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COMPARISON OF PULSED ELECTRIC FIELD GENERATION TECHNIQUES FOR MICROBIAL INACTIVATION APPLICATION

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ABSTRACT

This paper presents a comparative study on various pulsed electric field (PEF) techniques for liquid food sterilization applications. Pulsed Electric Field (PEF) is an alternative method compared to the conventional food pasteurization method in removing harmful bacteria contained in liquid food products. A Cascaded Multilevel Inverter (CHMI) is proposed as a PEF generator to produce a higher output voltage without using a transformer to inactivate microbial in liquid food. It will reduce the power losses of the system while yielding better sterilization effectiveness as well as reduce cost. The CHMI has been simulated using MATLAB/Simulink software to analyze the performance of the circuit. The simulation results demonstrate that the CHMI can produce both bipolar and unipolar square wave output pulses. This in turn contributes to the flexibility of the CHMI in testing the effectiveness of the PEF produced on liquid food sterilization compared to the conventional method and other power electronics circuits that have been used for similar application.

Keywords: *Pulsed Electric Field, Conversional Method, Cascaded H- Bridge Multilevel Inverter, Simulation*

1. INTRODUCTION

Food manufacturers typically use pasteurization to remove harmful bacteria contained in liquid food products. Pasteurization aims to reduce the number of viable pathogens most likely to cause disease. Although this method has been practiced and proven to be effective, the process associated with it comes with many side effects. As an example, high-temperature, short-time (HTST) pasteurization that has been investigated over inactivation of E. Coli has resulted in change of pH and colour for liquid food. PEF techniques preserve pH and colour much better when compared to HTST [1, 2]. Furthermore heat pasteurization also produces side effects including reduction in shelf life, altered appearance and diminished overall taste because of thermal damage [2, 3]. In order to produce quality foods, a non-thermal process known as Pulsed Electric Field (PEF) is used; it only requires injecting foods with electrical pulses without compromising the nutrients, flavor, smell and colour of the foods. This process is significantly different from pasteurization which uses thermal process where the heat emitted during the process will discolour the skin of the fruits, decrease the content of nutrients and diminish the aroma [2, 3].

The effect of PEF on the feasibility of microorganism, mainly bacteria in liquid foods has been studied since the 1960’s. Bacterial decontamination using high electric field pulses is first reported by Sale and Hamilton in 1967 and 1968 in a series of papers. In the 1970’s the group of Zimmermann, at the University of Wurzburg, Germany, has made a follow up on the concept of ‘dielectric breakdown’ of cell membranes, and published a series of papers related to the work [4] .

PEF is applied to the liquid foods using treatment chamber. Normally, PEF treatment systems consist of a pulse generator, treatment chambers, a handing system, and monitoring systems [1] in which a PEF treatment chamber is used to house electrodes and deliver high voltage to the food material and the chamber. Generally, it is composed of two electrodes held in position by insulating material, which forms an enclosure containing food material. Furthermore, the design of the treatment chamber is one of the pivotal factors in the development of the PEF treatment for non-thermal pasteurization technology because it should impart uniform electric field to foods with a minimum increase of the temperature and the electrodes should be designed to minimize the effect of electrolysis [4].

From time to time, the use of PEF has attracted many researchers in improving the efficiency of the PEF by applying advanced pulsed generator concepts. In the United States, the first commercial scale continuous PEF system has been installed at The Ohio State University's Department of Food Science and Technology. PEF equipment is also safe for the environment and this process uses ordinary electricity. The facility meets electrical safety standards and is not harmful to the environment [1].

The PEF generators in fulfilling the required specifications are based on transmission line techniques or pulse forming network (PFN) with high voltage ratings and power consumption. These techniques although effective in food sterilization, are associated with design complexity and high cost. In contrast to the power electronic circuits that have been proposed in [5-8] for the same application, the CHMI is capable of reducing the system power losses due to the omission of the winding coils.

Due to these issues, this paper proposed, the use of a CHMI system to produce the PEF characteristics that fulfill the required specifications for effective sterilization of liquid food. The main focus in this paper is to discuss the CHMI that can operate at high intensities in the range of up to 12 kV/cm, pulse width up to 1 ms and repetitive rate in the range of 10 Hz to 100 Hz. In practical, the CHMI circuit is designed using modern IGBT /MOSFET technology.

2. PULSE REQUIREMENTS

The application of PEF for liquid food sterilization through the use of three types of pulses which are Oscillatory Decay Pulses (ODP), Exponential Decay Pulses (EDP) and square wave pulses have been reported. ODP has been identified as the type of pulse with the least efficiency level because it hinders the bacteria cells in liquid food from being continuously exposed to electric field of high intensity for a long time. On the other hand, EDP has a drastic voltage surging rate but a very slow decaying rate causing long tail section that yields extra heat which is ineffective to kill the bacteria in the foods. Among the three pulse types, square wave is much better than EDP and ODP for liquid food sterilization process because it can produce stabile peak voltage for a long time and can reduce thermal effect [9, 10]. Figure 1 shows the waveform of ODP, EDP and square wave.

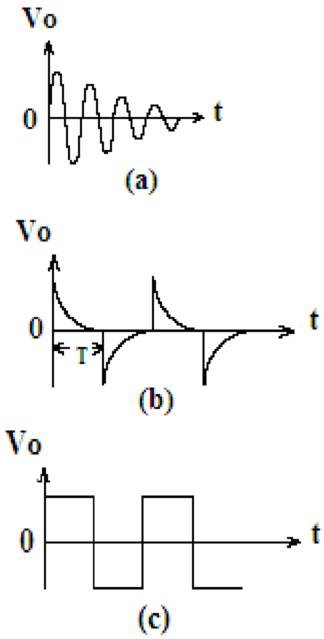

Figure 1: The waveforms for generating PEF
(a) Oscillatory Decay Pulse (ODP)
(b) An Expontantial Decay Pulse (EDP)
(c) Square Wave

3. PEF GENERATION TECHNIQUES

There are two types of PEF generation techniques that have been reported in literature. Details on these techniques are elaborated in the following sub-sections.

3.1 Conventional Techniques

3.1.1 Transmission Line Technique

This technique could produce a desirable square pulse when the circuit is connected to a matched load with a high voltage (HV) charged in the transmission line. However, this method is not practical in PEF generation. The characteristic impedance of the transmission line is the main problem in sense that it is often difficult to match the load resistance of the food product. The other problem in producing square pulses is the unsuitability of the real transmission line (a coaxial cable) for long pulses in microsecond [11].

3.1.2 Pulsed Forming Network (PFN)

A pulse forming network (PFN) as shown in Figure 2 has been discussed to solve the problem that occurs in the transmission line technique.

The circuit basically refers to a transmission line that contains a number of inductor-capacitor sections. The PFN in the pulse generating circuit includes three sections. Each section is composed of shunt capacitor C and series inductor L [11].

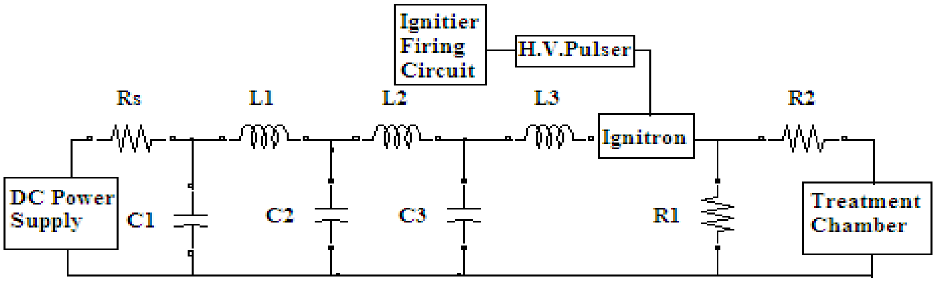

Figure 2. A Pulse- Forming Network schematic diagram consisting of three parameters

3.2 Power-Electronics Based

3.2.1 Bidirectional Flyback Converter

A flyback converter is a circuit based on buck-boost converter where the inductor is replaced by a transformer. The transformer allows increase in the output voltage and the resulting voltage and current isolation provides circuit protection. Due to the use of an isolated flyback converter, separation of the control circuit is required. There are two parts of the controller which are voltage mode control and current mode control to produce the desired output voltage. Figure 3 shows a bidirectional flyback converter that has been designed to produce a narrow bipolar pulsed electric field. Compared to unipolar pulses, bipolar pulses is much better because it can reduce unwanted electrolysis and is more efficient in the inactivation of microbial. Furthermore the bipolar pulses can reduce the solid-particle depositing on electrodes surface in more than 80% [12]. This circuit however is limited to producing only one type of waveform; a narrow pulse EDP causing a long tail which can affect the performance in the inactivation of microbes.

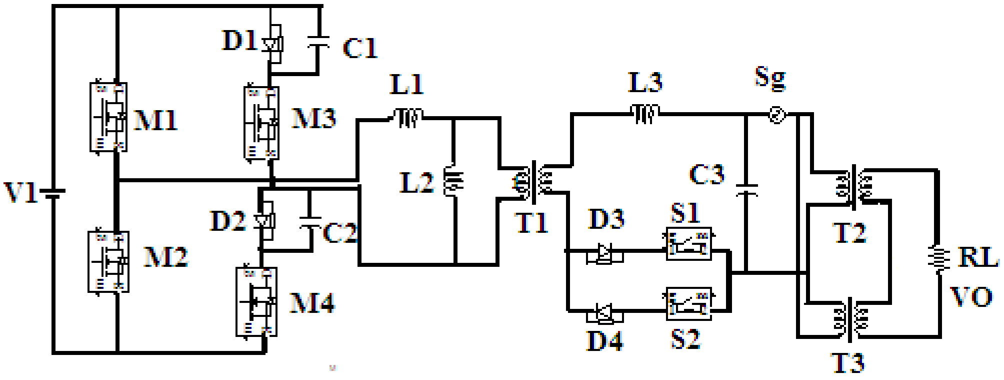

Figure 3. Bidirectional Flyback Converter with Energy Recover Circuit

3.2.2 Forward / flyback converter with two active hybrid clamp circuits and devices piezoelectric

This circuit is a modification of the bidirectional circuit flyback converter as shown in Figure 4. The addition of two active hybrid clamp circuit and piezoelectric [5] components is to reduce the voltage stresses on the components of the transformer secondary winding. Therefore, switches of lower voltage rating can be used which in turn reduces cost. Piezoelectric components are used to clean the electrodes resulting from the leakage inductor in the transformer which contributes to power losses in the circuit. However, this circuit is more complex than the bidirectional fly back converter circuit.

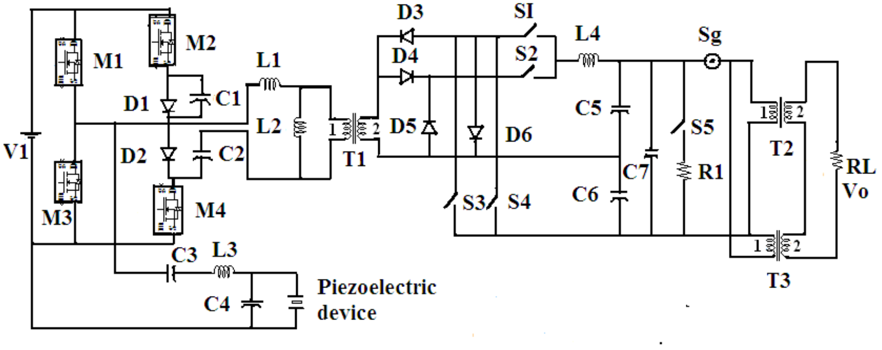

Figure 4. Forward / flyback converter with two active hybrid clamp circuits and devices piezoelectric

3.2.3 MOSFET-Based Pulse Power Supply

The advantage of using MOSFETs in the production of high-speed switching compared to IGBTs has been proven. A MOSFET has faster ON and OFF times but it has voltage and current limits that are lower than an IGBT [13]. MOSFET circuit-based Power Supply [14] is intended to examine electroporation-Mediated Plasma delivery of a DNA molecule in the pathogenic bacterium E. Coli O157: H7. By adding the power MOSFETs in series, the circuit can be expanded to be used for inactivation of microbial in liquid food. Referring to Figure 5, two MOSFETs are connected in series to produce an output voltage of 3 kV. A driver circuit has been built and controlled using a microcontroller which is intended to control the repetitive rate and pulse width of the MOSFET. The circuit has an advantage of being simple, thus reduces costs. However if any one of the MOSFET is damaged, the desired output voltage will not be produced. Moreover this circuit can only produce unipolar square wave output pulses.

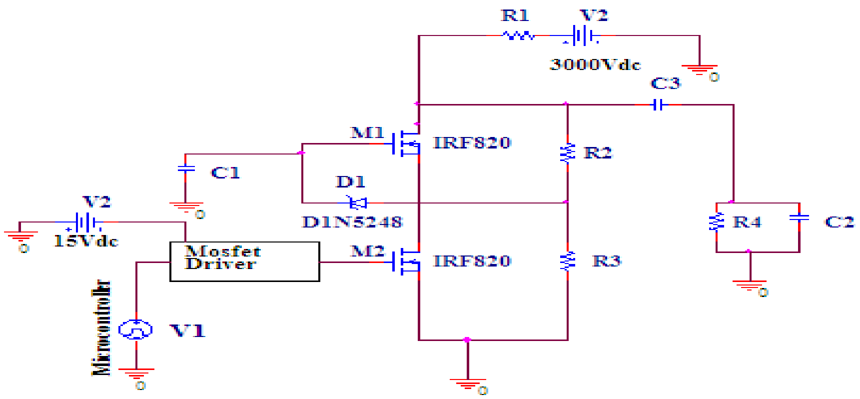

Figure 5. Circuit Diagram of a MOSFET Pulsed Power Supply

4. CASCADED H-BRIDGE MULTILEVEL INVERTER (CHMI)

A Cascaded H-bridge Multilevel Inverter (CHMI) topology as shown in Figure 6 is the proposed circuit in producing the pulses with characteristics that are suitable for effective inactivation of microbial in liquid food. CHMI is able to minimize the number of components needed without extra clamping diodes or voltage balancing capacitors as in other types of multilevel inverters. In addition CHMI also yields lower voltage and power consumption compared to transmission line or PFN methods. In order to test the effectiveness of PEF in liquid food sterilization, several different mechanisms have been proposed. PEF with suitable pulse width, repetitive rate and field intensity are a few important considerations in killing microorganism. To design proper PEF generators, the sterilization mechanisms and waveform consideration must be firstly understood [2]. Based on the characteristics of liquid foods, the most effective state for the inactivation of microbial in it is when the voltage is in the range of ±6 kV to ±20 kV, repetitive pulse rate (frequency) in the range of 0.1 to 100 Hz and pulse width in the range of nanosecond to microsecond [5].

In this paper, a 7-level CHMI is discussed to generate a ±6 kV output voltage. Each of the CHMI modules produces a ± 2 kV output voltage using a 2 kV high voltage DC power supply. Referring to Figure 5, when the first H-bridge is supplied with a 2 kV DC input voltage and the gates are triggered, the IGBTs 1 and 3 are turned on to generate a 2 kV positive output voltage whereas IGBTs 2 and 4 are turned on to generate a 2 kV negative output voltage. However, to generate a ± 6kV output voltage, three DC power supplies are needed. When the three DC power supplies are applied and the gates are triggered simultaneously, the IGBTs 1, 3, 5, 7, 9 and 11 is each represented as a closed switch to generate the positive output voltage of 6 kV, while the IGBTs 2, 4, 6, 8, 10 and 12 act as closed switches to generate the negative output voltage of 6 kV.

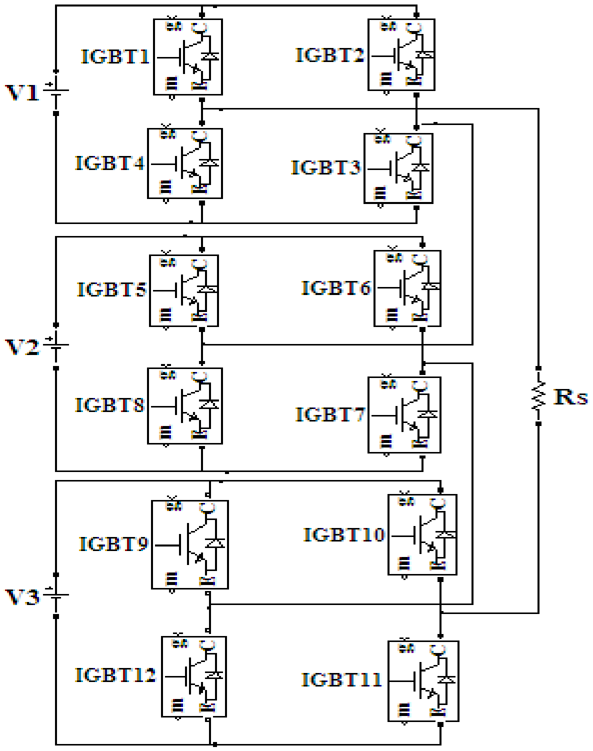

Figure 6. The proposed H-bridge cascaded multilevel inverter

5. SIMULATION RESULTS AND ANALYSIS

The simulation model of the CHMI based pulsed power supply using MATLAB/Simulink is as shown in Figure 7. MATLAB/Simulink contains many instructions and tools for system designing and control algorithms. Furthermore, MATLAB/ Simulink library involves SimPower System block that facilitates power electronics circuit simulation and analysis. The CHMI circuit output voltages in the form of unipolar and bipolar pulses are as shown in Figure 8, 9, 10, 11, 12, 13, 14 and 15. The frequency and pulse width of the output voltage applied across the electrodes can be varied accordingly to test the effectiveness of microbial inactivation for liquid foods. The simulation results show that the frequency and the pulse width of the output voltage can be controlled using pulse generator 1 and 2 of the gate signal generator by controlling the pulse delay of the former as shown in Figure 7. As explained earlier, the most efficient treatment to inactivate microbial is by using bipolar square-wave pulses [15]. From the simulation work, the bipolar output pulses obtained are as shown in Figure 8, 9, 10 and 11 at various frequencies and pulse widths. The outputs are obtained when both pulse generators are turned on. The pulse delay of pulse generator 1 is set at 0.005 s while the pulse delay of pulse generator 2 is set at 0.015 s for a 50 Hz frequency. For a 100 Hz frequency, the pulse delays are set at 0.002 s and 0.008 s respectively

These pulse delays can be varied depending on the treatment time of the liquid food sample. Treatment time can be calculated by multiplying the pulse width applied by the number of pulses [16]. If the number of pulses and pulse widths are increased, the treatment time and therefore the effectiveness of microbial inactivation will also be increased.

On the other hand, unipolar square-wave pulses can also be as effective if the pulse width is in the range of 1 µs to 2 µs [17-18]. Figures 12, 13, 14 and 15 show unipolar output voltage pulses of 6 kV at a frequency of 100 Hz and 50 Hz with pulse width of 1 µs and 1 ms respectively. Referring to Figure 12 and 13, the pulse delay is set at 0.01 s by using pulse generator 1 for a 50 Hz frequency. For a 100 Hz frequency, as shown in Figure 14 and 15 the pulse delay is set at 0.002 s. To obtain this unipolar output only one of the two pulse generators of the gate signal generator need to be turned on. It is important to highlight that the proposed CHMI based pulsed power supply allows flexibility in testing microbial samples in various types of liquid food as both bipolar and unipolar type of outputs can be produced.

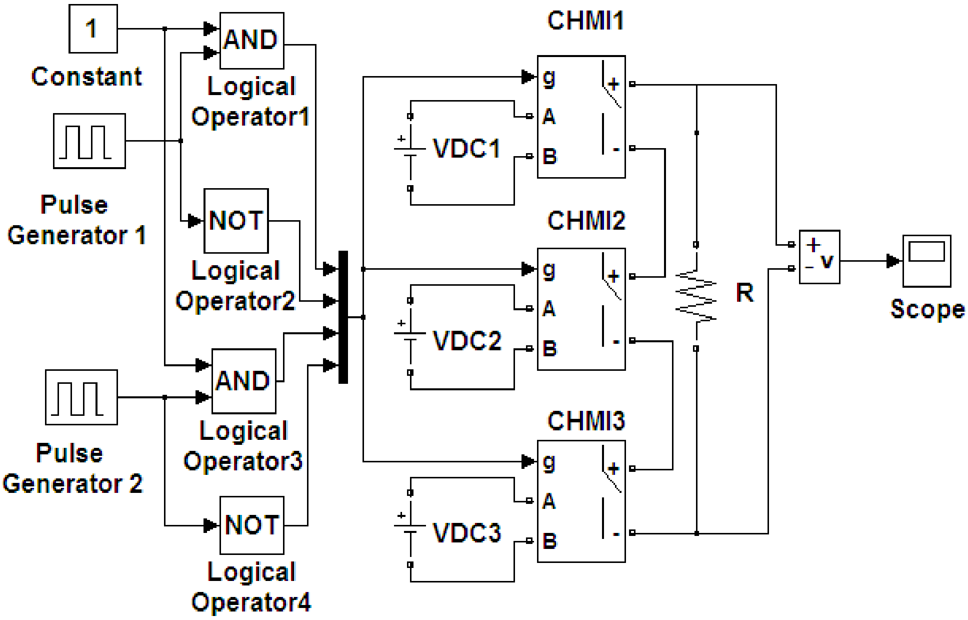

Figure 7. Simulation systems diagram based on MATLAB/Simulink

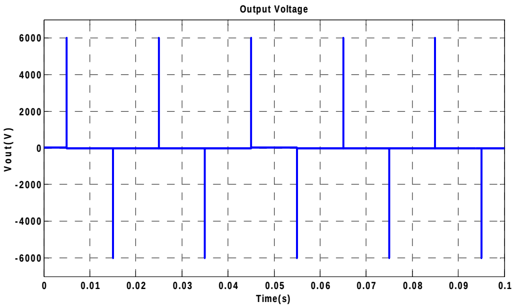

Figure 8. Bipolar pulsed output voltage for f = 50 Hz, pulse width = 1 μs

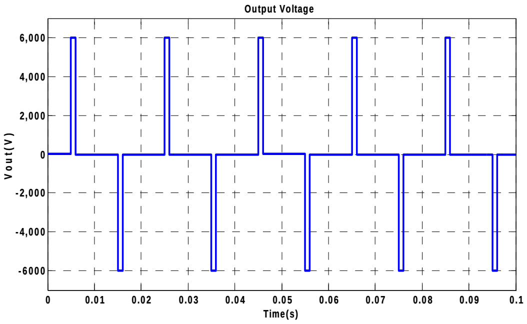

Figure 9. Bipolar pulsed output voltage for f = 50 Hz, pulse width = 1 ms

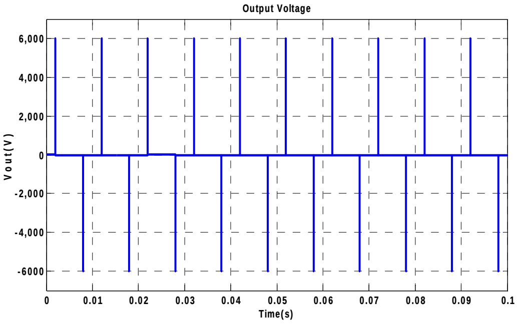

Figure 10. Bipolar pulsed output voltage for f = 100 Hz, pulse width = 1 μs

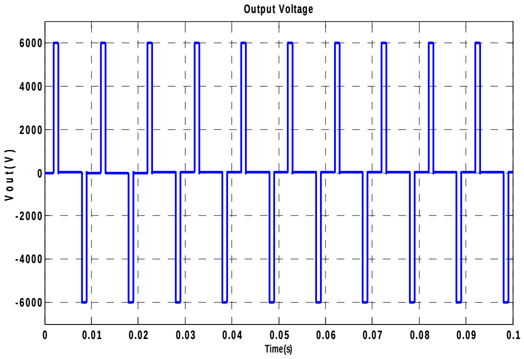

Figure 11. Bipolar pulsed output voltage for f = 100 Hz, pulse width = 1 ms

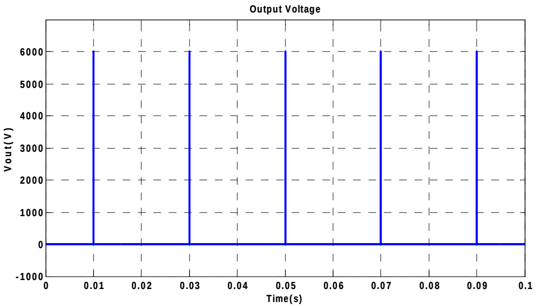

Figure 12. Unipolar pulsed output voltage for f = 50 Hz, pulse width = 1μs

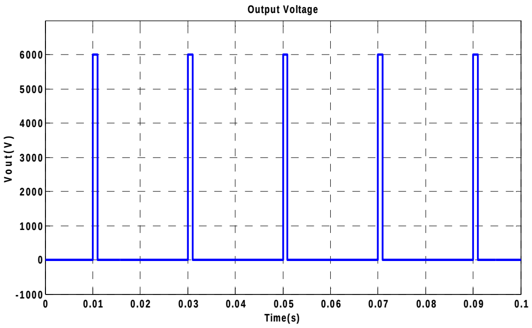

Figure 13. Unipolar pulsed output voltage for f = 50 Hz, pulse width = 1 ms

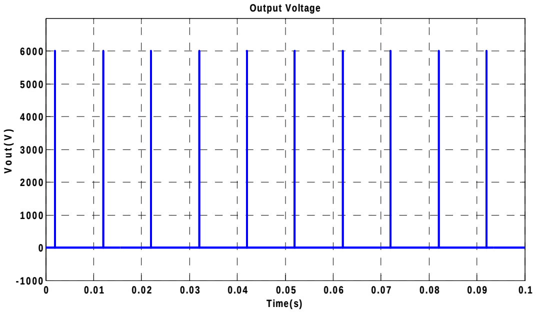

Figure 14. Unipolar pulsed output voltage for f = 100 Hz, pulse width = 1 μs

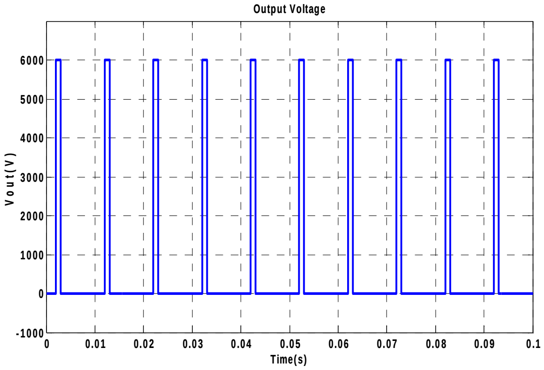

Figure 15. Unipolar pulsed output voltage for f = 100 Hz, pulse width = 1ms

6. CONCLUSION

This paper has presented a comparison study on various PEF generation techniques for microbial inactivation application and the results of a simulation study on the operation of the proposed CHMI based pulsed power supply**.** The simulation results have demonstrated that pulsed output voltage at repetitive rate in the range 10 – 100 Hz, pulsed width between 1 µs to 1 ms, and peak value of 6kV peak can be generated using the proposed circuit. The results can be used as a basis to develop an experimental set-up of the CHMI to verify its capability in generating PEF that are effective and suitable for liquid food sterilization. Most importantly, the simulation results have shown that the CHMI is capable of producing both bipolar and unipolar type of pulses which cannot be generated through conventional method or using power electronic circuits for similar application.

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