Rectangular current pulse generator to test varistors with pulsed electrical load

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Abstract. A brand-new circuit of a rectangular pulse current generator is presented. As a rule, generators consisting of 6-10 LC cells connected in series are used to obtain rectangular current pulses. Such units are very cumbersome and complicated in the selection of element parameters and adjustment, so a new scheme of pulse current generator was proposed. The main difference from the classical circuit is the method of generating a rectangular current pulse, i.e. by adding the currents from two parallel circuits connected to the load. The first circuit at discharge generates an aperiodic current pulse, the second generates an oscillatory current pulse. The total current pulse flowing through varistor has constant amplitude for some time. In a specified period of time, while the current pulse has a constant amplitude, there is an interruption of current with the help of a switching device. The given circuit solution is possible to implement when using fundamentally new switching devices of the IGBT module. A connection diagram of a pulse current generator for testing varistors with a classification voltage to 1200 V with adjustable pulse duration of 50, 1000, 2000 µs is proposed. The parameters of the generator circuit elements are determined. The measures aimed at suppression of overvoltages arising at break of current in circuits with high inductance as well as the tests confirming the operability of the designed circuit are carried out.

1. Introduction
The production of varistors requires constant monitoring of their main parameters, one of which is the ability to withstand the effects of a pulsed electrical load. Varistors are tested using two types of pulse current generators (hereinafter referred to as just "generator"). The first type includes generators that create aperiodic current pulse with a rise time of 8 µs, a pulse length of 20 µs and amplitude of up to several tens of thousands of amperes, the second is generators, generates rectangular current pulses with on-time of 50, 1000 or 2000 µs and amplitude of up to 1000 amperes. The circuit design of pulse current generators was developed in the middle of the last century and is described in the key issues of high voltage engineering [1, 2].

2. Materials and Methods
One can generate a rectangular current pulse of a long on-time using a (classical) circuit made up of series-connected \( LC \) cells (Figure 1). This circuit simulates a long uniform line that allows to get close
to ideal rectangular current pulses when the load resistance $R_n$ is equal to the characteristic resistance of the circuit $Z$ [3]:

$$ R_n = Z = \frac{L}{\sqrt{C}}, $$

(1)

where: $L = L_1 = L_2 = ... = L_n$, and $C = C_1 = C_2 = ... = C_n$ – parameters of $LC$ cells; the load resistance $R_n$ includes the damping resistance $R$ and the dynamic resistance of the test varistor $R_0$ (see Fig. 1).

![Figure 1. Classical circuit of a rectangular pulse current generator. $F$ – spark gap.](image)

The total values of capacitance and inductance in the circuit are determined by the formulas (2, 3):

$$ C_\Sigma \approx \frac{n \cdot T_p}{2R \cdot (n-1)}, $$

(2)

$$ L_\Sigma \approx C \cdot R^2, $$

(3)

where:

- $C_\Sigma$ is the total capacity of the generator, $n$ is the number of cells;
- $T_p$ is the time during which the current exceeds 0.9 of the amplitude value;
- $R_n$ is the load resistance, and $L_\Sigma$ is the total inductance of the generator.

However, even with a large number of cells, the shape of the current pulse will deviate from rectangular and approach the trapezoidal shape. To solve this problem, one needs to use different parameters of $LC$ cells. Moreover, as a rule, the capacitors $C_1$, $C_2$, ... $C_n$ take the same capacitance, and the inductance of the coils is varied so as to obtain the desired pulse shape. Experience shows that testing varistors using the classical generator circuit requires from 8 to 12 $LC$ cells. In this case, the inductors $L_1$, $L_2$ should have the largest value, and $L_{n-1}$, $L_n$ – the smallest of all available [3].

The following significant drawbacks are typical for the classical generator circuit:

- the complexity of the circuit. In addition to requiring many $LC$ cells, the magnetic coupling between them must be minimized so that its effect on the shape of the test pulse is negligible. Therefore, large distances are required between the cells, which increases the unit area;
- the shape of the current pulse strongly depends on the test object. The load resistance must match the characteristic resistance of the $LC$ circuits. This does not allow to standardize the unit;
- there is no possibility to control the on-time of the current pulse, namely, a separate generator is required for each pulse on-time;
- the load resistance strongly affects the shape of the current pulse;
- complex configuration of the unit parameters to obtain a current pulse of the required shape due to the large number of elements;
- the charging voltage of the generator must be at least twice the remaining voltage of the tested varistors;
- high cost.
To eliminate these shortcomings in the classical circuit of a rectangular current pulse generator, it was proposed to develop a unit using a component base of power electronics. In the last few years, new electronic power equipment has emerged that can break a circuit of hundreds of amperes and switch voltages of several kilovolts [4, 5]. Such switching devices can be easily controlled, unlike classic spark gaps, which depend on external conditions. Some of these devices operate on the basis of an IGBT transistor and are called an IGBT module, i.e. a bipolar transistor with a sealed gate. An IGBT transistor is a device that is a combination of a field-effect and bipolar transistor. Such combination has resulted in it having the positive qualities of both types of these transistors, with the field-effect transistor driving a powerful bipolar transistor.

The most significant and used in the development of the generator is the ability of IGBT modules to break the current pulse without passing through the zero value and the rated voltage up to 6.5 kV [6-8]. Taking this into account, a fundamentally new circuit of the pulse current generator was developed and further modeled in the OrCAD software (Figure 2).

![Connection diagram of the designed generator. VD – high-voltage diode; Rvn – upper arm of the voltage divider; Rnn – lower arm of the voltage divider.](image)

The generator circuit consists of two discharge circuits (1, 2), a switching device – an IGBT module (3), a snubber circuit (4) of an IGBT module (a protective RCD circuit), and a varistor as a load (5).

The discharge circuits of the circuit are series-connected capacitive, inductive, and active elements. The accumulated charge in the capacitor during switching is discharged to the load for a specified time (50, 1000, 2000 microseconds). This process can be either aperiodic or oscillatory. The parameters of the discharge circuits must be chosen so that the current in the first one changes according to the aperiodic law, and in the second one – according to the oscillatory law, respectively. Figure 3 illustrates the generation of a rectangular current pulse: the current of the first circuit changes in time according
Figure 3. Current waveform (at $t_1=1$ ms – switching on the IGBT module, at $t_2=3$ ms – switching off the IGBT module). 1 – current of the first discharge circuit, 2 – current of the second discharge circuit, 3 – total current.

to the aperiodic law (1), the current of the second circuit has an oscillatory feature (2). The addition of two current pulses gives the desired rectangular current pulse with the specified parameters (3). It should be noted that in the absence of a measured varistor in short-circuit mode, the generator circuit can withstand a maximum current of 1000 A.

When the IGBT module is disconnected, the current flowing through the inductive elements of the circuit is cut off, as a result of which significant overvoltages occur on the module terminals. To prevent this, an $RCD$ circuit is connected in parallel to the IGBT module, which is also called a protective or snubber circuit [9, 10]. A snubber circuit consists of a series-connected resistance and capacitance. The capacitor contained in the $RCD$ circuit must absorb the energy that has been accumulated in the inductance in kinetic form, and, as a result, protect the switching device from the effects of overvoltage. A high-voltage pulse diode, which is designed to regulate the charge and discharge time of the capacitor [11], is connected in parallel to the snubber circuit resistor. To avoid overvoltage, the resistor and capacitor of the snubber circuit must also have the lowest possible inductance. It is worth noting that the resistor and capacitor always have their own inductance, but the simulation results showed that the inductance of 0.1 µH is acceptable in this case [12, 13]. Figure 4 shows the voltage change at the module terminals in the absence and presence of a snubber circuit. The voltage on the IGBT module during switching in the absence of a snubber circuit (curve 1) reaches 9 kV, which will certainly lead to its destruction. If a snubber circuit is installed parallel to the IGBT module, the overvoltage will be completely suppressed (curve 2).

Figure 4. Voltage waveform on the IGBT module during switching (at $t_1=1$ ms – switching on the IGBT module, at $t_2=3$ ms – switching off the IGBT module).
Table 1 shows the parameters of the generator circuit elements that allow creating a rectangular current pulse in accordance with GOST (all-Union State Standard) [14, 15].

Table 1. The parameters and purpose of circuit elements of the generator.

| Element | Rating value | The purpose of the element |
|---------|--------------|----------------------------|
| C₁      | 1.1 mF       | Energy storage             |
| C₂      | 0.3 mF       | Energy storage             |
| C₃      | 4 µF         | Absorption of energy stored in the inductance |
| L₁      | 10 µH        | The formation of the pulse shape |
| L₂      | 10 mH        | The formation of the pulse shape |
| L₃      | 2 µH         | Self-inductance of the generator busbar |
| L₄      | 0.1 µH       | Self-inductance of the snubber circuit |
| R₁      | 3 Ohms       | The formation of the pulse shape |
| R₂      | 1 Ohms       | The formation of the pulse shape |
| R₃      | 1 Ohms       | The formation of the pulse shape |
| R₄      | 2 Ohms       | Limiting the discharge current of the snubber capacitor |
| R₅      | 100 Ohms     | The discharge of the varistor capacitance. Charging the snubber capacitor in the absence of the test object |
| R₆      | 50 mOhms     | Current measuring shunt    |
| VD      | 6000 V, 30 A | Regulation of the charge and discharge rate of the snubber capacitor |
| IGBT module | 6500 V, 500 A | Switching device |

3. Results
Figure 5 shows a photo of the IGBT module mounted on the radiator, along with the snubber chain. The correct choice of parameters of the snubber circuit is proved by oscillography of the voltage at the terminals of the IGBT module during switching. From the waveform shown in Fig. 6, it can be seen that there are no overvoltages when the current is turned off.

![Figure 5. Photo of an IGBT module with a snubber chain.](image-url)
4. Discussion
The proposed circuit of the pulse current generator makes the device much more compact and mobile. In addition, due to the small number of elements, compared to the classic circuit, setting the unit parameters has been much simplified. New oscillator circuit is designed using the latest achievements in the field of power electronics. It should be noted that due to the use of the IGBT module, it is now possible to control the on-time of the current pulse. The charging voltage of the developed generator is slightly higher than the remaining voltage of the tested varistors. The test varistor does not affect the shape of the pulse, but only affects the current amplitude, which can be adjusted using the charging voltage to the desired value.

5. Conclusion
In the developed circuit of the rectangular pulse current generator, which offers a fundamentally new circuit solution, a high-voltage IGBT module is used as a switching device, which makes it possible to generate test current pulses with an on-time of 50, 1000 and 2000 microseconds on one and the same unit. The developed unit can be used for various testing and technological circuits.

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