Methodology of Statistical Analysis of Oscillograms: Case Study of Continuous Intermittent Arcing in Mass Impregnated Paper Cable Insulation in 10 kV Distribution Network

A. V. Telegin, A. I. Shirkovets, V. F. Nadein

Abstract--To describe transients at single phase-to-ground faults analytically and develop correct mathematical models, it is necessary to use statistical characteristics for a number of arcing ground fault parameters. These parameters can be derived from real oscillograms of phase voltages recorded at a ground fault using a self-engineered high-frequency fault recording system. The high-frequency recording system was implemented in the 10 kV cable distribution network in Arkhangelsk, Russia. It is used for operational control of network insulation by monitoring of transients and overvoltage estimation.

Based on the recorded oscillograms of the specific ground fault, methodology of statistical analysis is developed. Then, statistical analysis is performed for parameters of the arcing ground fault in the wide cable network with mass-impregnated paper-insulated cables. For this purpose, random variables of arc duration t_{ARC}, duration of no-current period Δt, overvoltage levels K_U, breakdown voltage for a faulted phase u_{BR} are sampled for the analysis. For our investigations, power tests of D'Agostino, Sarkadi-Kosik and Kolmogorov-Smirnov were used. In the case of negative tests for the normal distribution, the uniform distribution and the exponential distribution, it is recommended to use Johnson curves determined by a transformation of the normal distribution.

***Keywords*: statistical analysis, high-frequency recording system, real oscillogram, intermittent arcing fault, mass impregnated paper insulation, normal distribution, Johnson curves**

I. Introduction

Simulation of transients at arcing ground faults in cable insulation is performed with neglect of randomness for a moment of restrike and interrelationships between amplitude, velocity and time parameters of an arcing ground fault. Thus, determination of statistical characteristics of ground fault parameters is of great importance. When developing mathematical models of single-phase breakdown development and single-phase arcing in cable insulation, it is recommended to use ground fault parameters obtained from long-time monitoring and recording of transients in cable networks.

To obtain information on abnormal events, a special device is needed. In Russia, electromagnetic voltage transformers used for primary signal transformation in 6-10 kV networks are not usually calibrated during 4-8 years of operation. Their frequency characteristics are limited up to 3-5 kHz and not standardized (i.e. not regulated by standards). Existing fault recording systems have low ADC sampling rates (in general, up to 1 kHz). Frequencies of real transients at single phase-to-ground faults (SPGF) and short circuits (SC) may reach 5–50 kHz. Therefore, detailed fault recording at abnormal events is not provided by typical fault recording systems.

To solve this problem, special high-frequency recording systems can be used. Such systems allow monitoring and digital oscillography of transient processes in electrical networks. It will increase power supply reliability due to on-line monitoring of network parameters and will give a possibility of planning maintenance schedule for power equipment.

The recording system, developed with the participation of authors, is used for monitoring and oscillography of high-frequency transients at different single phase-to-ground faults and short circuits in the 10 kV network [1]. Temperature-independent capacitive voltage dividers are used as phase voltage sensors. The fault recording system is equipped with such voltage dividers. Voltage dividers have the constant voltage ratio K = 4250 in the full frequency range from 20 Hz to 85 kHz with relative accuracy for primary signal conversion of ± 1.5%. Since 2005, such sensors have been used in our electrotechnical laboratory during experimental investigations in 6-10 kV networks [2]. Voltage dividers are regularly calibrated and checked.

In August 2012, the high-frequency recording system was put into trial operation at two large 110 kV power supply substations in Arkhangelsk, Russia. The first substation (hereafter referred to as Substation A) is operated with resonant neutral grounding of 10 kV busbars through Petersen coils, while the second substation (hereafter referred to as Substation B) is operated with an ungrounded neutral. Cable networks of substations A and B include mass-impregnated paper-insulated (MIPI) cables which have been operated since

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Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015

1980s. Total length of cable networks for the Substation A is 102 km, and for the Substation B is 63 km.

During trial operation of the recording system, there were a lot of abnormal events. Results of trial operation of the recording system in 10 kV networks of the Substation A (from 14 August 2012) and the Substation B (from 19 November 2012) till 01 December 2014 are presented in Table 1, where: 1ph – the number of arcing SPGF which self-extinguished or detected and disconnected with switching to the standby power supply; 1ph-ShC – the number of transitions of arcing SPGF into phase-to-phase short circuits with emergency outages; ShC – the number of phase-to-phase short circuits, without preceding SPGF.

TABLE I

RESULTS OF TRIAL OPERATION OF THE HIGH-FREQUENCY RECORDING SYSTEM IN 10 KV NETWORKS OF TWO SUBSTATIONS IN ARKHANGELSK, RUSSIA

Name of Substation / Type of abnormal event	1ph	1h-ShC	ShC	Total
Substation A 2x25 MVA	112 (66.7%)	35 (20.8%)	21 (12.5%)	168 (100%)
Substation B 2x40 MVA	44 (63.8%)	19 (27.5%)	6 (8.7%)	69 (100%)

Analysis of many oscillograms recorded by the high-frequency recording system shows correctness and adequacy of recording algorithms at different faults. These oscillograms in the COMTRADE format are stored at the dedicated server. Then, it can be used by personnel of a relay protection service and an insulation and overvoltage protection service for determination of causes and sequences of disturbances and faults in the electrical network.

II. ANALYSIS OF REAL OSCILLOGRAMS OF THE ABNORMAL EVENT

The result of each further restrike at intermittent arcing and consequences of an arcing SPGF in a power cable (or its terminal) depend on various factors which are random values except primary parameters (R, L, C) of a zero-sequence circuit. Therefore, the process of maximum overvoltage generation according to known hypotheses (e.g. W. Petersen, Peters and Slepyan, etc) may differ from a real transient process at a ground fault in cable insulation. Single-phase arcing in cable insulation is not similar to arcing in overhead lines.

Based on many investigations [3], engineering estimation of probability for overvoltage generation is proposed (see Fig. 1). Unfortunately, the type of the network (overhead or cable) is not considered. This diagram states that $p(K_U \geq 2.80) < 0.05$, where K_U – overvoltage level, p – probability. It is in good agreement with statements given in [4] and results of many investigations and observations in cable networks.

During a single phase-to-ground arcing fault in a cable network, the result of the second and further restrikes, depending on energy release in the arc channel, determines the degree of local destructions and phase-to-phase insulation damages. Duration of arcing SPGF with a residual fault current of 20-30 A is from 1-10 ms to tens of minutes (usually, for MIPI – 1-2 seconds [5]).

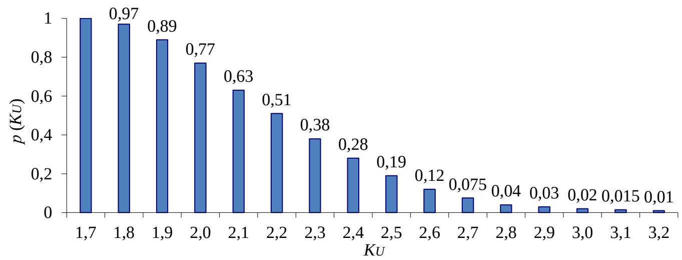


Fig. 1. Estimation of probability for overvoltage generation at arcing ground faults in a distribution network

Depending on the duration of no-current periods Δt between serial insulation breakdowns, single-phase arcing may be divided into two groups: with $\Delta t \geq 160 - 200$ ms, and with $\Delta t \leq 10 - 40$ ms. Duration of arcing t_{ARC} and duration of no-current periods Δt are random parameters with characteristics which depend on electric strength of insulation, voltage recovery rate on the faulted phase and other parameters of a transient process. Stochastic nature of these parameters is determined by randomness of a moment of insulation breakdown.

Recorded oscillograms in the 10 kV MIPI cable shown in Fig. 2, 3 represent different stages of the arcing ground fault: single-phase breakdown to ground with transition to serial impulse breakdowns, short-time intensification of self-quenching effect of the arc, transition into intermittent arcing, development of arcing SPGF into phase-to-phase short circuit with interruption, recovery of phase voltages with beating.

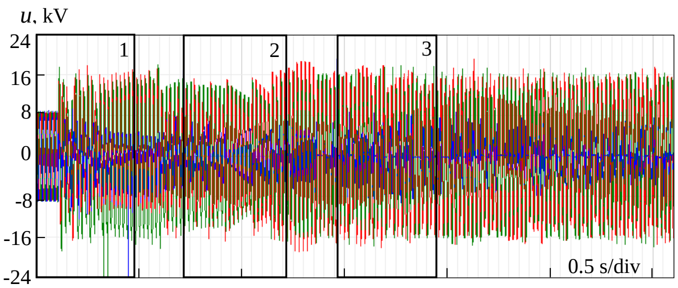
Description of the abnormal event

An arcing ground fault happened on the phase C in the moment of 110 ms from the beginning of the oscillogram (see Fig. 2). Stable arcing started from 1.3614 s. The arcing ground fault developed into the phase-to-phase short circuit (between phases B and C) after 94.4 ms which was interrupted after 637 ms as shown in Fig. 3.

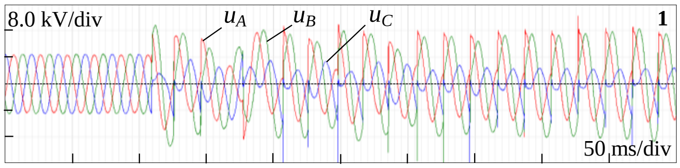
Summary of the arcing ground fault based on recorded oscillograms:

- *total duration of the arcing ground fault is 3.0844 s,*
- *duration of phase-to-phase short circuit is 0.637 s,*
- *the number of arcing breakdowns is 113,*
- *the number of periods of stable arcing is 43 with t_{ARC} = (4.0 ... 37.2) ms,*
- *maximum overvoltage level during the transient is 2.22 p.u. for phase A in relation to the maximum phase voltage before the fault ($u_{transientMAX} / u_{phMAX}$ = 18.96kV / 8.53kV).*

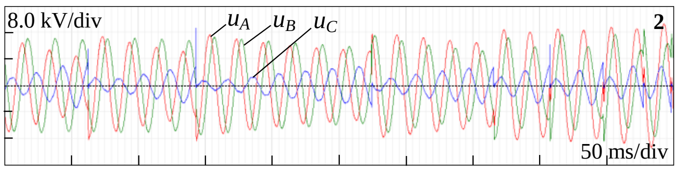
The following assumption was done before analyzing recorded oscillograms. As recorded oscillograms of phase voltages at busbars do not indicate a fault place, suppose that recorded transient processes correspond to a ground fault in cable insulation. This assumption is adequate because 10 kV cable networks have been operated for more than 30 years, and their average fault rate (10-12 faults per 100 km per year) is significantly greater than the fault rate of other network elements. It is known that about 90% of faults in distribution networks happen in power cable insulation.



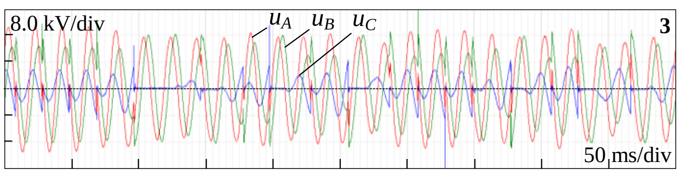
a) oscillogram of the fault



b) single-phase breakdown to ground with transition to serial impulse breakdowns, Δt = 20 – 30 ms

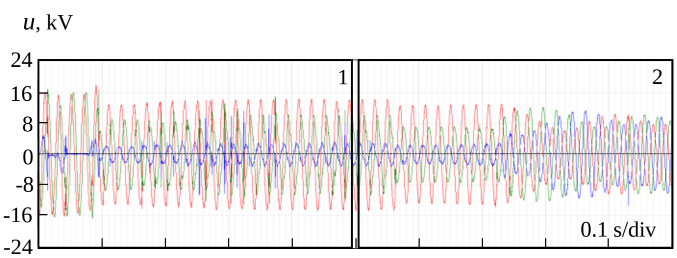


c) short-time intensification of self-quenching effect of the arc, Δt = 80 – 130 ms → 25 – 45 ms

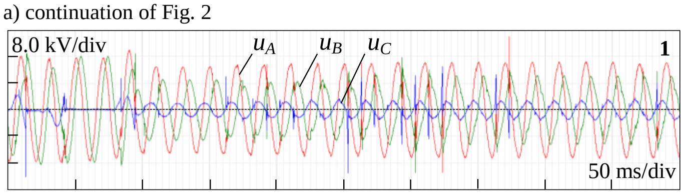


d) transition into intermittent arcing, t_{ARC} = 5 – 35 ms and Δt = 20 – 25 ms

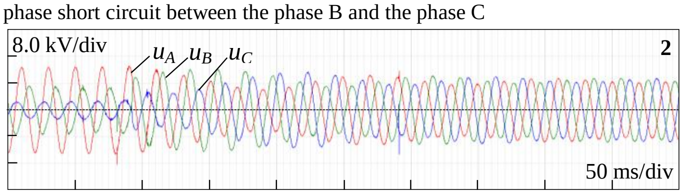
Fig. 2. Real oscillogram of the arcing ground fault in the MIPI cable in the 10 kV network (beginning of the fault)



a) continuation of Fig. 2



b) development of the arcing ground fault on the phase C into the phase-to-phase short circuit between the phase B and the phase C



c) interruption of the phase-to-phase short circuit after 637 ms and recovery of phase voltages with beatings

Fig. 3. Real oscillogram of development of the arcing ground fault into the phase-to-phase short circuit in the MIPI cable in the 10 kV network (ending of the fault)

Based on recorded oscillograms statistical analysis of arcing ground fault parameters was performed for the given distribution network. For this purpose, random variables of arc duration t_{ARC}, duration of no-current period Δt, overvoltage levels K_U, breakdown voltage for a faulted phase u_{BR} are sampled for the analysis. During the ground fault, voltage is changing significantly, that is u_{BR} = 2.51 ... 12.38 kV = (0.31 ... 1.52) u_{phMAX}. For correct statistical estimation of breakdown voltage u_{BR}, arc duration t_{ARC} = [4.0; 37.2] ms, duration of no-current period Δt = [4.6; 131.4] ms and overvoltage levels K_U = [1.47; 2.22] p.u., methods of mathematical statistics were used. Full random samples of arcing ground fault parameters are not given because of paper length limits.

III. Methodology of Statistical Analysis of Arcing Ground Fault Parameters

A. *Testing of the hypothesis for the normal distribution*

The hypothesis on the normal distribution for random samples is adequate, because it can be shown that for any x_i from any sample the Chebyshev criterion $x_i \in \left[\bar{x} - 3\sigma; \bar{x} + 3\sigma\right]$ is valid, where $\bar{x}$ – sample mean, σ – standard deviation. One of the most effective and robust criteria for normal distribution testing is the D'Agostino test which is recommended in the case of an unknown distribution law [6]. Results of testing samples for normality using the D'Agostino test are presented in Table 1.

As a D'Agostino test statistic for an ordered sample $x_1 \le \ldots \le x_n$ the ratio of Downton's estimator of the normal distribution standard deviation to the sample standard deviation is used:

$$D = \frac{T}{n^2 s}, \tag{1}$$

$$T = \sum_{i=1}^{n} \left\{ i - \frac{n+1}{2} \right\} \cdot x_i, \tag{2}$$

$$s^2 = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2. \tag{3}$$

The D'Agostino test gives percentage points [6] for D using the following equation:

$$Y = \sqrt{n} \cdot \frac{D - 0.28209479}{0.02998598}. \tag{4}$$

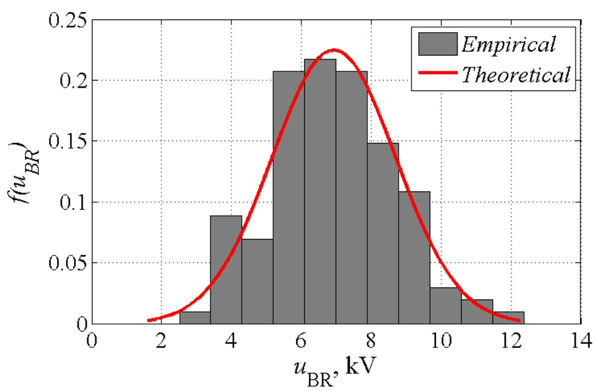
The hypothesis on normality is accepted if $Y_1(q) \le Y \le Y_2(q)$, where $Y_1(q)$ and $Y_2(q)$ – percentage points for the Y test statistic at the significance level of q = 0.05. Percentage points Y_1(0.05) and Y_2(0.05) for t_{ARC} are calculated as average values between n = 42 and n = 44 sample sizes. As for Δt, K_U, u_{BR} samples, percentage points for the closest table sample size of n = 100 are determined.

Table 1 shows that calculated D'Agostino statistics comply with the expression $Y_1 \le Y \le Y_2$ only for the u_{BR} sample. Therefore, the hypothesis of the normal distribution for the u_{BR} sample is accepted at the significance level of q = 0.05.

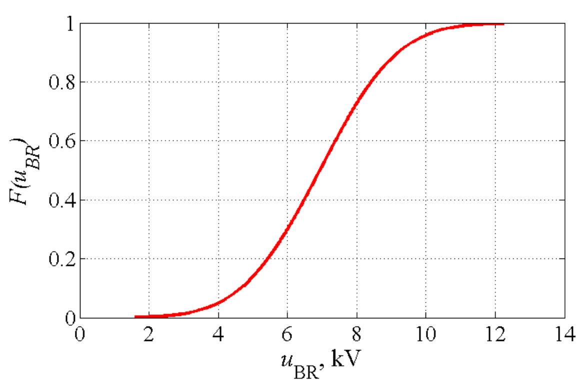
TABLE 1
RESULTS OF TESTING SAMPLES FOR NORMALITY

Calculated parameters of the D'Agostino test	t_{ARC}, ms	Δt, ms	K_U, p.u.	u_{BR}, kV
n	43	113	112	113
T	3346.4	39276.2	441.68	6348.05
s^2	62.226	262.24	0.017	3.13
D	0.22943	0.18994	0.27118	0.28115
Y	-11.51641	-32.66796	-3.85109	-0.33323
Percentage points				
$Y_1(0,05)$	-2.79	-2.54	-2.54	-2.54
$Y_2(0,05)$	0.998	1.310	1.310	1.310

Curves of the density function and the distribution function for the u_{BR} sample are presented in Fig. 4.



(a)



(b)

Fig. 4. Density function (a) and distribution function (b) for the breakdown voltage u_{BR} sample

For finding outliers in the u_{BR} sample we used Smirnov – Grubbs criterion. It was shown that there are no any outliers in this sample caused by recording or processing mistakes.

Statistical characteristics of the u_{BR} sample based on the normal distribution with the confidence level of $p = 1 - q = 0.95$ are given in Table 2.

The t_{ARC}, Δt and K_U samples should be tested for other distributions. Then, these samples were tested for the uniform distribution using the Sarkadi-Kosik test and for the exponential distribution using the Kolmogorov-Smirnov test [6]. The hypotheses were rejected at the significance level of $q = 0.05$.

TABLE 2
STATISTICAL CHARACTERISTICS OF THE EXPERIMENTAL SAMPLE U_{BR}

Parameter	Value
n	113
$u_{BR(MIN)}$	2.51
$u_{BR(MAX)}$	12.38
$M[u_{BR}]$	6.93
Confidence interval $M[u_{BR}]$, $p = 0.95$	(6.76; 7.10)
$s^2 = D[u_{BR}]$	3.155
$s = \sigma[u_{BR}]$	1.776
Confidence interval $\sigma[u_{BR}]$, $p = 0.95$	(1.571; 2.044)
Coefficient of variation	0.256
Skewness α_3	0.201
Kurtosis α_4	0.137

B. Determination of the type and parameters of the distribution for the t_{ARC}, Δt and K_U samples

As hypotheses on the normal, uniform and exponential distributions for the t_{ARC}, Δt and K_U samples were rejected at the significance level of $q = 0.05$, thus we need to choose the proper distribution which describes the statistical data correctly.

To approximate this experimental data, it is reasonable to use Johnson curves determined by a transformation of the normal distribution. N.L. Johnson proposed three types of transformations [6]:

$$f_1(x;\varepsilon,\lambda) = \ln\left(\frac{x-\varepsilon}{\lambda}\right), x \ge \varepsilon; \tag{5}$$

$$f_2(x;\varepsilon,\lambda) = \ln\left(\frac{x-\varepsilon}{\lambda+\varepsilon-x}\right), \qquad \varepsilon \le x \le \varepsilon+\lambda; \tag{6}$$

$$f_3(x;\varepsilon,\lambda) = \mathrm{Arsh}\left(\frac{x-\varepsilon}{\lambda}\right), \ -\infty < x < \infty; \tag{7}$$

where ε and λ – parameters of the Johnson distribution.

These types of transformations determine three types of Johnson families.

Selection of the proper type of Johnson curves on experimental data is performed in two stages. In the beginning, we determine which of distribution families (S_L, S_B or S_U) is applicable. Then, we find parameters of the selected distribution family.

To select an appropriate family of the Johnson distribution which represents experimental data correctly, we estimate the 3rd moment (α_3) and the 4th moment (α_4).

Then, the following approximate procedure is recommended:

if $\hat{\alpha}_4 > 3\left(1+0{,}641\hat{\alpha}_3^2\right)$ – select the S_U family;

if $\hat{\alpha}_4 \approx 3\left(1+0{,}641\hat{\alpha}_3^2\right)$ – select the S_L family;

if $\hat{\alpha}_4 < 3\left(1+0{,}641\hat{\alpha}_3^2\right)$ – select the S_B family.

If $\alpha_4 < 1 + \alpha_3$, Johnson curves are not applicable.

Calculated parameters for selection of Johnson distribution curves are presented in Table 3.

TABLE 3
SELECTION OF JOHNSON DISTRIBUTION CURVES FOR THE t_{ARC}, Δt AND K_U SAMPLES

Parameters for selection of Johnson distribution curves	t_{ARC}, ms	Δt, ms	K_U, p.u.
n	43	113	112
$s^2=\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2$	63.708	264.580	0.017
$\hat{\alpha}_3=\frac{1}{ns^3}\sum_{i=1}^{n}(x_i-\bar{x})^3$	1.811	4.060	-0.470
$\hat{\alpha}_4=\frac{1}{ns^4}\sum_{i=1}^{n}(x_i-\bar{x})^4$	5.340	23.746	4.181
$3\left(1+0{,}641\hat{\alpha}_3^2\right)$	9.309	34.698	3.425
$1+\hat{\alpha}_3$	2.811	5.060	0.530
Family of Johnson Curves	S_B	S_B	S_U

The equation for the density function of the S_B family is given by:

$$f(x)=\frac{\eta}{\sqrt{2\pi}}\frac{\lambda}{(x-\varepsilon)(\lambda-x+\varepsilon)}\cdot$$
$$\cdot\exp\left\{-\frac{1}{2}\left[\gamma+\eta\ln\left(\frac{x-\varepsilon}{\lambda-x+\varepsilon}\right)\right]^2\right\},\qquad (8)$$
$$\varepsilon\le x\le\varepsilon+\lambda$$

where $\eta>0,-\infty<\gamma<\infty,\lambda>0,-\infty<\varepsilon<\infty$ – parameters of the distribution.

The equation for the density function of the S_U family is given by:

$$f(x)=\frac{\eta}{\sqrt{2\pi}}\frac{1}{\sqrt{(x-\varepsilon)^2+\lambda^2}}\cdot$$
$$\cdot\exp\left\{-\frac{1}{2}\left(\gamma+\eta\ln\left\{\frac{x-\varepsilon}{\lambda}+\left[\left(\frac{x-\varepsilon}{\lambda}\right)^2+1\right]^{\frac{1}{2}}\right\}\right)^2\right\},\qquad (9)$$

where $-\infty<x<\infty,\ \eta>0,-\infty<\gamma<\infty,\ \lambda>0,$ $-\infty<\varepsilon<\infty.$

Determine parameters of the Johnson distribution for the t_{ARC}, Δt and K_U samples. A random variable x which corresponds to the Johnson distribution S_B is limited by ε and $\varepsilon+\lambda$. Based on the physical nature of arcing duration t_{ARC} and duration of no-current period Δt, assume $\varepsilon=0$. A random variable x which corresponds to the Johnson distribution S_U is not limited in theory. Thus, parameters γ, η, λ and ε are not known and should be estimated. Formulas and calculated parameters for the parameters of Johnson distributions S_U and S_B are given in tables 4, 5.

Using the known formulas for the density function, the distribution function can be derived by integrating *f(x)* at the given interval. It is difficult to integer above-mentioned functions *f(x)* analytically, then we use MATLAB which allows numerical integration and plotting distributions functions for any density functions.

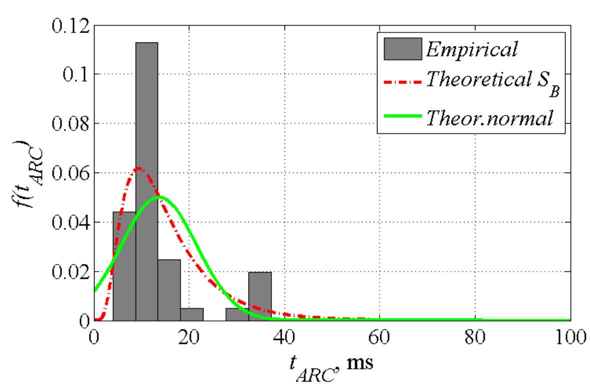
Curves of density functions and distribution functions for the t_{ARC}, Δt and K_U samples with empirical density histograms are presented in Fig. 5-7.

TABLE 4
CALCULATED PARAMETERS OF THE JOHNSON DISTRIBUTION S_B FOR THE t_{ARC} AND Δt SAMPLES

Formula	Calculated value	
	t_{ARC}	Δt
ε	0	0
$\hat{\lambda}=(\tilde{x}-\varepsilon)\left[\frac{(\tilde{x}-\varepsilon)(x_\alpha-\varepsilon)}{(\tilde{x}-\varepsilon)^2-(x_\alpha-\varepsilon)(x_{1-\alpha}-\varepsilon)}+\frac{(\tilde{x}-\varepsilon)(x_{1-\alpha}-\varepsilon)}{(\tilde{x}-\varepsilon)^2-(x_\alpha-\varepsilon)(x_{1-\alpha}-\varepsilon)}-\frac{2(x_\alpha-\varepsilon(x_{1-\alpha}-\varepsilon))}{(\tilde{x}-\varepsilon)^2-(x_\alpha-\varepsilon)(x_{1-\alpha}-\varepsilon)}\right]$	266.16	150.22
$\hat{\eta}=\frac{u_{\alpha''}-u_{\alpha'}}{\ln\left[\frac{(x_{\alpha''}-\varepsilon)(\varepsilon+\lambda-x_{\alpha'})}{(x_{\alpha'}-\alpha)(\varepsilon+\lambda-x_{\alpha''})}\right]}$	1.642	1.542
$\hat{\gamma}=u_{\alpha''}-\eta\ln\left(\frac{x_{\alpha''}-\varepsilon}{\varepsilon+\lambda-x_{\alpha''}}\right)$	4.867	3.219

TABLE 5
CALCULATED PARAMETERS OF THE JOHNSON DISTRIBUTION S_U FOR THE K_U SAMPLE

Formula	Value
$\varepsilon=\bar{x}+\hat{\lambda}\sqrt{\omega}sh\left(\frac{\hat{\gamma}}{\hat{\eta}}\right)$	1.809
$\hat{\lambda}=s\left\{\frac{1}{2}(\omega-1)\left[\omega ch\left(\frac{2\hat{\gamma}}{\hat{\eta}}\right)+1\right]\right\}^{-\frac{1}{2}}$	0.271
$\hat{\gamma}$	–0.7503
$\hat{\eta}$	2.396



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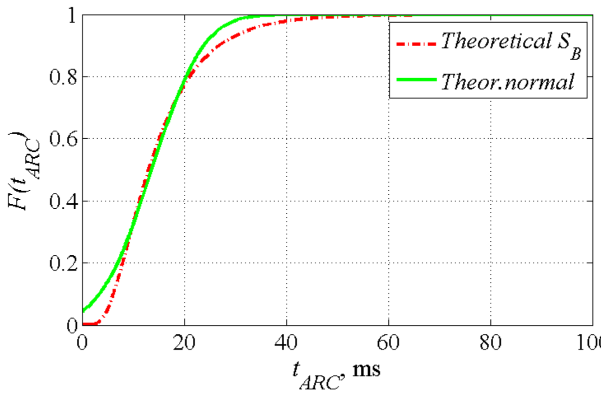
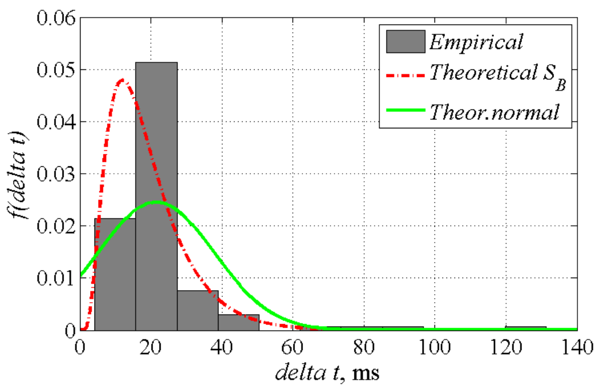


(b)

Fig. 5. Density (a) and distribution (b) functions of the Johnson distribution S_B for the arc duration t_{ARC} sample



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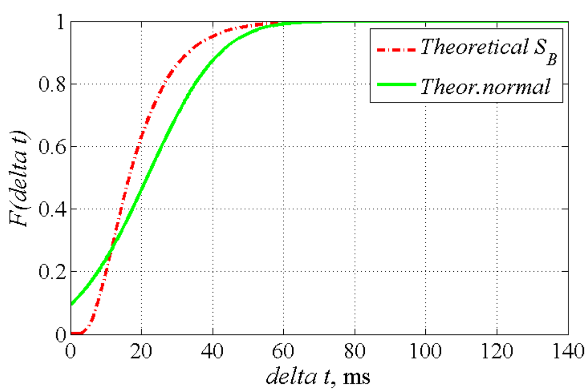
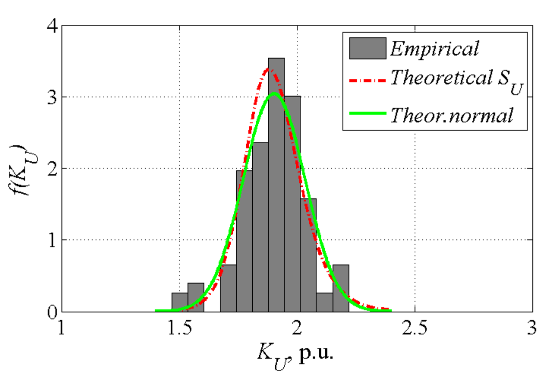


(b)

Fig. 6. Density (a) and distribution (b) functions of the Johnson distribution S_B for the duration of no-current period Δt sample



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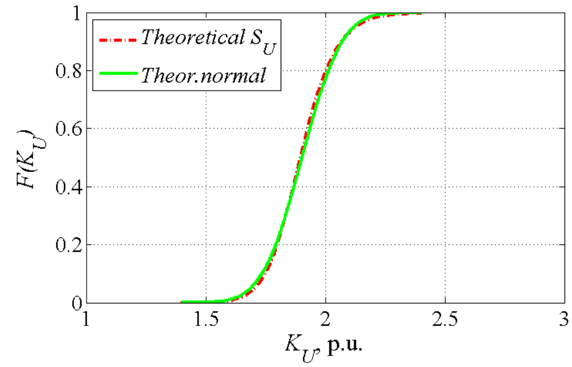

(b)

Fig. 7. Density (a) and distribution (b) functions of the Johnson distribution S_U for the overvoltage level K_U sample

Based on the physical nature of the parameters, the samples are not reduced. Smaller values of t_{ARC} correspond to impulse breakdowns in the MIPI, higher values of t_{ARC} – to the transition into stable arcing during arcing channel development in the insulation. Duration of no-current period Δt is limited by the electric strength recovery rate depending on arcing conditions (i.e. a stage of arcing).

IV. Conclusions

To obtain correct information on the parameters of various faults in electrical networks (i.e. correct displaying primary signals in the wide frequency range), the fault recording system should be equipped with special voltage dividers. Voltage dividers being used in medium voltage networks should provide the bandwidth not less than 80 kHz and correct process recording at the power frequency (50/60 Hz).

Obtained results on overvoltage levels ($K_U \leq 2.2$) in the electrical network with MIPI cables may be extend to underground urban networks operated more than 20-25 years. Based on the real oscillograms, it is shown that stable arcing in mass-impregnated paper insulation is of low probability. Due to cable oil viscosity and gas-blasting in the area of an arcing breakdown, multiple short-time arc extinctions with voltage recovery up to breakdown voltages u_{BR} = (0.4...0.6)u_{phMAX} can occur.

To approximate experimental data on the parameters of electromagnetic processes which do not comply with basic distribution laws, it is reasonable to use Johnson curves determined by a transformation of the normal distribution.

It is confirmed that large sample sizes (n ≥ 100) for arcing ground fault parameters do not guarantee their conformity to the normal distribution. The samples can be tested with the use of D'Agostino, Sarkadi-Kosik and Kolmogorov-Smirnov tests.

Statistical characteristics of voltage parameters at ground faults in power cables obtained from real oscillograms can be further used in modification of existing arcing ground fault mathematical models, checking of efficiency for ground fault relaying based on controlling transient process parameters.

V. References

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