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Final Implementation of a Subnanosecond Rise Time, Variable Pulse Duration, Variable Amplitude, Repetitive, High-Voltage Pulse Source

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Abstract—In this paper, we present the final implementation of our 0–50-kV picosecond rise time 0.5–10-ns pulse generator. The pulse generator will be used in future work to generate a (sub-)nanosecond streamer plasma for air purification research. The pulse generator is a single-line pulse generator with an oil spark-gap (SG), which generates 0.5–10-ns pulses with a 200-ns rise time and can operate at repetition rates of over 1 kHz into a 50-Ω load. It is an improvement over the first implementation of our nanosecond pulse generator that we designed and verified experimentally in previous work. In this paper, we evaluate the performance of the final design. Furthermore, we present 3-D electromagnetic simulations of the nanosecond pulse generator and show that the simulations are in good agreement with the measurements. A variation in pulse duration from 0.5 to 10 ns is possible and the output pulses are square shaped without the large plateau behind the main pulse that was present in the pulses from the first implementation of the nanosecond pulse generator. At high voltages, the pulse top becomes less flat due to a time-dependent mismatch in the spark-gap. Furthermore, investigation of electrode erosion of the oil spark-gap shows that the erosion rate of the electrodes is in the range of 200–600 μcm²·C⁻¹ for the electrode that is mainly the cathode and 100–300 μcm³·C⁻¹ for the electrode that is mainly the anode, respectively. This is almost an order of magnitude higher than most gas spark-gap studies show for brass electrodes. Therefore, electrode erosion in the oil spark-gap will be a limiting factor on the lifetime of the system. We designed a new electrode with a stainless steel head to increase this lifetime.

Index Terms—3-D electromagnetic (EM) modeling, electrode erosion, high voltage, nanosecond pulses, oil switch, pulsed power supply, spark-gap (SG).

I. INTRODUCTION

RECENT research has shown that plasmas generated by very short nanosecond high-voltage pulses are very efficient for a variety of applications [3]–[7]. Nonthermal plasma proves especially useful for air purification purposes [8], [9]. In our research, we will study a corona reactor in which we generate a streamer plasma with very short (<10 ns) high-voltage pulses for air purification.

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Fig. 1. Schematic of the single-line pulse generator. The pulse charger charges the PFL, which is then discharged by the spark-gap in a matched cable. When the voltage pulse reaches the corona reactor, it generates a streamer plasma.

Fig. 2. Best obtainable pulse shape with the first implementation of the pulse generator. We uses a shorter outer conductor than the inner conductor in the PFL and has ferrites at the end of the outer conductor to block the incoming wave from the spark-gap and mimic an open end (the disturbance at around 20 ns is the reflection of the pulse on the nonideal load and can therefore be ignored).

We will investigate what effect pulse parameters such as pulse duration (0.5–10 ns), pulse polarity, and pulse amplitude (up to 50 kV) have on different air purification applications. Therefore, we need a pulse generator that is able to generate this variety of pulses.

In [1], we designed this flexible nanosecond pulse generator. The schematic of this pulse generator is shown in Fig. 1. It is a classical single-line pulse generator where the output waveform is square, has an amplitude of half the charging voltage, and a pulse duration of twice the transit time of the pulse forming line (PFL) [10].

A pulse charger charges the PFL. The PFL is then discharged by a spark-gap (SG) into a matched coaxial cable that is connected to a load (a corona plasma reactor in our case). The cable acts as a delay line for synchronization of plasma diagnostics with the switching of the spark-gap. When the spark-gap switches, a wave propagates from the spark-gap to the end of the PFL. Here, it is reflected back toward the
Fig. 3. Cutaway drawing of the first implementation of the nanosecond pulse generator. It is an oil-filled coaxial structure with a fixed length inner and outer PFL conductors (reproduced from [2]).

spark-gap (the end of the PFL should be an open end) and finally into the cable. Together with the wave that travels into the cable, the moment the spark-gap switches, these two waves make up the output pulse.

We presented the first 5-ns implementation of our pulse generator in [2]. It had a fixed length PFL and therefore a fixed output pulse duration. Its purpose was to evaluate the performance of such a pulse generator, verify 3-D time-domain electromagnetic (EM) simulations and to solve a variety of challenges that arise when working with very short pulses. One of these challenges was the measurement of the pulses. We were successfully able to measure the very short pulses with a calibrated D-dot sensor. The pulse generator performed as expected, with a well-defined square 5-ns output pulse with a rise time of less than 200 ps. A critical point was the connection of the pulse charger to the PFL of the pulse generator. When the pulse charger was not properly decoupled from the PFL, the wave that propagates to the end of the PFL could partially travel along the connecting wire toward the pulse charger, when it should have reflected on an open end back into the PFL. This remained a point for future investigation.

A second purpose of the first implementation of the nanosecond pulse generator was to test the variable pulse duration ideas that we proposed in [1]. These ideas consisted of using a variable length outer conductor for the PFL, magnetic materials at a variable position in the PFL, and a combination of both. The results showed that a variation of pulse duration was possible with these three configurations, but that the pulse shape was far from ideal. The best configuration was a combination of a variable length outer conductor for the PFL with magnetic material at the end of the PFL to mimic an open end. Fig. 2 shows the best obtainable pulse shape with that configuration. Most noticeable is the plateau behind the 2-ns pulse and the disturbance at around 20 ns. This disturbance can be ignored; this is the reflection of the pulse on the nonideal load used in that experiment. However, the plateau is an issue for our application, because this low voltage could sustain the plasma in our corona plasma reactor [11]. It was therefore necessary to design a new pulse generator where the inner conductor of the PFL changes length as well to avoid the low-voltage plateau behind the pulse.

In Section II, we discuss the design and simulation of the final implementation of the nanosecond pulse generator. In Section III, we briefly present the experimental setup, and Section IV contains the results of the experiments and an investigation of the electrode erosion in the oil spark-gap of the nanosecond pulse generator. Finally, Section V presents the conclusion.

II. Pulse Source

A. Design

The design of the first implementation of the pulse generator is a coaxial structure with an integrated oil spark-gap. It is shown in Fig. 3. It is an oil-filled structure with Polytetrafluoroethylene, Teflon (PTFE) mechanical supports. The pulse generator performed as expected, with a well-defined square 5-ns output pulse with a rise time of less than 200 ps. A critical point was the connection of the pulse charger to the PFL of the pulse generator. When the pulse charger was not properly decoupled from the PFL, the wave that propagates to the end of the PFL could partially travel along the connecting wire toward the pulse charger, when it should have reflected on an open end back into the PFL. This remained a point for future investigation.

In the new design of the pulse generator, the inner and outer PFL conductors both have to change the length to obtain a variable pulse duration without a plateau at the end of the pulse. We redesigned the oil input of the spark-gap in such a way that the inner conductor can be changed at will (in the previous pulse generator, the inner conductor served as the oil input). Now, the oil is fed through the PTFE support between the PFL and the spark-gap. Furthermore, the length of the PFL can be changed by adding or removing sections of the inner and outer conductors. Fig. 4 shows the design of the new pulse generator.

Sections of 100 and 50 mm of inner and outer conductors represent 1- and 0.5-ns pulse durations, respectively. They can be added up to a total length of 1000 mm (10 ns). This results in a pulse duration variability of 0.5–10 ns in steps of 0.5 ns.

B. Simulation Results

Previously, we simulated the pulse generator using the time-domain 3-D EM solver in CST Microwave Studio (CST MWS) [1]. We use the same simulation technique
III. EXPERIMENTAL SETUP

In addition to the nanosecond pulse generator, we described in the previous section, we also require a microsecond pulse charger to charge the PFL of the nanosecond pulse generator, electrical diagnostics to measure the output waveform of the pulse generator, and an oil setup for the spark-gap flushing. These provisions are described in detail in [2] and [12] and are summarized briefly in this section.

A. Oil Setup

The nanosecond pulse generator is submerged in a 1.3 x 0.35 x 0.3 m (length x width x height) stainless steel container filled up to 0.15 m with transformer oil (Shell Diala S3-ZX-I Dried). Aside from the oil in the container, a second oil system feeds high-pressure oil (up to 0.5 MPa) into the spark-gap. Fig. 6 shows a schematic of this system. The oil is pumped into a filter and through the spark-gap of the nanosecond pulse generator. After passing the spark-gap, the oil flows back into an oil reservoir. We can set the oil pressure by adjusting the speed of the pump.

B. Microsecond Pulse Charger

The hold-off voltage of an oil spark-gap is much higher for a pulsed voltage as compared with a dc voltage [13]. Therefore, we need to charge the PFL of the nanosecond pulse generator with a high-voltage pulse with a duration of several microseconds. Shorter pulses would be able to cross the spark-gap through capacitive coupling and longer pulses would result in a lower hold-off voltage. We described the required 120-kV microsecond pulse charger in [12] and use it in this paper.

C. Voltage Measurements

We use a D-dot sensor that is integrated in the SA24272 cable at the output of the pulse generator to measure the output pulse of the pulse generator. It was introduced in [2]. It is working fully in the differentiating domain up to at least 4 GHz. To convert the measured signal from the D-dot sensor to the actual waveform of the output pulse, the measured signal is first corrected for the attenuation of the measuring cable assembly and then integrated. A calibrated gain is applied on top of offset correction to obtain the final result.

In [2], we used an SA24272 cable of only several meters with a matched load. In the experiments of this paper, we use a longer SA24272 cable (around 30 m) that will be needed in future work to delay the output pulses for synchronization with an intensified charge coupled device camera. For the moment, there is no load at the end of this cable. The longer SA24272 is equipped with a similar calibrated D-dot sensor, as in [2].
IV. RESULTS

A. Connection of the Pulse Charger

During our previous experiments in [2], we noticed that the connection of the pulse charger to the nanosecond pulse generator is an important consideration. Ideally, the wave that travels from the spark-gap to the end of the PFL should reflect on a perfect open end to generate a perfect square-shaped output pulse. In reality, the end of the PFL is the position where the pulse charger is connected to charge the PFL. Therefore, the wave is partially transmitted over the wire that connects the PFL to the pulse charger. It will reflect on the pulse charger and add to the output pulse at a later point in time. This causes a plateau after the pulse. Fig. 7 shows this problem: it is the 2-ns output of the new pulse generator with a 0.5-m long wire connecting it to the pulse charger.

We require an impedance between the pulse charger and the PFL of the nanosecond pulse generator to decouple the two systems for high frequencies. This ensures that the nanosecond pulses cannot travel over the connecting wire. However, the microsecond pulses from the pulse charger should still be able to charge the PFL. An inductor with the right value $L$ would be a good choice for the decoupling impedance, because its impedance increases linearly with frequency: $j\omega L$.

Adding an inductor between the PFL and the pulse charger achieved moderate success with the first implementation of the nanosecond pulse generator in decoupling the two systems [2]. However, the inductor should be placed as close to the PFL and be as compact as possible.

To obtain a good indication on how big the inductor should be, we used the circuit of Fig. 8 to simulate the pulse charger connection in LTSpice. The pulse charger block represents the simulation circuit from [12]. All the transmission line components in the circuit are lossless and ideal. The first of these transmission lines represents the wire connecting the pulse charger to the PFL of the nanosecond pulse generator, followed by the inductor under investigation and the transmission line representing the PFL itself. After that comes an ideal switch, which represents the oil spark-gap and a transmission line to simulate the SA24272. This last transmission line is terminated with a resistor $R_l$ with the characteristic impedance of the line. This simulation model is very simplistic and ideal, but should give a good impression on the behavior of the proposed inductor between the pulse charger and the nanosecond pulse generator.

Fig. 9 shows the simulated voltage over $R_l$ for a number of values of $L$. The results show that at $L = 1\, \mu\text{H}$, the pulse charger is properly decoupled. However, the practical implementation of such an inductor would be very large. Furthermore, the voltage across this inductor while charging the PFL becomes quite large for this inductor value. This indicates that the PFL also starts to become decoupled for the microsecond charging pulse. As a compromise, and after the experimental verification, we chose a value of 200 $\mu\text{H}$.
We designed and built a compact inductor of around 200 $\mu$H, which is connected to the end cap of the inner conductor of the PFL. This value for the inductor ensures an impedance of only several hundreds of ohms for the microsecond pulses, but hundreds of kiloohms for the nanosecond pulses. Fig. 10 shows this decoupling inductor and Fig. 11 shows the impact it has on the output of the nanosecond pulse generator: it is successfully able to remove the plateau from the pulse.

**B. Variable Pulse Duration**

With the decoupling inductor in place, we varied the length of the PFL of the nanosecond pulse generator in steps of 1 ns and measured the output pulse. Fig. 12 shows the results.

The figure shows that the new pulse variation method works very well with square-shaped output pulses as a result. The slight rise toward the end of the pulse for longer pulse durations will be addressed in the following section. Apart from this issue, the results show a very good agreement with the CST MWS simulations of Section II-B. The pulses have a rise time of around 200 ps.

**C. Variable Voltage**

We can vary the output voltage by changing the gap distance (in the range 0.25–1 mm) of the spark-gap and the charge voltage of the PFL. Fig. 13 shows the result of such an experiment. The figure shows that a variation in output voltage is possible. The lowest voltage for which the spark-gap still performs well is around 3 kV. For the moment, we limit the output voltage of the nanosecond pulse generator to 40 kV because there is no load at the end of the SA24272 cable. This results in a doubling of the voltage at the end of the cable, which might damage the cable for higher voltages. This brings the practical output voltage range at the moment to 3–40 kV, which can be extended to at least 3–50 kV on a matched load.

In Fig. 12, we already noticed that the pulse rises toward the end of the pulse duration. The results of Fig. 13 shows that this effect becomes more pronounced at higher voltages. At low voltages, the pulse top is very flat, but at high voltages, it takes some time before the pulse reaches its end value. There is no noticeable difference between positive and negative output voltages.

The explanation for the nonflat pulse top at high voltages is an impedance mismatch at the spark-gap in the pulse generator. When the spark-gap switches, one wave travels toward the end of the PFL and another propagates toward the SA24272 cable. However, when there is a mismatch at the spark-gap, a part of the wave that should propagate toward the cable is reflected toward the PFL. It then travels the entire length of the PFL, reflects at the end and then adds at the end of the pulse.

The reason that the spark-gap is mismatched at high voltages is twofold. First, the gap distance is larger at high voltages, and therefore the discontinuity in the 50-\(\Omega\) structure around the spark-gap is bigger. This in itself causes more mismatch than at low voltages. Second, when the spark-gap has just switched on, the spark channel is very thin. It then heats up and expands. This decreases the resistance of the spark and simultaneously lowers the transmission line impedance of the spark-gap. Therefore, in time, the mismatch reduces and the wave propagating toward the SA24272 cable is reflected to a lesser extent. Therefore, the voltage rises in time. When the main pulse has passed the spark-gap (SG), the original reflected wave arrives at the spark-gap, is now not reflected, and propagates toward the load. This is the tail that is apparent after the main pulse has finished. The mismatch caused by the expanding spark channel is less pronounced at low voltages because it has less effect at smaller gap distances.

Fig. 14 shows a more detailed figure. At \(t_1\), the pulse begins, but its amplitude is lower than when it finishes at \(t_2\) because of the time-dependent mismatch. Between \(t_2\) and \(t_3\), we see the tail caused by the reflected initial wave. To show that this
tail is indeed the reflected initial wave, we add this tail ($t_2 - t_3$) to the period $t_1 - t_2$. The result is a square-shaped pulse as it was intended (dashed line).

The tail of the pulse is not nearly as pronounced as the plateau that we had previously with the first implementation of the pulse generator (Fig. 2) and is not expected to influence the plasma in the corona plasma reactor much.

The most straightforward method to improve the pulse shape at high voltages is to keep the gap distance small. However, the oil pressure would have to be increased significantly (by a factor of at least 10) to be able to switch the very high voltages required for a high output voltage [14]. This is currently not possible in our nanosecond pulse generator, but would be an option for the future. For our plasma experiments, the current implementation is deemed sufficient.

D. Spark-Gap Erosion

When the oil spark-gap switches, a thin channel of plasma is created between the electrodes of the spark-gap. This channel heats up rapidly as the current density through the channel increases. It locally heats the electrodes to very high temperatures, causing melting and evaporation of electrode material. The molten metal at the base of the arc may furthermore be removed from the surface when the surface is rapidly cooled by the oil. A second mechanism of erosion is the formation of liquid jets as vapor bubbles inside the oil collapse [15].

The erosion processes limit the lifetime of the spark-gap. Furthermore, debris from the electrodes ends up in the oil, which further limits the lifetime of oil and the oil filter.

Numerous studies on erosion of electrode materials in gas SGs have been carried out previously [16]–[21]. Unfortunately, there have been little studies on electrode erosion of liquid SGs [15], [22]. While electrode erosion is not a key research interest for our nanosecond pulse generator, it is worthwhile investigating because of the influence on the lifetime of the spark-gap.

After around $4 \times 10^7$ shots of the oil spark-gap, we removed the electrodes to investigate the amount of electrode erosion the oil spark-gap suffered. At this point, the spark-gap still performed well for high output voltages (>20 kV)—albeit with a higher statistical deviation on the amplitude of the output voltage—but performed less well at lower output voltages (frequent prefires). The output voltage waveform did not change significantly from the situation with new electrodes to the situation after $4 \times 10^7$ shots.

Fig. 15 shows a close up drawing of the spark-gap for reference. Fig. 16(a) shows a brass electrode 1 after $4 \times 10^7$ shots. An estimated $2 \times 10^{-8}$ m$^3$ of material has been removed from the brass electrode by the discharges. During its lifetime, an estimated 35–100 C of charge has been switched by this electrode, which brings the erosion rate of electrode 1 of the oil spark-gap in the range of 200–600 $\mu$m$^3$·C$^{-1}$. In comparison, brass electrodes in gas SGs have erosion rates in the range of 1–100 $\mu$m$^3$·C$^{-1}$, with most in the lower part of this range [16], [18], [21]. Therefore, the electrode erosion rate of the brass electrode 1 in the oil spark-gap is on average almost an order higher than the brass electrode erosion rates of gas SGs. This indicates that a future improvement of the
lifetime of the spark-gap could be to use a gas spark-gap. However, with a gas spark-gap, we would lose the constant 50-Ω impedance across the length of the pulse source and we would have to operate it at very high pressures to be able to switch high voltages across small gap distances. Using a gas spark-gap is therefore deemed unfeasible at the moment.

The erosion of electrode 2 of the oil spark-gap shows similar erosion as electrode 1. It is shown in Fig. 16(b). During about 70% of the experiments, electrode 2 served as the anode of the spark-gap (positive output voltage). An estimated $1 \cdot 10^{-8} \text{ m}^3$ of material has been removed from the brass electrode 2 by the discharges, which brings the erosion rate of electrode 2 of the oil spark-gap in the range of 100–300 $\mu \text{cm}^3 \cdot \text{C}^{-1}$. Therefore, the erosion rate of electrode 2 is only half that of electrode 1. If we consider that electrode 2 was mainly the anode, the result that the cathode erosion rate is higher than the anode erosion rate is consistent with gas spark-gap studies, but is also highly dependent on repetition rate and electrode material [18], [21], [23].

Another possible explanation for the higher erosion rate of electrode 1 is that the oil in the spark-gap flows from electrode 2 to electrode 1, therefore carrying any debris from the electrodes past electrode 1. This might result in extra intense discharges on the surface of electrode 1. Proof of the latter statement is also evident in Fig. 16. There are no erosion pits in the interior of electrode 2 (where the oil flow originates), while there is a significant amount of pits upstream on electrode 1. The position these pits are located on electrode 1 are away from the highest electric field region (where the electrodes are closest to each other) and are therefore not likely positions for a self-breakdown discharge of the spark-gap.

In gas spark-gap studies, different electrode materials show different electrode erosion rates. For instance, stainless steel and copper–tungsten alloys seem to outperform brass [18], [20], [21]. Therefore, our new electrodes will be made of stainless steel. In our pulse generator, electrode 2 is relatively easily exchanged, whereas changing electrode 1 requires the disassembly of the entire pulse generator. With this in mind, we designed a new electrode 1 for our spark-gap. It has a threaded head that can be exchanged without the complete disassembly of the entire pulse generator. Furthermore, the head can be made up of a different material than the body allowing for a high conductivity material body and a hard material head. A drawing of the new electrode is shown in Fig. 17 and will be used in a future implementation of the nanosecond pulse generator. The implementation of our nanosecond pulse generator with this improved electrode will be the actual final implementation of our pulse generator.

Another future improvement of the spark-gap electrodes could center around preventing turbulent oil flow around the electrodes and ensuring this flow is laminar by techniques used in [15]. This could decrease the standard deviation on the output pulse amplitude of the nanosecond pulse generator. At the moment, we use this standard deviation to our advantage in our experiments, because it allows us to perform a high number of experiments at different output voltages without having to adjust the spark-gap distance constantly. For example, we can investigate the matching of our nanosecond pulse generator to a corona plasma reactor for voltages from 5 to 40 kV with just five spark-gap distances.

A final observation on the electrode erosion of the oil spark-gap is the size of the deformations on the electrodes. These appear to be roughly 25–75 $\mu \text{m}$ in diameter, which is consistent with previous studies in gas SGs [21]. Fig. 18 shows a detailed view of the erosion on brass electrode 1.

V. CONCLUSION

In this paper, we presented the final implementation of our 0–50-kV picosecond rise-time 0.5–10-ns pulse generator. The pulse generator will be used in future work to generate a (sub-)nanosecond streamer plasma for air purification research. The pulse generator is a single-line pulse generator with an oil spark-gap, which generates 0.5–10-ns pulses with a 200-ps rise time and can operate at a repetition rates of over 1 kHz into a 50-Ω load. It is an improvement over the first implementation of our nanosecond pulse generator that we designed in [1] and verified experimentally in [2].

In this paper, we evaluated the performance of the final design. Furthermore, we presented 3-D EM simulations of the nanosecond pulse generator and showed that the simulations
are in good agreement with the measurements. A variation in pulse duration from 0.5 to 10 ns is possible and the output pulses are square shaped without the large plateau behind the main pulse that was present in the pulses from the first implementation of the nanosecond pulse generator. At high voltages, the pulse top becomes less flat due to a time-dependent mismatch in the spark-gap, but this is not expected to influence the plasma in our corona plasma reactor. The lowest voltage for which the spark-gap still performs well is around 5 kV. This brings the practical output voltage range to 3–50 kV.

Finally, we investigated the electrode erosion of the oil spark-gap in the nanosecond pulse generator. The erosion rate of the electrodes were in the range of 200–600 µcm³·C⁻¹ for the electrode that was mainly the cathode and 100–300 µcm³·C⁻¹ for the electrode that was mainly the anode. This is almost an order of magnitude higher than most gas spark-gap studies show for brass electrodes. Therefore, electrode erosion in the oil spark-gap will be a limiting factor on the lifetime of the system. We designed a new electrode with a stainless steel head to increase this lifetime.

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