.125 and if all goes well, that ballot should be concluded by the time this issue of Transformers Magazine reaches you. The final draft contains tables of tests whose interpretation can help with the diagnosis of problems. I mentioned some of the new tests which I included in the "Alphabet test" category in the last article on Trends in transformer failure analysis contained in the second edition of Transformers Magazine [4]. There are other documents to which one can refer to obtain values where industry norms have set limits. It still remains up to the individual to analyse the test results and compare them to previous readings to detect trends or to detect when limits indicate that either a failure has occurred or is imminent.

> **Failure analysis is an ever evolving process**

While we have been revisiting the document, we have been made aware of several failure modes which have revealed themselves. These and perhaps others which manifest themselves in the future will have to become part of the next revision since there is a time limit on completing a revision within the cycle required by the sponsoring body (in this case IEEE-SA)

What is new in the latest revision of the guide for failure analysis?

1. Expanded safety clause

– A significant change to the C57.125 Guide is the inclusion of a comprehensive safety clause for the hazardous conditions which may be encountered when performing field inspection and testing on a suspected failure.

2. Additional test techniques

– Besides the addition of the safety clause, additional test techniques which were not in common practice at the time when the original guide was written have been added where their results point to a cause or narrow the possibilities for causes.

3. Reliance on more comprehensive test interpretation which is contained in IEEE Field Testing Guide

– The interpretation of test results from tests suggested by the C57.125 guide now refer to the more comprehensive IEEE C57.152 *Guide for diagnostic field testing of power apparatus - Part 1: Oil filled power transformers, regulators, and reactors* [5]. This guide, published in 2013 is an expanded and completely overhauled version of IEEE 62 which had the same title. It contains a clause devoted to all commonly used field tests, the interpretation of test results, and in many cases, the appropriate action to determine if a test specimen has passed. It recognises that some tests are PASS/FAIL while others must be evaluated by analysis of TRENDS.

What is not in the revised c57.125 guide?

1. Guaranteed methods that ensure that a cause will be found are not in the Guide. One must remember that the fault current flow available, and the resulting energy of the fault, will likely vaporise (or at minimum, relocate some distance) traces of contamination, chemical compounds, and other possible root causes of the

> **The effort by the IEEE/PES Working Group has progressed to ballot of a final draft of PC57.125 and if all goes well, that ballot should be concluded by the time this issue of Transformers Magazine reaches you**

events which follow and ultimately lead to the fault current flow. The precision and thoroughness of data collection is also important to obtain conclusive results.

2. Failure Modes and Effects Analysis (FMEA). Those that feel the need for such analysis should refer to IEEE C57.140 *Guide for evaluation and reconditioning of liquid-immersed power transformers* [6]. This guide contains a number of charts from which FMEA analysis could begin.

3. The Guide cannot supply or guarantee that the investigation will always be performed in a safe manner. Safety should be inherent in the design, comprehensive in worker training, and under constant review for improvement. Equally important is that safety regulation is an evolving process and what may be standard practice today may be viewed as an unsafe practice in the future. Regulations and work practices have certainly come a long way in providing worker safety and property damage reduction but accidents can still happen. Caution is of the utmost importance.

4. While writing the introduction to the latest revision, I made the plea to the industry to use the guide to allow users of the guide to reach the same or nearly the same conclusion when investigating failures and I made a plea to the industry to create and use a database to collect and facilitate analysis of failures to permit early awareness of deficiencies in design or application. These are statistical tools which will help but not guarantee success in determining the root cause. Nevertheless, progress is being made to answer that need. We are not quite there but are getting closer. Data analytics techniques being developed for digesting the data available from all the smart devices on the smart grid may in the future be applied to data collected to arrive at a more conclusive result.

5. I believe that there is an expectation that we will reach a point when industry recalls will take place so that an awareness of potential failures will be created before similar failures occur. The underlying approach to the original Failure Reporting Guide (then known as C57.117) would establish

> **Some want to compare transformer failure analysis to medicine and some want to compare the failure investigations to crime drama that is so popular on television these days**

such a database and that one company's failure would appear with the same severity as another; that identical causes could be located in the data and steps necessary to correct whatever was causing them to be corrected. There is also hope that an unequivocal conclusion can be reached every time the process described in the guide is followed. This, unfortunately, is not the case. On many occasions, the power of a short-circuit fault will destroy the evidence of the underlying cause.

6. We want to believe that all transformers are alike and that the results of tests will provide enough evidence to solve the mystery. Pick your genre – some want to compare transformer failure analysis to medicine and some want to compare the failure investigations to crime drama that is so popular on television these days. While I enjoy a good crime drama or a medical drama on TV, I also know that no two people are exactly alike, just as for every transformer design there are only an average of 1.3 transformers built. Statistics can reveal only so much and there will always be "outliers" which do not conform to the statistical norm.

– If we stay on the medical treatment analogy, there is always a need to tailor the treatment to the uniqueness of the human patient. We must consider doing the same for the transformer patient as well.

7. The abstract to a paper written in 1985 for the Summary of Changes in IEEE *Guide for protective relay applications to power transformers,* ANSI/IEEE Standard C37.91 [7], described the updates and re-organisation which took place under the auspices of the IEEE/PES Power System Relaying Committee. The revision described was an update which guided the user to the correct application of the various methods and devices used to protect power transformers. The paper highlighted the scope and usefulness of the C37.91 guide and initiated discussion of future enhancements. That guide has since undergone at least two major revisions, however, the fundamental protection principles have not changed.

– The paper was, of course written almost 30 years ago when many transformers were still protected by electro-mechanical relays. Protective devices have since become intelligent electronic devices (IED) with more capabilities than, perhaps, the entire station designed and built 30 years ago.

– Advancements in protection and modern circuit breakers design have helped minimise the damage of an internal fault in a transformer, but I still believe the goal of the devices protecting the transformer are really protecting the system from the transformer. Even minimum damage still requires a substantial effort to repair, and since we are talking about an internal fault, there are few utilities and probably no manufacturer who would jeopardise the transformer, the workers, or the system by returning a transformer to service after an internal fault is well confirmed. Most would return the transformer to a shop where it could be properly and thoroughly cleaned, repaired, dried, reprocessed, and tested to confirm it was in good (like new) condition.

8. The Guide does not provide a comprehensive list of all the components on your transformer that could fail or could have caused a failure. Only your transformer specification will have that and only if the documentation has been updated as accessories have been added or removed.

9. The Guide cannot tell you how to design a transformer which is adequate to perform in the application the owner intends.

10. The Guide cannot tell you how to correctly apply and specify a transformer for your needs.

11. The Guide will not tell the manufacturer what type of design to use (unless you have a design expert to provide you with reasons why certain design features are required for your application / conversely, the Guide does not tell the user who has done diligent system analysis what their design features must be (e.g., turns RATIO, impedance, BIL, etc).

12. The Guide does not define the duration of the bottom of the bathtub curve. Hence the need for detailed failure analysis along with all of the „normal" operating parameters to which a transformer population was exposed.

> **Core gassing in wound core medium voltage transformers have been found because the operators of wind farms monitor DGA. Does the same problem exist on medium voltage distribution systems?**

Recent failure mechanisms on which to keep a watchful eye:

1. Core gassing in wound core medium voltage transformers

– Found because the operators of wind farms monitor DGA while most distribution organisations do not.
– May also be a problem on medium voltage distribution systems, but units are usually not tested (e.g., no DGA, no routine maintenance)
– A Task Force has been established to investigate whether routine testing can detect possibility of a problem. This is something to consider adding to the specifications, if not to the standards.
– It has not been established with a high degree of certainty that the gas is the result of partial discharge (PD) in the core and if so, is it a sign of high dielectric stress between core laminations or at the edges of core lamination.
– What are the consequences of the high dissolved gas? Will the gas come out of solution and present an explosion hazard? Will it simply mask the occurrence of a winding PD problem? Everyone agrees that gas is an undesirable symptom and so is the possibility that PD is causing the gas to develop. More analysis and research will be necessary to determine the best solution. Designs can be formulated to solve the problem once the cause is confirmed.

2. Magnetic shunts shorted to the frame in core form units resulting in increased combustibles discovered by DGA
– No final cause identified.

3. How many transformers shipped from manufacturers (anywhere) have been found damaged by forces during transport?

– Logic behind IEEE C57.150 *Transportation Guide*
– One of the reasons for development of SFRA

4. Not so recently, a transformer failed with the following scenario:

– Short-line fault occurred due to lightning
– Station rod gaps flashed to move the fault from 1 - 2 km from the station to the station entrance
– A circuit breaker on the ring-bus directly adjacent to the transformer connection flashed internally from current carrying part to grounded tank.
– The transformer experienced part-winding resonance and failed internally from the overvoltage produced by the part winding resonance.
– Conclusion was that the frequency response to these specific conditions MIGHT have been prevented by installation of a snubber circuit or part winding thyristor valves (essentially surge arresters) installed within the winding.
– No further action was taken as the low risk of a similar failure plus the cost of the system studies to determine the size and capacity of the internal valves could not be justified.
– No failures have occurred at that station since.
– Does this mean that the problem was incorrectly diagnosed or that the probability of such an event occurring is low enough to take the risk?
– Perhaps the cause was not the short-line fault, but the flashing of the rod gaps or the failure of the circuit breaker.
– System studies, though expensive to perform, are becoming a more important part of the failure analysis.

5. Studies have indicated that corrosive sulfur is a problem

– The simplest solution was to improve the quality of the mineral oil.
– Other solutions have been offered and considered by manufacturers.

6. Studies have demonstrated that under certain conditions, oil flow results in build-up of static charge on insulating surfaces. The phenomenon of static electrification is fairly well understood and was identified more than 20 years ago but continues to result in failures (as recently as early 2014 as reported in the Transformers Magazine Newsletter).

– One must always keep up-to-date with developments in the industry as solutions present themselves.

7. Transformer and breaker interaction was a phenomenon addressed, first in papers, then in an application guide titled IEEE C57.142 *A guide to describe the occurrence and mitigation of switching transients induced by transformer-breaker interaction* [8].

System studies, though expensive to perform, are becoming a more important part of the failure analysis

Conclusion

Failure analysis is an ever evolving process. The fundamental process is still a representation or application of the scientific method, but whether designs are fine tuned or radically improved, there will always be an opportunity for a new failure cause to evolve. Keeping aware of the latest findings, practices, and sharing failure information will improve both the failure analysis process, the likelihood of reaching the root cause, and the overall reliability of the system (which is the ultimate goal, is it not?).

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Author

Wallace BINDER has experience in scope development, planning, design, construction, start-up, operation, and maintenance of distribution, transmission and customer utilisation substations, back-up power generation, transmission and distribution lines, and systems.
Wallace Binder has been an active member of the IEEE/PES Transformers Committee for more than 30 years. He has served twice as Chair of the Working Group on Failure Analysis, a position he currently holds. He served as Chair of the Transformers Committee for two years in the late 90's and has contributed to numerous guides and standards developed by the Transformers Committee.
Wallace Binder is currently an independent consultant with his office located in Western Pennsylvania. He has served a variety of clients - both manufacturers and users of substation apparatus.

Power transformer protection – an outline

What are the main protection types to protect major substation element?

ABSTRACT

Power transformers are used in High Voltage (HV) / Extra High Voltage (EHV) / Ultra High Voltage (UHV) systems as they transfer a huge amount of power to the customers but the volume of vulnerability and damage is also huge and destructive. Therefore, in order to avoid such destruction and loss, protective devices are used with different protection schemes to provide safe and secure power to the customers. These devices not only protect the equipment but also preserve human life and secure the system from impairment.

KEYWORDS

protection, relays, schemes, faults

1. Introduction

The transformers in HV networks are always protected by one main protection device and at least one back-up protection device. Main Intelligent Electronic Device (IED) uses all the protection functions, and the back-up IED has at least an (overcurrent) OC low stage with Inverse Definite Minimum Time (IDMT) curves, an OC high stage and an Earth Fault (EF) protection. In EHV we use two identical main protection devices in a redundant protection system.

In the field of power systems, the role of a power transformer is well known. It is so called backbone of the power transmission systems. High reliability of the transformer is therefore essential to avoid disturbances in transmission of power. When a fault occurs in a transformer, the damage is usually severe. The transformer has to be transported to a workshop and repaired, which

When a fault occurs in a transformer, the damage is proportional to the fault time. The transformer should therefore be disconnected from the network as soon as possible

takes considerable time. To operate a power transmission system with a transformer out of service is always difficult. The impact of a transformer fault is often more serious than a transmission line outage. To prevent faults and to minimise the damage in case of a fault, transformers are equipped with both protective relays and monitors. The choice of protective equipment varies depending on transformer size, voltage level, etc.

2. Failure statistics

Table 1 lists failures for six categories of faults (IEEE C37.90, *Guide for Protective Relay Applications to Power Transformers,* Ref. 1). Winding and tap changers account for 70% of failures. Loose connections are included as the initiating event as well as insulation failures. The miscellaneous category includes CT failure, external faults, overloads, and damage in shipment. An undisclosed number of failures starts as incipient insulation breakdown problems.These failures can be detected by sophisticated online monitoring devices (e.g. gas-in-oilanalyser) before a serious incident occurs [1].

3. Transformer protection

When a fault occurs in a transformer, the damage is proportional to the dissipated fault energy which relates to the fault time. The transformer should therefore be disconnected from the network as soon as possible. Fast reliable protective relays are therefore used for detection of faults. Monitors can also detect faults and sense abnormal conditions which may develop into a fault. The size of the transformer and the voltage level has an influence on the extent and choice of protective equipment. Monitors prevent faults and protective relays limit the damage in case of a fault. The cost for the protective equipment is marginal compared to the total cost and the cost

Table 1: Failure rates

	1955-1965		1975-1982		1983-1988	
	Number	**Percent of total**	**Number**	**Percent of total**	**Number**	**Percent of total**
Winding failures	134	51	615	55	144	37
Tap changer failures	49	19	231	21	85	22
Bushing failures	41	15	114	10	42	11
Terminal board failures	19	7	71	6	13	3
Core failures	7	3	24	2	4	1
Miscellaneous failures	12	5	72	6	101	26
Total	262	100	1127	100	389	100

involved in case of a transformer fault. There are often different opinions about the extent of transformer protection. However, it is more or less normal that transformers with an

The cost for the protective equipment is marginal compared to the cost involved in case of a transformer fault and the total cost

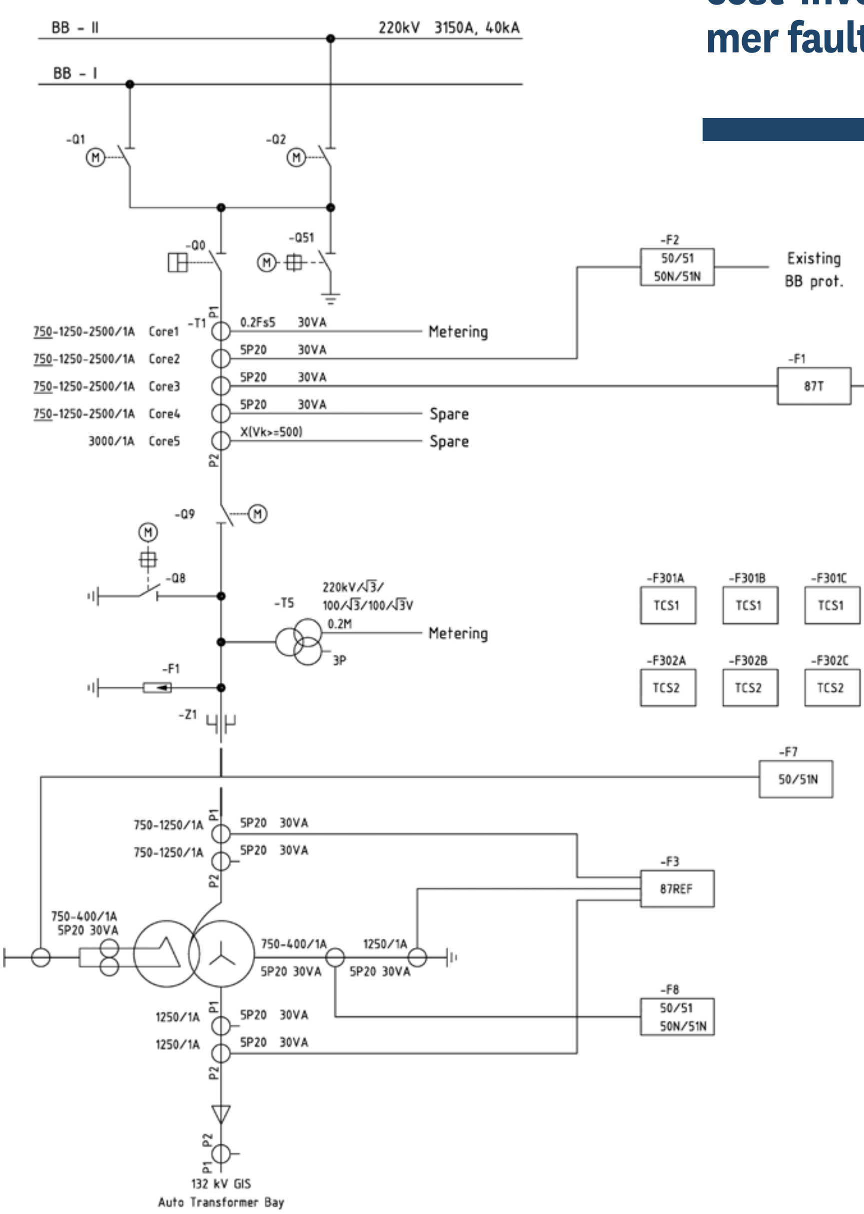

Figure 1: Typical single line diagram of a 220 kV transformer bay with protection

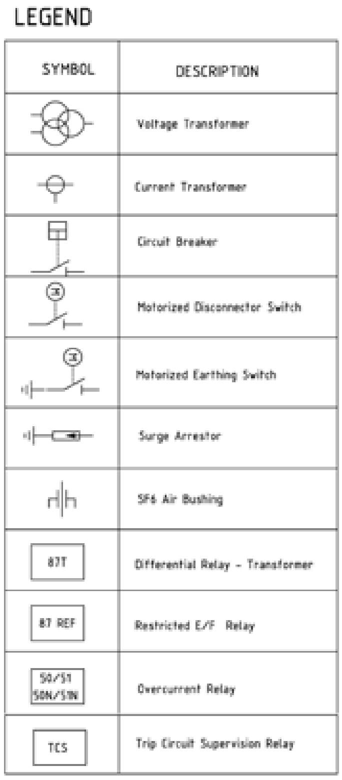

Figure 2: Description of symbols used in Figure 1.

oil conservator are equipped with the equipment showed in Table 2 [2].

The types of protection in Table 2 are used with different schemes depending upon the ratings of the transformer and fault levels. In order to plot the protection schemes, we have different codes for different type of protection called ANSI device numbers or ANSI codes, Figure 1.

Figure 1 shows typical single line diagram for the 220 kV substations in which the transformer is protected by differential protection along with overcurrent and restricted earth fault protection.

Figure 2 shows the description of symbols and codes used in Figure 1, types of protection devices / IED's and other switching / measuring devices.

Description of codes

A. Current protection functions

ANSI 50/51 – phase overcurrent

Three-phase protection against overloads and phase-to-phase short-circuits.

ANSI 50N/51N or 50G/51G – earth fault

Earth fault protection based on measured or calculated residual current values:

- ANSI 50N/51N: residual current calculated or measured by 3-phase current sensors
- ANSI 50G/51G: residual current measured directly by a specific sensor.

Table 2: Protection used for ratings above 5 MVA

List of protection types used for transformers of rating above 5 MVA
Gas detector relay (Buchholz relay)
Overload protection (thermal relays or temperature monitoring systems)
Overcurrent protection
Ground fault protection
Differential protection
Pressure relay for tap-changer compartment
Pressure relief device

B. Differential protection
ANSI 87T – Differential

Three-phase differential protection has a task to protect particular zone from difference in current which is entering and leaving from one side to another in a particular zone. The differential protection function protects the zone between the main and additional current sensors inside the protected zone between the two sets of current transformers (CT) [5].

4. Transformer protection types

OVERCURRENT PROTECTION

Basic principle

Fault impedance is no greater than the load impedance, therefore fault current is greater than load current. Over current relays sense fault current and also overload current. When the fault current is above a certain level called the pickup level, relays pick up and disconnect the circuit.
Types of over current include:

- overload current
- short circuit current

Overload current

We exercise different characteristic curves to cover possible overloads during shorter periods of time, e.g. during through faults.

Three-phase differential protection has a task to protect particular zone from difference in current which is entering and leaving from one side to another in a particular zone

Short circuit current is 5 to 20 times the full load current

Because of high currents, these stress the equipment thermally and high thermal power is dissipated. On the other hand they cannot be detected by thermal relays because there is no time for a temperature rise.

While the high stage overcurrent operates as a back-up protection and the differential protection is the main protection, the low stage with its characteristic curve protects from possible overloads during through faults and is not a back-up protection. If there is a through fault just behind the transformer, the differential protection would not trip. Yet, the transformer would be overloaded and if the circuit breaker behind the transformer does not trip, then the whole transformer must be disconnected.

Short circuit current

This includes phase faults, winding faults and earth faults. Usually short circuit current is 5 to 20 times the full load current, therefore fault clearance is desirable.

Characteristic curves

IEC 60255 defines a number of standard characteristics as follows, Table 3:

- Standard Inverse (SI)
- Very Inverse (VI)
- Extremely Inverse (EI)
- Definite Time (DT)

Table 3: IEC Inverse Characteristic Equations

IEC Inverse Characteristic Equations		
IEC SI (Standard Inverse)	IEC VI (Very Inverse)	IEC EI (Extremely Inverse)
$t = TMS\ x \frac{0.14}{(I/_{Is})^{0.02} - 1}$	$t = TMS\ x \frac{013.5}{(I/_{Is})^{1} - 1}$	$t = TMS\ x \frac{80}{(I/_{Is})^{3} - 1}$

In protecting power transformer, overcurrent relay is typically used as a backup protection following Inverse Definite Minimum Time (IDMT) curve with coordination of other relays.

Where,

TMS = time multiplier setting (relay operating time can be varied by varying the TMS setting)
Is = set current value
I = measured current value
t = operating time (sec)

A Earth fault protection

Earth fault is the most frequent occurring fault in the power system. In HV/EHV networks an earth fault manifests as a flow of current through neutral/return conductor of the grounded system. Although phase fault relay responds to earth faults, such protection lacks sensitivity. To overcome this, separate earth fault

Earth fault is the most frequent occurring fault in the power system

relays are used which respond to residual component of current and thus are unaffected by the unbalanced load conditions. Since neutral earthing resistance is generally used, low settings are required.

There are two types of earth fault protection:
1. Restricted
2. Unrestricted

Restricted earth fault (REF)

Under normal conditions and by application of Kirchhoff's laws the sum of currents in both current transformers (CTs) equals zero. If there is an earth fault between the CTs then some current will bypass the CT's and the sum of currents will not be zero. By measuring this current imbalance, faults between the CTs can easily be identified and quickly cleared.

Fault detection is confined to the zone between the two CTs hence the name 'restricted earth fault'.

A restricted earth fault (REF) is an earth fault from a restricted/localised zone of a circuit. The term 'REF protection method', means that earth faults outside this restricted zone are not sensed. REF is a type of 'unit protection' applied to transformers or generators and is a more sensitive differential protection.

REF protection is fast and can isolate winding faults extremely quickly, thereby limiting damage and consequent repair costs. If CTs are located on the transformer terminals only the winding is protected. However, quite often the secondary CT is placed in the distribution switchboard, thereby extending the protection zone to include the main cable.

Without REF, faults in the transformer star secondary winding need to be detected on the primary of the transformer by the reflected current. As the winding fault position moves towards the neutral, the magnitude of the current seen on the primary rapidly decreases and could potentially not be detected (limiting the amount of winding which can be protected). As the magnitude of the currents remain relatively large on the secondary (particularly if solidly earthed), nearly the entire winding can be protected using REF. As it is essential that the current in the CTs is balanced during normal conditions (and through faults), historically REF has been implemented using high impedance relays. CT's have also been specified as matched pairs and the impedance of leads/wires and interconnecting cables has had a large influence on the functioning of the relay. Measurement errors associated with these issues have been responsible for nuisance tripping and the system can be difficult to commission. This may be the reason some people avoid the use of REF. Recent advances in numerical relay technology have all but eliminated these issues, making the implementation of REF relatively easy, ensuring no nuisance tripping and simplifying commissioning [6].

During normal condition, the current with no interruption flows through the protected equipment and the net current through the relay is zero

Unrestricted earth fault

It responds to earth fault from any point in network. This protection is used to sense earth fault at any point in the system.

In the absence of earth fault the sum of three line currents is zero hence the vector sum of three secondary currents is also zero:

$I_{as} + I_{bs} + I_{cs} = 0$
$I_{rs} = 0$,

Where,
I_{rs} = residual current
$I_{as} + I_{bs} + I_{cs}$ = per phase currents (red, yellow, blue)

In case of a fault, residual current is not zero. The earth fault relay is connected in such a way that residual current flows through it if the relay operates above pickup level, as in Figure 3.

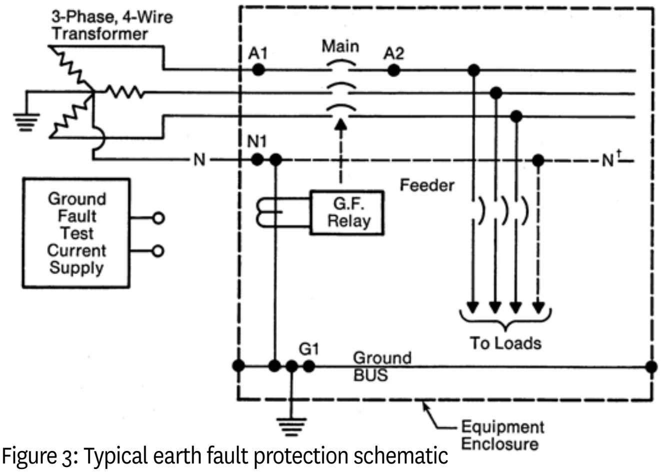

Figure 3: Typical earth fault protection schematic

B Differential protection

Basic principal

It is based on the principle of Kirchhoff's current law, i.e. by comparing the secondary current of the current transformers located at each end of the protected equipment. During normal condition, the current with no interruption flows through the protected equipment, and the net current I_n through the relay is zero. The figure shows a scheme of differential protection. Let us assume I_1, I_2 and I_3 are the three respective secondary currents of the relay in case of normal operation. If any fault occurs outside the boundary defined by current transformers, the relay would not operate. But if it occurs in the region bounded by the two current transformers, the relay will give the signal to the circuit breaker to trip the circuit.

The differential protection designed for the transformer is of a percentage type where restraint coils are employed.

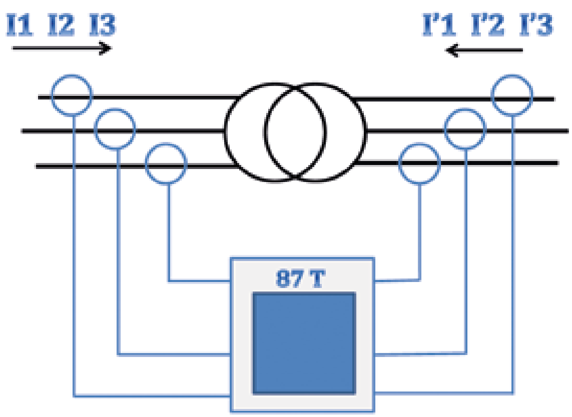

Figure 4: Transformer differential protection schematic

Restraining coils are also called bias coils. Due to the difference in the magnetising currents of the high and low voltage current transformers, the current through the operating coil will not be zero even under normal loading conditions or external fault conditions. Therefore to provide stability on external faults bias coils are provided. To obtain the required amount of biasing, a suitable ratio of the biasing coils with restraining coils needs to be provided.

Following points while designing a differential protection scheme for a transformer must be considered:

- There is always a certain amount of unbalanced current in the operating coil of a transformer differential relay because the current transformers are not ideally matching due to the turns ratio of transformer and also due to the resistance of coil.
- Due to the requirement of magnetising current, some unbalanced current remains in the operating coil as there is no current in the secondary while the current in primary performs excitation.
- Inrush current does exist in transformers. Its magnitude and duration depends on residual field present in the core and the point on the ac cycle where the re-energisation has occurred. Initially its value is 10 to 20 times the full load current in large transformers and becomes negligible in few minutes.
- The presence of tap changer in the transformer also adds complexities [4].

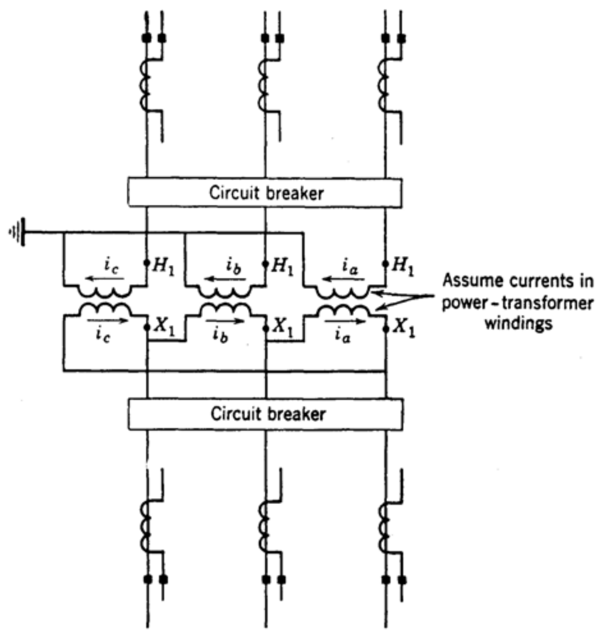

Figure 5: Transformer differential protection - single line diagram

The presence of tap changer in the transformer causes additional complexities in the protection

The scheme on the Figure 5 shows the typical differential protection for a star/delta transformer showing the connection for current transformer and relay coils.

C Bucholz relay

- Buchholz relay is a gas-actuated relay installed in oil immersed transformers for protection against several types of faults. Named after its inventor Mr. Max Buchholz (1875–1956) in 1921, relay is used to set off an alarm in case of incipient (i.e.slow-developing) faults in the transformer and to disconnect the transformer from the supply in the event of severe internal faults, Figure 6. It is usually installed in the pipe connecting the conservator to the main tank.
- It is a universal practice to use Buchholz relays on all oil immersed transformers having ratings in excess of 750 kVA. The Buchholz relay is a protective relay for equipment immersed in oil for insulating and cooling purpose, Figure 7 and Table 4.

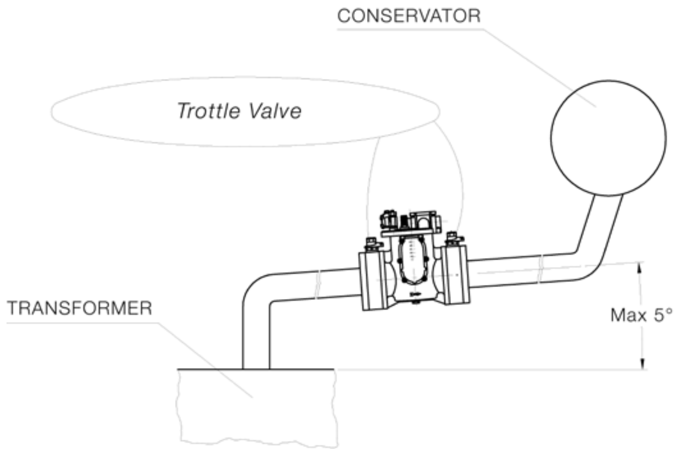

Figure 6: Bucholz relay fitting location

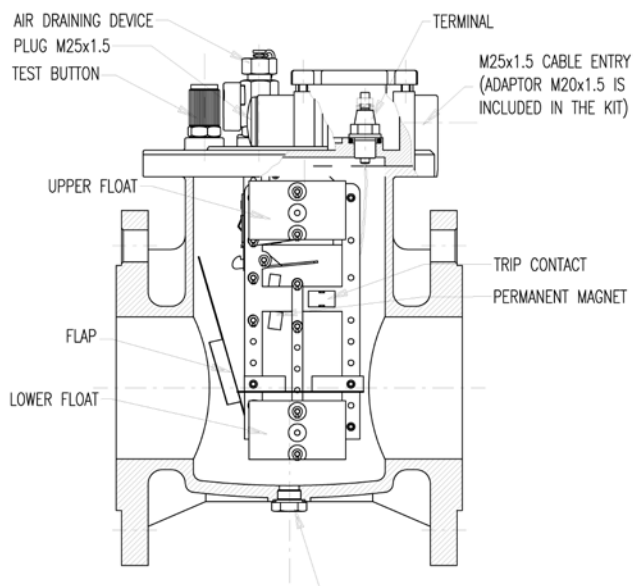

Figure 7: Bucholz relay

5. Monitoring of transformer

A Winding temperature indicator

The winding is the component with the highest temperature within the transformer and is subject to the fastest temperature increase as the load increases. In order to have control of the temperature parameter within the transformer, the temperature of the winding as well as top oil, must be measured. An indirect system is used to measure winding temperature, since it is dangerous to place a sensor close to the winding due to the high voltage. The sensor in the winding temperature indicator directly measures the CT current and uses the algorithms associated with IEC 354 to provide accurate winding temperatures for all cooling gradients via the feedback system, Figure 8.

Figure 8: Winding temperature meter

B Oil temperature indicator

The oil temperature indicator (OTI) measures the top oil temperature. This is a specific measurement location at the top of the transformer. Its temperature is used for the transformer control and protection, Figure 9.

Figure 9: Oil temperature meter

C Oil level indicator

An oil level gauge is required so that the correct oil level can be maintained, Figure 10. There is usually a mark on the gauge that indicates the 25 °C level, which is the proper oil level at that temperature. Maintaining the proper oil level is extremely important because if the oil level falls below the level of the radiator inlet, flow through the radiator will cease and the transformer will overheat [5].

Figure 10: Oil level meter

Conclusion

This article explains the basic information and provides an overview on different types and schemes of transformer protection. The protection schemes so far designed can successfully protect the transformer and mitigate the risk of enormous destruction that can be caused by transformer explosion; protecting major and expensive power system equipment and human life. The engineers and researchers are still working on utilising the new technologies for protecting transformers more successfully and more cost effectively.

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Fire testing for transformer pit fire protection

ABSTRACT

Transformer pits are conventionally filled with rocks in order to achieve passive fire safety in the event of an oil leak from the transformer. Other solutions also exist but there is no well defined test method that allows an assessment of the fire performance. In this brief article, such a test is presented together with test results for an alternative system where profile planks are used instead of rocks.

KEYWORDS

transformer pit, transformer oil, transformer fire, profile plank, experimental measurements

On the use of alternatives to rocks for passive fire protecton

1. Introduction

Burning transformer oil that has been ignited due to a transformer rupture can be a large problem and the fire can cause huge damage to the surroundings. To handle the leaking oil, a transformer is often placed above a concrete pit (transformer pit) to capture all the leaking oil. If the leaking oil is ignited, the fire can effectively be extinguished by using different systems in the transformer pit. The traditional way of improving the fire safety of transformer stations is to fill the transformer pit with rocks. The purpose of these rocks is that, in the event of an incident involving leaking and burning of transformer oil, the oil should be cooled as it comes into contact with the stones and that the limited amount of oxygen would help to avoid a long lasting fire when the oil runs into the transformer pit. Stone filled transformer pits can make it hard for service personnel to work on the transformer. It can also be expensive to sanitise the stones after the oil leak. An alternative to filling the pit with stones is to cover it with a profile plank. A profile plank is in this case a product based on a steel grid that is a kind of floor inside the transformer pit. The steel grid needs to have holes that will drain the leaking oil down into the transformer pit. The tested product is shown in Figure 1. This solution has the advantage

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Burning transformer oil that has been ignited due to a transformer rupture can be an extensive problem and the fire can cause huge damage to the surroundings

of allowing the entire volume of the pit to be available for rainwater and for any oil, instead of having most of the volume filled with stones. Another advantage is that it is easier to perform service work on the transformer station with a smooth profile plank as the base instead of stones. It is also easier to clean and restore the transformer pit after an oil leak.

Today no technologically neutral description of the requirements for extinguishing burning oil in a transformer pit is available. Swedish standard SS 421 01 01 [1] states:

"Preferably arrangements that contribute to extinguishing the fire in the leaked liquid shall be used, for example the use of a layer of stones (approximately 300 mm deep and with a grain size of about 40/60 mm) that extinguishes the burning liquid that enters the layer."

A search through the literature, both national and international standards and guidelines, finds that several documents describe the problems of burning oil, but none of them state specific requirements for fire extinguishing [2-6]. Rather, the documents typically contain guidelines similar to the translated citation from SS 421 01 01 above. SP Fire Research has, therefore, performed fire tests simulating a transformer failure by tipping burning transformer oil into a transformer pit covered by profile planks.

2. Experimental method

The test setup is shown in Figure 1. The transformer pit was 4 m long, 3 m wide and 1 m deep. Instrumentation consisted of thermocouples at various heights above and below the profile plank, and gas sampling probes mounted 5 cm below the plank. The oil was stored in a tippable trailer and heated by means of an LPG burner. Detailed information about the tests can be found in [7] and [8]. Three tests were carried out, see Table 1.

Table1. Diagnosis methods and related problems

Test No.	Scenario
1	With the oil heated to 90 °C.
2	With the oil heated to 90 °C. The transformer pit had been filled with water down to a depth of 19 cm to represent rainwater.
3	With the oil heated to 140 °C.

Figure 1: The transformer pit covered with the profile planks. Instrumentation consists of thermocouples and gas sampling probes. The tippable trailer on the left was used to contain the oil while being heated.

A new alternative for passive fire protection of transformer pits has been tested

3. Results and discussion

Figure 2 shows a series of pictures from Test 2, where it can be seen that the flames were self-extinguished within a few seconds after tipping the burning oil into the transformer pit. The burning oil was self-extinguished. The self-extinguishing occurred mainly due to the low oxygen level in the transformer pit as shown in Figure 4. It is important to remember that other fire scenarios and operational factors need to be studied regarding different safety solutions for transformer pits. Examples of operational factors are the reduction of oil drainage rate due to different construction solutions and debris, the cost of maintenance and the cleaning cost after an eventual oil leakage or fire. In this study no reference test using classic rocks instead of profile planks was performed. Such a comparison can be found in reference [9].

Figure 3 shows how the temperature rises rapidly as the burning oil contacts the profile plank. The flames disappear quickly and the temperature above the plank falls back to a low level. Beneath the planks the temperatures remain at elevated values for a longer period of time. For Tests 1 and 2 this is primarily due to the limited ventilation through the grating, but in Test 3 (in which the oil was heated to 140 °C) there was some heat release for about two minutes.

Figure 4 shows the oxygen concentration which quickly falls to low levels beneath the planks and helps to extinguish the fire.

Figure 2: A series of pictures from Test 2. The time lapse in minutes and seconds can be seen on the display in the bottom right hand corner of the pictures. It can be seen that the flames are extinguished within a few seconds of tipping the burning oil into the pit.

The result shows that solutions other than transformer pits filled with rocks are promising

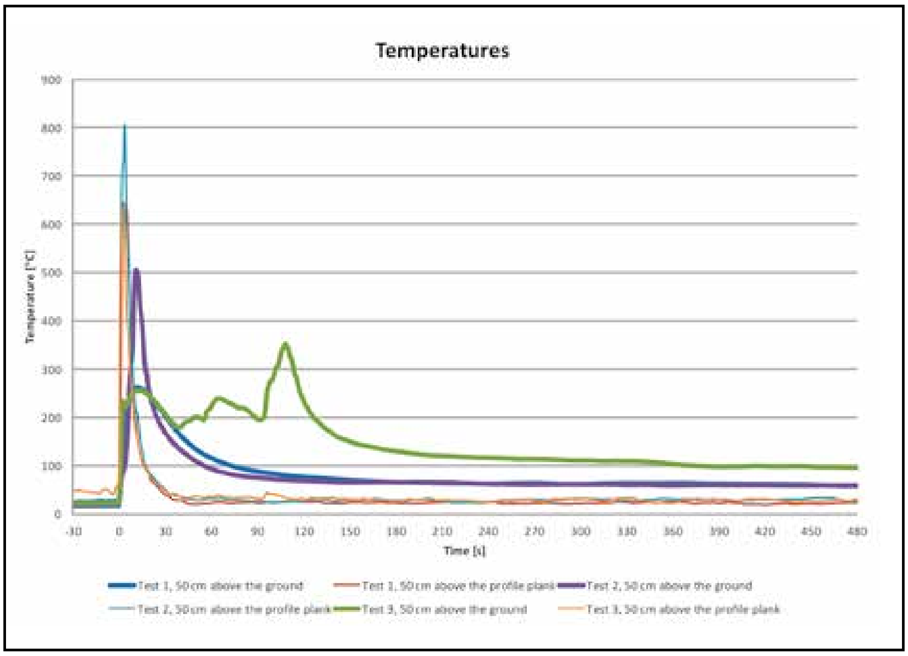

Figure 3: Temperatures in the centre of the pit, 50 cm above the bottom (i.e. beneath the planks), and 50 cm above the planks.

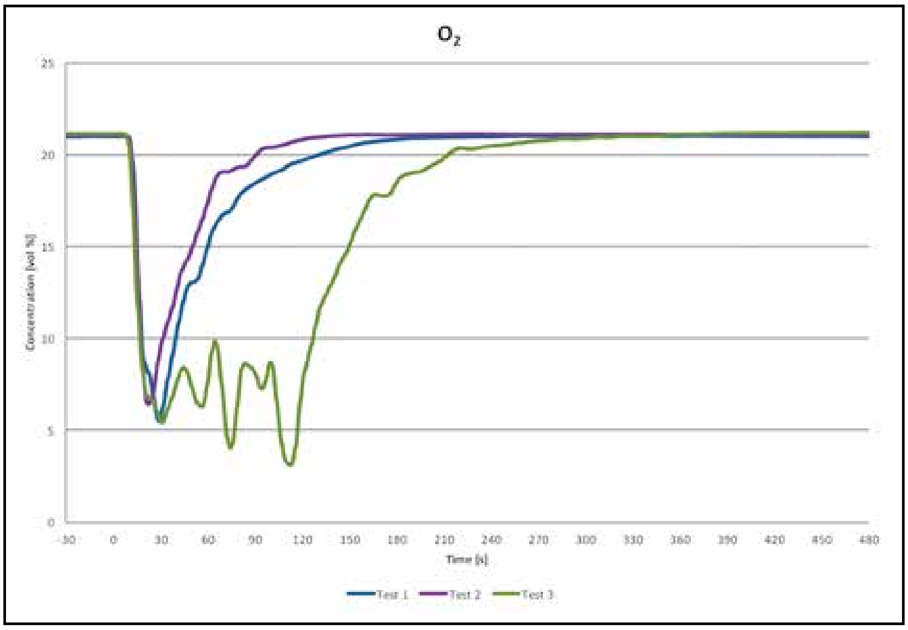

Figure 4: Oxygen concentration in the centre of the pit, 5 cm below the planks.

Conclusion

In summary, a method has been developed to evaluate the fire protection performance of covered and/or filled transformer pits. The result for the particular profile planks that were tested shows that the flames above the planks are self-extinguished within a few seconds.

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ABSTRACT

To verify that the inner design and its performance are satisfactory and that there are no failures in the winding insulation system and core displacement during long-trip transport, we need to do several tests such as SFRA test or single-phase excitation test. Defect in magnetic core structure, shifting of windings, failures in turns to turns or block to block insulation or problems in tap changers are conditions that change the effective reluctance of the magnetic circuit, thus affecting the current required to establish flux in the core. In order to deal with these problems, we would use low voltage single-phase excitation for power transformers. This is also a kind of auxiliary judgment method to guide us about the condition of transformer.

KEYWORDS

low voltage single-phase excitation, core type transformer, auxiliary judgment, magnetic flux

Low voltage single-phase excitation for power transformers

In the transformer factory, we also use low voltage single-phase excitation during the semi-finished processing of the products, another test to help us confirm the product before the final assembly. This may take several attempts, but if the product is defective, it will reduce labour and financial resources. This test may find that the quality is defective which cannot be found in turns ratio test and winding resistance test. For example, a short-circuit fault between the winding parallel wires will not be obvious in the turns ratio and winding resistance or other test, but it will indeed be evident in the single-phase excitation test because when we do the test, we will see that current change occurs.

We always use 220 V / 380 V single-phase excitation for diagnosis. The test voltage should normally be applied from the low voltage (LV) side for easier connection. This test method can more or less be performed with the Doble test set or another tester designed for this purpose. (Doble test set always supplies 10 kV to the high terminal but has the same

The single-phase excitation test can help to identify the defective quality of a transformer, which cannot be found by turns ratio test and winding resistance test

purpose.) This method is safer and easy to perform because not every client has the Doble unit but a usual contact voltage regulator. One should be aware of voltage appearing at other terminals and to ensure safe limits are not exceeded when performing the test. A note should be taken with regards to safety considerations when performing these measurements.

Also, just to note on terminal designations, it is probably best to keep it simple, e.g. A-B-C-N for HV and a-b-c-n for LV etc., mainly to keep it easy and consistent for the reader. Before you perform the test, it is important to review the factory test report to determine if the tap position and test voltage are in the same condition as when the test was performed in the factory, otherwise you will get the wrong guidance.

For single-phase unit as well as three-phase transformer bank, when we perform the single-phase excitation test, we could

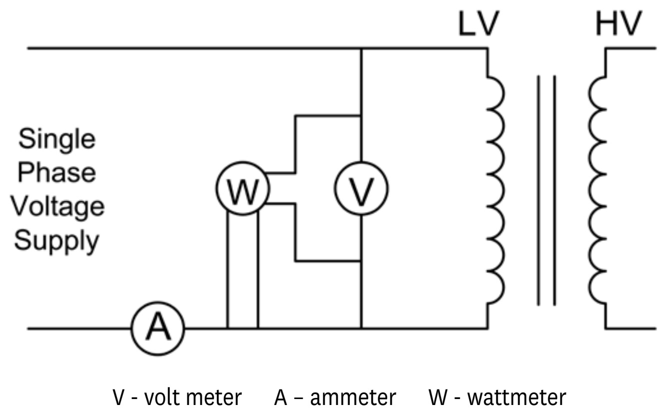

Figure 1: Standard requirement for single-phase excitation

Before performing the test, it is important to review the factory test report to determine if the tap position and test voltage are in the same condition as when the test was performed in the factory, otherwise a wrong guidance could appear

compare the results with the factory report. At the same voltage, the result compared with single-phase units will differ less than 5 % for the loss and current.
For three-phase transformer, the following should be performed: the entire test method phase by phase, for a three leg or five leg core structures. When we test the middle phase, we will get high readings for current and loss because the magnetic flux has a long way to flow.

For transformers with wye-connected LV windings, measure the following:

- supply l1-l0, short circuit l2-l0
- supply l2-l0, short circuit, l3-l0
- supply l3-l0, short circuit l1-l0

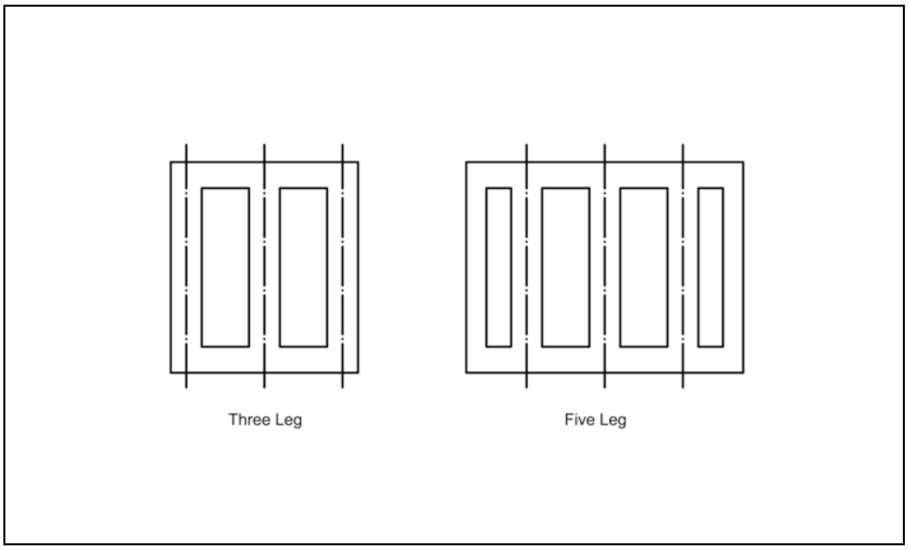

Figure 2: Three-phase core types

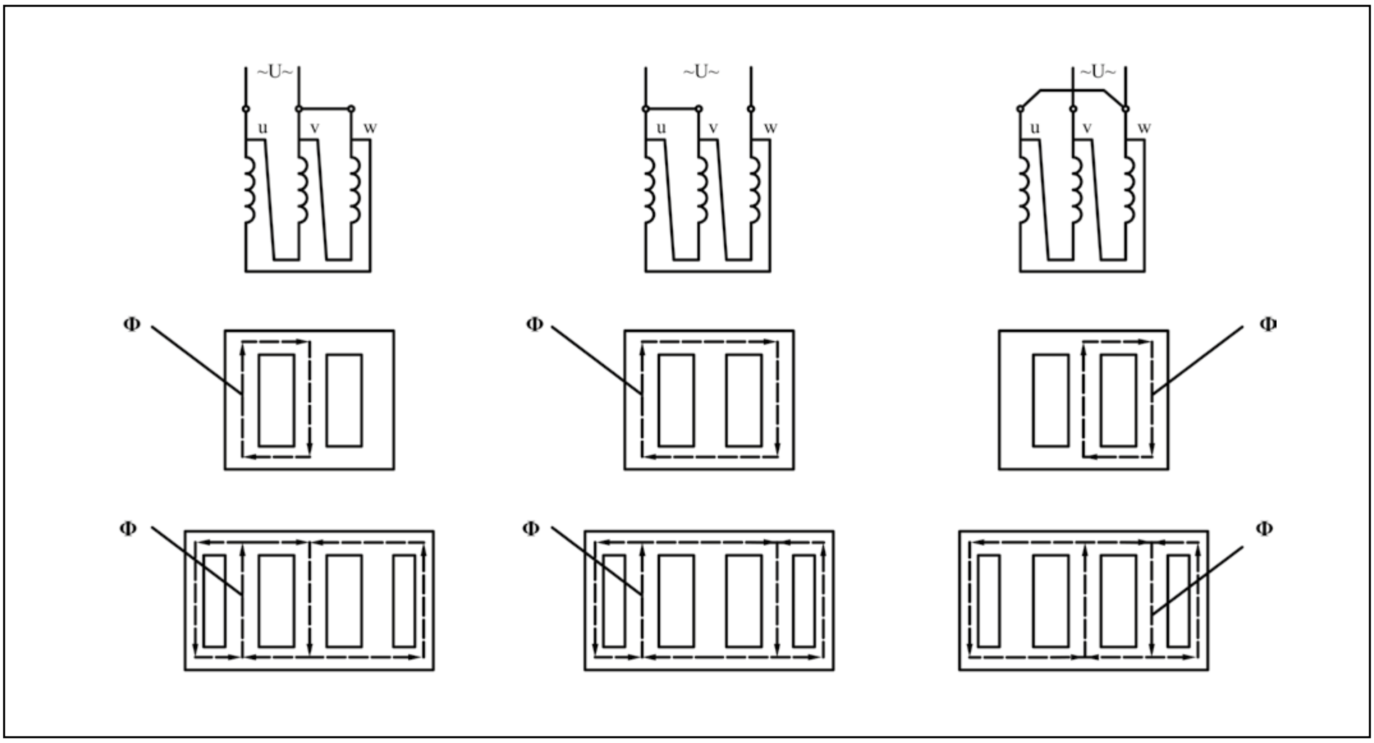

Figure 3: Single-phase excitation for three phase transformer, d11

Table 1: Single-phase excitation for three-phase transformer 220 kV, 180 MVA, five leg ,YNd11

	Supplied	Shorted	Voltage (V)	Current (A)	Loss (W)
Before DC resistance	uv	vw	220.0	0.3167	42.2
	uw	uv	63.1	0.5273	64.2
	vw	uw	220.2	0.3102	41.5
After DC resistance	uv	vw	220.0	0.4658	66.1
	uw	uv	220.4	0.9077	96.1
	vw	uw	220.4	0.4597	

		Supplied	Shorted	Voltage (V)	Current (A)	Loss (W)
Factory report		uv	vw		0.4518	49.2
		uw	uv	220.2	0.8123	84.2
		vw	uw		0.4502	48.8
Test result on site	Before demagnetised	uv	vw		0.7658	85.1
		uw	uv	220.4	1.177	126.1
		vw	uw		0.7707	83.1
	After demagnetised	uv	vw		0.4523	50.8
		uw	uv	220.0	0.8317	87.2
		vw	uw		0.4499	50.0

Table 2: Single-phase excitation for three-phase transformer 110 kV, 200 MVA, five leg ,YNd11

For transformers with delta-connected LV windings, measure the following:

For d11
- supply L1-L3, short circuit L1-L2
- supply L2-L1, short circuit L2-L3
- supply L3-L2, short circuit L3-L1

Excitation tests must be performed before any DC tests because the application of DC voltage may alter the test results. The results from single-phase and three-phase excitation will not always correlate. If the voltage applied in the field is not properly selected, we should also notice that in waveshape of the supply, it is really better if the reading of root mean square (r.m.s.) voltage and root mean (r.m.) voltage is within 3 %. Then the data may be influenced by the magnetising reactance. If there is suspected residual magnetism in the transformer, transformer being tested may be demagnetised before the commencement of magnetising current test.

Here is the comparison of the same three-phase unit before and after the DC resistance, where we can see very high readings for current and loss.

Comparing several types of transformers and structures, either in factory or on site, when we perform the test after the DC resistance test, we will always measure erroneous results, but generally after demagnetising, the measurement data is in a good agreement.

But we should note, although we get a high reading, the highest one is still when we short the middle leg. That does not change.

Low voltage single-phase excitation test should only be considered as a diagnostic tool, not a pass/fail acceptance test. But if the measured exciting current value is many times higher than the value measured during pre-commissioning checks, then there is likelihood of a fault in the winding, which needs further analysis.

The identical test results help us confirm no damage occurred due to transportation. The availability of test data for both normal and faulty condition results help us analyse the problem in the future.

Compared with several types of transformers and structures, either in factory or on site, when we perform the test after the DC resistance test, we will always get an erroneous results, but generally after demagnetising, the measurement data is normal

Author

Zhan Yangang holds Bachelor's degree in Electric Engineering which he obtained in 2003 and is currently working in Baoding Tianwei Baobian Electric Co., ltd. in China. He has been a test engineer for more than 10 years and has experience in testing of power transformer and shunt reactors up to 1000 kV, phase-shifting transformers up to 600 MVA, 260 kV and HVDC convertor transformers up to 800 kV. Zhan is also experienced in handling and solving the problem of power transformer and reactor assembly work and commissioning test onsite. He has been responsible for South America market since 2012.

Our main differentiators are our employees' technical expertise and good customer relationship. These two main drivers help us deliver valuable products and services while meeting market needs

Interview with Mr. Lars Martinsson, Vice President for Alstom Grid Power Transformers business

TM: Mr. Martinsson, Alstom has stood out this year due to more than one out of the ordinary news, starting with successful testing of HVDC transformers. We are very pleased you have accepted our request for the interview and look forward to finding out more about you and power transformer business management.

You are known as Vice President for Alstom Grid Power Transformer business. Can you give us a little background about yourself?

LM: I studied electrical engineering at the Royal Institute of Technology in Sweden (my home country), where I got the MSc certificate. My professional career started in 1992 working for ABB. I held various senior positions such as technical manager ABB Transformers in Ludvika, managing director of ABB Transformers UK, managing director of ABB Transformers Ludvika, global head of Large Power Transformers business and subsequently became the head of Power Products Division.

Prior to my actual position at Alstom Grid, I was the CEO of Pharmadule, a supplier of advanced modular production facilities for the pharmaceutical and biotech industries.

TM: What do your responsibilities as Vice President for Alstom Grid Power Transformer business include?

LM: Generally speaking, my responsibility is linked to the definition of power transformers and bushings strategy and activity within the company including the business development, the manufacturing and the sales at the worldwide level.

TM: What are your greatest challenges as a Vice President in a large company?

LM: Right people at the right places around the world to be close to our customers and to achieve an efficient organisation. Ensuring the correct understanding of the market needs and developing our business to be in line with them.

About the company

TM: Before we go to the hottest part of the interview, please tell us a few words about Alstom Grid Power Transformers. What is annual sales turnover and how many people does the business employ?

LM: Annual sales turnover is around €700 million to €900 million, depending on the phasing of the projects with a team of over 3,500 people.

TM: How many manufacturing and engineering sites do you have worldwide?

LM: We have 11 manufacturing units with same technical concept, manufacturing processes and the same quality assurance. We have also got one global R&D centre and technology centres for different products distributed in various units.

TM: How does the business serve different markets (company and territorial organisation) and makes it stand out?

LM: We are close to our customers through regional sales organisation supported by the technical knowhow of our factories.

TM: What is your secret to achieving customer satisfaction?

LM: It is not really a secret but it is to ensure a high level of technical competence and being able to support the customer to choose the best solutions and to be able to manage complex requirements.

TM: Where do you see Alstom Grid Power Transformer business heading to?

LM: We will continue to be among the leading players. The most important aspects - global presence, customer relationship and quality.

TM: Transformers Magazine has recently published news regarding successful HVDC 800 kV transformer FAT testing in China as well as successful testing of the HVDC bushing. Can you tell us more about this?

LM: We have made tremendous progress. The work that has been done not only included the technical solutions, but also the build-up of competence and the capability and infrastructure to manufacture these advanced products. I am very pleased about the performance of our R&D organisation and the response we have received from our customers.

TM: How long did it take to complete the development?

LM: The work has been done in a relatively short time, less than five years. Part is based on our previous extensive experience in HVDC technology.

TM: How do you see the demand of these products developing in the future?

LM: We see significant increase in the demand for HVDC systems driven by interconnection on asynchronous systems, connection to renewable energy generation pools, narrow corridors and land impact along with the long transmission distance. We can expect the HVDC market to be a significant part of our volume.

> **We see significant increase in the demand for HVDC systems**

Recent projects

TM: Can you tell us a bit more about your recent projects?

LM: There are several but to mention a few, we can highlight Rio Madeira 600 kV, the world longest HVDC transmission line (2375 km) with 28 transformers. Manufacturing was split among three of our units. Another important project is Champa 800 kV DC with 32 transformers which are being delivered as we speak.

TM: During the past few years the market price of power transformers was affected by global overcapacity of production. Do you think that this trend will remain?

LM: There is still an overcapacity of power transformer production but we believe that this capacity will not increase in the coming years. Besides, we believe that the market price will remain stable in the upcoming years.

TM: Besides the traditional manufacturers, nowadays-emerging industrials are penetrating the power transformer market. What are Alstom Grid's differentiations in this market?

LM: Our main differentiations are the internal technical expertise of our engineers and technicians, and a good relation with our customers and end-users. These two main drivers help us to develop valuable products and services meeting the real customer needs.

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Transformers Magazine is the primary source for the latest power transformers industry news, expert views, technology, and trends, with particular focus on green solutions and solutions for smart grid. We publish scientific and professional articles on topics covering all aspects of transformer R&D, design, manufacturing, testing, operation, maintenance, monitoring, diagnosis, fault investigation, decomissioning and more.

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ABSTRACT

There are many trends that shape the global transformer market right now. In this article a number of trends and market drivers are looked at in order to discuss the transformer market outlook. A clearer market view can support a better strategy creation and tactics planning. Market drivers are changing and more focus is on the renewable energy generation as well as energy efficiency and smart grid investments, while at the same time the globalisation of the manufacturing base including high tech transformer capabilities is continuing.

KEYWORDS

transformer market, market changes, market drivers, trends, growth, competition

Power Transformer Market Review

Trends that shape the transformer market

Transformers have existed for over 130 years and even though base materials have improved, the fundamental transformer physics is still the same as when it was defined during the second half of the 19th century. Despite the relatively old age of basic transformer technology, current trends in society and technology shape the transformer business faster than ever before. In this article we will look at what these trends are and how they shape our business future. Using trendspotting as a tool for shaping strategies is an old school method with new opportunities given by the ever increasing flow of information.

Today we can easily gain information even from countries where we do not know the language, simply by pushing the "translate internet page" button on the browser, and gain access to updated information from all parts of the world. My trendspotting

will start with what information technology can do for us in the transformer business, and all the way to what the new market drivers will do for the global transformer market.

Which are then the trends that shape the transformer business environment? Let us have a look:

The Internet as a game changer for global transformer business

The Transformers Forum on LinkedIn has just celebrated the 6th anniversary and it is interesting that on the anniversary day, we could see that new members joined from all the continents! This to me shows that the interest for what is happening within transformer technologies and market is subject to a wide interest. Most of you that have been in the business long remember that the transformers world was much more local than what it is now. Today a lot more players can and will go global in order to grow the business potential. One of the most important matters as we shape our strategies, be it developing new technologies or looking at new markets, is to have timely and correct information. Today, this is easily available without having large organisations for market research, and can be done with very simple means at your desk or even on the go when travelling. Today we have to assume that everybody is equally updated on what is going on, therefore strategies have to be kept updated accordingly.

At the same time the available information makes prospective employees updated on what and how companies are doing, which is shaping their understanding and brand attitude. The Internet is therefore shaping our understanding of the business from all aspects and the global impact is instant.

Mergers and acquisitions (M&A) as well as partnering through joint ventures (JV) are also moving more rapidly and shaping new constellations in order to have a broader product portfolio and deeper market reach. By partnering, new JVs can get a larger geographical reach, business scope and capacity. The pace of change is high where strategies and tactics need to be fluid in a way we have never seen before. The Internet may not create new business as such, but with the free flow of information it will have an impact on how the global transformer business is conducted.

Renewable energy and energy change

Several independent studies show that the majority of energy investments will be made in renewable energy sources during the coming decades. An expected 64% of new generation investments [1] will be made in renewables up to year 2030, and are also most likely to increase its balance against energy based on fossil fuels beyond that time. This will have a deep impact on the transformer market as the countries that have the largest renewable energy investments have the renewable energy bases far from the populated areas.

Looking at energy demand, the quickest growth will be in Asia and Africa followed by South America. The powerhouses for energy demand growth will remain China and India, with India having the fastest growth out of all of the larger economies. Here the investments are expected to be slightly different compared to China where solar and wind investments far away from the populated areas will continue, while in India a high portion of the investments will be rooftop solar installations. Rooftop installations will naturally have a positive impact on the local community but may have a more limited impact on the transformer business as such, due to a lesser weight of long transmission investments.

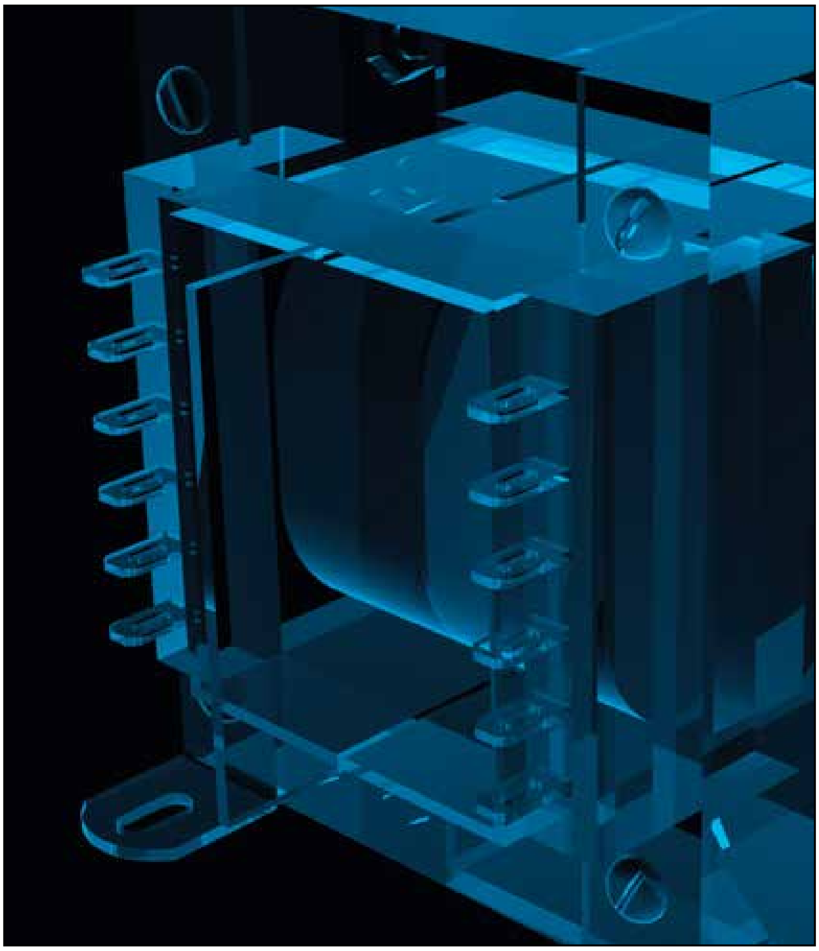
Majority of power investments continue to be in Asia, with Africa as strong runner up for growth

Renewable energy investments are rapidly approaching parity with fossil fuel energy due to the development of solar voltaic panels, which will drive investments more into the traditional Return On Investment (ROI) type of decisions rather than subsidised government policies, which has been the norm up until only a few years ago.

While a number of developing countries have an increasing demand on electric energy, there are a number of countries that will have a shrinking energy need at the same time. This is driven by energy efficiency investments in combination with a lower industry output. The change going from fossil fuels to renewable energy sources is driving a need for more investments in transmission capacity. This is the case for many developed countries, specifically for Europe and North America.

Other countries with shrinking energy need, like Japan that also has a transformer supply base, will need to export more in order to even remain on the same transformer factory output volume. We can expect Japanese transformer vendors to get even more active on the export arena due to this fact and M&A activities to enable the growth will be targeted based on domestic market of the factory as well as currency development.

Due to the intermittency of renewable energy, HVDC and FACTS will play an even more important role in the decades to come, in combination with new right-of-way restrictions. HVDC VSC [2] technology will thus play an increasingly important role in the shaping of the future transmission landscape. With this, for transformer suppliers it is of increasing importance to understand these technologies in order to tap into the market opportunities as HVDC investments are expected to outgrow the speed of the general transformer market growth for years to come. The current expected CAGR (compound annual growth rate) of HVDC is at 17% [3], which is effectively 10 percentage points higher than the global transformer market growth, and thus driving a relatively high demand for HVDC connected transformers.



Energy efficiency

The European Commission issued an Ecodesign Regulation [4] that will ensure that transformers progressively become more efficient. This is good news as it will result in better performance of the electricity grid and decrease the European carbon footprint, and it will at the same time make the industry sharper as the regulation will effectively see to that all that want to participate on the European market have to live up to the more strict standards. Those that fail to do so will have to turn to business elsewhere.

This may be a small step when it comes to lowering emissions but as a part of solving the bigger carbon emissions picture, it is still important. When this kind of measure is followed up in other regions, eventually the sum of energy efficiency measures will be notable.

For transformers alone the EU Commission has estimated that the energy savings is equivalent to 50% of Denmark's yearly consumption of electric energy. For one type of product it is already a good start, and when followed up by other industry and domestic energy savings, it will be a very good progress.

The effect on the transformer business will be that the demand for efficient core steel will increase. For those suppliers that do not have access to low loss core steel it will be tougher to get access to the European market, and at the same time make those that make it on the European market even more attractive in other markets as well due to having more efficient products while driving down the lifetime cost of ownership of such transformers.

Energy efficiency will remain an important driver for the whole transformer industry and we can expect that countries that positively drive these kind of policies will also drive a more efficient domestic transformer industry. Countries that put up trade barriers on the other hand will slowly but surely make the domestic industry uncompetitive.

> **Global competition is increasing with high tech transformer capabilities spreading to growth countries**

Technology development directly related to transformers performance

Power transmission technologies are being developed quickly based on the high need for energy in several countries with long distances between energy sources and demand areas. With this we now experience the development of 1100 kV DC in China as well as 1200 kV AC in India. All this development will have a fundamental impact on the overall market due to the fact that high tech development tends to create a quality trust within the market quicker. High tech development tends to have this effect on all markets, and here the transformer market is not expected to be different.

As much of the high tech development is currently in Asia, the trust in players from these countries can also be expected to develop in a positive manner. Just consider how Japanese cars were seen in the 70s and how it is today. We can expect the same kind of development within our industry. There are few products that remain in service as long as transformers do, therefore trust in a supplier's quality has paramount importance for the long term attractiveness of these players. As new transformer manufacturers gain this kind of market trust, it will have an equally paramount effect on the global transformers market playfield. Old and new players have to take this into account when shaping strategies (plans) and tactics (actions) going forward.

> **Energy efficiency requirements from governments will drive transformer designs**

Conclusions

Market forecast reports on the transformer market are frequent and the majority are presented in the Transformer Magazine´s online version, which make it easy for all of us to follow the forecasting trend in case we are interested.

Looking at recent market research studies, the global CAGR indicators were in the first quarter of 2014 at a consensus level of 7-8% for the coming 5-year period. During the last few months there has been a slight expected decline in the same "index" towards 6-7%. As these predictions estimate a development of a global and complex business, we have to treat these predictions with some caution. While looking at global CAGR data, it is important to also get a total view of manufacturing capacity and regional CAGR and market drivers in order to understand the near future. When doing so, we can see that the market outlook for the transformers business looks promising, while at the same time we can expect the global competition to get even tougher. Transformer technology development is not only driven by the development of new materials, but also by the fact that countries where the transmission is developed most quickly have the largest installed bases for transformer manufacturing (Asia).

At the same time we can see great plans for energy investments in South America, Mexico and Africa. In further addition there is an impressive plan for onshore and offshore renewable energy investments in Europe and North America. With all this we can expect a healthy grow within the transformer market for the coming decades, with an increased competitiveness driven by the quick development of the Asian manufacturing base, where the volatility will be driven by currency fluctuations rather than lack of trust for a broader base of new transformer suppliers.

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[1] Bloomberg New Energy Finance´s 2030 Market Outlook, July 1, 2014
[2] *Transformers in HVDC Transmission*, Transformers Magazine issue 2, July 2014
[3] MarketsAndMarkets *HVDC Transmission Market worth by 2018*
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Author

Matti STOOR has 30 years of global experience in working with transformers as well as HVDC. During more than 17 years within HVDC, he was involved in design and development of HVDC control systems and later managed the HVDC control systems department and finally was General Manager of the Converter Technologies operation, covering LCC and VSC HVDC technologies in Ludvika, Sweden. Within transformers Matti has had many roles, where the latter included heading ABB´s overall Chinese Transformer operations as well as Global Business Development for Power Transformers. Matti is now running a business with focus on supporting clients in improving their holistic performance within the power industry. Matti holds an engineering degree in Control Systems, a Bachelor's degree in Business Administration and an MBA in International Business from Uppsala University, Sweden.

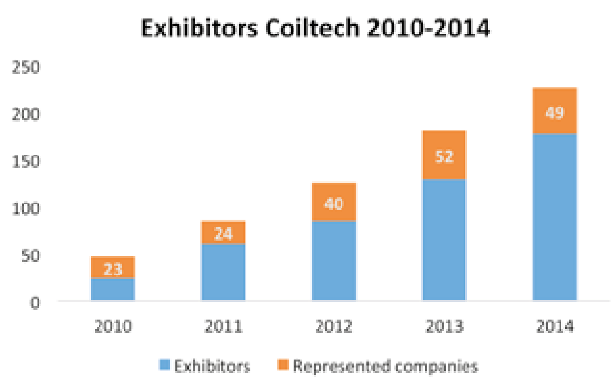
Coiltech 2014 puts a smile

Only four years after its launch in 2010, the exhibition has established itself as a compelling meeting point for the industry. At Coiltech's fifth edition, 177 exhibitors from 18 countries welcomed 1.769 visitors from 37 countries during two very busy days.

"We are only truly happy when all exhibitors tell us that they have had an excellent show and all attendees declare that their time at Coiltech was well spent." stated Matteo Vezzini, client services director at QUiCKFairs® when the doors of Coiltech closed. "And this year we came very close to it. From our personal conversations with the visitors and exhibitors, and the first analysis of the customer satisfaction survey, we know that we have once again taken Coiltech to the next level."

At the World Magnetic Conference, Luca Castellini of Umbra Cuscinetti and Peter Frauscher of the Fraunhofer Institute Dresden received the second Coiltech Energy Efficiency Award.

"We were impressed with the quality of Coiltech," stated Prof.



Highest customer retention rate in Coil Winding Exhibitions:
For the third consecutive time, more than 90% of the exhibitors from previous exhibitions presented themselves to the market at this year's Coiltech. Other shows in the industry have reached a returning exhibitors rate of about 75% within the same time span.

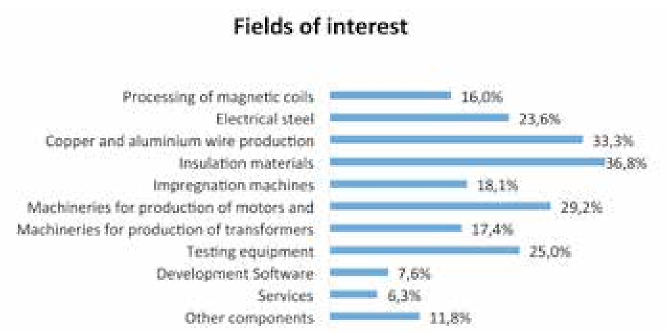
on many faces

Coiltech

Marco Villani of L'Aquila University and President of the Conference“ and it was a difficult choice to assign this years' Coiltech Energy Efficiency Award. In the end, the Fraunhofer Institut presentation convinced us with the evidence it provided for the improvement of magnetic properties using new laser technologies and the Umbra Cuscinetti presentation for its lateral thinking resulting in useful innovation used in aeronautics and automotive applications."

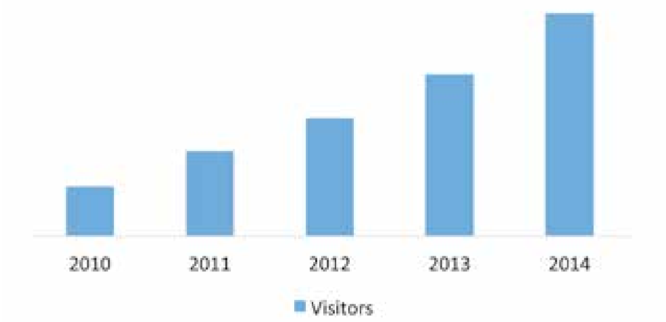
The next edition of Coiltech will be held 23-24 September 2015 at the Pordenone Venue near Venice.
More info: www.quickfairs.net;
www.youtube.com/watch?v=iYChwBJEWmw

At the World Magnetic Conference, authors of 37 technical papers presented the results of their R&D for efficiency improved electrical machines. The 2014 Coiltech Energy Efficiency Award was conferred to Luca Castellini of Umbra Cuscinetti and Peter Frauscher of Fraunhofer Institute.



Coiltech visitors were informed about the entire range of materials, techniques and machinery for the production of electrical machines. In average, every visitor negotiated with 8,5 exhibitors during their visit at the exhibition.

Coiltech 2014 attracted visitors from 37 nations. Compared to the 2013 event, the number of exhibitors grew by 38% and the number of international visitors increased by 51%.



Coiltech is the only exhibition in the industry that has its visitor and exhibitor statistics certified by an independent auditing institute, guaranteeing reliable numbers for marketing planning. The certification protocol does not allow counting exhibitors' staff as attendees.

1.769 visitors discussed their projects in detail with the exhibiting companies at Coiltech. 41,2% of them met up with at least 10 exhibitors during their visit creating a fruitful atmosphere for all participants.

CIGRE 3rd International Colloquium Transformer Research and Asset Management

15th October - 17th October 2014.

Grand Hotel LAV Le Meridien, Split, Croatia

About 200 attendees are expected from all over the world and about 50 papers with scientific insights and new results covering the most critical aspects of power and instruments transformers.

IEEE Conference on Electrical Insulation and Dielectric Phenomena - (CEIDP 2014)

19th October - 22th October 2014.

Nicola BowlerMahmoud Abou-Dakka National Research Council Ca Des Moines, Iowa, USA

Topics of interest to the Conference include: ageing, biodielectrics, charge storage and transport, electro-hydrodynamics, flow electrification, high-field effects, high frequency dielectric phenomena, measurement techniques, nano-dielectrics, outdoor insulation, partial discharge measurements, polarisation phenomena, pre-breakdown and breakdown in solids, liquids, gases, and vacuum, surface flashover, treeing, and cryogenic dielectrics.

IEEE/PES Transformers Committee Fall 2014 Meeting

19th October - 23th October 2014.

Washington DC Metro Area, USA

The Transformers Committee is one of the largest and most active of the 16 technical committees of the IEEE Power & Energy Society (PES). The Committee is comprised of technical and managerial representatives from manufacturers, consultants, vendors, and end-users of electrical transformers & components. The continuing scope of the Committee is to develop and update standards & guidelines for the design, testing, repair, installation, operation and maintenance of transformers, reactors, and associated components that are used within the electric utility and industrial power systems.

EuroDoble Colloquium

Maintenance and Re-investment Strategies in our Power Networks, Stations and Industrial Sites

20nd October - 22th October 2014.

Manchester, UK

Share best practices in maintenance, protection and asset management of power utility assets.

Participate in technical sessions, tutorials and users groups. Engage with top experts and manufacturers from Europe and around the world.

The 15th International Exhibition on Electric Power Equipment and Technology

22th October - 24th October 2014.

Beijing, P.R. China

Established in 1986, EP China is organised by the most authoritative organisation, China Electricity Council (www.cec.org.cn), and fully supported by all major Power Group Corporations and Power Grid Corporations. Over 28 years successful track record and experience, it has become the largest and the most reputable electric power exhibition endorsed by UFI Approved Event in China.

Transformer Life Management - Dubai 2014

28th October - 29th October 2014.

Dubai, UAE

Manufacturers, operators, engineers and scientists will present methods and possibilities for transformer condition assessment and improvement, giving you the information to help develop an efficient maintenance concept. Different diagnostic methods lead to a holistic condition appraisal, helping to identify age related changes and malfunctions at an early stage. This procedure allows early intervention to implement condition improvements that optimise operational reliability.

Transformer Life Management – Guangzhou 2014

12th November - 13st November 2014.

Guangzhou, China

The symposium and associated technical exhibition is directed at engineers, physicists, chemists, technicians and consultants involved in the manufacturing, design, operation, assessment and maintenance of transformers, as well as universities and research institutes with an interest in the reliable operation of electrical networks.

The 12th Annual Euro TechCon 2014

2nd December - 4th December 2014.

Holiday Inn Stratford-upon-Avon, Warwickshire, United Kingdom

EuroTechCon Worldwide Conferences and Expos are annual events devoted to the discussion of technology development and solutions which improve key high voltage maintenance programmes and asset management strategies for the ageing electrical grid infrastructure. Produced by TJH2b Analytical Services, delegates will meet with a mix of utility industry experts as presenters, utility workforce members, corporate suppliers and decision-makers eager to network and share their vast knowledge and experiences. Delegates will have contact with exhibitions that afford extensive networking opportunities and access to the latest industry technology developments and successes.

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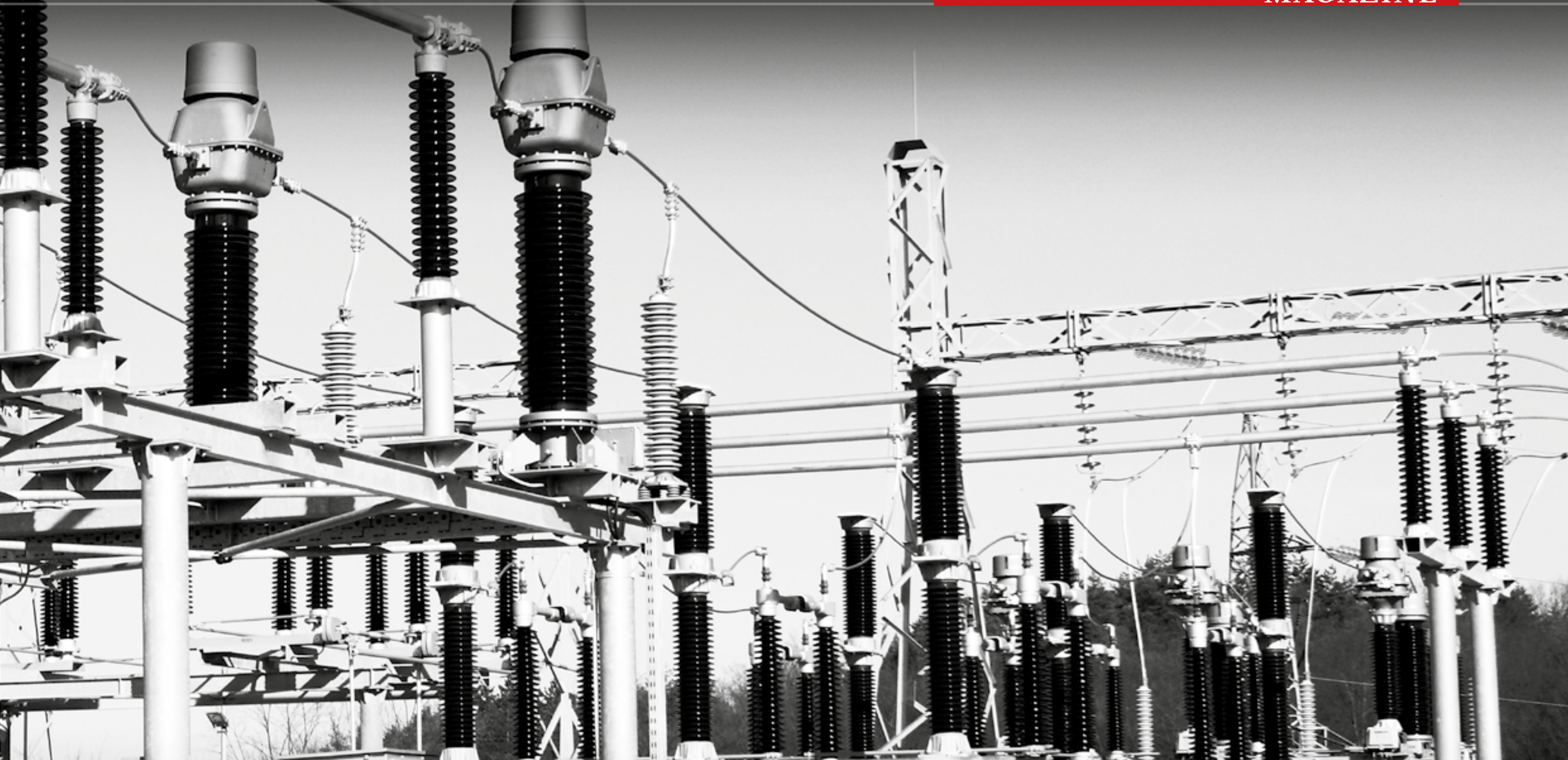

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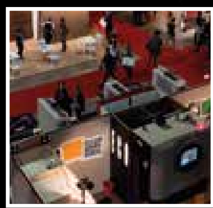

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As an independent voice worldwide, our objective is to advance and promote innovations, growth and progress of the transformer industry. Our website covers business, products and people related news and trends; provides information about the transformer industry related fairs and conferences; provides a forum for information exchange, technology advancements discussions or troubleshooting; and offers access to a global audience of prospective buyers to our advertisers.

Our readers are professionals in the transformer industry who have an opportunity to continuously improve and grow.

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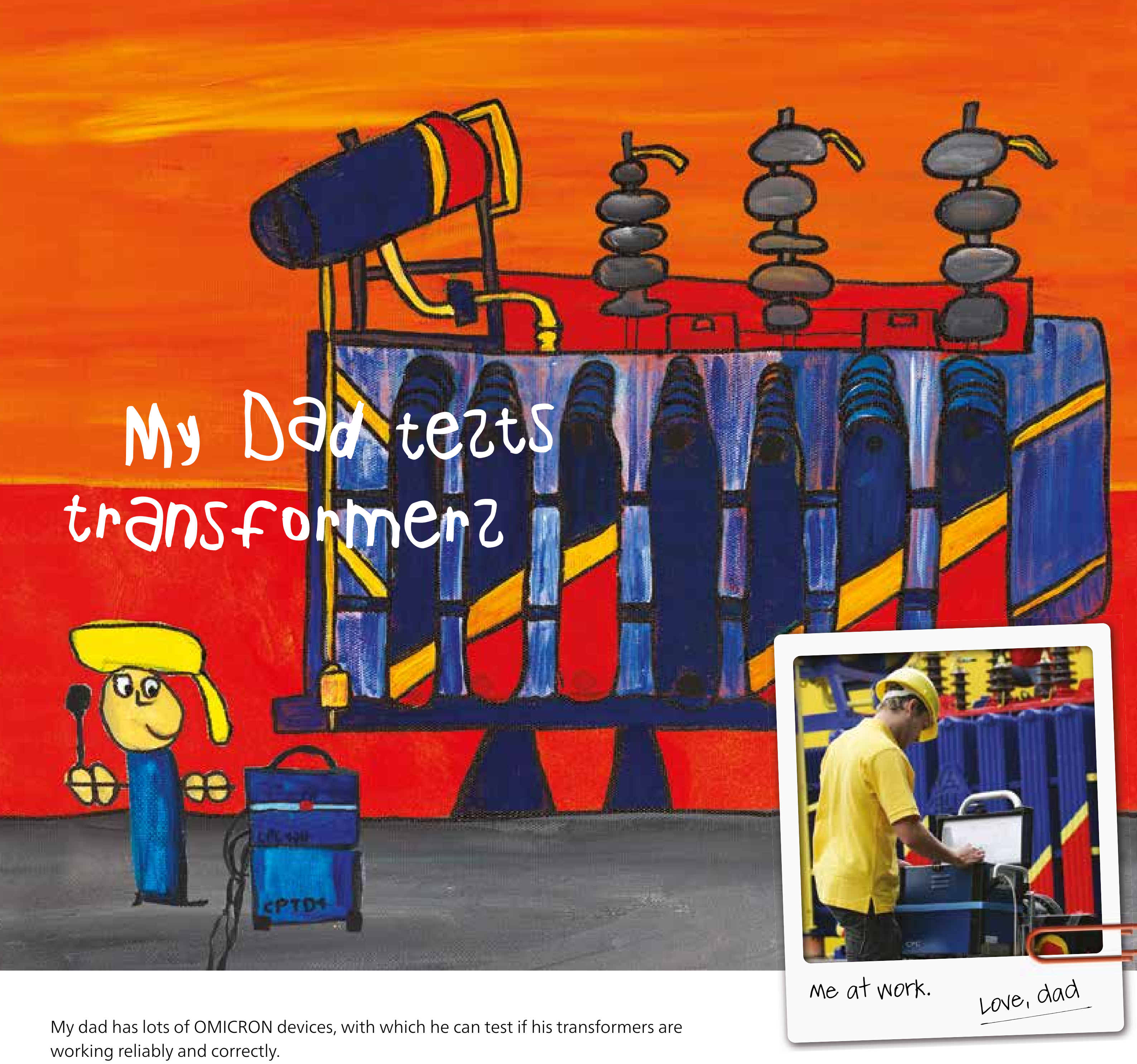
My Dad tests transformers



My dad has lots of OMICRON devices, with which he can test if his transformers are working reliably and correctly.

With just one single device, the **CPC 100**, dad can test a wide range of different parameters such as winding resistance, turn ratio or leakage reactance. In addition, he can test dissipation/power factor and capacitance by combining the CPC 100 with the **CP TD1**. Alternatively, dad can use **DIRANA** for measuring the dielectric response to determine the condition of transformer's insulation. With the **FRAnalyzer**, he can detect defects and faults in windings and in the core. But in some cases, this is not enough, especially if dad suspects partial discharges. With OMICRON's **MPD system** he can detect them, long before the insulation fails and causes a breakdown.

The OMICRON devices work very fast and are accurate. Dad likes this.
And I really like that OMICRON makes sure that dad is safe when he uses them.