Research Article

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Simulation of High-voltage Pulse Generator for Environment-friendly, Non-thermal Pasteurization Applications

B. Vaishali, S. Chandrasekar*, K. Karpagavani

Sona PERT R & D Centre, Department of EEE, Sona College of Technology, Salem, TN, India

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*chandrukvt@gmail.com

ABSTRACT

Nowadays, the demand for high-voltage pulse generators has begun to proliferate in many industries. Particularly in the food processing industries, the conventional method of pasteurization involves the use of heat treatment processes, which are not environment-friendly; hence, researchers are working towards environment-friendly, non-thermal food processing techniques by which the microorganisms present in the liquid food can be eliminated. High-voltage pulsed electric field technology is one of the popular non-thermal food processing techniques. Recent advancements in power electronic switching technology have facilitated the development of solid-state pulse generators for these applications. In this paper, the simulation of a high-voltage pulse generator for eco-friendly pasteurization applications has been attempted using a cascaded boost converter topology. The entire simulation is carried out using MATLAB/Simulink software. The designed two-stage cascaded boost converter is tested for varying duty cycles and loads. The results with resistive and inductive loads have been analyzed.

Keywords: Non-thermal pasteurization; High-voltage pulse generator.

1. INTRODUCTION

Non-thermal food processing technologies are the most preferred ones in recent times. The drawbacks of the conventional heat treatment process for the pasteurization of liquid foods are well known – the primary one being the lack of its eco-friendliness. High-voltage pulse generator using a pulsed electric field concept is emerging as a preferred technology for food pasteurization applications (Min *et al.* 2007; Huang *et al.* 2012; Chen, 2010), in which microorganisms are inactivated in liquid foods. This process happens by the application of a high-voltage pulse which helps in the electroporation of cell membranes in microorganisms (Marselles *et al.* 2009; Gurtler *et al.* 2010). This technique is also being adopted in wastewater treatment, pollution control and medical diagnostics.

In many earlier research works, HV pulses are generated through vacuum tubes and spark gap technology. Advancements in power electronics have transformed the technique of high-voltage pulse generation into a much easier and preferred one. Recent high-voltage MOSFETs and IGBTs make the work easier in obtaining the high-voltage pulse generator. Series connection of IGBTs for power converter applications are being discussed in many research papers (Van *et al.* 2011; Zarghani *et al.* 2016); however, a series connection of solid state switches for obtaining the required high voltage pulse is not a good idea, as it leads to transient over-voltages and non-uniform voltage sharing between the switches. Voltage balancing techniques in series connected IGBTs have been discussed in several research works and for practical high-voltage cases, the suitability of these techniques has to be investigated in detail (Lim *et al.* 2011; Ji *et al.* 2015). Another major issue in the design of high-voltage pulse generators lies in the high DC voltage source in the input section.

Both the above problems can be solved by adopting a cascaded arrangement of high-voltage pulse generators using DC-DC boost converter-based topology. The major factors affecting the food processing through this technique are the electric field intensity, electrical conductivity of the medium, treatment time, pulse wave shape and temperature. Liquid foods with high conductivity need a stable pulse generator to keep the necessary electric field between the electrodes.

In this work, a brief illustration of the design and operation of the cascaded boost converter-based high voltage pulse generator to attain 5 kV output voltage is given. Simulations are carried out with varying load and duty cycles and the experimental results are provided to interpret the efficacy of the converter for continuous high-voltage short pulse generation. Closed loop feedback control is used to attain the desired output voltages. A comparison between resistive load and inductive load is done and analyzed for the better outcome of the pulse generator.

2. BASIC STRUCTURE OF BOOST CONVERTER

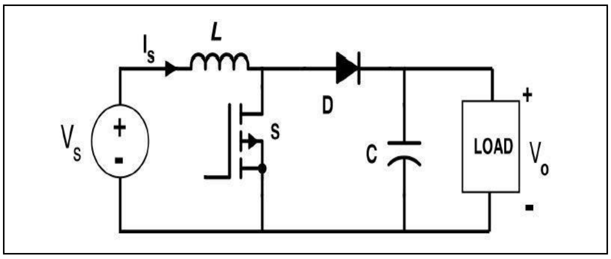

Fig. 1: Basic design of DC-DC boost converter

Fig. 1 shows the basic DC-DC boost converter used to build the proposed converter. The DC-DC boost converter is designed to attain a 5 kV output voltage. MOSFET switch is preferred along with an inductor, diode and a capacitor. The LC acts as a filter, mainly to reduce the voltage and current ripple factor. In this work, the continuous conduction mode is preferred, as it maximizes power capability.

2.1 The Converter Operates in Two Modes

1st Operating Mode: MOSFET is turned ON; the diode is reverse-biased which represent a short circuit. As a result, energy is accumulated in the inductor in the form of a magnetic field. Thus there is a rise in inductor current.

2nd Operating Mode: MOSFET is turned OFF; the inductor starts discharging the current which makes the diode turn ON (forward-biased). The accumulated energy is released by the diode and therefore output capacitor is charged which in turn appears across the load.

2.2 Topology Derivation

In the case of boost converter topology, the output voltage is given by,

$$V_{out} = \frac{V_{in}}{1-D}$$

The output voltage is directly related to the duty cycle.

V_{out} = output voltage

V_{in} = input voltage

D = duty cycle

For the proposed structure, the input voltage = 220 V AC and the output voltage = 5000 V.

The switching frequency, f = 30 kHz

The inductor is selected with maximum ripple current at minimum duty cycle D, at maximum input voltage V_i. The inductance, L is given by,

$$L = R*D(1-D)^2/2f = 6.5\ \mu H$$

A low equivalent series resistance capacitor is used to minimise the ripple at the output voltage. The capacitors are designed in such a way as to match the output voltage specification and handle the ripple current stress.

$$C = D/R_l V_r = 2\ \mu F$$

3. SIMULATION OF HIGH VOLTAGE PULSE GENERATOR

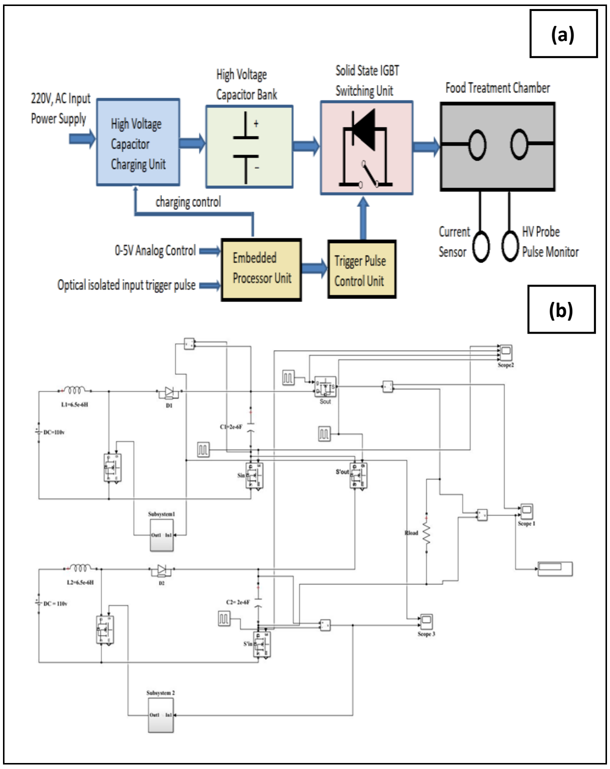

Fig. 2: a) Block diagram representation of high-voltage pulse generator for food treatment process b) Simulink model of the cascaded two-stage boost converter-based high-voltage pulse generator

The block diagram of the proposed high-voltage pulse generator for the food treatment process is shown in Fig. 2 a. MATLAB/Simulink model of the two-stage cascaded boost converter-based high-voltage pulse generator is shown in Fig. 2 b. The pulse width is maintained as low as 1 to 10 µs, based on the requirement. MOSFET switch is chosen for fast switching applications and less turn-off loss. Output voltage and pulse parameters are monitored with an oscilloscope.

4. RESULTS AND DISCUSSION

Simulation results for a high-voltage short pulse generator using a cascaded boost converter and pulse generator with different load values are discussed below.

4.1 Change in Output Voltage and Current with Varying R Load for Constant Pulse Duration.

The output voltage and current waveforms are simulated when the load is varied from 5, 10, 15 and 20 ohms with a constant pulse width of 6 µs, as shown in Fig. 3. Output voltages up to 5.9 kV and currents up to 1 kA are obtained.

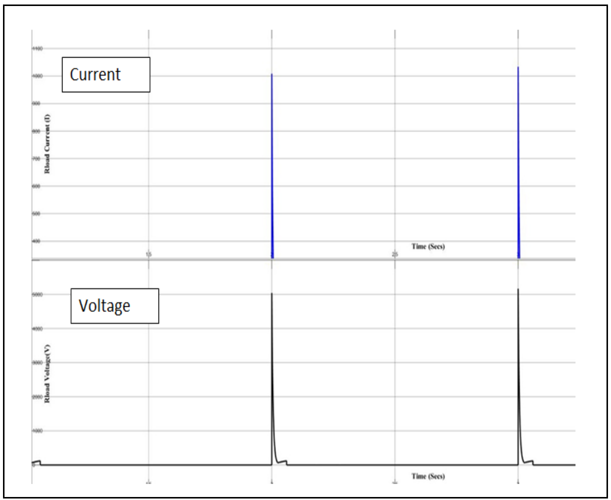

Fig. 3: Output voltage and current waveform of cascaded high voltage pulse generator with R=5 ohms

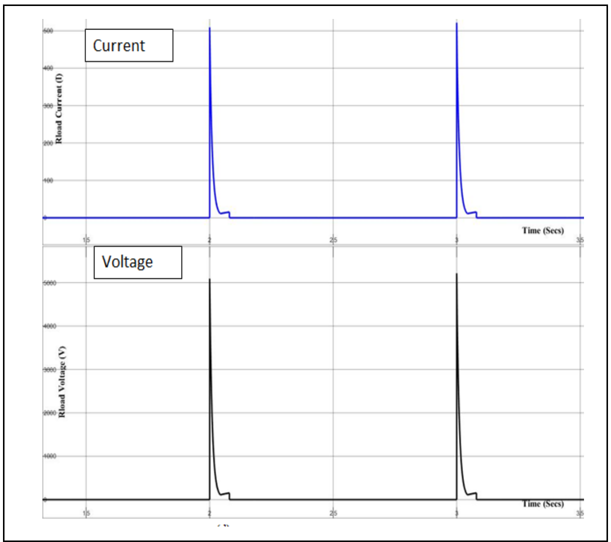

Fig. 4: Output voltage and current waveform of cascaded high voltage pulse generator with R=10 ohms and pulse width duration of 8 µs

Fig. 4 shows the output voltage and current waveforms with a constant 10 Ω resistive load and a varying pulse width of 8 µs. The output voltage reaches up to 5 kV and the current reaches up to 500 A. Note that a cascaded system of boost converters can provide the required high-voltage pulse widths in the microsecond range.

4.2 Variations in Capacitor Voltage

Fig. 5 shows the variation of the capacitor voltage waveform for the charging and discharging period regardless of all load values and the total pulse width of the period.

It can be seen that the closed-loop system of the boost converter allows both C1 and C2 to reach their rated output voltage of 2.5 kV within 0.1 ms. A closed-loop system controls the capacitor so that the desired output value is not exceeded. The cascaded system finally provides a total voltage of 5 kV. A cascaded system of high-voltage short pulse generators is designed to provide microsecond high-voltage pulse outputs, so the capacitors must be rapidly charged and discharged to meet the requirements.

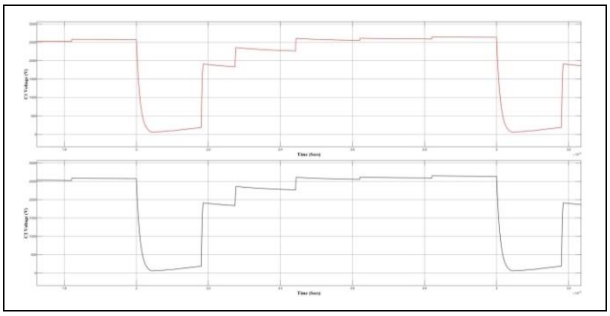

Fig. 5: Variations in capacitor voltage of C1 and C2 for all loads and pulse width

Fig. 6 shows the pulse generator switching sequence for various pulse widths and loads. It is to be noted that the MOSFET switches used in the simulation studies can provide the microsecond pulse switching required to generate short HV pulses.

From the simulation results, it is seen that the cascaded boost converter generates continuous short pulses of 5 kV in 1 to 10 µs at a constant switching frequency of 30 kHz. By varying load and pulse duration at constant input voltage and frequency, the voltage is stepped up from 220 V to 5 kV.

5. SIMULATION RESULTS OF PULSE GENERATOR WITH RL LOAD

Performance comparison of the cascaded high-voltage pulse generator with RL load for 6 µs pulse duration at 10 ohms is presented in this section.

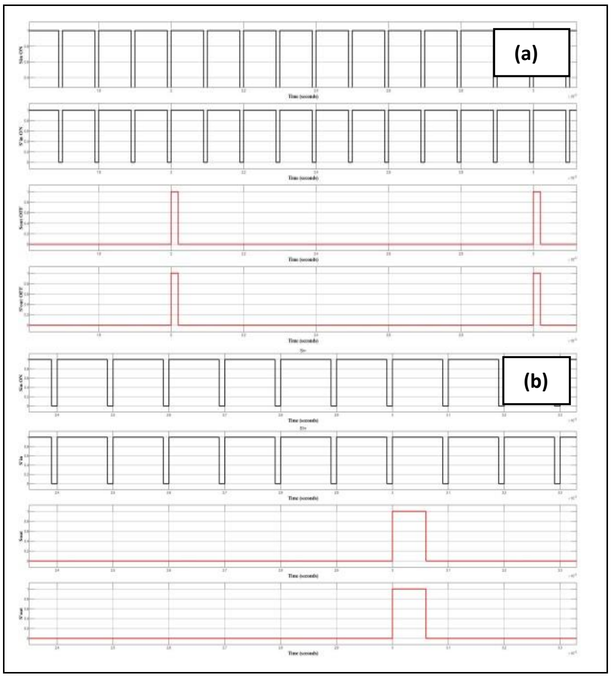

Fig. 6: Pulse generator waveform for (a) 2 µs at 10 Ω (b) 6 µs at 10 Ω

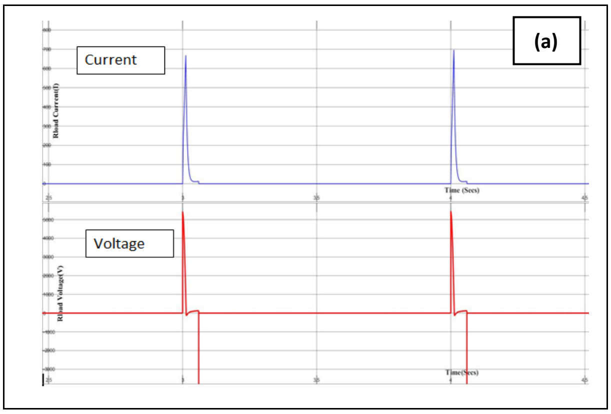

Fig. 7: Output load voltage and current waveform of the pulse generator with series RL load

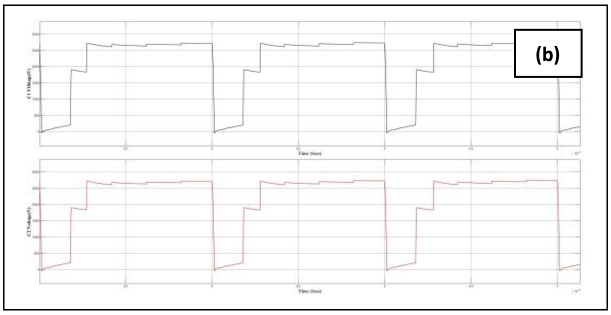

Fig. 8: Variations in capacitor voltage C1 C2 of pulse generator with series RL load

Fig. 9 shows the output current comparison of a high-voltage pulse generator with respect to R and RL load at different pulse durations. With respect to the increase in load values, the current value reduces naturally and there is no major change in the amplitude of the current with respect to the increase in pulse duration up to 8 µs. Since the proposed high voltage pulse generator is mainly intended to produce microsecond pulses for food processing applications, simulations in this work are carried out only up to 8 µs pulse duration.

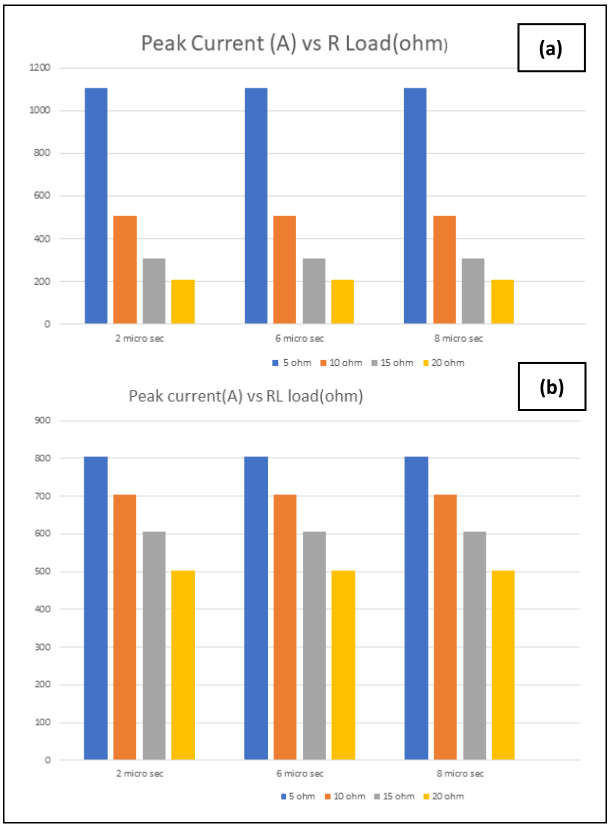

Fig. 9: Variation in peak current with respect to load at pulse duration 2, 6 and 8 µs (a) R load of the pulse generator (b) series RL load of the pulse generator

From the above comparison, it is observed that the output voltage remains stable at 5.8 kV in series RL cascaded pulse generator and there is no abrupt decrease in output current. In general, as the load increases, the peak value of the output pulse current decreases; however, there is no appreciable change in peak current for increasing pulse width in microseconds.

10. CONCLUSION

A high-voltage short pulse generator based on a two-stage cascaded boost converter topology was designed and simulated using MATLAB/Simulink software, to obtain an output of 5 kV. Variations in load, pulse duration and output magnitude were also observed and studied for the interpretation of the cascaded boost converter. The capacitor voltage was also analysed with respect to the load and pulse duration variations. The comparison study of the cascaded boost converter with series load resistance and load inductance was done to analyze the performance of the boost converter. The output pulse peak currents of both converters were studied and analyzed. Results demonstrate that based on the proposed topology, it is possible to develop a high-voltage pulse generator for food processing applications.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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