Picosecond semiconductor generator for capacitive sensors calibration

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Abstract. The paper describes a semiconductor picosecond pulse generator that can be used to calibrate capacitive high voltage sensors of MV range. The generator is designed as a base unit, to which external pulse converters are connected. In the base unit, semiconductor devices – first a semiconductor opening switch (SOS) and then a semiconductor sharpener (SS) – generate an output pulse with a rise time of 220 ps and a subsequent flat-top of 2 ns in duration. The pulse amplitude is around 1 kV across 50 $\Omega$ load. An external diode sharpener generates a pulse with 120 ps rise time and 500-ps flat-top at the amplitude of 850 V. To switch the semiconductor sharpeners to the conducting state, the shock-ionization wave mode is used. Additional pulse converters make it possible to generate output pulses across 50 $\Omega$ load with the rise time of 70–150 ps, the pulse duration of 135–310 ps, and the amplitude of 130–480 V. The electrical diagram of the generator and waveforms of the output pulses are presented. An example of the calibration of capacitive sensors of a multi-gigawatt picosecond generator is also shown.

1. Introduction

Since the end of the XX century, active development of the picosecond time range began in pulsed power technology, that is, the development of devices for generating and using picosecond pulses of electrical energy [1]. High-power high-voltage generators with picosecond pulse widths and rise times are used, for example, in generation of picosecond x-ray pulses and electron beams [1], ultra-wide bandwidth (UWB) microwave pulses [2], runaway electrons in air [3] and in studies of gas discharges at picosecond time scale [4, 5]. In the last few years, a new class of picosecond pulse generators was developed – all-solid-state multi-gigawatt picosecond generators [6–8]. In these generators a pulse created by a semiconductor opening switch (SOS) is compressed in time and amplified in power using gyromagnetic non-linear transmission lines. At the present day these generators can achieve peak power of more than 77 GW and peak voltage of more than 1.9 MV at pulse length of about 100 ps [8].

Registration of such pulses requires the usage of MV-withstand voltage sensors with the voltage ratio (voltage division factor) of about $10^3$, so that the pulse can then be safely attenuated by wide-bandwidth attenuators and fed into an oscilloscope. Such voltage sensors usually are custom made for a specific device’s needs. One popular construction is a capacitive voltage sensor [9], which is constructed by placing a sensing electrode on the inner side of the outer conductor of the pulse-carrying transmission line. The capacitances between the inner conductor of the line and a sensing electrode, and between the sensing electrode and the outer conductor, act as a capacitive voltage
divider. The signal from the sensor is then transmitted through a coaxial cable to the measuring system.

To measure a reaction of such voltage sensor to a fast pulse, a calibration is required. As the sensor has a high voltage division factor, calibration pulse needs to have an amplitude of 100-1000 V to increase signal-to-noise ratio. The rise time of the pulse needs to be less than or equal to the rise time of the measured pulse. In this work a compact calibration generator, which provides such calibration pulses, has been developed and tested.

2. Electrical circuit and operating principle

A simplified circuit diagram of the generator is shown in figure 1. It can be divided into two main parts: nanosecond driver ND (all the components before and including the SOS) and output pulse forming system OPFS (all the components after the SOS). The ND provides initial high voltage pulse of several kV in amplitude and several ns in duration. The initial pulse is then supplied to the OPFS, where it is converted into a pulse with picosecond parameters. Both ND and OPFS are designed using all-solid-state approach, which provides increased pulse stability and maximizes pulse repetition frequency (PRF).

![Figure 1. Simplified circuit diagram of the SOS-based nanosecond driver.](image)

Functionally ND is a compact SOS-based nanosecond pulse generator, to which OPFS acts as a load. The capacitor C1 acts as primary energy storage and is charged to a voltage of 1 kV from a high voltage power supply. C1 is made up of polypropylene low-ESL capacitors, with a total capacitance of 47 nF, corresponding to a charging energy of about 24 mJ. Primary switch S1 is made up of 2 IRG4PH50UD IGBTs connected in parallel. Pumping capacitor C2 is ceramic high-voltage KVI-3 model with 2.2 nF capacitance and 10 kV maximum operating voltage. Pulse transformer PT1 is wound on a toroidal ferrite core of M3000NM material with outer diameter of 32 mm, inner diameter of 20 mm and height of 9 mm. Primary winding consists of 3 turns and secondary winding consists of 6 turns.

The ND’s operation is as follows. When the primary switch S1 closes, energy from the primary storage C1 is transferred through a pulse transformer PT1 into the pumping capacitor C2. The current corresponding to this process on the secondary side of PT1 provides the forward pumping of the SOS, with peak current $I_+ = 40$ A and duration $t_+ = 210$ ns. After the forward pumping is complete, the core of PT1 reaches saturation and the pumping capacitor C2 rapidly discharges through the secondary winding of saturated PT1 and the SOS, providing the reverse pumping current with amplitude $I_-$ of 160 A and duration $t_- = 45$ ns. When the reverse pumping current achieves maximum value, the energy previously stored in the electric field of C2 is fully converted into the energy of magnetic field.
of the secondary winding of saturated PT1, which acts as an inductive storage. At that moment SOS cuts off the current in less than 10 ns, resulting in rapid energy transfer from the magnetic field of the secondary winding into the load, resulting in a nanosecond pulse being formed across the load (OPFS). The waveforms of pumping current and load voltage are shown in figure 2. The polarity of the output pulse is negative.

The duration of the reverse pumping needs to be as short as possible to achieve the shortest current cut-off time in SOS. This duration is determined by the saturated inductance of PT1 secondary winding. To decrease this inductance, PT1 has several construction features. The secondary winding consists of two windings of 6 turns each, connected in parallel and distributed across the core. The transformer itself is magnetically biased by the means of an additional winding, consisting of 4 turns with a DC current of 1.7 A. The bias allows reducing the size of the transformer and hence helps to further reduce the saturated inductance of the secondary winding.

![Figure 2. Waveforms of SOS operation.](image-url)

The pulse generated by SOS has amplitude of 7.6 kV and rise time of 5.6 ns. This nanosecond pulse is fed into the OPFS as the input one, by means of voltage divider R1-R2, which steps down the voltage of the pulse to experimentally found optimal value. The divider is made of non-inductive carbon-composition TVO resistors. The stepped-down pulse charges the pulse-forming line PFL1. At the same time the charging voltage wave applies to the silicon sharpener SS1. The optimal amplitude of the charging voltage ensures the voltage rise rate of about $10^{12}$ V/s needed to initiate a shock-ionization wave in a diode, which allows it to switch to the conducting state in a sub-nanosecond time interval. The switching connects PFL1 to the generator’s output, forming a pulse with the amplitude of about 1 kV and a rise time of about 200 ps across a 50-ohm matched load. PFL1 is made of a 20-cm length of 50-ohm 5D-FB radio-frequency coaxial cable with N-connectors on both sides.

The pulse formed by PFL1 and SS1 is supplied to the output terminal of the base unit of the generator. N-type connector is used as an output terminal. Various external converters can be attached to this terminal to change the parameters of the pulse. Several external converters have been constructed: external silicon sharpeners, differentiating networks, and short-circuited stubs.

The generator has internal triggering system, which allows it to operate in three modes: single-pulse mode, repetitive mode with PRF of 10 Hz, and repetitive mode with PRF of 100 Hz.
3. Waveforms of the output pulses

The waveforms of the output pulses were recorded using Tektronix DPO70404C 4 GHz and Tektronix DPO73304D 33 GHz digital oscilloscopes and wide-bandwidth attenuators made by Barth Electronics and Weinschel with the bandwidth of 18 GHz. To carry the signal, microwave coaxial cables Eacon 4C by H+S were used, also rated at 18 GHz. All the rise time measurements were made at 0.1-0.9 levels of the fast part of the pulse front, not including the prepulse. Such method was chosen because for sensor calibration only a rapid voltage transition is of interest.

The waveform of the pulse formed at the output of the base unit is shown in figures 3a and 3b. The rise time is 220 ps, and the flat-top amplitude is 1020 V. The duration of the flat top is 2 ns. SS1 and other silicon sharpeners are mounted in the manner shown in figure 4. The sharpener module is made of N-socket to N-socket adapter screwed into N-type end connector meant for RG-213 cable. The sharpening diode is soldered between two leads which fit inside the N-type module, resulting in a coaxial construction with a diode being soldered into the break in the center conductor. For SS1 a reverse-biased low-frequency silicon diode BYM10-600 by Vishay is used.

![Figure 3. Waveforms of the base unit output pulse.](image)

![Figure 4. Construction of the silicon sharpener module.](image)

Adding a second silicon sharpener SS2 to the output of the generator forms a pulse shown in figure 5. The pulse has the amplitude of 850 V, the rise time of 120 ps, and the flat-top duration of about 500 ps. For SS2 the low-frequency KD102A and KD104A diodes were found to provide optimal performance. The relatively large prepulse is caused by the displacement current flowing through the diode’s junction capacitance at the fast portion of the incident pulse. The chosen diodes provide the lowest amplitude of the prepulse out of all tested models. SS2 is mounted into an N-type module analogous to SS1 module. Attempts were made to mount SS2 into a break of one of the conductors of FR4-based stripline and microstripline sections. It was found that the rise times of pulses formed in
such configurations are comparable to, but not as fast as the ones formed in the coaxial configuration (130-150 ps compared to 120 ps). However, it should be noted that manufacturing pulse shaping modules using stripline technique is far easier than using coaxial constructions, so the striplines seem to be a viable option for constructing small-scale picosecond pulsed power elements.

Figure 5. The waveform of the output pulse after SS2 sharpener.

The square-like pulses formed by silicon sharpeners can be converted into bell-shape pulses by adding a differentiating network to the output. Depending on the exact waveform of the input pulse, differentiation can reduce its rise time from about 1.5 up to 2 times. The network can be comprised of a lumped inductance connected in parallel to the characteristic impedance of the transmission line, or of a lumped capacitance connected in series with the characteristic impedance of the transmission line. For short, these networks will hereafter be called “L-network” and “C-network” respectively.

To differentiate the output pulse of the base unit, a C-network was used. The waveform of the resulting pulse is shown in figure 6. The pulse has the following parameters: amplitude of 480 V, rise time of 150 ps, duration of 310 ps. The C-network consists of a capacitor mounted into a break in the central conductor of the coaxial line, which effectively introduces a small capacitive discontinuity in series with the transmission line. The pulse mostly reflects from the discontinuity, only the fast portion of the pulse being transmitted. It was found that using junction capacitance of reverse-biased diodes as a capacitive discontinuity is quite convenient. The waveform in figure 6 was obtained with 1N5393 diode as the capacitor mounted in the coaxial configuration (construction analogous to SS1 and SS2 modules). Making a C-network based on a stripline with FR4 substrate was also found to be feasible. In that case the capacitor is made by creating a short break in one of the line conductors, and soldering a piece of copper foil to one side of the break, with the other side of the break insulated, such that the foil overlaps the break. This approach allows easily tuning the capacitance to achieve needed pulse parameters.

To convert the pulse after SS2 into a bell-like pulse the L-network was used, which proved more convenient than C-network to differentiate faster pulses. The waveform after the network is shown in figure 7. The pulse has the following parameters: amplitude of 130 V, rise time of 70 ps, duration of 135 ps. The L-network was made as a piece of FR4-based stripline with a small copper short soldered
between the conductors. When the pulse passes the short, only the fast portion of the pulse is transmitted, while most of the pulse is reflected.

This introduction of a small inductive discontinuity in parallel to the transmission line can also be viewed as an extreme case of a short-circuited stub being placed in parallel to the line, which is also a technique used to shaped pulses [9]. When aiming for the fastest rise time, the stub is made as short as possible. If in these attempts the length of the stub becomes much shorter than the electrical length of the input signal’s rise time, the stub operates in a lumped mode, which for a short-circuited length of a transmission line is simply an inductance. This puts a limit on the reduction of the rise time by the stub technique, because with the stub getting shorter and shorter, the system transitions into operation as a differentiating L-network, which cannot shorten the rise time more than twofold.

Figure 6. The waveform of the output pulse after a C-network.

Figure 7. The waveform of the output pulse after an L-network.
4. Example of capacitive sensors calibration

The calibration generator was tested on a test setup for the measuring section of a powerful picosecond pulse generator. The setup consists of a 50-ohm measuring section of a coaxial line with the inner diameter of the outer conductor of 50 mm, and conical transitions between the measuring section and N-type input and output connectors of the setup. Measuring section contains several capacitive voltage sensors, the signals from which are outputted via N-type and SMA connectors.

The calibration procedure is as follows. Firstly, a calibration pulse is chosen from available options, corresponding to the time range of interest. This pulse is fed into the oscilloscope through wide-bandwidth attenuators and saved as a reference. After that the pulse is fed into the input terminal of the test setup. While traveling through the measuring section, the pulse interacts with a capacitive voltage sensor and the measured waveform is sent from the sensor into the coaxial cable to the oscilloscope. When the pulse reaches the output of the test setup, it is also sent to the oscilloscope through a cable and wide-bandwidth attenuators. All the data is pulse-to-pulse averaged using at least 100 pulses to mitigate any pulse instabilities. The ability of the calibration generator to operate with PRF of up to 100 Hz allows quickly obtaining hundreds and thousands of samples for averaging. To summarize, the measured data set on the oscilloscope consists of the reference pulse, the pulse from the output of the test setup, and the registered pulse from voltage sensor.

![Typical sensor calibration waveforms.](image)

All the pulses are synchronized in the oscilloscope, so that their rise times overlap. That is done via “Deskew” function of the oscilloscope to account for different electrical lengths of “sensor - oscilloscope” and “setup output - oscilloscope” signal paths. Simple math functions are then used to analyze the data. The reference pulse and the setup output pulse are mathematically averaged together to account for the inevitable distortion of the pulse in the test setup. The distortion, according to additional TDR (time-domain reflectometry) measurements, is mainly caused by non-ideal conical transitions. At this stage the registration capabilities of the sensor can be observed directly by comparing the averaged pulse and the registered pulse. The performance of the sensor can also be characterized numerically, by mathematically dividing the averaged pulse by the registered pulse, which results in a function of voltage ratio over time. Figure 8 shows typical waveforms obtained after the calibration: the averaged input pulse, sensor’s registered pulse, and the resulting input-to-output voltage ratio. To increase the accuracy, the whole procedure can then be performed with the input and the output of the test setup swapped. The obtained data can then be mathematically averaged with the previous data to further account for the distortion of the pulse in the test setup.
5. Conclusion
The paper describes a calibration generator constructed for calibration of MV-range picosecond capacitive voltage sensors with high voltage division factors. The generator was constructed using all-solid-state approach to maximize pulse stability and pulse repetition frequency. To generate the initial high-voltage pulse, a semiconductor opening switch (SOS) is used. The fast rise times of the output pulses are generated using rectifier diodes operating as silicon sharpeners with impact-ionization wave initiation. The pulses obtained from the sharpeners have a flat-top with an amplitude of about 1 kV and rise time as low as 120 ps. The pulses can then be converted to short bell-shape pulses using differentiating networks, achieving rise times as low as 70 ps and durations of several hundreds of ps. An example of calibration of capacitive sensors using obtained pulses was shown.

Acknowledgements
The authors are grateful to the Electrophysics department of the Ural Federal University for offering the possibility to perform measurements using the Tektronix DPO73304D oscilloscope. The experiments were carried out on the equipment of the Collective Use Center at the Institute of Electrophysics, UB RAS.

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