AC and lightning breakdown strength of mineral oil Nytro Gemini X and 10GBN

AC AND LIGHTNING BREAKDOWN STRENGTH OF MINERAL OIL NYTRO GEMINI X AND 10GBN

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ABSTRACT

Nynas Nytro 10GBN, one of the most commonly used mineral oils, was replaced by Nynas Nytro Gemini X recently. To understand the impact of this change, it is necessary to compare dielectric strength of 10GBN and Gemini X. In this paper, the standard methods of electrical breakdown tests for insulating liquids were introduced and assessed based on literature review, and then both AC and lightning breakdown voltage tests of mineral oils were carried out according to ASTM standard D 1816 and D 3300 respectively. The results of AC tests show that breakdown voltage of Gemini X is about 4 to 6 kV lower than that of 10GBN for 1mm gap of VDE electrodes. Meanwhile, the results of lightning tests indicate that mean breakdown voltage of Gemini X is about 55kV higher than that of 10GBN for a 3.8mm gap of sphere to sphere electrodes, and this is considered to be caused by lower aromatic content in Gemini X (10%) than 10GBN (14%).

INTRODUCTION

Power transformers, whose insulation system usually consists of oil and paper, are vital components of electrical power network systems. The oil used in power transformers has three main functions: electrical insulation, thermal coolant and information carrier[1].

Mineral oil has been widely and successfully used as transformer oil over the past century, it consists mainly of carbon and hydrogen in molecules with different structures, as shown in Figure 1[2]. Paraffinic, naphthenic and aromatic are the three basic structures, and they are normally indicated by percentage for a certain type of mineral oil. Paraffinic and naphthenic are the predominant components of a mineral oil, but aromatic compounds are always present and remain as the most interesting group for discussions. Aromatics contribute to the gas absorption and oxidation stability of oil. However, as the aromatic content in particular presence of polyaromatic molecules increases, the negative lightning impulse breakdown voltage decreases[3].

Nynas Nytro 10GBN, an uninhibited naphthenic-based mineral oil, was one of the most popular mineral oils. However, it was replaced recently by a new mineral oil Nynas Nytro Gemini X which is inhibited and has good performance regarding copper corrosion and oxidation stability. The physical, chemical and basic electrical properties of 10GBN and Gemini X are compared and shown in Table 1[4, 5].

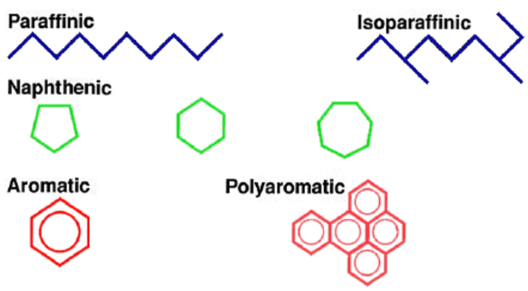


Figure 1 Basic molecular structure in mineral oil[2]

Table 1 Basic property of 10GBN and Gemini X

Property	Unit	Test Method	10GBN	Gemini X
Density@20℃	kg/dm^3	ISO12185	0.887	0.882
Viscosity @40℃	mm^2/s	ISO3104	9.1	8.7
Pour point	℃	ISO3016	-57	-60
Flash point, PM	℃	ISO2719	148	144
Acidity	mg KOH/g	BS2000.1*/ IEC62021**	<0.01*	<0.01**
Aromatic content	%	IEC60590	14	10
Water content	mg/kg	IEC60814	<20	<20
Furfural content	mg/kg	IEC61198	<1.0	<0.1
Antioxidant, phenols	Wt%	IEC60666	Not detectable	0.38
Dielectric dispassion factor@90℃		IEC 60247	<0.001	<0.001
Interfacial tension	mN/m	ISO6295	49	50

Mineral oil, as an essential component of transformer insulation, should withstand not only power frequency AC voltage but also transient impulse voltage (such as lightning impulse and switching impulse). AC breakdown test is normally used for oil quality check and control due to its sensitivity to particle, water and other contamination[6, 7]. Lightning breakdown test as BIL is used as criterion for large power transformer insulation design, and it is also generally regarded to be predominated by the oil intrinsic properties. In another word, it can be used to identify the difference of oil property. Since many transformer manufactures, utilities and university researches have gone through this generation change of mineral oil from 10GBN to Gemini X, it is important to carry out comparative tests on dielectric strength between these two oils and understand the differences, if any.

In this paper, first the ASTM and IEC standard methods of electrical breakdown tests for insulating oils were compared and discussed. Both the AC and lightning breakdown voltage tests were then investigated per using ASTM D 1816 and D 3300 respectively. All the oil samples were filtered, degassed and dehydrated before tests in order to make sure that the results reflect the natural properties of these two oils.

STANDARD METHODS OF ELECTRICAL BREAKDOWN TESTS FOR INSULATING LIQUIDS

Methods for AC Breakdown Tests

As manufactures tend to use different test methods, difficulties arise when directly comparing breakdown voltage across liquids. American manufactures quote the ASTM D 1816[8] while European industries refer to IEC 60156[9]. In the standards mentioned above, different types of electrode configurations, voltage ramp rate, time intervals and sample size are specified, as shown in Table 2.

Table 2 Comparison of ASTM D1816 and IEC 60156

Property	ASTM D 1816	IEC 60156
Electrode type	Brass; VDE type	Brass, bronze or stainless steel; sphere or VDE type
Electrode gap (mm)	1 or 2	2.5
Voltage ramp rate (kV/s)	0.5	2.0
Time interval between tests (s)	60~90	Minimum120
Results	5 or 10 breakdowns; 5 breakdowns/sample	6 breakdowns; 6 breakdowns/sample

It was emphasized in both standards that AC breakdown voltage indicates the presence of contaminating agents such as water, dirt, cellulose fibres or conducting particles in dielectric liquid. In IEC 60156, it is even said that AC breakdown voltage of insulating liquids is not a basic material property. Generally, AC breakdown tests are used for acceptance testing on delivered new liquids, quality control of liquids during transportation or filling into apparatus and measure of the liquid's ability to withstand electric stress at power frequency.

When comparing the withstand ability across new liquids, in the authors' opinion, it is necessary to filter the liquids in order to control the particle number to a low level or at least particle counts for different test liquids should be at the same level, usually in the same order of magnitude (specified as particle number per 100ml oil sample). Besides, the degassing and dehydrating procedure are still requested. Furthermore, if considering the request of industry design, withstand voltage at quite low breakdown probability is more meaningful than the mean breakdown voltage. Therefore, neither 5 or 10 breakdowns in ASTM D1816 nor 6 breakdowns in IEC 60156 are enough for such a purpose. A large sample size of test is requested to obtain the withstand voltage by using normal or weibull statistical analysis.

Methods for Lightning Breakdown Tests

Similar to AC breakdown tests, there are also two frequently used standards, ASTM D3300[10] and IEC 60897[11], for lightning breakdown tests by American and European industries respectively. The basic comparison including the electrode configurations, voltage increasing method, time intervals and sample size is given in Table 3.

Table3 Comparison of ASTM D 3300 and IEC 60897

Property	ASTM D 3300	IEC 60897
Electrode type	Steel or brass; point-to-sphere or sphere to sphere	Steel; Point-to-sphere
Electrode gap (mm)	25.4 for point-to-sphere; 3.8 for sphere-to-sphere	25, 15, 10 depends on the expected voltage range
Voltage increasing method (kV)	Step by step, 3 shots per step Step voltage 5 or 10	Step by step, 1 shot per step Step voltage 5 or 10
Time interval between shots (s)	Minimum30	Minimum60
Results	5 breakdowns; 1 breakdown/sample	5 breakdowns; 1 breakdown/sample

Both methods are most commonly performed using a negative polarity point opposing a grounded sphere (NPS). It is believed that lightning breakdown voltage at NPS configuration depends on oil composition rather than such contaminants as moisture and particles. The methods may serve to differentiate dielectric liquids between each other and to detect variations in their characteristics due to modifications in their chemical composition. Since there is no highly divergent field in the practical insulation systems, experience on lightning breakdown properties under uniform / semi-homogenous field is necessary before the results of impulse breakdown voltage obtained at NPS configuration can be referred to in industry design.

In terms of sample size of tests, it seems that 5 breakdowns are not enough to obtain a reliable estimation especially in the case when large variation of breakdown voltages occurs. However, in lightning breakdown tests, the liquid sample and electrode should be frequently changed due to high energy damage of impulse shots, which increases the difficulties of large sample size test when considering the constraints of manpower, finance and so on so forth. So finding a proper way to carry out the impulse breakdown tests is still of importance.

EXPERIMENTAL DESCRIPTION

Pre-processing of Oil Samples

First, the original oil was filtered by Nalgene® MF 75 Nylon Membrane Filter whose pore size is 0.2µm. A HIAC/ROYCO 8000A 8-Channel Particle Counter was used to measure the particle number of oil samples. It was found that particle number of oil filtered once decreases dramatically, less than one tenth of that of original oil. Particle number of filtered oils including the background influence (such as oil container) could reach the level of lower than 200 per 100 ml for particles with size larger than 5 µm, which was classified as 'clean oil' in CIGRE brochure[12], as shown in Figure 2.

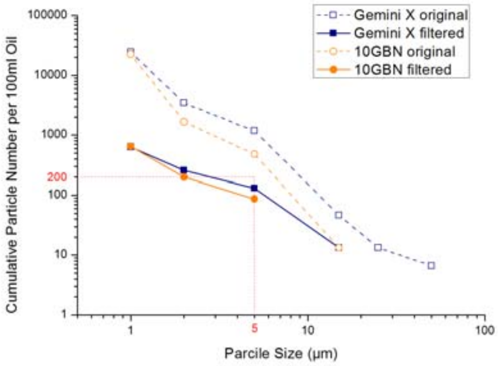


Figure 2 Particle count of 10GBN and Gemini X

Second, the filtered oils were degassed and dehydrated in vacuum oven under 10 mbar at 85 ˚C for 48 hours, then were given a further 24 hours to cool down to ambient temperature also under vacuum condition. Water content of oil samples after pre-processing, per using Karl Fisher titration analysis, were lower than 3ppm equal to relative humidity at 20˚C of 5.5%.

AC Breakdown Voltage Test

A Buar DPA75 oil tester was used to measure AC breakdown voltages as per ASTM D 1816 using brass partially spherical electrodes (named VDE electrodes) set at 1mm gap, as shown in Figure 3. The rate of rise of the voltage was 0.5kV/s. The cell filled with sample oil was degassed in vacuum oven for 15 minutes. After that, the initial standing time of 3 minutes was fixed before the application of voltage. The time interval with stirring action after each breakdown was set at 1minute. All experiments were performed at room temperature.

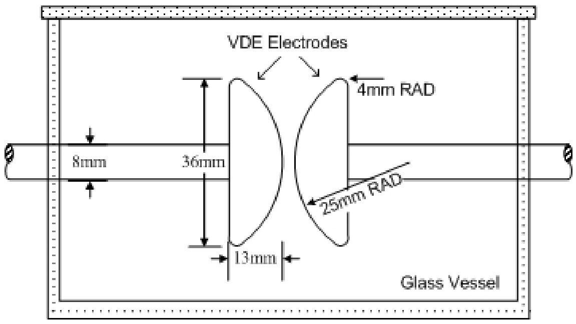


Figure3 AC breakdown test cell with VDE electrodes

In standard, at most 2 sets of 5 breakdowns are required, but in order to get the statistical distribution and give a reliable evaluation, 3 samples of each type of oils were done, and 10 sets of 5 breakdowns were carried out per sample oil. Totally, 150 breakdowns based on 3 samples were obtained for 10GBN and Gemini X respectively. According to the large number of experimental data, the withstand voltage at 1% and 0.1% breakdown probability were calculated by using normal and weibull distribution.

Lightning Breakdown Voltage Test

A Haefely 10 stages impulse generator was used to provide 1.2µs/50µs standard lightning impulse. According to ASTM D 3300, 3.8 mm gap of sphere to sphere electrodes was chosen in the following tests. However test cell was designed refer to IEC standard, as shown in Figure 4. The test voltage was increased from 140kV in steps of 10kV and three shots were applied for each voltage level. Similar to AC tests, the cell filled with sample oil was degassed in vacuum oven for 15 minutes. The initial standing time was 5 minutes, the time interval between two successive shots was fixed at 1 minute. All experiments were performed at room temperature. After one breakdown occurs, the oil sample and electrodes were changed, totally 5 samples were carried out for each type of oils.

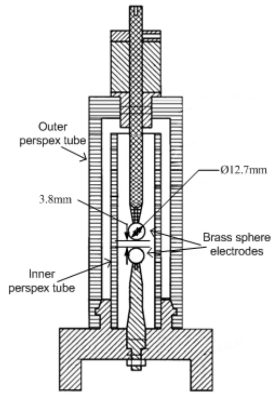


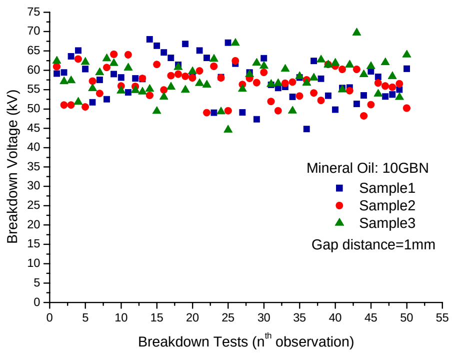
Figure 4 Lightning breakdown test cell with sphere electrodes

RESULTS AND DISCUSSIONS

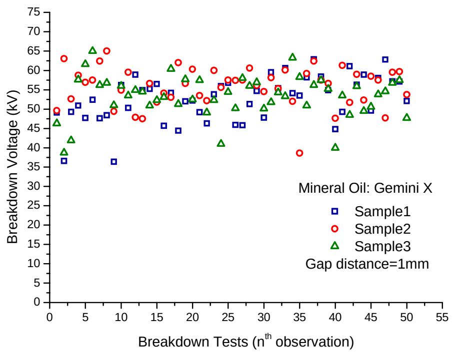
Comparison of AC Breakdown Strength

Results of breakdown voltage

The results of AC breakdown tests for 10GBN and Gemini X are plotted in Figure 5. The mean breakdown voltages and standard deviations are given in Table 4. It was found that breakdown voltages level-off with the increasing test number, no upward or downward trend was observed in experiments, which owes to the effective energy control of the test equipment [8]. The mean breakdown voltage of 10GBN is 57.4kV (average of 3 samples), slightly higher than that of Gemini X, 53.9kV (average of 3 samples) and the standard deviation of 10GBN is evenly lower than that of Gemini X.



(a)



(b)

Figure 5 Results of AC breakdown voltage. (a) 10GBN, (b) Gemini X

Table 4 Comparison of AC breakdown voltages between 10GBN and Gemini X

Oil		Breakdown Strength (kV)	
		Mean	S. D.
10GBN	Sample 1	57.8	5.4
	Sample 2	56.5	4.2
	Sample 3	57.9	4.7
	Average	57.4	4.8
Gemini X	Sample 1	52.6	5.9
	Sample 2	55.8	5.0
	Sample 3	53.3	5.4
	Average	53.9	5.4

Statistical calculation of withstand voltage

Normal distribution and weibull distribution are the popular statistical methods used to model the probability distribution of breakdown voltage and thereby calculating the withstand voltage at very low breakdown probability.

The cumulative distribution functions of normal distribution and weibull distribution are given in Formula (1) and Formula (2) respectively.

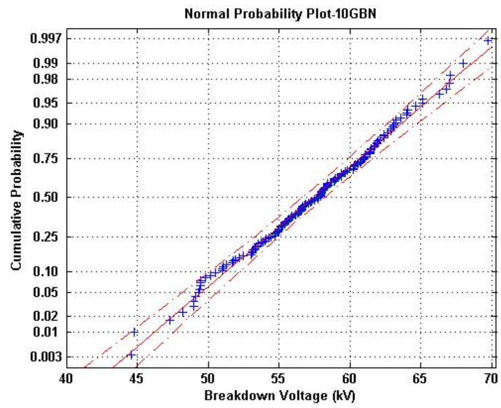
$$F_{Normal}(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{(t-\mu)^2}{2\sigma^2}} dt \qquad (1)$$

Where, μ is mean,
σ is standard deviation.

$$F_{Weibull}(x) = 1 - e^{-(\frac{x}{\beta})^{\alpha}} \qquad (2)$$

Where, α is shape parameter,
β is scale parameter.

Test results of every sample based on 50 breakdowns were modelled individually first, and then results of different sample size, sample 1 plus sample 2 as 100 breakdowns sample size and all three samples together as 150 breakdowns sample size, were modelled in order to get a comprehensive comparison of the oils by using different statistical methods. It was found that no obvious difference exists among different sample sizes since sample size is large enough, equal or over 50. The modelling results of total 150 breakdowns for 10GBN and Gemini X are shown in Figure 6.



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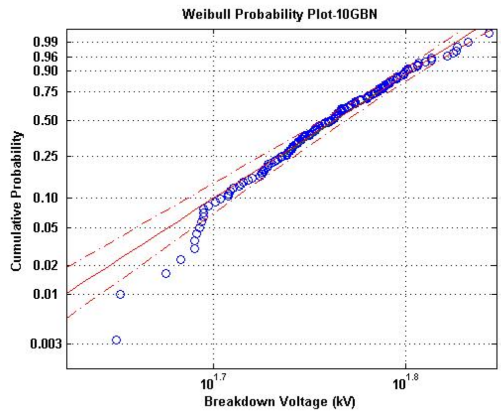

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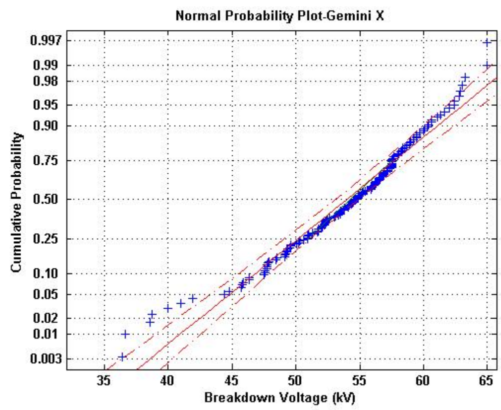

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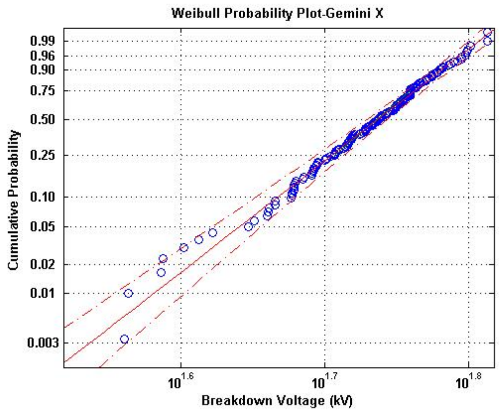

(d)

Figure 6 Normal and weibull fitting of AC breakdown results. Solid line stands for the fitting results; dashed line indicates the 95% confidence level. (a) normal fitting of 10GBN, (b) weibull fitting of 10GBN, (c) normal fitting of Gemini X, (d) weibull fitting of Gemini X.

As shown in Figure 6, it is difficult to say which kind of distribution is better for modelling the breakdown results. Looking into the results of 10GBN, for normal distribution, all the data located inside the 95% confidence limit of the fitting result. However for weibull distribution, a number of data at the left tail located outside the 95% confidence level. So it is obvious that normal distribution adheres to the experimental data of 10GBN better than weibull distribution in present tests. Considering Gemini X, it is opposite. A serious of data at the left and right tails located outside the 95% confidence level of normal fitting result while almost all the data located inside the 95% confidence level of weibull fitting result. Therefore weibull distribution becomes better than normal distribution in this case. To balance both mathematic methods are employed to calculate the withstand voltage, and the results are given in Table 5. In any case, no matter normal or weibull, 1% or 0.1% breakdown probability, AC withstand voltage of 10 GBN is about 4 to 6 kV higher than that of Gemini X.

Table 5 Calculation of withstand voltage (kV)

Oil	Normal Fitting			
	Parameters		Breakdown Probability	
	μ	σ	1%	0.1%
10GBN	57.4	4.8	46.2	42.5
Gemini X	53.9	5.6	40.9	36.7
	Weibull Fitting			
Oil	**Parameters**		**Breakdown Probability**	
	β	α	**1%**	**0.1%**
10GBN	59.6	13.1	41.9	35.1
Gemini X	56.3	11.8	38.1	31.4

Comparison of Lightning Breakdown Strength

The results of each single test along with mean and standard deviation are given in Table 6. Comparison between 10GBN and Gemini X is shown in Figure 7. It is clear that lightning breakdown voltage of Gemini X is obviously higher than that of 10GBN. For mean value, Gemini X is 243.9 kV, 54.6 kV higher than that of 10GBN, 189.3 kV. Considering the lowest breakdown voltage, the difference becomes small, about 33 kV.

Table 6 Results of lightning breakdown voltage

Oil Samples	Breakdown Voltage (kV)	
	10GBN	Gemini X
1	180.2	219.9
2	188.5	209.0
3	181.8	290.0
4	175.8	260.2
5	220.4	240.6
Mean	189.3	243.9
S. D.	18.0	32.3

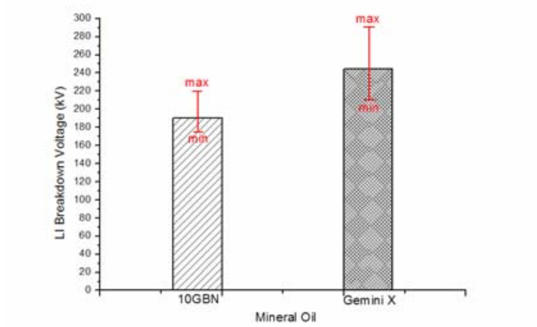

Figure 7 Comparison of lightning breakdown voltage between 10GBN and Gemini X.

The water contents of samples before and after tests were measured, no obvious change was observed due to the sealed test cell. The particle numbers of samples before test were also monitored, which made sure that particle counts of different oil samples in present tests are in the same level. So it can be drawn safely that the difference is not due to the contamination of any one of the oils.

If looking into Table 1 carefully, it can be found that aromatic content of Gemini X (10%) is significantly lower than that of 10GBN (14%), because Gemini X is a kind of highly refining oils as compared to 10GBN. Though previous experience about relationship between aromatic content and lightning breakdown voltage was obtained under NPS condition, it was found in present experiments that it is also suitable for negative sphere to sphere (NSS) configuration. So the difference of lightning breakdown voltage between 10GBN and Gemini X is believed due to the composition change of the oils, especially aromatic content difference. The large dispersion of breakdown voltages for Gemini X needs to be further investigated, and the improvement of lightning test method is still being studied.

CONCLUSIONS

A comprehensive comparison of breakdown properties between mineral oil 10GBN and new generation of mineral oil Gemini X were carried out in this paper. As refer to AC breakdown voltage, the mean value of 10GBN is 3.5kV higher than that of Gemini X, the withstand voltage of 10GBN, no matter at 1% or 0.1% breakdown probability, is 4 to 6 kV higher than that of Gemini X. Although the difference exists, the AC breakdown voltages of 10GBN and Gemini X are comparable. In terms of lightning breakdown voltage, Gemini X is about 55 kV higher than 10GBN for a 3.8mm gap of sphere to sphere electrodes due to its lower aromatic content as a result of the highly refining manufacture process.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to AREVA T&D, EDF Energy, Electricity North West, M&I Materials, National Grid, Scottish Power, TJ|H2b Analytical Services and United Utilities for their financial and technical contributions to form the research consortium on 'Application of Alternative Oils in Large Power Transformers' at The University of Manchester. A sincere thank you is given to Bruce Pahlavanpour of Nynas Naphthenics Ltd for his valuable comments.

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