Design of a Pulse Generator for Testing Partial Discharge Measurement Systems

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***Abstract*—This paper deals with the design and implementation of a pulse generator serving as a reference generator for setting up measuring systems for monitoring partial discharges (PD) in high-voltage power transformers or gas insulated switchgear (GIS). After installing the measuring device, it is advisable to test the entire measuring chain and, if necessary, set parameters that would validate the correct detection of PD signals. Fast pulse generators are important for this verification. In systems that sense the electromagnetic activity of PD. The proposed generator should serve as the output stage of a programmable generator, which did not reach sufficient parameters for output pulses. The goal was to achieve a rising time around 100 ps and an amplitude of more than 6 V using very fast operational amplifiers and step recovery diodes to sharpen the input pulse. The measurements show waveforms of the output voltage pulse to evaluate its performance.**

Keywords—partial discharge, pulse generator, step recovery diode, UHF band

I. INTRODUCTION

Pulse generators are used in the field of partial discharge (PD) measurement to artificially create similar signals to PD. An important element of any PD measurement system is therefore a pulse test generator, which verifies the functionality and settings of the entire PD measurement chain. Different approaches can be used to generate very short and very fast edge pulses and these are described briefly in the following sections. This paper will mainly deal with the design of a generator with a step recovery diode (SRD), which is the most suitable for our purposes in terms of parameters and required properties.

II. METHODS FOR GENERATING SHORT PULSES

There are a number of ways in which very short and fast-edge pulses can be generated. This section lists several methods that are based on various electronic components or parts.

A. *Mercury relay switches*

One way to generate fast rising voltage pulses is to use reed relays that have contact surfaces covered with a layer of mercury. This method is one of the older ways of generating pulses, but it performs very well. Leading and falling edge times are in the order of tens of picoseconds, and the magnitude of the output pulse can be up to several hundred volts, and in special cases even kilovolts, [1], [2]. Another advantage is their relatively simple construction, which allows a coaxial feed arrangement. However, the mercury relay is not suitable for PD pattern simulation because, due to its mechanical switching it is not possible to achieve a higher repetition frequency than several hundred hertz [3], [4]. Furthermore, environmental issues associated with the use of mercury are not ideal.

B. *Marx generators*

Another option is the Marx generator, the principle of which is to charge a bank of capacitors connected in parallel and then switch them in series and discharge them, for example, across a spark gap. It is possible to obtain high voltage pulses with these generators, but the leading edges of the pulses range from tens to hundreds of nanoseconds [5], [6]. Again, this is unsuitable for the required design purposes, as we do not need to obtain high voltages but very fast rising pulses.

C. *Nonlinear transmission lines*

Pulse generators based on the principle of nonlinear transmission lines (NLTL) are circuits used for pulse sharpening. They consist of a cascade of coils and capacitors. However, the capacitors are replaced by a nonlinear semiconductor element - most often a varactor or a Schottky diode, for which the capacitance-voltage dependence is nonlinear [7]. The principle of an NLTL is that the part of the pulse with a higher amplitude will propagate faster as the capacitance decreases with increasing voltage. This creates a pulse with a very short leading edge at the output with the pulse slope dependent on the number of elements in the cascade connection. With NLTL, it is possible to achieve very short leading edges (down to picoseconds) [8]. The output voltage may however be limited by semiconductor components.

D. *Avalanche transistors*

Another way to generate very steep pulses is to use an avalanche breakdown of a bipolar transistor. An avalanche breakdown occurs when the intensity of the electric field at the reverse biased junction reaches such a level that the minority carriers acquire high kinetic energy and impact ionization of the crystal lattice atoms can occur, i.e., electron-hole pairs are formed [9]. The current through the junction increases sharply and is limited only by an external circuit limitation (usually a resistor). If the current is not limited, the transistor will fail. A sharp increase in current can be used to create a very steep pulse edge. The avalanche transistor circuit is controlled by positive rectangular pulses. As soon as a positive pulse arrives at the input, the transistor begins to conduct, and an avalanche breakdown occurs [10]. The disadvantage of this solution for PD simulation is that the amplitude of the output pulses is fixed (not proportional to the input) and also the lifetime of the transistor in this mode of operation tends to be quite limited.

E. Step recovery diodes

The final technique for generating short pulses that we shall consider here involves using step a recovery diode (SRD). SRDs use only the diffusion capacity of the diode P-N junction polarized in the forward direction for their operation. Under forward bias, minority carriers accumulate near the P-N junction. These carriers do not recombine, which is ensured by a suitable doping profile around the junction. The structure then resembles a PIN diode with a very narrow intrinsic region. When the polarity reverses, the minority carriers return through the junction. However, they are depleted only after a certain time given by $t_{OFF} = t_{rr}$, where t_{rr} is reverse recovery time, see Fig. 1. Narrow current pulses rich in higher harmonic components are generated [11], [12], [13].

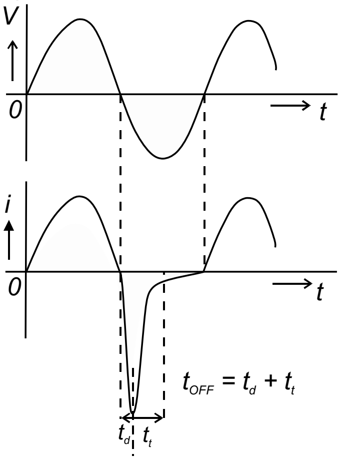

Fig. 1. SRD characteristic voltage and current in time.

Using SRDs, picosecond pulses with transition times in the range 15 - 200 ps can be achieved. The generator output must be capacitively isolated from the DC bias on the SRD. The reverse SRD voltage is normally around 20-35 V. SRD application note HP AN918 [14] describes the processes in more detail. The number of SRD manufacturers is currently very limited; the best-known manufacturers were MACOM and Hewlett-Packard (manufacturing is closed down but stocks are still available from some suppliers).

III. DESIGN OF PULSE GENERATOR

This section will describe the design of individual parts of the generator. A programmable generator is described in more detail, which will serve as an trigger for the SRD circuit. The SRD pulse generator forms the output part of the programmable generator, which itself does not reach sufficient magnitude of output pulses, since it is designed for use directly into the sensitive UHF detection electronics input, rather than to inject signals into a UHF sensor on a high voltage test object such as a transformer or GIS. Fig. 2 shows the programmable generator referred to as "G1". The generator has three high frequency (HF) and three (UHF) outputs. It is powered from and synchronized to the mains and can be programmed via USB using software on a PC. The software allows different PD phase-resolved patterns to be programmed, even based on recorded ‘real’ PD activity.

Fig. 2. Programmable generator “G1”.

Predefined patterns can be selected and activated using the buttons on the generator. The times of rising and falling edges of the pulses were 5-7 ns, for the purpose of validating PD detection systems the output voltage was also small (maximum 2.8 V). Figs. 3 and 4 show examples of the outputs of G1. The aim of the work described in this paper was to develop a circuit to boost the output of G1, maintaining its PD pattern programmability while generating pulses more similar to PD current pulses.

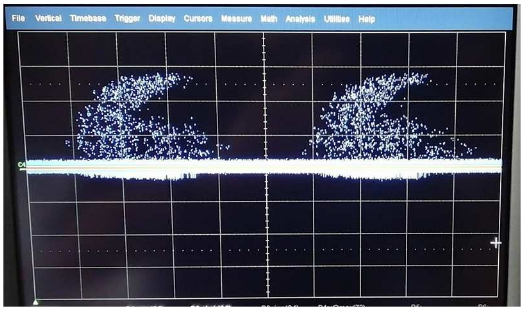

Fig. 3. A programmed ‘void-type’ PD pattern replayed to a 50 Hz line-triggered oscilloscope with persistence display enabled (500 mV/div; 2ms/div).

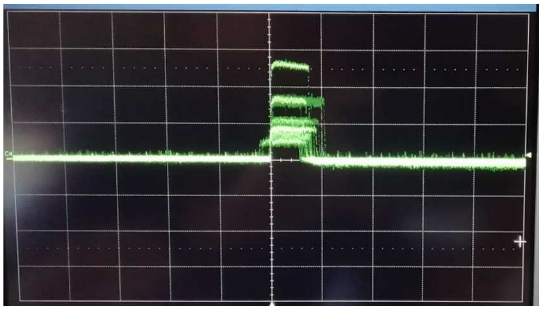

Fig. 4. Individual pulses on the HF output channel have variable amplitude (shown here with display persistence enabled, 500 mV/div). Pulse duration is about 150 – 200 ns (200 ns/div).

Individual parts of the proposed pulse generation system represented in the diagram of Fig. 5 will now be described.

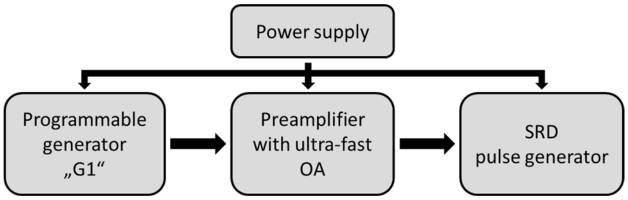

Fig. 5. Block diagram of pulse generation system.

A. *Preamplifier with ultra fast operational amplifiers (OA)*

To boost the SRD excitation voltage, a preamplifier with the OA was included after the generator G1. This is a two-stage non-inverting amplifier. The minimum required slew rate (SR) to transmit a signal with an amplitude of 8 V and a transition time of 5 ns is

$$SR = \frac{\Delta V_{out}}{\Delta t}, \qquad (1)$$

where ΔV_{out} is a change in the output voltage and Δt is the transition time. If we assume an output voltage from the PD pattern generator G1 is 2 V, after amplification ×4 it will be 8 V, which requires an SR of 1600 V/µs. Operational amplifiers type THS3491 from Texas Instruments were chosen for the amplifier, which achieve a slew rate of up to 8000 V/µs and their bandwidth ranges from 320 to 900 MHz (320 MHz for large-signal bandwidth). The selected OAs have a maximum recommended output voltage of 20 V_{pp} (for supply voltage ± 15V). Thus, their output meets the expected requirements at an input voltage of around 2 - 2.5 V. This ensures that the input signal from G1 is not distorted. According to the manufacturer's recommendations [15], suitable sizes of feedback resistors were calculated and chosen. The first stage of the amplifier has a gain of ×4 and the second stage ×2. The total gain is therefore ×8. The circuit schematic is shown in Fig. 6. Capacitors C14 and C19 were added to limit the frequency range and prevent amplifier oscillation.

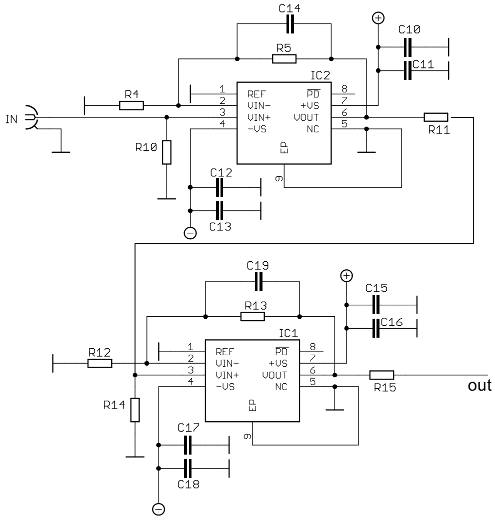

Fig. 6. Schematic of two-stage preamplifier circuit.

B. *Step recovery diode pulse generator*

The second part of the design is a circuit with SRD [17]. The SRD perform the role of leading signal edge sharpener. A pulse-forming network is also included, which generates the desired narrow pulse. References [11] and [12] were used to design the generator. Designs of the generator with SRDs and their possible modifications and improvements are described in [13], [14]. The SRD connection contains a Schottky diode and a delay line, which allows the generation of narrow pulses to maximise the signal bandwidth. A further advantage of this design is the reduction of ringing. The schematic of SRD generator is given in Fig. 7.

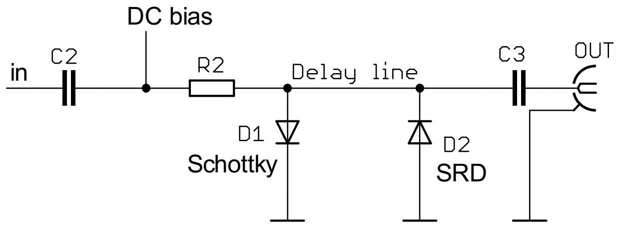

Fig. 7. Schematic of SRD pulse generator.

The generator also requires a power supply. A laboratory symmetrical source was used for supplying the OAs and a linear regulator of the LM337 series, included on the PCB, was used to set the DC bias current of the SRD. The power supply of the OAs is ± 15 V. The fabricated and populated PCB is shown in Fig. 8.

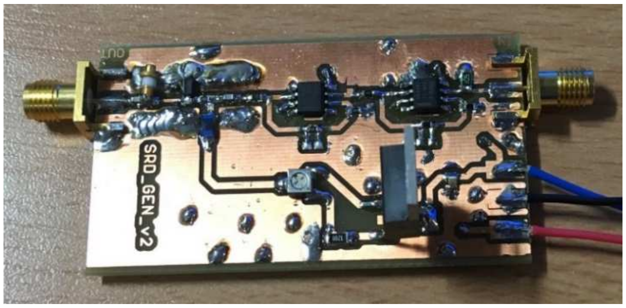

Fig. 8. Complete PCB with SRD generator. Input is at the right and the output from the SRD circuit is at the left.

IV. PULSE GENERATOR MEASUREMENTS

This section deals with measurements of output pulses from the pulse generator. Both the laboratory generator and the G1 generator for which the proposed generator is intended were used for the measurement. A Tektronix TDS 694C oscilloscope (bandwidth 3 GHz, sampling rate 10 GS/s) was used to measure the output waveforms. The limiting risetime of this oscilloscope based on its bandwidth is theoretically 133 ps. Hence, for measurements on the timescales involved here, the true risetimes will be lower than those apparent on the oscilloscope.

A. *Driving signal from laboratory signal generator*

In the first tests, the SRD generator was driven from a laboratory generator by rectangular pulses. The risetime of the pulse was 7 ns and the repetition frequency was 3.15 MHz. After amplification, the SRD driving pulse had an amplitude of 12 V. Under these conditions, the SRD circuit had a peak of 8.8 V and a risetime (without correction for the oscilloscope risetime) of approximately 150 ps, as shown in Fig. 9.

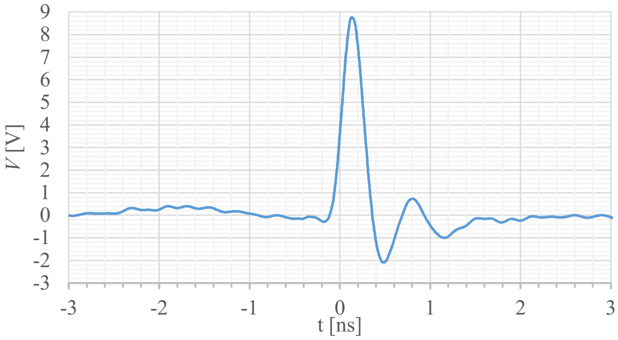

Fig. 9. Measured output impulse of SRD generator.

B. *Driving pulses from programable generator*

A further measurement was performed with the PD pattern generator G1 to show that the output pulses from the SRD are dependent on the magnitude of the driving pulses. This confirmed the operation as the pulses have different amplitudes according to the G1 PD pattern programming. Depending on the repetition frequency and the shape of the driving pulses the rise times of the output pulses also changed slightly. An example captured waveform is shown in Fig. 10.

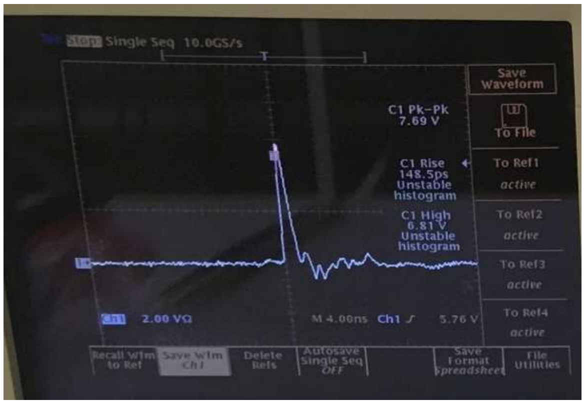

Fig. 10. Screenshot of an SRD generator output impulse when driven by G1. In this example, the observed risetime and amplitude were approximately 145 ps and 6.81 V respectively.

V. CONCLUSION

In this paper, we have described the design of an impulse generator as the output stage for a programmable PD pattern generator G1, which is used to check and validate UHF PD sensors for GIS or transformers. The impulse generator consists of a preamplifier using a pair of high speed operational amplifiers followed by an SRD edge sharpener with pulse-forming network. The whole device was built and its performance evaluated by measurements. The results show a maximum pulse amplitude of 11.5 V and a risetime that is expected to be below 100 ps once the bandwidth limitations of the measuring oscilloscope are taken into account. The output pulses show a slight ringing, which may in part be due to the PCB material used or aspects of the PCB layout. We have thus successfully improved the G1 programmable generator to the requirements for on-site pulse injection. Subsequently, further trials will take place during the testing of GIS or transformers equipped with UHF PD sensors.

ACKNOWLEDGMENT

The preparation of this paper was assisted by the general student development project BD FEKT-S-20-6360 in progress at Brno University of Technology and Erasmus exchange project at the University of Strathclyde.

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