THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,
Volume 8, Number 3/2007, pp. 000–000

RELIABILITY OF THE IEC 60156 (1995) STANDARD FOR DETERMINING BREAKDOWN VOLTAGE OF ELECTROINSULATING OILS

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This investigation has analyzed the recommended test method for determining the breakdown voltage of electroinsulating oils according to the IEC 60156 (1995) Standard. Insufficient accuracy of the Standard has been pointed out, which may lead to a large measurement uncertainty, within an allowable reliability. Special consideration is given to the size of the statistical sample. By means of Chauvenet's criterion, U-test (Wilcoxon's rank-sum test) and Student's distribution, inadequacy of the recommended sample, as well as the method of processing the obtained results, have been exhibited. Recommendations for improving the Standard are given based on these considerations, regarding: measurement procedure, statistical sample size and statistical treatment of measurement results.

Key words: IEC, standards, insulator testing, oil insulation, statistics, error analysis.

1. INTRODUCTION

Breakdown voltage of electroinsulating oil is an indicator of its capability to withstand the electric field without breakdown. It is a stochastic quantity, determined by stochastic result analysis of a number of repeated, mutually independent (non-correlated) measurements. Procedure set by the IEC 60156 (1995) Standard [1,2] is used for determining the breakdown voltage of electroinsulating oils.

According to the IEC 60156 (1995) Standard, the procedure for testing dielectric hardness requires the use of a test voltage obtained by using a step-up transformer supplied from an a.c. (48 Hz to 62 Hz) voltage source. After applying such a voltage to the electrodes, the Standard further gives the following instructions: "The first application of voltage is started approximately 5 min after completion of filling and checking that no air bubbles are visible in the electrode gap. ... Uniformly increase voltage from zero at the rate of $2{,}0\ \mathrm{kV\ s^{-1}} \pm 0{,}2\ \mathrm{kV\ s^{-1}}$ until breakdown occurs. ... Carry out six breakdowns on the same cell filling allowing a pause of at least 2 min after each breakdown before re-application of voltage. Check that no gas bubbles are present within the electrode gap. ..." [1]

Remarks on the IEC 60156 (1995) Standard are:

1. Although it is well known that breakdown voltage of electroinsulating oil depends substantially on its humidity (water content), absolute humidity of a room wherein measurements are performed is not defined, nor cited from another standard.
2. The required number of breakdowns (six) is insufficient for a thorough statistical analysis.

The aim of this investigation is to revise statistical sample size adequacy for determining the breakdown voltage of electroinsulating oil, as well as to provide recommendation for improving the Standard in regard to stated remarks.

2. STATISTICAL SAMPLE ANALYSIS

Expanding the statistical sample (to more then 6 measured values) would provide a more reliable value of breakdown voltage. How big the statistical sample should be depends upon a compromise between the number of tests required by the laws of mathematical statistics for obtaining a reliable mean value, time spent performing the tests, and irreversible changes in oil resulting from breakdowns, since oil is not entirely a self healing insulator (which is contrary to the assumption of non-correlated statistical sample elements) [2].

In order to determine the optimal number of tests, the following experiment was performed: fresh, unused, mineral oil was acquired. Breakdown voltage of this oil was measured according to the IEC 60156 (1995) Standard (with regard to everything except the number of tests), for two days. In order to minimize the influence of humidity and various atmospheric conditions, measurements were performed in stable climatic conditions during two successive days. 120 tests were performed per day. Graphs in Fig. 1 show the values of critical electric field E_c (corresponding to the values of breakdown voltage) versus the test number for both days.

It is clearly visible from Fig. 1 that, for both days, first few measured values of breakdown voltage are considerably lower then others, and that breakdown voltage rises with the test number. Moreover, second-day results do not continuously follow first-day results. Therefore, it wasn't possible to form a single statistical sample based on the tests performed on those two days, and they were treated as two independent samples.

Values obtained by tests performed on day one and day two were analyzed as follows:

1. Statistical samples with 6, 8, 10, 12, 15, 20 and 24 results were formed (separately for each day).
2. Separate mean values of the critical electric field ($E_{c\ mean}$), its limiting values ($E_{c\ min}$ and $E_{c\ max}$) and Type A measurement uncertainties u_A (standard deviations) [3,4] were determined for each sample, applying Student's distribution.
3. The procedure was repeated after the use of Chauvenet's criterion of spurious result elimination [Appendix].

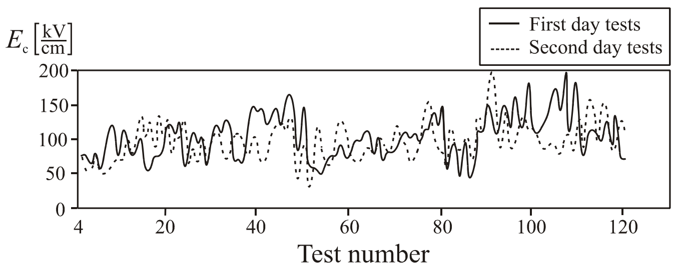

Fig. 1 Critical electric field versus the test number (both days).

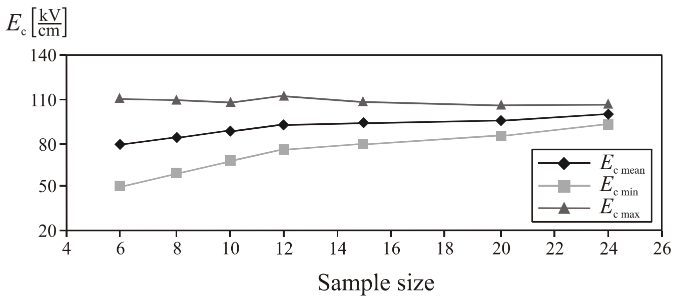

Fig. 2 Critical electric field versus sample size (first-day tests).

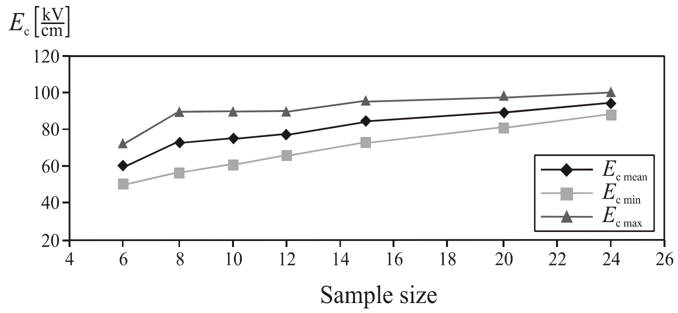

Fig. 3 Critical electric field versus sample size (second-day tests).

Figs. 2 and 3 show the critical electric field versus sample size (number of tests), for first- and second-day tests, respectively. Fig. 4 shows Type A measurement uncertainties u_A versus sample size corresponding to Figs. 2 and 3. Graph in Fig. 5 shows the critical electric field versus sample size after the application of Chauvenet's criterion, for first-day tests alone. Type A measurement uncertainties for both days versus sample size, with Chauvenet's criterion applied, are given in Fig. 6. In Fig. 7 Type A measurement uncertainty versus sample size is shown, both with and without the application of Chauvenet's criterion, for first-day tests only. Fig. 8 shows the mean value of critical electric field $E_{c\ mean}$, obtained from first-day tests, versus sample size, with and without applying Chauvenet's criterion.

Based on the results presented here it can be deduced that a sample of 6 tests is insufficient for obtaining breakdown voltage with satisfactory Type A measurement uncertainty. It is also noticeable that measurement uncertainty for samples of 15 tests (performed on each day) is much lower that the one for samples of 12 tests, while further expansion of sample size (20 and 24 tests) decreases the measurement uncertainty only slightly. Based on this analysis it can be concluded that minimal sample size for obtaining sufficiently accurate measurement uncertainty is 15 tests, with the application of Chauvenet's criterion.

In order to verify whether during 15 tests irreversible changes in oil occur, these samples are divided into sub-samples, each with 5 measurements. U-test (Wilcoxon's rank-sum test) [5,6] is applied to the obtained set of sub-samples in order to establish whether they belong to the same basic set. The result was positive in both cases, with and without the application of Chauvenet's criterion. The same test was negative when applied to 20 and 24-test samples. In view of these U-test outcomes, it is concluded that irreversible oil changes do not occur during 15 tests, and that all tests within the sample belong to the same random variable.

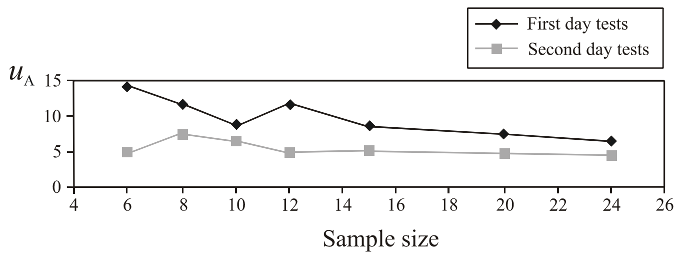

Fig. 4 Type A measurement uncertainty versus sample size (both days).

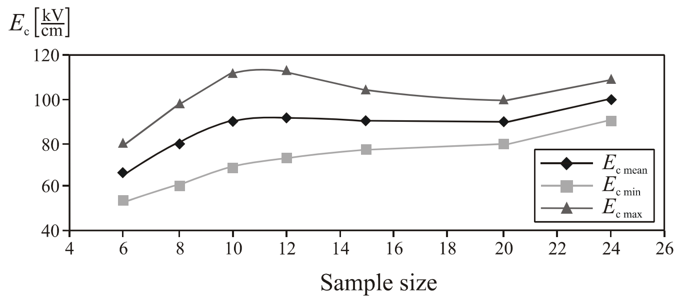

Fig. 5 Critical electric field versus test number after the application of Chauvenet's criterion (first-day tests).

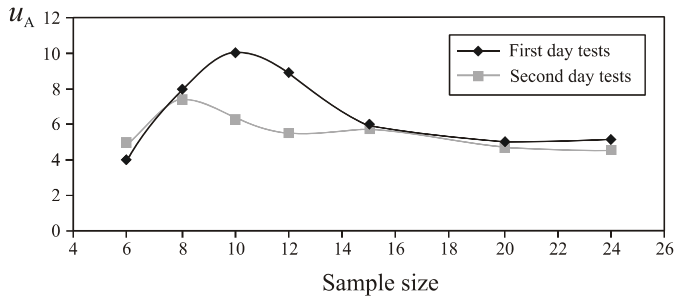

Fig. 6 Type A measurement uncertainty versus sample size with Chauvenet's criterion applied (both days).

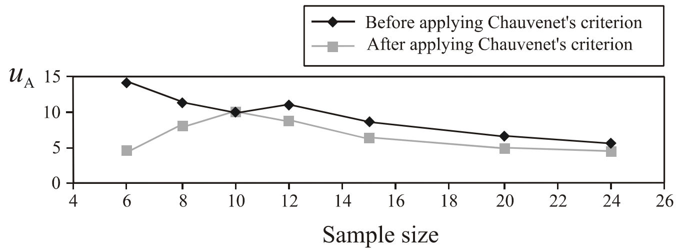

Fig. 7 Type A measurement uncertainty versus sample size, with and without Chauvenet's criterion applied (first-day tests).

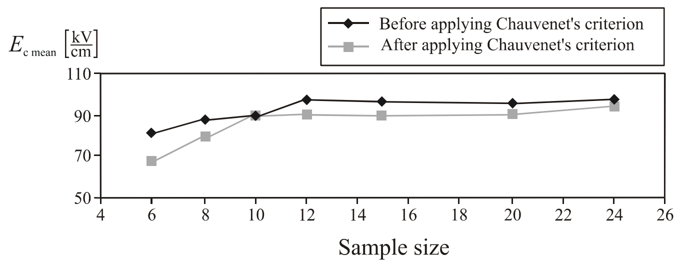

Fig. 8 Mean value of Critical electric field versus sample size, with and without Chauvenet's criterion applied (first-day tests).

3. CONCLUSIONS

It can be inferred that the ICE 60156 (1995) Standard could be improved toward reduction of combined measurement uncertainty by:

1. Defining temperature and humidity conditions of the room wherein tests are performed.
2. Conditioning the oil sample with 10 to 15 breakdowns before testing.
3. Expanding statistical sample to 15 tests.
4. Applying Chauvenet's criterion to obtained results, and only then determining breakdown voltage as the mean value.

Modification 1 would reduce Type B measurement uncertainty, and modifications 2, 3, and 4 Type A measurement uncertainty.

APPENDIX

Chauvenet's criterion

1. It is checked whether the population or sample distribution is normal, or it is asserted to be so.
2. Group parameter is determined as

$$q_n = \mathrm{F}^{-1}(n) = \mathrm{F}^{-1}\left\{ \frac{2}{\sqrt{2\pi}} \int_0^t e^{-\frac{t^2}{2}} dt = 1 - \frac{1}{2n} \right\} = t$$

3. For a set of results $x_1, x_2, ..., x_n$ mean value and standard deviation are determined as

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n} \quad \text{and} \quad \sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{x})^2}{n-1}}$$

4. Chauvenet's parameters q_i are determined as

$$q_1 = \frac{|\overline{x} - x_1|}{\sigma}, \ldots, \quad q_i = \frac{|\overline{x} - x_i|}{\sigma}, \ldots, \quad q_n = \frac{|\overline{x} - x_n|}{\sigma}$$

5. The set of Chauvenet's parameters is sorted and compared to the group parameter. If the largest of the parameters q_i is greater than q_n, the corresponding result x_i is discarded from the population or sample as being spurious, and the procedure is repeated from step 2.

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Received August 24, 2007