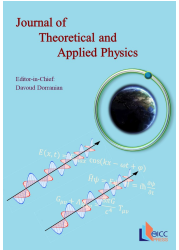


Volume 17, Issue 3, 172326 (1-6)

Journal of Theoretical and Applied Physics (JTAP)

https://dx.doi.org/10.57647/j.jtap.2023.1703.26

Modeling of discharge processes in a new type of pulsed plasma ignition systems with a controlled spark gap

Farit A. Gizatullin, Renat M. Salikhov*, Andrey V. Lobanov

Department of Electromechanics, Ufa University of Science and Technology, Ufa, Russia.

***Corresponding author**: texpromrs@gmail.com

Received 6 February 2023; Accepted 9 March 2023; Published online 11 March 2023

Abstract:
The results of computer and physical simulation of discharge processes in a new type of pulse-plasma ignition systems of gas turbine engines with a controlled switching spark gap are presented. A circuit design model of a pulse-plasma ignition system has been developed, which makes it possible to evaluate the regularities of discharge processes in a semiconductor spark plug depending on the parameters of the discharge circuits - the capacities of the high-voltage and low-voltage storage capacitors, the inductance of the main discharge circuit. The results of computer simulation are confirmed experimentally, the increased efficiency of the ignition system with a controlled spark gap compared to the known circuit solutions containing two switching spark gaps is substantiated.

Keywords: Pulse-plasma ignition system; Controlled three-electrode spark gap; Discharge processes; Circuit model

1. Introduction

The ignition system is one of the most critical units of the gas turbine engine starting system. The ignition of the combustible mixture and, as a result, the success of starting the engine depends on the ignition system. The launch of a gas turbine engine can take place on the ground and in flight conditions in the event of a sudden cessation of the fuel combustion process in the combustion chamber. At the same time, the growth of speeds and flight altitudes of aircraft entails more and more difficult conditions for fuel ignition. This leads to the need to improve existing GTE ignition systems and search for new circuit solutions in this area.

Recently, the development of plasma ignition systems for gas turbine engines, which involve the use of special power sources, has been underway. Plasma ignition systems are less critical to the location of the spark plug compared to traditional capacitive and inductive systems, since the plasma jet penetrates over considerable distances and has a larger contact surface area with the combustible mixture [1, 2].

A variety of plasma ignition systems are pulse-plasma ignition systems, which occupy an intermediate position between traditional capacitive and plasma ignition systems. In pulse-plasma ignition systems in plugs, two types of discharge are combined - powerful short and low-power long [3–5]. As a rule, two spark gaps are used in such ignition systems, which reduces the overall energy efficiency of the discharge circuits. Questions of studying the patterns of discharge processes in pulsed plasma ignition systems are described in [6–8].

2. Problem statement and solution

The article solves the problem of modeling discharge processes in a new type of pulse-plasma ignition systems in which one controlled three-electrode spark gap is used instead of two uncontrolled spark gaps. The simulation results will make it possible to solve the problems of studying discharge processes when designing such ignition systems and choosing the optimal parameters for the elements of discharge circuits.

To solve this problem, the scheme of the pulse-plasma ignition system, the structure of which is described in [7], was taken as a basis. The use of a controlled spark gap in the scheme of a pulsed plasma ignition system has a number of advantages compared to the known schemes of similar ignition systems [9–11]. Firstly, in addition to reducing the weight and size indicators of the ignition system, in this circuit solution it is possible to use both semiconductor and spark plugs with an air spark gap. This is due to the fact that in the discharge circuit of a low-voltage capacitor there is a separating element - a controlled spark gap, which elim-

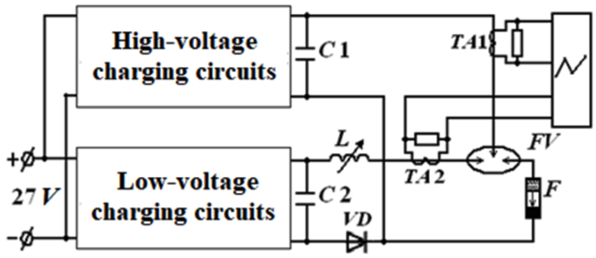


Figure 1. Scheme of a pulse-plasma ignition system with a controlled spark gap

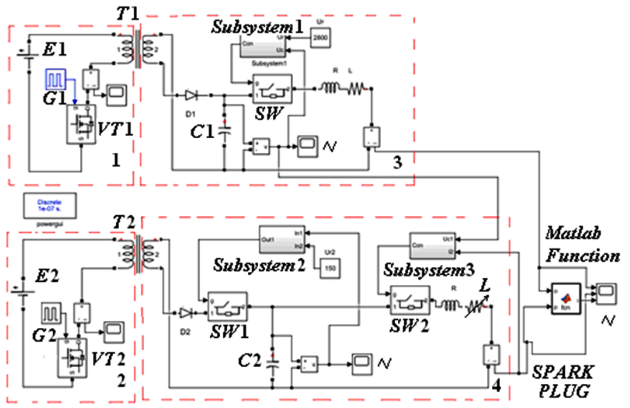


Figure 3. Circuit model of a pulse-plasma ignition system with a controlled spark gap

inates current leakage through the semiconductor element of the plug. Secondly, due to the absence of the second switching element, the energy released in the spark plug increases, and thus the igniting ability of the ignition system improves [12].

The developed scheme of a pulse-plasma ignition system with a controlled three-electrode spark gap is shown in Fig.1. The converters used in the high-voltage and low-voltage charging circuits in the manufactured layout of the ignition system are made according to the circuit diagram shown in Fig. 2. The circuit diagram is assembled on the basis of a single-cycle flyback transistor converter controlled by an integral timer operating in the mode of a rectangular pulse generator. The operation of the field-effect transistor VT is controlled by a signal generator - timer DA2, operating at different frequencies for high-voltage and low-voltage charging circuits. The frequency of the converter is set by the elements R1, R2, R3, C1, VD1, VD2. The output voltage also depends on the parameters of the step-up transformer TV [13].

Features of the layout of the pulse-plasma ignition system are as follows. The high-voltage storage capacitor C1 is charged to the breakdown voltage between the control and right electrodes of the controlled spark gap FV, while the low-voltage storage capacitor C2 is charged to a voltage lower than the breakdown voltage between the main electrodes of the spark gap. After the voltage on the high-voltage storage capacitor reaches a certain value, a breakdown of the controlled spark gap occurs and the high-voltage storage capacitor is discharged through the control and right electrodes of the spark gap to spark plug F. After that, the pre-charged low-voltage storage capacitor is discharged through the left and right main electrodes of the controlled spark gap on spark plug. High-voltage diode VD protects capacitor C2 from breakdown by high-voltage voltage from capacitor C1.

Synchronization of processes in the charging circuits of high-voltage and low-voltage capacitors is carried out by equalizing the time constants of the charging circuits by selecting the appropriate resistances connected in series with the rectifier diodes.

The inductor L, included in the low-voltage discharge circuit, provides the required duration of the discharge pulses and, as shown in [7, 12], makes it possible to increase the igniting capacity of the ignition system. Replaceable inductors have equal active resistances, the change in inductance is achieved through various winding methods. The equality of the active resistances of the coils allows you to change the quality factor of the discharge circuit. The inductance and active resistance of the high-voltage cable connecting the ignition unit to the spark plug are also taken into account.

Compared to the classical capacitive ignition system, this scheme, with comparable power consumption, achieves the following positive effects. Firstly, the accumulated energy losses are reduced due to the use of one controlled switching spark gap in the discharge circuits, secondly, the combination of two discharges of different power in the plug improves the conditions for igniting the air-fuel mixture, and thirdly, the reduction in the rate of energy supply of spark discharges in the spark plug leads to an expansion of the starting characteristics of the combustion device under certain conditions for organizing the processes of ignition

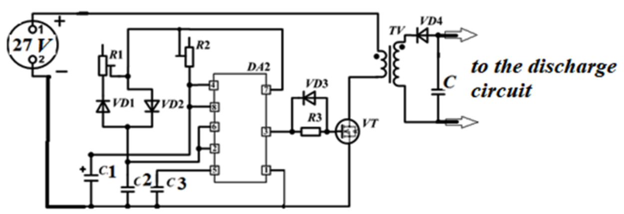


Figure 2. Scheme of a voltage converter for high-voltage and low-voltage charging circuits

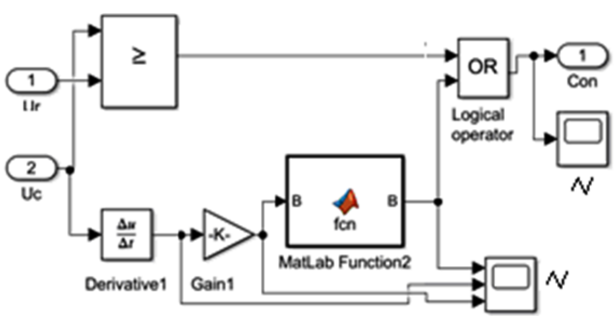


Figure 4. Subsystem 1

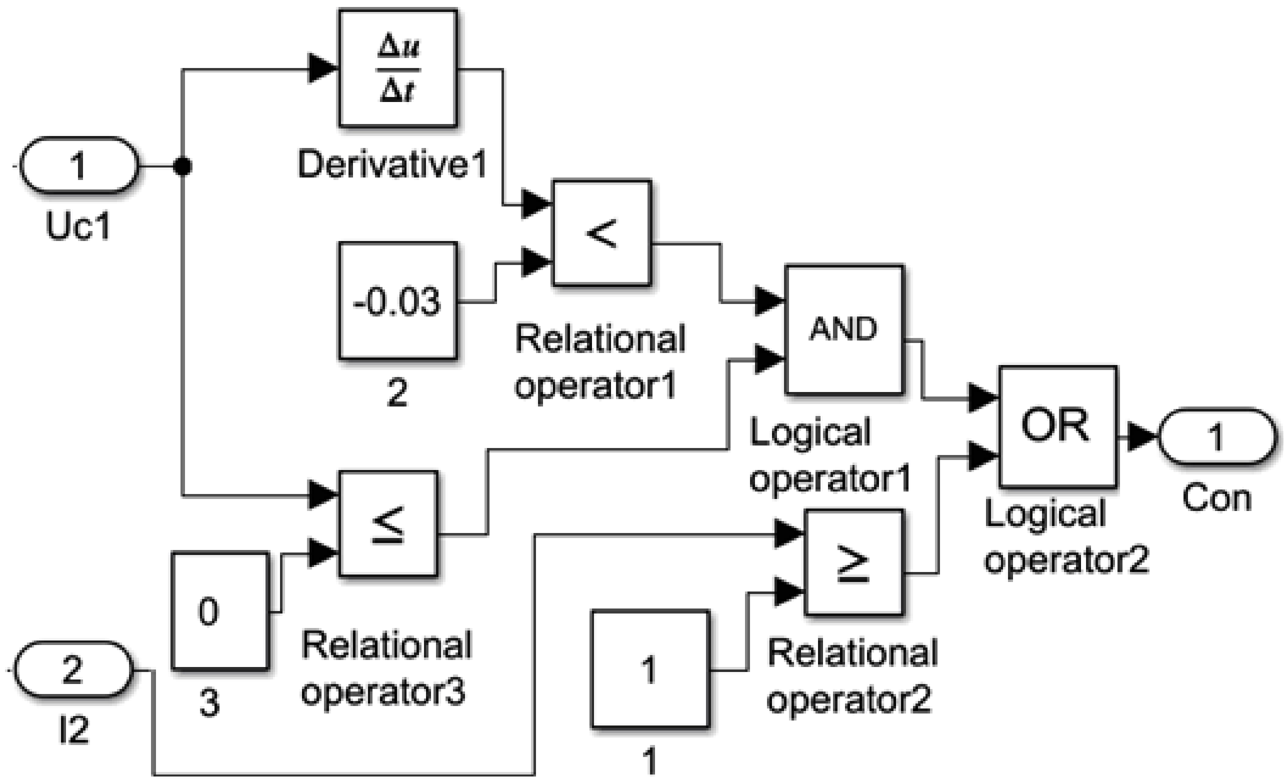


Figure 5. Subsystem 3

and stabilization of the flame in the combustion chamber of the gas turbine engine [12].

In circuit computer simulation, the features of which in relation to various ignition systems are given in [8, 14–18], the elements of the electrical circuit are represented by blocks that reproduce the physical essence of real elements. The developed circuit model of a pulse-plasma ignition system with a controlled spark gap is shown in Figure 3.

The circuit model of the pulse-plasma ignition system provides for the synchronization of processes in the discharge circuits.

The circuit model consists of a high-voltage charging circuit 1 and a low-voltage charging circuit 2, a high-voltage discharge circuit 3, a low-voltage discharge circuit 4, and a MatLab Function.

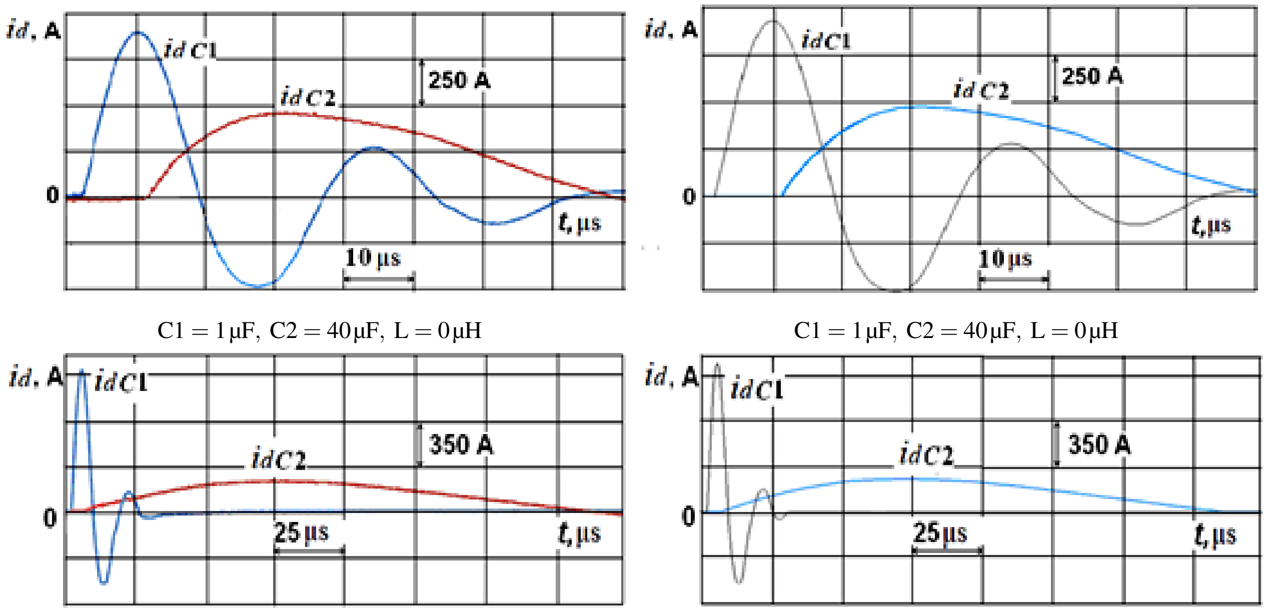
Power supplies 1 and 2 are direct current sources E1 and E2, simulating the parameters of an aircraft battery, switches VT1 and VT2 controlled by pulse generators G1 and G2, as well as the primary windings of transformers T1 and T2.

The high-voltage charge-discharge circuit 3 consists of the secondary winding of the transformer T1, the diode D1, the high-voltage storage capacitor C1, the SW switch, and the Subsystem1 subsystem.

The low-voltage charging-discharging circuit 4 contains

Table 1. Duration of high-voltage t_{hd} and low-voltage t_{ld} discharges

		Experimental data	Theoretical results
t_{hd} – duration of high-voltage discharge, μs	C1 = 1 μF	70 (by L = 0 μH) 30 (by L = 61 μH) 20 (by L = 106 μH)	73 (by L = 0 μH) 32 (by L = 61 μH) 23 (by L = 106 μH)
	C1 = 2 μF	90 (by L = 0 μH) 41 (by L = 61 μH) 33 (by L = 106 μH)	88 (by L = 0 μH) 38 (by L = 61 μH) 30 (by L = 106 μH)
t_{ld} – duration of low-voltage discharge, μs	C2 = 40 μF	69 (by L = 0 μH) 120 (by L = 61 μH) 170 (by L = 106 μH)	71 (by L = 0 μH) 118 (by L = 61 μH) 172 (by L = 106 μH)
	C2 = 60 μF	98 (by L = 0 μH) 168 (by L = 61 μH) 238 (by L = 106 μH)	102 (by L = 0 μH) 174 (by L = 61 μH) 246 (by L = 106 μH)



C1 = 1 µF, C2 = 40 µF, L = 0 µH   C1 = 1 µF, C2 = 40 µF, L = 0 µH

C1 = 2 µF, C2 = 40 µF, L = 106 µH   C1 = 2 µF, C2 = 40 µF, L = 106 µH

(a) - experimental dependencies   (b) - theoretical dependencies

Figure 6. Oscillograms of the discharge current i_d in the circuit of the high-voltage storage capacitor C1 and in the circuit of the low-voltage storage capacitor C2

the secondary winding of the transformer T2, the diode D2, the switches SW1 and SW2, the low-voltage storage capacitor C2, the inductance L, and the subsystems Subsystem2 and Subsystem3.

Power supplies work synchronously. The parameters of the pulse generators that control the keys VT1 and VT2 are set directly in the MATLAB parameter blocks. The open and closed state of the SW key is controlled by the Subsystem1 subsystem shown in Fig. 4, the input of which is a signal from the voltage meter on the capacitor and a constant that determines at what voltage the switch SW will open. The constant is set in accordance with the breakdown voltage level of the controlled spark gap.

The charge and discharge of the low-voltage capacitor C2 is controlled in the Subsystem2 subsystem and is arranged in such a way that the capacitor C2 begins to discharge automatically only during the discharge of the capacitor C1 to ensure synchronization of the discharge pulses and the most efficient operation of the ignition system [12].

Subsystem Subsystem3 Fig. 5 is designed to turn on the switch SW2 when the voltage across the capacitor C1 reaches zero when it is discharged.

The obtained values of the currents of the high-voltage and low-voltage circuits are summed using MatLab Function to obtain an oscillogram of the current on the spark plug. The spark gap spark plug is specified by the SPARK PLUG block, with the corresponding standard gap between the electrodes of a typical aviation spark plug.

To confirm the adequacy of the developed circuitry model of a pulsed plasma ignition system with a controlled spark gap, experimental studies were carried out.

In the course of modeling and experimental studies of a pulsed plasma ignition system with a controlled spark gap, the maximum values of the discharge currents were determined: the duration of the discharges depending on the capacitance of the high-voltage and low-voltage storage capacitors, and the inductance of the low-voltage discharge circuit.

The high-voltage storage capacitor C1 is charged to a voltage of 4200 V, the low-voltage capacitor C2 is charged to a voltage of 250 V. For oscillography of discharge currents, it is possible to connect a non-inductive coaxial shunt [19]. In this work, we used measuring transformers TA1 and TA2, which in this frequency range are successfully used to study fast discharge processes [20].

Characteristic oscillograms of the discharge current i_d in the circuit of a high-voltage storage capacitor and in the circuit of a low-voltage storage capacitor, obtained on a physical model for certain values of the capacitance of the storage capacitors and the inductance of the discharge circuit, are shown in Fig. 6a. Figure 6b shows the corresponding oscillograms obtained as a result of research of a computer circuit model with the same values of the circuit elements.

3. Results and discussion

It has been found that the formation of a low-voltage discharge in a spark plug occurs with a time delay in relation to the beginning of a high-voltage discharge. The delay slightly exceeds the duration of a quarter of the discharge period of the high-voltage capacitor, when the discharge current reaches its maximum value. The presence of a delay is associated with the dynamics of the development of a high-voltage discharge. the breakdown voltage between the left and control electrodes of the spark gap is minimal when the discharge current of the high-voltage capacitor reaches the amplitude value, when the geometric dimensions of the

discharge plasma reach a maximum.
The following feature of discharge processes should be noted. An increase in the inductance in the low-voltage capacitor circuit leads to a reduction in the duration of high-voltage discharge pulses. As follows from the obtained oscillograms, this occurs due to an increase in the attenuation coefficient of the discharge process, which is determined by the ratio of the active resistance and inductance of the discharge circuit. Obviously, the inductance of the discharge circuit of a high-voltage capacitor does not depend on the inductance of the discharge circuit of a low-voltage capacitor. Therefore, an increase in the attenuation coefficient can occur only as a result of an increase in the equivalent active resistance of the high-voltage discharge circuit, which naturally follows from the falling current-voltage characteristic of the spark gap. With an increase in the inductance of the low-voltage capacitor discharge circuit, the discharge current decreases, and, consequently, the active resistance of the arrester increases, which leads to an increase in the equivalent active resistance of the high-voltage capacitor discharge circuit.
Comparison of the experimentally obtained oscillograms of the discharge currents with the oscillograms determined in the course of computer simulation, other things being equal, showed a difference of up to 8%, which is quite acceptable for engineering practice. The discrepancy between the theoretical and experimental results in this case is due, among other things, to the errors introduced by the measuring sensors-current transformers TA1 and TA2.
Table 1 shows the duration of high-voltage t_{hd} and low-voltage t_{ld} discharges obtained during experimental studies and during simulation depending on the inductance L at different values of the capacitance of the high-voltage storage capacitor C1 and the capacitance of the low-voltage storage capacitor C2.

4. Conclusion

The increased efficiency of the pulse-plasma ignition system with a controlled three-electrode spark gap in comparison with the known circuit solutions with two uncontrolled spark gaps is substantiated.
The conducted experimental studies confirm the adequacy of the developed circuit model of the pulse-plasma ignition system.
The created computer circuitry model makes it possible to solve the problems of studying discharge processes in a new type of pulse-plasma ignition systems for gas turbine engines with a controlled three-electrode spark gap at the development and design stages.
The study was supported by a grant from the Russian Science Foundation №23-29-00713, https://rscf.ru/project/23-29-00713/.

Conflict of interest statement
The authors declare that they have no conflict of interest.

References

[1] S. Liu, N. Zhao, J. Zhang, J. Yang, Z. Li, and H. Zheng. "Experimental and Numerical Investigations of Plasma Ignition Characteristics in Gas Turbine Combustors". *Energies*, **12**:1511, 2019.

[2] I. Matveev, S. Matveeva, A. Gutsol, and A. Fridman. "Non-Equilibrium Plasma Igniters and Pilots for Aerospace Application". *43rd AIAA Aerospace Sciences Meeting and Exhibit*, **1**:1191, 2005.

[3] J. R. Berliner, J. C. Driscoll, S. J. Kempinski, and T. S. Wilmot. Turbine Engine Ignition Exciter Circuit Including Low Voltage Lockout Control. *U.S. Patent No. 5,852,381*, 1998.

[4] F.A. Gizatullin, A.V. Lobanov, and Sh.B. Nureyev. Combined ignition system. *RU Patent No 62664 / Utility model patent of the Russian Federation*, 2007.

[5] F.A. Gizatullin, R.M. Salikhov, D.N. Dmitriev, and A.L. Ignatiev. Combined ignition system. *RU Patent No 62664 / Utility model patent of the Russian Federation*, 2013.

[6] A.V. Lobanov. "Patterns of discharge processes in pulse-plasma ignition systems with spark and semiconductor plugs". *Modern problems of science and education*, **2014**:240, 2014.

[7] F.A. Gizatullin, R.M. Salikhov, A.Yu. Demin, Z.G. Gabidullina, and A.R. Salikhova. "Estimation of the igniting ability of the pulse-plasma ignition system". *Aviation industry*, **2017**:23, 2017.

[8] F.A .Gizatullin and A.V. Lobanov. "Modeling of discharge processes in a pulse-plasma ignition system". *Bulletin of USATU*, **11**:161, 2008.

[9] F.A. Gizatullin, R.M. Salikhov, A.R. Salikhova, and A.A. Nikolsky. Combined ignition system. *RU Patent No 152660 / Utility model patent of the Russian Federation*, 2015.

[10] F.A. Gizatullin, R.M. Salikhov, and A.V. Kamensky. Combined ignition system. *RU Patent No 144838 / Utility model patent of the Russian Federation*, 2014.

[11] P. Osmokrovic, N. Arsic, Z. Lazarevic, and N. Kartalovic. "Triggered vacuum and gas spark gaps". *IEEE Transactions on Power Delivery*, **11**:858, 1996.

[12] F.A. Gizatullin and R.M. Salikhov. "Pulsed Plasma Ignition Systems with Synchronization of Discharge Processes". *Russian Engineering Research*, **41**:97, 2021.

[13] F.A. Gizatullin, R.M. Salikhov, and R.P. Sitnikov. "Two-Channel Capacitive Ignition System with a Transistor Converter for Ground-Based Gas-Turbine Engines". *Russian Engineering Research*, **38**:748, 2018.

[14] F.A. Gizatullin and R.M. Salikhov. "Circuit model of a DC ignition plasma system". *Aviakosm. instrument.*, **2011**:1, 2011.

[15] Hanna Bassam and Bassam Habib. "A Simple Model of Capacitor Discharge Through a Spark Gap". *Chemical Engineering & Technology*, **33**:1299, 2015.

[16] K. Song, Z. Y. Gao, and J. B. Liao. "Modeling and simulation of switching power supply of aviation ignition device". *Journal of System Simulation*, **18**:4991, 2008.

[17] F.A. Gizatullin, R.M. Salikhov, N.V. Efimenko, and A.G. Karimova. "A.U. Demin. Instrumentation for modeling of discharge processes in ignition capacitive systems". *Journal of Theoretical and Applied Physics*, **13**:263, 2019.

[18] J. C. Pouncey and J. M. Lehr. "A spark gap model for LTspice and similar circuit simulation software". *2015 IEEE Pulsed Power Conference (PPC)*, **1**:1, 2015.

[19] R.S. Vakhitov and F.A. Gizatullin. "Tubular broadband shunt for measuring high-current pulses". *Measurement Techniques*, **21**:1136, 1978.

[20] F.A. Gizatullin, R.M. Salikhov, and A.YU. Barabanov. "Oscillatory–Discharge Processes in Capacitive Ignition Systems with a Unipolar Pulse". *Russian Electrical Engineering*, **89**:156, 2018.