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Purification of Drinking Water by Application of High Voltage Electric Pulses Generated from Boost Converter and Voltage Multipliers

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Abstract: Drinking water can be purified by application of electric pulses across the water sample that has to be treated. Application of high Pulsed Electric Field (PEF) to the water kills the germs and the bacteria present and thus purify it. In this paper, a high voltage electric pulse generator module is proposed, which consists of boost converter and a capacitor diode voltage multiplier (CDVM) with a closed loop control on its output voltage. A low voltage DC source is used at the input and the output of the module will be a pulsed output voltage. The proposed generator is validated by simulation study.

Keywords: Pulsed Electric field, Capacitor Diode Voltage Multiplier, Boost Converter, Closed Loop Control.

I. INTRODUCTION

When Pulsed Electric Field (PEF) is applied to the water sample which has to be purified; PEF is one of the efficient methods present to purify water [1] an irreversible permeabilisation of the cell membrane takes place [2] which ensures killing of germs in drinking water. To avoid electrolysis of the electrodes in the treatment chamber PEF is used instead of continuous electric field [3, 4].

For the purification of water duration of the pulses in the pulsed electric field can be ranged from few tens of nanoseconds to few tens of microseconds [5], with a voltage level up to 50kV/cm to cause irreversible permeabilisation of the cell membrane.

A DC-DC Boost converter is used for producing high pulsed output voltage [6]. CDVMs are used with boost converter to get a high voltage gain [7]. The CDVMs have small size and weight and high efficiency [8].

II. PROPOSED HIGH VOLTAGE ELECTRIC PULSE GENERATOR

A. Circuit Configuration

The high voltage electric pulse generator is shown in the Fig 1. The module is fed from a DC source. An IGBT is used to chop the generated DC voltage with a desired rate. The IGBT used is a high voltage controlled switch which is rated at output voltage of the module. The output DC voltage will have a voltage magnitude of V_{out} and duration of the pulses will be equal to the turn on time of the IGBT,S_i. The frequency of the generated pulses is $(1 / T^*)$, where T^* is the periodic time of the gate pulses of the IGBT switch which equals T_{on}^*/D_0, whereD_0 is the duty cycle of the gate pulses of the IGBT ($D_0 = T_{on}^*/T^*$). A diode is connected across the output of the module to bypass the module during deactivation/ fault module.

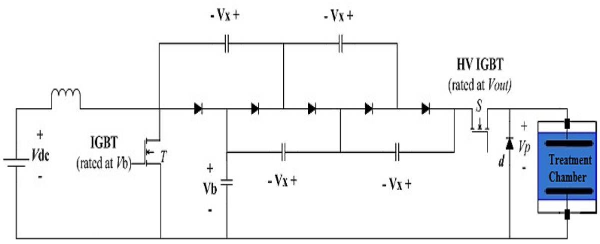

Fig.1.Construction of the Proposed High Voltage Electric Pulse Generator.

The construction of module is showed in Fig. 1. The module has a boost converter whose output voltage is regulated. The output voltage of the module (V_{out}) is compared with its reference value and the corresponding voltage error is fed to the Proportional Integral controller (PI controller) to generate the boost converter duty cycle (D_b). The generated duty cycle is then compared with a high frequency triangular wave to generate gate pulses for the controlled switch of the boost converter (T).

B. Number of CDVM stages

Based on Fig.2, the output voltage of the module,V_{out} , is given by (1);

$$V_{out} = V_b + mV_x (1)$$

Where V_b is the output voltage of boost converter, m is the number of CDVM stages, and V_x is the voltage of each capacitor in CDVM. The voltage of each multiplier stage is given by (2);

$$V_x = V_b \quad (2)$$

Then, the output voltage of each module, V_{out} is given by (3);

$$V_{out} = (m+1)V_b \quad (3)$$

The relation between boost converter output voltage, V_b, and the input DC voltage is given by (4);

$$V_b = \left(\frac{1}{1-D_b}\right)V_{dc} \quad (4)$$

Where D_b is the duty cycle of boost converter. Substituting from (4) into (3) yields (5).

$$V_{out} = \left(\frac{m+1}{1-D_b}\right)V_{dc} \quad (5)$$

Equation (5) can be used to find the expression of D_b in terms of the number of voltage multiplier stages (m), the desired output voltage, and the given input DC voltage as in (6);

$$D_b = 1 - \left((m+1)\frac{V_{dc}}{V_{out}}\right) \quad (6)$$

Equation (6) is used to choose the required number of voltage multiplier stages, m, to ensure operation within a moderate range of converter duty cycles.

TABLE I Relation Between Number of Stages and Duty Cycle

m	1	2	3	4	5
D_b	0.8	0.7	0.6	0.5	0.4

III. CAPACITOR DIODE VOLTAGE MULTIPLIERS (CDVM)

Voltage multipliers are AC-to-DC power conversion devices, consisting of diodes and capacitors that produce a high DC voltage from a low voltage AC source. Multipliers are made up of multiple stages. Assembly type used here is Half-wave Parallel Multiplier, Fig.2.

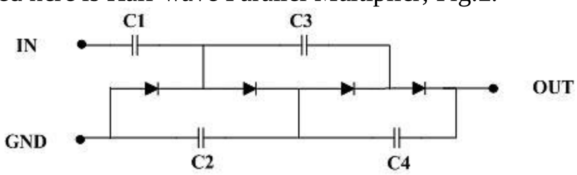

Fig.2. CDVM Schematic.

Its characteristics are:
1) Small size
2) Highly efficient
3) Uniform stress on diodes
4) Increasing voltage stress on capacitors with successive stages

IV. DESIGN OF MODULES

A. Selection of Boost Converter Inductor

Equivalent resistance of the switched load and the equivalent resistance seen by the boost converter output are

$$R_{eq} = \frac{R_{Load}}{D_0} = \frac{T^* R_{Load}}{T^*_{on}} \quad (7a)$$

$$R_b = R_{eq}\left(\frac{V_b}{V_{out}}\right)^2 = \frac{R_{Load}}{D_0}\left(\frac{V_b}{V_{out}}\right)^2 \quad (7b)$$

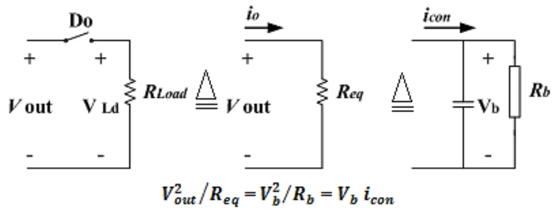

Fig.3.Equivalent Resistances.

Continuous current mode with low current ripple is used so that the inductor core losses reduced. The selected inductance should be greater than the critical inductance to ensure the above condition.

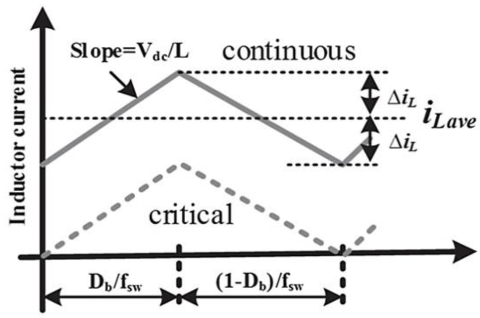

Fig.4.Steady State Variation of the Inductor Current.

From Fig.4, the ripple current through the inductor during the continuous current mode is given by (8);

$$\Delta i_L = \frac{D_b V_{dc}}{2\,L\,f_{sw}} \quad (8)$$

During the critical condition mode, the ripple current will be equal to the average inductor current. Hence the critical inductance will be calculated from (9);

$$L_{critical} = \frac{D_b V_{dc}}{2\, i_{L\,ave}\, f_{sw}} \quad (9)$$

Based on Fig.3, the average conductor current is given by (10);

$$i_{L\,ave} = \frac{i_{con}}{1-D_b} = \frac{(V^2_{out}/(V_b R_{eq})}{1-D_b} \quad (10)$$

Where i_{con} is the boost converter output current, then the critical inductance, $L_{critical}$ is given by substituting (7a) and (10) in (9).

$$L_{critical} = \frac{D_b\,(1-D_b)R_{Load}\; V_{dc} V_b}{2\,D_0 (V^2_{out})f_{sw}} \quad (11)$$

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B. Selection of Capacitors Used in the Module

All the capacitors in the module are assumed equal. The capacitance is chosen to ensure acceptable output voltage ripple.

$$\frac{\Delta v_b}{V_b} = \frac{D_b}{f_{sw}\, R_b\, C_m} \quad (12)$$

Equation (7b) is substituted in (12) and the expression for capacitance is obtained as (13).

$$C_m = \frac{D_b\, D_0\, V_{out}^2}{f_{sw}\, R_{Load}\ \ \Delta v_b V_b} \quad (13)$$

C. Numerical Example

For the proposed high voltage electric pulse generator, a DC input voltage of V_{dc} = 300V is applied and the output voltage of the module will be 3kV, the generated output voltage pulses are chopped at a rate of 5000 pulses/s and with a pulse width of 10µs. the resistance of water is taken as 1kΩ.

- From (6), the relation between boost converter duty cycle and the CDVM stages is given by

$$D_b = 1 - ((m+1)\frac{300}{3000}) = 0.1\ (9 - m)$$

For m = 3, the duty cycle of the boost converter will be 0.6.

- From (4), The output voltage of the boost converter will be

$$V_b = (\frac{1}{1-D_b})V_{dc} = (\frac{1}{1-0.6})300 = 750V$$

- The switching frequency of the boost converter is selected as 20 kHz, then the critical inductance of the boost converter can be obtained from (11).

$$L_{critical} = \frac{D_b\ (1-D_b)R_{Load}\ \ V_{dc}\, V_b}{2\, D_0 (V_{out}^2)f_{sw}}$$

$$= \frac{0.6\ (1-0.6)\ (1000)(300)\ (750)}{2\ (0.05)(3000^2)(20000)} = 3mH$$

- The capacitor voltage ripple is taken as 3%, the capacitance of the capacitors present in the module will be

$$C_m = \frac{D_b\ D_0\ V_{out}^2}{f_{sw}\ R_{Load}\ \ \Delta v_b\, V_b}$$

$$= \frac{(0.6)(0.05)(3000^2)}{(2000)(1000)(0.03*750)(750)} = 0.8\mu F$$

- The duty cycle of the output voltage which is in form of pulses will be,

$$D_0 = \frac{T_{on}^*}{T^*} = \frac{10\times10^{-6}}{1/5000} = 0.05$$

V. SIMULATION

A software simulation model has been built for the high electric pulse generator with the data as mentioned in the numerical example. The corresponding simulation results are shown in the figures below. A well regulated output voltage of the module is obtained.

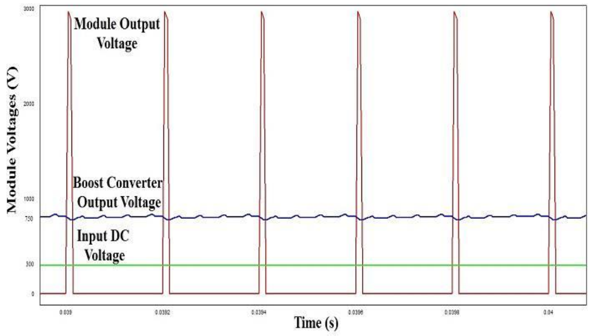

Fig.5. Module Voltages.

Fig.6. shows the inductor current flowing through the module. The inductor current here is continuous.Fig.7. shows the CDVM capacitor voltages. It is clear that the capacitors and the diodes have relatively low voltage rating of 1kV.

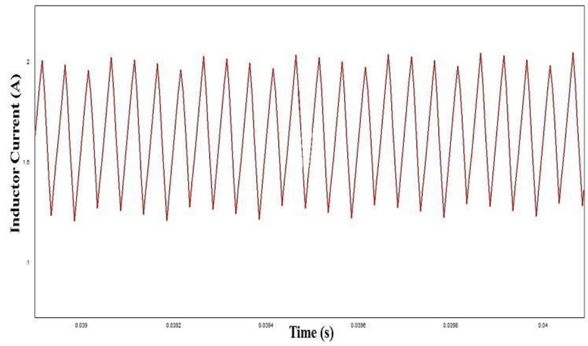

Fig.6. Boost Converter Inductor Current.

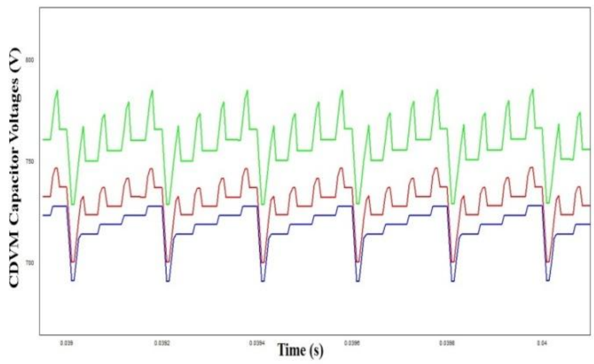

Fig.7. CDVM Capacitor Voltages.

IV. CONCLUSION

In this paper, a high voltage electric pulse generator has been proposed for purification of water. The module of the proposed pulse generator is fed from a low voltage DC source, and has a boost converter with a capacitor- diode voltage multiplier (CDVM). The proposed generator provides high voltage pulses using low/ medium voltage components. In the output stage a controlled switch is needed to chop the output voltage with desired width and rate. The pulsed output voltage is connected to high voltage electrodes and applied across the water sample which has to be purified, so that the generated PEF kills the germs and bacteria present in water. Finally, simulation validation has been done to confirm the viability of the proposed approach.

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