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Instrument Transformers and Bushings using alternative and eco-friendly High Voltage insulation systems

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SUMMARY

Demand of energy is increasing and it's expected to be more and more growing due the installation of new users' electrical assets and the electrification completion of all areas not yet served. Besides this increasing demand, the market trend also shows a growing attention to assets optimisation and a preference for environmental low-impact solutions and equipment.
Customers are looking and giving more and more value to solutions and equipment that have a reduced environment impact during the complete supply chain including Manufacturing, Service, End of life.

A failure on an high voltage Instrument Transformer (IT) or Bushing (BU) has a big impact in terms of continuity of electrical power supply then one of the main challenges of equipment manufacturers is to develop products that use eco-friendly solutions but keeping at the maximum level the product reliability and performances.

Historically two of the main high voltage insulation systems of ITs and BUs use Paper/Mineral Oil or SF6 gas. These technologies are well known and reliable then the challenge is to develop new solutions matching above market trend, without any kind of compromise in terms of product reliability and performances. Deep investigation about different solutions has been done in the past years and now products portfolio that use a fully eco-friendly high voltage insulation systems instead of the existing mineral oils and SF6 gas is available on the market.

This paper provides details about actual development status of follow high voltage products:

1 - High Voltage Bushings Ester Insulated
2 - High Voltage Instrument Transformers synthetic air Insulated
3 - High Voltage Instrument Transformers Ester Insulated

KEYWORDS

Bushing
High Voltage
Instrument-Transformer
Natural-Ester
Synthetic-Ester

1. High Voltage Bushing Ester Insulated (CET)

Capacitive Ester-impregnated Transformer (CET) Bushings (fig.1) have been developed to participate to the efforts for substations decarbonization, but also to increase the service performances of high voltage apparatus equipped with bushings. Actually, ester based dielectric fluids were found to beat mineral oils in thermal and environmental aspects. Hence, the use of ester has been widely studied and promoted for power and distribution transformers in the last two decades and feedbacks are consistently positive. Moreover, the need for monitoring solutions for predictive maintenance strategies is increasing on a global scale. Thus, the use of ester filled bushing on ester or mineral filled transformer allows to expand the monitored parameters, as well as DGA (Dissolved Gas Analysis). Such monitoring possibility is not available with the use of dry bushings.
Combining the high thermal performance of used synthetic ester to monitoring possibilities offered by liquid filled bushings, allows CET bushings to meet top level technical requirements of high voltage transformers. Therefore, risk would be simply mitigated when operating in overload conditions for longer period than the one allowed by standards.

Figure 1: First capacitive ester-impregnated transformer bushing

1.1 Enhanced performances of CET bushings

1.1.1 Thermal performances

The enhanced thermal performances of synthetic ester filled bushing compared with mineral oil is one of the key advantages of this technology. The international standards organizations IEEE and IEC presented as informative data that that the thermal class of the complex kraft paper/ester liquid may be considered 120°C (class E) instead of 105°C (class A) for the complex kraft paper/mineral oil [1], [2]. This represents a huge improvement for liquid-filled bushings and so for power systems. The increased thermal performance of bushings can positively impact the transformer's condition by allowing many options for overload operation. It also offers a greater margin for thermal design than can be exploited to improve the operation performances of transformers.
In fact, the capability of bushings to withstand thermal loading varies depending on the bushing design, the used insulation material, the ambient conditions in which bushings operate and the energy demand. According to IEEE C57.19.00 [3], the utilization of insulating mix with a temperature index 105°C for the bushing condenser implies that the hottest-spot temperature of Oil Impregnated Paper (OIP) bushing, operated at rated current, is limited to a 75°C rise over ambient. Considering 30°C ambient temperature, or a 105°C total temperature. If ambient temperature exceed 40°C for long time or transformer, in case

of long overload, develops a top oil rise more than 65°C, the normal life expectancy of bushing will be shortened due to accelerated aging of the insulating complex.
To overcome this situation, the solution is either to use bushings that have nameplate ratings greater than the transformer current ratings or by using bushings with special high temperature insulation. Ester Bushings are developed to offer this possibility.
In [4] we have highlighted the improved thermal resistance of the new ester bushings and their overload capability and we share the results of different special temperature rise tests of ester bushings in comparison with mineral oils. Evaluating the temperature margins for each voltage level depending on the design to estimate the maximum admissible operating temperature according to IEEE C57.154 and IEC 60076-14, we have finally proposed a general method to evaluate the overload capability of bushing depending on the rating current of the transformer.
The calculation of the overload capability of ester bushing portfolio [5] is shown in table I below. We note a maximum tolerance of 49% additional capability for the 100kV type, which means that for normal life expectancy (normal aging conditions), the bushing can be operated with 49% additional load while respecting a maximum hottest spot temperature for solid insulation in accordance with IEEE C57.154 given informative data.

Table I - Overload tolerances for ester bushing

	Bushing types					
Rated highest voltage Um [kV]	72.5	100	123	145	170	245
Rated current Ir [A]	800	800	800	800	800	800
Overload capability [p.u.]	1.27	1.49	1.27	1.41	1.30	1.30

1.1.2 Moisture tolerance

Another aspect that provides the ester bushings with an excellent technical performance, is the high moisture tolerance of synthetic ester. This means that it maintains its electrical characteristics even with a high volume of water content [5]. Its use in ester bushings prevents several known failure modes, including:

- Bubble generation during overloads: according to IEC 60076-14, the temperature for bubble generation is directly related to the moisture content of cellulose. For example, at one percent paper humidity bubbles will appear at 170°C while, at three percent of paper humidity bubbles will appear at 125°C.
- Condensation: during cycling service conditions (e.g. solar energy), water migration between paper and liquid is contained by ester with no effect on electrical performance.
- Hydrolysis: water is one of the degradation products of paper. Unlike mineral oil, the water tolerance of synthetic ester allows more water to be trapped, which may slow down cellulose aging.
- Oxidation: the ester bushing development included a completely sealed design, and so there’s no risk of cellulose oxidation.

1.1.3 Increased fire safety

The ester based dielectric insulation offers an excellent fire safety, thanks to his high flash point and high fire point compared to traditional insulation liquids, therefore is the perfect solution in terms of fire risk mitigation. The fire point and flash point of synthetic esters compared with mineral oils [3] are shown in table II. The synthetic ester used in the new bushing portfolio is classified according to IEC 61039 as a Class K3 fluid.

Table II - ester vs mineral oil

	Synthetic ester	Mineral oil
Fire safety class	K3	O1
Readily/fully biodegradable	Yes	No
Pour point °C	-56	<-50
Flash point °C	275	150
Fire point °C	316	170
High temperature	Excellent	Poor

1.2 Design activities

1.2.1 Design upgrade

Regarding the electrical design, an important amount of searches indicate that there are some differences between ester-based liquid and mineral oil in terms of dielectric behavior. In fact, the difference concerns principally the ester withstand under transients with a particular shape of electrodes[6]. Some searches state that such difference can be attributed to the difference of dielectric permittivity. As for CET bushings, the required improvements are considered to avoid such issues during service. It is an unchangeable intrinsic characteristic of liquids, but it brings advantages for CET bushings. Relative permittivity of use ester liquid is 3.2 versus 2.2 for mineral oil. This helps to create more homogenous electrical stress inside the CET bushings between liquid and impregnated paper.

1.2.2 Materials compatibility

To avoid any risk of pollution or premature degradation of CET bushings, all materials used in contact with ester, including gaskets, have been checked through oil compatibility test. It is checked by accelerated aging tests of materials in mineral oil and in ester liquid. Then, the potential pollution of liquids is checked by measuring their characteristics as well as loss factor, breakdown voltage or interfacial tension with adaptation of acceptance criteria (based on standard values for mineral oil and the difference with ester fluid). The main change was observed for interfacial tension, which normally gives an overview on pollution done by polar compounds. As ester fluid and water are miscible, this test was replaced by the measurement of total acid number. In a different context, impact of fluids on the material has been checked through the impact on the mechanical properties (elongation strength, hardness, etc.).

1.3 Conclusions

The validation of a new insulation technology for Bushings was a long and difficult process. The performances of complex kraft paper / ester liquid have been already proven for power transformers applications. However, its use in other high voltage apparatus must be deeply evaluated and approved. To validate CET bushings, several test protocols according to standards -as shown below- has been applied:

- Standard type tests according to IEC 60137-2017.
- Qualification and special test according to IEC 60505 and experience feedbacks

2. Instrument Transformers (ITs) insulated with Synthetic Air

For more than five decades SF_6 has been widely used as insulation medium in high voltage GIS, circuit breakers and outdoor instrument transformers due to its excellent physical and dielectric properties. Due to its high global warming potential (GWP) of 23,500 and a lifetime of 3,200 years in the earth's atmosphere [7], the search for SF6 alternatives with lower GWP is the subject of current research and development activities. Electrical equipment filled with synthetic air, fluoronitrile, fluoroketones as alternatives to SF_6 is currently under development. However synthetic air is the only alternative gas with a greenhouse potential of GWP =0 while the other gases mentioned above are still fluorinated "gases".

2.1 Performance

Synthetic air consists of 80% nitrogen and 20% oxygen [8] and is free of other gases that are otherwise in atmospheric air, as well as free of moisture and hydrocarbons. In contrast to other alternative gases, synthetic air is completely environmentally and climate-neutral and harmless to humans and animals. Synthetic air neither contributes to the greenhouse effect (GWP = 0), nor is it harmful to the ozone layer (ozone depletion potential ODP = 0). Synthetic air insulation does not pose any risk of groundwater or soil contamination. Thus, synthetic air insulated devices are ideal for increased environmental protection requirements, such as use in water protection areas. In contrast to other alternative gases, synthetic air does not have to be mixed with carrier gases as CO_2 or N_2 for use in electrical equipment and can be easily filled from the gas cylinder directly into the High Voltage equipment without additional efforts and time-consuming gas handling. Instrument transformers with synthetic air insulation up to Um 420kV (ref. IEC61869-1) were developed based on the same design principles and performance as SF_6-insulated devices. The biggest challenge when using synthetic air insulation is the lower electrical strength, which is 2.5 to 3 times lower than that of SF_6. To compensate for the lower dielectric strength of air insulation, either a larger electrode spacing and or a higher gas pressure must be applied (fig.2). In order to achieve same housing dimensions and footprint with synthetic air instrument transformers as for SF_6 devices, a filling pressure of 12,5 bar rel. is used which is approx. 2 times higher compared to SF_6. All housing parts of SF_6 and synthetic air instrument transformers are designed according to the same design criteria and pressure vessel standards but synthetic air ITs are designed for the higher service and design pressures. This means that all parts have been qualified with a corresponding higher test pressure and bursting pressure where applicable, e.g. for casted aluminum or resin parts. Moreover, all parts are subjected to a pressure test as a routine test for quality assurance and to ensure the highest possible level of safety. A rupture disk provides pressure relief in case of overpressure inside the housing to prevent personal injury and damage to adjacent apparatus as know from SF_6 equipment.
Therefore, there are no concerns about EHS aspects related to the higher filling pressure for synthetic air instrument transformers since the same quality standards, safety rules and requirements are applied for synthetic air equipment coming from today’s standards that reflect the state of the art for pressurized parts and apparatus which were also applied for components designed for even higher pressures exceeding 100 bar, e.g. high pressure autoclaves.
In contrast to SF_6 or other alternative gases, synthetic air shows no liquefaction in the relevant pressure and service temperature range despite the high filling pressure. As illustrated in figure 3 there is no liquefaction of synthetic air insulation even at high pressures up to 30 bar and temperatures well below -100°C. Synthetic air insulated instrument transformers can therefore be used in a wide temperature range from -60°C to + 55°C without any restrictions to low ambient service temperatures.

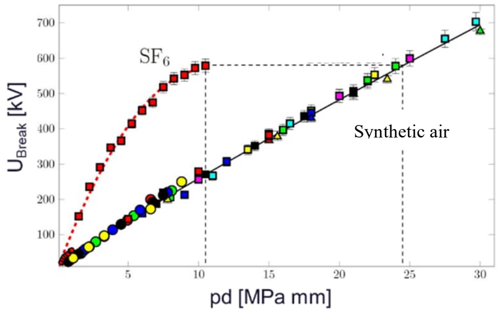

Figure 2: BIL breakdown voltage Ud50 for synthetic air and SF_6 [9] Paschen law is only valid for synthetic air.
Different colored values for synthetic air had been obtained for different pressure and electrode spacings which proof Paschen's law.

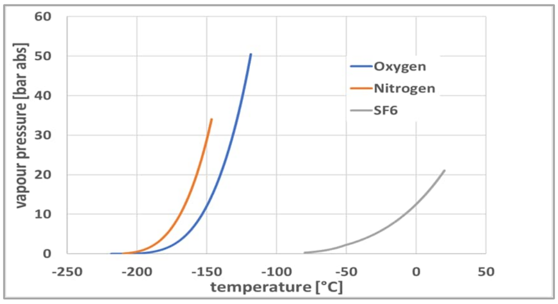

Figure 3: Vapor pressure curves for oxygen and nitrogen as the two components of synthetic air. [10]

2.2 Internal arc fault protection

A decisive criterion for the use of gas-insulated instrument transformers is the high operational reliability and operational safety, especially due to the explosion-proof design.
Applying gas insulated technology with explosion proof housing, composite insulator and rupture disk an explosion proof instrument transformer can be realized which fulfils the highest protection classes according to the corresponding IEC and IEEE standards up to 80kA (r.m.s). For synthetic air technology the rupture disk design was adapted to the higher filling pressure and much faster and higher pressure rise compared to SF_6 gas [11]. The higher and faster pressure rise is related to different gas dynamics and power dissipation of the arc discharge in synthetic air.

According to the current state of development the arc fault resistance with protection class II and protection stage 2 acc. IEC 61869 has been successfully proven (table III) on following synthetic air insulated models and parameters (also covering IEEE C57.13.5):

Table III - arc fault tests performed

Synthetic Air model	Arc fault current / duration
Combined transformer 123 kV	40 kA / 300 ms
Voltage / current transformer 245 kV	50 kA / 300 ms
Voltage transformer 420 kV	80 kA / 300 ms

The performed tests also proof that there is no increased fire hazard for synthetic air insulation in case of an internal insulation failure. The fire load from an external fire source is identical to that of SF_6 devices since the same components are used.

2.3 Type Tests

All instrument transformers developed so far had been tested in compliance with IEC61869 and third party witness of an independent test lab (fig.4 and 5). There are no restrictions of the tested ITs compared to the corresponding SF_6 devices with regard to the technical parameters, such as service temperature, rated current, short-circuit current, lightning impulse resistance including chopped wave, as well as the mechanical load capacity.

The main parameters of combined transformer (combi), current transformer (CT) and voltage transformer (VT) developed so far are listed in below table IV

Table IV - synthetic air equipment tested

	CT/VT/combi 123 kV	CT/VT/combi 245 kV	VT 420 kV
Um [kV]	123	245	420
AC [kV]	230	460	680
BIL [kV]	550	1050	1425
CW [kV]	630	1200	1640
SIL [kV]	-	-	1050
Ipr [A]	4000*	4000*	5000*
Ith [kA]	40	50*	80*

*current through HV-terminals in case of VT

Legend (ref. IEC61869) :
Um: Highest Voltage for equipment (rms)
AC: Rated power-frequency withstand voltage (rms)
BIL: Rated lightning impulse withstand voltage (peak)
CW: Chopped wave withstand voltage (peak)
SIL: Rated switching withstand voltage (peak)
Ipr; Rated primary current (rms)
Ith: Rated short-time thermal current (rms)

Figure 4: 245 kV combined transformer during type tests

Figure 5: 245 kV CT after internal arc fault test successfully passed with 50 kA/300 ms

2.4 Conclusions - Portfolio and service installations

The first developed synthetic air ITs were 123kV combined transformers which were put into service in June 2018 (fig. 6) followed by 245kV and 420kV developments (fig. 7). While the first 123kV synthetic air devices were “downgraded” SF_6 devices working with similar pressure as SF_6 ITs [11], the subsequent developed 245kV and 420kV instrument transformer were specifically designed for synthetic air insulation, using higher service pressure and with very similar dimensions and same footprint as SF_6 designs (fig. 8). 420kV current and combined transformers and the next generation of 123/145kV instrument transformers optimized for synthetic air insulation are currently under development. More than 400 products with synthetic air insulation had been delivered and the number of installed ITs from 72.5 to 420kV is continuously increasing (fig. 9) gathering meanwhile more than 250 years of service experience without failure.

Figure 6: First pilot installation of 123kV synthetic air combi in German substation [12]

Figure 7: 420kV synthetic air voltage transformer installed in German's TSO grid.

Figure 8: On the left comparison of 245kV synthetic air (blue) and SF_6 (green) voltage transformers. On the right 245kV synthetic air CT and Combi showing the same footprint

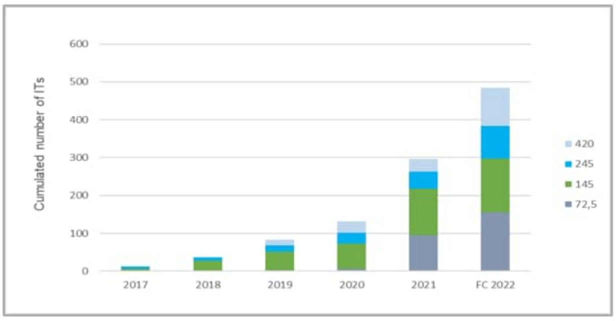

Figure 9: Evolution of installed AIS ITs with synthetic air insulation.

3. Instrument Transformers Ester Insulated (ITs)

Since the beginning of instrument transformers development (IT), paper and mineral oil were used as main high voltage insulation system. During the years their design has been improved and optimized step by step up to now when this kind of insulation is worldwide used with fully satisfaction of users.

Modern ITs are sealed products and then, in standard conditions, no contact between mineral oil and environment is possible. However, considering the transformer has a lifetime of more than 30 Years, in very few cases an oil leakage can happen and this brings to a potential oil development in the environment. Considering the small oil qty contained in ITs compared to power transformers and their high reliability, paper/mineral oil was and is the most common technology accepted worldwide.

In the last 30 years the technology of power transformers is moving gradually to ester insulation systems (fig.10) together with the growing sensitivity of the users to environment topics and then also the ITs are an will be in the focus of this change. Mineral oil is not a biodegradable fluid, then alternative as ester fluids were investigated to replace the mineral oil applications [13]. General information about synthetic esters can be found already in the paragraph 1 of this paper. In this paragraph we focus on ITs showing the investigation findings and giving some guidelines about the application of this insulation technology [14].

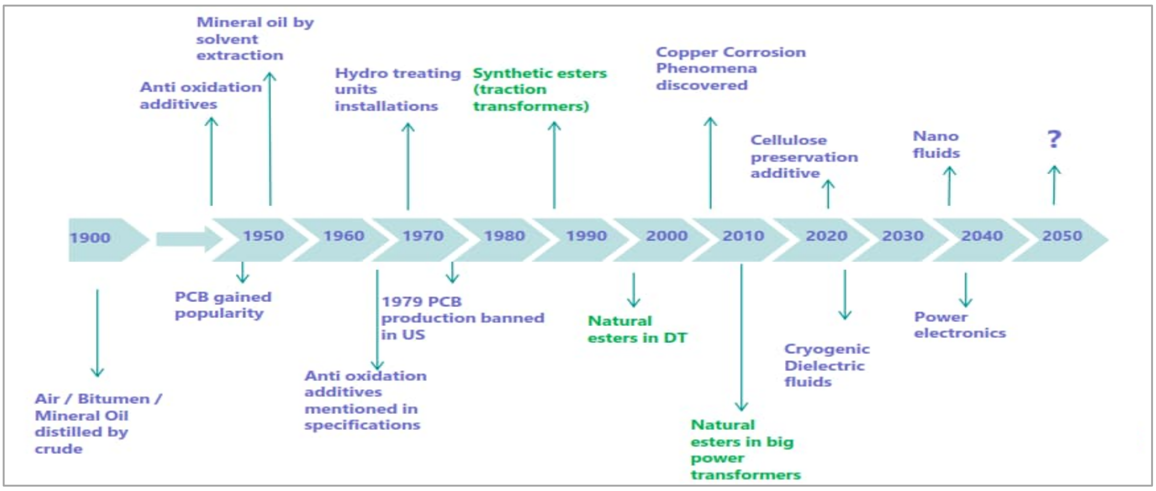

Figure 10: Reference CIGRE Brochure 436

3.1 High Voltage Insulation - Design and Production Process

A typical sectional view of high voltage oil insulated IT (current transformer top core design) is shown in figure 11. The high voltage insulation is made by high quality insulating paper and mineral oil impregnated. The bushing part uses a design similar to bushing for power transformers while the top part is made applying paper's layers using semiautomatic special machines. The paper compactness is a key factor to ensure the high dielectric strength keeping the dielectric stresses inside the design limits for the whole service lifetime and in all service conditions. During manufacturing process ITs are dried applying high vacuum and high temperature and then filled with degassed and filtered mineral oil (ref. IEC 60296). Sealings between the different assemblies are ensured by rubber gaskets and the oil volume variations due the temperature change is compensated by an inox steel bellows.

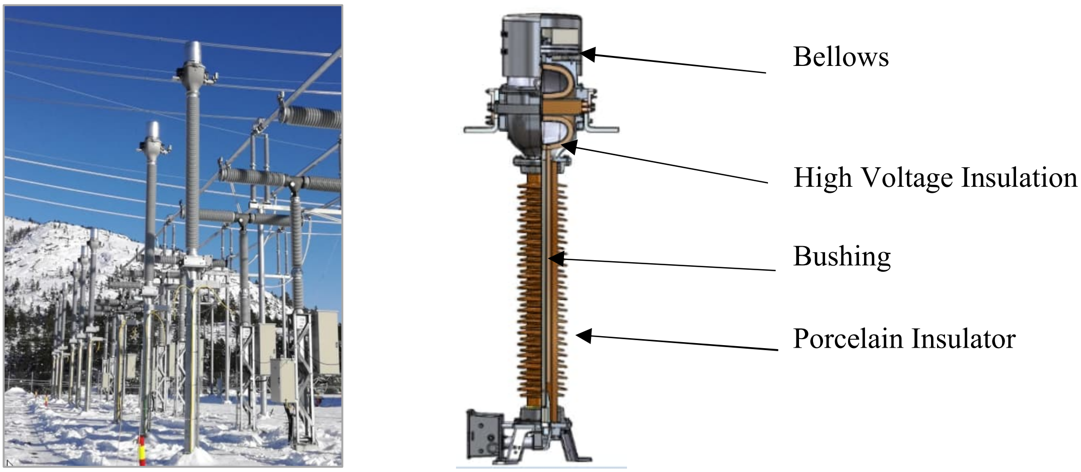

Figure 11: High Voltage oil Current Transformer installed and sectional view (top cores design)

The high compactness of the insulating paper ensures the best electrical performances but became also a critical point during manufacturing oil filling step because paper impregnation become difficult and tens of hours are necessary to be completed in proper way. Low-viscosity fluids are used to allow better paper impregnation and, additionally, to reduce the viscosity of mineral oil the transformer is usually filled with a temperature of 50/60°C on vacuum conditions. Ester fluids have naturally an higher viscosity compared to mineral oils (table V) and then the paper impregnation became a more critical item to be considered during manufacturing. Investigation trials and electrical tests have been performed checking the possibility to use the same main insulation design (paper type and thickness, manufacturing process) and to adapt carefully the drying and impregnation process to the different ester fluids. Synthetic and natural esters were investigated and a solution to apply them has been found optimising the whole production process including also the ester filling temperature (increased up to 80-90°C) and the impregnation time (increased at least two times respect mineral oil one). Partial discharges electrical tests were performed at the end of each process trial and finally it was possible find values as mineral oil insulated ITs confirming that the manufacturing process was completed in proper way.

Table V – Typical viscosity values

	Mineral Oil	Synthetic ester	Natural Ester
Viscosity at 40°C (cSt)	9.5	29	35

3.2 Electrical Tests

Dielectric type tests according IEC61869 Standard have been performed in high voltage laboratories with positive results. Different types of ITs have been tested (current and voltage ITs) as well different voltage levels up to Um 420kV confirming that the ITs ester filled have the same performances as mineral oil insulated ones.

3.3 Internal arc fault protection

IEC61869 Standard defines a specific special test referred to the behavior of an IT during an internal arc fault. Tests on ITs using mineral oil have been performed with positive results fulfilling the level "Protection class I and Protection stage 2". Using the same proven design and replacing the mineral oil with ester the behavior of the IT will be the same with the benefit that the fire generated by the arc will be lower and damped quickly due esters' higher flash point and self-extinguishing characteristics, increasing then the product safety level.

3.4 Service installation and maintenance

Overall an ester IT needs the same activities usually indicated for mineral oil insulated one.
IT is filled with ester, sealed and tested in the manufacturer's factory then no specific or additional activities have to be planned by the user during the installation due the presence of ester instead of mineral oil. About maintenance ITs are hermetically sealed and usually the only regular maintenance is the external visual check to detect eventual damages or oil leakages and this's valid for mineral as well ester insulated ITs. Oil DGA (Dissolved Gas Analysis) can be performed also on ester ITs but, due the actual limited experience on ester ITs installed fleet, the involvement of IT's manufacturer is recommended to have a specific evaluation of the results and a correct judgement of IT's status.

3.5 Additional Items to be considered

3.5.1 Materials compatibility

To guarantee the best reliability ITs are sealed and, additionally, it's very important ensure that all the materials in contact with the insulation liquid will not release any pollution in the fluid because this will reduce the dielectric strength of the main insulation. Compared with mineral oil ester fluids are surely better about environment aspects but this does not mean that all materials suitable to be used in contact with mineral oil are also suitable to be applied with esters (synthetic or natural). Specific and deep compatibility tests investigation, also using existing experience from power transformer and bushing manufacturers (see item 1.2.2), have been performed to check if the materials tested with mineral oil can be used as well with synthetic and natural esters. For these reasons it's not recommended to fill/refill with ester (synthetic or natural) an IT that was originally designed to be used with mineral oil without the full knowledge about internal design and materials used to prior check their suitability with ester.

3.5.2 Oxidation stability

The modern high voltage ITs are fully sealed type, a metallic bellows compensates the oil volume due the temperatures changes and keep the inner pressure as the ambient one (fig.11). This design prevents any kind of oxidation phenomenon during service conditions also in case of ester insulation.

3.5.3 Very low ambient temperature

Usually the "pour point" of the filling insulation fluid defines the minimum temperature at which the IT can be installed and used. The standard mineral oil for ITs is usually suitable up to -35/-40°C and there're some kinds able to reach lower temperature (up to -50°C or even lower). Synthetic ester can be used in whole set of ambient conditions as mineral oil while natural ester only up to -25°C (table VI).

Table VI – Typical pour point values

	Mineral Oil	Synthetic ester	Natural Ester
Pour Point (°C)	-50	-56	-25

3.6 Conclusions

The experiences done and the tests performed show that actually it's possible design and produce an high voltage IT ester filled keeping the same dimensions and performances as mineral oil insulated one.
From user's perspective an ester IT ensure same or even better technical performances and it needs the same maintenance activities as mineral oil insulated one with the additional benefit to be filled with a biodegradable fluid.
Ester ITs match users' needs that want to keep the high voltage liquid insulation system but at the same time they're looking for an environment friendly solution to replace mineral oil [15].

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