

LONG-TERM TEST OF A TRIGGERED MARX-GENERATOR IN REPETITIVE OPERATION *

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Abstract

For the industrial-scale electroporation of sugar beets the use of a set of synchronized, hence triggered, Marx-generators promises an energy-efficient processing. Such generators need to operate during a seasonal campaign of 100 days without interruption. In order to obtain some experience in the possible problems of the design, a long-term test is performed. The following issues are considered to be critical: the wear of the spark gaps, the jitter of the switching time (important for the synchronization), and the durability of the over-voltage trigger circuit directly switched into the charging current's path. The paper deals with some aspects of the test.

I. INTRODUCTION

Marx generators have been in use for many decades in high-voltage test fields and for scientific test setups. For these applications the generators are mostly used in single-shot operation. Hence, commercially available Marx generators are usually designed for a life time of not more than 1 – 10 million shots.

During the last few years, some industrial applications for repetitively operated Marx generators have been investigated, e.g. the fragmentation of concrete [1] and the electroporation of sugar beets [2, 3]. For such industrial applications, a reliable long-term operation without the needs for maintenance is important. Furthermore, these generators have to be placed next to the media to be processed and, hence, are neighbouring other machines, electrical installations and control circuitry. Therefore, a sophisticated EMC concept for such apparatuses is crucial.

The maintenance interval for a Marx generator is mainly determined by the life time of the capacitors and the wear of the spark gaps. For the case of a triggered operation, the life-time of the trigger circuitry has to be considered additionally. The paper describes some aspects

of a long-term test of a triggered Marx-Generator intended to drive an electroporation reactor for sugar beets.

For the industrial electroporation of sugar beets, voltage pulses of typically 250...300 kV peak voltage and a pulse width of 1...3 μ s are needed. The Marx generator is part of an RLC-circuit with stray inductances of the generator and leads and the electroporation reactor representing an electrolytic load resistor. This arrangement typically results in an aperiodically or strongly dampened oscillating voltage shape. As the sugar beets are immersed into water to guarantee a good electric contact to the electrodes, and due to their own conductivity, the current through the electroporation reactor is not negligible, although the electroporation process is driven by the electric field. Hence, a generator has to deliver a current of up to 6...8 kA. This is a rather small current compared to other pulsed power applications.

II. TEST SET-UP

For the long-term test one Marx-Generator is connected to an electrolytic load-resistor. The resistor consists of a cubed polypropylene tank equipped with a set of electrodes. The tank is filled with water. The diameter and distance of the electrodes is calculated such, that the resistance matches that of an electroporation reactor. The average power during the test is approximately 25 kW. The load-resistor is cooled by means of pumping the water continuously through a cooler. Due to the water quality required by the cooling device the conductivity of the water cannot be adjusted by adding salt. Instead the conductivity is tuned by varying the temperature. A feed-back control switches a bypass valve to the tank depending on the temperature of the water flowing out of the tank. To protect the circuitry next to the tank from leakage currents, the inlet and outlet are equipped with grounded electrodes. The Marx generator is supplied by a regulated

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high-voltage power supply usually used for powering electrostatic precipitators.

III. MARX-GENERATOR

The Marx-generator has been designed for operation at a repetition rate of 20 Hz. It is equipped with charging coils rather than charging resistors. Essential for the life time are the capacitors and the spark-gaps. It is well known, that the life time of capacitors depends on the field strength inside the dielectric, the capacitor has been designed for, if the requirements for the voltage and current shape are met. The capacitors in use are equipped with metal coated polypropylene foils, showing a self healing behaviour in the case of a local breakdown. Hence, the end of the life-time can be detected by means of measuring the capacitance. The estimated life time of the capacitors is 10^9 shots.

The spark gaps are fabricated from a tungsten-copper alloy (80/20) and equipped with a Borda profile in order to foster a homogeneous wear across the whole diameter. As the photo of one electrode after 10 Million shots demonstrates, the arcs occurred randomly throughout the entire surface (Figure 1). The spark gaps are mounted inside a tube filled with pressurized nitrogen. For the current design, the breakdown-voltage is being controlled by the variation of the pressure only. The tungsten-copper alloy exhibits an increased wear as long as the electrodes are new and the copper is removed out of the matrix. Therefore, measurements of the wear have been performed after 10 Million shots. Table 1 shows the loss of mass per electrode pair after 500 000 pulses with a current amplitude of $\hat{I} = 4.5$ kA, $t_n = 1.4$ μ s, load-integral 20.4 A²s, charge 49 mC.

Spark gap	Wear during 500 000 shots	Wear per shot
#1	0.080 g	160 ng
#3	0.084 g	168 ng
#5	0.080 g	160 ng
#7	0.093 g	186 ng

Table 1. Wear of spark gap electrodes.

After 10^9 shots this corresponds to 168 g. For an electrode diameter of 4 cm the electrode distance is expected to increase on average by 8.9 mm during that operation time. During a typical seasonal campaign of sugar production the electroporation device delivers in the order of $2 \cdot 10^8$ pulses, resulting in an expected increase in distance of 1.7 mm. The change of the breakdown voltage has to be compensated, e.g. by the variation of the pressure. After the campaign, the electrodes can be re-adjusted or replaced.

The powder of the erosion is partly transported to the rear side of the electrode and the walls. This field-driven process works much like an electrostatic precipitator. A

strong fan establishes a circulation of the nitrogen. The gas flow through the tube transports the major part out into a filter. Fig. 1 shows the powder on the walls. So far, this has not been a problem. Another purpose of the gas flow is the cooling of the arc after the switching process. As the Marx generator is charged by a constant charging current in the order of 1 A without interruption powering the arc, the DC-arc has to be extinguished actively. Additionally, the gas is cooled down to prevent the tube from being over-heated.

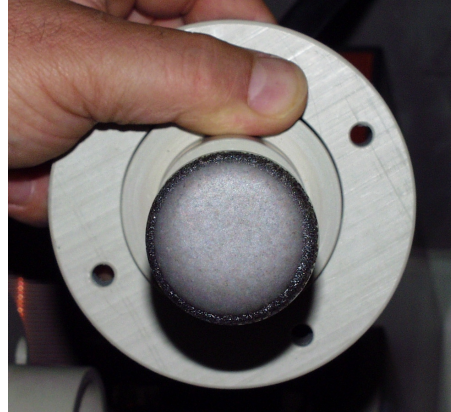


Figure 1. Spark gap electrode after 10^7 shots.

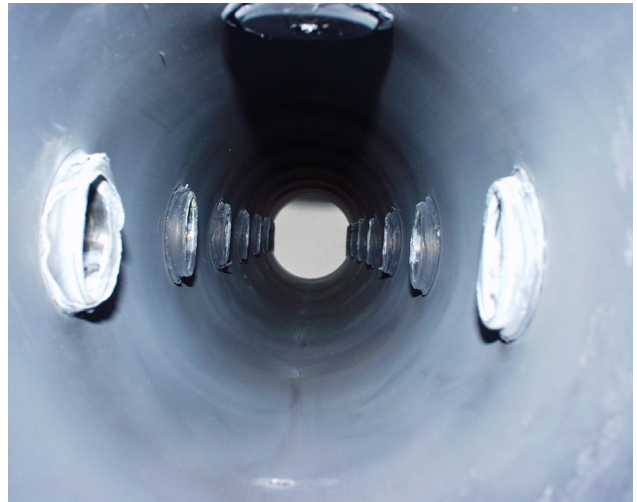


Figure 2. Powder coating from the erosion of the spark gap electrodes on the inner walls after 10^7 shots.

IV. TRIGGER CIRCUIT

For industrial-scale electroporation devices a synchronized, hence triggered operation of several Marx-Generators is required, [7]. For testing purposes the Marx Generator is equipped with an over-voltage trigger circuit. This circuit induces an over-voltage across the 1st stage's spark gap by means of two transformer-coupled pulse generators replacing the charging coils between the 1st and 2nd stage (Figure 3). These two pulse generators are pow-

ered by the charging current to be completely separated from ground potential. The further details about this trigger-method are described in [6] and [7]. Figure 4 shows the voltage across the first two stages. The negative pre-pulse before the rise of the voltage is the superimposed trigger pulse.

As the trigger circuit is directly connected to the generator's charging path, special protection against over-voltage had to be taken. When the 1st spark gap switches, the stage voltage is applied to the high-voltage side of the trigger transformer. The switches on the low-voltage side are protected against over-voltage due to the design of the transformer. The ratio has been chosen such that the low-voltage is all the time well below the breakdown voltage of the semiconductor switches (IGBTs) of 1100 V. Additionally, suppressor-diodes protect the semiconductors against induced voltages of the stray inductances when opening the switches. The experiments showed that this design works fine; so far, none of these semiconductors failed.

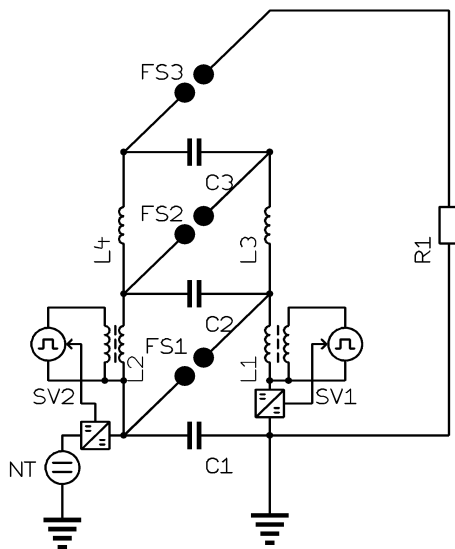


Figure 3. Marx-Generator equipped with over-voltage trigger-circuit.

While taking the circuit into operation, an over-voltage problem occurred at the power-supply of the trigger circuit. The inductance of the trigger transformer's high-voltage coil and a capacitor at the input of the trigger's power supply form a low-pass filter. The capacitor is bypassed by an IGBT, if the voltage across the capacitor becomes too high. Due to a misalignment of the second spark gap the switching time of the Marx-generator became much longer, especially when being operated with nitrogen. Without the electronegative oxygen delivering charge carriers during the run of the avalanche the breakdown-time of the second spark gap was longer than the duration of the over-voltage, and the spark gap did not trigger until the traveling wave had been reflected and came back after approximately 1.2 μ s. Subsequently,

more power had been coupled into the LC-low-pass filter resulting in a higher current. When switching off the bypassing IGBT, an induced over-voltage caused by a series inductance occurred, the snubber circuit could not cope with and the IGBT was destroyed by an over-voltage pulse. To solve this problem, the control circuitry has been modified such that the bypassing IGBT is not switched off, as long as the current is above a critical limit.

When designing the printed circuit boards special care to the electromagnetic interference has been taken. Where ever possible, ground planes have been used and conductor loops possibly working as frame antennas have been avoided or made as small as possible, e.g. the supply connections. With these measures, the logic circuitry works without problems, except for one exception: The fiberoptic receiver for the trigger signal -an integrated combination of the photo diode, the amplifier, and a Schmitt-trigger circuit- is very sensitive to electromagnetic interference. The circuit triggered several times without an optical signal, especially after the trigger generator had fired. Therefore, the trigger circuit had to be placed inside a shielded housing equipped with low-pass filters for the supply- and signal lines.

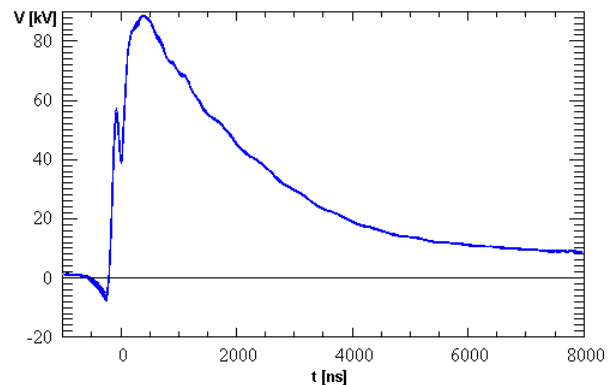


Figure 4. Voltage across the first two stages (superposition of 15 acquisitions).

V. Jitter

For a good synchronisation of several Marx-Generators a low jitter of each generator is essential. The jitter and switching time of the Marx generator is influenced on one hand by the distance of the spark gaps, on the other hand by the delay time of the triggered spark gap. To obtain best results, all spark gaps have been adjusted carefully to the same distance except for the 1st spark gap with slightly lower distance.

The breakdown of the spark gaps is caused by a traveling wave along the generator. Initially, the over-voltage causing the subsequent breakdown of all spark gaps depends mainly on the ratio of a capacitive voltage divider formed by the stray capacitances between two adjacent stages on one hand and the sum of the stray capacitances

to ground and to the subsequent stages on the other hand. The over-voltage decay is caused by charging the stray capacitances via the two charging coils in parallel configuration. For the existing design, the over-voltage across the second spark gap has been measured (Figure 5). For the measurement, the first spark gap has been bridged by a relay with mercury-wetted contacts. The measurement has been performed at a voltage of 200 V, so usual probes could be used. The over-voltage is approximately 80 % of the charging voltage and decays to zero within 210 ns. In addition to the over-voltage the presence of initial charge carriers is of importance. Usually, the UV-light of the previous, ignited spark-gap is used for the production of the charge carriers.

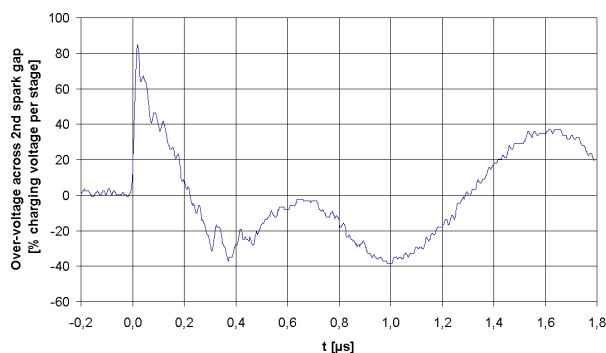


Figure 5. Over-voltage across the 2nd spark gap.

To obtain a low jitter for the over-voltage triggering, either a rather high over-voltage is required, or a pre-ionization technique is applied. Both techniques have been evaluated. The pure over-voltage triggering has been tested in nitrogen at a rise of 40 kV/μs. The charging voltage has been chosen to 45 kV while the self breakdown voltage of the spark gap was 52 kV. The triggered breakdown occurred with a standard deviation of +/-205 ns.

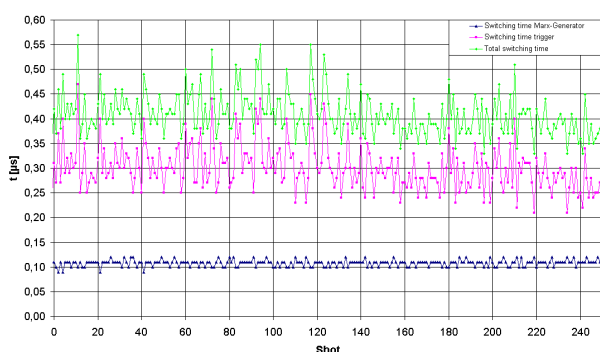


Figure 6. Switching delay of trigger and Marx generator.

With a pre-ionisation of the 1st spark gap the breakdown occurred within a narrower time interval. In Figure 6 the breakdown times of the triggered 1st spark gap and the whole generator for an operation at 50 kV charging voltage and with nitrogen filling are shown. The average overall switching time of trigger-circuit and generator is

0.4 μs with a standard deviation of +/-46 ns. The overall jitter is less than 100 ns, which is considered to be sufficient for the described application.

VI. ACKNOWLEDGEMENT

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VII. CONCLUSION

A test bed for a long-term test of a Marx generator in repetitive operation has been designed, and a long term test of a Marx-Generator has been started. The measurement of the wear of the spark gaps over 500000 shots showed no excessive wear for the desired current shape. The operation of the over-voltage trigger circuit up to 50 kV charging voltage per stage has been shown, although some improvements of the circuitry were necessary to bring the device to reliable operation. To reduce the generator's over all jitter, a pre-ionisation method has been applied and the distances of the spark gaps have been adjusted carefully.

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