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STATISTICAL STUDY OF THE OIL DIELECTRIC STRENGTH IN POWER DISTRIBUTION TRANSFORMERS

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A number of distribution transformers have been studied regarding their dielectric strength and their previous stressing. The study has been carried out with the aid of statistical analysis. It seems that the distribution of oil breakdown voltage values follows the normal distribution. This is in agreement with previous published data, although it should be pointed out that the nature of distribution (normal or extreme) depends also on the breakdown mechanism in each particular case and/or on the particular conditions under which a fault has occurred.

K e y w o r d s: transformer oil, breakdown voltage, dielectric strength, normal distribution

1 INTRODUCTION

In previous publications ([1–3]) a number of distribution transformers of the PPC (Public Power Corporation) were investigated for correlation between their oil dielectric strength and their previous history. Data from a grid-network of 39963 transformers in the broader region of Eastern Macedonia and Thrace (Northern Greece) were examined and three of their properties were measured: the breakdown voltage (z), the age of oil (y) and the number of malfunctions (x). Our sample comes from Xanthi area where 1631 distribution transformers are in the network.

We recall that transformer oil is a vital component of distribution transformers (15-20 kV). Its electrical behavior is determined by a variety of factors, such as electric stress, transient phenomena, oil purity, filtering cycles, the conditioning phenomenon, area and volume effect (the so-called size effects), viscosity, velocity of circulation, temperature and pressure ([4–6]). Some of these factors result in, what we call, ageing of the transformer oil and therefore of the distribution transformers. An aged oil is characterized by byproducts which are the result of partial discharges and/or overstressing. Such byproducts can be suspended particles from carbonization, gas bubbles, etc. Byproducts contribute greatly to the lowering of the dielectric strength of the oil. Aged oil exhibits a rather low dielectric strength and therefore it is unfit for further use [5].

For the control and measurement of the breakdown voltage of the transformer oil taken from the distribution transformers, a Foster test cell was used (BS 148/78) with Bruce profile electrodes of 50 mm in diameter and a gap spacing of 2.5 mm. The breakdown measurements were carried out according to the PPC distribution regulation No20 ([7, 8]).

In Xanthi's sample of approx 200 distribution transformers (see [3]), we derived results on descriptive statistics (the arithmetic mean, the median, the mode, the percentiles, the variance, the standard deviation, the relative standard deviation *etc*) and we provided a linear relationship between the number of malfunctions and the breakdown voltage. Especially, from the study of linearity of the relationship $z = -0.226x + 33.458$ the breakdown voltage tends to stabilize around 33 kV, which approaches the limit of the acceptable breakdown value according to the IEC 296/82 standard.

In this paper we focus on the breakdown voltage (z) of the previous data (the cardinality of Xanthi's sample is exactly 224 transformers) and we use the well-tested statistical package SPSS version 13.0. First, using the aforementioned package, the descriptive statistics results of [3] come true. In addition, the statistical distribution that most accurately describes the population of transformers is derived and the cumulative probability distribution is calculated. On the other hand, by considering the Xanthi sample as the representative sample of the whole population, useful results of all the transformers in Northern Greece are obtained. Finally, some interesting applications are given and specific examples are represented.

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Table 1.

	N	Mean	Std. Dev.	Min	Max	Percentiles 25th	50th (Median)	75th
zkV	224	30.1846	10.50328	5.90	63.00	24.40	28.30	36.375
Y	219	10.88	8.446	0	31	4.00	8.00	18.00
X	149	4.40	5.287	0	25	1.00	3.00	6.00

Table 1.1

			Statistic	Std. Error
zkV	Mean		30.846	0.70178
	95% Confidence Interval for Mean	Lower Bound	28.8016	
		Upper Bound	31.5675	
	5% Trimmed Mean		29.7999	
	Median		28.3000	
	Variance		110.319	
	Std. Deviation		10.50328	
	Minimum		5.90	
	Maximum		63.00	
	Range		57.10	
	Interquartile Range		11.98	
	Skewness		0.712	0.163
	Kurtosis		0.851	0.324

Table 1.2

		Percentiles 5	10	25	50	75	90	95
Weighted Average(Definition 1)	zkV	14.7500	18.6000	24.4000	28.3000	36.3750	45.0000	49.8750
Tukey's Hinges	zkV			24.4000	28.3000	36.2500		

Table 2. One-Sample Kolmogorov-Smirnov Test 1

		zkV
N		224
Normal Parameters(a,b)	Mean	30.1846
	Std. Deviation	10.50328
Most Extreme Differences	Absolute	0.114
	Positive	0.114
	Negative	−0.057
Kolmogorov-Smirnov Z		1.708
Asymp. Sig. (2-tailed)		0.006

a Test distribution is Normal, b Calculated from data.

Table 3. One-Sample Kolmogorov-Smirnov Test 2

		zkV
N		224
Uniform Parameters(a,b)	Minimum	5.90
	Maximum	63.00
Most Extreme Differences	Absolute	0.251
	Positive	0.251
	Negative	−0.129
Kolmogorov-Smirnov Z		3.762
Asymp. Sig. (2-tailed)		0.000

a Test distribution is Uniform, b Calculated from data.

Table 4. One-Sample Kolmogorov-Smirnov Test 3

		zkV
N		224
Exponential parameter.(a,b)	Mean	30, 1846
Most Extreme Differences	Absolute	0.366
	Positive	0.149
	Negative	−0.366
Kolmogorov-Smirnov Z		5.482
Asymp. Sig. (2-tailed)		0.000

a Test Distribution is Exponential, b Calculated from data.

2 BREAKDOWN VOLTAGE STATISTICAL DISTRIBUTION

2. 1 Calculations and Results

In what follows we denote the breakdown voltage by zkV and we keep over the same denotation for the age of oil (y) and the number of malfunctions (x), respectively (see [1–3]). Moreover, in order to achieve the statistical results, data from [3] (see also [1, 2]) and the well-tested statistical package SPSS v.13.0, are used. After inserting

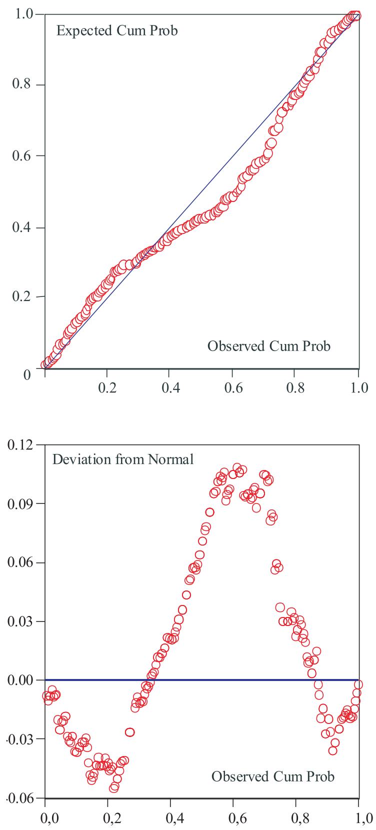

Fig. 1. Normal P-P plot of zkV - above, and Detrendend Normal P-P plot of the same - below

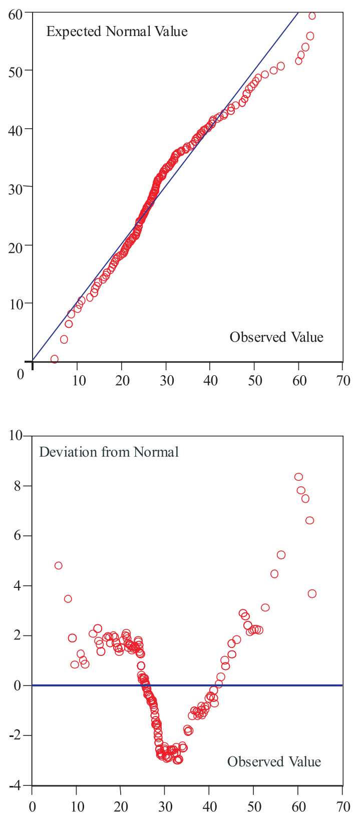

Fig. 2. Normal Q-Q plot of zkV - above, and Detrendend Normal Q-Q plot of the same - below

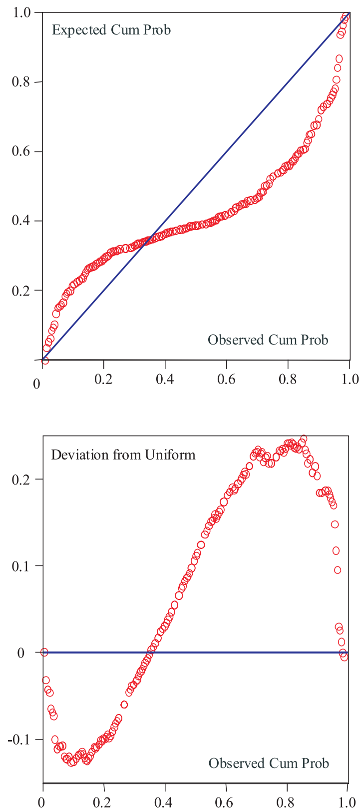

Fig. 3. Uniform P-P plot of zkV - above, and Detrendend Uniform P-P plot of the same - below

our data we first derive and re-establish the standard descriptive statistical calculations already performed in [3], which for the sake of clarity we present in Tables 1, 1.1 and 1.2.

It is obvious that the SPSS results (Table 1) match within 0.1 % with the standard statistical calculations performed in [3]. Especially, the results for the break down voltage zkV (Tables 1.1 and 1.2), are too close with regard to arithmetic mean ($\overline{z} = 30.22$), to standard deviation ($S_z = 10.71$), to the median (28.49) and to 10^{th} (18.06), 25^{th} (23.65), 75^{th} (35.87), as well as to 90^{th} percentile (45.25), of [3]. From all the previous results for zkV (see also the skewness and the kurtosis) it is obtained that the probability distribution is quite symmetric and smooth.

Next, we focus on the break down voltage zkV and we use the Kolmogorov-Smirnov test and we calculate the K-S Z-number, which is a rough measure of the error of fitting a certain statistical distribution to our data for our aforementioned parameter. One sample K-S test was run for the normal, the uniform and the exponential statistical distributions. Our results for the breakdown voltage (zkV) are presented in Tables 2, 3 and 4, for choosing the best statistical distribution for our data.

It is clear that the minimum Z-number ($Z = 1.708$) is given by Table 2. Therefore, the distribution that most accurately could answer all probability questions regarding our Xanthi sample of transformers, is the normal (or Gaussian) one.

Further, in order to strengthen the previous conviction, we present, in the following Figs 1–6, the standard statistical and the detrended P-P plots, as well as the Q-Q plots (see [9]), for the three distributions.

In the previous plots, the observed (P-P and Q-Q) cumulative probability distributions and the expected theoretical cumulative probability distributions are given in upper part of figures. Similarly, the lower part of figures present, the observed cumulative probability distribution and the deviations from the distributions. For example, the plots concerning the normal distribution with respect to P-P and Q-Q, respectively, are presented in Figs 1 and 2 in the upper part. The deviations with respect to the observed probability distribution are given in Figs 1 and 2 in their lower parts, where it is seen that the deviations from the normal range between $-6\,\%$ and $+10\,\%$. In the same way, deviations from the uniform distribution are calculated in Figs 3–4 and they range between $-12\,\%$ and $+25\,\%$. Finally, the deviations for the Exponential distribution range between $-35\,\%$ and $+15\,\%$, as one can see in Figs 5, 6. These graphs clearly indicate that the deviations of the Xanthi data are the smallest by a factor of approximately 10 to 50 for the normal distribution.

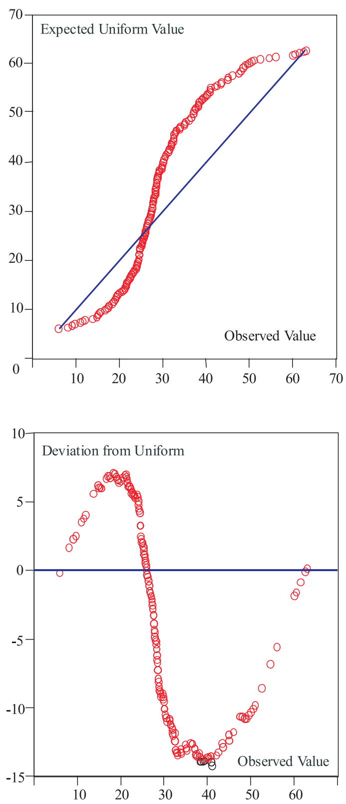

Fig. 4. Uniform Q-Q plot of zkV - above, and Detrendend Uniform Q-Q plot of the same - below

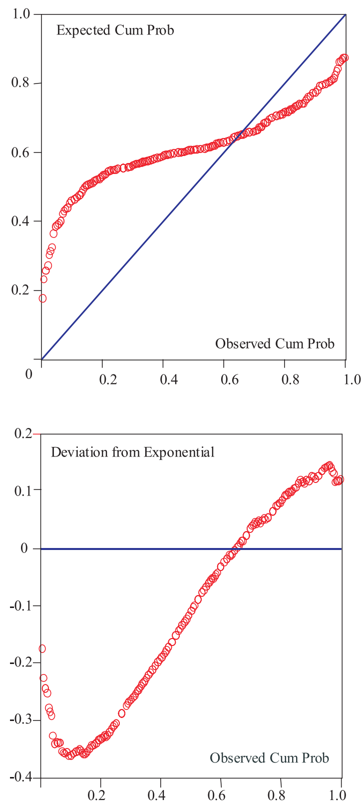

Fig. 5. Exponential P-P plot of zkV - above, and Detrendend Exponential P-P plot of the same - below

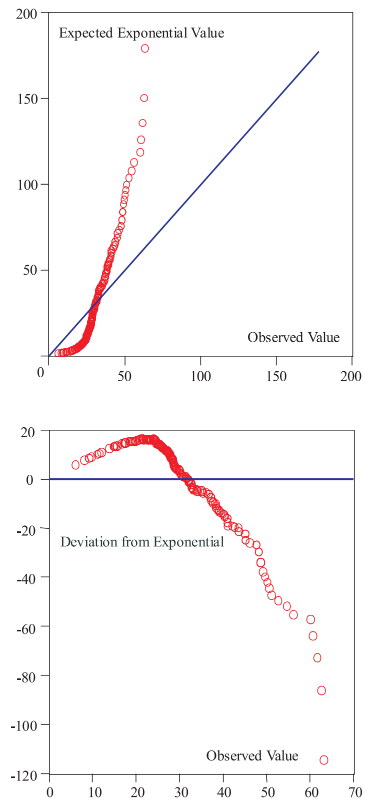

Fig. 6. Exponential Q-Q plot of zkV - above, and Detrendend Exponential Q-Q plot of the same - below

Consequently, the normal statistical distribution $N(\mu,\sigma) = N(30.19, 10.50)$ is the optimum one for the frequency table of our zkV variable Xanthi transformer sample and it is given by the graph in Fig.7.

2.2 Applications and Examples

Since, the normal statistical distribution $N(\mu,\sigma)$ is chosen for the random variable zkV, then, according to the classical theory, the probability density function f and the probability of the event $a < zkV < b$, are given as follows:

$$f(zkV) = \frac{1}{\sigma\sqrt{2\pi}}\exp\Big(-\frac{(zkV-\mu)^2}{2\sigma^2}\Big)$$

$$, \text{ where } 0 \le zkV < \infty$$

and

$$\mathrm{P}(a < zkV \le b) = \int_a^b f(zkV)\mathrm{d}(zkV) = \\ = \frac{1}{\sigma\sqrt{2\pi}}\int_a^b \exp\Big(-\frac{(zkV-\mu)^2}{2\sigma^2}\Big)\mathrm{d}(zkV)\,.$$

The standard values for the above integral normal probability distribution, which can be found in any main text tables in statistics (with $0.5 \le \Phi(z) \le 0.9998$), are used, where the parameter $z = \frac{zkV-\mu}{\sigma}$ (called the critical ratio) is the dimensionless reduced standard normal probability distribution's $N(0,1)$ parameter. So, the new form of the cumulative normal probability distribution is the following one

$$\mathrm{P}(a < zkV \le b) = \mathrm{P}\Big(\frac{a-\mu}{\sigma} < \frac{zkV-\mu}{\sigma} \le \frac{b-\mu}{\sigma}\Big) = \\ = \mathrm{P}(a^* < z \le b^*) = \Phi(b^*) - \Phi(a^*) \quad (2.2.1)$$

where, $zkV \approx N(\mu,\sigma)$, $z \approx N(0,1)$, $a^* = \frac{a-\mu}{\sigma}$, $b^* = \frac{b-\mu}{\sigma}$, $a^*, b^* \ge 0$ and

$$\Phi(c) = p \ge 0.5\,,\ c \in \{a^*, b^*\}\,. \qquad (2.2.2)$$

$$\text{Moreover, if } c < 0\,,\ \text{then } \Phi(c) = 1 - \Phi(-c)\,. \qquad (2.2.3)$$

Conversely, for a given cumulative probability $p \ge 0.5$ the z_p parameter is given as

$$z_p = \Phi^{-1}(p) \qquad (2.2.4)$$

$$\text{and } z_p = -\Phi^{-1}(1-p), \text{ for } p < 0.5\,. \qquad (2.2.5)$$

Notice that, the results are based on the indices found in the Typical Normal Distribution Table, for $0.5 \le \Phi(z) < 1$.

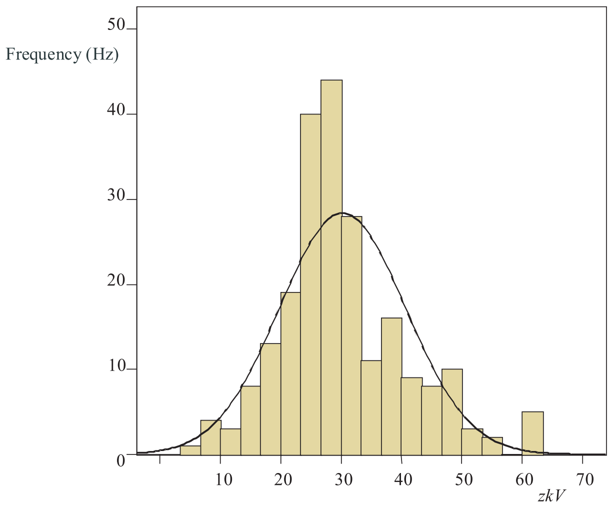

Fig. 7. The Normal distribution of the break down voltage zkV.

EXAMPLE 2.2.1. Suppose that, the transformers that are industrially produced and are disposed to the market, follow the normal distribution $N(30.19, 10.50)$, with respect to the breakdown voltage (zkV). If the tolerance for zkV values is between 26.5 kV and 32.8 kV, then find the expected percentage of the well-working transformers. Applying the (2.2.1), (2.2.2) and (2.2.3) formulas, for $a = 26.5$ and $b = 32.8$ we obtain the following

$$P(26.5 \le zkV < 32.8) = \Phi(0.2486) - \Phi(-0.3514) =$$
$$\Phi(0.2486) - 1 + \Phi(0.3514) = 0.5968 - 1 + 0.6374 = 0.2342\,.$$

So, 23.42 % of the transformers will be expected to perform within specifications.

EXAMPLE 2.2.2. We suppose that a network of transformers follows the normal distribution $N(30.19, 10.50)$, with respect to the breakdown voltage (zkV). Find the critical value z_1kV of zkV such that, the probability for each transformer to have breakdown voltage value greater than the critical one, is precisely 2.5 % *ie* $P(z_1kV < zkV) = 0.025$. Since,

$$P\Big(\frac{z_1kV - 30.19}{10.50} < \frac{zkV - 30.19}{10.50}\Big) = $$
$$= P\Big(\frac{z_1kV - 30.19}{10.50} < z\Big) = 0.025$$

it follows that $1 - \Phi\Big(\frac{z_1kV - 30.19}{10.50}\Big) = 0.025$

$$\text{that is } \Phi\Big(\frac{z_1kV - 30.19}{10.50}\Big) = 0.975\,.$$

Moreover, applying (2.2.4) formula, we obtain that

$$\frac{z_1kV - 30.19}{10.50} = \Phi^{-1}(0.975) = 1.96$$

$$\text{and so, } z_1kV = 50.77\,.$$

Thus, the critical breakdown voltage value satisfying the previous condition (probability 2.5 %) is 50.77 kV.

3 STATISTICAL RESULTS FOR THE WHOLE POPULATION OF TRANSFORMERS

In order to study the whole population of transformers, we divide the Xanthi area ($N = 1631$) in $Z_1, Z_2, \dots, Z_n$ random samples, where $n = 1631 : 224 \approx 7$. In addition, we consider Xanthi's sample Z_I, $I \in \{1, \dots, n\}$, $\operatorname{card} Z_i = 224$, as our representing sample. Since, in Z_i the zkV distribution is the Gaussian one $N(30.19, 10.50)$, then, according to the Central Limit Theorem., the distribution of the means of $Z_1, Z_2, \dots, Z_7$, is also Gaussian approx. Therefore, the critical ratio for the distribution of the means, is given by

$$z = \frac{(\overline{zkV} - \mu)\sqrt{\eta}}{\sigma} \approx N(0,1)\,. \tag{3.1}$$

$$\text{So, } z = \frac{(\overline{zkV} - 30.19)\sqrt{7}}{10.50} = \frac{(\overline{zkV} - 30.19)\sqrt{7}}{10.50}$$

and thus, the probability of the event $\overline{zkV} < a$ (respectively, $\overline{zkV} > a$), $0 \le a < \infty$, is given by

$$P\big(\overline{zkV} < a\big) = \Phi(0.252a - 7.6079) - 0.5 \tag{3.2}$$

and

$$P\big(\overline{zkV} > a\big) = 1 - \Phi(0.252a - 7.6079)\,. \tag{3.3}$$

EXAMPLE 3.1. If we are to find the percentage of the transformers in the Xanthi's area network that have average breakdown voltage greater than 33 kV, by applying (3.3) for $a = 33$, we obtain that $P(\overline{zkV} > 33) = 1 - \Phi(0.7081) = 0.2405$ *ie* 24.05 %.

EXAMPLE 3.2. If we are to calculate how many more transformers should be installed in the Xanthi's area network so that the percentage of the network transformers at which the average rate of the breakdown voltage $\overline{zkV}$ is higher than $\mu = 30.19$ (*ie* the average zkV of the population), at 2.81 kV ($\overline{zkV} > \mu + 2.81$), to be exactly 20 %, then according to the assumption

$$P(\overline{zkV} > \mu + 2.81) = 0.20$$
$$\text{, where } N(\mu, \sigma) = N(30.19, 10.50)\,.$$

We have

$$P\Big(\frac{(\overline{zkV} - \mu)\sqrt{\eta}}{\sigma} > \frac{(\mu + 2.81 - \mu)\sqrt{\eta}}{\sigma}\Big) =$$
$$= P(z > 0.2676\sqrt{\eta}) = 0.20$$

and so

$$1 - \Phi(0.2676\sqrt{\eta}) = 0.20 \text{ that is, } \Phi(0.2676\sqrt{\eta}) = 0.80\,.$$

Thus, $0.2676\sqrt{\eta} = 0.84$, that means that $\eta = 9.8534 \approx 10$. Consequently, the Xanthi's area population is given by $N_{\text{Xanthi}} = 224\eta = 2240$. Finally, in the Xanthi's network we must install a number of $2240 - 1631 = 609$ transformers more.

EXAMPLE 3.3. Suppose that a population of a transformers network (for example, $N = 39963$) can be subdivided in samples $Z_1, Z_2, \dots, Z_n$, with approx similar characteristics (cardinality of the samples, quality, external conditions *etc*), as Xanthi's sample Z_i, $i \in \{1, \dots, n\}$, $\operatorname{card} Z_i = 224$, $N(\mu, \sigma) = N(30.19, 10.50)$. Then,

(i) What will be the percentage of the transformers network that have average breakdown voltage greater than 31 kV?

(ii) Find a new network with similar characteristics as Xanthi's sample, such that $\mathrm{P}(\overline{zkV} > 31) = 8\,\%$.

In order to answer the previous questions we apply the formula (3.1) for $n = 39963 : 224 \approx 178$, that is

$$z = \frac{(\overline{zkV} - 30.19)\sqrt{178}}{10.50} = \frac{(\overline{zkV} - 30.19)13.342}{10.50}.$$

(i) $$\mathrm{P}(\overline{zkV} > 31) = \mathrm{P}\Big(z > \frac{(31 - 31.19)13.342}{10.50}\Big) = \\ = 1 - \Phi(1.02924) = 1 - 0.8479 = 0.1521 \approx 15.21\,\%.$$

(ii) In the new network (according to example 3.5) must be

$$\mathrm{P}(\overline{zkV} > 31) = \mathrm{P}(\overline{zkV} > \mu + 0.81) = \\ = \mathrm{P}\Big(P(z > \frac{0.81\sqrt{\eta}}{10.50}\Big) = 0.08.$$

Therefore,

$$\mathrm{P}(z > 0.0771\sqrt{\eta}) = 1 - \Phi(0.0771\sqrt{\eta}) = 0.08 \text{ that is}$$
$$\Phi(0.0771\sqrt{\eta}) = 0.92$$
$$\text{and so, } 0.0771\sqrt{\eta} = 1.41\,. \text{ Thus, } \eta = 334.5 \approx 335\,.$$

Consequently, the new network in which the percentage of the transformers with average breakdown voltage greater than 31 kV is exactly 8 % consists of $\mathcal{N} = 335 \times 224 = 75040$ distribution transformers.

4 DISCUSSION

What was presented above indicates that the distribution of the oil breakdown voltage for the investigated distribution transformers is rather normal. Such normality agrees approximately with previous publications, such as those of [10], and not so much with those of [11], where data were presented supporting that the distribution of oil breakdown voltage can be better interpreted with the extreme value statistics. Still some others (like the authors of [12]) pointed out that breakdown voltage data can be either normal or an external distribution. It seems, however, that in the present case of distribution transformers taken from the grid-network of Eastern Macedonia and Thrace, the breakdown data follow the Normal distribution.

What sort of statistical distribution prevails, depends on the particular breakdown mechanism and/or the specific conditions under which a fault has occurred. It may also depend on whether weak links (existing either in the oil volume or on the electrode surfaces) or physical size factors (such as, the collection process of particles from outside the stressed volume via the gap edge, the oil flow in the gap from both deliberate external pumping and intrinsic oil motion due to electric stress, stored electrostatic energy in the neighborhood of the oil gap and the dependence of the charge of a particle on the gap voltage and not so much on the local electric field) prevail [5, 13]. Moreover, as it was pointed out elsewhere, carefully controlled conditions affect the breakdown of transformer oil. Relatively poor quality oil is expected to give a positively skewed distribution since there is a lower limit to oil dielectric strength. Relatively good quality oil is expected to give a negatively skewed distribution since the extremal law is obeyed and breakdown is initiated by the largest weak link. Medium quality oil is expected to give a more or less normal distribution since the breakdown values will be between the above two cases [14].

5 CONCLUSIONS

A sample of distribution transformers has been investigated *wrt* their breakdown voltage. Oil samples have been tested with the aid of the Foster test cell. It seems that the distribution of breakdown voltages is normal.

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