

Breakdown Voltage of the Transformer Oils under Certain Conditions

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Abstract:

The transformer is considered one of the most important equipment in the electrical power system networks and the most problems occurred in it were related to the defects and weakness of the insulation systems. The oils were used in the transformer for coolant and insulation purposes; therefore, maintaining the dielectric strength of it at high level was the highest goal of the manufactures. In this study, some experimental works were performed to investigate the effect of the voltage types, electrode configurations, and the impurities on the breakdown voltage of the insulating oil. The results demonstrated that the direct current high voltage was a danger voltage type which caused breakdown of the insulating oil at lower voltage levels. In addition, the point-plate electrode configuration was the worst electrode configuration shape compared to other configurations in this study, which reduced the dielectric strength of the transformer oil due to the developing of the non-uniform field. Finally, the oil impurities had a significant effect for dielectric strength reduction of the insulating oil.

Keywords: Power transformers, Insulating oil, Impurities, Electrode configurations, Voltage types

INTRODUCTION

The insulating oils were used in power transformers for coolant and electrical insulating purposes. The reason of transformer failures comes from defects in its insulation system specially the insulating oil. Enhancing the dielectric strength of the insulating oil induces the researchers to investigate the reasons that changed the transformer oil properties, characteristics and performance. There are many parameters such as water content, electrode configuration, the electrical stress from the applying voltage, and the contamination particles on the breakdown voltage that result in the insulating oil failures [1-7].

Kurita et. al. (1992) [8] investigated the dielectric strength of filtered and clean oil. It was found in the wide range of cleanness; the breakdown strength was enhanced as reducing the number of dispersed particles. It referred that, in the case of impulse, the dielectric strength was influenced by the stressed oil volume but in case of AC voltage, the dielectric strength of the oil relied on the electrode area.

K. Farooq, (1996) [9] illustrated that the particulate and water content affected the dielectric strength of the insulating oils. The harmful effect of the water content and solid contaminants

on insulating oils was reflected in the processes of manufacturing, commissioning, and maintenance of the wetted electrical equipment. The work also discussed the filtration, counting, and controlling the particles in the dielectric oil.

Mahmud et. al., (2015) [10], investigated the dynamics of the pressboard particles that exist in the transformer oil during its operation under the effect of DC, AC, and DC biased AC electric field for different particle concentrations. The particle accumulation and conduction currents were recorded to study the constitution of the conduction bridge between the electrodes. A full conduction bridge from cellulose particles between the electrodes was observed in case of DC and DC biased AC electric field but in case of AC electric field the particles accumulated on the electrode surface but didn't constitute the bridge between them.

Li, et. al. (2016) [11] explained and compared the effect of carbon and iron particles on the breakdown strength of insulating oil. The breakdown voltage was measured with the variation of Carbon particle numbers under DC voltages. Identical experiments were conducted under AC voltage for comparison. A relation that linked between the particle numbers and the breakdown voltages was proposed. A linear relation between the particle numbers and breakdown voltage was concluded. The dielectric strength was highly affected by applying DC voltages rather than AC voltages because the impurity bridge was formed under DC voltages.

Non-uniform electric fields using needle-plane gap were applied on the contaminated transformer oil. Moreover, the effect of the electrode configurations was studied in [12]. DC, AC and DC biased AC were applied to investigate how can the contaminated particles bridged the gap space between the electrodes.

The contaminating particles (metallic and non-metallic) influenced the dielectric strength of the transformer oils since the particles in high electric field led to particle discharge which resulted in a catastrophic failure in the transformer. In [13], AC/DC composite experiment platform was constructed to investigate the effect of the contaminating particles (carbon particles) on the breakdown voltage of the insulating oil. The results revealed that the type of the applied voltage, concentration of the contaminating particles, and its diameters influence on the breakdown voltage of the transformer oils.

Contaminating insulating oil with different size iron particles was tested under AC and DC voltage according to ASTM D877 in [14]. The COMSOL Simulation software was used to explain the electric field distribution due to the presence of the

contaminating different size particles under AC/DC voltage. An increase of particle concentration led to maximum and nonuniform field inside the insulating oil. Under DC, a full impurity bridge was constructed between the gap of electrodes and therefore, the probability of breakdown was high.

In this paper, an experimental setup to develop different voltage types (DC, AC and impulse voltages) was established to study the effect of voltage types, electrode configurations, and the contaminating particles on the breakdown voltage of the insulating oils were carried out. The experiments were performed according to IEC Standard 60156.

EXPERIMENTAL SETUP

Test Circuits for Impulse, DC, and AC Voltage Generation

Three experimental setups were established to investigate the performance of the insulating oil (Shell Diala S3 ZX-I Dried). The first test circuit was for generating impulse voltage with ($t_f/t_r=1.2/50\mu s$) which was appeared in Fig. 1. The components of the test circuit were H.V. transformer, digital impulse voltmeter, measuring resistor (280 M Ω), 2 HV silicon rectifiers; voltage divider capacitor ratio (400/1), charging resistance, wave-front resistance, tail resistance, sphere-gap and the test cell containing the insulating oil at different electrode configurations was shown in Fig. 2. The second experimental setup was used to generate DC high voltage up to 140kV. The components of the test circuit were H.V. Transformer, Digital DC voltmeter, Measuring resistor, HV Silicon rectifier, capacitor, and the oil test cell. The test setup for generating DC high voltage was shown in Fig. 3. The last experimental setup was for generating AC high voltage up to 100kV. The components of the test circuit were H.V. transformer, AC peak voltmeter, measuring capacitor, some other test accessories, and oil test cell. Fig. 4 shows the test circuit components for generation AC high voltage.



Figure 1. Experimental setup for generation the impulse voltage

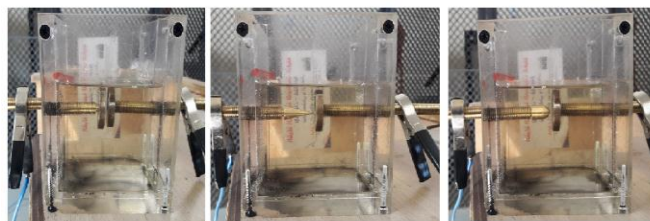


Figure 2. oil test cell with different electrodes configuration; a) plate-plate electrodes b) point-plate electrodes c) rod-plate electrodes



Figure 3. Experimental setup for generation DC high voltage

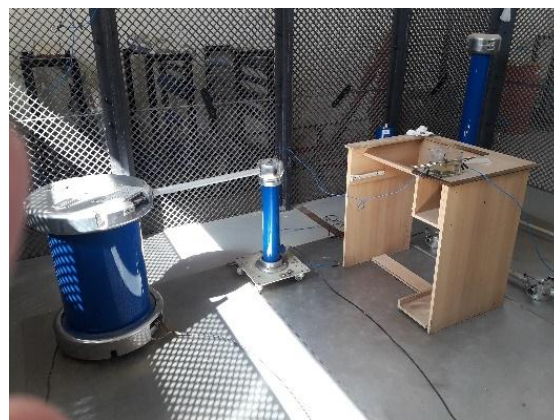


Figure 4. Experimental setup for generation AC high voltage

Oil Specifications

Shell Diala S3 ZX-I Dried was manufactured from highly refined mineral oil and it was used as inhibited electrical insulating oil in transformer and electrical equipment. The dielectric strength is very good, good oxidation stability and introduced an efficient heat transfer at low temperature. The features and characteristics of the oil is shown in the Table 1.

Electrodes Specifications

Three electrode configurations were used in this study. The plate-plate gap (to present the uniform filed gap

configuration), the point-plate and rod-plate gap (to produce the non-uniform filed gap) configurations were considered. The electrode made of brass and its shape was depicted in Fig. 2.

Impurities

The impurities used in this study were iron filings collected from iron workshop. The iron filings were added to the insulating oil with 0.2 g/ 400 milliliter and 0.6g/400 milliliter.

Testing Procedures According to IEC Standard

The IEC Standard procedures used to test the insulating oil would introduce as follows;

1. To assess the dielectric strength of the insulating oil, a sample of the oil in a test cell that the electrode space was 2.54 mm and the applied voltage was gradually increased by 2kV/s.
2. The breakdown voltage was the voltage that causes an electric arc which leads to a collapse of the test voltage.
3. After breakdown occurred, the test voltage was automatically switched off.
4. According IEC standard, six measurements were carried out on the insulating oil.
5. The mean of the six measurements was determined.

Table 1. Properties and characteristics of the shell Diala S3 ZX-I Dried*.

Property	units	methods	IEC 60296	Shell Diala S3 ZX-I Dried
Kinematic viscosity at 40 °C	mm ² /s	ISO 3104	max. 12	8
Kinematic viscosity at -30 °C	mm ² /s	ISO 3104	max. 1800	720
Density at 15 °C	kg/m ³	ISO 3675		881
Dielectric Breakdown Voltage Oil as received	kV	IEC 60156	min. 30	>60
After treatment	kV		min. 70	>70
Dielectric Dissipation Factor (DDF)		IEC 60247	Max 0.05	0.005
Dielectric Dissipation Factor (DDF) at 90 °C				0.005
Oxidation stability (500 hr) Sludge	%m	IEC 61125 C	Max 0.05	0.01
Oxidation stability (500 hr) total acidity at 120°C	mg KOH/g	IEC 61125 C	Max 0.3	0.02

*The source of the table (technical data sheet, https://www.fmv.se/FTP/M7789-000183/datablad/M0746-067000_Shell_Diala_S3_ZX-I_Dried.pdf)

RESULTS AND DISCUSSIONS

Effect of voltage types

One of the effective parameters that describe the performance of the insulating oil was the type of the applied voltage. There were three voltage types that were applied on the insulating oil (impulse voltage with t_r/t_f of 1.2/50 μ s, AC voltage, and DC voltage). Fig. 5 illustrates the effect of the types of applied voltage on the dielectric strength of the insulating oil and the breakdown voltage. It illustrated that, the breakdown voltage in the DC voltage type was lower than that of the impulse and AC voltage types. The reason for this fact was due to when the oil tested under the DC voltage, the bridge between the electrodes would be investigated and the ionization process of the oil molecules was very fast and high.

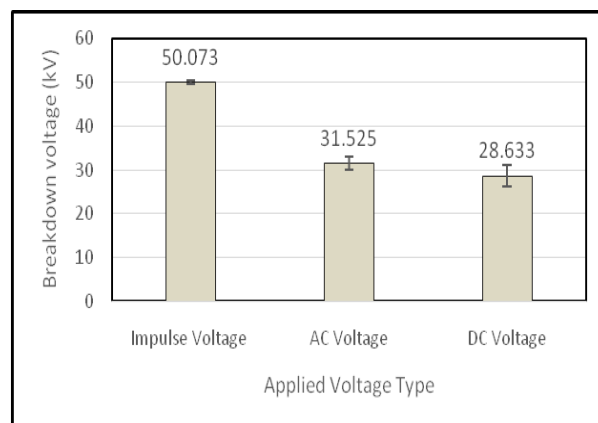


Figure 5. Effect of the applied voltage type on dielectric strength of the pure insulating oil

Effect of electrode configurations

Several electrode configurations were used to study its effect on the breakdown voltage of the insulating oil. The mean and standard deviation of the measurements that accomplished for pure oil were estimated and assigned in Fig. 6. This figure explains that the breakdown voltage at point-plate gap configuration was lower than that of plate-plate and rod-plate gap configurations. The reason of low breakdown voltage in point-plate configuration was due to high nonuniformity of the generated electric field. The curvature of the rod electrode mitigates the enhancement of electric field and then the dielectric strength in case of rod-plate gap was very high. Fig. 7 and 8 describe the probability density function (PDF) and the cumulative distribution function (CDF) at different gap configuration. The two figures demonstrate that the breakdown strength of the insulating oil was very high for rod-plate gap configuration.

Effect of Impurities

The dielectric strength of the insulating oils was affected by the presence of impurities. The effect of different impurities concentration on the dielectric strength was discussed. In order to investigate the significant of difference between the different impurities concentration cases, the t-test will be

carried out. Table 2 illustrates the t-test for plate-plate gap configuration at different impurities configuration and the results showed that a significant difference was observed between the measurements of the pure oil and the 0.2 and also the measurement between pure oil and 0.6 g impurities concentration due to the t-test for the two cases (6.16, and 5.28) which were higher than the $t_{critical}$ (2.571). On the other hand, there was no difference between the measurements of 0.2 and a 0.6 g impurity where the t-test was 1.13 versus the $t_{critical}$ was 2.31. In case of point-plate and rod-plate gap configurations the difference of all measurements was significant as in Tables 3 and 4 due to the t-test in every case was higher than $t_{critical}$, in addition, the pValue for all comparing measurements were less than the probability of significance level or the risk interval α (0.05).

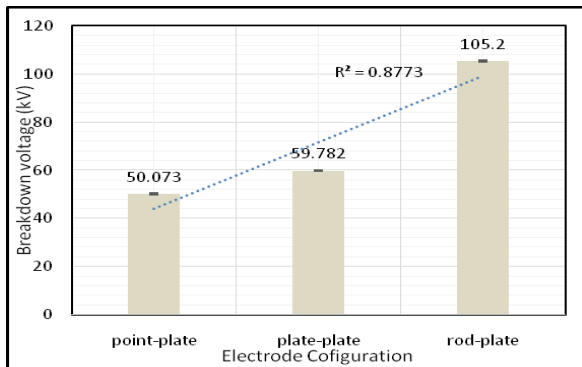


Figure 6, Mean and standard Deviation of the breakdown voltage at different electrode Configuration for pure oil

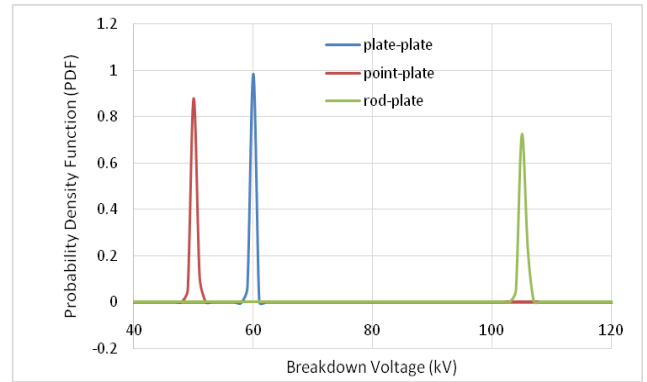


Figure 7, Probability Density Function versus the breakdown voltage at different electrode Configuration for pure oil

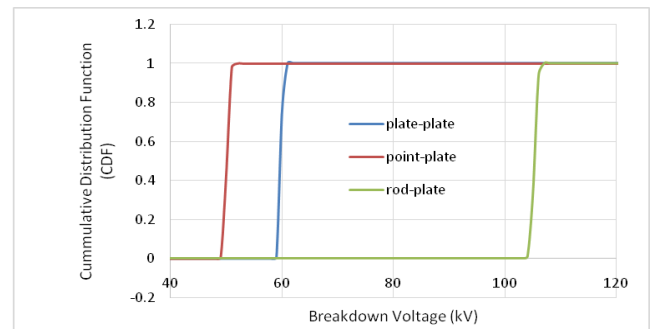


Figure 8, Cumulative Distribution Function versus breakdown voltage at different electrode configuration for pure oil

Table 2. Statistical t-test for plate-plate gap configuration at different impurities concentration

Statistical Parameters	Comparison 1		Comparison 2		Comparison 3	
	Pure oil	Oil with 0.2g impurities	Pure oil	Oil with 0.6g impurities	Oil with 0.2g impurities	Oil with 0.6g impurities
Mean	59.78	55.69	59.78	54.3	55.69	54.3
Variance	0.103	2.55	0.103	6.36	2.55	6.36
Observations	6	6	6	6	6	6
Hypothesized Mean Difference	0		0		0	
df	5		5		8	
tstat	6.16		5.28		1.131	
P(T<=t) one-tail	82E-5		162E-5		14E-2	
$t_{critical}$ one-tail	2.015		2.015		1.86	
P(T<=t) two-tail	164E-5		0.0032		0.291	
$t_{critical}$ two-tail	2.57		2.57		2.31	

Table 3. Statistical t-test for point-plate gap configuration at different impurities concentration

Statistical Parameters	Comparison 1		Comparison 2		Comparison 3	
	Pure oil	Oil with 0.2g impurities	Pure oil	Oil with 0.6g impurities	Oil with 0.2g impurities	Oil with 0.6g impurities
Mean	50.1	47.04	50.1	44.4	47.04	44.4
Variance	0.2	0.109	0.2	0.145	0.109	0.145
Observations	6	6	6	6	6	6
Hypothesized Mean Difference	0		0		0	
df	9		10		10	
tstat	13.31		23.64		12.88	
P(T<=t) one-tail	1.6E-07		2.08E-10		7.49E-08	
tcritical one-tail	1.83		1.81		1.81	
P(T<=t) two-tail	3.2E-07		4.16E-10		1.5E-07	
tcritical two-tail	2.26		2.228		2.228	

Table 4. Statistical t-test for rod-plate gap configuration at different impurities concentration

Statistical Parameters	Comparison 1		Comparison 2		Comparison 3	
	Pure oil	Oil with 0.2g impurities	Pure oil	Oil with 0.6g impurities	Oil with 0.2g impurities	Oil with 0.6g impurities
Mean	105.2	89.4	105.2	80.2	89.4	80.2
Variance	0.26	4.77	0.26	0.338	4.77	0.338
Observations	6	6	6	6	6	6
Hypothesized Mean Difference	0		0		0	
df	6		10		6	
tstat	17.24		79.158		9.964	
P(T<=t) one-tail	1.22E-06		1.26E-15		2.96E-05	
tcritical one-tail	1.94		1.81		1.94	
P(T<=t) two-tail	2.44E-06		2.53E-15		5.91E-05	
tcritical two-tail	2.447		2.228		2.447	

CONCLUSIONS

The breakdown voltage in case of the DC voltage type was lower than that of both the AC and impulse voltages types due to the establishment of a continuous bridge between the electrodes. The impurities had a significant effect on reducing the dielectric strength of the insulating oil. Using the *t-test*, the significant difference of the measurements between the pure oil and oil with impurities can be observed. The non-uniform electric field was developed when the point-plate electrode was used and therefore, the dielectric strength of the oil was lower than in the other plate-plate and rod-plate electrodes. The curvature of the rod electrode mitigated the electric field and hence, the breakdown voltage enhanced rather than in plate-plate and point-plate electrodes.

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