

Bipolar Square Wave Pulses for Liquid Food Sterilization using Cascaded H-Bridge Multilevel Inverter

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Abstract—This paper presents the generation of bipolar square wave pulses with characteristics that are suitable for liquid food sterilization using a Cascaded H-bridge Multilevel Inverter (CHMI). Bipolar square wave pulses have been reported as stable for a longer time during the sterilization process with minimum heat emission and increased efficiency. The CHMI allows the system to produce bipolar square wave pulses and yielding high output voltage without using a transformer while fulfilling the pulse requirements for effective liquid food sterilization. This in turn can reduce power consumption and cost of the overall liquid food sterilization system. The simulation results have shown that pulses with peak output voltage of 2.4 kV, pulse width of between 1 μ s and 1 ms at frequencies of 50 Hz and 100 Hz can be generated by a 7-level CHMI. Results from the experimental set-up based on a 5-level CHMI has indicated the potential of the proposed circuit in producing bipolar square wave output pulses with peak values that depends on the DC source level supplied to the CHMI modules, pulse width of between 12.5 μ s and 1 ms at frequencies of 50 Hz and 100 Hz.

Keywords—pulsed electric field, multilevel inverter, bipolar square wave, food sterilization

I. INTRODUCTION

QUALITY nutritious food is essential in ensuring the welfare and health of each individual. A healthy body can produce an intelligent mind which in turn enables an individual to enjoy a better quality of life. Due to the importance of good and quality food, the method of pulsed electric field (PEF) has been used for the inactivation of microbial in liquid food. PEF is a non thermal method that is an alternative to the existing thermal methods for liquid food sterilization. This method requires the injection of food with electrical pulses without reducing its quality in terms of either aroma, flavor, nutrient, color or vitamin content [1]-[2]. PEF is also a safer method for

consumers compared to thermal methods while it can also increase the shelf-life of food [3]. It is different from the thermal methods of which the use of high heat is known to reduce the quality of food in terms of enzyme, color, and vitamins [1]-[2]. On the other hand, the use of PEF for bacteria inactivation is highly dependent on the type of specimen that it is applied to. It has been reported in literature that pulses with widths in the range of microseconds and electric field strength of up to 100 kV/cm are suitable for killing bacteria in water and liquid food [4]-[5]. To deliver medicine to a mammalian cell, pulses with pulse width of 100 μ s and electric field strength of 1 kV/cm is known to be effective while for gene delivery, a 20 ms pulse width with electric field strength of 5 kV/m is appropriate [6]. PEF however is a method of continuous processing, which is not suitable for pumpable solids food [7]. There are three types of pulses that can be used to kill bacteria which are the oscillatory decay pulse (ODP), exponential decay pulse (EDP) and square waves. ODP is a pulse wave that results in low efficiency. The output voltage is not stable of which the value varies from a maximum and oscillate to a minimum. The process is repeated as long as the power supply is applied to the circuit. As a result, the process of bacteria inactivation is not effective and the quality of food has not been improved [8]-[9]. 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 in killing bacteria in food [8]-[9]. Among the three pulse types, square wave is much better than EDP and ODP for liquid food sterilization process because it can produce stable peak voltage for a long time and can reduce thermal effect [8]-[10]. In addition, square wave pulses resulted in an average of 60% more inactivation than exponential decay pulse waveforms [10]. Furthermore ODP, EDP and square wave pulses can be in the form of unipolar or bipolar. Bipolar square wave pulses have many advantages compared to unipolar such as causing extra stress on the cell membrane thus enhancing its electric breakdown, offers better energy utilization, reduces deposition of solids on the electrode surface and impulsive food electrolysis [9]. Even though square wave pulses can yielding high effectiveness to inactivate microbial in liquid food sterilization, it requires more complicated circuit to generate pulses compare to ODP

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and EDP [10]. Due to these issues, the CHMI circuit has been simulated and constructed to generate bipolar square wave pulses that can meet the specifications required for sterilizing an identified liquid food. The CHMI is a power electronics circuit that can generate high voltage without using a transformer. In contrast to the power electronic circuits that have been proposed in [12]-[15] for the same application, the CHMI is capable of reducing the system power losses due to the omission of the winding coils. Furthermore, by using the CHMI, it can minimize the number of the components needed without extra clamping diodes or voltage balancing capacitor as well as to yield lower voltage and power consumption compared to transmission line or pulse forming network (PFN) methods. A resistive load can be used to represent the chamber used for liquid food sterilization as pointed out in [15]-[16]. This paper presents the results of a simulation study and experimental set-up of the CHMI as the main part of a liquid food sterilization system. With the CHMI, bipolar square waves pulses have been generated to produce a stable output voltage that can be effective for liquid food sterilization. A 7-level CHMI proposed in this work is described in the next section followed by the details of its experimental set-up. The results obtained from both simulation and experimental set-up are then presented and analyzed before concluding the work in the last section.

II. CIRCUIT DESCRIPTION

Based on the characteristics of a bacteria known as *saccharomyces cerevisiae* commonly found in orange juice, its inactivation can be accomplished by applying an electric field strength of 6.7 kV/cm [17]. Fig. 1 shows a 7-level CHMI circuit. By applying a DC voltage of 800 V to each of the H-bridge inverter representing a module of the CHMI, bipolar square wave pulses with the magnitude of 2.4 kV can be produced across the resistor representing the treatment chamber [15]-[16]. The magnitude of the pulsed output voltage can be increased further by increasing the number of CHMI modules or the applied voltage of the CHMI, depending on the sample of liquid food and the microbial related to it that requires inactivation. Referring to Fig. 1, the CHMI operates when each of the IGBTs is triggered and the DC input voltages are applied. When IGBTs 1, 3, 5, 7, 9 and 11 are closed, a positive pulsed output voltage of 2.4 kV is produced. On the other hand, IGBTs 2, 4, 6, 8, 10 and 12 are closed to produce a negative pulsed output voltage of 2.4 kV. With the circuit, calculation based on (1) has determined that with a gap of 0.2 cm between the electrodes across the chamber, electric field strength of up to 12 kV/cm can be achieved.

$$E = V/d \quad (1)$$

where E is electric field strength, V is the voltage (kV) and d (m) is the distance between the electrodes.

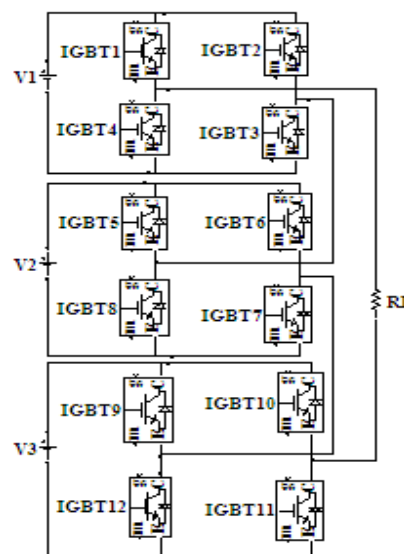


Fig. 1 The Cascaded H-Bridge Multilevel Inverter (CHMI)

In addition, *QuickField* simulation software has also been used to plot the electric field strength as shown in Fig. 2. Quick field software is a numerical technique for finding an approximate solution especially on partial differential and integral or other mathematical equations. In this work Quick field software has been used to simulate the gap distance between the electrodes in order to produce the electric field 12 kV/cm. Referring to Fig.3, the results have revealed that with 1.2 MV/m, the electric field is uniform in all areas. This 1.2 MV/m electric field strength is equal to 12 kV/cm whereby the potential peak voltage is 2.4 kV as can be depicted from Fig. 4. Furthermore, the value of the electric field strength affects the effectiveness to inactivate microbial in the liquid food. The stronger electric field strength is a more effective treatment for microbial inactivation as pointed out in [4].

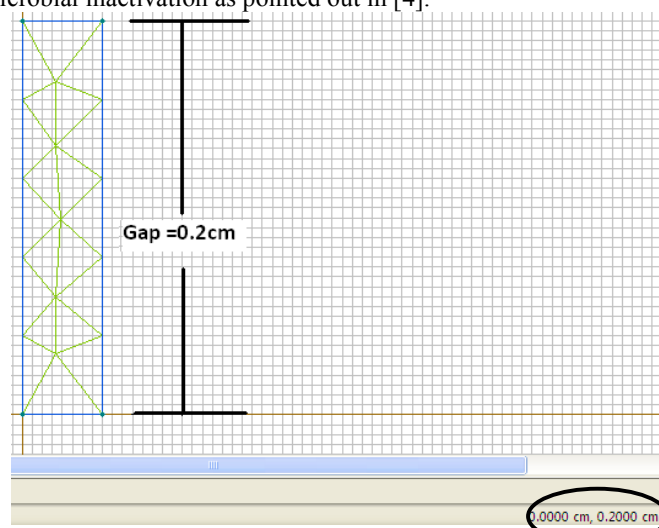


Fig. 2 Plot of electrode with 0.2 cm gap

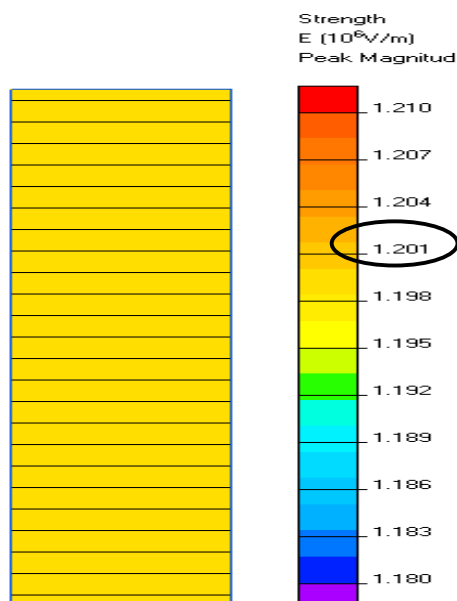


Fig. 3 Plot of electric field strength

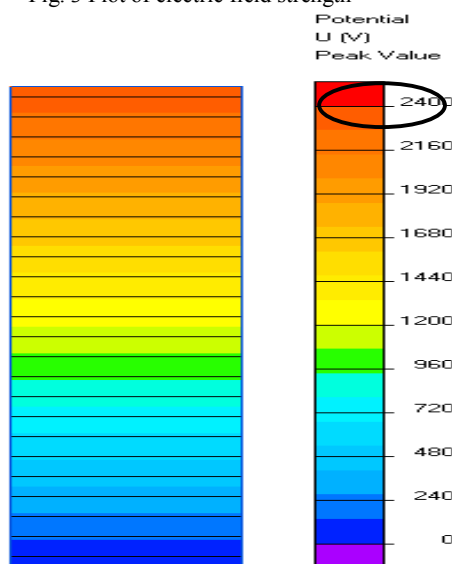


Fig. 4 Plot of output voltage, $V_{out} = 2.4$ kVpeak

The CHMI is simulated using *MATLAB/Simulink* as shown in Fig. 5. The pulse generators are used to set the repetitive rate, pulse width and pulse delay of the high voltage pulses generated by the CHMI. The logic gates AND are used as a gate signal generator in order to trigger each gates of the CHMI. The logic operator 1 and 2 are as shown in Fig. 5 have been operated alternately, in order to generate a positive and negative output voltages of the CHMI. In the simulation, a resistor value of 100 k Ω is used to represent the treatment chamber in producing a peak pulsed output voltage of 2.4 kV and output power of 57.6 W. This value has been selected to reduce the current flowing through the circuit which in turn reduces the power consumption.

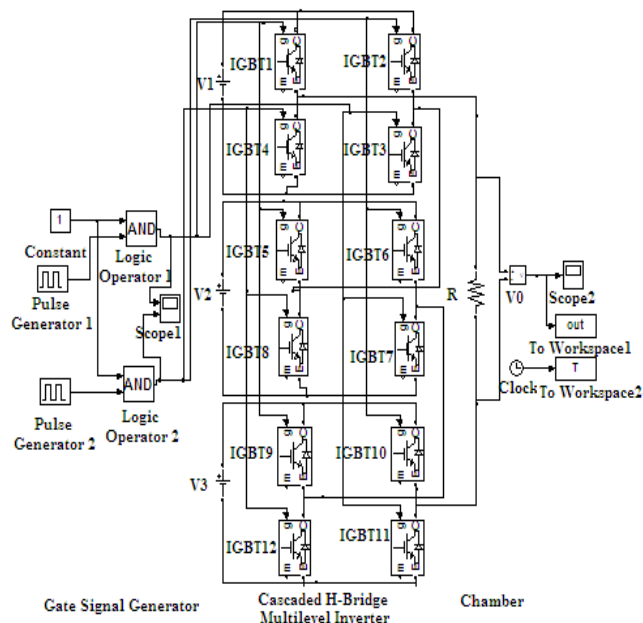


Fig. 5 Simulation systems diagram based on SIMULINK/Power System Block

The output power can be calculated as follows,

$$P_o = (V^2 / R) \text{ Watt} \quad (2)$$

where V is the voltage across the electrodes. Practically, the value of the resistor depends on the design of the electrodes, type of insulating material and the sample of liquid food.

III. EXPERIMENTAL SET-UP

In developing the experimental set-up of the pulsed power supply, IGBT SKM40GD123D is used as the CHMI power device. With this type of IGBT, the switching frequency is in the range of 1 kHz to 10 MHz which translates to achievable pulse width of between 1 ms to 10 μ s. In addition, dSPACE DS1104 controller board with TMS320F240 digital signal processor (DSP) is used as the platform for gate signal generation. This is due to the characteristics of dSPACE DS1104 that allows for the generation of gate signals that can meet the specifications suitable for liquid food sterilization particularly in terms of pulse width.

Two 60 V, DC power supplies are required as inputs to the CHMI in producing pulses with peak output voltage of ± 120 V. The peak output voltage, pulse width and the frequency of the pulses produced can be varied depending on the sample of liquid food and the microbial related to it that requires inactivation. In this work, *saccharomyces cerevisiae* and *E. Coli* spoilage microorganisms in pineapple juice, are proposed as the samples to be tested. A parallel plate static treatment chamber is proposed to test the ability of the CHMI based pulsed power supply in inactivating microbial for liquid food application.

IV. ANALYSIS OF RESULTS

A. Simulation Results

From the simulation work, the bipolar square wave output pulses obtained are as shown in Fig. 6, 7, 8 and 9 at various frequencies and pulse widths. Referring to Fig. 5, the delay in pulse generator 1 is set at 0.005 s while the delay in 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. The logic operator 1 and 2 of pulse generator 1 and 2 are as shown in Fig. 5 have been operated if the output logic of the AND gates are 1. The output pulses are obtained from AND gates then have been used to trigger the each gates of the CHMI. By designing the gate signal generator, the CHMI output voltages in the form of bipolar square wave pulses have been produced. The output pulses of the gate signal generator are as shown in Fig. 10 and 11 for a 50 Hz frequency with pulse width 1 ms and 1 μ s respectively. These output pulses of logic operator 1 have been used to trigger the gates of IGBTs 1, 3, 5, 7, 9 and 11 to produce a positive output voltage of 2.4 kV while the output pulses of logic operator 2 have been used to trigger the gates of IGBTs 2, 4, 6, 8, 10 and 12 to produce a negative pulsed output voltage of 2.4 kV as shown in Fig. 5. The pulse delay of the CHMI is important to be considered in order to avoid short circuit between the gates during a switching condition.

These pulse delays, frequency and pulse width can be varied depending on the treatment time of the liquid food sample and microbial to inactivate. The treatment time can be calculated by multiplying the pulse width applied by the number of pulses [19]. If the number of pulses is increased, the treatment time and therefore the effectiveness of inactivating the microbial will also be increased.

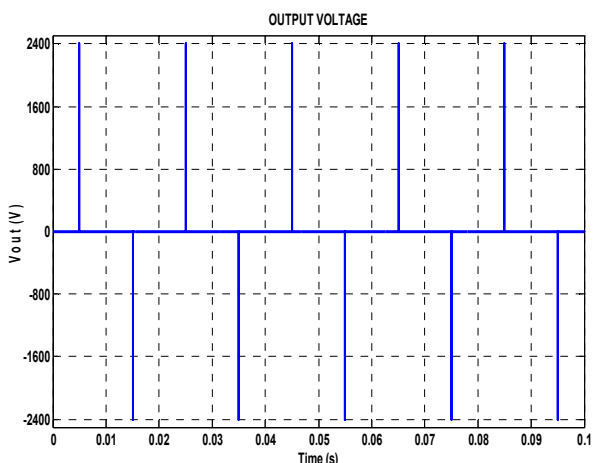


Fig. 6 Bipolar output voltage of 2.4 kVpeak, f = 50 Hz, pulse width = 1 μ s based on simulation

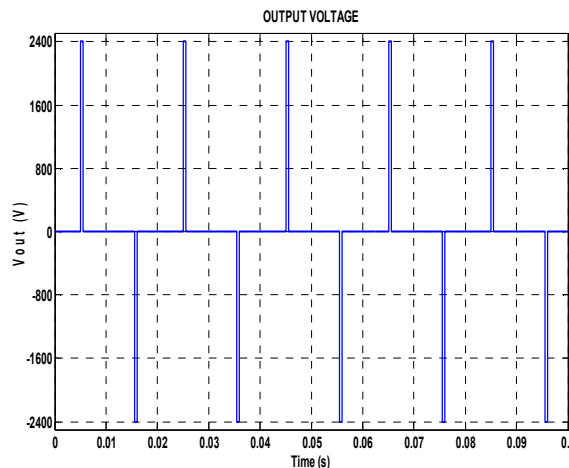


Fig. 7 Bipolar output voltage of 2.4 kVpeak, f = 50 Hz, pulse width = 1 ms based on simulation

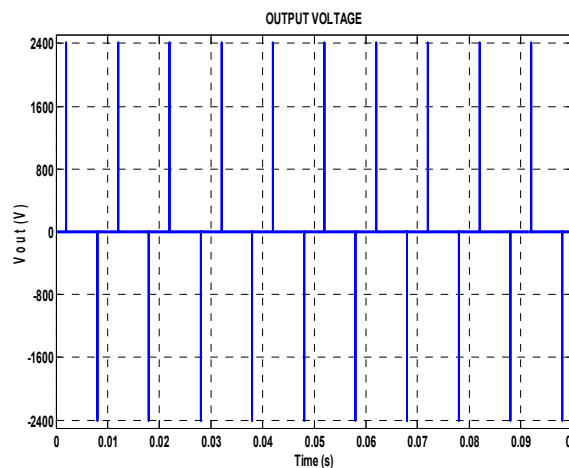


Fig. 8 Bipolar output voltage of 2.4 kVpeak, f = 100 Hz, pulse width = 1 μ s based on simulation

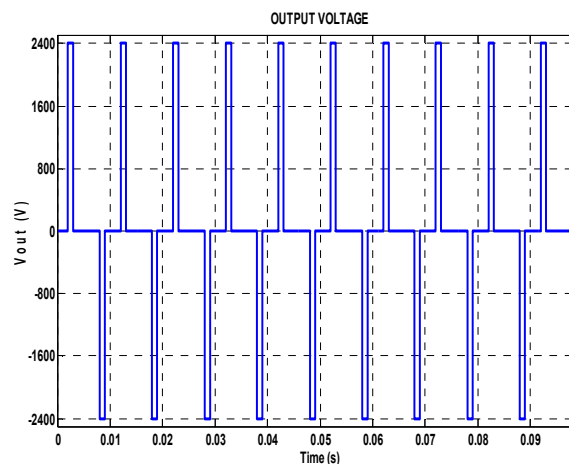


Fig. 9 Bipolar output voltage of 2.4 kVpeak, f = 100 Hz, pulse width = 1 ms based on simulation

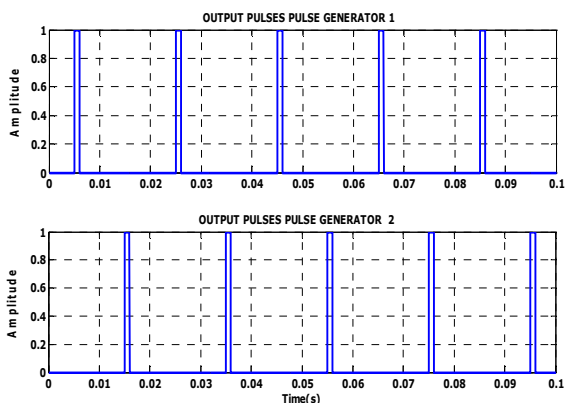


Fig. 10 The output pulses of pulse generators for pulse width = 1ms

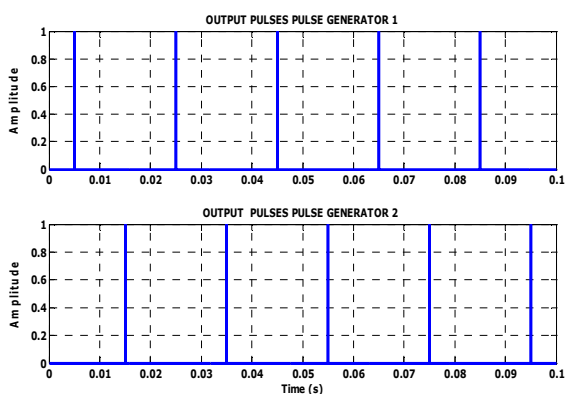


Fig. 11 The output pulses of pulse generators for pulse width= 1μs

B. Experimental Results

The experiment has been conducted using a 5-level CHMI as shown in Fig. 12 and Fig. 13 in order to generate bipolar square wave pulses from the proposed system. In this case, only two DC power supplies of 60 V each is used to respectively supply each of the two modules of a 5-level CHMI. With this circuit, a ± 120 V pulsed output voltage is produced as shown in Fig. 14, 15, 16 and 17. The frequency and the pulse width of the pulsed output voltage can also be controlled using pulse generator 1 and 2 of the gate signal generator as shown in Fig. 5. The output voltages of pulse generator based on experiment are as shown in Fig. 18. Referring to Fig. 18, the output pulses obtained from the DSP interface is 5 V. The 5 V pulses are then connected to gate driver to produce 15 V output pulses to trigger the gates of IGBTs. Similar to the parameter values used in the simulation, the frequency of pulse generator 1 and 2 is set at 50 Hz and 100 Hz. The delay in pulse generator 1 is set at 0.005 s while the delay in 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.

The gate signal generator consisting of the pulse generators and logic gates AND are then connected to the *master bit out* in *MATLAB/Simulink*. The DSP block, also in *MATLAB/Simulink* as shown in Fig. 12 is then simulated using the DSP interface that links to the experimental set-up as

shown in Fig. 13. The treatment time is set to infinity for the system to run continuously. By changing the stop time in *MATLAB/Simulink*, the treatment time can be varied as needed by specifications. In addition, with the ability to easily vary parameters such as treatment time, frequency and pulse width in the experimental set-up, its effect on microbial inactivation in various liquid food samples can be analyzed.

The experimental set-up is currently being expanded to include the use of a parallel plate treatment chamber instead of the resistor. The treatment chamber will be filled with the liquid food sample, in this case the pineapple juice for further analysis. Although the current experimental set-up is limited to only two modules of the CHMI at lower DC input voltages, the results presented have clearly shown the potential of the CHMI in producing bipolar square wave pulsed output voltage that fulfills the specifications necessary for liquid food sterilization.

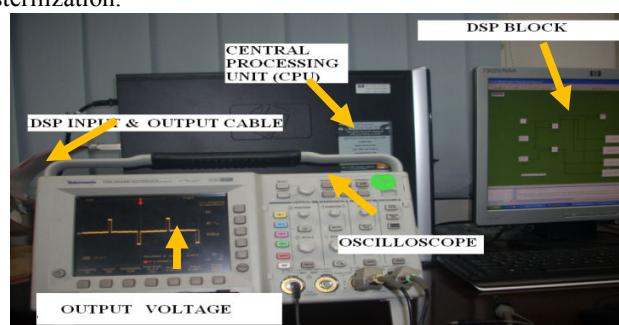


Fig. 12 The control part of the experimental set-up

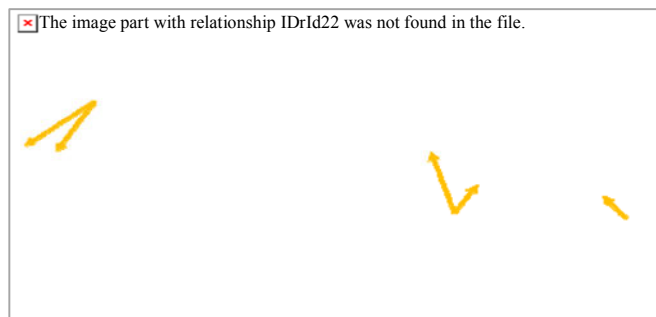


Fig. 13 The experimental set-up

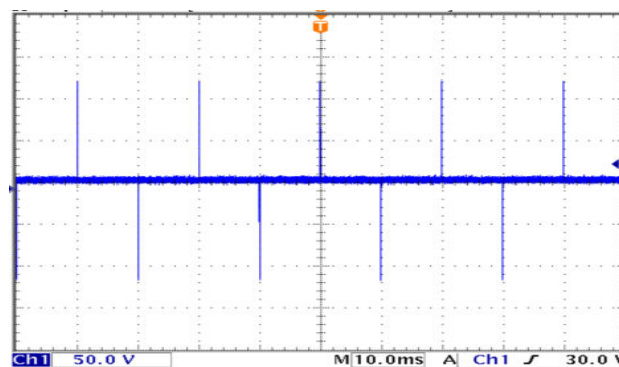


Fig. 14 Bipolar output voltage of 120 Vpeak, $f = 50$ Hz pulse width = 12.5 μ s based on experiment

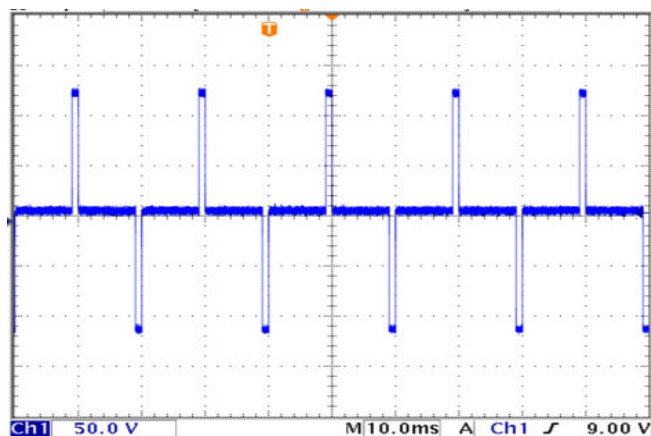


Fig. 15 Bipolar output voltage of 120 V_{peak}, $f = 50$ Hz, pulse width = 1 ms based on experiment

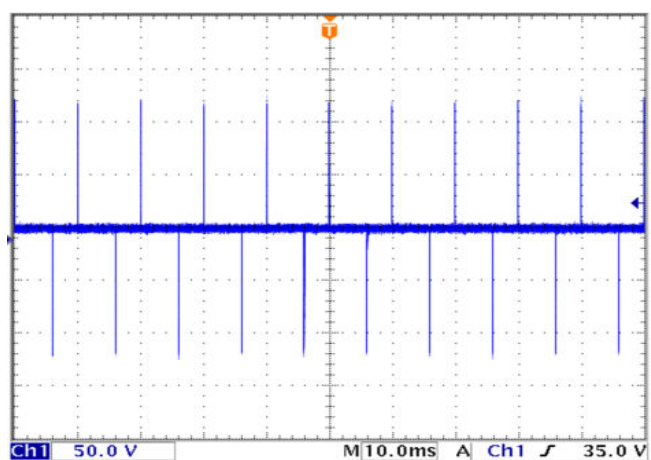


Fig. 16 Bipolar output voltage of 120 V_{peak}, $f = 100$ Hz, pulse width = 12.5 μ s based on experiment

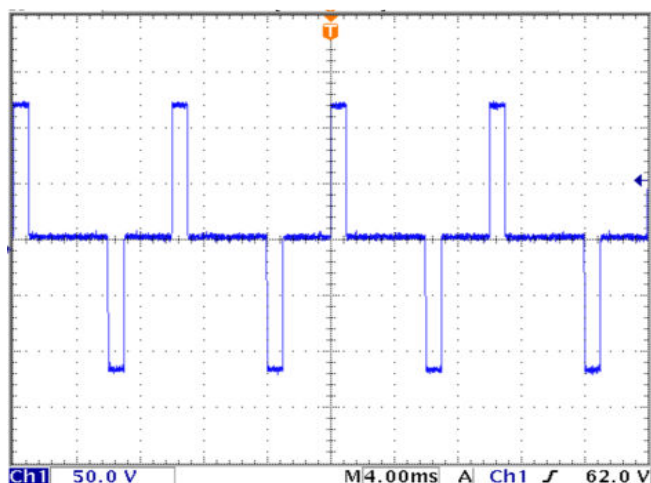


Fig. 17 Bipolar output voltage of 120 V_{peak}, $f = 100$ Hz, pulse width = 1 ms based on experiment

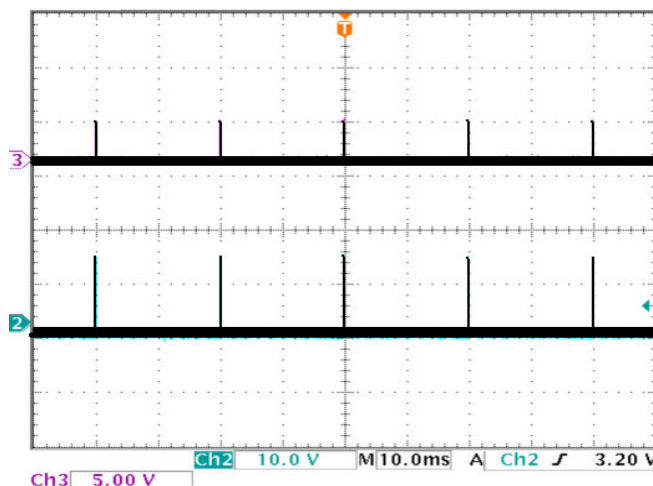


Fig. 18 the output pulses based on experiment from DSP interface = 5 V and gate driver circuit = 15 V

V. CONCLUSION

This paper has presented the simulation results as well as experimental results of a proposed CHMI-based pulsed power supply for liquid food sterilization. The simulation results have shown that the 7-level CHMI is capable of producing bipolar square wave output voltage at a repetitive rate in the range 10 – 100 Hz, pulse width of 1 μ s to 1 ms and output voltage of 2.4 kV_{peak} that would be effective for liquid food sterilization. The peak value, repetitive rate and pulse width of the pulsed output voltage can be varied depending on the sample of liquid food and the microbial related to it that requires inactivation. From the hardware results, the proposed CHMI is found to be functional in producing the bipolar square wave pulsed output voltage at a specified peak value depending on the DC input of each CHMI module, repetitive rate in the range of 50 Hz to 100 Hz and pulse width of 12.5 μ s to 1 ms. Both simulation and experimental results have revealed the potential of the proposed CHMI-based pulsed power supply in producing bipolar square wave type of pulses that is known to be more superior than the unipolar type for effective liquid food sterilization.

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