FEATURES OF ACTIVE POWER DEFINITION IN HIGH-CURRENT PULSED DISCHARGE

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The calculation method of active power dynamics in high-current plasma diode has been presented in this paper. The main features that should be considered in the calculations have been identified. It is shown that it is possible to obtain the high power levels (over 100 MW) at a slight stored energy of capacitor bank (up to 200 J) under the conditions of the space charge double layer formation in the plasma.

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INTRODUCTION

High-current pulsed discharges are widely used in various fields of science and technology. This is directly connected with a relatively simple obtaining method of the pulse power $10^6…10^{12}$ W. Thus, the relevant issue is the correct calculation of the active power dynamics released in the discharge. Using high-speed digital oscilloscope allows carrying out such work with high efficiency and degree of precision. However in this case it is required a specific accuracy since neglect, although small, but important components, leads to fundamental errors, such as "negative energy in the spark discharges".

The method of power calculation in the microsecond range discharges when the discharge current is measured by the integrating current transformer is given in this paper. Accents on the fundamental points that should be considered in these measurements were made. As an example, the calculation method of the active power dynamics in a plasma diode with a limited working surface of high-voltage electrode has been given.

1. PHYSICAL MODEL

Calculation of the active power dynamics released in the discharge is based on the discharge circuit equation of the high-current pulsed discharge:

$$V_0 - \frac{1}{C}\int_0^t i(\tau)d\tau = L_c \cdot \frac{di(t)}{dt} + \frac{d\left[i(t)\cdot L_d(t)\right]}{dt} + R_d(t)\cdot i(t) + R_c \cdot i(t). \quad (1)$$

An equivalent electrical scheme of this circuit is shown in Fig. 1.

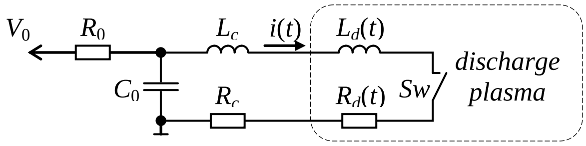

Fig. 1. The equivalent scheme of the discharge circuit

The capacitor bank C_0 is charged to a voltage V_0. After the closure of switch *Sw* (breakdown of discharge gap) the capacitor bank is discharged via inductance of the supply circuit L_c, inductance of the discharge gap L_d, active resistance of supply circuit R_c and active resistance of the discharge gap R_d. In this case the inductance of discharge gap and its active resistance changed during the discharge: $L_d = L_d(t)$ и $R_d = R_d(t)$.

The dynamics of active power released in the discharge $P_d(t) = i^2(t)\cdot R_d(t)$ according to equation (1) is given by expression (2):

$$P_d(t) = i(t)\cdot\left[V_0 - \frac{1}{C_0}\int_0^t i(\tau)d\tau\right] - \frac{L_c + L_d(t)}{2}\cdot\frac{di^2(t)}{dt} - i^2(t)\cdot\frac{dL_d(t)}{dt} - i^2(t)\cdot R_c. \quad (2)$$

$P_d(t)$ includes the ohmic and beam heating of the plasma. To obtain high values of power it is necessary to reduce the discharge gap inductance and to create conditions for the space charge double layer formation in the current-carrying plasma. This electric double layer of space charge is responsible for the powerful electron beam generation [1]. To provide the formation conditions of the double layer the working surface of the high-voltage electrode specifically has been limited in this work.

The following calculation of the active power dynamics released in the discharge was carried out on the basis of the discharge current waveform from the digital oscilloscope *Tektronix TDS 2014*. In addition, the parameters of the discharge supply circuit, the measurement circuit of the current sensor and the model of the discharge gap inductance changes have been used in the calculation. The capacity of the capacitor bank was $C_0 = 1.94$ μF and the charging voltage $V_0 = 4…14$ kV.

2. RESULTS AND DISCUSSION

In spite of seeming simplicity, the calculation of the active power dynamics released in the discharge contains a number of fundamental points.

The first point deals with the fact that the waveforms of digital oscilloscopes always have a certain level of noise. (The numeralization principle, assuming the appearance of steps on the signal, immediately imposes a certain level of noise.) When taking the derivative of the current signal by numerical methods even micro noise enough to obtain in equation (2) the noise derivative but not the derivative of the discharge current. This value may be ten times greater than the desired value. Therefore it is very important to choose an approximation method of the current signal for cleaning it from unnecessary noise.

It should be noted that the approximation by the generally accepted method Savitsky-Golay is not always possible to obtain the necessary results. Sometimes more acceptable is the multiple (100 times or more) sequential signal cleaning by sliding window method using a simple averaging over several points. Here it is necessary to select the optimal number of averaging points. A large number of points, although improves the signal cleaning, but can lead to the signal "fine structure" loss, which, as a rule, is responsible for input of high active power into the discharge.

The multiple cleaning by three points with different weight coefficients shows the acceptable results:

$$i_{k*} = 0.25 \cdot i_{k-1} + 0.5 \cdot i_k + 0.25 \cdot i_{k+1}, \quad (3)$$

where i_{k*} – the new value of the current signal k[th] point; i_{k-1}, i_k, i_{k+1} – the previous cycle values of the corresponding points.

Since the obtained data from a digital oscilloscope look like a spreadsheet, using an appropriate software, it is possible easily organize the multiple sequential signal smoothing and thereby completely automate the process. While processing a large number of signals it is enough to insert a new waveform into the existing form.

The following feature related to the fact that any current sensor always distorts the real signal, and it is necessary to restore the experimentally obtained dependence of the discharge current.

In this work the current was measured using the integrating current transformer, the equivalent circuit of which is shown in Fig. 2.

There are two main factors that distort the shape of the current for integrating current transformer:

- the active resistance consisting of the coil wire resistance R_w and the measurement resistance R;
- the parasitic capacity C_p including the capacity of the sensor itself, the capacity of the transmission cable and the input capacity of the oscilloscope.

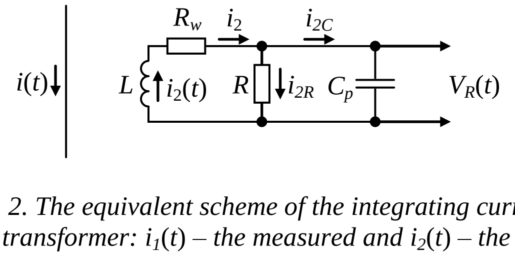

Fig. 2. The equivalent scheme of the integrating current transformer: $i_1(t)$ – the measured and $i_2(t)$ – the inducible currents; $V_R(t)$ – the observed signal; R_w – the coil wire and R – the measuring resistance; L – the coil inductance; C_p – the parasitic capacity

The main applicability condition of the integrating current transformer – multiple excess of the inductive coil resistance over the total active circuit resistance:

$$\omega L >> R_w + R . \quad (4)$$

The additional condition – multiple excess of the capacity resistance of the measuring path parasitic capacity C_p over the measuring resistance R:

$$\frac{1}{\omega C_p} >> R . \quad (5)$$

The last condition limits the maximum value of the measuring resistance that does not allow raising the signal level above the certain. In our case, the value of the measuring resistance was R = 1Ω.

Based on the equations system describing the currents flowing in the scheme (Fig. 2.) it is possible to obtain the relationship of the discharge current $i(t)$ and the observed signal $V_R(t)$:

$$i(t) = \frac{1}{\mu} \cdot \left[V_R(t) \cdot \left(1 + \frac{R_w RC}{L} \right) + \right.$$
$$\left. + RC \cdot \left(\frac{dV_R(t)}{dt} - \left. \frac{dV_R(t)}{dt} \right|_{t=0} \right) + \frac{R_w + R}{L} \cdot \int_0^t V_R(\tau) d\tau \right], \quad (6)$$

where μ – the current transformer sensitivity.

The correctness of the current restoration can be confirmed with the graph of the capacitor bank discharge $U_C(t)$, which should be like the damped cosine oscillations:

$$U_C(t) = V_0 - \frac{1}{C_0} \cdot \int_0^t i(\tau) d\tau . \quad (7)$$

Fig. 3 shows the waveform of the discharge current (*a*) at the charging voltage V_0 = 12 kV and the dynamics of the capacitor bank discharge (*b*). The index *1* corresponds to the observed discharge current and index *2* corresponds to the restored discharge current. It is seen that a slight difference between the observed and the restored current form eventually leads to significant errors. In case of the restored current signal (curve *2*) takes place a physically plausible dynamics of the capacitor bank discharge in the damped cosine oscillations form, while for unrestored (observed) current (curve *1*) there is an abrupt up withdrawal. Physically, this means the charging of the capacitor bank from some additional source that is contrary to the law of energy conservation and experimental observations. This pseudo-charging often interpreted as "energy pumping from the vacuum in the spark discharge".

As a rule, in pulsed discharges is very difficult initially to determine the inductance and active resistance of the system. These values are calculated from the discharge characteristics. Therefore, in the third step it is very important to choose the adequate determination methods of these values, and determine the monitoring methods over the operations correctness.

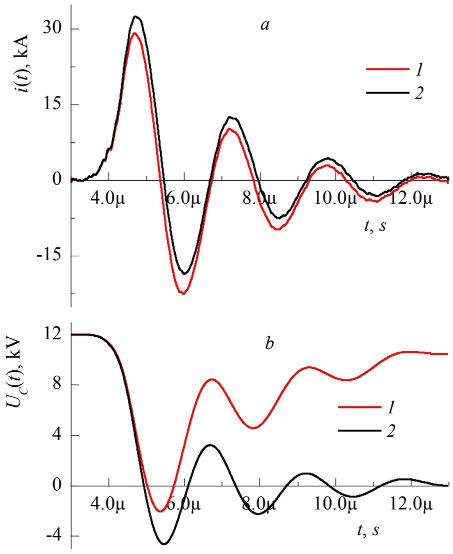

Fig. 3. The dynamics of the discharge current (a) and the dynamics of the capacitor bank discharge (b) for the observed (1) and restored (2) signal

The fourth feature is associated with a changing of the discharge gap inductance. Since the obtaining of high discharge current is directly related to decrease the total inductance of the discharge circuit L_c, the inductive term $i^2(t)\cdot L_d(t)/dt$ in equation (2) associated with a changing of the discharge gap inductance may have a significant impact on the obtained results. Therefore, one should choose the most accurate mathematical model corresponding to the changing of the discharge gap inductance $L_d(t)$.

In our case, the total inductance of the discharge circuit was significantly higher (in 4 times) than the average inductance of the discharge gap: $L_c >> L_d(t)$. This allowed us to use a simple model which assumed that the inductance of the discharge gap synchronously changes with the value of the discharge current. In this case the plasma column changes its radius $r_d(t)$ from a maximum to a minimum value in proportion to the discharge current.

At the coaxial scheme of the discharge cell when the discharge electrodes are arranged in front of each other on the axis of the discharge, and the reverse current bus are on the external cylindrical surface the value of the discharge gap inductance can be represented as:

$$L_d(t) = 2l_d \cdot \ln \frac{r_{bc}}{r_d(t)}, \qquad (8)$$

where l_d – the length of the discharge gap, r_{bc} – the cylindrical surface radius of the reverse current bus.

The changing of the plasma column radius $r_d(t)$ is proportional to the discharge current and can be described by the expression:

$$r_d(t) = r_{dm} \cdot \left(1 - \frac{\Delta r_d}{r_{dm}} \cdot \frac{i(t)}{i_{\max 1}}\right), \qquad (9)$$

where $\Delta r_d = 0.5 \cdot (r_{d\max} - r_{d\min})$ – the amplitude changing of the plasma column radius; $r_{dm} = 0.5 \cdot (r_{d\max} + r_{d\min})$ – the average value of the plasma column radius; $r_{d\,\max}$ and $r_{d\,\min}$ – maximum and minimum plasma column radii accordingly (estimated from the photographic images of the discharge gap in the visible range); $i_{1\,\max}$ – the maximum amplitude of the discharge current in the 1st half period.

It is appropriate to note that full scheme of calculations using proposed method has been completely automated. The computer realization of the scheme on the basis of program *Microsoft Excel* has been performed. Although this form looks bulky, but it saves open all steps of the program that is very useful for tracking the correctness of all procedures implementation.

In general, this system has the following basic components:

- cleaning of the current signal $V_R(t)$ from the noise using the expression (3);
- calculation of the current signal derivative $V_R(t)/dt$ for each cleaning pass with visualization of each tenth cycle. (This allows to control the efficiency of the signal cleaning process from the noise);
- definition of the average inductance of the discharge circuit, its active resistance and the current transformer sensitivity μ on ratio of signal maximums at half periods. (The automatic finding of the maximum values and the corresponding time moments has been applied);
- restoring of the current signal by means of the expression (6), and test check of the capacitor bank discharge dynamics using expression (7);
- calculation of the active power $P_d(t)$ from equation (2) using the expressions (8) and (9).

During carrying out the calculations it is enough to enter the initial conditions: the capacity of the capacitor bank, its charging voltage, the geometric parameters of the discharge gap, the electrical parameters of the measurement circuit and download the investigated waveform. All following calculations performed automatically.

Fig. 4,a shows the waveform of the discharge current at the charging voltage $V_0 = 12$ kV. Fig. 4,b shows the dynamics of total active power $P_1(t)$, released in the whole discharge circuit and active power $P_2(t)$, released on the average active resistance of the discharge circuit R_c. The difference between $P_1(t)$ and $P_2(t)$ is given in the Fig. 4,c and corresponds to the active power additional inputted into the discharge $P_d(t)$. It is seen that the level of $P_d(t)$ reaches a value $P_d \sim 100$ MW at the stored energy in the capacitor bank $W_0 \sim 140$ J.

As shown the additional investigations, the active power is released near the high-voltage electrode surface in the plasma diode with a limited working surface of this electrode. Here, due to the double layer formation, the acceleration of the powerful electron beam occurs towards the electrode. This electron beam heats the plasma and evaporates the electrode material [2]. In this case, the beam power density reaches ~ 1.5 GW/cm^2.

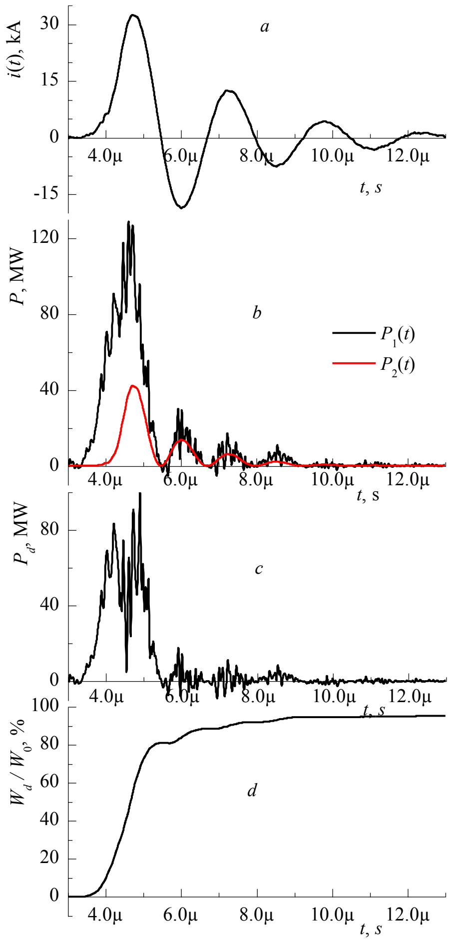

Fig. 4. Dynamics of the discharge current (a), the total active power in the circuit (b), the additional active power released in the discharge (c) and the absorbed energy (d)

Fig. 4,d shows the dynamics of absorbed capacitor bank energy. It is seen that the main part of the energy (~ 80 %) is absorbed in the 1st half period of the discharge current oscillations.

CONCLUSIONS

The method of active power definition which has been presented in this paper allows determining the dynamics of active power released in the high-current pulsed discharge with high degree of precision. The main features that should be considered in the calculations have been determined. One of the important moments is the correct restoring of the discharge current shape, since any current sensor produces a signal with a certain degree of precision. It has been noted that this circumstance leads to significant error. It is shown that in high current plasma diode with limited working surface of high voltage electrode the high levels of power (over 100 MW) are reached at a relatively low stored energy of capacitor bank (up to 200 J).

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ОСОБЕННОСТИ ОПРЕДЕЛЕНИЯ АКТИВНОЙ МОЩНОСТИ В СИЛЬНОТОЧНОМ ИМПУЛЬСНОМ РАЗРЯДЕ

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Представлена методика расчёта динамики активной мощности в сильноточном импульсном плазменном диоде. Выделены основные особенности, которые необходимо учитывать при проведении расчётов. Показано, что в условиях образования в плазме двойного электрического слоя объёмного заряда возможно получение высоких уровней мощности (свыше 100 МВт) при незначительном (до 200 Дж) энергозапасе конденсаторной батареи.

ОСОБЛИВОСТІ ВИЗНАЧЕННЯ АКТИВНОЇ ПОТУЖНОСТІ В СИЛЬНОСТРУМОВОМУ ІМПУЛЬСНОМУ РОЗРЯДІ

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Представлена методика розрахунку динаміки активної потужності у сильнострумовому імпульсному плазмовому діоді. Виділені основні особливості, які необхідно враховувати при проведенні розрахунків. Показано, що в умовах утворення в плазмі подвійного електричного шару об’ємного заряду можливо отримувати високі рівні потужності (більше 100 МВт) при незначному (до 200 Дж) енергозапасі конденсаторної батареї.