The role of emission properties in non-sustained disruptive discharge (NSDD) evolution

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Abstract - The peculiarities of field-emission current and NSDD-capability of SSS CuCr 70/30 vacuum gap have been investigated for the commercial vacuum interrupters. It has been found that 1)NSDD is not a result of long-term (more than 100 µs) increase of field-emission current; 2) there is no correlation between average level of emission current and NSDD capability of vacuum gap; 3)there is a strong correlation between NSDD-capability of the contact gap and capability of the gap to generate sharp short-term bumps of the emission current; 4) NSDD and the bumps of the current (often) are followed by the step increase of average emission current, return to the initial value takes the emission current several following periods of applied 50Hz voltage. It has been determined that the duration of the bumps is not more than 10 µs and the bumps are not preceded by field-emission current increase. It has been demonstrated that under the test condition the phenomena of current bumps can not be explained by the mechanism of explosive auto emission. The authors suppose that NSDD and current bumps have the same origin – the bombarding of the contact surface by the particles.

I. INTRODUCTION

After the contact opening the various phenomena concerned with lost of insulation can be observed in VI. One of such events is the non-sustained disruptive discharge, which occurred during the several hundred milliseconds after the contact breaking [1]. Disruption discharge is closing the circuit decreasing voltage up to zero. The high frequency current of discharge is interrupted shortly afterward so that power frequency current does not sustain this breakdown.

Investigations by various authors of different aspects concerning NSDD [2, 6, 10-12] revealed the list of factors certainly influenced on NSDD-capability:

1. contact material;
2. contact surface finishing and condition of VI assembling;
3. design of VI;
4. dynamic of switching;
5. circuit conditions: level of applied voltage, level of making and breaking currents.

The statistic dependency of NSDD probability from the time elapsed from commutation has also been achieved [e.g. 4,5,8]. It has been revealed that NSDD is not preceded by increase of emission current [4, 8].

Therefore experiments of different authors were usually carried out in the circumstances different from the condition of real commercial VI. In this work authors try to make direct experiments with real commercial VI produced by IG “Tavrida Electric”.

The work was carried out to answer following questions:

1. Is there any dependency between the average emission current in the vacuum gap and the probability of NSDD?
2. Is there any amplification of field emission current directly before the NSDD?
3. Is there any other phenomena bounded with NSDD?

II. EXPERIMENTAL SET-UP

A. Measuring circuit

Test circuit is shown in Fig. 1. This scheme allowed to fulfill measures of applied voltage and emission current of VI with sampling rate of 100 microseconds and to fix NSDD appearance during 1.2 seconds after contact opening. The fact of NSDD appearance was registered by the voltage drop.

Main electrical parameters of this circuit are shown in the table 1.

TABLE I

MAIN ELECTRICAL PARAMETERS OF THE CIRCUIT

E, rms	32 kV
power frequency	50 Hz
C	0.5 nF
R_b	1.2 MOhm
R_l	100 Ohm
R_m	150 Ohm
C_{comp}	≈10 pF
Current measure accuracy	3 µA

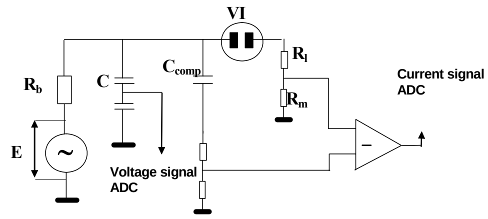

Fig. 1 Test circuit

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B. Test duty

Test sequence for each VI included the set of consequent test duties “O”.

Test duty “O:

1) the test VI at the initial moment is closed; 2) VI is opened, the moment of opening is synchronized with maximum voltage of power frequency; 3)during 1.2 seconds after opening the signal of applied voltage and current of VI is being measured; 4) VI is closed.

C. Test VCB

Three commercial VI TEL were investigated. The gap was 6 mm. The contact material is CuCr70/30. The number of test duties “O” carried out with each VI presented in the table 2.

III. Experimental Results

A. NSDD and emission current

The table II demonstrates the estimation of NSDD probability for each VI computed on the basis of the achieved experimental results.

TABLE II

QUANTITY OF TEST DUTIES AND NSDD PROBABILITY

VI number	“O” quantity	NSDD quantity	NSDD probability
1	85	13	0,15±0,05
2	141	10	0,07±0,03
3	40	3	0,07±0,05

As it can be observed from the table II the NSDD probability is the highest on the VI 1, and the VI 2 and 3 is almost equal. However, the value of average emission current on VI 2 is substantially higher than on VI 1 and 3. There are no events with emission current preceding NSDD. But it has been revealed that NSDD can cause the emission current intensification degrading during 1-2 periods. Such effects were observed during the test duties on all VIs. The Fig. 2 demonstrates the fragment of oscillogram of the test duty where emission current was increased after NSDD.

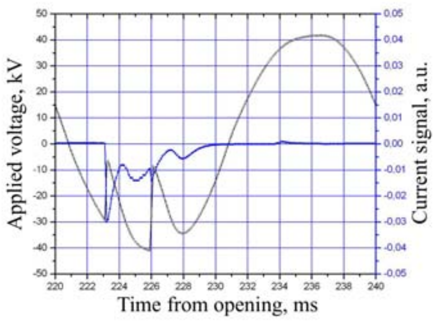

Figure 2 The amplification of emission current after NSDD.

Apparently, NSDD had influenced the structure of the electrodes’ surface and new emitters appeared. Relatively high emission current did not lead to NSDD.

Hence, there are some conclusions:

There is no correlation between emission properties and NSDD, in the way that NSDD is not a consequence of field emission process.

Changing the structure of the electrodes’ surface NSDD can cause increase of emission current.

B. Short-term current bumps

During the test duties the new phenomenon has been observed. Short-term current bumps – the current pulse of high amplitude with the duration below the sampling rate. The bumps were observed during the tests on all VIs. The example of current bump is shown on the Fig. 3.

Current bumps are correlated with NSDD; in 24 from 26 cases of NSDD occurrence current bumps were also observed.

The amplitude and quantity of bumps are being decreased with time elapsed from commutation (Fig. 4).

With the decreased amplitude of power frequency voltage the number and intensity of bumps are also decreased.

Fig. 5 demonstrates the voltage of occurrence distribution for current bumps. Almost all of bumps occurred on the positive slope of power frequency voltage.

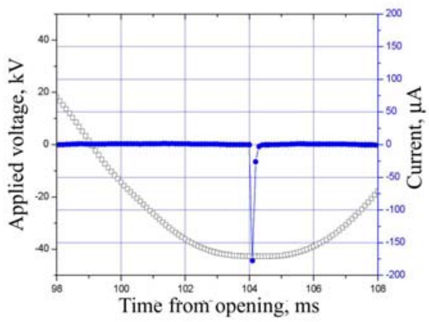

Figure 3 The example of current bump.

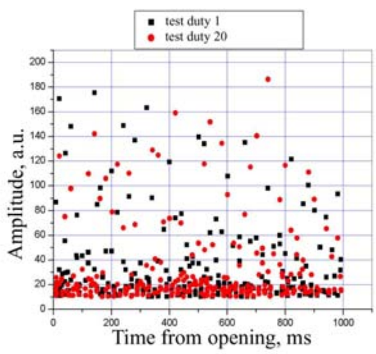

Figure 4 Amplitude-time distribution of current bump.

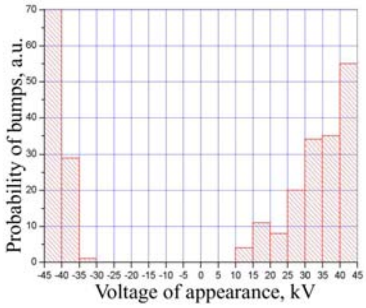

Figure 5 Probability-voltage distribution of current bumps.

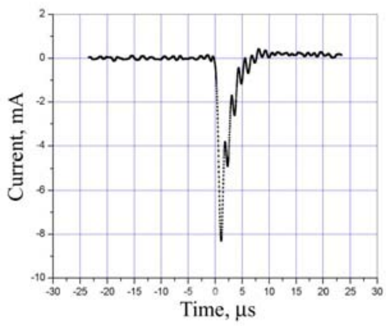

Figure 6 The example of current bump measured with 20 ns sampling.

The emission current amplification before the bump was not registered. But bumps similarly to NSDD could cause the increase of emission current degrading during 1-2 periods of power frequency.

The measuring circuit was adjusted with the purpose of investigation of exact shape and duration of current bumps. So the current bumps were measured with sampling rate of 20 ns.

The oscillogram of one of current bump is presented on the Fig. 6. As it can be seen from the figure above the current bump has the duration of about 5-10 microseconds, the real amplitude of bump can achieve milliamps. The bumps on all VIs were not differ qualitativly.

C. Current bumps in the glass tester

In order to verify the acquired results and to prove the fact of bumps concerned with process in the gap and not bounded with breakdown of VI insulation, corona or others the experiment with the tester of VI was carried out. The tester of VI consisted of two opposite electrodes (diameter 9 mm, gap 4 mm) placed into the evacuated volume (pressure is better than 10^{-3} Pa) of glass envelope. The material of tester's electrodes corresponded to commercially used contact material of VI. The phenomenon of current bumps was also observed in the tester. The shape and duration of bumps were qualitatively equal to the results of real VI.

IV. Discussion

The results obtained during the experiments allow to assume that there is a connection between NSDD and short-term current bumps.

The following can be said to support this fact: almost in all test duties with NSDD current bumps were also observed; NSDD and current bumps can cause the increase of emission current; the intensity of bumps and the probability of NSDD are the decreasing function of time elapsed from commutation; the majority of bumps in the same way as NSDD (as in Ref. [4]) were detected during the positive slope of voltage. So the answer to the question about the nature of bumps can help us to understand the phenomenon of NSDD clearly.

One of possible explanations of the origin of current bumps is explosive emission of microspikes on cathode. The explosive emission is determined by thermal heating of the top part of emitting microspike by the emission current [7]. The typical duration of explosive emission current splash is determined by the speed of cathode plasma expansion $2{\cdot}10^4$ m/s [7]. So for the 6 mm gap the duration is about 0.3 microseconds, this value is close to duration of current bump. During the certain exceeding critical current density (by the Ref. [7,13,14] $j_{cr} = 10^7 – 10^8$ A/см^2) the explosive emission is observed, here the electric field strength near the top of spike is $E_{кр} \approx (5\text{-}10){\cdot}10^7$ В/см.

In the vast majority of experiments (by literature data) the field emission current 1 -100 milliamps has been observed just before the explosion. During our tests current bumps occurred at the voltage of 20-40 kV (in a special cases even at 10-15 kV) on the 6 mm gap, i.e. average electric field strength in the gap at the moment of bump was (30–70)· kV/cm. It is possible to achieve 10-fold amplification of average field by means of macro geometry; but reaching the value of E_{cr} takes the amplification factor $\beta \approx 150$. Generally such values of β are possible for cylindrical and conical spikes; but the ratio of its height to radius should be equal to 150–300. At the same time the radius of spike should not be larger then 2-4 microns (from the relation of total voltage to E_{cr}). In all our test duties the emission current was not registered just before the bump. The only explanation of this fact is that emission current was smaller than 3 microamps (the accuracy of measuring circuit). But if the total current is determined by the expression $j_{cr} \cdot r^2$, where r – the radius of spike, then r must be smaller than 15–45 angstrem. Taking into account the required amplification factor β the height of spike must be near 0.3-1.3 microns. In the estimation above we assumed that the spike is the only one on the surface of cathode. But such assumption does not allow us to explain the multiplicity of current bumps. In general if the spikes can be formed there must be the sufficiently multiple spikes. It is supposed that there are 100 spikes on all cathode's surface, then we can achieve the estimation for radius of spike $r < 1{,}5–4{,}5$ angstrem. Such value of r matches to the size of atoms, hence, the existence of such spike is hardly possible. Thus, assuming explosive emission model of bumps does not allow us to explain such effects.

The other possible explanation is microparticels impacts onto the surface of electrodes. It has been demonstrated experimentally that there is no bound between emission properties of contact system and NSDD. Thus, the disruptive discharge and the current bump affect the contact system behavior in such way that spontaneous increase of field emission is registered. In the case of NSDD the emission amplification can be explained by some breakdown effects. But in case of bump there was no breakdown, therefore, the bump deformed the contact surface, thus, explaining the existence of degrading emission current. Moreover, the fact of degrading current allows us to suppose that there is a small quantity of appeared emitters situated in a small region of cathode surface. Another consequence of emission current existence is the fact that particles strike exactly the cathode. According to Ref. [3,9] the particle can cause the breakdown only during the impact on cathode. In that way the current bump is the consequence of the impact. The following mechanism is supposed: the particle accelerates in the gap; hits the cathode; evaporates certain amount of metallic vapor; the cloud of vapor ionizes; the plasma cloud expands in that way closing the gap; the plasma cloud charge flows down to electrodes creating the current bump. If the total charge of cloud was big enough the condition for breakdown could be met and NSDD would occur, otherwise the current bump would be registered. Let us evaluate the mass of cloud material sufficient to form the current bump presented on Fig. 6. The charge flowed during the time of bump is $20\cdot10^{-9}$ coulombs, then, in assumption of singly ionized plasma the mass of material in cloud is 10^{-14} kg. This value corresponds to mass of copper contained in a volume with radius 0.5 microns. Such copper mass evaporates; e.g. during the impact of 10 microns radius particle at the speed of 40 m/s (on condition that all the kinetic energy will transfer to heat). This speed and size of particle are quite workable. This fact is confirmed by our mathematical modeling of spheroid particles moving in the gap and by the experiments and computation of other authors presented in Ref. [3,8,9].

IV. CONCLUSION

The following facts have been revealed:

In all investigated VIs the field emission is not the cause for NSDD. On the contrary, NSDD appearance can cause the emission amplification.

During the analysis of prebreakdown currents the short-term current bumps are discovered. Such bumps appear after commutation, and their amplitude and frequency are the decreasing function of time. Current bumps can be explained by impacts of microparticles on cathode. At least, observed distribution of bumps for time and voltage does not contradict with this hypothesis. The test with glass tester proved the bound between bumps and the intercontact gap process.

NSDD and the current bumps can affect the contact system behavior in such way that spontaneous increase of field emission is registered.

These experimental results and discussion allow us to assume the particles nature of current bump. Another conclusion is that the current bump may be the same as NSDD but undeveloped to disruptive stage for any reason.

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REFERENCES

[1] A. Greenwood, "Vacuum switchgear", *The Institution of Electrical Engineers, Stevenage, 1994*

[2] M. Schlaug, L.T.Falkingham, "Non-Sustained Disruptive Discharges (NSDD) – a New Investigation Method Leading to increased Understanding of This Phenomena", *Proc.19th Int. Symp. Discharges and Electrical Insulation in vacuum, X'ian 2000,* pp. 490-493

[3] N.B. Rozanova, V.L. Granovskij, Tech. Phys. Volime 26, *№3 (1956) 489-496*

[4] C. Bernauer, W. Rieder, E.Kny, "Non sustained Disruptive Discharges in Vacuun Circuit-breakers", Proc.13th Int. Symp. Discharges and Electrical Insulation in vacuum, Paris 1988, pp. 338-340

[5] F. Platter, W. Rieder, "Long Range Dielectric Behaviour of Vacuum Interrupter" Proc.13th Int. Symp. Discharges and Electrical Insulation in vacuum, Paris 1988, pp. 335-337

[6] A. M. Chaly, L. V. Denisov, V. N. Poluyanov, I. N. Poluyanova "Peculiarities of Non-Sustained Disruptive Discharges at Interruption of Cable/Line Charging Current" Proc.13th Int. Symp. Discharges and Electrical Insulation in vacuum, Paris 1988, pp. 335-337

[7] G. A. Mesyats, Cathode Phenomena in a Vacuum Discharge: the Breakdown, the Spark and the Arc. M.: Nauka, 2000.- 400 pp

[8] L.A. Rylskaya, A.A. Pertsev, "Dielectric Strength of a Sacuum Interrupter after Current Interruption", Proc.11th Int. Symp. Discharges and Electrical Insulation in vacuum, Berlin, 1984, pp. 267-270

[9] N.B. Rozanova, Academy of Science USSR, vol. 26, №7 (1962) 1438-1440.

[10] E. Dullni, D. Gentsch, I. Kleberg, K. Niayesh, W. Shang, "Switching of Capacitive Currents", Proc.21th Int. Symp. Discharges and Electrical Insulation in vacuum, Yalta, 2004, pp. 407-410

[11] Z.Zalucki, «Dielectric strength of vacuum contact gap after making current and No-load contact opening», Proc.20th Int. Symp. Discharges and Electrical Insulation in vacuum, Tours, 2002, pp. 75-78

[12] Z. Zalucki, «Restrike and Reignition voltages of a short contact gap during capacitance switching using vacuum circuit breakers», *Proc.19th Int. Symp. Discharges and Electrical Insulation in vacuum, Tours, 2002,* pp. 56-59

[13]. W.W. Dolan, W.R. Dyke, J.K. Trolan, Phys.Rev., v.91, #5 (1953) 1054-1057.

[14]. Е.А. Литвинов, А.Ф. Шубин, Изв. вузов. Физика, #11 (1974) 90-93.

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