> **Metallic sulfides deposited in the paper insulation or detached from metal surfaces significantly reduce dielectric status of the transformer's active part**

ABSTRACT

The article describes the asset and risk management approach of a primary electrical company in the Middle East area. A specific maintenance strategy has been carried out for loss prevention of giant transformers, addressing mainly the corrosive sulfur.

Starting from the international standards and considering the specific context, the appointed consultancy company GCC Lab selected the most efficient long-term mitigation technique: the selective depolarization. This process, developed and operated by Sea Marconi, is proven to be effective in the removal of DBDS and oil corrosive compounds, even after one year, also restoring all chemical and physical properties of the oil.

KEYWORDS:

corrosive sulfur, depolarization, metallic sulfides, oil regeneration, on-line treatment

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On-load integrated treatment of giant power transformers in a severe scenario

Case history of an asset and risk management and maintenance strategy of oil-filled power transformers with corrosive sulfur in the Middle East area

1. The scenario

For transmission enterprises, asset and risk management (according to ISO 55001:2014 [1] and ISO 31000:2018 [2]) is a core function, and it is strongly linked with both revenue and reliability of electricity supply.

Understanding that transformers are the backbone of its grids, a primary electrical company in the Middle East area invested a lot of resources in the assessment of its strategic assets.

Looking to increase the resilience of its system, the electrical company appointed GCC LAB as assets manager, particularly in the project of maintenance service for the prevention of failures / damages to improve the reliability and availability and to extend transformer service lifetime.

2. From literature to asset management

Problems encountered with corrosive sulfur in mineral insulating oil are related to the formation of metallic sulfides (copper and silver) in the active part of the transformer under operating conditions, which can be the cause and contributing factor to transformer failures. Metallic sulfides deposited in the paper insulation or detached from metal surfaces significantly reduce dielectric status of the transformer's active part.

The CIGRE Technical Brochure 378 [3] reports that from 2005, the problem of the formation of copper sulfide (Cu_2S) in transformer insulation has been investigated as this phenomenon had caused numerous failures in transformers and reactors. It is reported that "even though it has only relatively recently [2009] been recognized as a serious problem, the re-examination of old failure cases indicates that the problem is not new" [4].

The CIGRE Technical brochure 625 [5] similarly reports that transformers that failed during the last two decades, where corrosive sulfur was at least partly responsible, were filled with insulating mineral oils containing dibenzyl disulfide (DBDS) in a very large majority of cases. Again, temperature and concentration of reactive sulfur are the main risk factors.

Removal of corrosive sulfur from the oil or oil replacement is recommended as long-term solution in the cases of highly stressed and fully loaded units with high winding temperature and intensive oxidative degradation

Appendix 2 of the CIGRE TB 625 summarises the failure cases.

The corrosions determine a functional risk for transformers and equipment filled with mineral insulating oils that can be classified as: C1-DBDS and corrosive sulfur; C2-NOT DBDS and corrosive sulfur; C3-SCBP (sulfur combustion by-products) and corrosive sulfur; C4-NOT corrosive sulfur and metal dissolution [6].

The state-of-the-art international guidelines approach, like CIGRE Brochures, has been the basis of the asset management strategy proposed by the GCC LAB.

The electrical company, supported by GCC LAB, carried out an extensive investigation of corrosive sulfur and DBDS presence in its fleet transformer oils, considering the average age of the company fleet (25 years old), the high constant load level, and the thermal stress of transformers due to the load and hot climate of the Middle East. The trigger of the investigation was the asset management approach, just like a physical check-up of a person – looking for a disease related to age, familiarity or symptoms. For example, it is like searching for cholesterol or glycemia in a sedentary middle-aged man.

3. Decision tree for the choice of risk mitigation techniques

The CIGRE Technical Brochure 625 – *Copper sulphide long term mitigation and risk assessment* [7] is internationally recognized as the most comprehensive available document on this matter.

The brochure reports the current best understanding of the copper sulfide formation mechanism, details of service experiences, failures related to copper sulfide, and results of mitigation techniques. The following list of mitigation techniques and recommendations is reported:

- "Addition of metal passivators (Irgamet® 39) would be an efficient solution, especially if performed in the early days of service with corrosive oil. In order to make a decision on whether to perform the second addition of metal passivator, monitoring oil corrosiveness and concentration of reactive sulfur compounds is important.
- […]
- Removal of corrosive sulfur from the oil or oil replacement is recommended as long-term solution in the cases of highly stressed and fully loaded units with high winding temperature and intensive oxidative degradation." [8]

Although passivation is the most widely used strategy, for easy application and economic reasons, Brochure 625 warns about the effectiveness and possible side effects of passivation [9]. In particular, examples of failure after metal passivator addition have been reported. This unsuccessful experience has been attributed to the late addition of metal passivator after copper sulfide was already deposited in the windings and considering the possible depletion of metal passivator and the fact that passivation does not remove the

Although passivation is the most widely used strategy, there are possible side effects of passivation, therefore the removal of corrosive sulfur from the oil or oil replacement is recommended as long-term solution

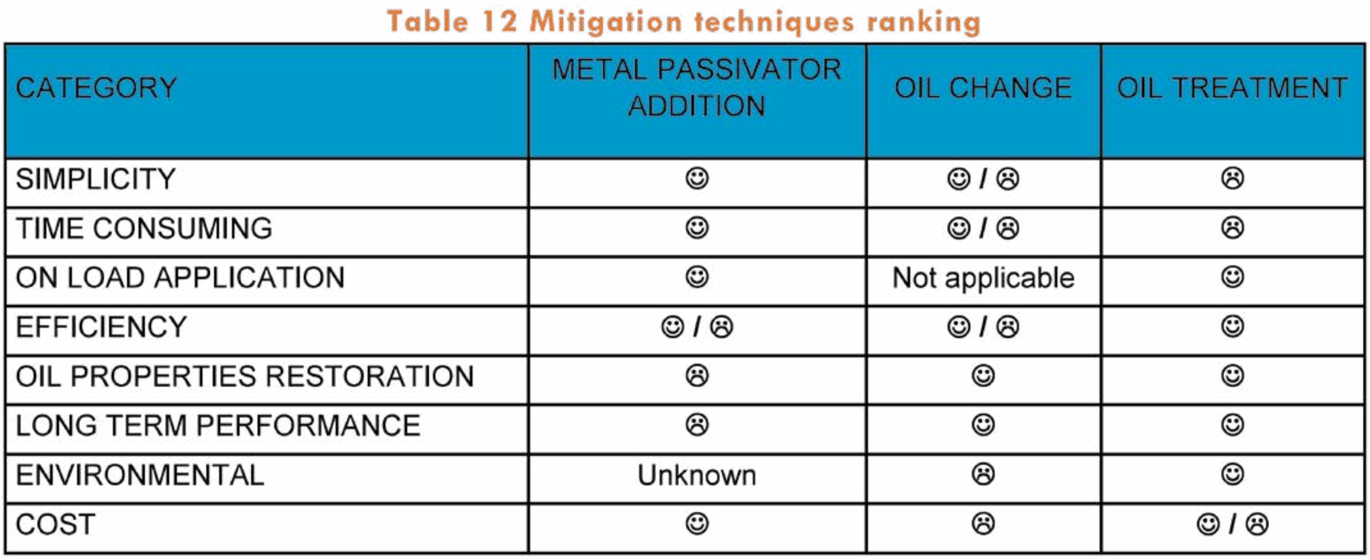

Table 12 Mitigation techniques ranking

CATEGORY	METAL PASSIVATOR ADDITION	OIL CHANGE	OIL TREATMENT
SIMPLICITY	☺	☺ / ☹	☹
TIME CONSUMING	☺	☺ / ☹	☹
ON LOAD APPLICATION	☺	Not applicable	☺
EFFICIENCY	☺ / ☹	☺ / ☹	☺
OIL PROPERTIES RESTORATION	☹	☺	☺
LONG TERM PERFORMANCE	☹	☺	☺
ENVIRONMENTAL	Unknown	☹	☺
COST	☺	☹	☺ / ☹

Figure 1. CIGRE TB 625 – Table 12 – Mitigation techniques ranking [11]

Table 1. Comparison of integrated treatments and Fuller's earth treatments [13]

Key factors	Integrated treatments	Treatment with typical Fuller's earth	Treatment with typical Fuller's earth and regeneration > 600–700 °C
Recovery: physical properties KV, DGA, H2O	✓ Yes	✓ Yes	✓ Yes
Recovery: chemical properties TAN, DF, IFT	✓ Yes	✓ Yes	✓ Yes
Removal: DBDS and corrosive sulfur	✓ Yes	✗ No	✗ No
Decontamination: dissolved metals	✓ Yes	✗ No	✗ No
Dehalogenation: PCBs/POPs in oils	✓ Yes	✗ No	✗ No
Classification: BAT/BEP – best available techniques / best environmental practices (PCBs/POPs)	✓ Yes	✗ No	✗ No
Self-cleaning unit from: DBDS, PCBs/POPs	✓ Yes	✗ No	✗ No
Cross contamination by DBDS, PCBs/POPs	🛡 Safety	⚠ Danger	⚠ Danger
Corrosion by sulfur degradation by-products (SDBP) as H2S, RSH, etc., due to high temperature	🛡 Safety	🛡 Safety	⚠ Danger
Dioxins emissions (PCDDs, PCDFs) due to high-temperature degradation by-products	🛡 Safety	🛡 Safety	⚠ Danger

source of corrosiveness. "Conversely, no failures have thus far occurred for any of the retro-filled (oil change) units". [10]

Considering that typical conditions of the transformers in the electrical company's fleet are high stress and a severe load of the units, the oil change or removal of corrosive sulfur (oil treatment) are recommended as long-term solutions.

Within the project, the removal of DBDS and corrosive sulfur compounds from mineral insulating oil was performed for 22 specific pieces of equipment, including transformers, autotransformers, and shunt reactors

The electrical company explored different mitigation techniques, but the mitigation techniques ranking table reported in the CIGRE brochure and a cost and benefit evaluation have led the electrical company to the choice of oil treatment (removal of corrosive sulfur) as a mitigation technique to remove the DBDS and corrosive sulfur compounds from a set of transformers. Some literature reports a comparison between different oil treatment technologies [12].

Besides this, the company conducted some trials using its own plant for treatment with typical Fuller's earth, without reaching completely satisfactory results, in particular regarding the long-term results.

The electrical company issued a tendering for the selection of the technique for removal of corrosive sulfur, supported by the consultancy service provider.

4. Long-term mitigation activities: the project

The object of this project is the removal of DBDS and corrosive sulfur compounds from mineral insulating oil filled in power transmission transformers of the fleet of 380 kV, belonging to the company, which were found to contain DBDS.

The project addresses 22 specific pieces of equipment, including transformers,

> **The whole ongoing project is performed by keeping the transformers energized (on-load process) under rated load conditions**

autotransformers, and shunt reactors, containing a total of about 1,710,000 kg of oil, having a maximum oil content of 130,000 kg (average of 78,000 kg each), a rated voltage of 380 kV and an average rated power of 320 MVA (minimum 60 MVA and maximum 500 MVA).

The huge dimension of transformers and the need to limit outages due to the grid stress represent the scenario of the project.

Moreover, the peculiarity of the project is that the mitigation activities have to be performed in severe climate conditions, with temperatures reaching as high as 50 °C and in barren sites.

The restoration and improvement of the dielectric, physical and chemical properties of the oil are requested as well (see Table 2).

Since the DBDS acts as an oxidation inhibitor [15], the removal of it may reduce the oxidation stability of the oil. Due to so, at the end of all removal processes within the project, is requested to restore the capability of the oil to withstand oxidation by adding di-tert-butyl-para-cresol (DBPC—an inhibitor commonly used in insulating oils) at a concentration of approximately 0.35 % by mass (see Table 2).

The project requires the removal of DBDS and corrosive compounds: DBDS concentration must be lower than 10 mg/kg immediately after the treatment and after one year following the end of the removal treatment.

Other insulating oil properties must comply with the limits recommended by IEC 60422 [16] standard for mineral insulating oils used in electrical equipment.

5. The process of selective depolarization

In order to get the best compromise between the cost and effectiveness, the process of removing the corrosive compounds, the so-called selective depolarization process, was selected. The process, developed by the Italian company Sea Marconi, is based on the chemical-physical treatment of the oil to remove the corrosive sulfur compounds.

The depolarization process is performed using decontamination modular units (DMU) connected to the transformer in order to realize a continuous closed-loop circulation of the oil, without emptying the transformer, even partially.

Considering that the duration of selective depolarization is typically in the range of days or weeks, depending on the size of the transformer and concentration of corrosive sulfur compounds, it will be operating on-load with a very limited outage time. The whole ongoing project is performed by keeping the transformers energized (on-load process) under rated load conditions.

This technique is based on increasing the polarity of sulfur compounds by means of a chemical solid reagent, whereby they can be subsequently removed by absorption. It thus removes not only DBDS along with most other known corrosive sulfur compounds (elemental sulfur, aliphatic and aromatic mercaptans, sulfides, disulfides, thiophens) but also polar substances. The strong base included in the chemical solid reagent reacts with the DBDS by cracking the disulfide creating a salt of the mercaptan, which is subsequently absorbed by the sorbent materials.

The chemical solid reagents are a mixture of inert aluminosilicate support and active chemical reagents, closely mixed to form a media with an average granulometry of 0.5–1 mm. The sorbent materials are a suitable mixture of clay, earths and other sorbents with a highly active surface.

The former step takes place at a temperature between 80 and 90 °C; later, the oil is cooled down to 55–60 °C for the following absorption step, where polar substances are retained on the active surface.

The replacement of the sorbent material, instead of the typical reactivation of clays at high temperature applied by most of the oil reclamation techniques, avoids risks of any by-product formation and their release into the oil, making the oil more corrosive after reclamation [17]. The residues arising from the process are classified as a standard industrial waste that can be disposed on a landfill. The average quantity is in the range of 2 % in weight on total oil-treated mass.

A vacuum dehydrator ensures the removal of moisture and gases that may result from chemical reactions. An auxiliary circuit, which transfers a part of the flow directly to the vacuum dehydrator, is used to keep the oil at a temperature compatible with the temperature of the oil inside the transformer; this eliminates any thermal deviation within the circulation and cooling path-flow in the electrical equipment.

A simplified hydraulic flowchart of the depolarization processor is shown in the Fig. 2.

6. The selective depolarization processor

The depolarization processor is composed of two decontamination modular units (DMU) hydraulically connected among themselves and with the transformer to be processed.

The main unit provides circulation, heating, mechanical filtration, dehydration, and under-vacuum degassing of the oil.

The auxiliary unit contains a series of percolation columns to be filled with chemical solid reagent and sorbent material.

An additional unit is interconnected between the main unit and the transformer,

> **The depolarization processor is composed of two decontamination modular units which are hydraulically connected among themselves and with the transformer to be processed**

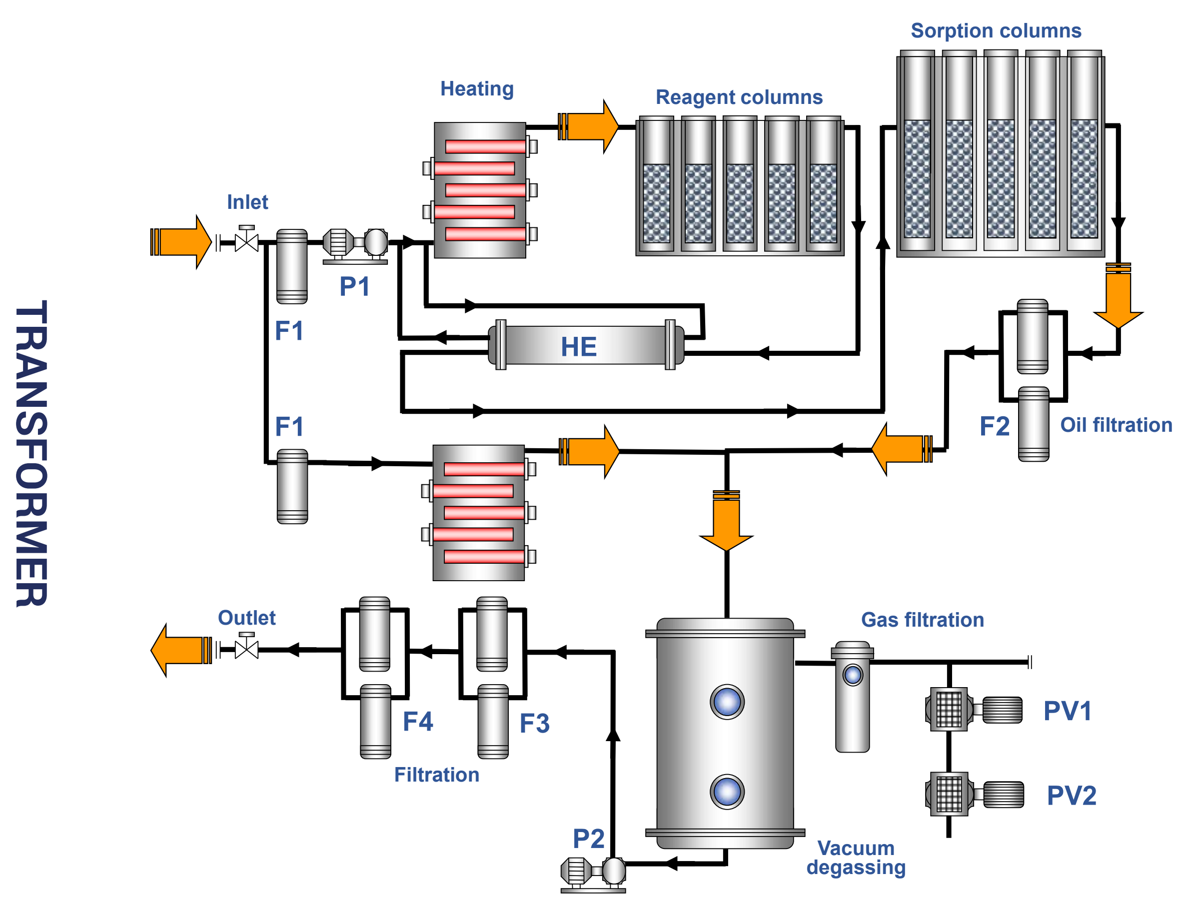

Figure 2. Hydraulic flowchart of the depolarization plant

Figure 3 – A general view of the depolarization technology

> **The depolarization units DMU are equipped with a supervisory control system and safety devices, ensuring the safe operation even without the continuous presence of operators**

having the function of an oil buffer. The purpose of the unit is to ensure a constant flow (without transients) at a low flow rate toward the transformer tank and compensate for the pressure and level of the oil during the replacement of chemical and sorbent material filled in the percolation columns. This procedure avoids the introduction of overpressures or negative pressures into the transformer tank.

The DMU runs 24 hrs per day, 7 days a week, unmanned during the night shift. The depolarization units DMU are equipped with a supervisory control system and safety devices, ensuring the safe operation even without the continuous presence of operators.

In the event of a process alarm, the system is automatically set under alarm conditions, immediately stopping the oil circulation and shutting off valves located at the end of the hydraulic pipes, on the system side and transformer side. Regardless of the alarm type, the system sends a telephone call (GSM) to the work supervisor on-call, committed to reaching the worksite within the shortest notice.

Particular attention is given to environmental issues: quick-drop couplings, steel flexible double-wall hoses and pneumatic isolation valves are used to prevent any oil leakage.

The supervision and alarm system of the depolarization processor can be electrically connected to the transformer protection relay (Buchholz) in order to immediately stop the oil circulation in case of an alarm coming from the Buchholz relay.

7. Method of statement

The dimensions and peculiarity of the pieces of equipment to be submitted to the decontamination process, together with the need to reach long-term warranty results, have led to a specific study and development of a method statement for each piece of equipment. The process has to involve all transformer oil compartments, such as cable boxes, main tank, and conservator. Starting from the evaluation of the transformer hydraulic scheme, including the shape and size of each oil compartment, the oil circulation has been defined. The specific approach for each transformer allows to reduce and mitigate risks.

The use of multi-connection devices (MCU) allows the hydraulic connection of the Decontamination Modular Unit to separate oil compartments (as OLTC, HV cables boxes, conservator) both for

Figure 4. Multi-connection devices (MCU)

Figure 5. General view of the depolarization technology

Figure 6. A general view of the depolarization technology

Within approximately one year of activity, 8 transformers have been successfully decontaminated (36 % of the total), containing about 809 tons of oil (47 % of the total amount), considering 255 operational days

suction and delivery pipes, making the whole oil volume included in the depolarization circuit.

The MCU devices also allow the electric isolation of the depolarization processor from the transformer tank and the accumulation and venting of the air, which eventually enters the oil pipes.

The rated flow rate of oil circulation is controlled and regulated, not exceeding 2,000 l/h, to avoid unwanted Buchholz trips.

8. Results

At the time of writing this document, within approximately one year of activity, 8 transformers have been successfully decontaminated (36 % of the total), containing about 809 tons of oil (47 % of the total amount), considering 255 operational days.

The DBDS concentrations before depolarization of transformers that have been treated were between 135 mg/kg and 171 mg/kg, measured according to IEC 62697-1:2012 [18].

Fig. 7 shows the DBDS removal trend for all pieces of equipment filled with of mineral oil.

As recommended by the guidelines [19] and as required by the scope of work, at the end of the process of DBDS's removal, the oil has been inhibited by adding di-tert-butyl-para-cresol (DBPC—an inhibitor commonly used in insulating oils) corresponding to a concentration of approximately 0.35 % by mass.

All activities have been successfully performed in on-load conditions limiting the outages to an average of 8 to 12 hours for the connection and 2 to 4 hours for the disconnection. During the rest of the processing time, the transformers have been kept to their full operation.

The process and the DMU Units run 24/7. The process has run without significant alarms during all depolarization treatments. The warranty results of the scope of work have been fully achieved.

The final concentration of DBDS measured at the end of treatment processes for all treated transformers are below the warranty limit (< 10 mg/kg) and below the determination method's detection limit (< 5 mg/kg), and in most cases, largely below it.

Oil properties at the end of the treatment fully comply with the contractual scope of work and even with the limits recommended as "good" by the International Standard IEC 60422 Ed. 4 2013 for mineral insulating oils used in power transformers.

Even considering very good initial values, many parameters have been enhanced and, in several cases, reached thresholds applicable for new equipment prior to the first energization [20].

The typical values of oil properties achieved at the end of the depolarization process are given in the Table 2.

The DBDS concentration is to be checked one year after the depolarization treatment in order to prove the effectiveness of the DBDS removal activity.

At the time of writing this document, three transformers / reactors have been checked approximately one year after the end of the depolarization. The results are reported in Table 3.

The advantage of the selective depolarization process, compared with oil passivation, is that its action is always effective in stopping the corrosive reaction

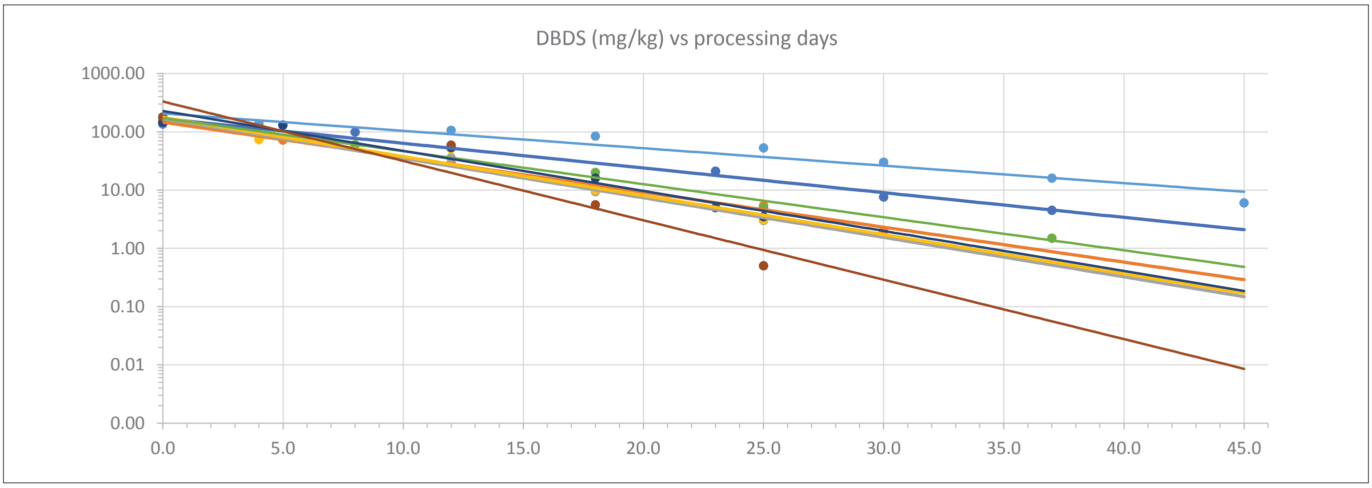

Figure 7. DBDS removal trend

Table 2. Oil properties warranties results and IEC thresholds

Property	Test method	Before treatment (range)	After treatment	Limits(a)	Limits IEC(b)
Sampling temperature (°C)			>40.00		
Colour	ASTM D1500	0.3 – 1.2	< 0.5		≤ 2.0
Water (mg/kg)	IEC60814	4.00 – 8.00	< 2.00	≤ 10.00	≤ 15.00
Breakdown voltage (KV)	IEC 60156	67.00 – 79.30	≥ 70.00	≥ 60.00	≥ 60.00
DDF at 90 °C	IEC 6027	< 0.01	< 0.01	≤ 0.10	≤ 0.10
Acidity (mgKOH/g)	IEC 62021	< 0.01	< 0.01	≤ 0.05	≤ 0.10
DBDS (mg/kg)	IEC 62697	135 – 171	< 5.00	< 10.00	absent
Total corrosive sulphur (TCS)	IEC 62697-2	42 – 189	< 2.50	< 10.00	
Interfacial tension (mN/m)	ASTM D971	29.20 – 37.20	≥ 40.00	≥ 32.00	≥ 28.00
DBPC (%)	IEC 60666	< 0.01 – 0.04	0.3÷0.4	≥ 0.3	0.3÷0.4
Oil passivator IRGAMET39 (mg/kg)	IEC 60666	29.00 – 65.00	< 0.01	absent	absent
Total combustible gases (TDCG)	IEC 60567	217 – 860	≤ 10 µl/l	≤ 300 µl/l	
PCB (mg/kg)	IEC 61619	< 2.00	< 2.00		< 2.00

(a) Requested by the contract specification
(b) Recommended by IEC 60422 ed. 4-2013 international standard for mineral oils in service

Table 3. Oil properties results after one year of three pieces of equipment (available data at the time of writing)

Property	Test method	Transformer 1 after one year	Transformer 2 after one year	Reactor 3 after one year
Sampling temperature (°C)		62	58	72
Colour	ASTM D1500	0.7	0.3	1.3
Water (mg/kg)	IEC60814	8.00	4.00	8.00
Breakdown voltage (KV)	IEC 60156	75.10	66.80	66.40
DDF at 90 °C	IEC 6027	0.008	0.001	0.002
Acidity (mgKOH/g)	IEC 62021	< 0.01	< 0.01	≤ 0.01
DBDS (mg/kg)	IEC 62697	< 5.00	< 5.00	5.10
Total corrosive sulphur (TCS)	IEC 62697-2	< 2.50	< 2.50	< 2.50
Interfacial tension (mN/m)	ASTM D971	40.40	36.90	29.30
DBPC (%)	IEC 60666	0.31	0.32	0.32
Oil passivator IRGAMET39 (mg/kg)	IEC 60666	< 5.00	< 5.00	< 5.00
Total combustible gases (TDCG)	IEC 60567	304 µl/l	215 µl/l	557 µl/l
PCB (mg/kg)	IEC 61619	< 2.00	< 2.00	< 2.00
Potentially corrosive sulfur - CCD Test	IEC 62535	Not corrosive	Not corrosive	Not corrosive
Corrosive sulfur on copper	ASTM D1275	2e - Not corrosive	1b - Not corrosive	1b - Not corrosive
Corrosive sulfur on silver	DIN 51353	Not corrosive	Not corrosive	Not corrosive

9. Conclusions

The electrical company, supported by GCC LAB, is carrying out an asset and risk management strategy to promote the resilience of the grid and its fleet of electrical equipment, through an approach based on diagnosis, prognosis and integrated treatment of technological "pathologies". In the framework of this strategy of the company, the selective depolarization process is proving to be the most effective long-term mitigation technique for the loss prevention caused by corrosive sulfur.

The selective depolarization process, developed and operated by Sea Marconi in cooperation with GCC Lab, has proved to be effective in the removal of DBDS and oil corrosive compounds, even after one year. All chemical and physical properties of the oil have been improved fully complying with the contractual scope of work, fulfilling the requirement of international standards for mineral oils and, in several cases, reaching thresholds applicable for new oils in equipment prior to the first energization. The fact that all the activities were realized with the transformer energized allowed the elimination of energy losses and related costs.

Since 2008, the selective depolarization process has been applied to about 800 pieces of equipment containing approximately 12,000 tons of mineral insulating oil, up to 500 MVA rated power, and 500 kV maximum voltage.

The advantage of the selective depolarization process, compared with oil passivation, is that its action is always effective in stopping the corrosive reaction, differently from the passivator, which cannot eliminate the source of the corrosiveness and can suffer from its depletion. Additionally, some experiments support the idea that the passivator is less effective when the copper sulfide formation has already started, i.e., in the case of late passivation [21]. Moreover, the corrosive compounds are definitively eliminated from the oil, and there is no need for further addition of copper passivators, in particular considering possible side effects such as stray gassing that can be confused for an indication of a fault and / or pre-failure condition of a transformer [22].

Compared to oil replacement, selective depolarization has proved to be more effective and less expensive. Experiences from the field indicate that in case of oil replacement residual corrosiveness may appear as a consequence of incomplete rinsing of the active part. The selective depolarization involves the whole oil mass filled into the electrical equipment and avoids the costs related to the provision and disposal of a such big oil masses [23]. Moreover, the avoidance of draining the transformers (even partially) prevents the risks related to the possible contamination by humidity and air.

Authors

Vander Tumiatti is the founder and owner of SEA MARCONI TECHNOLOGIES (since 1968), Torino, Italy, an international company that is involved in research, technologies, products, and services for energy and environment. He has developed BAT and BEP Sustainable Solutions for Life Cycle Management (LCM) of insulting liquids and transformers focalized on inventory, control, diagnosis, decontamination, depolarization (DBDS, TCS, and polar compounds) end dehalogenation / detoxification (PCBs/POPs). He holds 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 June, he received "1906 Award", the IEC's award for "the precious contribution to the understanding of the potentially corrosive behaviour of mineral insulating oil used in power transformers and for his discoveries, recognised worldwide, in the development of diagnostic chemical analyses".

Simone Maina holds a degree in chemistry from the University of Turin. He is currently Project Manager in Sea Marconi (for UNIDO, UNDP, private sector projects). He was recently involved as PCBs expert in consultancy and training projects for environmental and technical entities (such as in Brazil, Mongolia, FYROM (Former Yugoslavian Republic of Macedonia)). He also participate as project manager in projects for decontamination technology transfer for UNIDO, private sector utilities and electrical equipment user in different countries (such as in the UK, Philippines, Turkey, Mongolia, FYROM (Former Yugoslavian Republic of Macedonia), South Africa, and the Republic of Korea).

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PEER REVIEWED

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In addition to the above, he currently volunteers as the Chairman of Scientific Council as well as the member of SEC steering committee and advisor for the experts' development program in National Grid SA.

Omar Al-Ghamdi holds a master and bachelor's degrees in electrical engineering with more than 15 years of experience in electrical power systems operation and maintenance in Saudi Aramco and the GCCLAB. He also holds a registered engineer fundamental engineering certificate [FE] in electrical and computer engineering. Omar is currently the Director of GCC Lab Technical Services in the GCC Electrical Testing Laboratory Company.

Omar has obtained Best IEEE-SASG-18 Paper for the paper titled "Saudi Arabia Residential Buildings Rooftop PV Solar System: Economic Feasibility Study."