Quality of oil makes the difference
ABB discovers the solution to transformer breakdowns

Combined efforts by ABB specialists in power transformer technology and chemistry have discovered a new reason for extreme caution when selecting the proper transformer oil. These new findings are based on a better understanding of the phenomena that takes place in oil filled transformers.

The chemistry of the insulating oil has an even greater impact on the life of the transformer than was predicted by previous knowledge, especially in combination with repetitive transients arising from, for example extreme numbers of line faults on an HVDC line. As a result, new firm recommendations and diagnostic methods will support all customers in eliminating a previously not understood cause of transformer breakdowns.

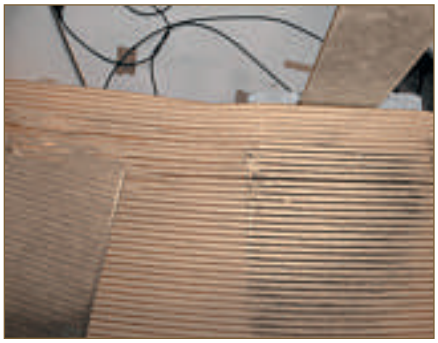
Among the various causes for a power transformer breakdown, ABB has investigated one that is not very common, but can nevertheless occur depending on materials and operating conditions. With a very large installed base of AC and HVDC transformers combined with extensive field experience, ABB was able to investigate, in depth, this uncommon type of transformer failure that have been limited to a few geographical locations.

Some similarities were found between transformers that had broken down. These similarities were:

- Frequent and high amplitude transients
- Failures occurred in normal operation – shortly after external transients. However, no direct external cause for the breakdown was identified
- Turn-to-turn breakdowns in windings
- No break down paths to earth in the transformers

Based on these observations the investigation was launched with only one goal in mind: To find the 'transformer killer'!

1 Part of a winding with copper sulphide deposits on both conductor insulation and on a spacer.



The investigation

The first step involved looking for any possible manufacturing or design deficiencies. A careful inspection of the windings revealed nothing in the area of the breakdown to indicate any manufacturing mistakes.

The design was scrutinized with current state-of-the-art design tools. The voltage transient behaviour of the windings was evaluated by using both calculations and measurements. The measurements were performed by RSO (Recurrent Surge Oscillation). These two methods gave approximately the same result. The strength of the insulation against repetitive transients was also verified by experiments. The turn-to-turn insulation was subject to repetitive voltage transients with a wave shape similar to those caused by line faults. Not one breakdown occurred during this experiment even though the peak voltage of the transients was twice as high as the measured value, and the number of transients corresponded to millions of line faults. The windings should resist these transients with a considerable margin. It was concluded that no design deficiency is causing the breakdowns.

Copper sulphide deposits

When a failed winding was entirely disassembled turn-by-turn, a new piece of evidence was discovered. In some locations there was a shiny deposit on the spacers and the conductor insulation, especially in the wedges between spacer and conductor 1. This deposit was identified as copper sulphide, Cu_2S.

Influence on dielectric strength

The electric conductivity of Cu_2S is significantly higher than the conductivity of paper and oil. This means that the presence of Cu_2S may change the electric field distribution, thereby decreasing the electric withstand strength inside the windings. In order to check this, a series of tests on turn-to-turn models was carried out. These models were so called 'pig-tail' models. Conductors/spacers from a scrapped winding were investigated and both Cu_2S –contaminated materials and unaffected materials were tested.

The tests were performed using AC-voltage. Both partial discharge (PD) initiation voltage and breakdown voltage were registered.
The results of these tests show that:

- PD initiation voltage and the breakdown voltage of the Cu_2S-coated material are significantly reduced as compared to the uncoated material 2.
- Uncoated and unaffected insulation has the same strength as a brand new insulation.

The outcome of the test showed that the PD-initiation level, using coated materials, was reduced to levels comparable to the ones occurring during voltage transients.

Impact from transients

Although Cu_2S lowers the PD-initiation level, depositions of copper sulphide on

the windings alone are not sufficient to create a short circuit or partial discharge between two turns. For either of these to happen, the insulation has to be further degraded by frequent repetitive transients. Indeed, such transients may occur in HVDC applications.

An HVDC transformer is exposed to a commutation process when the current is transferred from one phase to another. A rapid increase in terminal voltage during this process results in fast voltage transients in the windings which locally stress the insulation.

These transients may be high but even the worst transients in operation will be significantly lower than the transients imposed on the winding during dielectric testing of the transformer before delivery.

The control angle (firing angle) a is critical when it comes to the severity of the transients. The firing voltage introduce transients proportional to sin a.

In normal continuous operation the rectifier valves are fired at $\alpha \approx 15°$ and the voltage stress is low.

However, the HVDC converters have the possibility to continuously operate at higher control angles. An extraordinary and serious event is the α–90 operation that causes very high stresses on the turn-to-turn insulations. This operation occurs, for example, during line faults which are normally rare and of short duration 3.

Thus, the road to this type of breakdown is as follows:
A PD partial discharge will be ignited in the Cu_2S contaminated insulation during the transients. This discharge will ultimately not extinguish. It will in fact remain at normal service voltage until the insulation breaks down, leading to a turn-to-turn fault.

Mechanism of Cu_2S formation

Copper is available in large quantities in a transformer, but the question remains as to where the sulphur that reacts with the copper comes from. Before answering this, a few words about oil chemistry is required. Transformer oil is basically a highly refined mineral oil. It consists mainly of a mixture of hydrocarbons, ie, compounds containing only carbon and hydrogen. There are also, however, compounds containing other elements, eg,. oxygen, nitrogen and sulphur. Most compounds containing sulphur can react with copper under extreme conditions. However, only the mercaptans have any significant reactivity under normal conditions. Mercaptans react readily with many metals, for example copper, to form mercaptides. Some aspects of the chemistry of mercaptans have been thoroughly studied and present an explanation for our findings. It is the following chain of events that eventually leads to the formation of copper sulphide:

1. The oil dissolves copper oxide.
2. Dissolved copper reacts with mercaptans and forms oil-soluble copper mercaptides.
3. The copper mercaptides are transported by oil, and where conditions are right they decompose forming Cu_2S and an oil-soluble organic residue.

The key reactions can be represented as

$Cu_2O + 2RSH \Rightarrow 2\ CuSR + H_2O$
(net of steps 1 and 2 above)

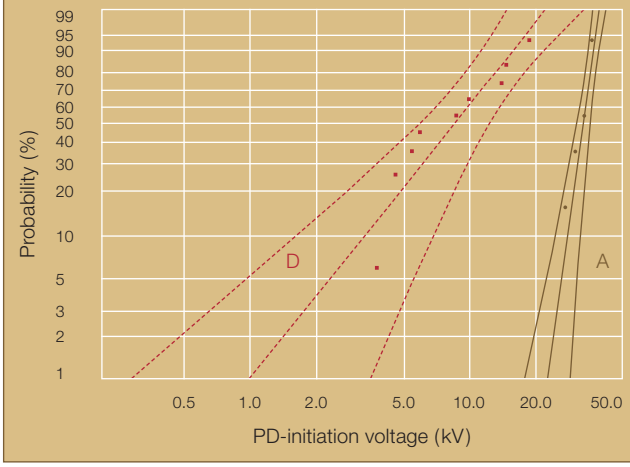
$2\ CuSR \Rightarrow Cu_2S + RSR$
(step 3 above)

where RSH is a mercaptan and R is any alkyl or other hydrocarbon radical. There are of course many different R's.

The reactions above can, to some extent, take place in any transformer. Problems occur, however, when low-refined oils of uninhibited or trace-inhibited type are used.

If all steps 1–3 take place in the immediate vicinity of the copper conductor, copper sulphide will only be found on the innermost paper. However, if some copper is transported away from the copper surface, the final decomposition may take place elsewhere. For this process components in oil other than the mercaptans will come into play. Basic nitrogen compounds and early oxidation products, such as peroxides, will help mobilize the copper. As a rule, not only do poorly refined oils contain more mercaptans than high-grade oils, they also contain considerably

2 Weibull diagrams mercaptans for PD initiation voltage level.



Series A relates to uncoated (healthy) insulation while series D shows the behavior of an insulation coated with Cu_2S.

more of these other harmful components.

Copper sulphide precipitation, like the type found in some of the disassembled transformers, has been reproduced in the laboratory from mercaptan-rich oil and also by directly adding a copper mercaptide to oil.

The mercaptan content of new transformer oils may vary widely, from 0,2 to 10 ppm. The mercaptan content is significantly reduced in transformer oil that has been in use for several years since it is consumed by the reaction with metals.

In addition to the oil, other potential sources of mercaptan sulphur in a transformer have been investigated. So called 'leaching experiments' showed that only insignificant amounts could be traced.

This leads to the conclusion that only low refined virgin oil can be the origin of the 'transformer killer' – Cu_2S.

Diagnostic Methods

Mercaptan content

By a simple chemical analysis we can measure the mercaptan content of oil. However, this is really only meaningful for virgin oil as the mercaptans are consumed with time.

Oil Fingerprinting

It is not always known which type of oil a transformer contains. However, at our disposal is a range of fingerprinting techniques that makes it possible to distinguish between different products. Oils known to cause problems can be recognized, as well as those with a clean track record.

DFR measurement

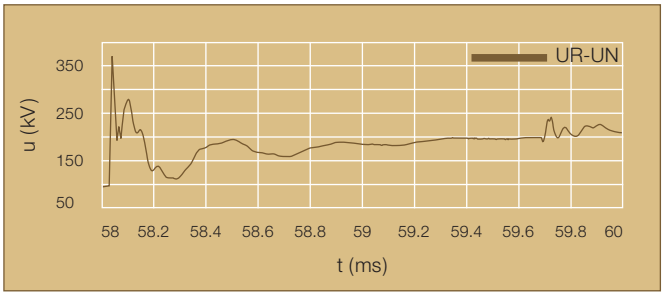
An important electric test method used for transformer insulation diagnosis is the Dielectric Frequency Response measurements (DFR) method. This is a development of the traditional power factor method or tan δ measurement method. Instead of just measuring at power frequency, the capacitances and losses are measured as a function of frequency, typically from a few mHz to 1000 Hz.

The DFR is sensitive to moisture in the cellulose and to oil conductivity, but can also be used to detect contamination on the surface of cellulose insulation. Even though DFR cannot directly detect the copper sulphide contamination inside the winding coils, it will show if copper sulphide deposits have contaminated the transformer in other places. The presence of the contamination will show up in the DFR spectrum with a characteristic profile.

To best interpret the DFR results, knowledge about the design and the dielectric properties of the insulation materials is important. ABB is the leading company in modeling and understanding DFR measurements.

On top of this, ABB is continuously working to better serve our customers with effective failure-proof design/manufacturing measures and on field diagnostics/maintenance services.

3 The voltage transient during α-90 operation.



The wave shape is similar to a standard lightning impulse surge.

Brief summary of conclusions

- Aggressive oil produces copper sulphide.
- Copper sulphide weakens the insulation.
- Repetitive transients further degrade the insulation. In the case of HVDC, transients arising from α-90 operation or transients from continuous High Mvar operation are sufficient to initiate partial discharges.
- A partial discharge PD in the degraded insulation will not extinguish.
- When the insulation is sufficiently degraded, partial discharge will continue at normal service voltage levels.
- A partial discharge leads to a turn-to-turn fault and transformer breakdown.

Compared to earlier research and findings on aggressive oils, we have now been able to explain the chemical process in greater detail. In addition, we now know why certain service conditions in combination with unsuitable oils degrade the insulation faster.

The final conclusion is that the 'quality of oil makes the difference'.

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ABB Group R&D Center – Bangalore, India

ABB's first R&D centre outside Europe and the USA was set up in early 2002 in Bangalore, India. Its focus is on Industrial^{IT} – ABB's open architecture based technology platform which aims at interconnecting plant automation, optimizing plant asset availability and performance, and integrating information for improved visibility and reduced time to decision and action. By doing this in real time, it provides better business decisions faster and hence a greater return on assets. With Industrial^{IT}, ABB wants to enable utility and industry customers to make their processes more productive and efficient.

The centre in Bangalore is an integral part of ABB's global R&D network which has labs in the US, Sweden, Germany, Norway, Finland, Poland and Switzerland. By linking and integrating operations across these centers, ABB is able to bring together a global team of highly skilled scientists in an innovative climate that focuses on developing cutting edge technology solutions for its customers. This network of expertise also plays a leading role in quality assurance for future ABB products and services. Included in its charter is the task of managing the certification process within ABB.

Highly skilled domain experts at work in the Bangalore research center

The Bangalore research facility also has an important role in ABB's strategy for supporting the Asian growth market. The plan is that the center will lead the group-effort by leveraging India's strong engineering, information technology and software development skills, thus providing a significant competitive edge. It also works on products which are more tuned to the requirements of the Asian markets – Asia being a targeted key growth area. An increasing proportion of ABB's product portfolio is fast becoming IT enabled; the Group R&D labs are supporting ABB divisional development centers across the globe to speed up the IT configuration process for their products and systems.

The Indian Industrial IT center develops and supports software intensive products, and provides expertise to the Global Automation Lab in developing and adopting new technologies for ABB. The center in Bangalore is a key strategic technology partner to ABB's businesses in the automation area, with a mandate to monitor, assess and develop technologies for the future.

The center's mission is to create high quality software for ABB by playing a key role in global Industrial IT development and deployment. It also develops, maintains and supports a range of software intensive products, and acts as a partner for ABB R&D centers and business areas within the group.

The concept of the center is based on two main planks:

- A core group of highly experienced ABB personnel with domain knowledge across industries working closely with ABB units and Indian partners.

A set of selected 'partner' companies in India specializing in core software technologies and processes.

ABB has invested heavily in terms of intellectual capital.

This centre brings together men and women who are highly skilled domain experts, and who form the core research team which selects and works with software engineering partners.

Key achievements to date:

- The center in India is one of four global centers authorized to certify products and systems for Industrial IT compliance. The other three are in Sweden, Germany and USA.
- The ABB Group has been very encouraged by the results of two years of operations at the center, which is now entering a rapid growth phase.
- Around 30 projects have already been successfully completed in collaboration with other R&D labs and divisions.
- Over 1000 products have been certified by the Indian center to date, and around 25 projects are currently in progress.
- Products manufactured locally in India have been Industrial IT certified by this center.
- The center has helped achieve considerable cost savings and substantially reduced time to market for several Industrial IT enablement projects, including the release of the new 800xA automation system in December 2003. Globally, more than 800 people, 50 of whom came from the center in India, worked in collaboration to deliver this project.
- The research center is focusing on the following areas:
  - Fieldbus technologies
  - Automated testing
  - Migration tools
  - New graphics technologies
- The lab facilities can handle the same levels of complexity as that of the other centers in Europe and US.

According to Markus Bayegan, Chief Technology Officer, ABB Group, 'Our R&D experience in India has been very satisfying. During its two years in operation, our Automation lab has done excellent work in Bangalore. We are now expanding the scope, complexity, infrastructure and manpower to increasingly leverage the high level of technical expertise, domain competence and experience available here. Moreover, our Bangalore center will extend its role to actively participate in applying automation to power technologies, while continuing to expand its role in the development of automation technologies.'

Demo center in Bangalore

Demo facility

In conjunction with the Bangalore research facility, a first class demo center has been built.

Here many ABB's products are on display in simulated applications, illustrating the plug and produce ability of the product portfolio and the versatility of the core 800xA software. The developers have "live" systems on which to test new software and new applications.

With high expectations and bursting with creativity, the latest ABB R&D lab is ready to welcome and take on some serious challenges.

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