Switching Impulse of Long Oil Gaps of Natural Ester Fluid

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***Abstract*—Switching impulse breakdown values, negative and positive polarities, were measured for long oil gaps of natural ester fluid and mineral oil. A switching surge wave shape of 250x2500 µs was used for gaps of 50-150 mm between a high voltage bushing shield and a simulated tank wall (an electrode arrangement used to obtain previously published 60 Hz and 1.2x50 µs lightning impulse breakdown values). We compare these results with data obtained from 10-35 mm gaps using an electrode configuration developed by Weidmann Electrical Technology Inc. The results of this testing are consistent with previous results that showed natural ester fluid has equal or better dielectric breakdown characteristics compared to mineral oil for 10 to 150 mm gaps.**

I. Introduction

Use of natural ester dielectric fluid in transformers is growing worldwide. Measurable benefits of fire safety, environmental sustainability and enhanced chemical interactions of natural ester fluid with cellulosic insulation systems have grown in importance [1-3]. To date, the highest voltage rating of natural ester filled transformers is 245kV. Investigations are progressing to apply natural ester fluid in 345 to 500 kV class power transformers.

Increased congestion in urban settings around the globe has made fire safety an important motive for using natural ester fluid. Additionally, developers of wind and solar energy generation are focusing on natural ester fluids because of their inherent fire safety benefits [4] for close-coupled inverter-transformer solar installations and off-shore wind platforms.

Environmental considerations are more important than ever, as sustainability and overall “green thinking” become favored business models. Quick and complete biodegradation is an important environmental factor. The enhanced life of cellulose solid insulation when using natural ester fluid has extended the thermal limits used by transformer designers. Higher temperature natural ester fluid transformer designs provide the advantage of reduced construction materials, even considering overload conditions.

Dielectric breakdown and withstand voltages of the insulating fluid using AC power frequency, lightning impulse and switching impulse voltages must be considered for high voltage applications with natural ester fluids in comparison to mineral oil [5]. The natural ester fluid and fluid/cellulose insulation interface was tested using power frequency and lightning impulse voltages. Results of 50-60 Hz AC and 1.2x50µs lightning impulse have been previously reported [6]. We report switching surge breakdown and withstand values of long oil gaps using the same HV bushing shield and tank wall as in [6].

The bushing shield to tank wall is a critical part of power transformer insulation design. We report switching surge data mean breakdown at 50% probability and withstand values using Weibull 1% probability. Positive and negative 250x2500 µs switching impulse waves were applied between 50 mm and 150 mm gaps in natural ester fluid and mineral oil. The switching impulse results of natural ester fluid gaps were higher than those of mineral oil at both polarities.

The bushing shield to tank wall results are compared with those obtained using an electrode configuration developed for testing fluid/pressboard creep by Weidmann Electrical Technology [7]. Overall, our results indicate that natural ester fluid has equal or better dielectric breakdown characteristics compared to mineral oil for gaps of 10 to 150 mm.

II. Bushing Shield To Flat Plate Gaps

The bushing shield to flat plate configuration was tested in natural ester fluid and mineral oil 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 x 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

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.

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 [9].

The switching impulse test was done in accordance with IEC and IEEE methods. The 250 x 2500 µs switching impulse wave was applied using the V50 up and down method [10, 11]. The applied impulses varied from 26 to as many as 67 shots with an average of 45 shots. The testing was done at

TABLE 1. NEGATIVE SWITCHING IMPULSE BREAKDOWN AND WITHSTAND VOLTAGES OF BUSHING SHIELD TO FLAT PLATE

Oil Gap	**50mm**		**100mm**		**125mm**		**150mm**	
Fluid	***NE***	***MO***	***NE***	***MO***	***NE***	***MO***	***NE***	***MO***
U_{avg} (KV)	712	782	992	872	1029	900	1188	1075
Std dev	66	136	129	68	72	106	127	203
S (%)	9.3	17	13	7.8	7.0	12	11	19
$U_{1\%W}$	516	424	629	662	802	591	797	550
α (scale)	740.7	837.3	1046	901.8	1062	945.6	1246	1157
β (shape)	12.71	6.766	9.025	14.91	16.37	9.796	10.29	6.189
R^2_W	0.982	0.940	0.928	0.983	0.888	0.945	0.947	0.933

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. As in previous testing in [6], the surface of the bushing shield was inspected for pits several times during the course of the tests. The fault current was limited by using an AC resonance test set, minimizing significant pitting. The test tank was cleaned and flushed after the change from mineral oil to natural ester fluid.

B. Switching Surge Results

The data from this work were analyzed using both normal mean and 1% Weibull two parameter probabilities using median ranking. The negative switching impulse breakdown results are summarized in Table 1. The average negative switching impulse results for the bushing shield to flat plate gaps show that natural ester fluid is 9% lower than mineral oil at 50 mm, but 11-14% higher than mineral oil at 100-150 mm. The withstand values calculated as 1% probabilities show a significant improvement over mineral oil, differing by over 24% for the combined 50-150 mm gaps. The relative standard deviations averaged 10% for natural ester fluid and 14% for mineral oil. The negative data is plotted in Fig. 2 using the voltage stress versus gap distance.

The positive switching impulse data for 50 to 150 mm gaps are summarized in Table 2. The positive polarity breakdown and withstand voltage comparisons show that the natural ester fluid is significantly better than mineral oil. The

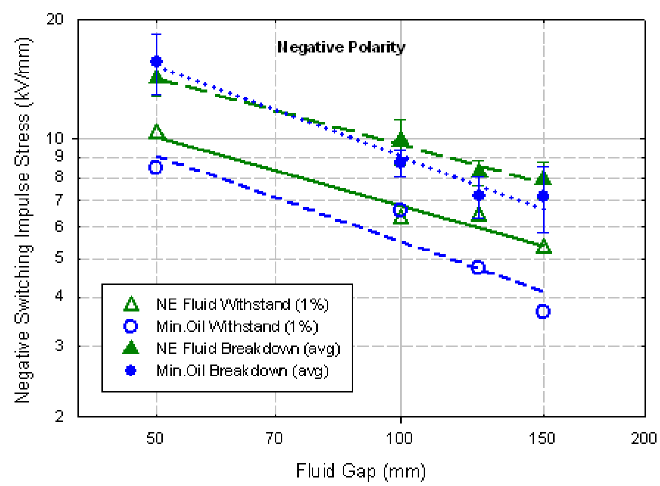

Figure 2. Negative Switching Impulse Stress - Bushing Shield to Flat Plate

TABLE 2. POSITIVE SWITCHING IMPULSE BREAKDOWN AND WITHSTAND VOLTAGES OF BUSHING SHIELD TO FLAT PLATE

Oil Gap	**50mm**		**100mm**		**125mm**		**150mm**	
Fluid	***NE***	***MO***	***NE***	***MO***	***NE***	***MO***	***NE***	***MO***
U_{avg} (KV)	766	668	1144	894	1215	1007	1280	1061
Std dev	74	111	66	106	136	106	68	110
S (%)	9.7	17	5.8	12	11	11	5.3	10
$U_{1\%W}$	546	377	935	591	815	695	1064	736
α (scale)	798.8	713.1	1174	939.4	1274	1053	1311	1109
β (shape)	12.07	7.221	20.24	9.940	10.30	11.09	22.00	11.22
R^2_W	0.927	0.931	0.956	0.965	0.987	0.900	0.981	0.935

average percent improvement over mineral oil for the 50-150 mm gaps is 21% for breakdown and 41% for withstand voltages. This trend is clearly displayed in Fig. 3. The relative standard deviations for the positive data averaged 8% for natural ester fluid and 12% for mineral oil.

III. WEIDMANN ELECTRODE GAPS

The Weidmann electrode configuration used for this work and in a previous study in [7] is shown in Fig. 4. How-ever, for our present work, the high density pressboard (1.6 mm) specimen was removed and not part of the test, since our focus was on oil gap breakdown. The high voltage electrode was wrapped with 1 mm of crepe insulation, the ground electrode was covered with 1 mm thick high density pressboard and fresh fluid was used for each breakdown. The gaps were set between the electrodes with a stainless steel gauge. The natural ester fluid and mineral oil gaps were tested at distances of 10, 20 and 35 mm.

A. Test Procedures

The paper wrapped HV electrode and ground electrode pressboard insulation were dried for 24 hours in an oven, vacuum dried at less than 100 microns for 24 hours, oil impregnated under vacuum and allowed to oil soak for 24 hours in accordance with [12]. The insulating fluids were tested for moisture content and dielectric strength using ASTM test methods D3277 and D1816 respectively.

The natural ester fluid and mineral oil gaps were tested for 60 Hz AC breakdown per ASTM D149 and negative 1.2 x 50

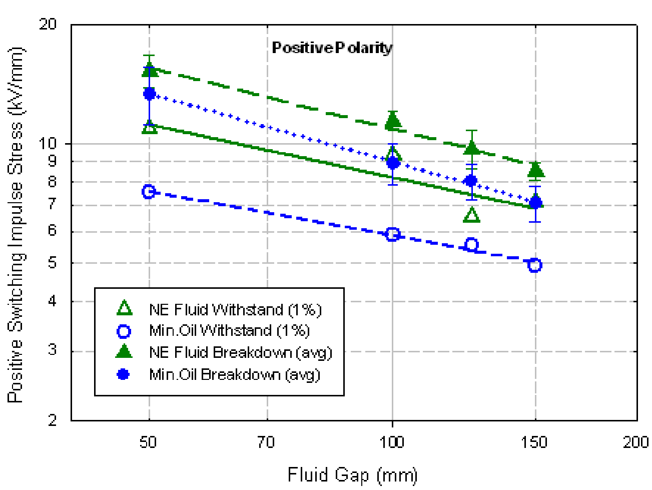

Figure 3. Positive Switching Impulse Stress - Bushing Shield to Flat Plate

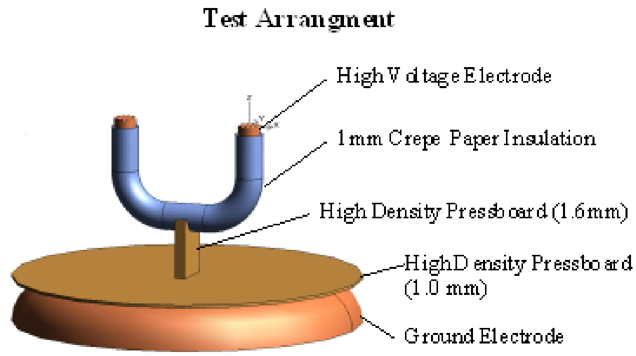

Figure 4. Weidmann Electrode Configuration used for Oil Gap Testing (without Pressboard Creep Specimen in place)

μs lightning impulse wave per ASTM D3426. The data was analyzed for the normal mean breakdown and 1% Weibull probability using two parameters with median ranking. A total of 24 fluid samples per gap were tested to breakdown or to the maximum voltage capability of the Weidmann testing equipment.

B. 60 Hz AC Results

The AC power frequency results are summarized in Table 3. The breakdown results (50% normal probability) are comparable for natural ester fluid and mineral oil. There are some small differences in the withstand results using 1 % probability, as the gaps at 10 mm and 35 mm favor mineral oil slightly while natural ester fluid is better at 20 mm. The Weidmann results were plotted in Fig. 5 together with results from 50-150 mm gaps tested at Powertech Lab, previously published in [6]. While the electrode configurations were slightly different, the data fit close to a linear regression line drawn from 10 mm to 150 mm.

C. Lightning Impulse -1.2 x 50 μs Results

The negative lightning impulse results are summarized in Table 4. The average breakdown results are comparable for natural ester fluid and mineral oil. There are some small differences in the withstand results using 1% Weibull probability, as the gaps at 10 mm and 20 mm favor natural ester fluid while mineral oil is better at 35 mm. The Weidmann results were plotted in Fig. 6 with results from 50-150 mm gaps tested at Powertech Lab, previously published in [6]. The data fit close to a linear regression line drawn from 10 mm to 150 mm.

TABLE 3. 60HZ BREAKDOWN AND WITHSTAND VOLTAGES OF WEIDMANN ELECTRODE ARRANGEMENT

Oil Gap	**10mm**		**20mm**		**35mm**	
Fluid	***NE***	***MO***	***NE***	***MO***	***NE***	***MO***
U_{avg} (KV)	191	175	252	245	276	273
Std dev	46	36	49	51	49	34
S (%)	24	21	19	21	18	13
$U_{1\%W}$ (KV)	75	84	119	107	131	172
α (scale)	208.8	189.7	272.7	266.2	298.1	288.5
β (shape)	4.50	5.61	5.56	5.06	5.59	8.85
R^2_W	0.968	0.873	0.978	0.970	0.944	0.947

TABLE 4. NEGATIVE LIGHTNING IMPULSE BREAKDOWN AND WITHSTAND VOLTAGES OF WEIDMANN ELECTRODE ARRANGEMENT

Oil Gap	**10mm**		**20mm**		**35mm**	
Fluid	***NE***	***MO***	***NE***	***MO***	***NE***	***MO***
U_{avg} (KV)	540	500	683	688	776	810
Std dev	71	76	53	66	81	77
S (%)	13	15	7.7	9.6	10	9.5
$U_{1\%W}$ (KV)	329	282	508	487	526	571
α (scale)	571.6	532.8	709.0	717.0	812.3	844.4
β (shape)	8.33	7.24	13.8	11.9	10.6	11.7
R^2_W	0.857	0.943	0.817	0.945	0.917	0.954

IV. DISCUSSION

The negative switching impulse results for the 50 to 150 mm gaps in natural ester fluid are about 10 % higher than mineral oil for breakdown and over 20% for withstand voltage. The variability in the mineral oil breakdown data is greater than the natural ester fluid by 4% using relative standard deviation for either polarity. The positive switching impulse results of natural ester fluid gaps are over 20% higher than mineral oil for breakdown and over 40% for withstand levels.

The AC and lightning impulse results of natural ester and mineral oil gaps obtained with the Weidmann electrodes closely fit linearly with results obtained previously for a simulated bushing shield to ground plate electrode. Both the electrode configurations are slightly non-uniform. Overall, the results fall where expected when compared to the work of others using Rogowski type electrodes.

The results from our combined work on gaps of 10 to 150 mm show that the breakdown and withstand voltages of natural ester fluid are comparable or higher than mineral oil. Statistically, the data for natural ester fluid is better than the mineral oil.

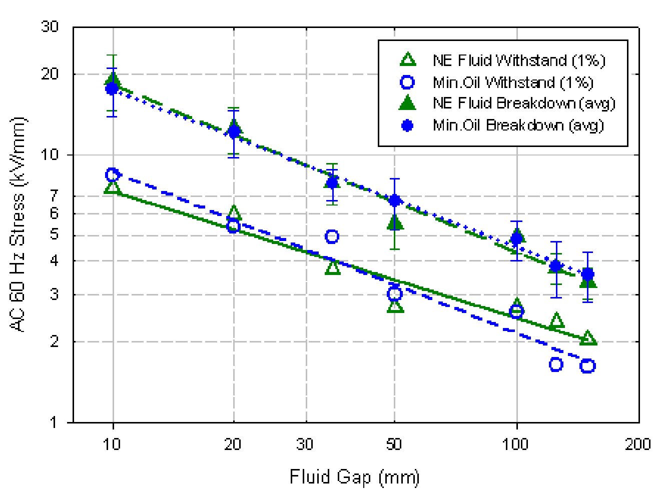

Figure 5. 60 Hz AC Stress – 10-35 mm Gaps at Weidmann – 50-150 mm Gaps at Powertech Lab [6]

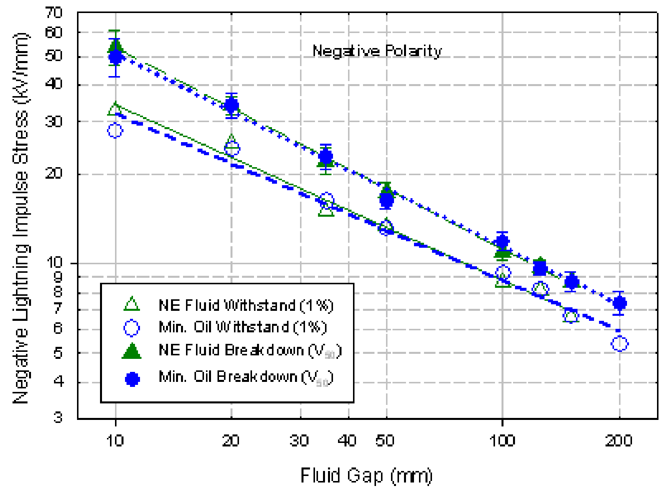

Figure 6. Negative lightning impulse stress: 10-35 mm gaps at Weidmann; 50-150 mm gaps at Powertech Lab [6].

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