Long Gap Breakdown of Natural Ester Fluid

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***Abstract*— Dielectric breakdown values were measured in 50-150 mm gaps in natural ester fluid and mineral oil. The tests included 50/60 Hz and 1.2x50 µs lightning impulse using negative and positive polarities. The voltage levels attained by natural ester fluid compare closely with mineral oil and would support the use of natural ester fluid in transformers through power insulation classes.**

I. INTRODUCTION

Testing activity on the natural ester (soy) fluid has significantly increased over the past several years [1,2]. However, the majority of focus has been on chemical aging, dissolved gas and dielectric strength of solid-liquid insulation systems [3,4,5,6,7,8]. Most recently, a few academic and corporate research departments have increased their attention on pre-breakdown phenomena known as streamers [9]. A common theme in all of the streamer work is using only the electrode geometry of needle to plane that is highly non-homogeneous. That electrode geometry is avoided in power transformers design. If present, the probability of significant partial discharge is very high.

This investigation is centered upon slightly non-homogeneous configuration that can often be found in two critical areas of power transformer insulation design: long oil gaps between the bushing shield to the tank wall and creep/ oil gaps between contacts inside the on-load tap changer (OLTC) compartment. Both areas are part of this investigation, in response to requests from power transformer and OLTC manufacturers for comparative withstand data. The breakdown tests for natural ester fluid and mineral oil included AC power frequency and lightning impulse voltages.

We found that the degree of electrical field uniformity has a stronger influence on natural ester fluid than on mineral oil. Certain testing procedures needed improvement before reliable results could be obtained. For example, one set of data testing OLTC tap rod contacts, indicated significantly lower values compared to a data set from a different lab testing an identical rod. The lower values were determined to be caused by an improper size test tank and procedures compared to those in a 2009 study [1]. Much higher values were obtained in the present study when the lab repeated the tests using a new, larger tank and improved processing of the fluid.

Both the large gap bushing shield to simulated tank wall tests and the repeat testing of the OLTC contact rods testing details and discussion follow.

II. BUSHING SHIELD TO FLAT PLATE GAPS

The bushing shield to flat plate configuration was tested in natural ester fluid[1] and mineral oil[2] at Powertech Labs (Surrey, BC, Canada). The bushing shield to plate electrode arrangement is shown in Fig. 1. The long oil gaps were tested in a 12,500 liter steel tank that was fitted with an AC 500 kV class power bushing having an 1800 kV BIL rating. The bushing shield was machined from a stainless steel disc with final dimensions of 216 mm diameter × 38 mm thick with a top and bottom edge radius of 4.3 mm. A 463 mm dia. steel plate ground plane acted as the tank wall. The grounded plate was mounted to ceramic insulators to raise it 310 mm off the tank bottom. This was done to minimize the effect of particulate matter on the bottom of the tank. The bare bushing shield to ground plate gap was orientated vertically in the tank. The size of the gap was changed by raising the bushing used to apply the high voltage. Gaps of 50, 100, 125, and 150 mm were tested.

A. Test Procedures

The fluid quality was maintained at each gap change with fluid processing apparatus consisting of vacuum degassing, water absorption and particle filtration throughout this work. The fluid quality was measured by water content, dielectric strength and dissolved gas analysis using common test methods to meet Canadian standard CSA-C50 [10].

The 60 Hz AC tests were done with 30 breakdowns with a five minute wait between shots. The AC and impulse tests were done in accordance with IEC 60060-1. The 1.2 × 50 µs impulse wave was applied using the V50 up and down method [11,12]. The applied impulses varied from 25 to as many as 42

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[1] Envirotemp® FR3® fluid, Cooper Power Systems

[2] Mineral oil per Can/CSA-C50

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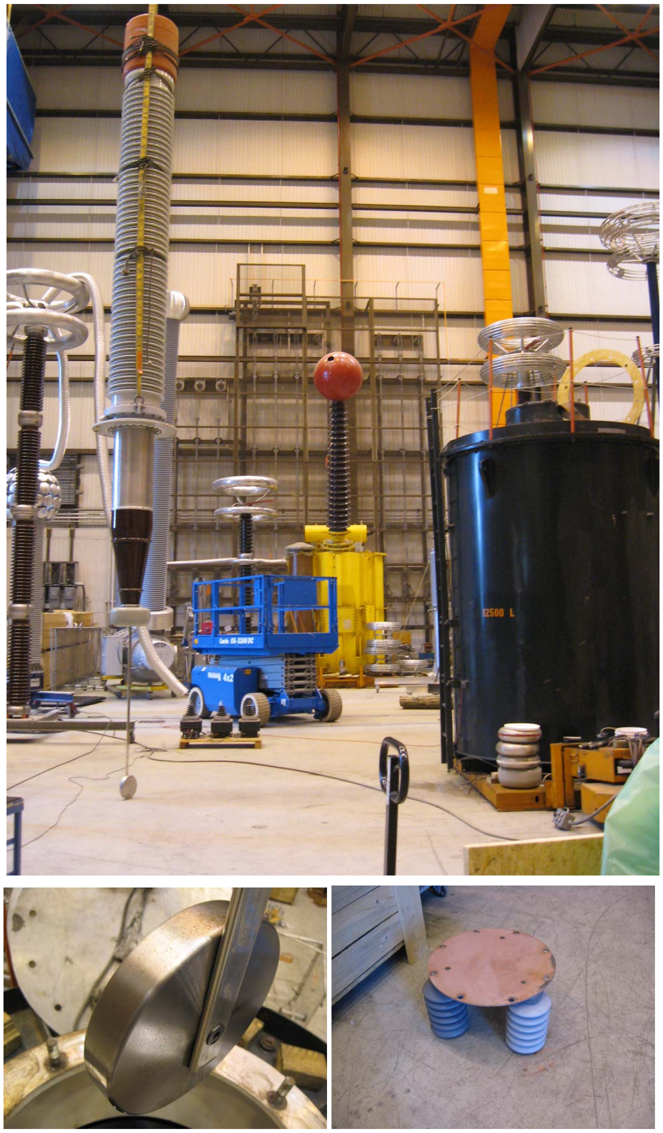

Figure 1. Bushing shield (22 cm dia.) stainless steel electrode attached to 1800 kV BIL bushing. Ground plate electrode is connected to and raised off the tank bottom.

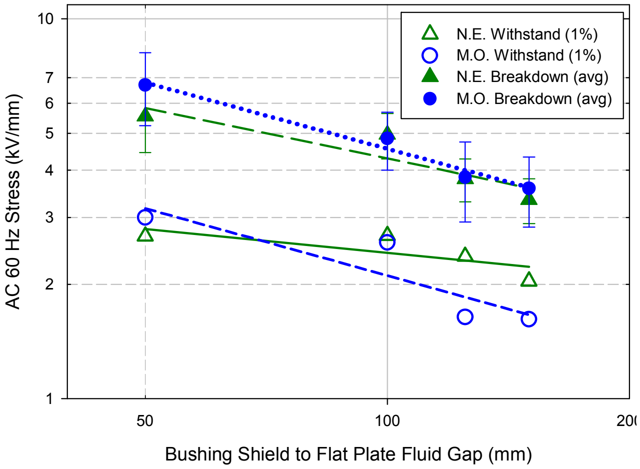

Figure 2. 60 Hz AC Results for Bushing Shield to Flat Plate

shots. The testing was done at positive and negative polarities. After one gap size was tested, the bushing was lifted and an appropriate spacer was added between the bushing and the tank top to obtain the next gap size. The fluid was continuously processed between tests and between each of the gap changes. The surface of the bushing shield was inspected for pitting several times during the course of the tests. The fault current was limited by using an AC resonance test set, preventing any significant pitting. The test tank was cleaned and flushed after the change from mineral oil to natural ester fluid.

B. AC Results

The data from this work were analyzed using both normal mean and 1% Weibull two parameter probabilities using median ranking. The AC results are summarized in Table 1. The results for the bushing shield to flat plate gaps of 50 to 150 mm show that the AC breakdown and withstand of natural ester fluid start out slightly lower than mineral oil, but converge to closely compare in breakdown and surpass mineral oil in withstand voltage stress beyond 100 mm fluid gap. The standard deviations of the mineral oil data are significantly higher than the natural ester fluid. The data is plotted in Fig. 2 using the voltage stress versus gap distance.

C. Lightning Impulse Results

The negative lightning impulse data for 50 to 150 mm gaps are summarized in Table 2. The breakdown and withstand voltage comparisons show that the natural ester fluid is about the same as mineral oil. This trend is clearly displayed in Fig. 3. The positive lightning impulse results for breakdown of both the natural ester fluid and mineral oil in Table 3 are comparably close. However, the higher standard deviation of the 50 mm gap mineral oil data negatively impacts its withstand stress curve as shown in Fig. 4.

Table 1. Bushing Shield to Flat Plate AC Breakdown and Withstand

Oil Gap	50 mm		100 mm		125 mm		150 mm	
Fluid	Nat. Ester	Min. Oil	Nat. Ester	Min. Oil	Nat. Ester	Min. Oil	Nat. Ester	Min. Oil
U_{avg} (kV)	277	335	496	484	473	479	500	537
Std Dev (kV)	54	73	68	84	62	113	67	112
s (%)	20	22	14	17	13	24	13	21
$U_{1\%W}$ (kV)	134	150	269	258	297	205	307	244
α (scale)	299.3	363.6	531.9	518.7	499.8	521.9	529.6	582.9
β (shape)	5.74	5.19	6.77	6.57	8.82	4.92	8.42	5.27
R^2_W	0.937	0.927	0.850	0.893	0.966	0.877	0.963	0.922

Table 2. Negative Lightning Impulse Breakdown and Withstand Voltages of Bushing Shield to Flat Plate

Oil Gap	50 mm		100 mm		125 mm		150 mm	
Fluid	Nat. Ester	Min. Oil	Nat. Ester	Min. Oil	Nat. Ester	Min. Oil	Nat. Ester	Min. Oil
U_{avg} (kV)	873	812	1099	1191	1225	1211	1305	1306
Std Dev (kV)	65	48	76	85	64	61	100	97
s (%)	7.5	5.9	6.9	7.1	5.3	4.8	7.6	7.4
$U_{1\%W}$ (kV)	669	661	864	932	1012	1031	995	1005
α (scale)	901.9	833.4	1133	1229	1256	1240	1350	1349
β (shape)	15.37	19.90	16.94	16.69	21.27	24.84	15.04	15.63
R^2_W	0.921	0.946	0.898	0.938	0.931	0.964	0.914	0.971

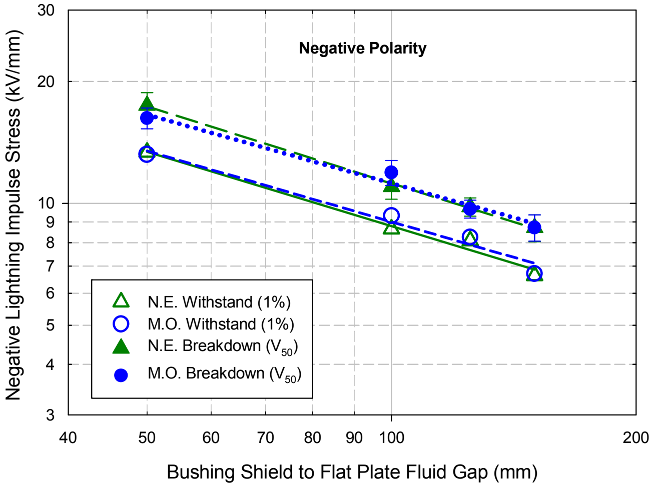

Figure 3. Negative Lightning Impulse Stress – Bushing Shield to Flat Plate

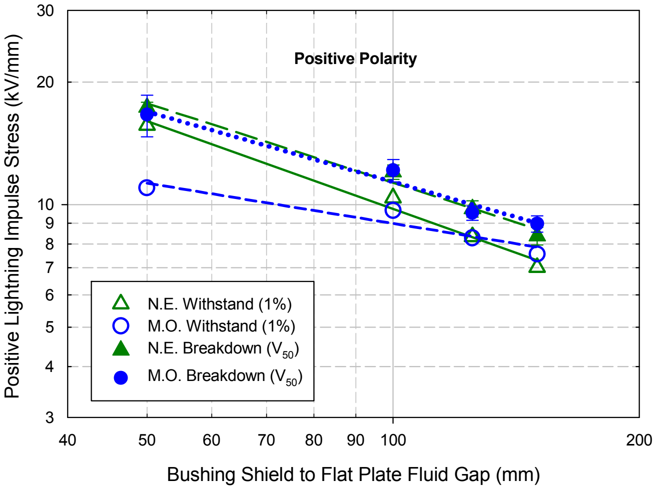

Figure 4. Positive Lightning Impulse Stress – Bushing Shield to Flat Plate

III. ON-LOAD TAP CHANGER TAP ROD GAPS

The OLTC tap contacts as shown in Fig. 5 were tested in natural ester fluid[1] and mineral oil[3] at the Universitat Stuttgart. A single rod of a tap-changer selector with six identical contacts on it was tested. The tested gap between two ring-like electrodes involves solid, liquid and the interface between these dielectrics. The contacts on the laminated rod provided a slight non-uniform field. Shorting bars/wires were used to short out contacts that were not being tested. After any of the five individual contact to contact oil gaps or insulation interfaces were tested to breakdown, the shorting connections were moved to provide a fresh gap.

A. Test Procedures

The rectangular tap selector rods[4] measured 55 mm W × 20 mm T × 850 mm L and were previously dried and impregnated with mineral oil at MR before shipment to Stuttgart. After assembling contacts on the rods, they were re-dried in an oven and impregnated with fluid.

The natural ester fluid and mineral oil were processed when the relative moisture saturation reached 10-15% using dehydration, particle filtering and degassing. The fluid quality was verified by periodic testing of dielectric strength and water content. Both fluids were maintained at greater than 50 kV using VDE electrodes at 2 mm gap.

Table 3. Positive Lightning Impulse Breakdown and Withstand Voltages of Bushing Shield to Flat Plate

Oil Gap	50 mm		100 mm		125 mm		150 mm	
Fluid	Nat. Ester	Min. Oil	Nat. Ester	Min. Oil	Nat. Ester	Min. Oil	Nat. Ester	Min. Oil
U_{avg} (kV)	867	831	1203	1215	1221	1193	1256	1346
Std Dev (kV)	25	98	50	77	56	49	64	62
s (%)	2.9	12	4.1	6.4	4.6	4.1	5.1	4.6
$U_{1\%W}$ (kV)	783	551	1040	967	1042	1035	1051	1134
α (scale)	878.9	873.2	1226	1250	1246	1216	1286	1377
β (shape)	39.97	9.984	27.94	17.90	25.70	28.55	22.89	23.74
R^2_W	0.973	0.952	0.924	0.904	0.955	0.952	0.983	0.801

The breakdown values were fitted with 95% confidence limits using two parameter Weibull and normal cumulative distribution functions. With defined function coefficients the low breakdown probability voltages (withstand voltages) were calculated.

The size of the tap selector rods caused them to be exposed to air during transfer to the test tank. The tank and samples were vacuum treated to remove trapped air prior to testing.

B. AC 50 Hz Results

The OLTC parts were tested with 50 Hz AC in a plastic drum with a diameter of 500 mm and a volume of 230 liters. The starting voltage was 60 % and the steps were about 6 % of the expected breakdown value. The voltage was applied for one minute at each step. For each fluid 25 gaps were tested with the results summarized in Fig. 6.

Mean breakdown values for both fluids are the same. The withstand voltage of natural ester fluid is 26 % higher than mineral oil due to more favorable standard deviation. The

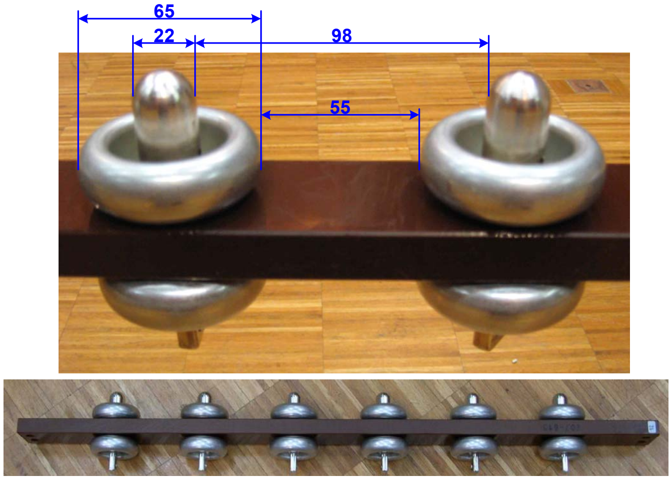

Figure 5. OLTC Tap Selector Rod and contacts with tested gap in mm.

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[3] Nynas Nytro 3000X

[4] Oiltap® M Type, donated by Maschinenfabrik Reinhausen, Germany (MR)

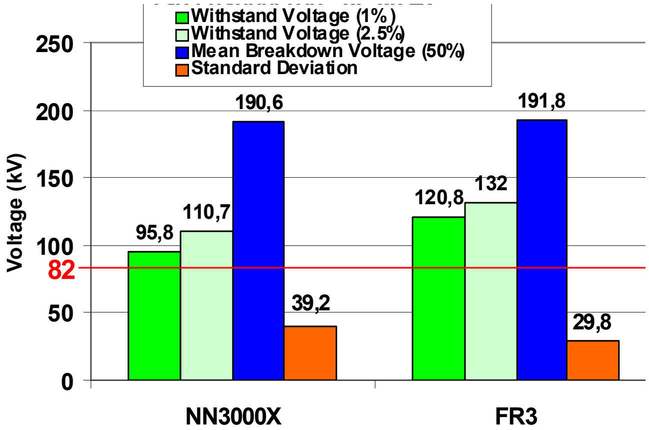

Figure 6. AC 50 Hz breakdown strength of tap-changer rod gap (Normal distribution)

withstand voltages of both fluids are higher than the withstand voltage set by design rules (82 kV).

C. Lightning Impulse Results

The 1.2 × 50 µs lightning impulse of the OLTC rods was initially measured in a metal tank with an inner diameter of 480 mm and volume of 320 liters. The impulse test started at positive polarity for three voltage steps, followed by a change to negative polarity. The voltage steps used and the step changes are detailed in [1]. The clearance between the test object and tank wall appeared to be critical for this configuration. This gap of approximately 190 mm flashed over as low as 350 kV. By adding two paper insulation cylinders around the tap rods inside the tank, the strength of the secondary gap to the tank wall was increased to 500 kV, but again the breakdowns appeared through this gap and not between the contacts on the tap rod, which was the primary focus of this testing.

To resolve this issue, the rods were tested in a 600 liter fiberglass sealed tank with inner diameter of 650 mm without paper insulation cylinders. This setup, with vacuum applied, allowed for the maximum applied voltage up to the laboratory limit (805 to 850 kV). In these conditions not all tested gaps experienced breakdown. For natural ester fluid, only 7 of 15 and for mineral oil 5 of 15 tested gaps had a breakdown within these voltage levels. Both fluids experienced a breakdown as low as 491 kV.

IV. DISCUSSION

The AC test results indicate that while the mean breakdown voltage of natural ester is slightly lower than mineral oil at 50 mm, the two fluids are about the same beyond 100 mm. The relative AC withstand increases significantly for the natural ester fluid as the gap increases. In general, the AC results for both fluids compare closely for the slightly non-uniform gaps that are critical for power transformer design. The lightning impulse breakdown and withstand levels of natural ester fluid are closely comparable with mineral oil.

As previous dielectric testing of natural ester fluid gaps has shown, proper testing procedures and handling of the fluid are important for obtaining accurate results [1]. For impulse tests, the conducting elements surrounding the tested gap have a strong impact if they are too close to the gap being tested. For bushing shield to flat plate a large tank was used. However, for the early OLTC contact tests a much smaller conductive tank produced low impulse voltages from flash over to the tank instead of between the test gap. When the test tank was changed in size and type, the impulse levels increased significantly. For all gaps tested in both fluids, the breakdown values were significantly higher than withstand voltage set by design rules of a major OEM.

Particulate matter produced from repeated breakdowns of the fluid gaps during the testing may have affected mineral oil more so than natural ester fluid, indicated by much larger standard deviations for mineral oil, causing lower withstand levels. A possible explanation is that the higher permittivity of natural ester fluid compared to mineral oil provides a better dielectric match with the particles, resulting in improved dielectric strength.

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