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Experience with biodegradable liquids in instrument transformers with an emphasis on dielectric testing

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SUMMARY

There is little thorough experience regarding the use of alternative, biodegradable insulation liquids in high-voltage instrument transformers while extensive research exists for power and distribution transformers.

Implementation of the mentioned dielectric liquids requires an extensive testing sequence to verify its expected performance. This is why the first aim of the paper is to detail the referent testing sequence which consisted of routine and type tests including increased partial discharge requirements, multiple chopped test, lifetime expectancy test, insulation breakdown test and additional tests such as: temperature rise, cold weather performance, internal arc and material compatibility tests. Each step of the testing sequence was also accompanied by DGA testing.

In addition to presenting the proposed testing sequence for qualification of new dielectric liquids, the main emphasis of this paper will be on aspect of dielectric performance. The body of this paper will be presented through actual testing performed on several prototypes. Two biodegradable dielectric liquids were used for this effort: MIDEL 7131, a synthetic ester and Nynas NYTRO BIO 300X, a bio-hydrocarbon based isoparaffinic oil. The main parameters considered include but are not limited to: tgδ, insulation capacitance, partial discharge inception voltage, gas increases, etc.

KEYWORDS

Instrument transformers, Biodegradable liquids, Dielectric performance, Simulated aging, Partial discharge, Impulse testing, Paper-liquid insulation systems

INTRODUCTION

Extensive research regarding the use of alternative, biodegradable insulating liquids exists for power and distribution transformers [1], [2] but this experience cannot easily be translated into the field of instrument transformers. There are two main differentiating factors why.

The first is the overall insulation design. Much like transformer bushings, insulation of high-voltage instrument transformers is based on homogenous liquid-impregnated paper insulation which is heavily capacitively graded [3]. This is in contrast to oil-barrier insulation found in power transformers of comparable voltage levels. All of this also influences heat transfer which, in instrument transformers, is on-going mostly through conduction and not convection nor directed flow.

The second differentiating factor are the dielectric stresses instrument transformers are subjected to during their operational lifetime. Instrument transformers function as “frontline” equipment in the power system as they are positioned directly after the disconnector, meaning they come under increased dielectric stress due to frequent transients resulting from common switching operations [4], [5].

Having in mind the severe dielectric stress and lack of historical experience, extensive testing needs to be performed in order to verify the expected performance of instrument transformers filled with the mentioned dielectric liquids. This is the why the first aim of the paper is to detail the referent testing sequence which consisted of routine and type tests including increased partial discharge requirements, multiple chopped test, lifetime expectancy test, insulation breakdown test and additional tests such as: temperature rise, cold weather performance, internal arc and material compatibility tests. Each step of the testing sequence was also accompanied by DGA testing. The sequence described above is shown in ***Figure 1***.

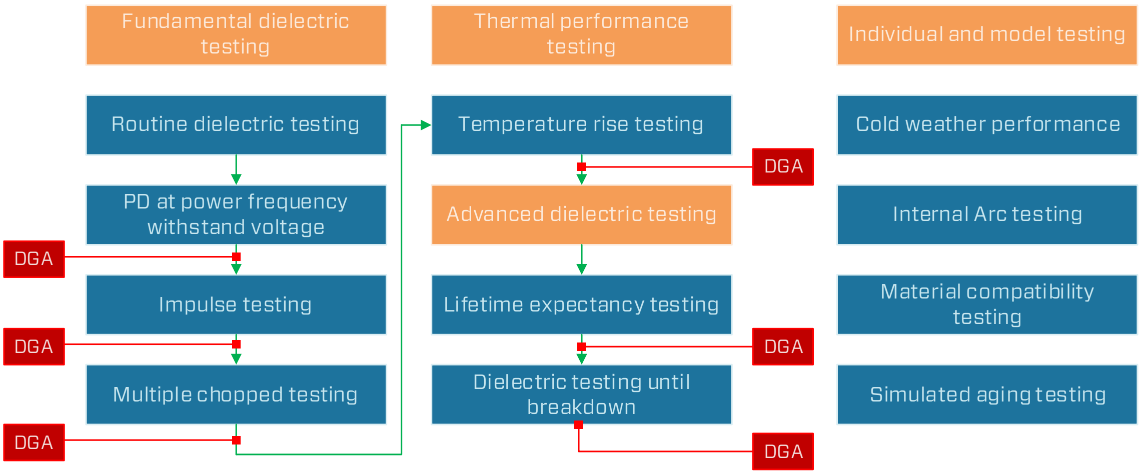


Figure 1 Testing sequence during implementation of biodegradable liquids

Special emphasis in this paper shall be given to dielectric testing. The idea of the paper is to detail all steps necessary for the qualification of a new dielectric liquid from a dielectric standpoint. The qualification sequence will be demonstrated through actual tests performed on several prototypes with service voltages ranging from 123 to 420 kV and including current, inductive voltage and combined instrument transformers as well as station service transformers (shown in ***Figure 2*** and ***Table I***). It should be noted that the listed prototypes have an identical insulation system to units filled with conventional mineral oil, meaning no specific alterations were made.

Figure 2 Produced prototypes

Table I Produced prototypes with their corresponding standard

Transformer type	Insulating liquid	Standard
400 kV CT	Synthetic ester	IEC 61869-2
400 kV CT	Bio-hydrocarbon based	IEC 61869-2
400 kV IVT	Synthetic ester	IEC 61869-3
400 kV IVT	Bio-hydrocarbon based	IEC 61869-3
110 kV combined unit	Synthetic ester	IEC 61869-4
110 kV combined unit	Bio-hydrocarbon based	IEC 61869-4
300 kV SSVT, 150 kVA	Synthetic ester	IEC 61869-1&3 IEC 60076
220 kV SSVT, 100 kVA	Bio-hydrocarbon based	IEEE C57.13-2016; IEEE C57.12.00-2015

Two biodegradable dielectric liquids were used for this effort: MIDEL 7131, a synthetic ester and Nynas Nytro BIO 300X, a bio-hydrocarbon based biodegradable oil [6], [7]. The main properties and characteristics of the considered liquids are given in [8] and [9] and will not be repeated here.

1 FUNDAMENTAL DIELECTRIC TESTING

1.1 Routine dielectric and impulse tests

The prototype units are routine and impulse tested (along with other above mentioned standard tests) according to either IEC or IEEE standard [10], [11], depending on what specification they are designed to.

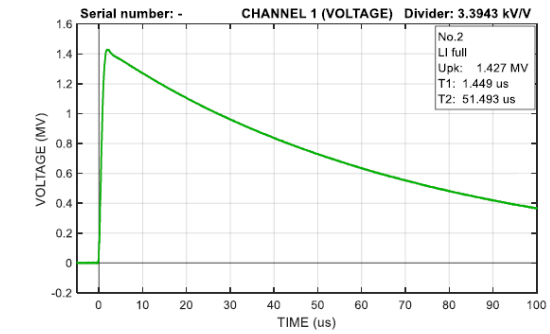
One of the more important criteria for validation of an insulation system is partial discharge measurement. While there are some differences between partial discharge requirements between IEC and IEEE standards, these units were tested to an internal criterion of < 10 pC at power frequency withstand voltage. This criterion was introduced and described in detail in [12]. Apart from verifying transformer aging performance, measurement of partial discharge at increased levels also verifies insulation production uniformity, production processes, oil impregnation quality and other parameters, which makes it extremely important. Actual recorded values for each unit are given in ***Table II***.

Table II Measured tgδ and partial discharge during routine testing

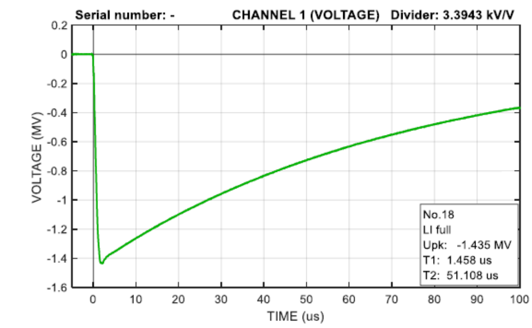
Transformer type	Insulating liquid	tgδ [%]	PD [pC] at 1,2 $U_m/\sqrt{3}$	PD [pC] at U_m	PD [pC] at PFWV
400 kV CT	Synthetic ester	0,293	2,4	2,5	9
400 kV CT	Bio-hydrocarbon based	0,216	2,4	2,5	4
400 kV IVT	Synthetic ester	0,390	2,5	2,6	5
400 kV IVT	Bio-hydrocarbon based	0,360	2,6	2,7	5
110 kV combined unit	Synthetic ester	0,405	2,8	3,0	5
110 kV combined unit	Bio-hydrocarbon based	0,293	2,1	2,2	4
300 kV SSVT, 150 kVA	Synthetic ester	0,405	2,4	2,5	5
220 kV SSVT, 100 kVA	Bio-hydrocarbon based	0,391	2,3	2,3	9

All of the units passed the routine test successfully, including having partial discharges below 10 pC at power-frequency withstand voltage. Also worth noting is the fact that units filled with the bio-hydrocarbon based liquid showcased a smaller value of tgδ across the entire product range, even when compared to traditional mineral oil units.

The next step is impulse testing, which is performed according to the type test sequence which consists of 15 positive, 15 negative and 2 chopped standard lightning impulse waves. This sequence was followed by 15 positive impulses with a standard switching impulse for units of 300 kV and above. Exemplary waveforms for 400 kV CT can be seen in ***Figure 3.***



(a)



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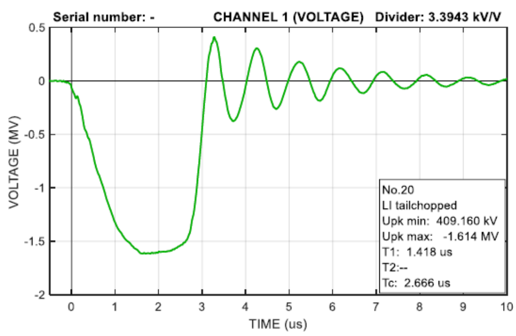

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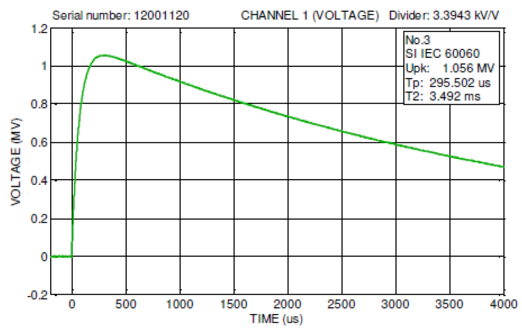
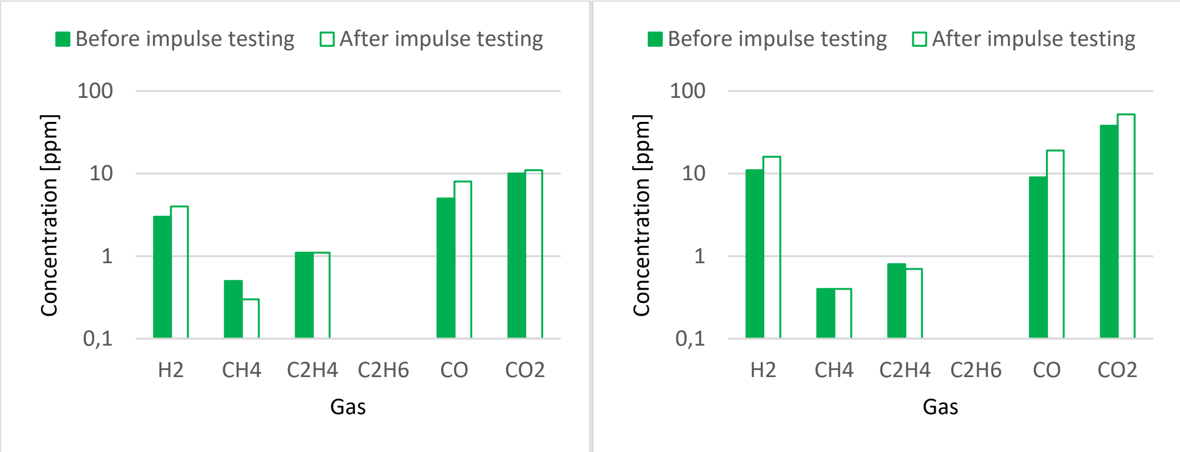


(d)

Figure 3 Test waveforms for 400 kV CT: (a) Positive LI, (b) Negative LI, (c) Chopped LI, (d) Positive SI

After the completion of the impulse test sequence listed above, a DGA sample was taken from every unit and compared to a sample taken before impulse testing. ***Figure 4*** shows comparison of gas concentrations for two 400 kV CT units, each unit with its own biodegradable liquid. The results of remaining units were excluded from the paper due to space constraints, but the general behaviour and recorded values and trends are identical to what was shown for the two CT units. This also applies to the majority of subsequent tests presented.
From the presented results it can be concluded that the recorded, gas increases are low and expected.

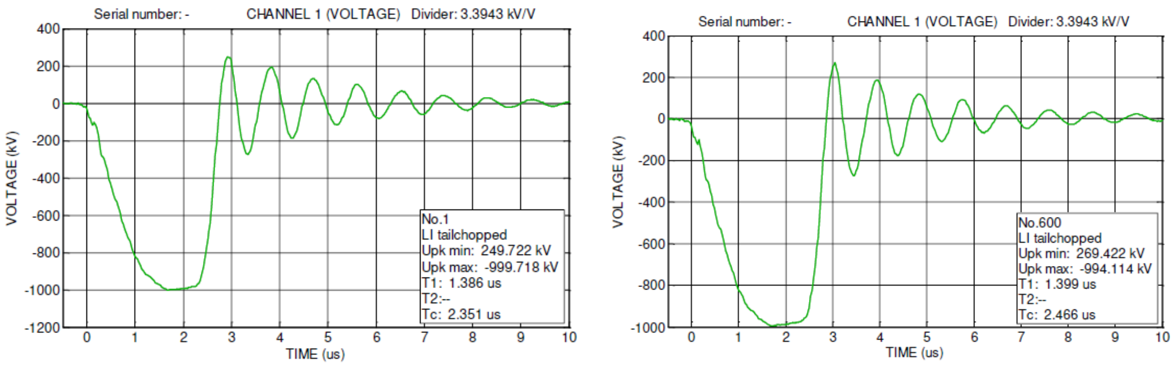


(a) (b)

Figure 4 DGA results before and after impulse type testing: (a) 400 kV CT (bio-hydrocarbon based), (b) 400 kV CT (synthetic ester)

1.2 *Multiple chopped testing*

Multiple chopped impulse testing is a demanding dielectric test since it simulates current interruption with a disconnector, which, as stated before, is one of the normal situations an instrument transformer finds itself in [4], [5]. The test was performed with 600 negative chopped impulses with 70% to 80% of the wave amplitude, depending whether it is performed according to IEC or IEEE standard. The test procedure is coordinated and performed according to the new methodology as outlined in the CIGRE WGA 3.42 [13]. Exemplary waveforms for 400 kV CT can be seen in ***Figure 5.***

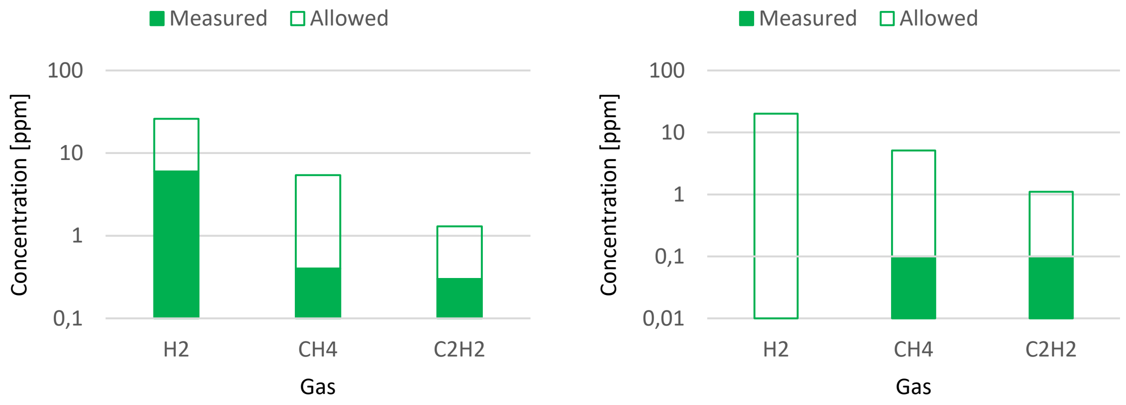


(a) (b)

Figure 5 MC waveforms for 400 kV CT : (a) 1st impulse, (b) 600th impulse

The test is deemed to be successful if no dielectric breakdown occurs and rises of specific gases (Hydrogen H_2, Methane CH_4 and Acetylene C_2H_2) are within standard-prescribed limits.

Figure 6 shows comparison of gas rises (with outer outline being the prescribed limits and the green fill being the measured gas values) for two 400 kV CT units, each unit with its own biodegradable liquid. As with the impulse tests, the results of remaining units were excluded from the paper due to space constraints, but the general behaviour and recorded values and trends are identical to what was shown for the two CT units.



(a) (b)

Figure 6 Gas increases after multiple chopped testing: (a) 400 kV CT (bio-hydrocarbon based), (b) 400 kV (synthetic ester)

As it is clear from the figure above, gas increases are well within standard-prescribed limits. For some of the units, gas increases were below the detection limit.

2 ADVANCED DIELECTRIC TESTING

2.1 Lifetime expectancy test

Lifetime expectancy test is a proprietary non-standard test that was developed in cooperation with Končar Electrical engineering institute [14]. The purpose of the test is to simulate dielectric aging during the transformer lifetime. The instrument transformer is placed under power-frequency withstand voltage for 20 to 24 hours (in contrast to the routine test where the duration is only 1 minute). This way, by extrapolating the procedure, 24 hours on power-frequency withstand voltage equals to, over 40 years on rated voltage [10], [12], [14]. During the test, tgδ, capacitance and partial discharges are continuously measured. The criterion for successful completion of the test is that partial discharge, capacitance and tgδ remain constant (i.e. do not show a tendency to rise during the test) and that a DGA done after the test does not show substantial gas increase. ***Figure 7*** shows graphs for measured tgδ, capacitance and partial discharge, along with the applied voltages for 400 kV CT units filled with both dielectric liquids. ***Figure 8*** shows the gas increases for the above mentioned units after the lifetime expectancy test.

The graphs show satisfactory dielectric performance of both unit types. Gas rises after testing are not pronounced, so the conclusion is that the units successfully passed the test.

However, there are two aspects that have to be noted. The first is that bio-hydrocarbon based filled unit types exceeded expectations during the test, with results being even better than comparable mineral oil filled units. Partial discharges during the whole duration of testing are below 5 pC while tgδ never exceeded 0,25%, as shown in ***Figure 7 (a)*** and ***(b)***.

The second aspect is visible in ***Figure 7 (c)***. For synthetic ester filled units, the results show that, after approximately 8 hours at power-frequency withstand voltage, tgδ started to increase, but was not accompanied by an increase in partial discharge. The effect of increased tgδ for synthetic esters is already reported in available literature and is attributed to the polarity of the molecular structure of synthetic esters [15], [16]. According to the same literature, this behaviour is not considered detrimental, with an argument that dielectric losses of insulation media are insignificant compared to winding, core and stray losses, which is absolutely true for power and distribution transformers.

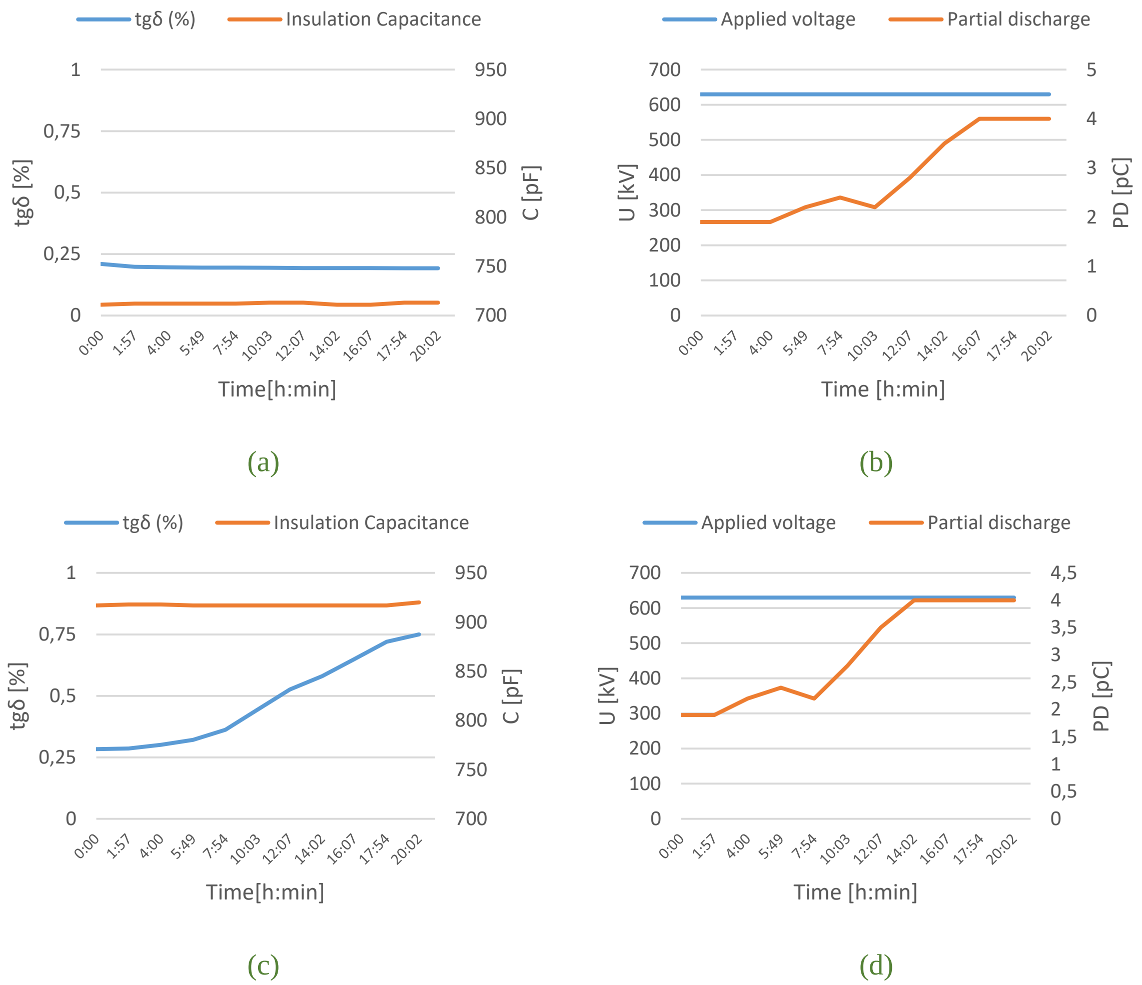


Figure 7 400 kV CT lifetime expectancy test: Bio-hydrocarbon based (a) tgδ and capacitance measurement, (b) partial discharge measurement and applied test voltage. Synthetic ester (c) tgδ and capacitance measurement, (d) partial discharge measurement and applied test voltage

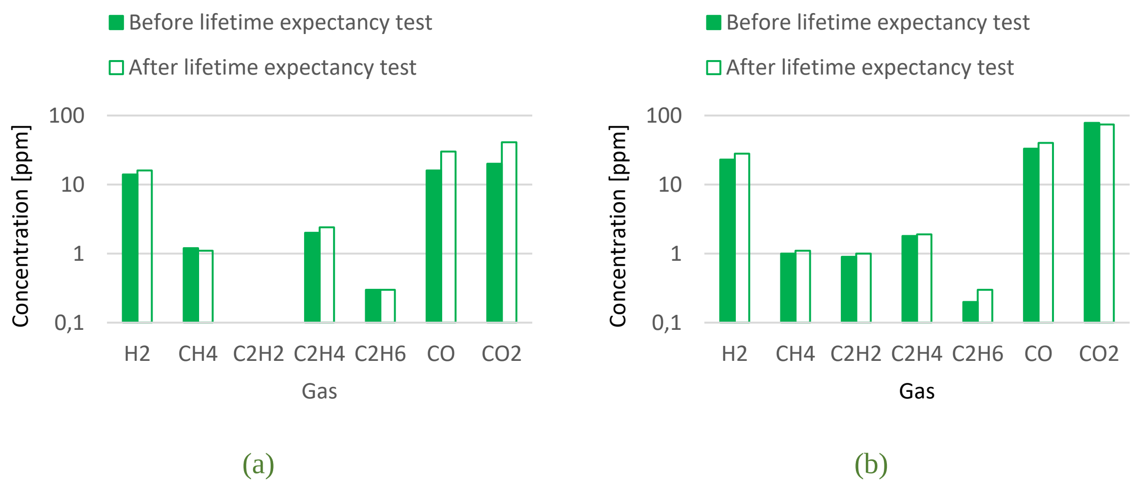
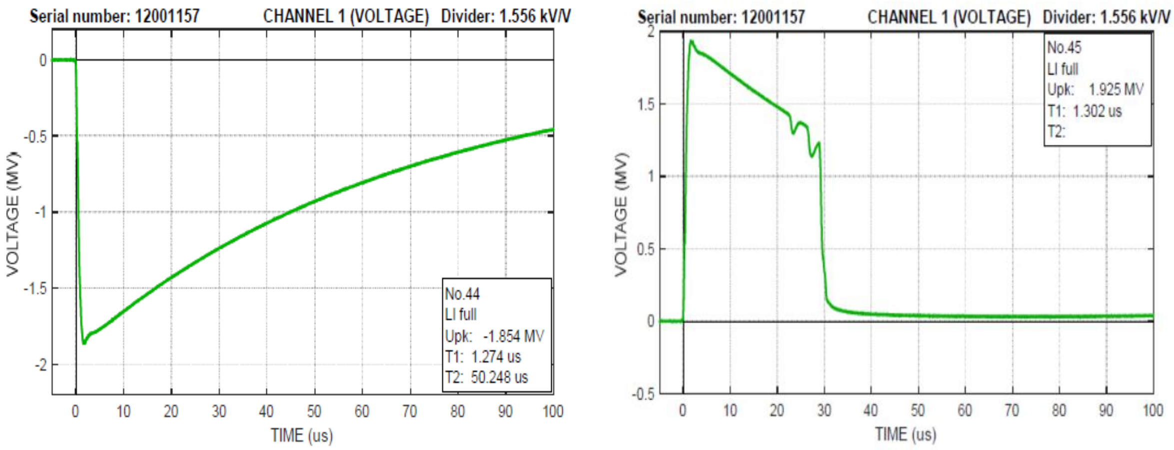


Figure 8 DGA results before and after before and after lifetime expectancy test: (a) 400 kV CT (bio-hydrocarbon based), (b) 400 kV CT (synthetic ester)

However, in instrument transformers, insulation losses are comparable in value to core and winding losses. While it is the authors' opinion that the observed effect does not have a detrimental effect on transformer lifetime, given the results of other accompanying measurements (partial discharge, capacitance and DGA), further investigation of this phenomenon is planned for future work.

2.2 Dielectric testing until breakdown

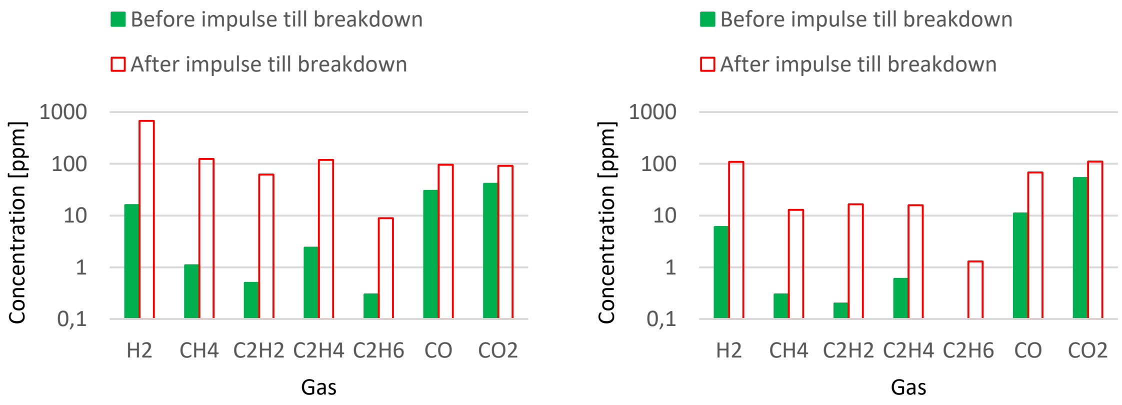
The procedure for impulse testing until breakdown is as follows: start of the test was at 1425 kV – rated lightning impulse voltage. The voltage is then raised in steps of 5%, with three positive and three negative impulses applied at each step. The transformer is tested until voltage breakdown. An example of a voltage impulse before and after experiencing breakdown can be seen in ***Figure 11***.



(a) (b)

Figure 11 LI voltage waveform: (a) before breakdown, (b) after breakdown

The bio-hydrocarbon based experienced breakdown at 1925 kV (45th impulse) or 135% of rated lightning impulse voltage while the synthetic ester unit did the same at 1780 kV (35th impulse) or 120% of rated lightning impulse voltage. It is worth noting that both units experienced breakdown during the positive impulse sequence. ***Figure 12*** shows the gas increases before and after breakdown.



(a) (b)

Figure 12 400 kV CT units DGA results before and after breakdown: (a) bio-hydrocarbon based, (b) synthetic ester

There are two main conclusions to this portion. The first is that existing design margins established for mineral oil are valid for both synthetic esters and bio-hydrocarbon based oil and they do not need to be increased by default. The second is that the performed tests validated that dielectric breakdown in these liquids results in a comparable gas increase footprint as conventional mineral oil.

3 INDIVIDUAL AND MODEL TESTING

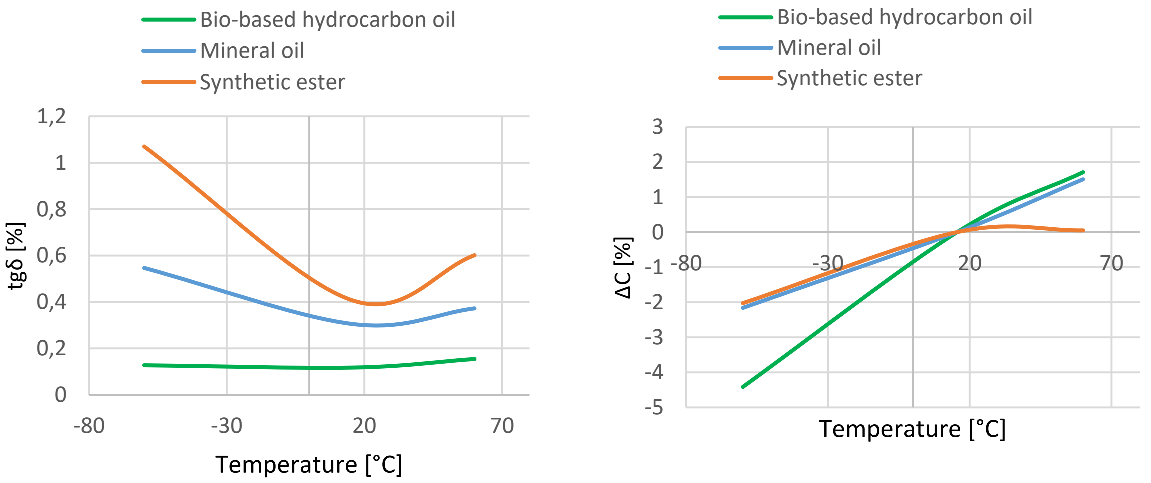
Regarding the scope of the extensive testing done in order to verify the design in a variety of aspects, one of the standout tests is internal arc testing. It is worth noting that, 170 kV CTs filled with synthetic ester and bio-hydrocarbon based oil, along with mineral oil filled units [12], passed the internal arc testing successfully thereby earning internal arc class II [17]. This and other tests will be the topic of future papers.

Since the focus of this paper is on dielectric performance, only cold weather performance (climate chamber test) shall be discussed here. Individual model tests are discussed within paper [18], which at the time of writing of this paper has been accepted for publication.

3.1 Cold weather performance

This test were performed only on the 110 kV combined units, both filled with synthetic ester and bio-hydrocarbon based oil, due to size constraints of the climate chamber in which the tests were performed in. The test procedure consists of 2 cycles with ambient temperature ranging from -60 to +60 °C. During each cycle, a thermal equilibrium of the units must be reached at either extreme temperature. Typically, after reaching the required ambient temperature, it is necessary that the temperature conditions within the climate chamber are maintained for more than 24 hours before measurement of capacitance and tgδ.

Figure 13 shows the measurement for tgδ and capacitance during the climate chamber test in comparison for the two alternative liquids and conventional mineral oil.



(a) (b)

Figure 13 Climate chamber test results for 3 liquids: (a) tgδ characteristic, (b) relative capacitance change

Bio-hydrocarbon based oil clearly exhibited the best climatic performance, again, surpassing even conventional mineral oil. Synthetic ester exhibited increased tgδ of approximately 50% resulting in a more pronounced saddle shaped curve. This increased tgδ value is a well-known phenomenon which stems from the polarity of the liquid [1], [15], [16]. Exhibited capacitance increase is negligible, as expected. Furthermore, when properties of liquids are analysed, namely the kinematic viscosity, the experienced results are absolutely expected.

4 CONCLUSION

This paper provides a detailed overview of the qualification process for the implementation of new, biodegradable liquids in paper-oil insulation system of instrument transformers. The focus of the paper is on the dielectric part of the qualification process. Within the scope of the paper two types of biodegradable liquids are examined: synthetic ester and bio-hydrocarbon based oil.

The conclusion that stems from the paper is that both dielectric successfully completed the proposed testing sequence and are acceptable for commercial implementation into instrument transformers. The acquired results of this paper are also applicable to similar insulation systems, such as bushings. It is clear that the qualification of dielectric liquids depends on a set of parameters highly proprietary to individual manufacturers or factories, so that should be considered and validated separately.

Regarding maintenance and diagnostics, DGA samples of units tested until breakdown, both for units filled with synthetic ester and bio-hydrocarbon based oil demonstrated visible gas increases in the same way as DGA samples after electrical breakdown in mineral oil [19].

It should be noted that bio-hydrocarbon based dielectric liquids demonstrated performance which in some instances surpassed that of conventional mineral oil, when used in paper-oil homogenous capacitively graded insulations systems. This is specifically observed in lifetime expectancy tests and cold-weather performance.

One interesting phenomenon with the synthetic ester is observed. Most probably due to the polarity of the liquid [1], tgδ value increased during lifetime expectancy tests, the additional simulated aging tests and the climate chamber test. While there is strong evidence to support that this phenomenon is not detrimental to the transformer performance, this occurrence will be investigated further.

As a final note, much like alternative gasses, the use of biodegradable dielectric liquids is a clear and necessary step forward in terms of improved sustainability and performance of high voltage instrument transformers. For that reason and because of lack of general experience with implementation of biodegradable liquids in instrument transformer, this paper is a valuable resource for proving an insight in which transformers performance aspects should be considered and validated, with a specific emphasis on dielectric performance.

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