SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 21, No. 1, February 2024, 39-52

UDC: 621.318.57:621.3.032.11 **DOI: https://doi.org/10.2298/SJEE2401039I**

Application of a Power Electronic Switch in a Vacuum Installation

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Abstract: This article proposes an original method of implementing a power electronic semiconductor switch using a technological process based on metal processing in a vacuum furnace. We give schematic diagrams of the power part and the control system, and oscillograms for their operation. Results from a practical application and experimental research on the operation of the vacuum installation are presented, and the variation in the glow discharge current with and without operation of the power electronic switch is explored. Photographs showing the details of the machining with and without the power electronic switch are included to demonstrate the effective operation of the proposed schematic solution.

Keywords: Power electronic switch, Vacuum furnace, Control system.

1 Introduction

The basic principles of vacuum technology and its potential have been reviewed in [1]. Glow discharge is widely used in the modern vacuum heat treatment of metals. Preliminary cleaning and activation of the surface for subsequent heat treatment or coating are carried out, and during these processes, the probability of the normal glow discharge transitioning into an arc discharge is high. As a result, defects on the surface of the details occur, which can lead to low quality and an increase in production waste, meaning that it is necessary to take measures to prevent the appearance of arc discharge.

There are several possible solutions based on the following process of operation: (i) the spontaneous transition of glow discharge into arc discharge is detected; (ii) the current is briefly reduced to zero to extinguish the arc; (iii) following this, the glow discharge is restored [2 – 4]. The main disadvantage of this process is that it does not prevent the occurrence of an arc discharge, and

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during the time it takes place, defects on the surface of the details can occur. Spontaneous transition of the glow discharge to an arc can be prevented by applying a pulsed power supply.

The choice of a scheme for supplying a pulsed power supply for glow discharge and the selection of an algorithm for its control are mainly determined by two factors:

a) The peculiarities of maintaining a glow discharge at high power value. At surface treatment of details in glow discharge, the operation must be in the area of the abnormal glow discharge. This is necessary so the entire surface of the details is covered by the gas discharge.
b) When operating in the abnormal glow discharge range, a spontaneous transition of the glow discharge into an arc occurs, as illustrated in Fig. 1.

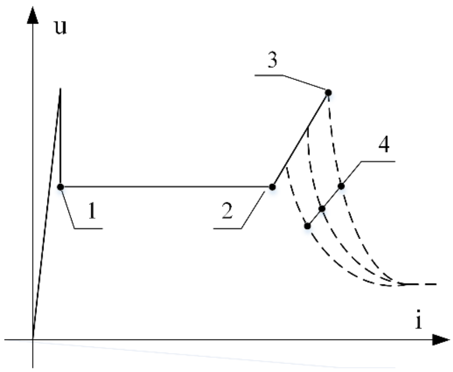


Fig. 1 – *Transition of the glow discharge into arc discharge: u – discharge voltage; i – discharge current.*

The range of normal glow discharge occurs between the points marked 1 and 2. The discharge voltage in this range remains constant as the current changes, and the current density on the cathode is also constant. The discharge covers part of the cathode surface. It is only at point 2 that the entire cathode is covered by the glowing discharge. The abnormal glow discharge is characterised by a voltage that increases with the current. This occurs between points 2 and 3 in Fig. 1. With points 4, a spontaneous transition from glow to arc discharge is illustrated. This transition depends on a large number of factors, and is observed at different operating points within the range of abnormal glow discharge. The arc discharge damages the surfaces of the samples and must be extinguished as soon as possible. The measures that can be used to decrease the probability of the glow discharge turning into an arc are limited to either decreasing the intensity of the discharge, which is disadvantageous, or providing a pulsed power supply, which can achieve the necessary conditions without reducing the intensity of operation.

The operating point corresponding to the abnormal glow discharge can be supported by both a source that sets a constant voltage (i.e., a voltage source) and by a source that sets a constant current (a current source), as illustrated in Fig. 2. When it is necessary to operate at the border between normal and abnormal glow discharge, a voltage source cannot ensure stable operation; however, a current source can provide a stable operating point over the entire range of possible variations of the operating points in both the abnormal and normal glow discharge ranges.

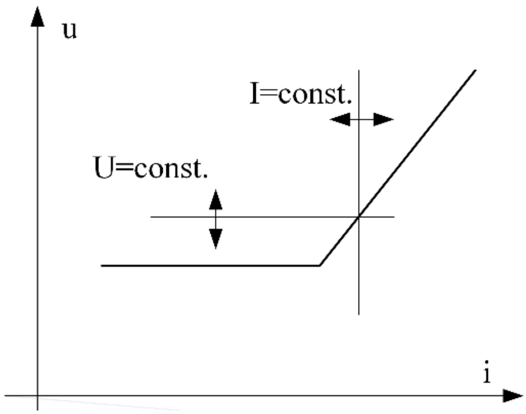


Fig. 2 – *Operation with a current source and a voltage source.*

When powered by a voltage source, as the glow discharge spontaneously turns into an arc, the current will rise inadmissibly. There is a high probability that local defects in the details will occur until the short circuit protection is triggered.

When powered by a current source, however, the current remains unchanged even if the system switches to arc discharge; this reduces the risk of causing defects at the surface of the samples, meaning that it is not necessary to resort to triggering the short-circuit protection. The following procedure is typically used. The spontaneous transition of the glow discharge into an arc is detected, and the current is briefly reduced to zero in order to extinguish the arc discharge, after which the glow discharge is restored. A pulsed power supply can be created by connecting a transistor short circuit semiconductor switch in parallel with the working chamber to interrupt the glow discharge. The control of the semiconductor switch enables periodic switching on and off, with a certain frequency and duration. The duration of the switched-off state should be set depending on the speed of deionisation of the discharge gap after an arc discharge has occurred and been extinguished, and the frequency of repetition of the interruptions is determined depending on the speed of the transition from glow to arc discharge.

Both processes are influenced by many factors, the most significant of which are the dimensions of the camera, the pressure and temperature at which the technological process is carried out, and the characteristics of the samples (such as their quantity, arrangement, shape and the cleanliness of their surfaces) [3].

In view of the above, the scheme chosen for the switch mode power supply should provide options for different settings of the frequency and duration of the interruption, to meet the needs of different technologies. According to preliminary estimates, the duration of the interruption should be in the range [10, 100] μs, and the repetition frequency should not exceed (10 –12) kHz.

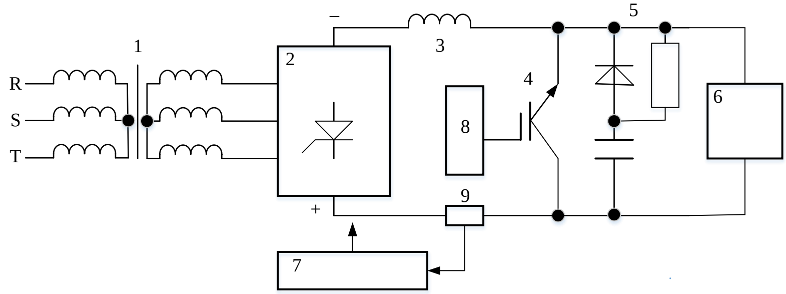
In addition to the need to adjust the frequency and duty cycle of the control pulses of the power semiconductor switch, there are also requirements for reliable operation and electromagnetic compatibility under strong disturbing effects and operation at high voltages.

Existing methods of implementing power electronic switches using different power semiconductor elements are discussed and systematised in [5 – 7]; for example, power thyristor switches can be used in electronic overvoltage protection circuits [8]. A DC thyristor switch is reviewed in [9]. In [10], the authors describe a bidirectional DC thyristor switch based on a G-source. The authors of [11] studied the operation of parallel-connected electronic DC switches, each of which consisted of two injection-enhanced gate transistors connected with each other in parallel along the diagonal of a single-phase diode bridge circuit. The DC switching circuit was connected along the other diagonal. A combination of parallel- and series-connected insulated gate bipolar transistors (IGBTs) for the implementation of a DC switch is discussed in [12]. A switch for DC networks is described in [13] based on a combination of a power transistor and inductances with mutual connection. In [14], a switch for low voltage DC networks based on IGBT is described.

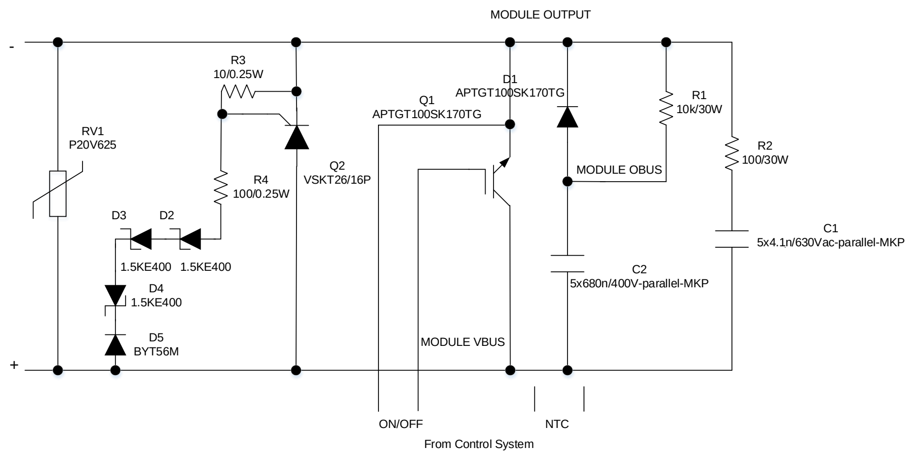
The purpose of the switch considered in this research is more specific than those considered in the studies described above, due to the requirement for a continuous interruption to the current with a certain frequency in a high-voltage DC circuit. To meet these requirements, the selection of a schematic solution, of elements and the practical implementation of a power electronic switch need to be made by researchers and designers with a great deal of knowledge and experience. This is due to the requirements for reliable operation, electromagnetic compatibility with strong disturbing effects and operation at high voltages.

2 Power Scheme and System for the Control of a Power Electronic Switch

Fig. 3a shows a block diagram of the proposed vacuum installation. Its elements are as follows: 1 − three-phase power transformer; 2 – three-phase full bridge thyristor rectifier with current stabilisation; 3 – filter choke sized to achieve continuous current mode and checked for pulse mode transients; 4 –transistor shorting power electronic switch, which is used to interrupt the glow discharge in the working chamber; 5 – filter used to create certain parameters of the recovery voltage in the chamber after interruption of the glow discharge; 6 – chamber for carrying out the technological treatments; 7 – current feedback rectifier control unit; 8 – transistor switch control unit; 9 – current sensor.



(a)



(b)

Fig. 3 – *Schematic diagrams of* (a) *the entire installation and* (b) *the power circuit.*

Fig. 3b shows the principle of operation of the power part of the transistor electronic switch (marked 4). It is implemented using an IGBT module APTGT100SK170TG from the company MICROSEMI, prepared according to Trench + Field Stop Technology with basic data $U_{CES} = 1700\,\mathrm{V}$ and $I_C = 150\,\mathrm{A}$ at 25°C [15]. Special attention is paid to the protection of the transistor during the transitional processes of switching. The features of the protective elements used in transistor switches for DC circuits with inductive load are discussed in [16–18], and their influence on the switching process is explained. In the present work, for protective purposes, we use an RCD group R1C2D1, an RC group R1C1, and an input varistor RV1. These three measures provide effective protection against operational overvoltages. The RCD group R1C2D1 controls the movement of the operating point when switching the transistor along a trajectory in the safe operating area. The RC group R1C1 and the varistor RV1 limit the switching overvoltages. In addition, for protection against extreme inadmissible overvoltage between the input terminals, the thyristor Q2 is used, together with the elements around it (R3, R4, D2, D3, D4 and D5). These are connected according to a short-circuit scheme, and in the event of an accidental increase in voltage outside the operating limits, the thyristor Q2 will be turned on, which will cause the automatic circuit-breaker of the supply voltage to switch off. The NTC terminals are connected to an internal module thermistor with a value of 50 kΩ at temperature 25°C, which is included in the scheme of the control system and is used to monitor the temperature of the module. The installation of the elements of the power scheme for a cooling radiator with natural air cooling is shown in Fig. 4. This scheme meets the requirements in terms of ensuring the necessary insulation voltages and minimising parasitic inductances.

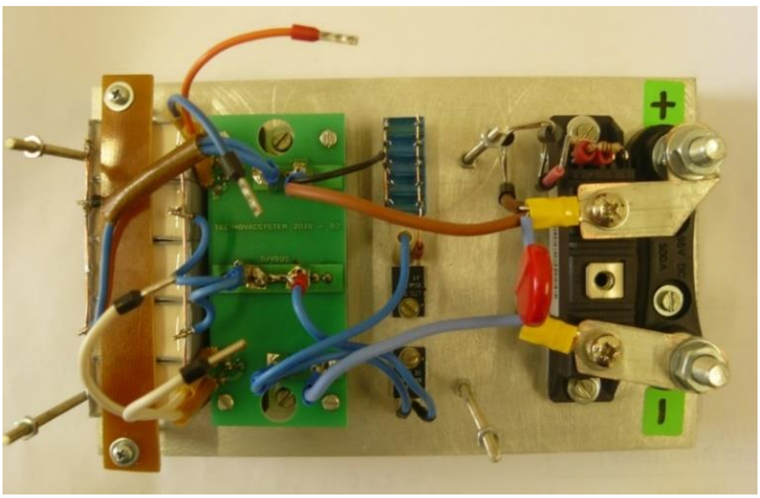


Fig. 4 – *Elements of the power circuit installed on a cooling radiator.*

Fig. 5 shows a schematic diagram of the control system. Its main element is the multivibrator in autogenerator mode, which is implemented with an integral circuit U1. By means of the potentiometer R3, the duration of the output pulse at terminal 3 is set to 30 μs at a frequency of 1–1.1 kHz. The integral circuit U3 is used to implement a comparator with hysteresis, and the internal thermistor from the power module is connected in a bridge measurement circuit. The value of its resistance R_T at temperature T (in degrees K) is given by the equation below [15],

$$R_T = \frac{R_{25}}{\exp\left[B_{25/85}\left(\frac{1}{T_{25}} - \frac{1}{T}\right)\right]}, \tag{1}$$

where $R_{25} = 50\,\mathrm{k}\Omega$, $T_{25} = 298.15\,\mathrm{K}$, $B_{25/85} = 3952\,\mathrm{K}$.

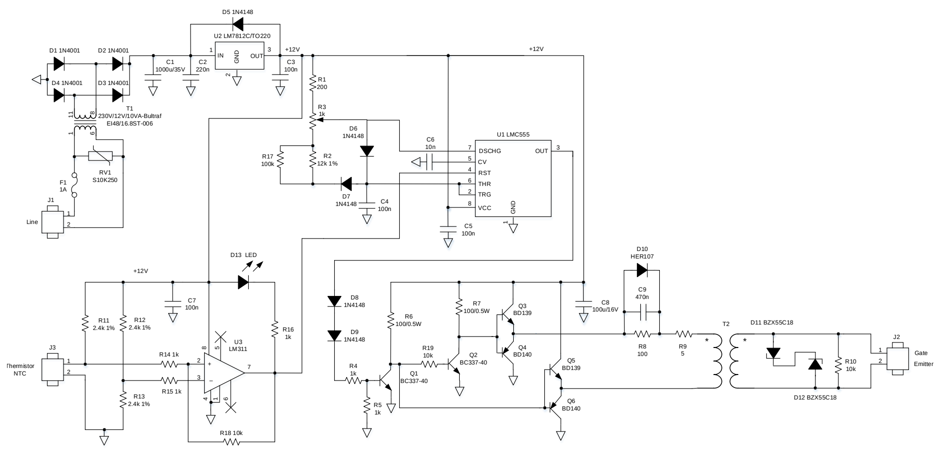


Fig. 5 – *Schematic diagram of the control system.*

If the permissible temperature is exceeded, corresponding to a value of NTC of below 2.4 kΩ, a low voltage level is obtained at the output of the comparator, which stops the generation of pulses from the multivibrator through terminal 4 of U1. According to (1), this takes place at a temperature of 386.69 K or 113.54°C. The maximum permissible temperature of the crystal of the power module is 150°C. As can be seen, a sufficient reserve is provided, and the power circuit and the cooling of the power module are designed in such a way that the maximum temperature of the crystal does not exceed 95°C at the maximum ambient temperature, at the operating frequency of the pulses, and during the switched-on state of the IGBT. There are several types of driver circuit for high-power IGBTs [19, 20], including integral circuits and hybrid modules offered by various manufacturing companies [21, 22]. In the present article, a simplified driver circuit with transformer separation is preferred, for the following reasons: the operating frequency is constant and relatively low (below 10 kHz); the duty cycle is constant for a fixed duration of the control pulse; no additional supply voltages or associated current supply sources are required; and the cost is significantly lower than the equipment from the aforementioned companies. The IGBT control driver is implemented with all elements connected to the right of terminal 3 of U1 at the bottom of the circuit. The circuit is optimised for the operating conditions described above with all necessary measures taken to ensure the shape of the control pulse. Galvanic separation is achieved with a high-frequency transformer at an isolation voltage of 3 kV. Fig. 6 shows the implementation of the entire power electronic switch. Oscillograms of the control pulses are shown in Fig. 7 for an operating frequency of 1 kHz and a duration of the control pulse of 30 μs. The switch-on voltage for the IGBT is about 10 V, and the switch-off voltage is about −5V.

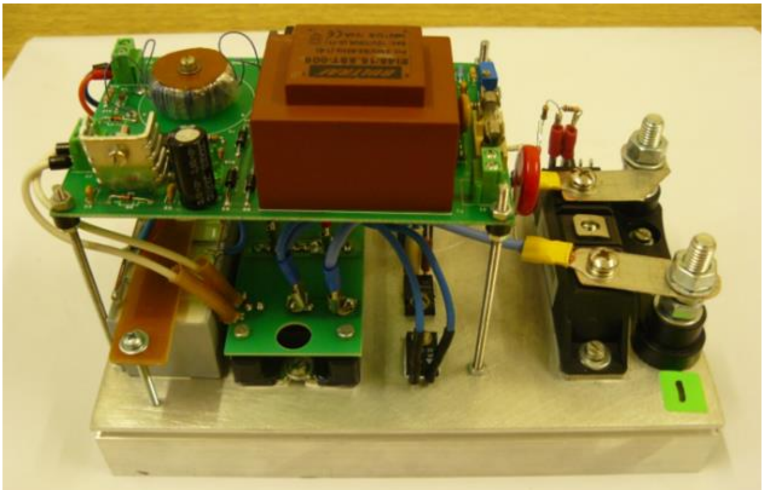


Fig. 6 – *External appearance of the entire power electronic switch with the control system.*

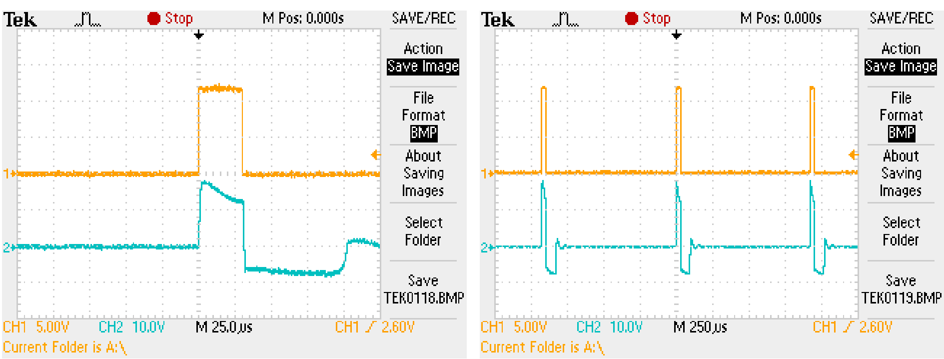


Fig. 7 – *Oscillograms of the control pulses: CH1 – at the anode of diode D8; CH2 – voltage G-E of IGBT.*

3 Experimental Research

In order to determine the effectiveness of the power switch, it was implemented in a vacuum furnace used for ion nitriding, carbonitriding, and nitrocementation, made by Technovacsystem Ltd., as shown in Fig. 8 [23]. Samples of the same shape and size were precleaned of the coolant required for machine treatment, and were dried. They were divided into two groups: the first set were cleaned under glow discharge conditions, without the use of the power electronic switch, and the second were cleaned with the operation of the electronic switch.

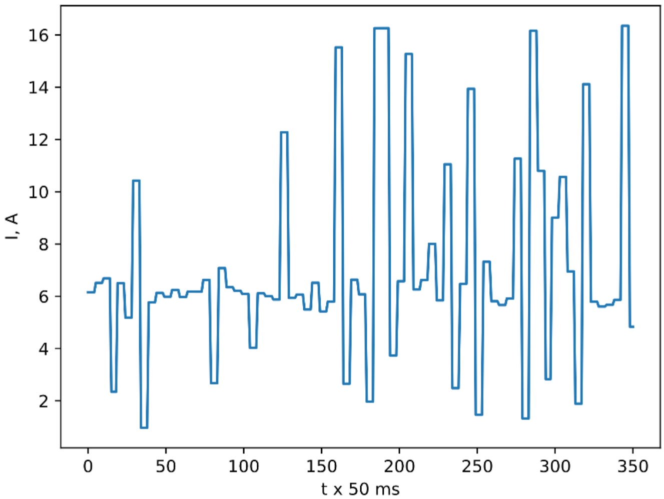
Fig. 8 – *Vacuum furnace for thermal and chemical-thermal treatment of metals with pulse glow discharge.*

The frequency and duty cycle of the pulses generated by the power switch were determined based on the results of the previous experiments. Values of $f = 8\ \text{kHz}$ and duty cycle D = 0.2 were defined to ensure optimal operation of the glow discharge in the existing setup.

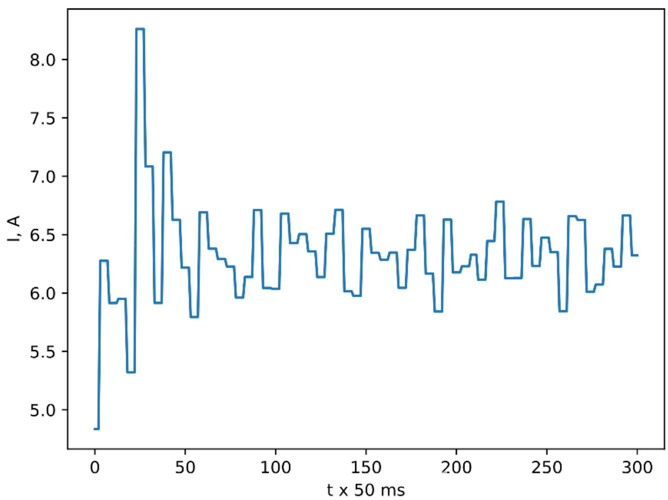
The details were loaded into the vacuum furnace. By means of a vacuum pump, the pressure of the working space of the furnace was set to 2 mbar. The glow discharge current was applied, and a program for recording the changes in this current throughout the process was started.

Numerous experiments were carried out. Given the large amount of data obtained and the impossibility of presenting all of the information, only a selection of results are presented in Fig. 9. It can be seen that in cases when the power electronic switch was not operational, the conditions for a repeated increase in the discharge current were created, leading to a transition of the glow discharge into an arc. The occurrence of such a discharge is shown in Fig. 10. As a result of this discharge, defects appear on the surface of the samples.

Fig. 11 shows the external appearance of details from both groups. On the left is an example from the group processed without turning on the power electronic switch, with the occurrence of an arc discharge, and on the right is an example from the group where this discharge was prevented through the use of the power electronic switch.



(a)



(b)

Fig. 9 – *Changes in glow discharge current:* (a) *without power switch;* (b) *with power switch.*

(a) (b)

Fig. 10 – *Arc discharge during processing of the details in glow discharge without operation of the power switch.*

From Fig. 11a, the defects on the surface of the detail on the left as a result of the action of the arc discharge can be clearly seen.

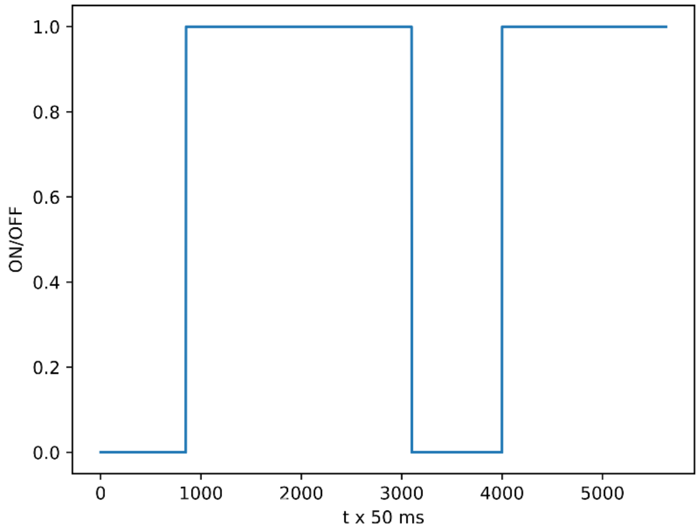
(a) (b)

Fig. 11 – *External appearance of details:* (a) *processed with power electronic switch;* (b) *processed without power electronic switch.*

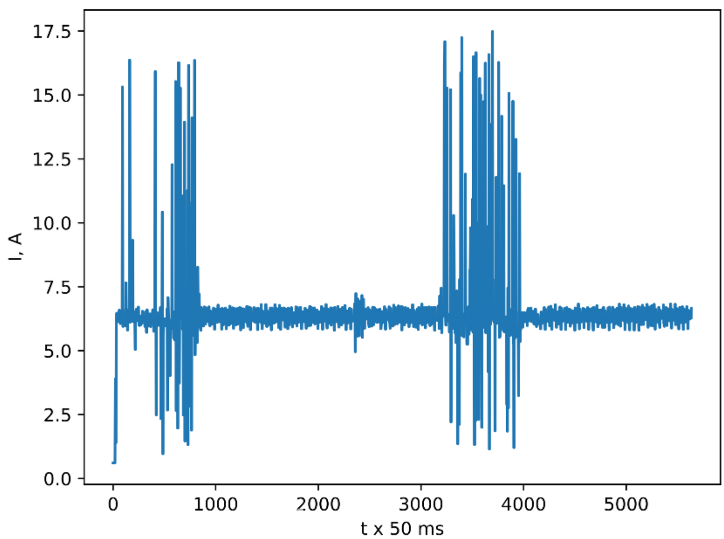
Additional experiments were carried out in which the details were placed in the vacuum furnace and processed under glow discharge conditions, with the same parameters as in the previous experiments. A program was written and loaded into the industrial computer to control the furnace, which generated operation times of random duration. This permitted the power electronic switch to be switched on or off at any time, and for a randomly selected duration. The shape of the signal used to enable the power switch is shown in Fig.12a. During the high level (logical 1), the operation of the power electronic switch is permitted. The variation in the glow discharge current is shown in Fig.12b.

From Figs. 12a and 12b, it can be seen that during the operation of the power electronic switch, the conditions necessary for an increase in the concentration of ions in the inter-electrode space and higher discharge current are not provided.

In most cases, in the event of an arc discharge, when the power electronic switch is turned on, the discharge was interrupted and the glow discharge was restored. Operation with power electronic switch and maintaining this discharge is presented in Fig. 13.



(a)



(b)

Fig. 12 – (a) *Control signal to the power electronic switch;*
(b) *Change in the glow discharge current.*

Fig. 13 – *Glow discharge with operation of the power electronic switch.*

4 Conclusion

In this article, we have presented an original method of implementing a power electronic semiconductor switch for metal processing in a vacuum furnace. The results of our experiments show a reduction in the glow discharge current variations when the power switch is used. From an analysis of these results, the following conclusions can be drawn:

- The efficiency of the process of cleaning the details in glow discharge increases with the use of a power semiconductor switch.
- The probability of occurrence of an arc discharge is significantly reduced.
- The probability of defects occurring on the surface of the details is decreased, and the creation of waste is reduced.

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