Conference Record of the 1998 IEEE International Symposium on Electrical Insulation, Arlington, Virginia, USA, June 7-10, 1998

AC (60 Hz) and IMPULSE BREAKDOWN STRENGTH OF A COLLOIDAL FLUID BASED ON TRANSFORMER OIL AND MAGNETITE NANOPARTICLES

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Abstract

A new class of colloidal dielectric fluids was developed by modifying the mineral oil based ferrofluids to enhance their dielectric performance. At its optimum composition, the colloidal insulation has AC (60 Hz) breakdown strength close to that of the carrier oil, while its impulse voltage withstand in needle to sphere geometry is improved: for the needle positive, the impulse breakdown voltage increased up to 50% as compared to the dry and degassed mineral oil (Exxon Univolt 60) while for the needle negative the breakdown value remains close to that of the oil carrier, so that the two values are practically equal. The PD inception voltage (AC, 60 Hz, 500 V/sec rise, needle to sphere geometry) showed and increase of up to 30%. The new colloidal insulation showed little change in electrical resistivity and kinematic viscosity after accelerated aging at 185 °C.

Introduction

A colloid is defined as a suspension of fine particles in a liquid carrier with no measurable (i.e., affecting the physical and chemical stability of the fluid) sedimentation of particles over time [1]. The first magnetic colloid for use as a transformer insulation liquid was developed to enhance the heat transfer from within the transformer windings by enforcing the magnetic interaction between the field produced by the windings and fluid [2]. This was achieved by converting transformer oil into a ***ferrofluid***, a well known magnetic colloid, used commercially in many applications [3,4]. Essentially, the colloidal fluid which has been investigated is a special ferrofluid with carefully chosen magnetic particles and additives to ensure the colloid's stability in service close to that of the carrier oil. In this paper, the terms colloidal fluid and ferrofluid will be interchangeably used defining a suspension of magnetic nanoparticles in a mineral oil.

From a conventional point of view, the addition of particles to transformer oil should be detrimental to its dielectric strength. It is a well established practice to purify the transformer oil to a maximum degree possible, while a colloidal fluid can only be obtained by intentionally mixing the oil with suspended particles. It shall be noted, however, that the average size of particles (magnetite) used is in the range of a few nanometers, i.e., two to three orders of magnitude smaller than the particles normally found in a transformer oil. Together with some specific properties of the particles themselves, this could explain the very unusual dielectric behavior of the colloidal transformer insulation fluid.

Data presented in this paper is limited to AC breakdown, impulse withstand, and PD inception measurements. The critical issue of the long term stability of colloidal insulation is also briefly addressed. In the meantime, an effort is under way to confirm experimentally the feasibility of the new insulation fluid for use in high voltage electric equipment and to better understand the mechanisms of the unusual dielectric behavior of the novel insulation liquid.

Experiment

Fluid preparation

Most of the experiments presented in this paper were performed using Univolt 60 Exxon mineral oil. The colloids were prepared by adding specific amounts of a mineral oil based ferrofluid specifically tailored for this study, to the oil. To check the effect of the carrier oil on dielectric strength of the colloid, in some cases, the Nytro 10 X oil was substituted for Univolt 60.

A mobile liquid processor Baron BA FPS 75 was used to dry and degas the oil prior to testing or to its use as a carrier liquid in a ferrofluid. The moisture content of oil carrier was measured by Mitsubishi moisture meter CA-05 for each batch of experimental fluid which was then kept in sealed jars. No additional treatment was applied after the colloid was prepared.

The colloid stability over the typical transformer "life in service" period was estimated from an accelerated thermal aging experiment when 5 ml of oil and colloid were held for up to 34 weeks in sealed containers placed in an oven set at 185 °C. After aging, electric resistivity (determined in a cell with 2.5 mm distance between the flat electrodes connected to a 60 volts DC power supply) and kinematic viscosity of the colloidal fluids were measured.

Dielectric strength measurements

AC breakdown voltage was measured in accordance with ASTM D877 standard, using Bauer Automatic 60 Hz Electrical Breakdown Tester DTA 100E. The tester generated a value of the mean of five individual tests along with the standard deviation for the whole test.

Impulse voltage withstand was tested for a needle to sphere geometry with the needle being a negative or positive electrode. Standard (ASTM D 3300 - 85) impulse wave having the shape 1.2 by 50 microseconds was produced by the Haefely Impulse Generator SGE 1200/60. A minimum of three impulse waves were applied to each sample and for each of the needle polarities. The amplitude and time of the wave "to chop" event were recorded by a PC-connected monitoring system and then the resulting data (1000 points on average) was converted into a Microsoft Excel worksheet for analysis.

Partial discharge inception voltage (PDIV) was tested using the same setup as for the impulse withstand with the difference that an AC voltage rising at a rate of 500 V/sec. was used to stress the fluids. The gap between the needle and sphere electrodes was decreased from 25.4 mm to 8.25 mm.

Results and Discussion

AC (60 Hz) breakdown strength

AC breakdown measurements produced close values for the oil and colloidal fluid (Table 1). It was noticed, however, that the colloid's AC strength was affected much less than that of oil after both fluids were exposed for several days to an open air with natural high humidity. This observation led to a more systematic study of moisture effect on colloid's AC strength. Oil samples were prepared with different moisture content: from less than 2 ppm to more than 30 ppm of water. The samples were then halved, and one half was subjected to a breakdown test in "as is" state while the other was used as a carrier to prepare a ferrofluid which then was subjected to the same test

As the data (Table 1) shows, AC breakdown voltage decreases for both the oil and ferrofluid when water content increases. The ferrofluid, however, shows much less dependence of its electric breakdown on the moisture than the oil carrier.

Practically identical result was obtained when Nytro 10X oil was substituted for the Univolt 60 oil. No specific mechanism to explain this finding can be suggested at this time.

Table 1. AC Breakdown voltage for ferrofluid and oil

Fluid	Moisture content, ppm, in the oil carrier							
	< 5		10 to 20		20 to 30		>30	
	kV	STD	kV	STD	kV	STD	kV	STD
Oil	50	3.5	43	4.2	37	4.5	28	5.7
Colloid	50	2.9	47	2.8	44	3.9	40	3.5

It should be noted that in a separate study it was established that colloids of mineral oil and magnetite particles are capable of binding part of the water dissolved in the oil carrier. It is thought that this property of the magnetic colloid can be responsible for alleviating the detrimental effect of moisture on the electric breakdown.

Withstand under needle to sphere electric impulse

It is well established that conventional mineral oil has a much higher impulse withstand value when the needle is a negative electrode [5]. This difference has been explained and confirmed by direct observation of the breakdown events, specifically the difference in streamer formation mechanism was confirmed [6]. The different mechanism of the streamer formation leads to its different geometry and results in that the positive streamer propagates across the fluid gap between the electrodes at a much higher speed than the negative one.

Taking these facts into account, multiple sets of data were obtained on the impulse breakdown of the colloidal fluid at both polarities of the needle electrode. The typical experimental data (Fig.1 through 4 and Table 2) reveal a very unusual character of the impulse breakdown in a colloidal fluid compared to that in the carrier oil. The most striking experimental observation is that for the colloidal fluid the impulse voltage withstand value is very close for both polarities of the needle. From a practical standpoint, the most significant result is that in a colloid the impulse voltage at both polarities of the needle is very close to the highest value measured for the carrier oil (with the needle negative). As a result, the minimum value of the needle impulse voltage withstand for the colloid is 30 to 40% higher than that for the oil carrier.

The impulse wave "chop" time in the colloid is close to that of oil for the needle negative, but it is always much longer when the needle is positive (Table 2).

The difference between the mineral oil and colloid for the impulse wave break voltage and for the time the streamer propagates across the gap between the electrodes has been confirmed for longer gaps: 40 and 55 mm (Fig. 3, 4) and for different mineral oil, Nytro 10X, which was used to prepare the colloidal ferrofluid as well (Table 2).

With longer gaps, the colloids vs. carrier oil difference in the impulse voltage withstand is even more pronounced than for the standard 25.4 mm distance. This suggests that colloid's higher strength is due to its intrinsic dielectric stability rather then some local effects on the needle electrode. It is further confirmed by a very unusual behavior of the streamer propagation velocity, namely the "chop" time for the positive wave increases along with the voltage withstand.

Table 2. Summary data for Impulse Voltage Withstand testing for two types of oil and colloids based on these oils

Fluid and Gap, mm	"Chop".Voltage, kV		"Chop" time, μsec	
	-/+	+/-	-/+	+/-
U-60, 25.4	170	86	27	12
Nytro,25.4	177	88	23	16
U-colloid, 25.4	154	157	15	26
N-colloid, 25.4	173	156	17	25
U-60, 55	340	225	28	25
U-colloid, 55	321	390	32	46

Standard deviation for the impulse withstand voltage in all cases was < 5% and for the chop time <20%., i.e., the difference in the test values between the oil and colloidal ferrofluid far exceeds the statistical variations.

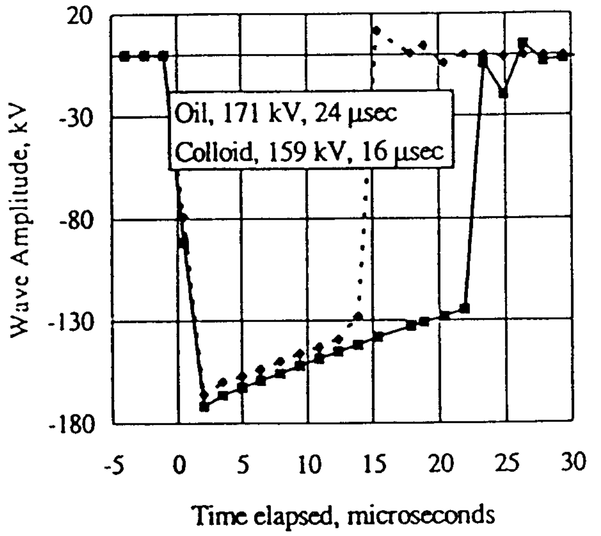

Fig. 1. Impulse Withstand. Needle Negative, Gap = 25.4

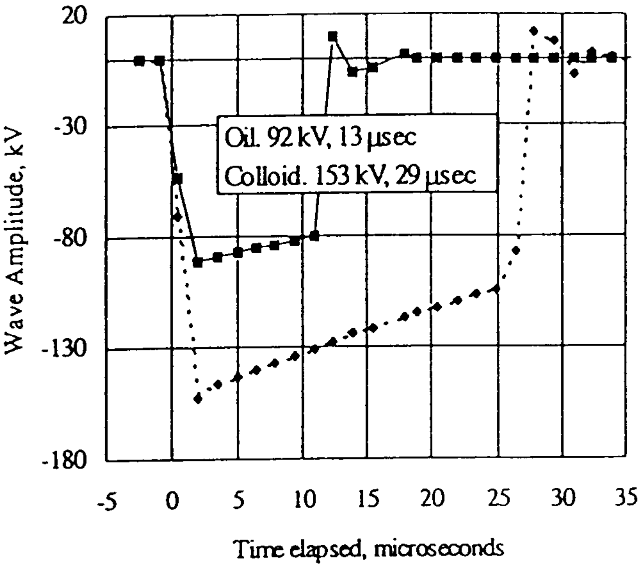

Fig. 2 Impulse Withstand. Needle Positive. Gap = 25. 4 mm

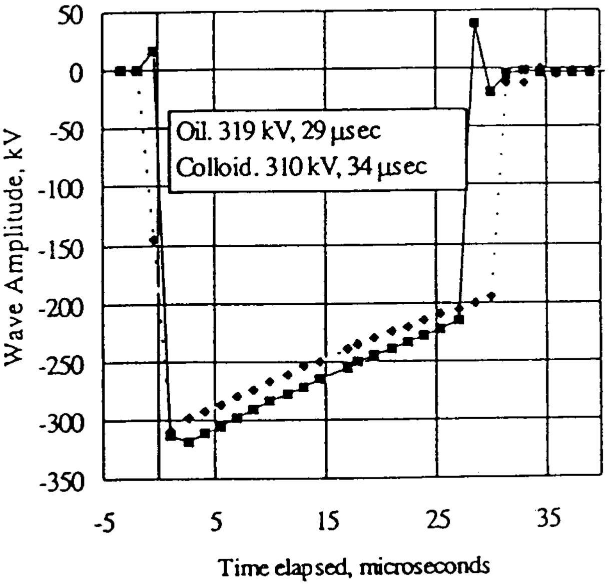

Fig. 3. Impulse Withstand. Needle Negative. Gap = 55 mm

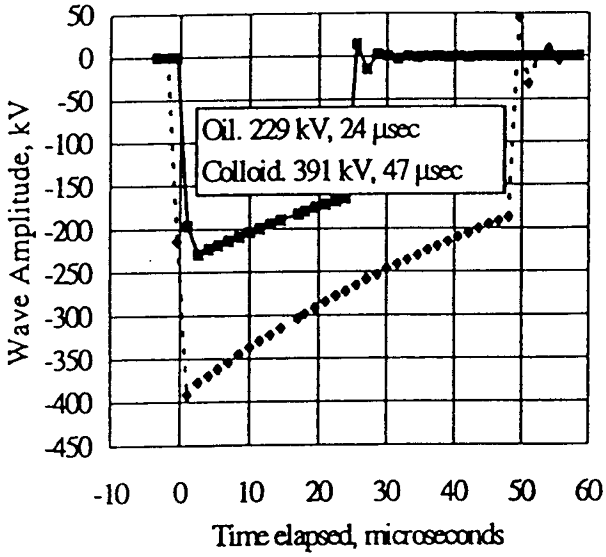

Fig. 4. Impulse Withstand. Needle Positive. Gap = 55

Partial discharge inception voltage (PDIV) experiments with a needle to sphere test geometry have confirmed the increased dielectric strength of colloidal fluid. About a 30% increase in PDIV value for the Univolt 60 – based ferrofluid vs. oil carrier was measured (Table 3)

Table 3. PDIV. 60 Hz, Needle to sphere. Gap = 8.25 mm

Fluid	PDIV, kV	Stand. deviation
Oil	15.1	3%
Colloid	19.5	1%

The viscosity (η) is practically the same for the two fluids in the whole temperature range tested (0 to 110 °C), while the difference between the oil and colloid's electric resistivity (R) decreases from about two orders of magnitude at room temperature (oil is less conductive) to less than one order at 100 °C (Fig. 5).

The accelerated thermal aging experiment has shown that after 34 weeks at 185 °C the colloid's resistivity and viscosity as well as the density of magnetite particles remained practically unchanged from their values before aging which suggests that the colloid's thermal stability is defined by that of the carrier oil and it is practically equal to the latter.

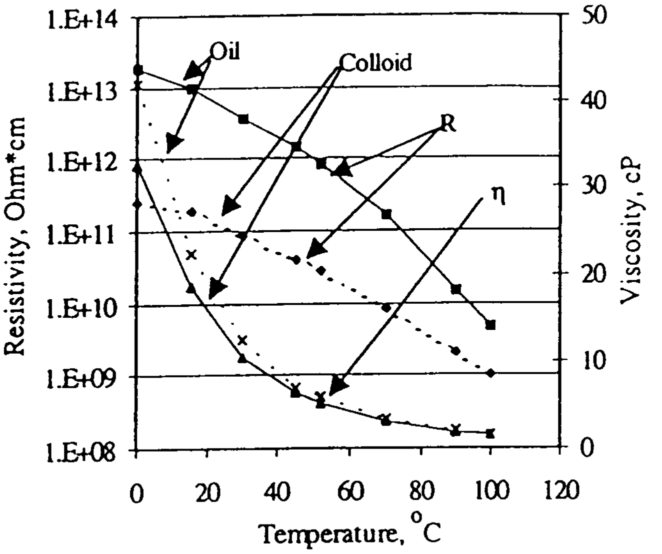

Fig. 5. Resistivity and Viscosity dependence on temperature. Colloid and Univolt 60.

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