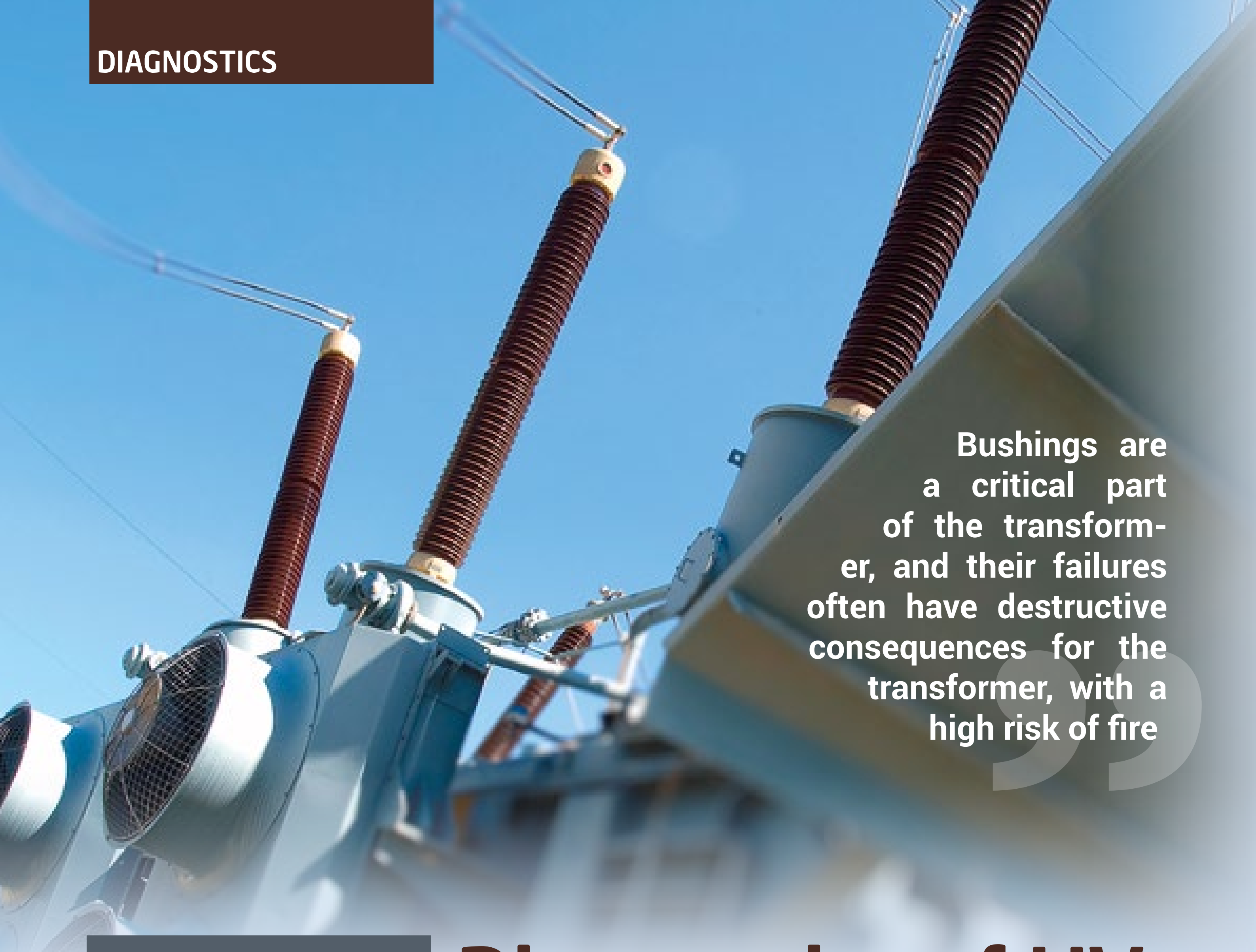

> Bushings are a critical part of the transformer, and their failures often have destructive consequences for the transformer, with a high risk of fire

Diagnostics of HV bushings through oil sampling and analysis

Experience with GSU transformers

ABSTRACT

Bushings are highly stressed parts of power transformers and their failures can lead to a transformer breakdown. The diagnostics and predictive surveillance of bushings is essential for uninterrupted operation of transformers. Diagnostic tools applied include electrical tests, thermography and, to a minor extent, oil analysis for oil-impregnated bushings. This paper gives a short review of bushing types and related applications, including procedures for in field inspection and oil sampling. Dissolved Gas Analysis (DGA) issues in bushings' mineral oil are briefly discussed and diagnostic criteria for DGA interpretation are given, comparing the experience of the authors with the available literature and standards.

KEYWORDS

mineral oil, SF_6, bushings, transformer, DGA, diagnosis

1. Introduction

Bushings are essential accessories of power transformers, circuit breakers and other electrical equipment, making the connection between high voltage windings and inlet or outlet conductors. They allow the high voltage conductor to pass through the tank walls, which are grounded.

Bushings are extremely stressed equipment, subject to a strong electric field intensity with great difference of electrical potential and close distances.

A significant percentage of all transformer failures is caused by defective bushings and such failures can destroy a transformer. A recent survey by CIGRE [1] concluded that 30 % of all bushing faults resulted in transformer fire and 10 % in burst or explosion.

Making a systematic diagnostic surveillance of HV bushing is essential for safe operation of transformers. Therefore, even if it is complex and quite expensive, many big utilities and power generation companies include monitoring of aging and degradation of bushing in their maintenance policy.

The most widely applied diagnostic and predictive tools are thermography and electrical tests, such as measurement of capacity, dielectric losses, power factor (tan delta) and partial discharges.

Oil analysis is not a common practice; nevertheless, it has been recognized as a reliable tool for detecting aging and bushing degradation at an early stage and, consequently, for driving the corrective and preventive maintenance actions in a very effective way.

Since 1998, a big nuclear power generation company in France has been performing a visual inspection and oil sampling and analysis of HV bushings of their GSU power transformers: more than 700 pieces of equipment are systematically controlled, with about 17 % of them being under enforced surveillance, and 5 % replaced before experiencing a failure.

2. Technology of bushings

Bushings for systems having a voltage over 36 kV are capacitor type, designed to reduce maximum field stress and optimize field distribution in both axial and radial directions when passing through a grounded transformer enclosure.

HV bushings are typically composed of a core, made from a conductor wounded as a fuse by several layers of paper, alternated with thin aluminium sheets, and of an external housing of porcelain or polymeric material.

Three main technologies for capacitor bushings have evolved over the years: the Resin-bonded Paper (RBP) type, the Oil-impregnated Paper (OIP) type and the Resin-impregnated Paper (RIP) type.

Due to their manufacturing process, RBP bushings are not guaranteed free from partial discharges and tend to show higher dissipation factors than OIP and RIP bushings. Moreover, since RBP cores are not gas tight, they cannot be used in applications involving SF_6 apparatus.

For the above mentioned reasons, and because of the relatively low acquisition cost, OIP bushings still dominate today's market. Here, the capacitor core is impregnated with transformer grade mineral oil and placed inside a housing made of porcelain or a composite insulator to avoid moisture ingress.

Among the OIP bushing population, two categories of equipment may be identified:

- Oil-air type bushing, where the capacitor core impregnated with mineral oil is sealed but in contact with dry air or nitrogen blanket, Fig. 1. The HV terminal is surrounded by open air
- Oil-SF_6 type, where the capacitor core is sealed, being completely filled with mineral insulating oil, and the HV terminal is surrounded by SF_6 gas

In both cases, the capacitor core remains in a closed liquid environment throughout its lifetime and there may be occasional problems of leakage around gaskets.

The oil-SF_6 type may also be affected by leakages of SF_6 gas, which have a higher pressure (up to 2 bar), into the oil compartment, resulting in an excessive increase of the internal pressure and the automatic disconnection of the transformer by electrical contact trip.

The SOT bushing, Fig. 2, is largely used in the gas insulated terminal of GSU transformers in French nuclear power plants.

The capacitor core of this bushing is filled with oil under vacuum and sealed to prevent air or moisture inlet. An expansion bellow allows for changes in oil volume under temperature variations, with two electrical switches operating an alarm if oil volume reaches the maximum or minimum level. Being completely isolated from the gas compartment and from the transformer tank, during outage periods, when oil temperature is low, the oil compartment may be at negative pressure. A loss of tightness of the sealing gaskets may induce moisture and air entering from the atmosphere. On the other hand, if the sealing gaskets between SF_6 compartment and filling oil are corrupted, an increasing amount of SF_6 gas may enter into the bushing's oil. The insulation properties of the liquid insulation are not affected by the presence of SF_6, but an excessive compression of the bellow may occur, resulting in an unexpected trip of the oil maximum level switch.

Other models of oil-SF_6 bushings, from different manufacturers, can be found in service, such as CTkg, CTg, CTzk, Fig. 3, etc. They have expansion bellows of ancient technology, where the filling oil of the bushing core is always kept at positive pressure, by the transformer oil hydrostatic pressure or by an inner spring.

3. Visual inspection and oil sampling

A regular inspection of the external state of bushings is the first method of collecting information about their health. Presence of rust, oil leakages or bleedings, as shown in Fig. 4, as well as ruptures or traces of discharges on the porcelain surface, moisture or dust into the capacitive plug are all evidence of aging easy to observe and useful to initiate a condition based maintenance action.

Oil sampling from oil-air bushings is not a critical or hard operation; it may be easily done from the top of the bushing using a syringe and a plugging hose. Oil sampling from a sealed type bushing, such as oil-SF_6 type bushings, can be done using the oil filling and/or drainage valves. The temperature of the oil and the expansion quota of the bellow should be measured before and after sampling. When necessary, a top-up with pre-treated unused mineral oil should be performed.

Oil sampling from and topping-up of oil-gas bushings are critical operations which

Even if not a common practice, oil analysis has been recognized as a reliable tool for early detection of bushing degradation

Figure 1. Oil-air bushing

Figure 2. Oil-SF_6 bushing SOT model

Figure 3. View of a CTzk bushing model

require skilled and trained personnel who are equipped with proper tools and operating a reliable and proven technical practice, Fig. 5. The air entering the bushing core during sampling operation or during oil top-up after sampling may generate partial discharges or insulation breakdown, thus it should be strictly avoided.

4. Oil analysis

A typical monitoring plan, based on oil analysis, generally includes a few basic tests, which require low oil volume, but provide key information about aging or degradation of the bushing core.

The recommended tests are:

- Dissolved Gases Analysis (DGA), according to IEC 60567 [1]
- Water content, according to IEC 60814 [3]
- Dielectric Dissipation Factor (DDF) of the oil, according to IEC 60247 [4]

For oil-gas bushings the DGA shall include the measurement of SF_6 dissolved in the mineral oil. Other tests such as particles, metals, furanic compounds or corrosive sulphur are considered complementary, addressed to specific investigation purposes.

4.1 DGA in bushing's oil

In the power transformer application, DGA is the main diagnostic tool which provides information about oil and paper thermal degradation and presence of partial discharges and other electrical faults. The measurement of SF_6 concentration in the insulating liquid is a key parameter for monitoring gasket tightness. SF_6 is not among the gases detected by the IEC 60567 [2] analysis method. There are two main problems which are encountered when a traditional DGA method is applied to SF_6 detection. First, this method, as well as ASTM D3612 [5], requires the use of an in-line methanizer to convert carbon oxides in methane in order to improve the sensitivity of quantifying CO and CO_2. SF_6 can react with the nickel-based catalyst of the methanizer and consequently be converted to nickel sulfide and get trapped. This leads to a partial or complete loss of SF_6, and a progressive reduction of the methanizer efficiency, resulting in underestimated values of carbon oxides, even in the following samples which are not affected by the presence of SF_6. Moreover, SF_6 cannot be easily separated from other gases (i.e. ethylene and acetylene) with the commonly used chromatographic columns, e.g. PLOT Q type (Agilent) or similar. PLOT type column (Porous Layer Open Tubular) belongs to the gas-solid GC (gas chromatographic) columns, and usually provides good separation of very volatile solutes (gases — C1-C3 hydrocarbons). The Q-type stationary phase is a porous polymer.

Different approaches have been used to detect SF_6 during the DGA test, with most of them requiring some modification to the ordinary DGA procedure. For example, gas chromatographic columns that allow a better separation of SF_6 from hydrocarbons have been tested, as well as shin-carbon type columns (Restek — high surface area carbon molecular sieve) which allow a good separation of SF_6, but require longer analysis runtime. Alumina type columns are also used.

Bushings are sealed equipment where gases accumulate during the life, and gas concentrations and ratios are different from those in transformers

The presence of the methanizer remains to be the main issue. SF_6 should not pass through this device in order to avoid irreversible retain. While this can be resolved by eliminating the methanizer, Fig. 6, it also implies that CO and CO_2 sensitivity will be severely jeopardized. The use of detectors different from FID (Flame Ionization Detector) and TCD (Thermal Conductivity Detector) is a possible solution to avoid the methanizer, such as PDD (Pulsed Discharges Detector), Figs. 7 and 8.

Other approaches use a multiple-valve switching to bypass the methanizer during the chromatographic run, while SF_6 is being eluted.

However, the above mentioned approaches are not standardized and would require an effort from normalization bodies (IEC and others) to produce standard methods for SF_6 detection.

5. Typical reference values for diagnostic purposes

Typical DGA values in bushings are reported in two IEC documents: IEC 60599 [5] (table A.10) and IEC TR 61464 [6], which is shown in Table 1. Both tables converge giving the same reference values, corresponding to the 90th percentile of the population.

These values are commonly used as a reference for the diagnostics of faults in bushings, but the experience of the authors suggests that some of them are not realistic. More than 10 years of regular DGA survey of HV bushings indicates that many gases can be present in much higher concentrations, even in absence of faulty conditions.

The authors' experience suggests that some of the values, commonly used as a reference for the diagnos-tics of faults in bushings, are not realistic and seem to require revision

It must be considered that bushings are sealed equipment, and thus gases have no way to escape from the oil (as happens in transformers through the open conservator). Gases accumulation during the life of the bushing may result in CO/CO_2 ratios higher than those expected in power transformer oils. Very often carbon monoxide is present at a concentration of the same order of magnitude of carbon dioxide; this behavior, which in power transformers leads to abnormal paper degradation conditions, is quite typical in bushings. In fact, CO is a very volatile gas which escapes quite rapidly from the oil in open systems (such as power transformers), leading to a lower CO/CO_2 ratio. The same carbon oxides' rate of generation in bushings causes an apparent enrichment in CO. This means that typical values of the two carbon oxides should be higher.

Other gases may accumulate in the bushing oil during the time. Ethane is one of them. Especially in the last decade when mineral oils with a relevant stray gassing formation have entered the market, ethane is formed and accumulated in the oil of bushings. The consequence is that a healthy apparatus can easily show ethane levels up to 250-300 µl/l (ppm by volume). The same can be said of hydrogen. This increasing tendency of oils to form stray gassing is currently under investigation by CIGRE, e.g. within the D1.70 WG.

So, the normal values reported in the currently available standards seem to require a revision, based on actual values observed in the tested bushings population. According to the experience of the authors, and relying on a population of 1,400 bushings regularly surveyed (which includes bushings from other generation plants), 90 % of the population values were estimated as reported in Table 2.

Finally, how to distinguish a problematic bushing from a healthy one? The answer relies more on gas increase rates than on concentrations.

Figure 4. Rusty and leaking valve on CTG bushing

Figure 5. Oil sampling from SOT bushing

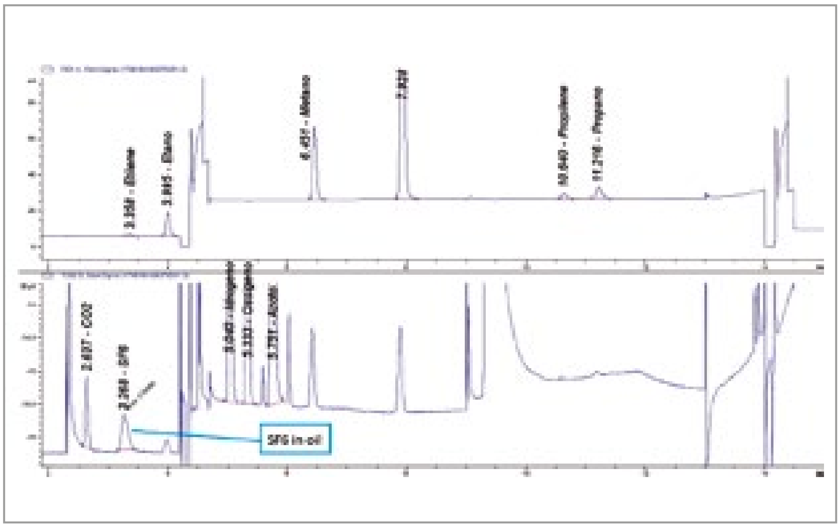

Figure 6. Example of SF_6 detection in DGA, TCD detector, with a switching valve to exclude the methanizer

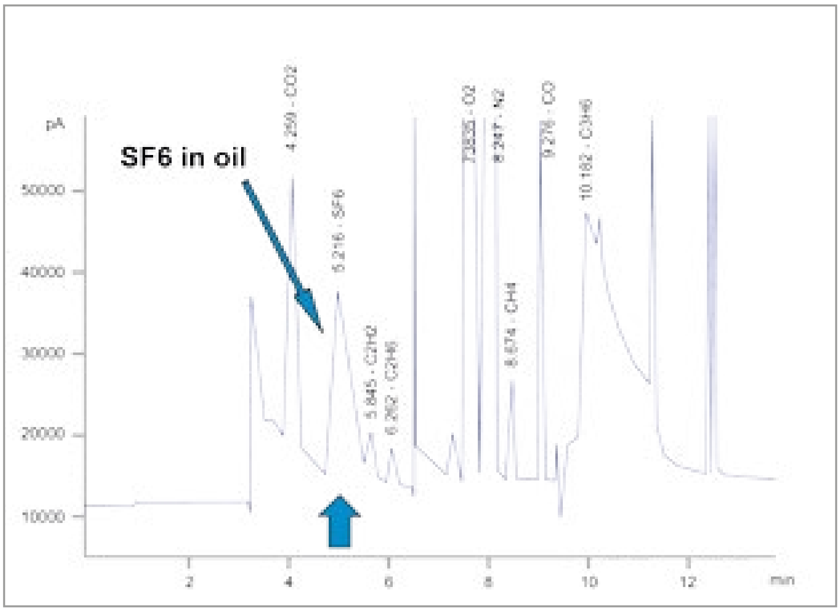

Figure 7. Example of SF_6 detection in DGA, PDD detector

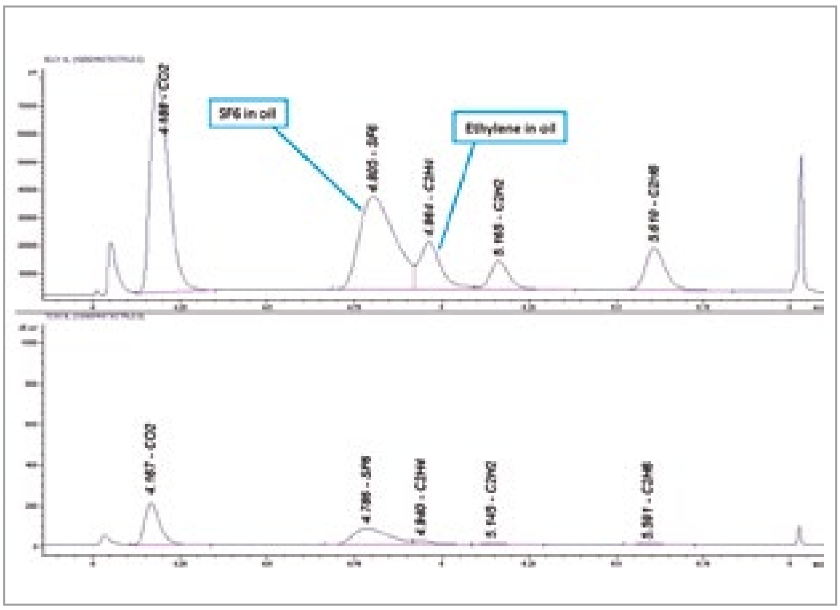

Figure 8. Example of SF_6 detection in DGA (separation from ethylene), PDD detector

Table 1. Normal values for dissolved gases in bushings (IEC TR 61464 [6])

Type of gas	Concentrations µl gas/l oil
Hydrogen (H_2)	140
Methane (CH_4)	40
Ethylene (C_2H_4)	30
Ethane (C_2H_6)	70
Acetylene (C_2H_2)	2
Carbon monoxide (CO)	1,000
Carbon dioxide (CO_2)	3,400

Table 2. Typical 90 % values for dissolved gases (expressed in µl/l) in bushings (author's enquiry)

GAS	90 % typical value
H_2	184
CH_4	98
C_2H_6	104
C_2H_4	22
C_2H_2	0
CO	902
CO_2	1,663

Gases accumulation along the time is quite slow, and can be observed in the trend analysis as a smooth-sloped curve. Fault-related gassing (typically hydrogen increase) can be identified as a rapid and sharp formation. To appreciate the difference, regular DGA survey is strictly necessary. Gas formation rates are not easy to calculate from robust statistical populations because of the relatively low testing frequency. In the authors' statistical enquiry, it was possible to calculate typical values, but calculating the increase rate requires a larger amount of data. As a rule of thumb, it is possible to consider a gas formation rate as abnormal if the slope of the gas evolution curve changes sharply compared to the historical data.

In the absence of fault symptoms, regular DGA testing frequency can be applied (each 12 to 36 months), but in case of evidence of abnormal gas formation, the controls should be run more frequently, even weekly or daily in worst cases.

DGA on bushings may require some special analytical solutions when SF_6 can contaminate the oil

> **As a rule of thumb, a gas formation rate can be considered as abnormal if the slope of the gas evolution curve changes sharply compared to the historical data**

Once an abnormal condition is found (based on the increase rate of gases), key ratios allow identification of the fault type. The key ratio criteria are very similar to the ones usually applied in power transformer diagnostics. The main difference is that the H_2/CH_4 ratio linked to partial discharges is quite higher than the one applied to power transformers: 13 vs. 10. This is another consequence of the fact that bushings are sealed units, and hydrogen cannot escape once formed.

Partial discharges are the most frequently observed type of fault in bushings. Of course, strong stray gassing can simulate PD, and the hydrogen formation should always be confirmed to be in positive and fast evolution to link it with a real PD phenomenon; and electrical PD measurement should be performed as a final confirmation. Localized overheating (that generates ethylene as the main gas) is quite rare. C_2H_2 formation above 2 µl/l is always an alarming symptom, and often leads to the replacement of the unit.

Conclusions

Bushings are a critical part of the transformer, and their failures often have destructive consequences for the transformer, with a high risk of fire. Their regular inspection, by means of electrical on-line testing (continuous) and oil sampling (annual), is of a paramount importance to ensure transformer reliability. DGA is a powerful tool for predictive maintenance, but its interpretation requires certain experience and a sufficient background in real cases in order to correctly estimate the typical values and, most of all, the gas rates of increase that can be associated to a faulty condition. DGA on bushings may require some special analytical solutions when SF_6 can contaminate the oil.

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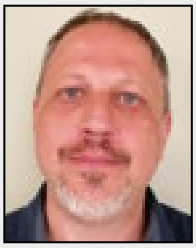
Authors

Riccardo Actis holds a degree in mechanical engineering obtained from Polytechnic University of Turin in 1995. Today he is the Head Manager of the On-Site Service Department at Sea Marconi, with 15 years of experience at the organization and follow-up on-site work activities gained in Italy, France, Spain and other EU countries. Riccardo has a deep knowledge of condition based maintenance, as well as treatment and decontamination techniques for mineral insulating oils. He participates in standardization working groups of IEC TC10 , CEI TC14, and CIGRE.



Riccardo Maina has been working for Sea Marconi Technologies since 2001. As the Laboratory Manager at Sea Marconi he has developed new analytical methods for oil analysis, diagnostics and decisional algorithms for test interpretation, software for data mining and LCA. Riccardo is a member of the Italian IEC TC10 National Committee since 2002, and is actively participating in several WGs and MTs of IEC TC10 and Cigre SC D1 and A2, dealing with analytical methods (particles, DGA, acidity, additives, metals), maintenance guides, and guides for interpretation and diagnostics (oil degradation, DGA, thermal life of cellulose). He is the author of many papers on diagnostics, transformers LCA, and corrosive sulphur. In 2008, he was awarded the IEC 1906 Award.

Vander Tumiatti is the founder and owner of Sea Marconi Technologies, established in 1968 in Torino, Italy. Within the company, which is involved in research, technologies, products and services for energy & environment, he has developed BAT & BEP Sustainable Solutions for Life Cycle Management (LCM) of insulting liquids and transformers focalized on inventory, control, diagnosis, decontamination, depolarization (DBDS, TCS, Polar Compounds) end dehalogenation /detoxification (PCBs/POPs). Vander has more than 40 international patents and is the author of many international technical and scientific publications. He has been the Assistant Secretary of IEC TC10 since 2000. He is also a member of several international groups, with major participation in technical normative activities (CEN, IEC, CIGRE, IEEE). In 2009, he was awarded the IEC 1906 Award.