Auxiliary Power Supply for a Semiconductor-based Marx Generator

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***Abstract*—An auxiliary power supply for stages of a semiconductor-based Marx generator has been designed and tested. The auxiliary power supply converts the Marx generator's stage voltage ranging from 50 V to 1000 V to stabilized voltages of 7 V and 18 V at a total output power of up to 1.5 W. It comprises a transformer for insulation between input and both outputs and features a flyback converter design. The on-time of the MOSFET switch has been designed to vary between approximately 1 µs and 20 µs depending on the generator's stage voltage. The power supply has been tested successfully in an 8-stage Marx generator.**

Keywords—*Auxiliary power supply, flyback converter, Marx generator.*

I. Introduction

Within the recent years, semiconductor-based pulse generators for generating pulses in industrial applications at voltages ranging from several kilovolt to several 10 kilovolts and currents up to the kiloampere range became available. Applications are for example the treatment of food by pulsed electric fields, bacterial decontamination, and drivers for generation of a pulsed electron beam [1-4].

A common approach for such generators is the Marx generator principle [5]. A Marx generator comprises a capacitor bank, which is charged in parallel configuration and discharged with the capacitors being connected in series. One advantage of such an arrangement is the fact that every component needs to be designed for the stage voltage only, while the generator is able to deliver a voltage much higher than the stage voltage, depending on the number of stages. In the original design, for establishing the series connection of capacitors spark gap switches have been used, which are nowadays replaced by semiconductor switches, which can be controlled much more versatile. However, the operation of semiconductors involves the need for an auxiliary power supply.

With respect to its topology, a Marx generator is similar to some well known arrangements like high-voltage converters or high-voltage switches, both consisting of stacked stages. For those circuits different approaches for on-stage auxiliary power supplies are common. A simple solution is a resistor serving as current source [6]. It is powered by the voltage applied to the stage and supplies a current in proportion to this voltage. In an arrangement of stacked switches the resistors form a voltage divider fostering equal voltage distribution among all stages at the expense of power losses. Another approach to supply power to the stages is based on an inductively coupled power supply comprising a transformer with a primary winding powered from ground potential and at least one secondary winding on each stage [4, 6, 7]. It allows for a power supply independent of the voltage applied per stage and can be set up quite simple using a single wire with appropriate insulation as primary winding. However, the insulation of this wire needs to withstand the sum of all stage voltages, i.e. $n \cdot V_{stage}$, provided that during operation all n stages are connected in series. In this respect the design rule for a Marx generator saying that no components need to withstand more than the voltage per stage is not fulfilled. In a Marx generator arrangement for auxiliary power supply a separate current path similar to the charging path can be installed. However, as the power needs to be distributed among the stages sequentially, to compensate for a voltage drop along the elements for transient insulation between the stages, e.g. diodes or transistors, requires feeding at an elevated voltage level, depending on the number of stages. Hence, a local step-down conversion at each stage and a local voltage regulation might be needed [8]. As an alternative, the auxiliary power for the control circuitry can be drawn from the stage capacitor and the power supply used for charging. If the stage capacitor is kept charged to an almost constant voltage level during operation, as it is required for the generation of rectangular pulses [9], the auxiliary power supply can be designed for this specific operation point. If the stage capacitors are discharged completely during each pulse and subsequently recharged, the auxiliary power supply needs to be designed to operate at a wide range of input voltage and buffer some energy to provide energy to the auxiliary circuits while the stage voltage is too low for operation. However, advantages of this approach are a more energy-efficient operation compared to using a resistor as current source and a design for the voltage level of the charging voltage per stage only. Moreover, the power supply can be implemented into each stage without additional external components as e.g. required for an additional current path for auxiliary power supply.

For a semiconductor-based Marx generator with a voltage of up to 1 kV per stage such an auxiliary power supply has been designed and put to operation.

II. Design Considerations for the Auxiliary Power Supply

A. Pulse Circuit and Marx generator

The properties of the pulse circuit define the requirements for both the pulse generator and the auxiliary power supply. For the treatment of plant material by pulsed electric fields a treatment chamber is connected to the generator acting in combination with the connecting leads as a combined resistive and inductive load. Together with the pulse generator's stage capacitors in series connection a RLC circuit is formed. It has been designed such that an aperiodically damped pulse shape with a pulse width of approximately 10 µs and a peak current of 500 A is achieved. The graph in Fig. 1 shows the measured pulse current I_P across the load resistor and the voltage V_P at the output of an 8-stage Marx generator operated at a voltage of 850 V per stage. In the course of each pulse the generator's stage capacitors are discharged completely, and re-charging starts almost immediately after each pulse. The generator is capable of operating at a pulse repetition rate of up to 500 Hz. As the Marx generator is intended to serve as power source for experiments, it is required to operate it at stage voltages ranging from 50 V up to 1000 V.

Fig. 2 gives a coarse overview of the generator arrangement. Each stage is equipped with a stage control unit comprising a microcontroller for control and monitoring tasks and a gate driver connected to an IGBT switch at each stage. A diode in parallel to each stage's pulse terminals serves as a bypass path for the pulse current in the case, that the stage's IGBT switch is turned off or delayed during pulse generation, e.g. due to a failure condition. During charging all stage capacitors are connected in parallel via charging coils serving as transient insulation during pulse generation. The stage control unit draws a power of up to approximately 0.5 W from an auxiliary power supply powered by the capacitor charger via the stage capacitor. To account for a safety margin of extra power it has been designed for a power of 1.5 W. The auxiliary power supply's input terminals are connected to the stage capacitor and its output terminals are referenced to the IGBT switch's emitter potential serving for the stage control unit as ground potential. Hence, an insulation between input and output is required.

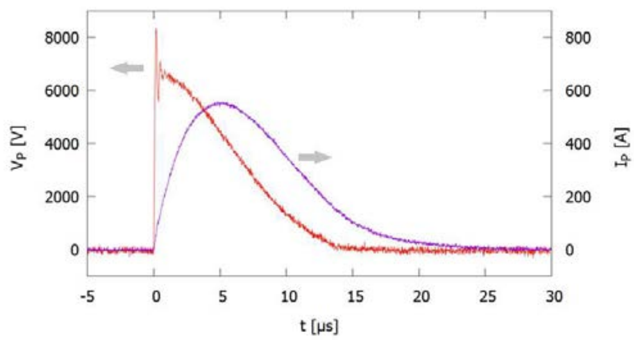

Fig. 1. Measured pulse current I_P across the load resistor and the voltage V_P at the output of an 8-stage Marx generator operated at a voltage of 850 V per stage.

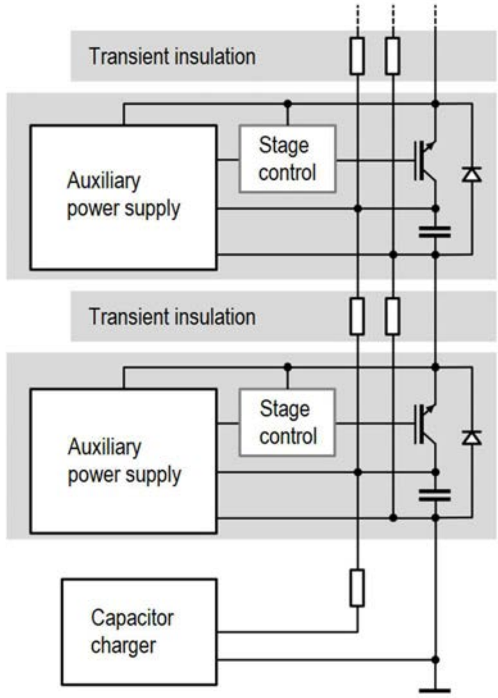

Fig. 2. Overview of the Marx generator arrangement.

B. Flyback Converter Design

For the auxiliary power supply the configuration of a flyback converter has been chosen, because it enables an easy implementation. For setting up a flyback converter there is a large choice of integrated circuits available on the market. However, the following additional requirements led to the choice of a custom design tailored to the specific needs. The on-time of the switch is given by (1).

$$t_{on} = \frac{I_{max} \cdot L_1}{V_i} \tag{1}$$

It depends on the inductance of transformer's primary winding L_1, the peak current I_{max}, and the applied voltage V_i. The influence of the primary's resistance has been neglected and discontinuous operation has been assumed. In order to cover an input voltage ranging from 50 V to 1000 V the on-time must be varied by a factor of 20. The time to ramp-down the current back to zero depends on the ratio of the number of turns of primary and secondary winding, and the output voltage according to (2).

$$t_{off} = \frac{I_{max} \cdot L_1}{V_o} \cdot \frac{n_2}{n_1} \tag{2}$$

In contrast to t_{on} the value of t_{off} is almost constant, as it depends on the stabilized the output voltage V_O. The sum of t_{on} and t_{off} limits the maximum switching frequency, and, hence, the maximum average power transfer. The spatial constraints of the design limit the size of the transformer core. Fig. 3 shows a photo of the one generator stage with the transformer in the foreground. A ferrite core of EE-shape has been chosen. With 55 turns the primary winding has an inductance of 7.9 mH and allows for a maximum primary current of 128 mA.

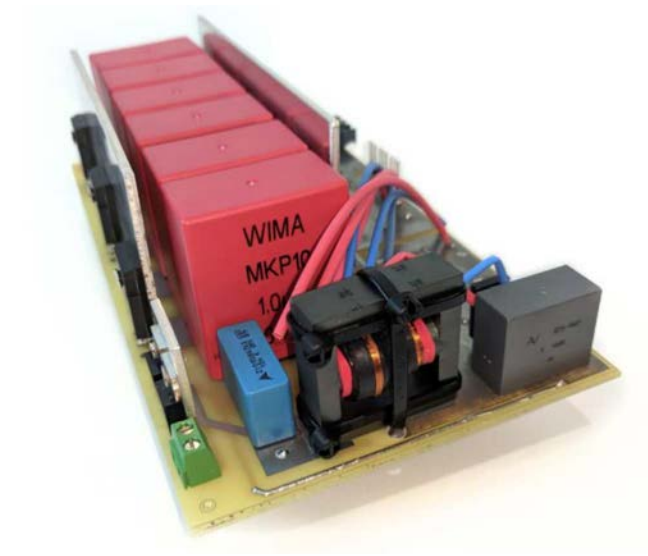

Fig. 3. Marx generator stage with the transformer for auxiliary power supply in the foreground.

For this design, the turn-on time varies between 1 µs and 20.2 µs over the input voltage range. Fig. 4 shows a simplified schematic of the auxiliary power supply. It has two voltage outputs with levels of 7 V and 18 V for a supply with 5 V and 15 V, respectively. Additionally, the internal consumption of the power supply is supplied from the flyback converter. This design requires an additional power supply for start-up. A linear voltage regulator supplies the required supply current until the flyback converter takes over the supply. The linear voltage regulator is disabled as soon as the level of the supply voltage is raised up to the minimum voltage for supply by the flyback converter.

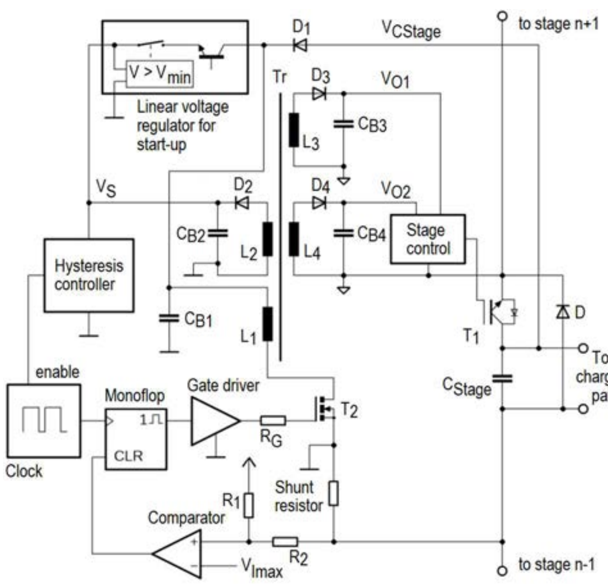

Fig. 4. Simplified schematic of the auxiliary power supply.

The internal supply voltage V_s is kept constant at approximately 14 V within a small tolerance band by means of a hysteresis controller. It causes the flyback converter to pause as long as the voltage V_s is above its lower threshold, i.e. the threshold for re-enabling the flyback converter. Due to the coupling between the transformer's windings the remaining output voltages follow the voltage V_s and, hence, are limited. Thereby, the transformers stray inductances may cause an additional inductive voltage drop.

The MOSFET T_2 serves as switch for the flyback converter with a rated drain-source voltage of $V_{DS,max} = 1500$ V. When T_2 opens, the circuit involves transients due to the transformer's stray inductance and the inductance of the connecting leads. A snubber circuit comprising three suppressor diodes with a rated breakdown voltage of 400 V each has been connected in parallel to the MOSFET. The suppressor diodes in series configuration have a capacitance of 35 pF without bias voltage. In order to reduce the power losses due to repetitive charging and discharging two silicon diodes, each having a capacitance of 8 pF, and an additional damping resistor of 330 Ω have been connected in series to damp oscillations.

A working cycle of the flyback converter is triggered by means of a clock. It switches a monoflop to its unstable state. The MOSFET T_2 is turned on via its gate driver. The current through the MOSFET and the transformer's primary is sensed by means of a shunt resistor and compared to its peak value of 128 mA according to the design. If this value is reached, the monoflop is cleared and the MOSFET T_2 is turned off. The use of a monoflop rather than a flipflop prevents the transistor T_2 from staying too long in on-state in the case that the auxiliary power supply's input voltage becomes too small to drive the current to the limit of 128 mA within reasonable time due to a discharge of the stage capacitor.

C. Current Sensing and Compensation of Delay Times

The voltage divider symbolized by the resistors R_1 and R_2 in Fig. 4 needs to be designed to have a sufficiently low impedance such that the low-pass filter formed in combination with the input capacitance of the comparator and the stray capacitances of the resistors and lines on the printed circuit board does not delay the signal significantly. However, for a resistive divider a low impedance involves a large bias current. A low current consumption of the auxiliary power supply is desirable to reduce self-discharge of the stages while not being charged. In order to combine both needs, a combined resistive and damped capacitive divider according to Fig. 5 has been employed. The resistive path provides DC bias to the circuit elements at a current level in the order of 20 µA while the damped capacitive divider provides the transient signals to the input of the comparator at a source impedance of only 400 Ω. The component values are listed in Table I.

The signal propagation times of the employed logic circuits and a turn-off delay of the MOSFET T_2 causes a total delay in switching off the MOSFET by 220 ns, which is significant in comparison to a total turn-on time of down to 1 µs.

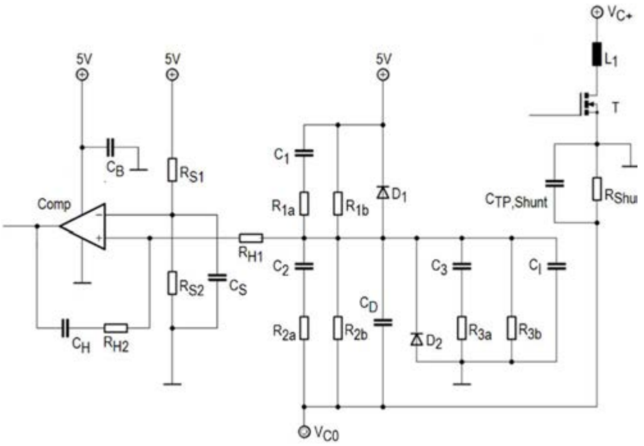

Fig. 5. Combined resistive and damped capacitive divider for current sensing (Component values are listed in Table I).

TABLE I. COMPONENT VALUES

Component	Value	Component	Value
R1a	2kΩ	C1	100nF
R1b	200kΩ	C2	200nF
R2a	1kΩ	C3	200nF
R2b	100kΩ	CB	10µF
R3a	1kΩ	CD	470pF
R3b	100kΩ	CH	100pF
RS1	130kΩ	CI	100pF
RS2	20kΩ	CTP,Shunt	3.3nF
RH1	1kΩ	D1	LL4148
RH2	110kΩ	D2	LL4148
RShu	6,66Ω	Comp	TLV3501

As a consequence, the current through the transformer's primary rises by a value of I_{add} above the designed threshold according to (3).

$$I_{add} = \frac{di_1}{dt} \cdot t_V = \frac{V_{in}}{L_1} \cdot t_V \tag{3}$$

The problem could be tackled by statically lowering the threshold voltage V_{Imax} in order to gain some headroom for the delayed switching. However, a static solution would be also in effect at longer switching times. Due to a negligibly low resistance of the transformer's primary winding, the current rise can be considered linear. Hence, a differential part of the current signal results in an offset signal, which is in proportion to the current rise and, hence, also with the input voltage of the auxiliary power supply. Fig. 6 shows a simulation of the voltage signal at the input terminal of the comparator (a) without and (b) with adding a differential part. Thereby, the values of the circuit components have been adjusted such that the signal with differential part reaches the threshold by the total switching delay of 220 ns earlier than it would without differential part in the case of operation with an applied input voltage of 1000 V. The differential part is adjusted by means of the capacitor C_D in combination with the resistors of the divider. The capacitor C_I increases the capacitance to ground in order to reduce the effect of a ground stray capacitance varying with the setup and environmental conditions. The differential part in the signal path emphasizes higher frequency components in the current signal. In order to compensate for this effect the capacitor $C_{TP,Shunt}$ forms a 1st-order low-pass filter with a cut-off frequency of 7.2 MHz in combination with the shunt resistor. This frequency is high enough not to have an impact on the current sensing.

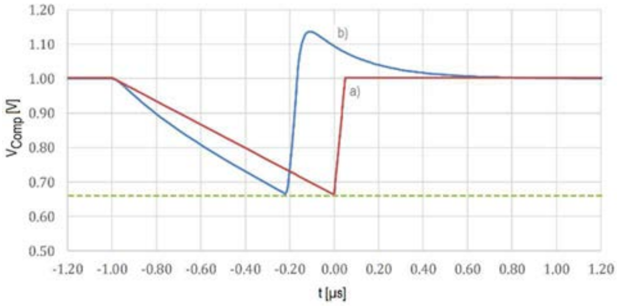

Fig. 6. Simulation of the voltage signal at the input terminals of the comparator according to Fig. 5 (a) without and (b) with adding a differential part to the divider ratio.

III. TESTING OF THE AUXILIARY POWER SUPPLY

Fig. 7 and Fig. 8 show the transformer's measured primary current together with the output voltage at the terminal O1 delivering a DC voltage of 18 V for an applied input voltage of 50 V and 1000 V, respectively. In both cases, the current rises to approximately the same peak value of 125 mA.

Fig. 9 shows the measured supply current through the linear voltage regulator depending on the internal supply voltage V_S during start-up with the MOSFET T_2 not switching. Up to a supply voltage of approximately 12 V the supply current is less than 1 mA. Up to a voltage 14 V the current rises to less than 2.5 mA. These currents can be easily supplied by the linear voltage regulator.

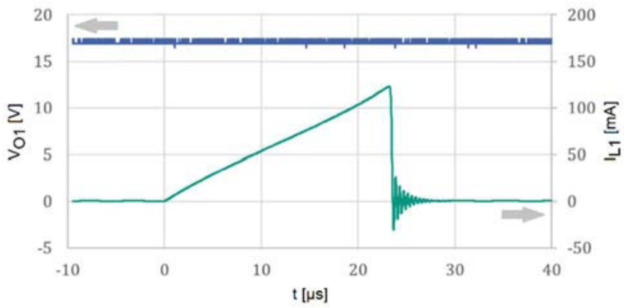

Fig. 7. Measurements of the transformer's primary current together with the output voltage at the terminal O1 delivering a DC voltage of 18 V while operating the auxiliary power supply at an input voltage of 50 V.

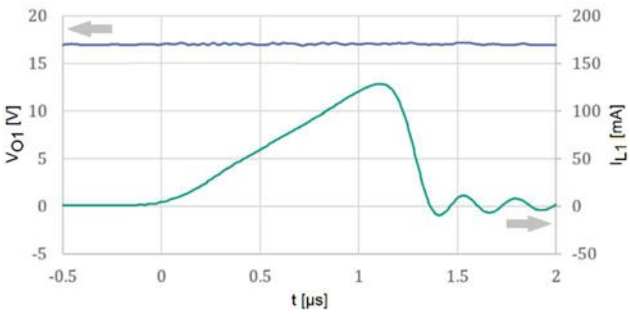

Fig. 8. Measurements of the transformer's primary current together with the output voltage at the terminal O1 delivering a DC voltage of 18 V while operating the auxiliary power supply at an input voltage of 1000 V.

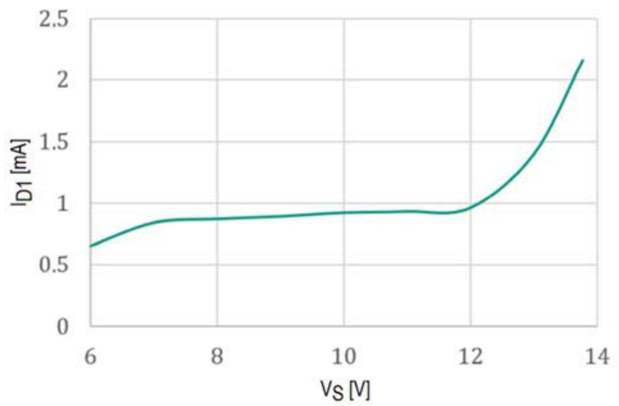

Fig. 9. Measured supply current through the diode D1 according to Fig. 4 depending on the internal supply voltage V_S during start-up.

Fig. 10 shows the efficiency of the auxiliary power supply while sourcing a power of 1 W to a resistor as an artificial load. The efficiency has a maximum of 58 % at a stage voltage of less than 150 V and it decreases to 29 % at a stage voltage of 1000 V. The main reason for this decrease in efficiency at higher stage voltage is a resistive divider as part of the linear voltage regulator for start-up. At a first glance, an efficiency of 29 % at 1000 V supply voltage could be considered as not so impressive. However, it correlates to an input current of 3.5 mA, which proved to be sufficiently small for the intended application.

The Marx generator stages comprising the auxiliary power supply has been tested successfully in Marx generator arrangements of up to eight stages at different stages voltages ranging from 50 V to 1000 V and pulse repetition rates between 2 Hz and 500 Hz.

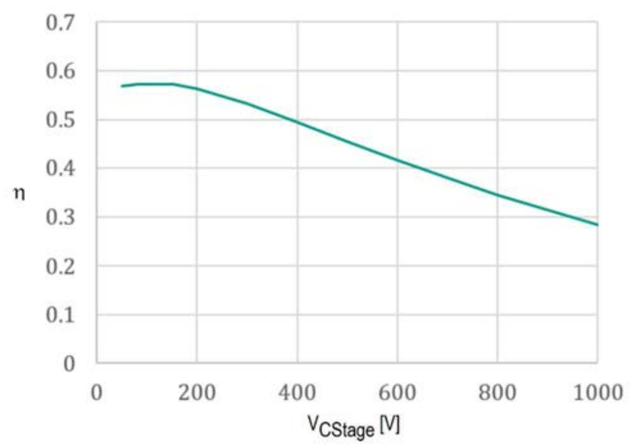

Fig. 10. Efficiency of the auxiliary power supply over the charging voltage per stage V_{CStage} while sourcing a power of 1 W to a resistor as an artificial load.

IV. Conclusion

An auxiliary power supply for the stages of a semiconductor-based Marx generator has been designed and tested. It delivers two stabilized output voltages within an input voltage range from 50 V to 1000 V. The output voltages are insulated from the input. The auxiliary power supply has been tested successfully in a Marx generator and is now ready for use in an experimental set-up for investigations on the electroporation of plant cells.

V. References

[1] M. Hochberg, M. Sack, D. Herzog, A. Weisenburger, W. An, R. Fetzer, G. Mueller, "A Fast Modular Semiconductor-Based Marx Generator for Driving Dynamic Loads", IEEE TRANSACTIONS ON PLASMA SCIENCE, Volume 47 Issue 1 Page 627-634, 2019

[2] L. M. Redondo, M. T. Pereira, M. C. Andrade, P. Brito, F. Barros, "Industrial Processing of Red and White Grapes Assisted By PEF", Proc. 4th Euro-Asian Pulsed Power Conf. (EAPPC 2012), 19th Internat.Conf.on High-Power Particle Beams (BEAMS 2012), Karlsruhe, September 30 - October 4, 2012, Proc.on CD-ROM

[3] M. Sack, D. Herzog, M. Hochberg, W. Frey, G. Mueller, "8-Stage Pulse Generator for Bipolar Ground-Symmetric Operation", Proceedings of PCIM 2019, Nuremberg, Germany, 07.-09. May 2019.

[4] M. Sack; J. Ruf; M. Hochberg; D. Herzog; G. Mueller, "A device for combined thermal and pulsed electric field treatment of food", Proc. OPTIM 2017, Brasov, Romania, 25-27 May 2017, DOI: 10.1109/OPTIM.2017.7974943

[5] E. Marx, "Verfahren zur Schlagprüfung von Isolatoren und anderen elektrischen Vorrichtungen", Patentschrift Nr. 455 933, Anmeldedatum 12.10.1923 (Patent No. 455 933, 10/12/1923)

[6] A. Welleman, E. Ramezani, J. Waldmeyer, Gekenidis, "Semiconductor Components up to 12 kV and 150 kA for Closing Switches", Pulsed Power Conference, 1999, Digest of Technical Papers 12th IEEE International, Vol.2, 1999, 1268-1271

[7] M. Sack, G. Müller, "EMV-Aspekte beim Aufbau eines schnellen Halbleiterschalters", Elektromagnetische Verträglichkeit - EMV 2014, Internationale Fachmesse und Kongress, Düsseldorf, 11.-13.03.2014, S. 517-524.

[8] M. Sack, M. Hochberg, G. Mueller, "Design considerations for a semiconductor-based Marx generator for a pulsed electron beam device", International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV 2014), Mumbai, India, September 28 - October 3, 2014.

[9] M. Sack, M. Hochberg, G. Müller, "Design of a semiconductor-based bipolar MARX generator", IEEE International Power Modulator and High Voltage Conference (IPMHVC 2014), Santa Fe, N.M., USA, June 1-5, 2014.