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High voltage pulse for electroporation to sterilize drinking water

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Abstract: The availability of safe drinking water in the community is always regarded as a significant public health achievement. It is seen that water-borne diseases are the world's third-leading reason for mortality. Most of the current water treatment systems rely on the use of chemicals to kill the harmful disease-causing bacteria and pathogens in the contaminated water. While the use of these chemicals is effective to some level but there remain concerns over the side effects of using such chemicals for water treatment. The alternative way to treat and sterilize water is to use the approach of electroporation to kill harmful bacteria in the contaminated water. In this technique, a very high voltage pulse is applied within the volume of water across the electrode. When a high voltage pulse is applied, the cell membrane of the bacteria becomes vulnerable, and it is then weakened or most probable deactivated. In this paper, a modular high voltage pulse-generator power electronic circuit is proposed and is simulated. The proposed pulse generator made of several modules each containing capacitors is sequentially charged from a comparatively low voltage direct current supply. The simulation result shows that a pulse of 6 kV could successfully be generated with a precise selection of capacitors. The generated voltage is applied across a load of 2.5 kΩ which represents electrode separation of 12.5 mm in regular tap water to mimic the electroporation in the contaminated water.

Keywords: electroporation, high voltage pulse, contaminated water, disinfect, bacteria, safe drinking water.

I. INTRODUCTION

Electroporation is one of the most effective methods of decontamination of bacteria in water since the high voltage electric field produced during the process is capable of killing contagious microorganisms by irreversible permeabilization of their cell membrane. It can be observed that when a bacteria cell is subjected to high electric intensity, small nanopores in the cell wall are created. These nanopores cause intensive dehydration of the cell which eventually leads to its death. The application of electroporation ranges from the removal of tumors in oncology to cosmetic purposes.

To sterilize water through electroporation, it is necessary to have a system that can generate a high-voltage pulsating signal whose values range in kilovolts with currents in tens of amperes. Classical high voltage pulse generators are classified into different types such as the single capacitor charge/discharge circuit, magnetic pulse compressor, pulse shaping network, multi-stage Blumlein lines, and Marx generator. For pulsed power applications, the Marx generator is the most common and dependable classical topology. The Marx generator's basic principle is to charge all capacitors in parallel (i.e., store energy), then bind them in series during discharging via closing switches. A modular high voltage pulse generator for pulsed power applications is proposed in this paper.

Like DC-AC and DC-DC serial multilevel converters, the proposed generator is made up of series-connected units (MMC). The capacitors in the modules are charged sequentially from a comparatively low voltage DC supply, then attached in series to be discharged in the load. A cascaded multilevel DC-AC converter is presented in . This topology is built on the use of cascaded half-bridge sub-modules (each submodule is fed from an independent dc source) to produce a repeated up-down staircase waveform, and an H-bridge is used at the load side to generate a bipolar output voltage. The proposed method differs from the presented system in in the following ways: the presented system in is a topology for DC-AC conversion, while the proposed system is a topology for producing an HV uni-polar pulse; and the presented system in includes independent DC sources. In contrast, the suggested solution requires only a single low voltage DC source to charge a series of capacitors, which are then attached in series to discharge in the load by adding high voltage pulses to the water sample.

In this paper, the suggested generator designs are for low repeated pulse rate applications, where the load resistance is used as the limiting resistance during the capacitor charging operation. The capacitors are charged sequentially, rather than in parallel as in the Marx generator. For a specified load resistance and desired output pulses parameters, detailed designs of the proposed pulse-generators have been presented. To test the proposed principles, simulation models for the proposed systems were developed.

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II. OVERVIEW OF PROPOSED MODULAR PULSE GENERATOR

The Figure 2 shows the proposed modular high voltage pulse generator along with its operating technique flow map is shown in Figure 1. The high voltage pulse generator consists of five series-connected units. As can be seen figure 2, each module is made up of two IGBTs and a capacitor. For the proposed generator, by turning on its corresponding S_{cd} switch and turning off its S_b, the capacitor in each module will become a part of the main circuit. While turning on the S_b switch and turning off the Scd , the module can be bypassed. Instead of charging all capacitors in parallel, as in the classical approach, the proposed generator would use sequential charging of the capacitors.

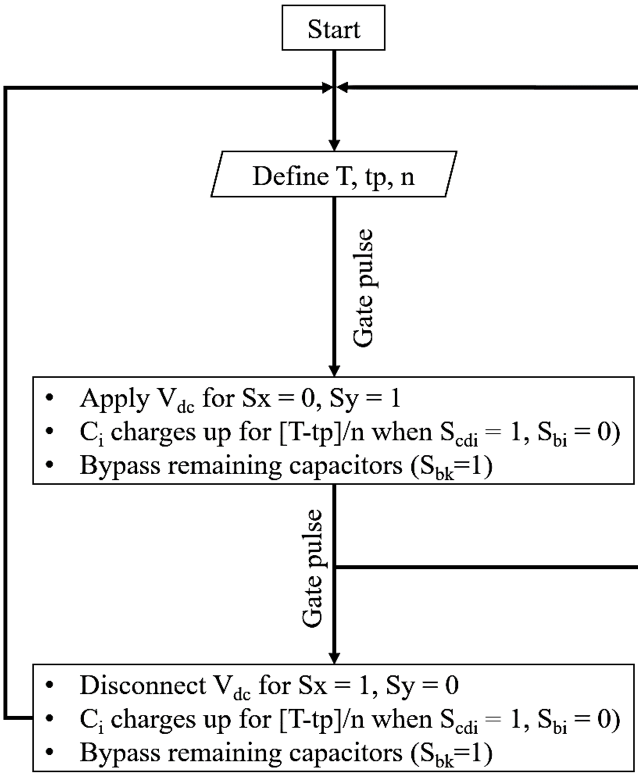

Figure 1 Flow diagram of operation of Pulse generator

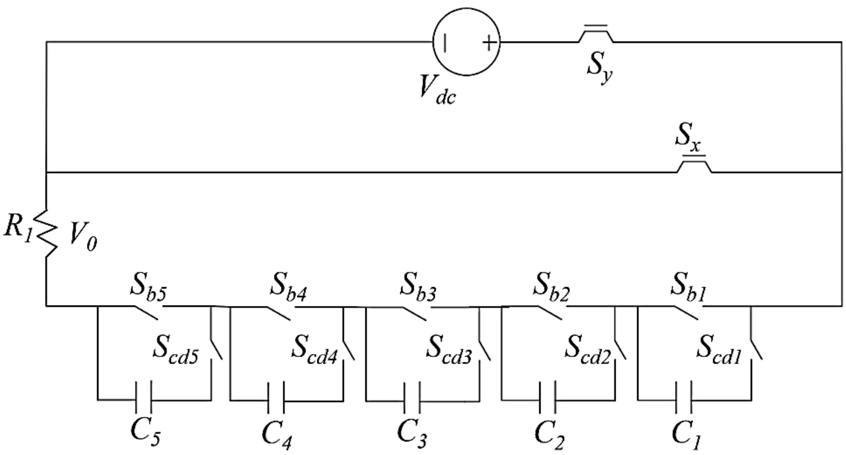

Figure 2 Topology of the pulse generator

The capacitors can be charged sequentially, then attached in series for discharging using semiconductor switches. It should be remembered that while charging or discharging a capacitor, Scdi should be closed, while Sbi should be closed to keep the capacitor floating when charging another capacitor. For example, C1 can be charged by closing Sy and Scd1, as well as Sb2 to Sb5. All capacitors can be charged using the same principle. As shown in Figure 3, the charging of the

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capacitor must be completed before the discharge operation is performed, i.e., the charging time must be less than or equal to (T-tp)/n, where T is the output pulse length, tp is the pulse duration, and n is the number of modules. After charging all capacitors, the discharge operation can be started by opening Sy and closing Sx while keeping all Scdi switches closed. It is important to remember that the load resistance will be involved in the charging process, and it will damp current transients while charging, resulting in low current stresses.

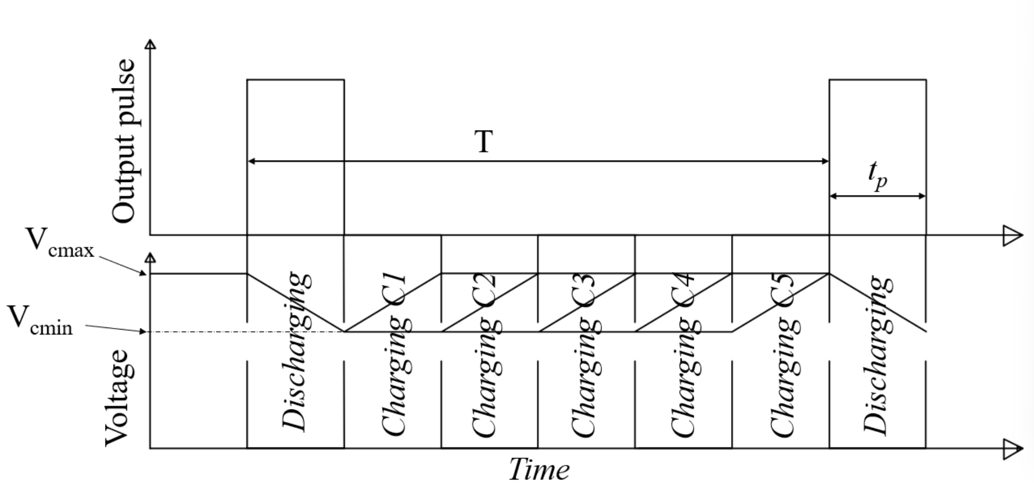

Figure 3 Sequential Capacitor charging and discharging

III. PARAMETER COMPUTATION OF THE PROPOSED HIGH VOLTAGE PULSE GENERATOR

The voltage of each capacitor should be held within a particular voltage window Vcmin < Vc < Vcmax at steady state in the proposed setup. It is easy to approximate the proper value of the capacitances, the number of units, and input DC voltage for any given output pulse specifications such as pulse magnitude Vo, pulse duration T, and pulse width tp. The Gate pulse for each individual semiconductor device during charging and discharging action must follow the switching scheme as summarized in Table I. Bit 1 indicate the switch is closed and 0 indicates the switch is open.

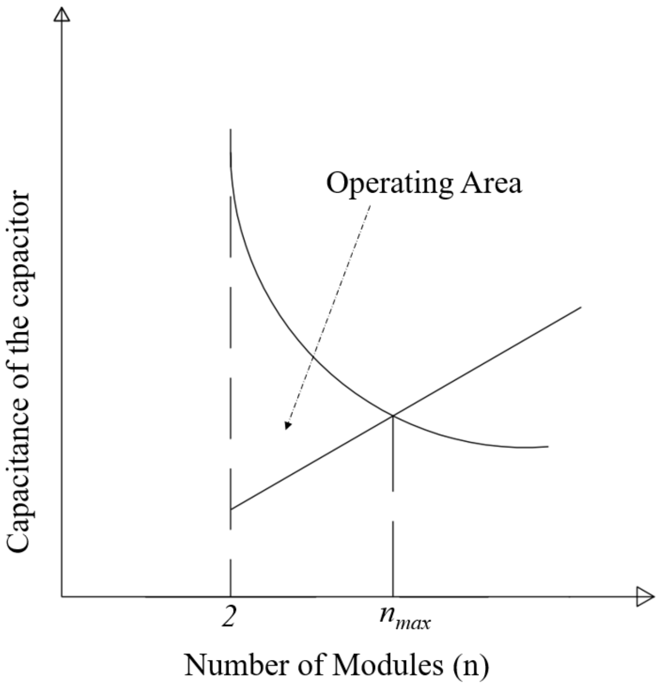

Figure 4 Relation between capacitance and number of modules.

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A. Charging parameters

The capacitor voltage difference during charging can be expressed as in equation 1, assuming t'=0 at the start of the charging operation.

$$V_c(t) = V_{dc} + V_{dc}e^{-\frac{t}{T_c}}(b-1) \qquad \text{Equation 1}$$

TABLE 1 SWITCHING SCHEME OF SWITCHES DURING THE OPERATION.

Capacitor	Status	Sx	Sy	Scd1	Sb1	Scd2	Sb2	Scd3	Sb3	Scd4	Sb4	Scd5	Sb5
C1	Charging	0	1	1	0	0	1	0	1	0	1	0	1
C2	Charging	0	1	0	1	1	0	0	1	0	1	0	1
C3	Charging	0	1	0	1	0	1	1	0	0	1	0	1
C4	Charging	0	1	0	1	0	1	0	1	1	0	0	1
C5	Charging	0	1	0	1	0	1	0	1	0	1	1	0
$C_{1:5}$	discharging	1	0	1	0	1	0	1	0	1	0	1	0

At the end of the charging period, $t' = \frac{T-tp}{n}$ the voltage must be equal to $V_{cmax} = a \cdot V_{dc}$ as related in the equation 2. The desired charging time constant can be obtained using equation 3.

$$V_{dc} = V_{dc} + V_{dc}e^{-\frac{T-tp}{n \cdot T_c}}(b-1) \qquad \text{Equation 2}$$

$$T_c \leq \frac{T-tp}{n \cdot \ln(\frac{b-1}{a-1})} \leq CR_L \qquad \text{Equation 3}$$

The capacitance of the capacitor in each module can be calculated using equation 4.

$$C \leq \frac{T-tp}{n \cdot R_L \cdot \ln(\frac{b-1}{a-1})} \qquad \text{Equation 4}$$

The charging period of one of the capacitors in the module can be calculated using equation 5

$$t' = \frac{T-tp}{n} \qquad \text{Equation 5}$$

B. Discharging parameter

The capacitor voltage during the discharging can be obtained using equation 6. The voltage across each capacitor must be at least equal to $V_{cmin} = b \cdot V_{dc}$ at the end of the discharging cycle as can be seen in equation 7.

$$V_C(t) = a \cdot V_C e^{-\frac{t}{T_d}} \qquad \text{Equation 6}$$

$$V_C(t) = b \cdot V_{dc} = a \cdot V_{dc}e^{-\frac{t}{T_d}} \qquad \text{Equation 7}$$

The discharging time can be calculated using equation 8, which is deduced using equations 6 and 7.

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$$T_d \geq \frac{tp}{\ln\left(\frac{a}{b}\right)} \geq \frac{C}{n} R_L$$

Equation 8

Where T_d is discharging period, tp is pulse width, V_o is the pulsating output voltage, T is the total time period of the output voltage. The capacitance under discharging condition can be calculated as equation 9

$$C \geq \frac{n \cdot tp}{R_L \ln\left(\frac{a}{b}\right)}$$

Equation 9

Using equation 4 and equation 9, the range of capacitance of the capacitor can be obtained as in equation 10.

$$\frac{n \cdot tp}{R_L \ln\left(\frac{a}{b}\right)} \leq C \leq \frac{T - tp}{nR_L \ln\left(\frac{a-1}{b-1}\right)}$$

Equation 10

The maximum number of modules n_{max} can be obtained using equation 11.

$$n_{max} = \sqrt{\frac{(T - tp)\ln\left(\frac{a}{b}\right)}{tp \cdot \ln\left(\frac{b-1}{a-1}\right)}}$$

Equation 11

IV. SIMULATION OF THE HIGH VOLTAGE PULSE GENERATOR

Based on the equations presented in the previous section, the parameters for the modular high voltage pulse generator are obtained as presented in the table 2. The simulation was performed to inspect and analyse the working of the proposed generator in the virtual environment.

TABLE 2 PARAMETERS FOR SIMULATION

Sl No	Parameter	Symbol	Value
1	Number of modules	n	5
2	DC voltage source	V_{dc}	1.2 kV
3	The capacitance of each capacitor	C	0.6433 μF
4	Load Resistance	R_L	2.5 kΩ

In the simulation model, the calculated parameters were incorporated during the simulation. The simulation results are shown in Figure 5 shows the sequential charging of capacitors in each module while taking module capacitors having no pre-charged voltages. It is observed that the capacitors are successfully charged in a sequential fashion, and each capacitor voltage is maintained within its given window of 0.95 Vdc < Vc < 0.98 Vdc. The charged capacitors are then connected in series to discharge across the load R_L. The load pulsating output voltage is shown in Figure 6; it is obvious that the output pulses are successfully produced as per the desired specifications. During the generator's start-up period, the output voltage is relatively high during the charging process due to charging the capacitor with zero pre-charged voltages, indicating a high energy loss. It can be observed that the produced output voltage during the simulation was approximately 6 kV which is sufficient for electroporation.

When the capacitor voltages exceed their steady-state values, the output voltage during the charging phase is reduced because the original voltage level of the capacitor to be charged b·Vdc is close to the input voltage level Vdc, i.e., the voltage difference around the output/charging resistor is negligible, resulting in low energy loss. It should be remembered that there is a limited amount of power dissipated in the load resistance during the charging cycle because it is involved in the charging circuit. The power dissipated during this time is mostly determined by the voltage around the load resistance, which is the difference between the input DC voltage and the capacitor voltage. By maintaining the capacitor voltage window as close to the value of the DC input voltage as possible (by selecting proper values for a and b close to unity), the voltage around the load resistance will be low during the charging phase, and the resulting dissipated power will be negligible in comparison to the effective power released to the load during discharge.

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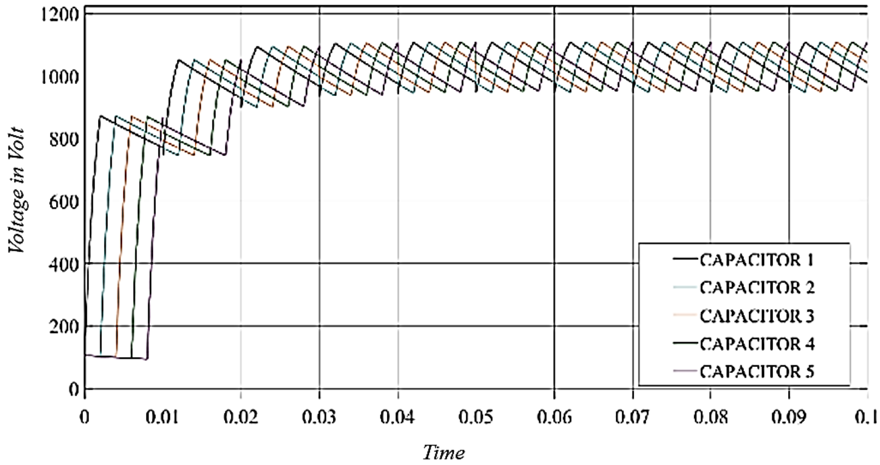

Figure 5 Module Capacitor Voltage

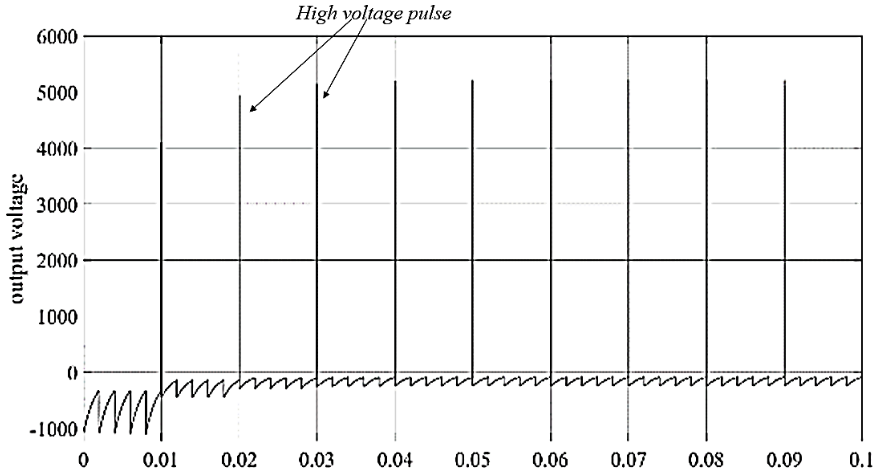

Figure 6 Generated pulsating output voltage

V. CONCLUSION

In this paper, a modular high voltage pulse generator for water treatment applications using underwater pulsed streamer corona discharge for electroporation is discussed. It is seen that the proposed high voltage generator is capable of generating pulsating voltage of up to 6 kV. The generated voltage by the proposed generator is suitable for application to the treatment of water. Which make the proposed scheme a potential candidate for water treatment application where people put more importance on avoiding chemicals to treat water.

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