Verification of experimental studies of pulsed plasma accelerators

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Abstract. Explosive-magnetic generators (EMGs) unlike capacitive storages (CSs), as a rule, have growing power. The effective operation of pulsed plasma loads, such as pulsed plasma accelerators (PPAs), plasma foci, plasma breakers, etc, can be provided at realization of the mentioned advantage of EMG as a power source. A technique of laboratory experiments with PPA is presented in this paper. The experiments with PPA powered by CS precede the explosive experiment with EMG. The dependencies of the load operation modes on the start parameters are determined by the analysis of the experimental data. They included the dynamics of the inductance and the position of the current shell inside the PPA. The technique allows reducing the number of expensive explosive experiments and supplements the database of nonlinear dependencies of the load parameters under various amplitudes of the current pulse that is important for mathematical modeling. The technique based on experiments together with the estimations allowed solving the problem of matching of non-linear loads type PPA with EMG. Thus, the productivity of experiments with EMG increases greatly. The developed technique can be adapted to a wide class of nonlinear loads.

1. Introduction

The principles of operation of inductive pulse sources [1,2], as well as an example of their effective matching with loads [3], are the basis of the presented investigations. As for explosive-magnetic generators (EMGs), operating into the load, there is a narrow range of load impedance values, in which it is possible to effectively output energy to the load. Because when EMG works on a plasma load, the load impedance is increased nonlinearly, mainly due to the inductive component. Therefore, the precise calculation, well developed for linear circuits, in this case is not applicable and additional experimental studies are required. With respect to pulsed plasma accelerators (PPAs), this investigation is a continuation of the studies performed by the JIHT RAS together with the State Research Center of the Troitsk Institute for Innovation and Fusion Research (SRC RF TRINITI) [4]. The conclusion of this work noted that studies related to the use of EMG as a pulse source are relevant and promising in the following cases:

- matching of the EMG with plasma loads in the MJ level energy can be more cost-effective at the limited number of starts than the creation of a corresponding high-voltage battery (the cost of a battery for a voltage of 50 kV with an energy capacity of 1 MJ is estimated at 100 million rubles);
for tasks where the critical parameters of the system are the weight and size characteristics of the power supply (there are no alternatives to EMG).

The purpose of these studies is to develop a technique of matching mode of EMG operation together with a nonlinear plasma load. The matching mainly means that the magnetic flux is efficiently outputting from the EMG to the load despite the load inductance dynamics. Too rapid injection of the magnetic flux in the load may cause to the significant overvoltage at the input to the load and lead to uncontrolled electrical breakdowns and even to the load damage. On the other hand, too slow increase in the current in the pulse load will lead to the fact that it will finish its work before the maximum current and, accordingly, before the maximum energy transferred into the load. Large number of experiments allowed us to understand the physical processes and refine mathematical models for each specific type of load. But due to the complexity and high cost of explosive experiments, especially in laboratory conditions, it was not possible to collect required number of data about the behavior of a specific load when it powered by the EMG.

2. Basic principles of the techniques for testing

PPA is the main type of load studied at the plasma-dynamic experimental set-up. The PPA is characterized by a pulsed input of working gas (hydrogen) and the forming of a quasi-stationary distribution of the magnetic field within the electrode system. It was decided to work out the method according to which the PPA test experiments with CS will precede its starts with EMG at comparable energy (CS up to 370 kJ and EMG from 500 kJ). Preliminary studies of the load when it powered by capacitive storage allow: to check the matching operation of all elements of the setup; to investigate the dynamics of the inductance of the plasma load; to configure an automatic data collection system. These stages also help to save money and time for the preparation of explosive experiments with EMG. Capacitive storage is not destroyed during the experiment and makes it possible to provide the level of supplied energy into the plasma load, sufficient to study the features of its operation modes and their dependence on the start parameters.

Different modes of operation of plasma loads were achieved by varying following parameters: pulse mode of the working gas injecting; working gas pressure; distribution of quasi-stationary magnetic fields and voltage of capacitive storage. The method is based on a consistent increase in the charging voltage of the capacitive storage with varying of gas density distribution and distribution of the quasi-stationary magnetic field in the electrode system of the accelerator. Then the analysis of the registered pulse currents and voltages at different points of the circuit is carried out, and the dynamics of the inductance (corresponding to the position of the current shell inside the plasma load) is determined.

The main results of the analysis are the data on the place of formation of the plasma shell and the dynamics of its movement within the electrode system. These characteristics of the load significantly depend on the mass of the working gas (“load” of the accelerator) involved in the motion and of distribution of the magnetic field within the electrode system. The most “overloaded” mode of load operation with CS is selected for the start with EMG, as potentially EMG can provide a much higher level of energy supplied to the load than the used capacitive storage.

3. Description of the experimental setup and data processing

The location of the experimental equipment of the setup is shown in the photo in figure 1. In the main room there is a load, charging and switching devices, a vacuum system and a gas injecting system. The plasma load is connected to the laboratory sample of the EMG, which is placed in an explosion-proof chamber. The initial magnetic flux in the EMG is formed from its own high
voltage power source and capacitive storage devices. There are CS1 \((U = 24 \text{ kV}, C = 1 \text{ mF})\), CS2 \((U = 36 \text{ kV}, C = 576 \text{ µF})\) and CS3 \((U = 24 \text{ kV}, C = 1 \text{ mF})\). A separate room is also allocated for power supplied systems for the system of formation of quasi-stationary magnetic fields for PPA. Remote control and data collection systems are placed in other room.

A controlled high-voltage switcher with a short action time is a key element at the use a power source based on a capacitive storage. The solid-state controlled dischargers were applied as such a switcher. The main task of the solid-state discharger (SSD) is to provide the fastest (less than 1 \(\mu\text{s}\)) commutation of currents with an amplitude of up to 3.5 MA and above with the minimum value of parasitic inductance. The insulator (polyethylene), placed between two electrodes and connected to the conductors of the supply and discharge, provides the operation of the SSD by means of electrical explosion of copper wires from a special unit on the basis of the ignition discharger IRT-6. The optical timed pulse from the common system synchronization comes into the start block of ignitron discharger. Ignitron discharger, in its turn, commutes capacitive storage of SSD ignition with decoupling transformer connected to exploding wires. The explosion of wires destroys the polyethylene insulator, and forms a plasma contact between the electrodes simultaneously at 6 points. Number of points is dictated also by the need to minimize the inductance of the spark gap and the current density at each point of contact.

By dischargers sections and parallelizing the lead cable and output cable lines, an overall effective inductance from the battery up to the load was reduced up to 50 nH. Due to the fact that the load is the plasma, cable partitioning allows to symmetrizing the process of current shell formation (be more homogeneously). For SSD design with the ignition unit, the action time within 5.5 \(\mu\text{s}\) was achieved. Based on a series of experiments, it can be concluded that the instability (jitter) of the action time does not exceed 500 ns. A special computer program was

\[ \text{Figure 1. General view of the test room of the plasma-dynamic experimental setup.} \]
developed for a large number of experiments and data processing. The program allows saving all the parameters of a particular start, the original data from the recording equipment and the results of their processing. After a series of experiments, the software allows to compare data for different starts to determine the dependence of the plant operation modes on the experiment parameters.

Automation of the process of processing experiments and the ability to compare experimental data for different starts can significantly speed up the development of modes of operation of the installation with a specific plasma load and conduct statistics of experiments. The saved parameters of the experiment include the time delay of operation of all components of the installation, the voltage on the capacitive storages, the table of compliance of the recorded signals, the geometry of the electrode system of the accelerator and the distribution of quasi-stationary magnetic fields. The main results of the experimental data processing are the restored oscillograms of current and voltage on the load and, calculated from them, the dependence of the load inductance on time.

In the frame of the experiments series, the data on the load inductance behavior are key in the investigation of the plasma load. Data allow to estimate current shell position and dynamics of its motion, under the assumption of its coaxial symmetry. This movement should be matching to the current distribution formed by the EMG at operating on the study load. The following calculation formula was used to calculate the time dependence of inductance in the processing of experimental data:

\[ L(t) \simeq \frac{\int U(t) dt}{I(t)}, \quad (1) \]

where \( U(t) \) and \( I(t) \) are experimentally measured pulse dependences of the voltage and the current, respectively.

It is valid under the assumption of a small active part of the load impedance. According to the estimates, the inductive part of the impedance exceeds the active part by at least an order of magnitude. Knowing of the geometry of the electrodes and the dependence of the load inductance on the positions of the current shell allows determining dynamics of the later. The initial distribution of working gas density fundamentally influences to the dynamics of both the formation and movement of the current. It depends on the mode of pulsed gas injection and the distribution of quasi-stationary magnetic fields regulated by charging voltages and by synchronization of the corresponding capacitive storage.

The created laboratory infrastructure allows providing for a series of experimental studies and testing of various types of loads to find the dependence of their modes of operation on the start parameters. The load bus system for connecting is changed on EMG current collector after selecting of optimal start parameters. It corresponds to start with EMG. Thus, the mode of operation using EMG was chosen experimentally thanks to the capacitive storage mode. The modes should be comparable in energy transmitted to the load. The plasma load is connected to the laboratory sample of the EMG, which is placed in an explosion-proof chamber. The initial magnetic flux in the EMG is formed from its own high-voltage power source (a capacitive storage). The compression of the magnetic flux is carried out by a copper liner under the action of explosives detonation products. Internal devices for forming a current pulse with adjustable delays form a current pulse in the load with a front of the order of 12–14 \( \mu s \) and with current amplitude of more than 2 MA.

The device for forming a current pulse includes two switches. The both are matched with the output of the residual inductance from the EMG circuit. The dynamics of magnetic flux output to the load mainly depends on the parameters of these devices. The law of derivation of EMG inductance depends significantly on the geometry of the spiral and the liner, as well as on the used explosives filled the liner. Investigation of the device was described in article [5]. Data
Figure 2. Electrical circuit of PPA powering from the capacitor. The red line is the motion of the plasma front in the PPA of coaxial type: $C$ is the capacity of the inductive source; $R$ is the ohmic resistance of the circuit; $L_{\text{pass}}$ is the passive inductance in the circuit; $S_1$ is the closing key to the capacitive storage.

Figure 3. Oscillograms of the selected mode of operation of the PPA when operating from a capacitive storage of 24 kV.

processing system of the experiment with EMG is similar to the system used when working from a capacitive storage. This fact allows comparing the relevant experiments and determining the scalability of the selected mode of operation of the load on the large discharge currents provided by the EMG.

4. The results of the modes processing
The above-described method of working out the modes of load operation was applied to the pulsed plasma accelerator. The series of experiments consisted of more than 50 starts with 24 and 36 kV class storage devices. The electrical circuit with operating from a capacitive storage source, is shown in figures 2. As a result of the modes processing, the mode with the maximum working gas filling the accelerator, excluding the breakdown of the accelerator on the insulator, was chosen. The oscillograms of this mode with operating from a 24 and 36 kV capacity stores are shown in figures 3 and 4 respectively.

As was noted in the previous section that due to the nonlinearity of plasma loads, it is difficult to build a mathematical model of the dynamics of the conducting current shell of a plasma. Therefore, we started with estimates of the position of the current shell from experimentally measured pulse values of currents and voltages on the load. With a fixed geometry of the
Figure 4. Oscillograms of the selected mode of operation of the PPA when operating from a 36 kV capacitive storage.

Figure 5. Oscillograms of the selected mode of operation of the PPA when powered by EMG.

electrodes and the presence of coaxial symmetry, the inductance is a function of the geometry $L(X) \propto X$. Each value of $X(t)$ correspondent to $L(t)$ calculated from the estimated formula (1) and the scheme in figure 2. It was found that a deviation of the current from the sinusoidal shape is insignificant, see figures 3 and 4. This indicates a weak nonlinearity of the load impedance in this mode. This statement is borne out by the relatively slow change in position of the current shell. It is indicated in the pictures by the curves with points.

The oscillograms of voltage and current at power supply of the investigated load from EMG are presented in figure 5. The total energy supplied to the load from the EMG was about 350 kJ, which is comparable to the energy stored in the capacity storage class 36 kV. The maximum amplitude of the current in the load exceeded 2.5 MA, that is greater than the maximum amplitude of the current received from capacitive storage. The rate of current growth slows
down when approaching the maximum. This feature indicates that the liner is decelerated when the current reaches the maximum value. This means that the kinetic energy of the liner has become insufficient. In general, for the studied type of load, a further increasing in the current amplitude will necessarily lead to the need to reduce the duration of the current front, but it requires changes in the design of the EMG.

5. Conclusion

Developed technique allowed to carry out the experimental investigations to the matching the plasma accelerators operation with power sources based on EMG, with use pre-start modes with CS. New solutions for the design of high-voltage low-inductive switchers for high-voltage capacitive storage class 24 and 36 kV were proposed and implemented. The results showed that this area of research is really promising. Further plans should focus on the following:

- continuation of work to match of nonlinear loads with a power source based on EMG with using the presented technique in MJ range;
- modifying EMG designs to shorten the front edge of the current pulse in the load.

References

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