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Plasma parameters after forced switching-off of the current in vacuum

***Abstract**. The paper presets experimental analysis of chosen parameters of plasma after forced switching-off of the current in vacuum. The switched-off current was sine half wave with amplitudes 400 A and 600 A, with frequency 30 Hz. In amplitude of this run the current was reduced to zero using counter-current. On the ground of realized measurement the calculations were performed of the peak value of the post current as well residual charge. Additional will be estimated the speed of ion layer on the boundary of post-arc plasma, formed in front of the post-arc cathode. (**Parametry plazmy po wymuszonym wyłączeniu prądu w próżni**).*

***Streszczenie.** Artykuł zawiera analizę eksperymentalną wybranych parametrów plazmy po wymuszonym wyłączeniu prądu w próżni. Wyłączany prąd był półfalą sinusoidalną o amplitudzie 400 A i 600 A, o częstotliwości 30 Hz. W amplitudzie tego przebiegu prąd był sprowadzany do zera przy użyciu przeciwprądu. Na postawie pomiarów przeprowadzono obliczenia wartości szczytowej prądu połukowego oraz ładunku resztkowego. Dodatkowo oszacowano szybkość przemieszczania warstwy jonów na granicy plazmy połukowej, tworzącej się naprzeciw katody połukowej.*

Keywords: vacuum arc; forced switching-off with counter current; parameters of the post-arc plasma.
Słowa kluczowe: łuk próżniowy; wymuszone wyłączanie przeciwprądem; parametry plazmy połukowej.

Introduction

This article is the continuation of problems reported in [1, 2] where were described most important parameters of post-arc current, which come into existence during switching-off in forced manner of a current in vacuum. This method of commutation is recommend in vacuum switches in order to attain the reduction of current to zero, which is the fundamental condition of switching-off in vacuum. In this way it is possible to switch-off a direct current (DC) using vacuum switches, i.e. in circuits, in which the current do not have their natural zero passage [3, 4, 5]. The most of the industrial manufactured vacuum switches are appropriated for operation in alternating current (AC) circuits [6, 7, 8], where current passages zero in natural manner, twice in each period of power frequency.

Idea of switching-off DC in vacuum using the counter current was described in [1], as well in other scientific research works [2-5]. The object of this article is the characterisation of chosen parameter of the post-arc plasma after forced switching-off of the current in vacuum. The given here parameters can be helpful in elaboration of a digital modelling of this type of the commutation.

Glinkowski and Greenwood [9], examined the switchig-off in vacuum, had described scientifically the current zero (CZ) process, wich is charactestied graphically in Fig. 1. The instant CZ is the point in which the electron current I_e is equal the ion current I_i in plasma (Fig. 1). Next follows the decay of the electron cureent I_e in the time t_e to zero (point t_B, Fig. 1) and at this point the post-arc current is formed only by the ion current I_i. From this point starts the incerease of the recorvery voltage U_P.

Similar description in modelling of the observed plasma state after current zero the authors of [3] applied the description of post arc phenomena in the contact space elaborated by Andrews and Varey [10]. This model bases on the certain plasma structure inside the contact gap between the post-arc cathode and the post-arc anode (Fig. 2). After CZ, the quasi neutral plasma begins to divide on the two layers: the first layer of the ions in front of the post-arc cathode with the thickness *s* (Fig. 2) and the second one of the neutral plasma in front of the post-arc anode. On the neutral plasma the recovery voltage U=0, when the transient recovery voltage ($U=U_P$) in the entire contact gap d_s is concentrated on the positive ion sheath *s.* The transient recovery voltage $U=U_P$ grows together with growing of the ion-layer *s*. The thickness *s* grows successively with the speed *ds/dt* and finally reached the whole inter-electrode gap d_s. In this moment the post-arc process is finished, and the recovery voltage U_P reaches its final value.

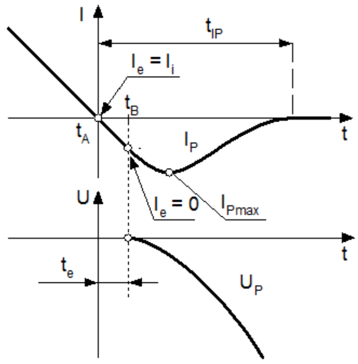

Fig. 1. Illustration of the current flow after zero the passage in vacuum [10]; I_e , I_i – electron and ion current respective; I_P – total post-arc current, t_{IP} – the time of post current flow, U_P – transient recovery voltage

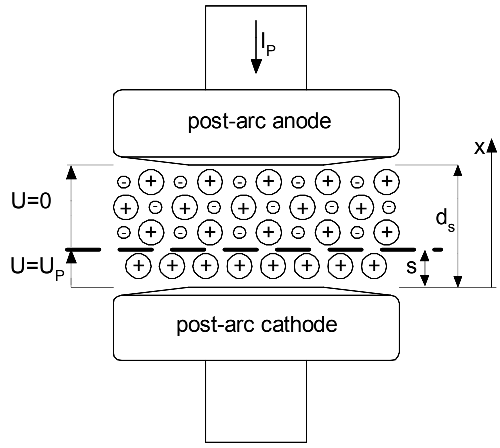

Fig. 2. Sketch diagram of the space charge distribution (ions and electrons) and growth of charge after current zero in vacuum; *s* – thickness of ion layer at post-arc cathode, d_s – the whole contact gap, *U*=0 – recovery voltage on the neutral plasma, $U=U_P$ – transient recovery voltage on the ion layer, *x*-marking of axis, I_P – total post-arc current, (explanation remaining symbols in the text)

Description of post arc phenomena, based on the Andrews and Varey model, had been used by many authors. This model was adapted also for the modelling CZ-process and post-arc phenomena of the switching-off of the current in vacuum, not only in the DC circuits, but also in the AC circuits [11].

Experimental setup

The reported measurements were performed in the laboratory arrangement (Fig. 3), which consists of two circuits connected parallel to the vacuum chamber VC. In the first circuit: C-L-S-VC-S2 flowed the main switched-off current i, while in the second one: C_K-L_K-S2-VC-S_K the counter-pulse current i_K was switched-on. The source of the tested arc current i was the capacitor C and that of the counter-pulse current i_K – the capacitor C_K. Both currents have the form of a sine half-wave with frequencies determined by the oscillatory circuits. The frequency of the main current i, determined by the capacitance C and inductance L was about 30 Hz, and near its amplitude a DC current flow was modelled. The frequency of the counter-pulse current i_K was determined by the capacitance C_K and the inductance L_K and it was set according to the given values of the rate of rise di_K/dt, in the range from 2 A/μs to 90 A/μs.

The vacuum chamber VC was the de-mountable laboratory chamber made from the stainless steel, equipped with the copper (OFHC) contacts, 30 mm of diameter, opened with the speed of 0,4 m/s up to the final contact distance 3 mm. The pressure maintained inside the vacuum chamber VC was in the range (4-5)x10^{-4} Pa. Both currents, i.e. i and i_K, were switched-on with the switches S and S_K respectively. The arc current was measured in the inductance-less shunt S2. The tested arc current i had amplitudes 400 A and 600 A, thus the produced vacuum arc during switching-off process was the diffuse one.

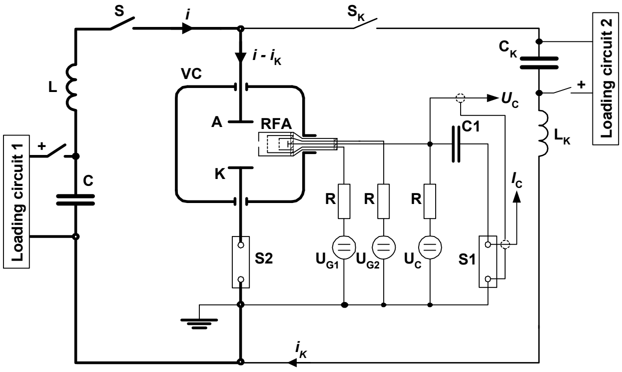

Fig. 3. Connection diagram of laboratory arrangement in which experiments were performed; VC – the laboratory demountable vacuum chamber, A – the anode, K – the cathode, RFA – the retarding field analyser, U_{G1}, U_{G2} – potentials of the first and the second grids of the RFA, U_C – the potential of collector of the RFA, S1, S2 – the induction -less shunts, I_C – the collector current, R – resistors, i – the switched-off current, i_K – the counter-current (explanation remaining symbols in the text)

The plasma parameters were measured using the electrical probe called retarding field analyser (RFA), described in detail in [1]. In reported experiments the RFA operated in so called “ion measuring mode”, i.e. potentials of the grids U_{G1} and U_{G2} were negative, whereas the potential of the collector U_C were positive, with reference to earthed cathode. These potentials were set as follow: U_{G1}= -10V, U_{G2}= -20V and U_C regulated from zero to +70V. In this way, the both grids separate electrons and the collector reach separated ions, which the collector brakes depended on its potential [1]. In this way at adjustment the collector potential U_C=0, the RFA measured the total ion current I_i coming to the probe, whereas at adjustment U_C>0 in the mentioned rage, the ions were braked. This enabled estimation some parameters of ions [1].

Measuring results

The probe RFA enabled to measure ion parameters, peculiarly during the post-arc phase [1, 2]. In this paper the results concerning the post-arc current, estimated speed ds/dt of the ion-layer growing and the residual charge are reported. The measured the post-arc current i after the zero passage (Fig. 4) had the typical form, in which one can distinguish the following specific elements:

a) the current zero point i = 0 in time t_0 (compare with t_A from Fig. 1), in which the electron and ion currents are equal $I_e \approx I_i$,

b) the peak post-arc current I_{Pmax},

c) the very short time of the growing phase from t_0 to t_{Pmax}, in which the layer of the ion with the thickness s is formed in front of the post-arc cathode; this time covert the time from t_A to t_B from Fig. 1 (t_e) when the electron current I_e goes to zero,

d) the slope of decreasing the post arc current to zero, from I_{Pmax} to when post current reach value zero; this run is in the oscillogram approximated with dashed line $i_{Papprox}$; in this time, according the model Andrews and Varey [10], the thickness s reaches the whole contact distance d and the transient recovery voltage U_P grows to final value.

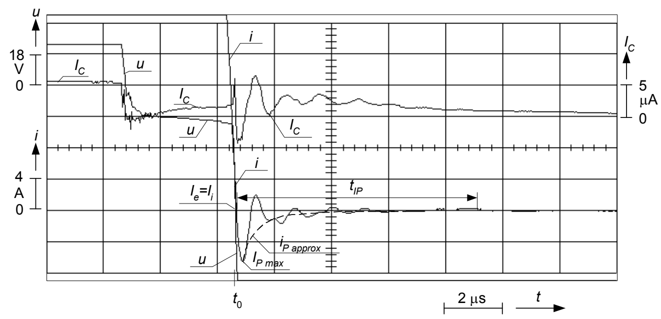

Fig. 4. The exemplary oscillogram of the arc current i, voltage on the contacts u and the collector current of the RFA I_C shortly before and after current zero (time instant t_0), t_{IP} – the time of flowing the post-arc current; explanation of other symbols in the text

The electron current decayed to zero during the growing phase from t_0 to I_{Pmax} (Fig. 4), and after the peak post arc current I_{Pmax} remained the ion current only [10]. This was confirmed by presence of the ion current I_C measured by the RFA. Thus, the whole post arc charge was formed by the ion current decaying from the I_{Pmax} to zero, on the slope, indicated in Fig. 4 with the dashed line $i_{Papprox}$. This run $i_{Papprox}$ can be approximated with an exponential function [3]. Finally the residual charge Q_P was calculated using the following equation:

$$(1)\quad Q_P = \int_{t_0}^{t_{IP}} I_{P\,max} e^{-\frac{t}{\tau_{IP}}} dt = \tau_{IP} I_{P\,max} \left(1 - e^{-\frac{t_{IP}}{\tau_{IP}}} \right),$$

where: τ_{IP} – the time constant estimated from the measurement.

One can see (Fig. 5), that the residual charge grew slightly for lower values of di_K/dt, but next diminished for bigger values of di_K/dt, in spite of increase of the peak post-arc current I_{Pmax} (Fig. 6). The reason of this diminishing was likely the significant decay of the flow-time t_{IP} of the post-arc current I_P (Fig. 4 and Fig. 7), with growing of the rate of rise di_K/dt. Thus, the rate of rise of the counter-current di_K/dt play considerable part in the determination post-arc current in vacuum, particular in the time of flow of the post-arc current I_P and of the residual charge Q_P. Furthermore, the residual charge Q_P is clearly dependent from the value switched-off current. Peak value of the residual charge for the amplitude 600 A of the switched-off current is near 30 μC, when for the amplitude 400 A is near 15 μC (Fig. 5). The residual charge is greater for the larger switched-off current.

The residual charge Q_P grows for the rate of rise of the counter-current di_K/dt in the rage from 2 A/μs to 25 A/μs, and then diminishes in the range from 25 A/μs to 90 A/μs. The maximum of Q_P appears for the rate of rise of the counter-current di_K/dt approximately 25 A/μs, and were:

- about 30 μC for the switched-off current with amplitude 600 A,
- about 15 μC for the switched-off current with amplitude 400 A.

The values of residual charge were in range (10÷30) μC and those of the peak post arc current in the range(1÷7) A, in examined research.

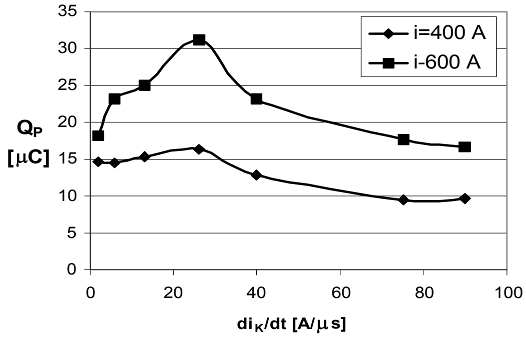

Fig. 5. The diagrams of calculated residual charge Q_P versus rate of rise of the counter-current di_K/dt

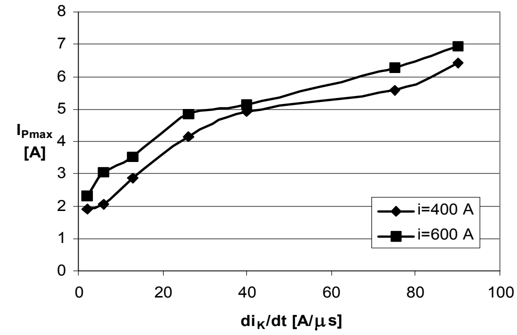

Fig. 6. The diagrams of the measured peak post-arc current I_{Pmax} versus rate of rise of the counter-current di_K/dt

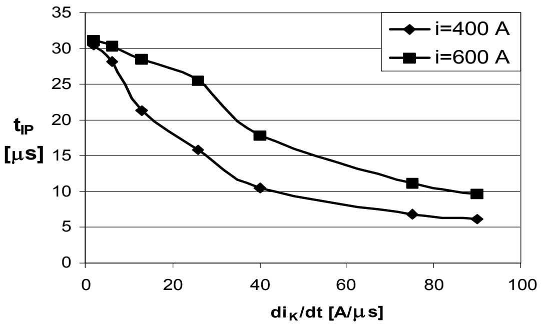

Fig. 7. The diagrams of the measured time t_{IP} of the flowing post-arc current I_P (Fig. 1and Fig. 4) versus rate of rise of the counter-current di_K/dt

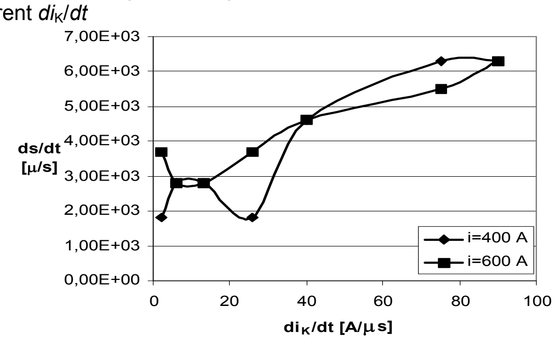

Fig. 8. The diagrams of estimated speed of the ion layer displacement ds/dt, versus rate of rise of the counter-current di_K/dt

The other observed parameter was the speed of ion layer growing ds/dt inside the contact gap [9-11], calculated with the following formula:

$$\frac{ds}{dt} = \frac{J_P}{n_{i(x=s)}Ze} - v_{i(x=s)}, \quad (2)$$

where: J_P – mean post-arc current density, $n_{i(x=s)}$, $v_{i(x=s)}$ – mean ion density and mean velocity of ions on the layer boundary (x = s).

The estimated values of the speed of ion layer growing ds/dt are in the range $(1÷7)x10^3$ m/s for the tested conditions. This values are presented in Fig. 8, and they grew for higher rate of rise of the counter current di_K/dt. In the Andrews and Varey model [10] this parameter is representative for the dielectric strength growth in the contact gap after extinguishing of the arc in vacuum.

Conclusions

In the article are presented the measuring and calculated results of some parameters of the post-arc plasma in vacuum, after forced switching-off of the current. The calculated results were obtained on the grounds of experimentally performed measurements. The main reported parameters were followings:

- the residual charge,
- the peak post-arc current,
- speed of growing of the ion layer in front of the post-arc cathode.

The reported experiments show, that this parameters are depended on:

- on the rate of rise of the counter-pulse current di_K/dt,
- on the value switched-off current

The measured values of these parameters can be useful in modeling of the phenomena during the counter-current switching-off of current in vacuum, i.e. modeling of the diffuse vacuum arc extinguished in forced manner in vacuum. In the literature were mainly publish parameters of post-arc current by switching-off of AC current in vacuum [9, 11], but not by forced switching-off current in vacuum. The article present this one exactly.

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