Statistical Characteristics for Parameters of Transient Processes at Arcing Ground Faults in Cable Networks

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***Abstract*- The paper presents the results of complex analysis of amplitude, velocity and time parameters for currents and voltages at arcing ground fault in power cable. The analysis is based on random samples obtained from real oscillograms. These oscillograms are recorded during experimental investigations in the 6 kV network. Hypotheses of distribution laws, outliers detection and correlational relationship are tested. Regression statistics is obtained for the following main parameters of arcing ground fault in cable insulation: duration of single breakdowns, duration of no-current condition, overvoltage level, rate of high-frequency arc current change before quenching, voltage recovery rate for a faulted phase under no-current condition, neutral-to-ground voltage amplitude after breakdown, breakdown voltage for a faulted phase. Obtained statistical characteristics for arcing breakdown parameters and stochastic relationships between them can be used for further development of mathematical models of arcing in power cable insulation and for checking of relay protection efficiency using physical models.**

Keywords: parameters of arcing ground fault, power cable, insulation breakdown, distribution law, statistical characteristics, correlation coefficient, linear regression

I. INTRODUCTION

During network operation there are various changes of ground fault conditions. Therefore, due to experiment continuity and uniform experiment conditions, field investigations are of great importance for practice.

Experiments of ground faults were conducted for a network with two parallel Petersen coils (total power is 650 kVA) and two 1000-Ohm resistors (total active current is 7.0 A). Total capacitance current for a network configuration at the time of experiment is 79.0 A, while detuning factor is not greater than 5%. With the use of a special needling device and an arc spark gap, arcing breakdown in a 10 kV three-core mass-impregnated paper-insulated (MIPI) power cable was forced.

During the experiment, artificial arcing ground faults were initiated in reduced 6-10 kV cable insulation (i.e. an artificial insulation defect like 'an artificial hole') by an arc spark gap with rotating sparking balls. The arc spark gap is used for voltage supplying to the faulted cable. The experimental circuit is shown in Fig. 1. To obtain stable results and record intermittent arcing faults, the cable was radially pierced by a needling device for a whole thickness of insulation from an outer surface to a cable core. Then, a needling device was removed 1 mm back from a cable core.

Transformation of signals is realized by common current transformers and special capacitance voltage dividers with 20 Hz – 2.5 MHz bandwidth. Phase-to-ground voltages and arcing fault current are recorded with a sampling rate not less than 500 kHz.

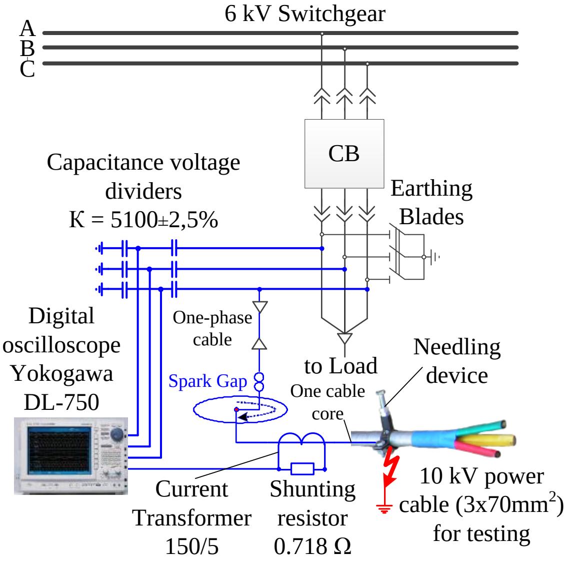


Fig. 1. The experimental circuit for the 6 kV network with arcing ground faults in the MIPI cable

The following parameters of arcing ground fault are analyzed: duration of single breakdowns t_{ARC}, duration of no-current condition Δt between serial breakdowns, overvoltage level K_U, rate of high-frequency arc current change before quenching di_{ARC}/dt, voltage recovery rate for a faulted phase under no-current condition du_{RECOV}/dt, neutral-to-ground voltage amplitude after single-phase breakdown u_{NMAX}, breakdown voltage for a faulted phase u_{BR}. Randomness of a moment of each single-phase insulation breakdown causes randomness of other parameters.

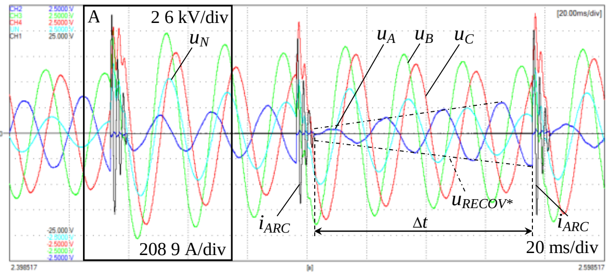
The main aims of our investigation are:

1. To test samples for normal distribution and determine statistical characteristics for amplitude, velocity and time parameters for currents and voltages at arcing ground fault in power cable (based on random samples obtained from real oscillograms): t_{ARC}; Δt; K_U; di_{ARC}/dt; du_{RECOV}/dt; u_{NMAX}; u_{BR}.

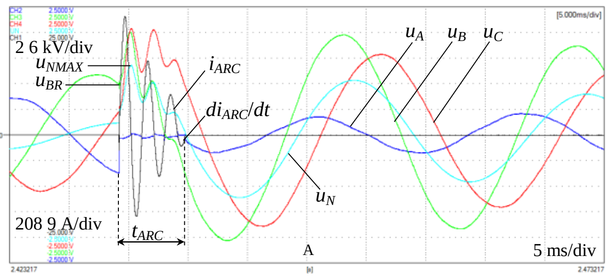
2. To test the significance of stochastic relationships between parameters of arcing ground fault in cable insulation and parameters of simple linear regression.

II. Testing for Normal Distribution and Determination of Statistical Characteristics for Parameters of Arcing Ground Faults in Cable Insulation

Consider a case of 63 serial breakdowns of cable insulation. A fragment of this oscillogram and its expanded part illustrating a single breakdown are shown in Fig. 2. The total duration of ground fault recording is 5.05 seconds. Based on the character of arcing ground fault, we state that there are serial impulse breakdowns of cable insulation during the experiment.



a)



b)

Fig. 2. Real oscillogram (a) and its fragment (b) of serial single-phase breakdowns in the MIPI cable insulation during experimental investigations in the operational 6 kV network.

Initial random samples of arcing ground fault parameters are not given because of paper length limits. To assume correct statistical hypotheses for testing, we set du_{RECOV}/dt = const.

To test hypotheses for normal distribution, we use a special D'Agostino criterion [1, 2] which is recommended in the case of an unknown alternative hypothesis. Tests of considered random samples of arcing ground fault parameters show that all the parameters comply with the expression $-2{,}68 \le Y \le 1{,}13$ (where -2.68 and 1.13 are critical values of the D'Agostino criterion for the closest table sample size $n = 60$ elements). Therefore, hypotheses of normal distribution for samples of arcing ground fault parameters are accepted at the significance level of $q = 0.05$.

For finding outliers we use Smirnov – Grubbs criterion [2] and Rosner criterion [3]. The last one also allows determination of the number of outliers. Using these criteria we state that there are no outliers in the considered samples. It means that used methods and experimental techniques and conditions are correct.

After identifying outliers, it is reasonable to give statistical characteristics for normally distributed estimated samples at the confidence level of $p = 0.95$ (see Table 1). For convenience, we call all the samples as a variable X.

Statistical analysis shows positive skewness for Δt и di_{ARC}/dt (α_3 = 0.510 and 0.643 respectively) and small skewness for t_{ARC}, K_U and u_{BR} ($|\alpha_3| < 0{,}5$). The smallest deviation is observed for samples of K_U и u_{NMAX}. The biggest deviation is calculated for di_{ARC}/dt: $\sigma[di_{ARC}/dt]$ = 130.2 A/ms = 0.29M[di_{ARC}/dt]. Estimation of the range of M[K_U] ± 3σ[K_U] for overvoltage levels show that observed levels of K_U = [1.86; 2.58] illustrate the case of reduced cable insulation with residual electric strength of not greater than 14–18 kV/mm.

Table 1 Statistical Characteristics of Normally Distributed Experimental Samples with Confidence Intervals for Mean and Standard Deviation

Parameter	t_{ARC}, ms	Δt, ms	K_U, pu	di_{ARC}/dt, A/ms	du_{RECOV}/dt, V/ms	u_{NMAX}, kV	u_{BR}, kV
n	63	62	63	62	62	63	62
x_{MIN}	3.8	35.0	1.98	239.3	21.0	5.20	2.00
x_{MAX}	7 9	133.6	2.47	797.4	52.0	7.24	4.37
$\bar{x} = M[X]$	5.6	73.2	2.22	446.7	36.9	6.31	3.17
Confidence interval $M[X]$, p = 0.95	(5.47; 5.74)	(70 2; 76.1)	(2.20; 2.23)	(430.1; 463 2)	(36.0; 37.8)	(6.24; 6.38)	(3.10; 3.24)
$s^2 = D[X]$	1.19	551.3	0.014	16948.6	46.6	0.28	0.30
$s = \sigma[X]$	1.089	23.5	0.120	130.2	6.83	0.528	0.550
Confidence interval $\sigma[X]$, p = 0.95	(0.926; 1.321)	(19.95; 28.53)	(0.102; 0.146)	(110.6; 158 2)	(5.80; 8 29)	(0.449; 0.640)	(0.467; 0.668)
Skewness α_3	0.194	0.510	0.042	0.643	0.257	-0.331	0.138
Kurtosis α_4	-0.447	-0.322	-0.689	-0.135	-0.340	-0.665	-0.901

III. Testing of Stochastic Relationship between Parameters of Arcing Ground Fault in Cable Insulation for Significance and Regression Analysis

Testing of the hypothesis for significance of correlational relationships between observed random parameters is an important task for practice. In other words, it is necessary to find significance of correlation coefficient deviations from zero. In this case, classical correlation analysis can be used due to normal distribution of random samples.

There are evident relationships between overvoltage levels K_U and neutral-to-ground voltages u_{NMAX} and breakdown voltages u_{BR}, and between durations of no-current condition Δt and breakdown voltages u_{BR}. Relation between breakdown voltage and duration of no-current condition $u_{BR} = f(\Delta t)$ can be described in the following way: rise of Δt leads to reaching of high values of recovering electric strength across the gap. Then, restrike will happen at higher values of breakdown voltage u_{BR}.

Physical relation between velocity parameters for arc current di_{ARC}/dt and recovering voltage on the faulted phase du_{RECOV}/dt can be supposed using the following hypothesis: the higher is the rate of the arc current before quenching, the higher should be initial electric strength for a gap. Then, according to the previous explanation (i.e. $u_{BR} = f(\Delta t)$) we assume that the rise of du_{RECOV}/dt may depend on the rise of di_{ARC}/dt. In this case, lack of restrikes (i.e. no-restrike state) is one of the limit states for arcing ground fault. It is caused by insufficient du_{RECOV}/dt for restrikes related to the rate of electric strength recovery de_{STR}/dt. It is also influenced by high values of initial recovering electric strength after the first breakdown.

Relationship between du_{RECOV}/dt and u_{BR} should be also tested, because these parameters are related to each other through a 'coefficient' Δt: to a first approximation we assume $u_{BR} = u_0 + \Delta t \cdot du_{RECOV}/dt$ where u_0 is initial voltage across the gap after arc extinction.

According to presented suggestions of relationships between considered random samples of arcing ground fault parameters, we test the hypothesis of correlational relationship for significance by comparison of sample correlation coefficient r with its critical value r_q [4]. When n > 10, r_q is estimated through a Student's distribution quantile $q = 0.05$ with $n-2$ degrees of freedom.

Correlation between random samples is significant if $|r| \geq r_q$. If correlation is not significant, it does not implicate that there are no any other statistical relations between parameters, for example, logarithmic or power dependences.

For adequate describing of correlational relationships between random samples, perform regression analysis: find coefficients of simple linear regression equation $y = bx + a$ using the method of least squares and test these coefficients for significance using the Fisher's criterion (F-test) [4] at the significance level of $q = 0.05$. Then we find a coefficient of determination R_2. The results of testing for the hypothesis of correlational relationships between K_U and u_{NMAX}, K_U and u_{BR}, Δt and u_{BR}, di_{ARC}/dt and du_{RECOV}/dt, du_{RECOV}/dt and u_{BR}, and regression statistics are given in Table 3.

Therefore, the hypothesis of stochastic relationships between K_U and u_{NMAX}, K_U and u_{BR}, Δt and u_{BR}, du_{RECOV}/dt and u_{BR}, are accepted at the significance level of $q = 0.05$. Calculations show that correlation and regression coefficients are very significant, because the hypothesis is not rejected at the confidence level of $p = 0.99$.

TABLE 3 TESTING OF THE HYPOTHESIS OF CORRELATIONAL RELATIONSHIPS BETWEEN RANDOM SAMPLES FOR SIGNIFICANCE AND REGRESSION STATISTICS AT THE SIGNIFICANCE LEVEL OF q = 0 05

Parameter	$K_U - u_{NMAX}$	$K_U - u_{BR}$	$\Delta t - u_{BR}$	$di_{ARC}/dt - du_{RECOV}/dt$	$du_{RECOV}/dt - u_{BR}$
Simple correlation					
r	0.40009	0.75519	0.91365	**0.24793**	-0.65058
$r_{q=0\ 05}$	0.24996	0.25003	0.25003	**0.25003**	0.25003
Significance of correlation	*significant*	*significant*	*significant*	*not significant*	*significant*
Simple linear regression					
a	2.4686	-4.6120	1.6073	31.097	5.1048
$\sigma[a]$	1.1376	0.8734	0.0943	3.0490	0.2962
b	1.7465	3.5154	0.0214	0.0121	-0.05238
$\sigma[b]$	0.5122	0.3939	0.0012	0.0066	0.00789
R^2	0.1601	0.5703	0.8347	0.0615	0.4233
F	11.625	79.640	**303.08**	**3.9299**	44.033
$F_{0\ 05\ 1\ n-2}$	3.9985	4.0012	**4.0012**	**4.0012**	4.0012
Significance of regression equation	*significant*	*significant*	*significant*	*not significant*	significant

Note that correlation and the linear regression equation for di_{ARC}/dt and du_{RECOV}/dt samples become significant at the significance level of $q = 0.053$ (in this case, $r = 0.2479 > r_{q=0\ 053} = 0.2469$; $F = 3.9299 > F_{0\ 053,1,n-2} = 3.8964$). This illustrates correlation relationship between these samples with a little decrease of confidence from 0.950 to 0.947.

IV. CONCLUSIONS

Performed the analysis of statistical characteristics for the parameters of an arcing ground fault with serial impulse breakdowns of MIPI cable insulation, we make the following conclusions:

1. It is obtained that mean of breakdown voltage $M[u_{BR}] = 3.17$ kV $= 0.62 u_{phMAX}$ at maximum phase-to-ground voltage $u_{phMAX} = 5.14$ kV. Taking into account the level of damage for mass-impregnated paper insulation and radial direction of its breakdown, high residual electric strength at the fault location is observed. It is caused by cable oil dribbling and relatively quick arc quenching

(M[t_{ARC}] = 5.6 ms). During the experiment (5.05 seconds) there were 63 serial cycles of arc ignition and arc extinction without transition into continuous arcing.

2. Duration of single arc breakdown is $t_{ARC} \leq 8$ ms with a small deviation of $\sigma[t_{ARC}] < 1.1$ ms. The higher is duration of breakdowns t_{ARC}, the bigger is the number of zero-crossings for high-frequency arc current before arc quenching. At the same time, the rate of high-frequency arc current change before quenching is di_{ARC}/dt = 240 – 800 A/ms and is not influenced by t_{ARC}.
3. Duration of no-current condition Δt is distributed with a high standard deviation: Mean of Δt is M[Δt] = 73.2 ms, while its standard deviation is $\sigma[\Delta t]$ = 23.5 ms which is caused by an unstable rate of electric strength recovery for cable insulation during arcing ground fault. Taking into account low rates of voltage recovery du_{RECOV}/dt = [21; 52] V/ms and possibility of restrikes at u_{BRmax} = 4.37 kV < u_{phMAX}, we may expect electric strength recovery rate de_{BR}/dt to be much less than its common values for calculations of 1–2 kV/ms.
4. Combined investigation of Δt, du_{RECOV}/dt and u_{BR} shows satisfactory precision of experimental results: $M[\Delta t]\cdot M[du_{RECOV}/dt] + u_0 = 2.7$ kV + $u_0 \leftrightarrow M[u_{BR}] = 3.17$ kV where $u_0 \neq 0.47$ kV because du_{RECOV}/dt is not constant under no-current conditions.

Results of investigations of simple correlational relationships between the parameters of arcing ground fault in cable insulation are the following:

1. The hypothesis of linear stochastic relationships between K_U and u_{NMAX}, K_U and u_{BR}, Δt and u_{BR}, du_{RECOV}/dt and u_{BR} is accepted at the significance level of $q = 0.05$.
2. The hypothesis of possible relationships between the rate of zero-crossing for high-frequency arc current before arc quenching di_{ARC}/dt and voltage recovery rate du_{RECOV}/dt is rejected at the significance level of $q = 0.05$. Additional testing shows that the hypothesis of relationships between di_{ARC}/dt and du_{RECOV}/dt is accepted with the confidence level of $p = 0.947$. This indicates physical relations between these parameters which have not been studied before. Such relations may be described by a non-linear function.

Statistical characteristics are supposed to be used for the development of a mathematical model of arcing in cable insulation. Moreover, based on obtained results and improved simulation we may develop requirements for correct choice of protective devices against arcing overvoltages. When adding statistical models into expanded physical models, we may also check algorithms of ground fault relay protection [5].

V. References

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