Evaluation of the reproducibility of the Breakdown Voltage in Transformer Oils (fresh and used) as per EN 60156:1998 (IEC 156:1995) based on Proficiency Tests performed from 2001 till 2016

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Introduction

Estimation of the target reproducibility (R(target)) of test method EN 60156:1998 (IEC 156:1995) for the determination of Breakdown Voltage in Proficiency Tests (PT) on Transformer Oils is not straightforward. The precision statement of EN60156 can be interpreted in different ways. The Institute for Interlaboratory studies has interpreted the calculation of the target reproducibility as follows:

1. Test method EN60156 shows in figure 3 of this test method on the y-axis the relative standard deviation (called coefficient of variation and expressed as SD/mean). This figure is also copied in this document as figure 1 below. The SD from "SD/mean" is interpreted as the **repeatability** standard deviation (SD_r).
2. The full line shows the distribution of the relative standard deviation (SD/mean) as a function of the mean Breakdown Voltage (in kV).
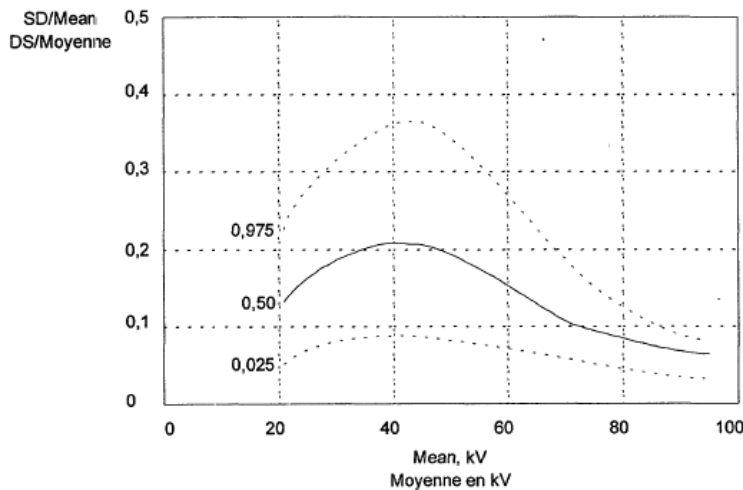

Figure 3 – Représentation graphique du coefficient de variation (rapport de l'écart type à la valeur moyenne) en fonction de la moyenne de tension de claquage
Graphical representation of coefficient of variation (standard deviation/ mean ratio) versus mean breakdown voltage

Figure 1: Copy of figure 3 from test method EN 60156:1998 (IEC 156:1995).

3. For the calculation of the repeatability (r) the value of RSDr has to be multiplied with a factor 2.8.
4. Empirically is found that the reproducibility (R) is 3 times the repeatability (r). With this 'rule of thumb' the reproducibility is calculated.
5. The above results in the following calculation for the reproducibility for the proficiency test:
   $R_{formula\ 1}$(target) = RSDr (from figure 1 above) * mean value (of the PT) * 2.8 * 3...................... *(formula 1)*

   For example, in PT report Transformer Oil (fresh) iis16L08 (2016) the mean Breakdown Voltage is 70.76, the RSDr in figure 1 at 71 kV is 0.1.
   The estimated reproducibility $R_{formula\ 1}$(target) = 0.1 * 70.76 * 2.8 * 3 = 59.44 kV/2.5mm.

Another point for discussion is the effect of the number of replicates done for the determination of Breakdown Voltage on the method precision. Test method EN 60156:1998 (IEC 156:1995) mentions in paragraphs 9.3 and 10 that the mean Breakdown Voltage is based on 6 measurements. This may or may not have an effect on the estimated method precision.

Discussion

One of the participants asked iis whether the SD mentioned in figure 3 of the test method (NB: figure 1 above) is the repeatability SD or the reproducibility SD. Unfortunately, this is not described in paragraph 11 of test method EN 60156:1998 (IEC 156:1995). The test method mentions 'a large body of test data in several laboratories'. In iis' point of view the phrase 'large body of test data' means the collected data per product per laboratory (and thus repeatability), but one could also argue that the phrase 'several laboratories' could be interpreted as the reproducibility. And the latter means that formula 1 above will become slightly different:

$R_{formula\ 2}$(target) = RSDr (from figure 1 above) * mean value (of the PT) * 2.8 .... *(formula 2)*

Please note that : $R_{formula\ 2}$(target) = $R_{formula\ 1}$(target)/3

Thus, for example $R_{formula\ 2}$(target) = 0.1 * 70.76 * 2.8 = 19.81 kV/2.5mm.

To solve this unclarity iis decided to investigate the data of all Breakdown Voltage determinations in Transformer oils (fresh or used) of the proficiency tests over the years from 2001 to 2016 (see figure 2 below and the appendix for the data).
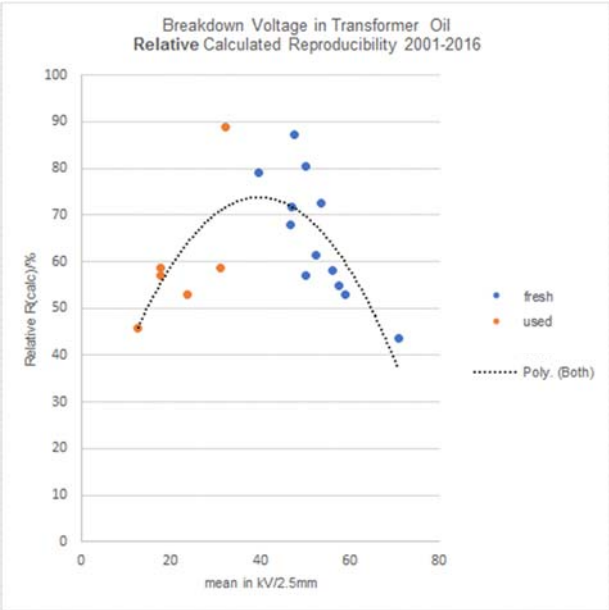

Figure 2: The observed reproducibility R(calc) vs the mean Breakdown Voltage in iis PT over a period of 2001 to 2016

Figure 2 above shows that the shape of figure 3 from test method EN 60156:1998 (IEC 156:1995) is valid. The observed reproducibility R(calc) in the PTs shows also a maximum between a Breakdown Voltage of 30 to 50 kV/2.5mm like figure 3 of the test method.

More interesting is to compare the observed reproducibility R(calc) to the reproducibility R(target) as calculated with formula 1 ($R_{formula\ 1}$(target)) and as calculated with formula 2 ($R_{formula\ 2}$(target)). This evaluation is shown in figure 3 below. The dotted line is the R(target) calculated with formula 1 and the striped line is R(target)/3 calculated with formula 2.
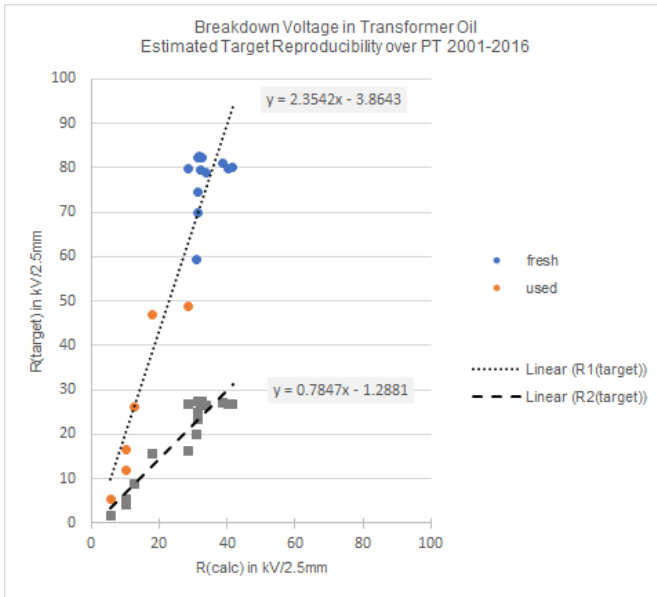
Figure 3: Comparison of the $R_{formula\ 1}(target)$ and $R_{formula\ 2}(target)$ to the observed reproducibility R(calc)

From figure 3 above it can be concluded that the observed reproducibility R(calc) correlates linear to the R(target). When the observed R(calc) is on average equal to R(target) the slope of the linear fit will be 1. However, the linear fit of the R(target) as calculated by iis by formula 1 overestimated the observed R(calc) as the slope is 2.35. And the R(target) as calculated by formula 2) underestimated the observed reproducibility R(calc) as the slope is 0.78.

As mentioned in the introduction the measurement of the Breakdown Voltage Determination is based on the average of 6 replicated measurements as per test method EN 60156:1998 (IEC 156:1995). These replicates are needed to reduce the variation between the determinations and therefore the reproducibility could be reduced with the square root of the number of replicates and thus with square root 6. This will give the following formula for the estimation of the target reproducibility:
$R_{formula\ 3}$(target) = RSDr (from figure 1 above) * mean value (of the PT) * 2.8 * 3 / √6 .... *(formula 3)*
This estimated target reproducibility as calculated by formula 3 has been plotted against the observed reproducibility (see figure 4 below).
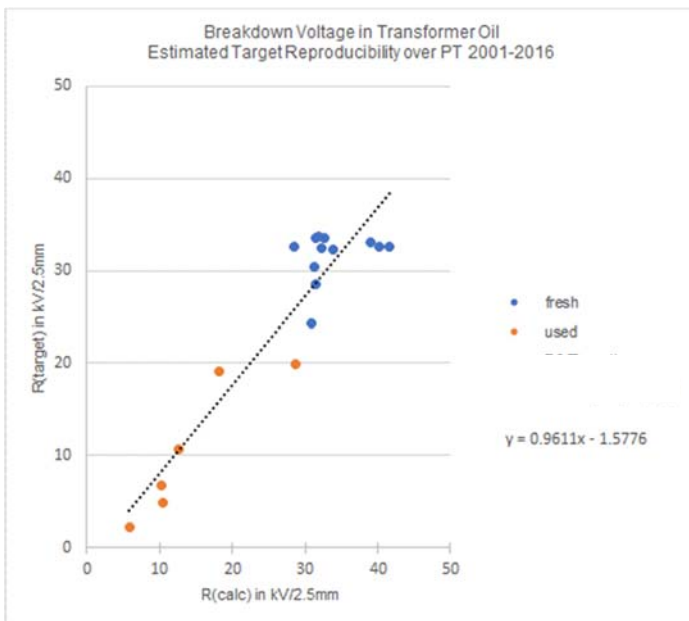

Figure 4 Comparison of R(target) calculated with formula 3 to the observed reproducibility R(calc).

Surprisely, the correlation between R(calc) and R(target) becomes very good and yielded a slope of 0.96 when the R(target) as estimated by iis is divided by square root 6 (as given in formula 3).

Conclusions

- The observed reproducibility as found in a period of 2001 to 2016 has a maximum which is in line with the shape of figure 3 of test method EN 60156:1998 (IEC 156:1995).
- The observed reproducibility correlates linear to the target reproducibility as estimated from figure 3 of test method EN 60156:1998 (IEC 156:1995).
- The target reproducibility as estimated by iis until now overestimates the observed reproducibility.
- The SD mentioned in figure 3 of test method EN 60156:1998 (IEC 156:1995) is not the reproducibility SD because this underestimates the observed reproducibility.
- The SD mentioned in figure 3 of test method EN 60156:1998 (IEC 156:1995) is the repeatability SD between measurements based on 6 replicates. This means that the calculation of R(target) needs to be corrected with $1 / \sqrt{n}$.
- The new calculation of R(target) will be adapted to formula 3, starting from November 2017:
  R(target) = RSDr (from figure 3 test method EN 60156) * mean value (of the PT) * 2.8 * 3 / $\sqrt{6}$.
  This means for the same example as mentioned for formula 1 where the mean Breakdown Voltage is 70.76, the RSDr in figure 3 test method EN 60156 at 71 kV is 0.1.
  The estimated reproducibility R(target) = 0.1 * 70.76 * 2.8 * 3 / $\sqrt{6}$ = 24.27 kV/2.5mm.

Appendix: *Summary of the Breakdown Voltage proficiency tests in Transformer oils over a period of 2001 till 2016; results in kV/2.5mm*

Year	Oil	Report	iis sample	n	outliers	Average in the PT	R(calc) in the PT	R(target) formula 1	R(target) formula 2	R(target) formula 3
2016	fresh	iis16L08	#16250	47	0	70.76	30.90	59.44	19.81	24.27
2015	fresh	iis15L08	#15222	46	0	50.01	40.26	79.82	26.61	32.59
2014	fresh	iis14L06	#14222	45	0	53.58	38.91	81.01	27.00	33.07
2013	fresh	iis13L05	#13206	55	0	47.62	41.58	80.01	26.67	32.66
2012	fresh	iis12L04	#12145	53	1	50.02	28.47	79.83	26.61	32.59
2011	fresh	iis11L04	#11104	54	0	46.80	31.81	82.56	27.52	33.70
2010	fresh	iis10L03	#1085	42	1	39.65	31.39	69.94	23.31	28.55
2009	fresh	iis09L03	#0988	31	1	55.98	32.59	82.29	27.43	33.59
2008	fresh	iis08L03	#0875	37	0	47.02	33.74	78.99	26.33	32.25
2007	fresh	iis07L03	#0783	7	0	57.53	31.52	82.15	27.38	33.54
2006	fresh	iis06L03	#0683	28	0	52.48	32.19	79.35	26.45	32.39
2005	fresh	iis05L03	#0581	22	0	59.05	31.31	74.40	24.80	30.37
2015	used	iis15L09	#15223	58	0	31.00	18.14	46.87	15.62	19.13
2014	used	iis14L30	#14223	54	0	32.32	28.71	48.87	16.29	19.95
2004	used	iis04L03	#0479	18	0	23.83	12.61	26.02	8.67	10.62
2003	used	iis03L03	#0373	14	1	17.84	10.19	16.48	5.49	6.73
2002	used	iis02T01	#0259	12	2	12.708	5.815	5.34	1.78	2.18
2001	used	iis01L02	#0124	11	1	17.832	10.440	11.98	3.99	4.89
					mean	42.56	27.25	60.30	20.10	24.62