MODELS FOR EVALUATING THE DURABILITY OF ELECTROINSULATING MATERIALS

M. OLTEAN, University of Oradea, ymoltean@yahoo.com
M. CÂRLAN, S.C. Formenerg S.A.

Abstract: This paper presents three models recommended for evaluating the duration in operation – durability - of a type of materials that cannot be repaired, used in the maintenance activity of energetic installations. That is the case for a lot of electro insulating products that have been tested and found to fit the quality requirements, before they were put in operation. Based on the information obtained during tests, the average operation time of the materials in question can be determined.

Key words: durability, dielectrics, electrical noise.

1. CASE STUDY

The subject of the case study presented is an electroinsulating product, a dielectric polyester material, type 5JF47, protected by a glass coat.

The statistical sample includes two lots that have been tested under different electrical tensions and with a low electrical noise level. In table 1 is presented the information resulted from testing these materials.

Table 1

Lot	Sample volume	No. of dropped products	Testing time - hours -	Electrical field intensity - MV/m -	Intensity kV	Temperature °C	Electrical noise - mV -
A	28	7	152	5,91	5	80	0,014
B	14	3	220	3,94	3	78	0,005

In order to obtain results as close to reality as possible, the following changes have been made in the structure of the calculation data:

- we consider the testing temperatures range, $\theta \in [70;80]$°C, the nominal value of this measure being the inferior limit of the interval, and the maximum allowed is the superior limit of the same interval;
- the faulty pieces from lot A have dropped in the time interval $\sigma \in [0;152]$ hours, and those included in lot B have deteriorated in the last part of the interval $\sigma \in [0;220]$ hours;
- the electrical field intensity is constant.

Next, we will analyse this set of 42 dielectric products (28 +14), from which 10 (7 + 3) materials no longer used, have been taken out.

The moments of dropping of the dielectric articles, from the two time intervals mentioned above, have been proposed by the authors of this paper. Thus, the only definitory measure for the durability of electroinsulating materials being analysed is the temperature, the other parameters (electrical field, intensity, electrical noise) being constant.

The specialty literature cites, in this respect, the following models for calculating the durability of the products that cannot be repaired:

- Arhenius model
- Montsinger model
- Dakin model,

the latter being the foundation of an impressive number of evaluation standards (IEC 216, IEEE 275/81 etc.). As the operating duration depends on the way of sharing the operating times – limited by the moments of drop of the products in question – the partition model suitable for this case is going to be set in the following.

The testing of the statistical hypothesis is made interactively: first, the exponentiality against the distribution of the operation times is checked, using one or more models (Hann-Shaphiro-Wilk, Finkelstein-Schafer, Hartley etc.); unless the hypothesis of an exponential evolution of the duration of elements of the statistic population is confirmed, other „nonexponentiality” tests are used: Weibul, Rayleigh, the latter model being frequently used in complex analysis regarding products’ durability.

Table 2 renders the calculation elements for checking the exponential nature of the life spans of this statistic sample’s components.

The value of the calculation quantile, W_0 is obtained from the relation:

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$$W_0 = \frac{\sum_i \left(\tau_i - \bar{\tau}\right)^2}{\sum_i \tau_i} \qquad (1)$$

where $\bar{\tau}$ - is the average of the τ_i values.

According to the Mann-Shapiro-Wilk model, a statistical distribution is exponential if it satisfies the following inequality:

$$W_{n;p}^{\inf} < W_0 < W_{n;p}^{\sup} \qquad (2)$$

Where $W_{n;p}^{\inf}$, $W_{n;p}^{\sup}$ represent the inferior/superior quantiles corresponding to a volume n of the sample and a likelihood threshold P (risk coefficient, α = 1-P).

The quantile values of the test are presented in table 3.

Table 2

i	τ_i	$\bar{\tau}$	$\tau_i - \bar{\tau}$	$(\tau_i - \bar{\tau})^2$	E -kV/m
1	48	125	-77	5929	5,91
2	55		-70	4900	
3	70		-55	3025	
4	81		-44	1936	
5	93		-32	1024	
6	103		-22	484	
7	152		+27	729	
8	210		+85	7225	3,94
9	218		+93	8649	
10	220		+95	9025	
$\sum_i$	1250	*	0	42926	*

The following relation (1) results:

$$W_0 = \frac{42926}{1250^2} \Rightarrow W_0 \cong 0{,}0275$$

According to inequality (2), the hypothesis of an exponential distribution of the life spans for these materials is confirmed:

$$W_{r=10;P=0,95}^{\inf} = 0{,}025 < W_0 = 0{,}0275 < W_{r=10;P=0,95}^{\sup} = 0{,}184$$

Table 3

r	P=0,95	
	$W^{\inf}$	$W^{\sup}$
7	0,025	0,26
8	0,025	0,230
9	0,025	0,205
10	0,025	0,184
11	0,025	0,166
12	0,025	0,153
13	0,025	0,140
14	0,024	0,128
15	0,024	0,119
16	0,023	0,113
17	0,023	0,107
18	0,022	0,101
19	0,022	0,096
20	0,021	0,090
21	0,020	0,085
22	0,020	0,080
23	0,019	0,075
24	0,019	0,069
25	0,018	0,065
26	0,018	0,062
27	0,017	0,058
28	0,017	0,056
29	0,016	0,054
30	0,016	0.053

2. DETERMINING THE AVERAGE DURABILITY OF PRODUCTS BROKEN IN THE TESTING PROCESS

The ***SVANTE ARRHENIUS model***

The calculation expression proposed by this model is :

$$\tau = e^{A+\frac{B}{\theta}} \qquad (3)$$

Where

τ – is the operation duration of the electroinsulating material that is being tested;

θ – the temperature in the checking period;

A, B – regression coefficients for the calculation relation.

For establishing these coefficients, the „method of the smallest squares" is used, in the following way:

- → the relation (3) is logarithmed (3),

$$\ln\tau = A + \frac{B}{\theta}$$

- → the condition that the sum of the squares of the deviations of τ_i's times' values obtained in the testing operation, as compared to the durations established based on the regression relation, be minimal:

$$S = \sum_i \left[(A + \frac{B}{\theta_i}) - \ln\tau_i \right]^2 \Rightarrow \text{minimum} \qquad (4)$$

- the following restrictions set is added to that

$$\begin{cases} \dfrac{\partial S}{\partial A} = 0 \\ \dfrac{\partial S}{\partial B} = 0 \end{cases} \qquad (5)$$

- the linear equations system results therein

$$\begin{cases} rA + B\sum_i \dfrac{1}{\theta_i} = \sum_i \ln\tau_i \\ A\sum_i \dfrac{1}{\theta_i} + B\sum_i \dfrac{1}{\theta_i^2} = \sum_i \dfrac{1}{\theta_i}\ln\tau_i \end{cases} \qquad (6)$$

r – is the volume of the testing sample – r=10.

Table 4 presents data for calculating the regression coefficients. The following values are obtained:

A = -7,70362;

B ≅ 922,166

The regression relation is :

$$\tau = e^{-7{,}70362} + \frac{922{,}166}{\theta} \qquad (7)$$

Table 4

i	θ_i	τ_i	$\frac{1}{\theta_i}$	$\frac{1}{\theta_i^2}$	$\ln\theta_i$	$\frac{1}{\theta_i}\ln\tau_i$
1	80	48	0,01250	0,000156	3,87120	0,04839
2	79	55	0,01266	0,000160	4,00733	0,05073
3	77	70	0,01299	0,000169	4,24849	0,05518
4	76	81	0.01316	0,000173	4,39445	0,05782
5	75	93	0,01333	0,000178	4,53260	0,06043
6	75	103	0,01333	0,000178	4,63473	0,06180
7	73	152	0,01370	0,000188	5,02388	0,06882
8	71	210	0,01408	0,000198	5,34711	0,07531
9	70	218	0,01429	0,000204	5,38450	0,7692
10	70	220	0,01429	0,000204	5,39363	0,07705
$\sum_i$	746	1250	0,13433	0,001808	46,83837	0,63245

The $\tilde{\tau}_i$ durations' values resulted from the regression expression are presented in table 5. The comparison for the „closeness" of the two samples of the τ_i operational times – statistically and $\tilde{\tau}_i$ – determined by the calculation presented, is emphasized by the Pearson correlation report:

$$\eta = \sqrt{1 - \frac{\sum_i (\tau_i - \tilde{\tau}_i)^2}{\sum_i (\tau_i - \bar{\tau})^2}} \qquad (8)$$

A strong correlation is observed between the two values series of the operation times:

$$\eta = \sqrt{1 - \frac{1088}{42926}} \Rightarrow \eta \cong 0{,}987$$

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Table 5

i	τ_i	$\tilde{\tau}_i$	$\bar{\tau}$	$\tau_i - \bar{\tau}$	$\tau_i - \tilde{\tau}_i$	$(\tau_i - \bar{\tau})^2$	$(\tau_i - \tilde{\tau}_i)^2$
1	48	46	125	-77	+2	5929	4
2	55	53		-70	+2	4900	4
3	70	72		-55	-2	3025	4
4	81	84		-44	-3	1936	5
5	93	99		-32	-6	1024	36
6	103	99		-22	+4	484	16
7	152	138		+27	+14	729	196
8	210	197		+85	+13	7225	169
9	218	237		+93	-19	8649	361
10	220	237		+95	-17	9025	289
$\sum_i$	1250	1262	*	0	-12	42926	1088

● ***MONTSINGER Model***

The calculation expression of the life span is the following:

$$\tau = Ke^{-m(\frac{\theta-\theta_0}{\theta_0})},\ \theta > \theta_0 \tag{9}$$

where

τ, θ have the meanings mentioned above,

θ_0 – temperature in the testing period,

K, m – regression coefficients, the values of which are obtained based on the statistical sample data, by the "smallest squares" method.

By logarithming the relation (9) and taking into consideration the minimum conditions imposed:

$$\begin{cases} S = \sum_i \left\{ \left[rk - m\left(\frac{\theta_i-\theta_0}{\theta_0}\right) \right] - \ln\tau_i \right\}^2 \Rightarrow \min imum \\ \frac{\delta S}{\delta k} = 0 \\ \frac{\delta S}{\delta m} = 0 \end{cases} \tag{10}$$

The following linear equation system is obtained:

$$\begin{cases} rk - m\sum_i \left(\frac{\theta_i-\theta_0}{\theta_0}\right) = \sum_i \ln\tau_i \\ k\sum\left(\frac{\theta_i-\theta_0}{\theta_0}\right) - m\sum\left(\frac{\theta_i-\theta_0}{\theta_0}\right)^2 = \sum\left(\frac{\theta_i-\theta_0}{\theta_0}\right)\ln\tau_i \end{cases} \tag{11}$$

By replacing the calculation data in table 6, the regression coefficients are deduced : k $\cong$ 225,94; m$\cong$ 11,2064, and the regression relation is:

$$\tau = 225{,}94\ e^{-11{,}2064\left(\frac{\theta_i-\theta_0}{\theta_0}\right)} \tag{12}$$

The calculated $\tilde{\tau}_i$ values are presented in table 6; the calculation of the Pearson correlation report is determined according to the data included in this table, expression of the connection relation.

Table 6

i	τ_i	$\tilde{\tau}_i$	$\bar{\tau}$	$\tau_i - \bar{\tau}$	$\tau_i - \tilde{\tau}_i$	$(\tau_i - \bar{\tau})^2$	$(\tau_i - \tilde{\tau}_i)^2$
1	48	46	125	-77	+2	5929	4
2	55	54		-70	+1	4900	1
3	70	74		-55	-4	3025	16
4	81	86		-44	-5	1936	25
5	93	102		-32	-9	1024	81
6	103	102		-22	+1	484	1
7	152	140		+27	+12	729	144
8	210	192		+85	+18	7225	324
9	218	226		+93	-8	8649	64
10	220	226		+95	-6	9025	36
$\sum_i$	1250	1248	*	0	2	42926	696

According to the relation (8), the correlation coefficient is deduced:

$$\eta = \sqrt{1 - \frac{696}{42926}} \Rightarrow \eta \cong 0{,}002$$

Also, the same is the case of a cogent correlation between the times obtained in the testing operation and the values resulted from the regression relation.

●*The DAKIN Model*

The operating time of a product that cannot be repaired is defined by the following relation:

$$\tau = ae^{-b\theta} \qquad (13)$$

where

τ, θ – have the meanings mentioned above,

a, b – are the regression coefficients, their values being set also based on the "smallest squares" method.

Following the same calculation itinerary, the linear equation system is deduced:

$$\begin{cases} r\ln a - b\sum_i \theta_i = \sum_i \ln \tau_i \\ \ln a \sum_i \theta_i - b\sum_i \theta_i^2 = \sum_i \theta_i \ln \tau_i \end{cases} \qquad (14)$$

Table 7 presents the data needed for establishing the regression relation, and table 8 renders the values of the durations calculated based on this relation; the last table offers the possibility of determining the correlation report. They are successively deduced:

$$a = 16515763;\ b = 0{,}16$$
$$\tau = 16515763e^{-0{,}16\theta} \qquad (15)$$
$$\eta = 0{,}991$$

The value of the correlation report, η has resulted based on the relation (8) and this model offers a high level of exactness of the couples of values τ_i, and $\widetilde{\tau}_i$ respectively, of the operation times

Table 7

i	θ_i	τ_i	θ_i^2	$\ln \tau_i$	$\theta_i \ln \tau_i$
1	80	48	6400	3,87120	309,6908
2	79	55	6241	4,00733	316,57932
3	77	70	5929	4,24849	327,13413
4	76	81	5776	4,39445	333,97814
5	75	93	5625	4,53260	339,94496
6	75	103	5625	4,63473	347,60467
7	73	152	5329	5,02388	366,74328
8	71	210	5041	5,34711	379,64463
9	70	218	4900	5,38450	376,91465
10	70	220	4900	5,39363	377,55393
$\sum_i$	746	1250	55766	46,83837	3475,79379

Table 8

i	τ_i	$\widetilde{\tau}_i$	$\overline{\tau}$	$\tau_i - \overline{\tau}$	$\tau_i - \widetilde{\tau}_i$	$(\tau_i - \overline{\tau})^2$	$(\tau_i - \widetilde{\tau}_i)^2$
1	48	46	125	-77	+2	5929	4
2	55	54		-70	+1	4900	1
3	70	74		-55	-4	3025	16
4	81	87		-44	-6	1936	36
5	93	102		-32	-9	1024	81
6	103	102		-22	+1	484	1
7	152	140		+27	+12	729	144
8	210	192		+85	+18	7225	324
9	218	226		+93	-8	8649	64
10	220	226		+95	+6	9025	36
$\sum_i$	1250	1249	*	0	13	42926	717

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3. DETERMINING THE AVERAGE DURABILITY OF THE TESTED ELECTROINSULATING PRODUCTS

The evaluation of the materials' durability, products that cannot be repaired, in case of incomplete statistical samples – a number of r = 10 faulty elements from the table of n = 42 which have been tested, according to table 1. The following relation is used:

$$T = \frac{1}{r}\left[\sum_{i} \tau_i + (n - r)t_r\right] \qquad (16)$$

Where T is the average durability of the products of the testing samples with volume n, and t_r is the moment when the last element dropped, the 10^{th} dielectric: $t_r = t_{10}$ =220 ore.
The average lot durability is deduced:

$$T = 829 \text{ ore}$$

4. CONCLUSIONS

● The models presented about the evaluation of the electroinsulating materials' durability converge to the same level of temporal functioning.

● A complete approach of the way the materials that cannot be repaired behave, is presented in the analysis of the evolution that is depending on other defining parameters– varying in the testing operation – for instance, the intensity of the electrical field and the intensity, for several of their values.

● This paper, based on the hypothesis that these two measures stay constant in the testing process, offered the solution for the durability issue, standing on the main dependence factor – working temperature in checking the quality of the electroinsulating materials in question, in time.

● Determining the regression relations is possible only if the evolution in time is known for the parameters that define the durability of the products being analysed.

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