Semiconductor generator of high voltage nanosecond pulses for plasma technologies

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Abstract. A generator of nanosecond pulses is discussed in the paper. The main output parameters of the generator are as follows: the maximum output voltage amplitude is 20 kV, the output current strength is 300 A, the maximum frequency is 3 kHz, the output pulse rise time is 4 ns, the output pulse energy is 25 mJ. The generator is based on a current interrupter, which is an assembly of drift step recovery diodes (DSRD). Effective operation of the DSRD is provided by assemblies of IGBT-transistors connected in series, the operating voltage of each assembly is 4 kV. It is shown that the generator can be effectively used for purification of air from organic pollutants and for ignition of car spark-plugs.

1. Introduction

Generators of power nanosecond pulses that can operate at frequencies of several kilohertz or tens of kilohertz are required to develop modern plasma technologies [1–8], which provide production of materials with new predetermined properties and purification of food, water, and air. Currently, semiconductor generators are the most promising ones.

There are well known semiconductor generators of high voltage nanosecond pulses with switches made in the form of an assembly of transistors connected in series. The main disadvantage of these generators is insufficient pulse power with switching time of less than 10 ns, limited by fundamental restriction of the switching abilities of the transistors.

In this regard, high voltage switches of nanosecond pulses that were developed at Ioffe Institute and made in the form of assemblies of drift step recovery diodes (DSRD) connected in series, possess certain advantages.

Their operation principle is as follows [9, 10]. First, a short pulse of turn-on current passes in the forward direction through a DSRD, providing accumulation of minor current carriers in the diode structure. At a point of high conductivity, a pulse of reverse voltage of the opposite polarity is applied to the DSRD, and rapidly rising turn-off current flows through the DSRD in the reverse direction. This current provide removal of the accumulated carriers and turns off the diode. In the process of the turn-off, the current I that flows through the DSRD is switched to a load circuit connected in parallel to the DSRD.

Provided the pulse duration of the turn-on current and turn-off current is less than 0.5 μs, and the density of the current I in the moment of the DSRD turn-off is optimal (not more than a few hundreds
amperes per one square centimeter), the current interruption rate in the diode is very high, and the rise time of the current through the load circuit is a few nanoseconds.

The modern technology of DSRD production provides highly reproducible injection properties of p–n junctions. As a result of this, in an assembly of DSRDs connected in series, the charge that accumulates in each diode during the passage of a common pumping current is almost the same. This determines their highly synchronous turn-off by common turn-off current, and ensures and a highly reliable operation of assemblies of DSRDs connected in series in high voltage circuits.

2. Experimental results

Figure 1 shows the schematic diagram of a high voltage nanosecond pulse generator with an assembly of DSRDs connected in series. This generator is designed by the authors of this paper. It is based on DSRD devices described earlier [11, 12].

An important advantage of the designed generator is high switching ability when operating at a high frequency. This ability is achieved as a result of forming of turn-on and turn-off current pulses by assemblies of IGBT-transistors connected in series, which have low energy loss and high reliability due to the use of power control circuits [13], which provide forming of control current pulses with an amplitude of up to 10 A and a rise time of less than 15 ns.

![Figure 1. Schematic diagram of DSRD generator.](image)

The operation principle of the DSRD generator is as follows. In the initial state, the capacitor C1 is charged up from a power supply PS to a voltage of ~4 kV. When the transistor assembly T1 is switched on, the discharge current of the C1 flows through the DSRD assembly in the forward direction. As a result of this, the capacitor C2 is being charged up (C2 ≈ C1). In the moment the charging up of C2 is completed, the switching-on of the transistor assembly T2 is initiated. The discharge current of the C2 flows through the DSRD assembly and turns it off. In the discharge process, the same amount of charge is being passed through the DSRD assembly in the reverse direction as the amount that was passed in the forward direction during the charging up of the C2 to the maximum voltage. Therefore the turn-off of the DSRD assembly occurs in the moment when C2 is completely discharged, and the current through the inductor L2 is at its maximum. In the process of the turn-off of the DSRD assembly, the current I that flows through the L2 is switched to the load Z. As a result of this, a rapidly rising voltage pulse is being formed at the load. The amplitude of the pulse is defined as the strength of the current through L2 multiplied by the load resistance value. After the DSRD is turned off, the energy that had been stored in the L2 is switched to the load.

NP0 type capacitors are used in the generator. They provide output energy amount of ~25 mJ. Each of the assemblies T1 and T2 consists of two parallel connected branches of transistors, each of the branches consists of four IGBT-transistors IRGPS60B120KDP with the operating voltage of 1,200 V connected in series. The amplitude of the generator output current is ~300 A, the current rise time is less than 4 ns. The generator is able to switch nanosecond voltage pulses with an amplitude up to ~20 kV at a frequency of 3 kHz. The pulses are formed by a DSRD assembly, which consists of 16 diodes with a diameter of 20 mm and with an operating voltage of 1,2 kV soldered to each other.
The designed generator was used in a plasma catalytic facility for air purification from organic pollutants, which included a discharge reactor, an output catalytic unit, and an air flow former, which intakes polluted air and its passing through the discharge reactor and catalytic unit. The catalytic unit was made in the form of airtight container filled with granules of activated carbon.

Plastic tubes with a length of 1 m were tightly fit to both reactor inlet and outlet. The end of the outlet tube was connected to the inlet of the catalytic unit. Valves for taking samples were fit into the tubes at the reactor inlet and outlet.

The DSRD generator was connected to the reactor with a coaxial cable. Since the end of the cable is open until an electric breakdown of the reactor, a voltage pulse with an amplitude 2 times higher than the amplitude of the generator output pulses was created at the end of the cable. As a result of this, an electric breakdown of the gap between the reactor electrodes occurred.

The discharge reactor had a coaxial design with a length of ~100 mm. The inner (central) electrode was made as a stainless steel rod with a diameter of 1.5 mm. The outer electrode was made as a copper tube with thin wall. The air flew between the inner and outer electrodes. Due to short duration of high voltage pulses that initiated the discharges, the discharges were not localized into a spark even when the distance between the electrodes was small (up to 10 mm).

Figure 2 shows a photograph of a discharge obtained at a frequency of 3 kHz with the distance between the electrodes of ~15 mm. It can be seen in the photograph that the plasma is evenly distributed over the length of the reactor, and the maximum density of the plasma is near the inner electrode.

Figure 3 shows a waveform of the voltage at the coaxial reactor.

Figure 2. A discharge in the coaxial reactor.

Figure 3. Waveform of the voltage at the coaxial reactor: the Y scale is 5 kV/division, the X scale is 4 ns/division.

A high rise rate of the supply voltage (~7 kV/ns) determined a high voltage level in the moment of an electric breakdown (~31.5 kV). A high electric intensity and small width of the discharge gap caused a high intensity of the ionization process and fairly uniform impact on the air flow, as evidenced by a high yield of ozone (the ozone concentration is ~ 100 mg/m$^3$), which is one of the main products of plasma-chemical reactions. The measurements were carried out with the use of calibrated indicator tubes, through which the ozone-air mixture was passed with the help of an aspirator.

Pilot air-purification experiments were performed with the considered plasma catalytic facility. Ethanol was used as a pollutant. Samples of air taken at both the inlet and outlet of the reactor were analyzed with the help of a gas analyzer “Kolion-1A”, which is able to measure the pollutant concentration with an accuracy of up to 15 per cent. When air was purified in the mode of the maximum generator power, the ethanol concentration at the reactor outlet was no higher than 30% of those measured at the inlet. Pollutants were virtually absent at the output of the catalytic unit.
The possibility to effectively form power pulses with nanosecond duration and the possibility of multiple increase in output voltage relative to the supply voltage without a step-up transformer allows one to use DSRD generators in fuel ignition systems of internal combustion engines.

In modern ignition systems, the breakdown of the spark-plug inter-electrode gap is carried out by a high voltage pulse with nanosecond rise time. The duration of the spark-plug discharge is a few milliseconds, the average energy of the discharge is 50 to 100 mJ. As a result of this, high temperature equilibrium plasma is produced, and the fuel ignition process develops by thermal mechanism.

In the thermal ignition process, the combustion reactions are confined in a small region of the discharge channel. In these conditions, high concentration of fuel and high energy are required to effective combustion of the whole fuel mixture.

The reviewed disadvantages of the standard systems defined the need to develop alternative solutions. Studies [14, 15] show that ignition systems, in which nonequilibrium plasma created by high voltage discharges of nanosecond duration is used to ignite fuel, open great prospects. High rise rate of voltage determines high voltage at the spark-plug in the moment of the discharge, and correspondingly the high intensity of electric field. As a result of this, plasma electrons accelerate to high speed and initiate intensive formation of active particles (atoms of oxygen and radicals OH and CH), which have relatively long life time and take part in exothermic reactions of oxidation.

The active particles increase the efficiency of the combustion process and allow one to lessen the amount of energy required to initial ignition. As a result of this, the use of nanosecond ignition allows one to lessen the fuel consumption and to achieve more complete combustion, and that reduces the toxicity of the exhaust gases.

To determine the prospects of the use of DSRD-generator to ignite fuel-air mixtures, a comparative study of the ignition process of car spark-plug DENSO Q20P-U with the use of the discussed DSRD-generator, which provide switching of the energy of ~25 mJ, and with the use of a standard generator of high voltage microsecond pulses, which is able to deliver two times higher energy (~50 mJ) into the discharge. The standard generator was made according to the traditional scheme of flyback invertor and included a supply source (12 V battery), an IGBT transistor, and an output step-up transformer (an ignition coil by Magneti Marelli company). After the IGBT transistor is turned on, the battery is connected to the coil, and slowly increasing input current of battery discharge flows through it. As a result of this, energy is accumulated in the magnetic system of the coil. When the IGBT transistor is turned off, the input current breaks, and a high voltage pulse is formed at the output of the coil and is applied to the spark-plug. After the breakdown of the spark-plug, the energy, which is accumulated in the coil, is released in the discharge channel. The amount of accumulated energy is determined by the input current strength in the moment of the transistor turn-off. The experiments were carried out with maximum current strength for the coil ~10 A, which do not lead to saturation of the choke of the coil. In the experiments with the standard generator, the spark-plug was connected to the output of the ignition coil, In the experiments with the DSRD-generator the spark-plug was connected to a coaxial cable 0.5 m long with a wave resistance of 10 Ohm, which was connected to the DSRD stack. The experiments were carried out at a frequency of 15 Hz.

As a result of the experiments, it was shown that in atmospheric air conditions, the standard generator forms at the spark-plug voltage pulses with an amplitude up to 7 kV and a rise time of ~2 μs, which initiate breakdown, and after breakdown it provides a flow of current pulse with an amplitude ~0.1 A and a pulse duration of ~2 ms through the spark gap. With the use of the DSRD-generator, a high voltage pulse rising at a rate of ~3 kV/ns was applied to the spark-plug. As a result of this, the breakdown of the spark-plug occurred at a voltage of ~13 kV. After the breakdown, current of ~300 A was switched into the spark-plug.

Since the DSRD-generator provides more than 5,000 times higher power in the moment of the breakdown of the spark-plug (3,900 kW and 700 W correspondingly), the nanosecond ignition produced a considerably more intensive discharge.

Figures 4 and 5 show photographs of discharges at the spark-plug produced by the standard generator and the DSRD-generator correspondingly.
Figure 4. A discharge at the spark-plug produced by the standard microsecond generator.

Figure 5. A discharge at the spark-plug produced by the nanosecond DSRD-generator.

The photographs show that with the nanosecond ignition, the brightness of the discharge and the volume of plasma at the spark-plug is considerably higher than those with the microsecond ignition, despite that the amount of energy, which is put in the discharge, is considerably less.

3. Conclusions
The results of the preliminary studies of the designed DSRD generator allow us to consider it very promising for its use in gas purification systems and in internal combustion engines.

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