■ Research Article

การออกแบบและพัฒนาในระดับนำร่องในการฆ่าเชื้อจุลินทรีย์ในน้ำส้มโดยใช้สนามไฟฟ้าพัลส์

Design and development of a pilot-scale pulsed electric field processing system for microorganism inactivation in orange juice

Papol Sardyoung[1] ,Chatchawan Kantala[2] and Panich Intra[3*]

[a]Department of Electrical Technology Industrial, Faculty Technology Industrial, Thepsatri Rajabhat university, Naraymarharaj road, Lopbur 15000, Thailand
[2,3*]Research Unit of Applied Electric Field in Engineering (RUEE), College of Integrated Science and Technology, Rajamangala University of Technology Lanna, Chiang Mai 50220, Thailand
* Corresponding Author: E-mail: panich_intra@yahoo.com

Abstract

This study aimed to design, develop and investigate a pilot-scale pulsed electric field processing system for the inactivation of microorganisms in orange juice. The developed system consists of the DC pulsed high voltage power supply, the sterilization chamber and the fluid flow system. The system operated by using the pump to recirculate an orange juice from the product tank into the sterilization chamber whose inner electrode was supplied with the DC pulsed voltage while the outer electrode was grounded in order to create the high pulsed electric field strength, about 20 kV/cm, inside this sterilization chamber. This electric field brings about inactivation of microorganisms in the orange juice inside the sterilization chamber by electroporation process. After the sterilization chamber, the treated beverage is pumped into the storage tank. In this study, the MATLAB/Simulink was used to simulate the 3-phase pulse high-voltage source circuit. It could generate a high-voltage unipolar exponential decaying pulse of approximately 22 kV with a pulse width of approximately 10 μs. The inactivation of microorganisms (*E.*-coli) in orange juice was experimentally investigated by the total plate count method for electric field strengths between 20 and 40 kV/cm and the pulse number between 10 and 100 and compared with orange juice treated by thermal processing. It was shown that both PEF and thermal treatments reduced the population of E. coli inoculated in orange juice. No viable cells were observed after thermal processing of orange juice, whereas PEF treatment achieved 5 logarithmic cycle reductions of the microbial viability at an electric field strength of up to 30 kV/cm and pulse numbers of approximately 20 pulses.

Keywords: Pulsed electric field, Microorganisms, Pasteurization, Orange Juice

Received:
8 November 2024
Revised:
9 June 2025
Accepted:
24 June 2025
Published:
27 June 2025

***Corresponding Author:**
panich.intra@gmail.com

ISSN
Print: 2586-8500
Electronic: 2586-8632

1. Introduction

In the beverage processing industry worldwide, orange juice is the most widely manufactured juice. Conventional preservation methods such as thermal pasteurization ensure safety and extend the shelf life of orange juice. However, they often lead to detrimental changes in the sensory qualities of the food product. High-quality and nutritious foods, with fresh flavor, texture, and color, having minimal or no chemical preservatives, and above all safe for consumption, are required by consumers Chan et al (1997); Michelle et al (2004); Cortes et al (2008). Therefore, newly developed food technologies usually focus on preservation while maintaining food quality attributes. Non-thermal pasteurization by pulsed electric field (PEF) processing has already been introduced. It can alternatively be applied to deliver safe and shelf-stable products such as juices, milk, yogurt, soups, and liquid eggs with fresh-like character, high nutritional value, and minimal or no chemical preservatives Sale et al (1968); Hulsheger et al (1981); Fleischman (2014); Jeyamkondan et al (1999). The PEF pasteurization process utilizes micro-second (μs) high-voltage pulses, producing high electric field strength (> 20 kV/cm) between the two electrodes. These electric pulses are applied to food products, at temperatures below thermal pasteurization, efficiently inactivating contaminating microorganisms without significantly affecting the quality of the food product by a phenomenon known as the electroporation phenomenon Sale et al (1968); Hulsheger et al (1981); Fleischman (2014); Jeyamkondan et al (1999). Generally, a PEF processing system consists of a high-voltage power source, an energy storage capacitor bank, a charging resistor, a discharge switch, a pulse controller, and a treatment chamber. Electrical energy from the power supply was stored in the capacitor and was then discharged through the treatment chamber to generate electric field strengths in the food product. The survival rate of the number of microorganisms in food products treated by PEF processing depends on process parameters, including electric field strength, total treatment time, pulse width, pulse waveform, and food conductivity Fleischman (2014). In the past several decades, there have been numerous research studies and developments on the PEF processing system for microorganism inactivation of food juice products Sale et al (1968); Hulsheger et al (1981); Fleischman (2014); Jeyamkondan et al (1999). (Ohshima et al, 1997, 2007); Sen-in et al (2012); Panyamuangjai et al (2012); Intra et al 2015; Mcdonald et al (2000); Gupta et al (2003); Qin et al 1998. Available commercial-scale PEF processing has been designed to inactivate microorganisms in tomato-orange juices Min et al (2003); Linton et al (2003). However, these commercial-scale PEF systems tend to be relatively large units, which are quite expensive with typical starting prices greater than ten thousand U.S. dollars. In

Thailand, commercial-scale PEF processing systems are not available for the micro, small, and medium-sized enterprises in the food and drink industries because of their high cost and enormous size. Therefore, a PEF processing system for micro, small, and medium-sized enterprises in the food and drink industries must have a low cost, a small and simple system, easy to use and clean, and its maintenance must be possible by low-skilled laborers.

This study aimed to develop and investigate a low-cost, simple PEF processing system for the inactivation of microorganisms in orange juice. In this paper, A detailed description of the pulsed electric field system design is also presented. The MATLAB/Simulink was used to simulate the 3 - phase pulse high-voltage source circuit. The inactivation of endogenous microorganisms (E - coli) in orange juice and the quality of orange juice were experimentally investigated, and the quality of pulsed electric field processed orange juice was compared with that of thermally processed orange juice.

2. Materials and methods

2.1 Description of a low-cost PEF processing system

Figure 1. The developed PEF processing system.

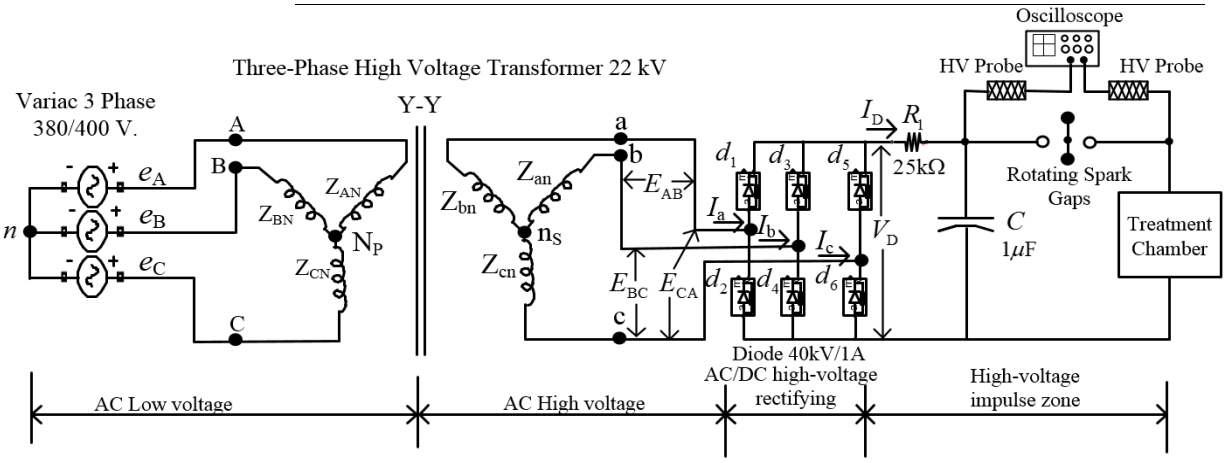


Figure 2. Schematic diagram of the developed PEF processing system.

Figure 1, shows a picture of the PEF processing system developed in this study for microorganism inactivation of orange juice. It consists of an AC power input, a rectifier circuit, a DC high-voltage power, an energy storage capacitor, a pulse controller to control the number and frequency of the pulse, a discharge switch to discharge energy from the energy storage capacitor across the food juice, and a sterilization chamber. A schematic diagram of the developed PEF processing system is shown in Figure 2, The DC high voltage power used in this study and step-up AC voltage from AC source form a 3-phase system high voltage power transformer connected to a Star-Star (Y-Y) connected 380 V / 22 kV, 33 kW rated 20 kVA. Six high voltage power diodes ($d_1 - d_6$) (40 kV / 1 A) were used. A high-voltage resistor (charging resistor), capable of withstanding several kiloamps of sparking current, was connected to a switching regulator (spark gap) for controlling the charging and discharging of the capacitor. The capacitor used in the experiment was a high-voltage pulse paper-in-oil (PIO) capacitor with a capacity of 1 μF/40 kV, which was charged via the charging resistor and discharged through the treatment chamber by a discharge switch, producing an electric field strength of about 20 to 40 kV/cm across the food product. The generated electric field strength triggered monopolar exponential decaying pulses causing microbial inactivation. Electroporation, or electropermeabilization, is the process in which the permeability of the cell membrane to ions and macromolecules is increased by exposing it to high-voltage electric field pulses, allowing chemicals, drugs, or DNA to be introduced into the cell. Under the electroporation phenomenon, a transmembrane potential ($U(t)$) is developed across the cell membrane in the direction of applied electric field strength (E), expressed as follows Sale and Hamilton (1968):

$$U(t) = 1.5rE \quad (1)$$

where r is the radius of the cell and E is the applied electric field strength. When the transmembrane potential reached around 1 V, lysis of the cell resulting from loss of membrane integrity occurred. This value was termed the breakdown transmembrane potential. A mathematical model for the survival rate (S), the ratio of the number of microorganisms present in the food after the treatment, and the initial number of microorganisms present before the treatment, as a function of E, and treatment time (t), is given by Hulsheger et al (1981):

$$s = \left(\frac{t}{t_c}\right)^{\left(-\left(\frac{E-E_c)}{k}\right)\right.} \quad (2)$$

where t is the product of the pulse number and pulse width, t_c is the critical treatment time, which is a threshold value above which inactivation occurs, E_c is the critical electric field strength, which is a threshold value above which inactivation occurs (kV/cm), and k is the specific constant for a microorganism. Taking the logarithms to base 10 on both sides of Equ. 2 gives us the following:

$$-log(s) = \frac{(E - E_c)}{k} log\left(\frac{t}{t_c}\right) \quad (3)$$

The left-hand side of the above equation is commonly referred to as inactivation ratio or log reduction. As shown in Figure 2, the 3-phase transformer Star-Star (Y-Y) connected, rated 20 kVA, 380/22 kV voltage output from the secondary winding of the transformer by the Star-Star (Y-Y) connected winding. The line voltage (E_{AB}, E_{BC}, E_{CA}) is higher than the voltage at the phase of the voltage across the secondary winding (e_A, e_B, e_C) of the 3-phase transformer is $\sqrt{3}$ time or line to line voltage $V_{L\text{-}L} = \sqrt{3}V_{phase}$ enters the 3-phase full-bridge rectifier, provided that the reference voltage across the secondary winding is expressed by the equation.

$$e_A = V\ sin\ \omega\ t \quad (4)$$

$$e_B = V\ sin(\omega t - 120°) \quad (5)$$

$$e_C = V\ sin(\omega t + 120°) \quad (6)$$

The value of the RMS current in each phase voltage output from the secondary winding can be calculated from Equation.

$$(I_A, I_B, I_C)_{rms} \cong \sqrt{\left[\frac{8}{12\pi}\right] \int_0^{\pi/6} I_m^2 \cdot Cos^2(\omega t) \cdot d(\omega t)} \quad (7)$$

where I_{m} is the peak value of the current flowing through the secondary winding. The average current flowing through each diode (d_1-d_6) can be calculated as follows:

$$I_{\mathrm{Dav}} = \frac{4}{2\pi}\int_0^{\pi/6} I_m \cdot cos(\omega t) \cdot d(\omega t) \tag{8}$$

Calculation of the average output voltage. Can be obtained from the equation below:

$$V_D = \frac{6}{\pi}\int_0^{\pi/6} \sqrt{3}\, V_m\, Cos(\omega t) \cdot d(\omega t) \tag{9}$$

where V_m is the peak value of the phase voltage. The RMS voltage on the phase can be calculated from the following equation:

$$V_{\mathrm{rms}} \cong \sqrt{\left[\frac{6}{\pi}\int_0^{\pi/6} \sqrt{3}V_m^2 \cdot Cos^2(\omega t) \cdot d(\omega t)\right]} \tag{10}$$

Table 1. Diode working state $d_1 - d_6$ of the high-voltage pulse rectifier.

Segment	$\boldsymbol{d_1(\omega_0 t)}$	$\boldsymbol{d_2(\omega_0 t)}$	$\boldsymbol{d_3(\omega_0 t)}$	$\boldsymbol{d_4(\omega_0 t)}$	$\boldsymbol{d_5(\omega_0 t)}$	$\boldsymbol{d_6(\omega_0 t)}$
$0 < \omega_0 t < 60^\circ$	1	0	0	0	0	1
$60^\circ < \omega_0 t < 120^\circ$	0	0	1	0	0	1
$120^\circ < \omega_0 t < 180^\circ$	0	1	1	0	0	0
$180^\circ < \omega_0 t < 240^\circ$	0	1	0	0	1	0
$240^\circ < \omega_0 t < 300^\circ$	0	0	0	1	1	0
$300^\circ < \omega_0 t < 360^\circ$	1	0	0	1	0	0

Table 1 shows the diode (d_1-d_6) operating status. While bias directly or conducting a current in pairs by working in the initial state at the diode phase angle $0 < \omega t < 60^\circ$and diode, d_1 and d_6 will be started first. In this study, a rotating spark-gap was used as the discharge switch. The spark gap provided a low-inductance path for charging and discharging the pulse-forming capacitor. The pulse repetition rate depended on the speed of the rotating switch. The low inductance in the spark gap aids in producing pulses of very narrow duration, typically less than 10 μs. In a monopolar exponential decaying pulse, the voltage across the treatment chamber rises

rapidly to a set point and then decays slowly with time, according to the following equation:

$$V(t) = V_0\, exp(-t/\tau) \tag{11}$$

where V_0 is the initial charging voltage of the pulse capacitor, and τ is the time constant defined as:

$$\tau = R_f C_0 \tag{12}$$

where R_f is the food resistance and C_0 is the capacitance of the pulse capacitor. It should be noted that the resistance of the electrodes is negligible compared to that of the food sample. Therefore, food resistance can be calculated using the following equation:

$$R_f = \frac{d}{\sigma A} \tag{13}$$

where d is the electrode distance, σ is the food conductivity, and A is the surface area of the treatment chamber. The maximum voltage across the energy storage capacitor is equal to the voltage across the DC power, typically approximately 22 kV. The energy stored in the pulse capacitor (W_c), depending on C_0 and V is given by:

$$W_c = \frac{1}{2} C_0 V^2 \tag{14}$$

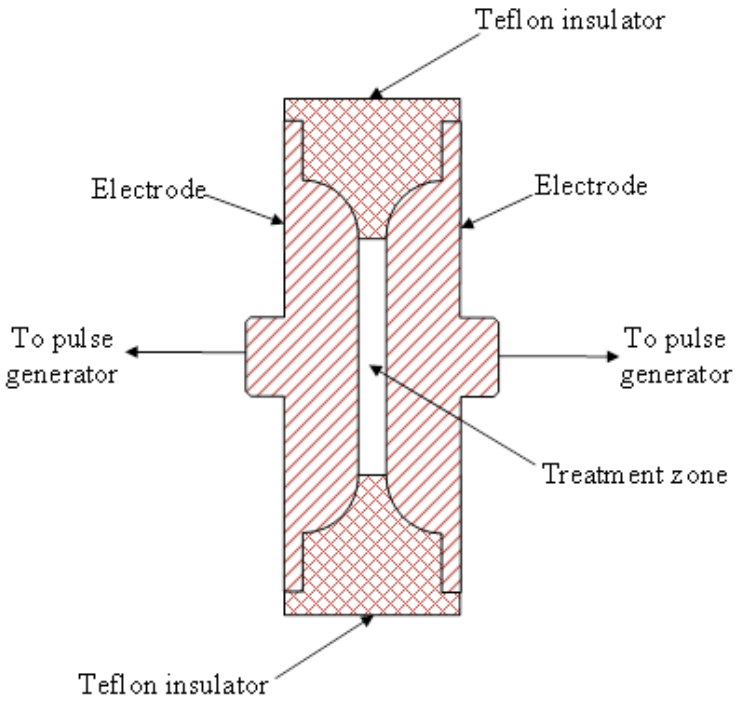


Figure 3. Schematic diagram of the treatment chamber.

As shown in Figure 3, a parallel plate sterilization chamber was used in this study because the parallel plate electrodes provide a uniform electrical field distribution along the gap axes and electrode surfaces. The sterilization chamber consisted of two parallel stainless-steel electrodes with a gap of 5 mm and a Teflon spacer. The chamber had an effective electrode area of 20 cm^2 with a height of 2 cm, an inner diameter of 10 cm, a chamber volume of about 75 cm^3, and a maximum voltage ranging from 5 to 20 kV. For the parallel plate treatment chamber, the average electric field strength E inside the chamber is as follows:

$$E = \frac{V}{d} \tag{15}$$

where V is the voltage across the food sample, and d is the distance between the electrodes. Therefore, the maximum electric field strength could reach 40 kV/cm without cooling the electrodes.

2.2 Experimental setup

The purpose of the studies was to examine how many of the microorganisms in orange juice could be inactivated by PEF and thermal treatments. For the microorganism inactivation study, a high microorganism load in orange juice was required. *Escherichia coli* (*E. coli*, TISTR 117) was purchased from the Thailand Institute of Scientific and Technological Research (TISTR). Further, fresh oranges were purchased from a local supermarket. The oranges were juiced with a screw-type juice extractor. Next, the juice was filtered with cheesecloth and stored at 4°C before treatment. Before PEF treatment, 18 mL of incubated culture was inoculated into 1000 mL of oranges juice to attain a final concentration of approximately 10^5 colony-forming units (CFU)/mL of microorganisms at 4 °C and held at 37 °C for 12 h to acclimate cells. The total plate count method using nonselective growth medium (nutrient agar) was performed at 37 °C for 24 h to count the initial and surviving number of viable cells before PEF and thermal treatment. For PEF treatment, electric field strengths of approximately 20, 30, and 40 kV/cm were provided to generate the pulse voltages of approximately 10, 15, and 20 kV, respectively, and pulse numbers of 10, 20, 30, 40, and 50 pulses were used. The pulse duration time and frequency (pulse number per second) were set at 10 μs and 1 Hz, respectively. For thermal treatment, orange juice was held at 70 ◦C for 30 s and then cooled with chilly water from a cooler to 25 ◦C. Table 2 shows the ranges and values of variables investigated.

Table 2. Ranges and values of variables investigated.

Variable	Range
Pulse width	10 μs
Pulse frequency	1 Hz
Number of pulses	10, 20, 30, 40 and 50
Pulse voltage	10, 15 and 20 kV
Electric field strength	20, 30 and 40 kV/cm

3. Results and Discussion

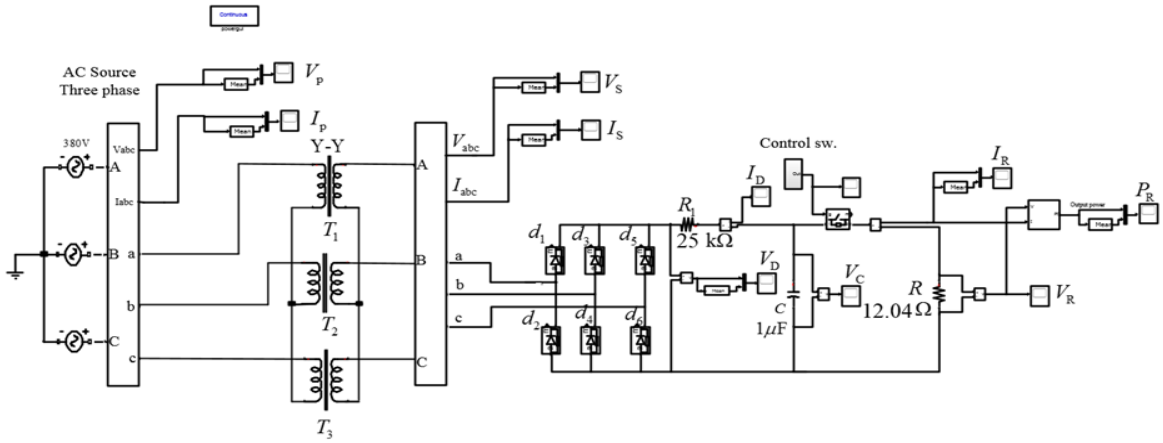


Figure 4. Simulated circuit in MATLAB/Simulink.

As shown in Figure 4, the 3-phase pulse high-voltage source circuit simulated in the MATLAB/Simulink. A 3-phase power supply was employed to supply power to the transformer by connecting its primary and secondary windings. The high-voltage output from the secondary winding was passed through a bridge-type full-wave, 3-phase rectifier, and through a high impedance to charge the capacitors. Charge: To generate a high pulse voltage to supply the electrodes in the sterilization chamber. Figures 5(a) and 5(b) shows the command signal used by mechanical switching at a time of 0.42 and 0.84 s to supply high-voltage pulses to the sterilization chamber.

The power measurement block is detailed in the sterilization chamber while the electrolytic capacitor is discharged to generate a high pulse voltage. To supply the electrodes to the sterilization chamber.
The 3-phase high-voltage source circuit was simulated, and the magnitude of the phase voltage (Vpeak) across the primary winding side was obtained.

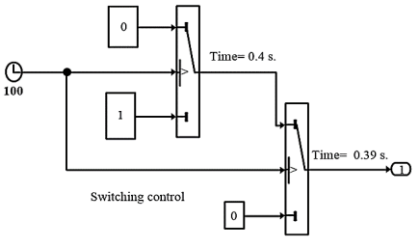


Figure 5(a). Switching control signal block in MATLAB/Simulink.

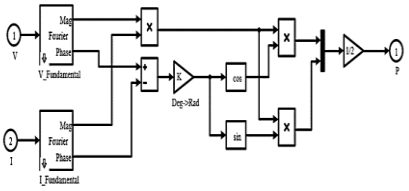
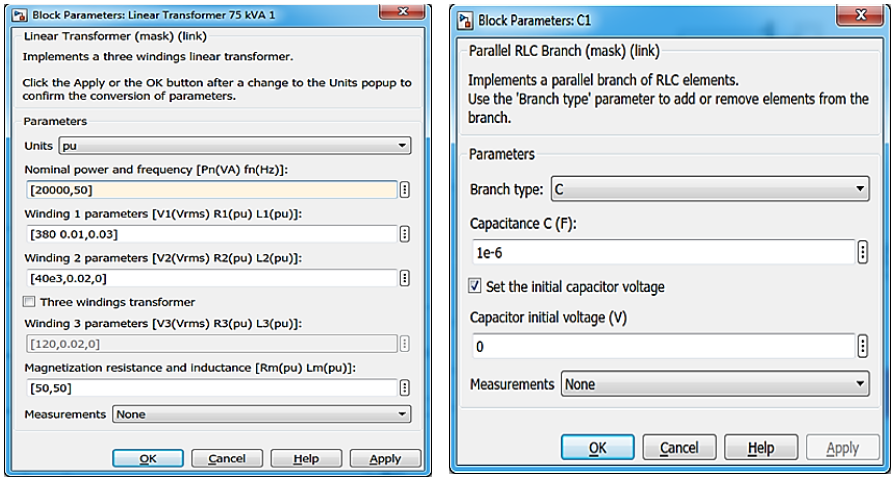


Figure 5(b). Power measuring block in MATLAB/Simulink.

Figures 6(a) shows the details of parameter configuration of a 20 kVA, 380/22 kV, 3-phase high voltage transformer operating at 50 Hz in MATLAB/Simulink program and the parameters of the high voltage capacitor $1\mu\mathrm{F}$ are shown in Figure 6(b).

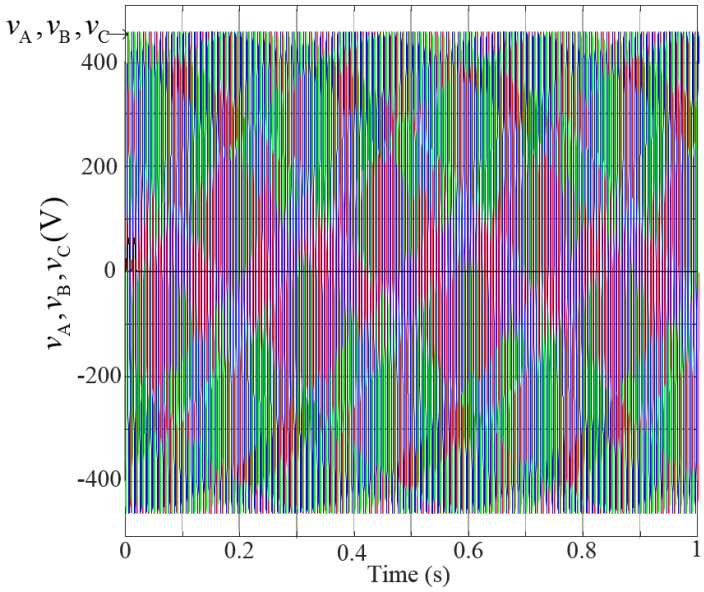


(a) **(b)**

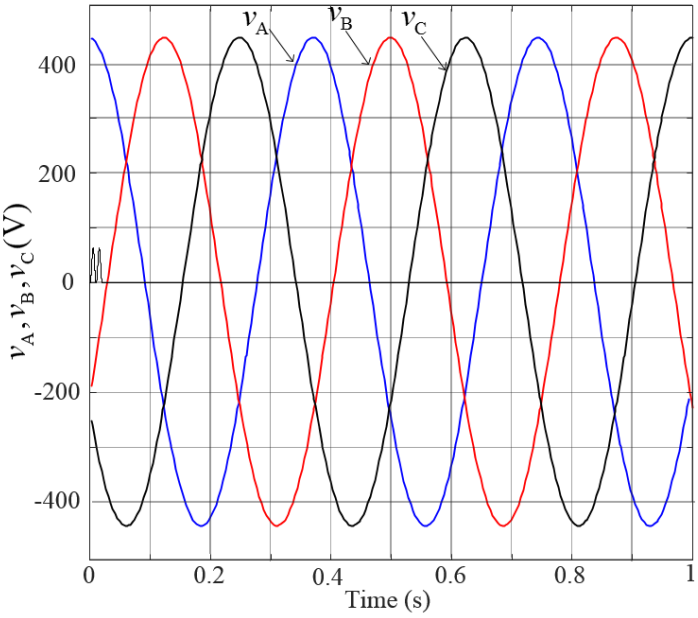
Figure 6. Transformer parameters in MATLAB/Simulink block
(a) Three-phase transformer, 20 kVA, 380/22 kV, (b) High voltage capacitor $1\mu\mathrm{F}$

The transformer landscape of 538 V is shown in Figures 7(a) and 7(b) as amplification forms, and on the secondary side of the transformer is 21.56 kV, as shown in Figures 8(a) and 8(b). The response of the output voltage from the full-wave filter circuit (V_D) while the mechanical switch is not operating. Figures 8(a) and 8(b) shows the response of the output voltage from a full-wave filter circuit. The response of the output voltage from the full-wave filter circuit was 24.6 kV when the mechanical switch was triggered at a

time of 0.42 and at 0.84 s to generate a high-voltage pulse pressure for the sterilization chamber.

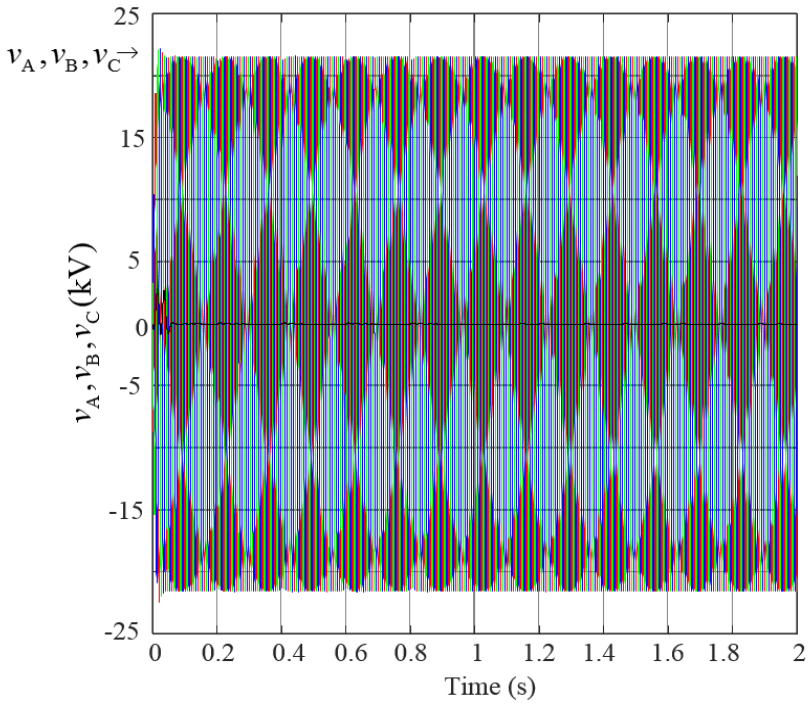


(a)

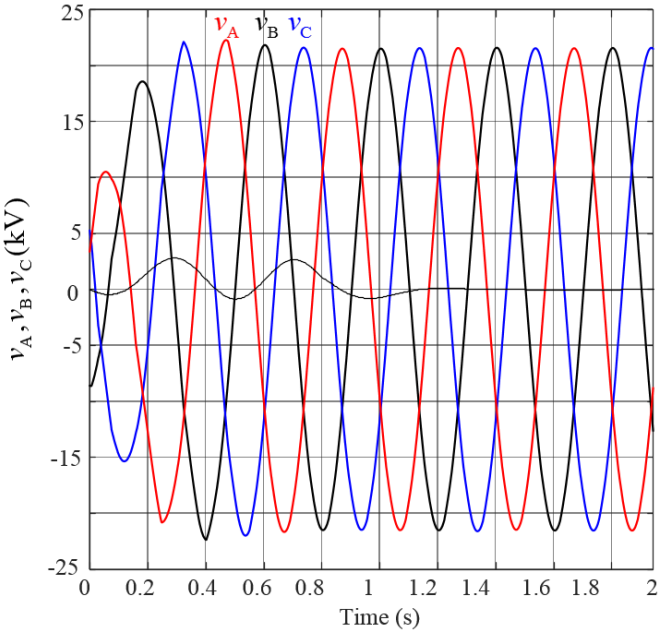


(b)

Figure 7. Three-phase input voltage: (a) voltage on the primary side and (b) voltage amplification on the primary side.



(a)

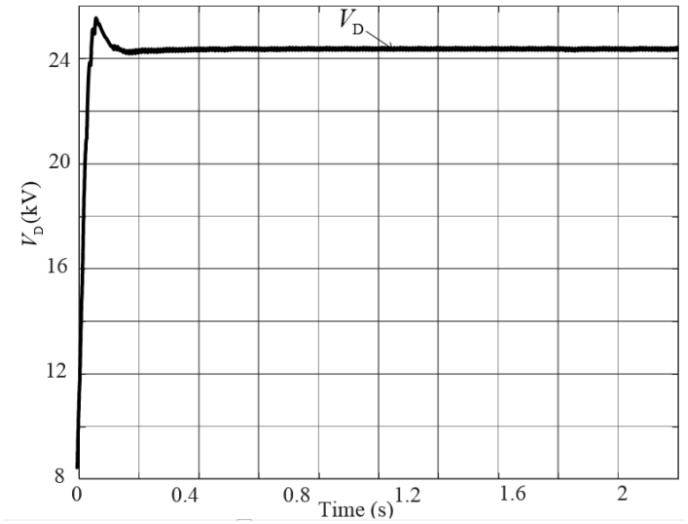


(b)

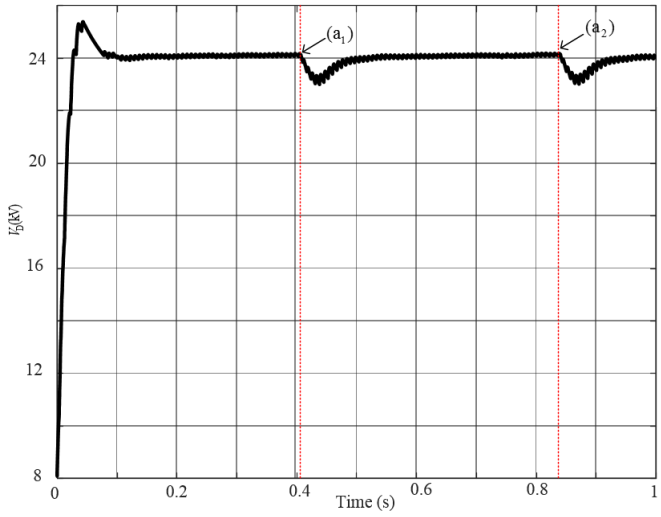
Figure 8. Three-phase output voltage: (a) voltage on the secondary side and (b) voltage amplification Figure on the secondary side.

The simulated and the experimental results of the charging voltage are shown in Figures. 9(a) and (b). It was found that for the repetitive pulse frequency of 2 Hz, in the experiment, at the time voltage of 0.42 s (point (a_1)), the maximum voltage was 19.1 kV, and the output voltage was 18.5 kV. Similarly, in the MATLAB/Simulink simulations, at the charging time of 0.84 s (point (a_2)), the maximum voltage

obtained was 19.1 kV, and the output voltage was 18.5 kV. Figure 10, shows control switching time.



(a)



(b)

Figure 9. Voltage drop across a bridge 3-phase full-wave rectifier: (a) in the normal state (b) with switching at a time of 0.42 s (a_1), and 0.84 s (a_2).

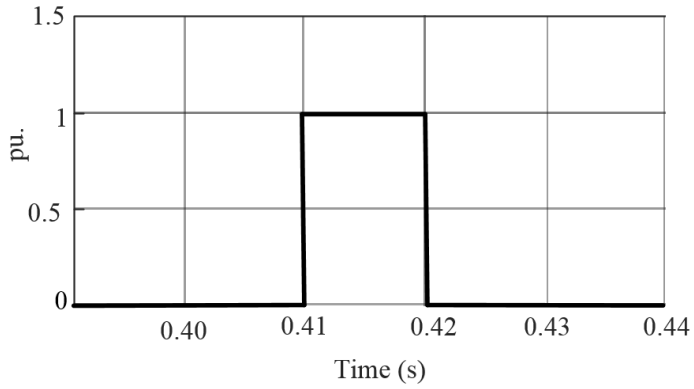
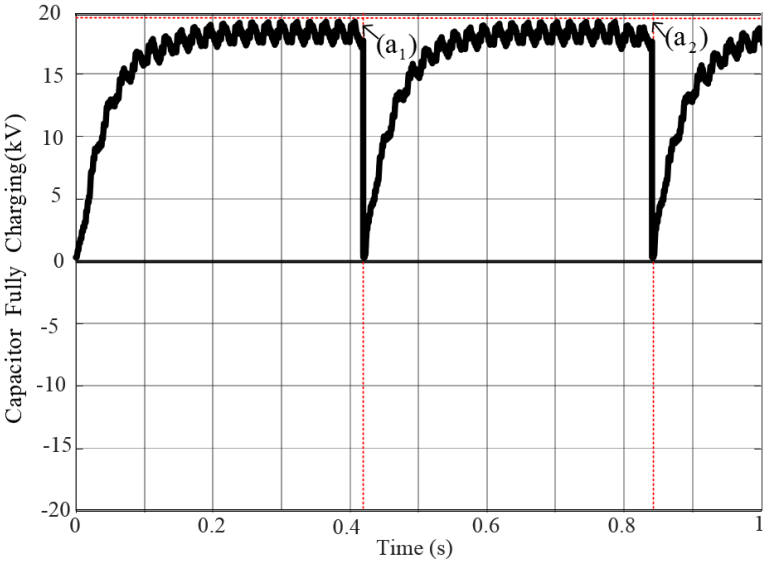
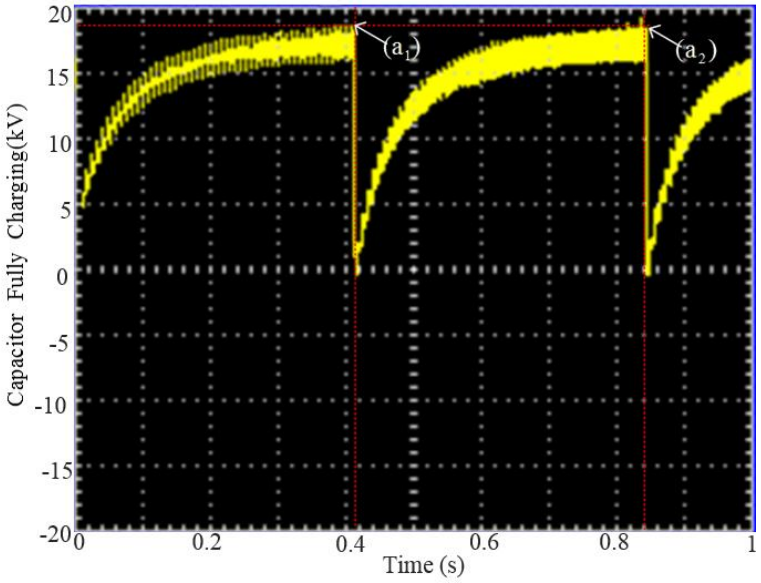


Figure 10. Control switching time at 0.01 s.

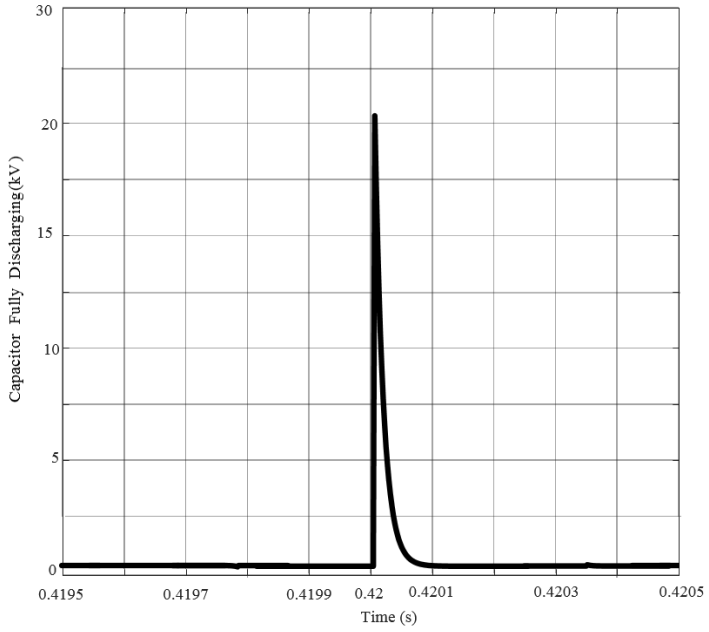


(a)

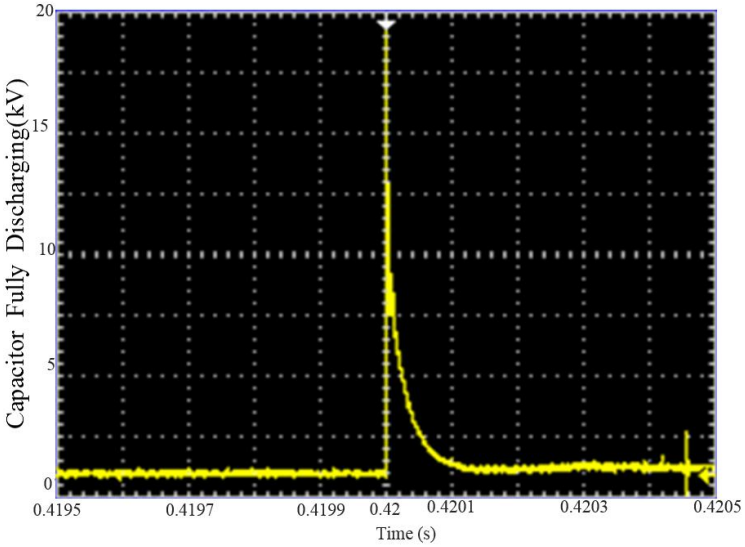


(b)

Figure 11. Capacitor charging: (a) MATLAB/Simulink simulation, (b) experiment.



(a)



(b)

Figure 12. Voltage drop across the sterilization chamber: (a) MATLAB/Simulink simulation, (b) experiment.

As shown in Figures. 11 (a) and 11 (b) present the graphs of the capacitor charging cycle for the MATLAB/Simulink simulation and the experiment, respectively. It was observed that at the pulse frequency of 1 Hz, the magnitude of the discharge voltage (Vpeak), which is the voltage across the sterile chamber, was 21.5 kV for a pulse width of 80 μs. However, for the experiment, it was observed that the voltage across the sterilization chamber was 20 kV for a 90 μs pulse width. The results are presented in Figures. 12 (a) and (b), Comparison of charge discharge between simulation results and program MATLAB / Simulink and Experimental results as shown in Figures. 12 (a) and 12 (b). A digital oscilloscope, Tektronix model TDS 210, and a high

voltage probe, Fluke model 80K-40, were used to observe the pulse wave form. It was found that the repetitive pulse at a frequency of 1 Hz was a simulation result of the magnitude of the discharge voltage (Vpeak) of the capacitor or the voltage at Across the sterile chamber is 21.5 kV, with the characteristic of the pulse voltage waveform is exponential decay pulses at a pulse width of 80μs by From the results of the experiment, the magnitude of the capacitor discharge voltage (Vpeak) or the voltage across the sterilization chamber was equal to 20 kV, with the characteristic of the pulse voltage waveform being unique. Exponential Decay Pulses at 90 μs pulse width.

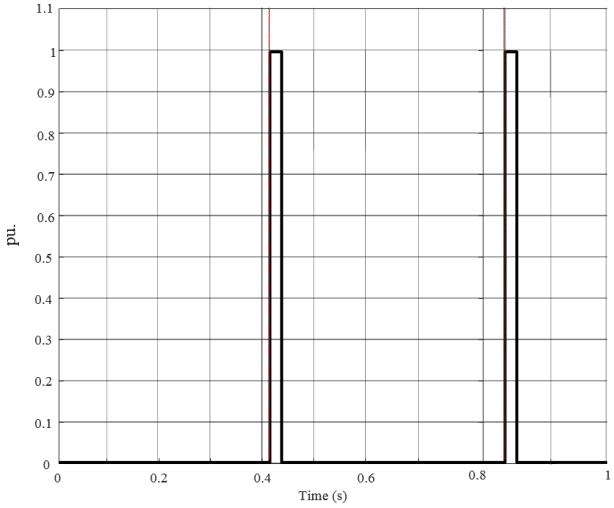


Figure 13. Switch control signal.

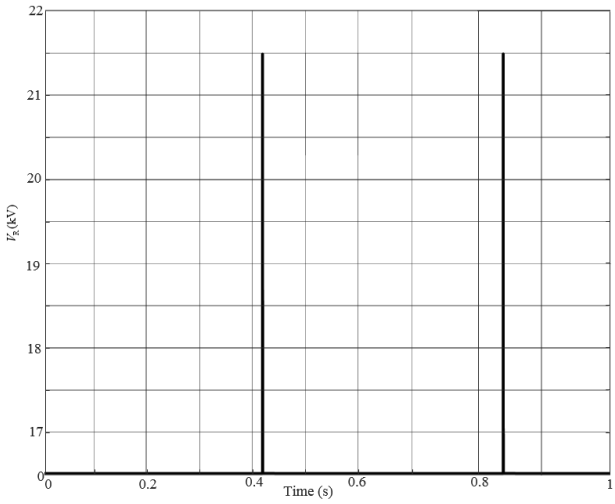


Figure 14. Voltage drop across the sterilization chamber for MATLAB\Simulink simulation.

Figure 13 shows the graph of the switch control. The switch triggered at 0.42 and 0.84 s with a pulse width of 0.01 s. A time-switch control signal was used for the simulation instead of a mechanical switch to generate a pulse signal to the load. The equivalent resistance of the sterilization chamber was 12.04Ω. The results of the simulation are

shown in Figure. 14. It was observed that the magnitude of the capacitor discharge voltage (Vpeak) or the voltage across the sterilization chamber was 21.5 kV at a pulse width of 80 μs. Figure 15 presents the instantaneous power output at the sterile chamber equivalent resistance of 12.04 Ω. The equivalent of liquid food is 5.88 W with an average square pulse width of 60 ms.

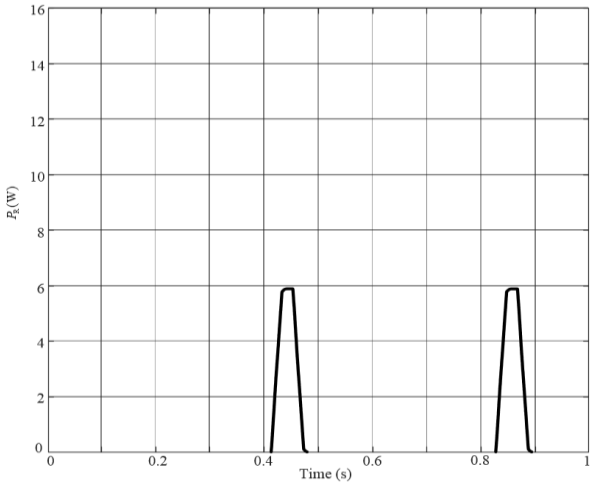


Figure 15. Instantaneous power at the sterilization chamber equivalent resistance of 12.04Ω.

The electric field strength and the pulse number (treatment time) are the major factors determining microorganism inactivation in PEF processing [7]. The experimental study of microorganism inactivation by PEF treatment was carried out for electric field strengths between 20 and 40 kV/cm and pulse numbers between 10 and 50. Figure 16 shows *E. coli* on nutrient agar after PEF treatment compared to the control sample at electric field strengths of approximately 20, 30, and 40 kV/cm after subjecting it to 10, 20, 30, 40, and 50 pulses, respectively. It was observed that the increase in the electric field strength and pulse numbers increased the inactivation of microorganisms. No viable cells were observed after PEF treatment of orange juice at the electric field strength of 30 kV/cm and 20 pulses.

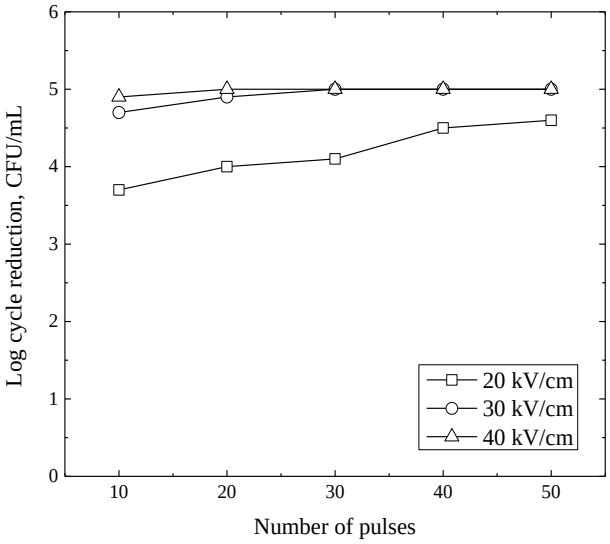


Figure 16. Variations in log cycle reduction of *E. coli* with pulse number at different electric field strengths.

Figure 17, shows the variations in log cycle reduction with the pulse number at different electric field strengths. Higher electric field strengths were found to have higher log cycle reductions of microorganisms. At the same electric field strength, the log cycle reductions increased with an increase in pulse number. At electric field strength of 20 kV/cm, the achieved log cycle reductions of the microorganisms were about 0.5, 0.8, 1.2, 2.0, and 2.3 CFU/mL for 10, 20, 30, 40, and 50 pulses, respectively. At electric field strength of 30 kV/cm, the achieved log cycle reductions of the microorganisms were about 1.25, 1.65, 2.8, 3.7, and 5.1 CFU/mL for 10, 20, 30, 40, and 50 pulses, respectively. At electric field strength of 40 kV/cm, the achieved log cycle reductions of the microorganisms were about 4.9, 5.0, 5.0, 5.0, and 5.0 CFU/mL for 10, 20, 30, 40, and 50 pulses, respectively. This study showed that the PEF treatment achieved 5 log cycle reductions of microbial viability at an electric field strength larger than 30 kV/cm for pulse numbers higher than 20 pulses.

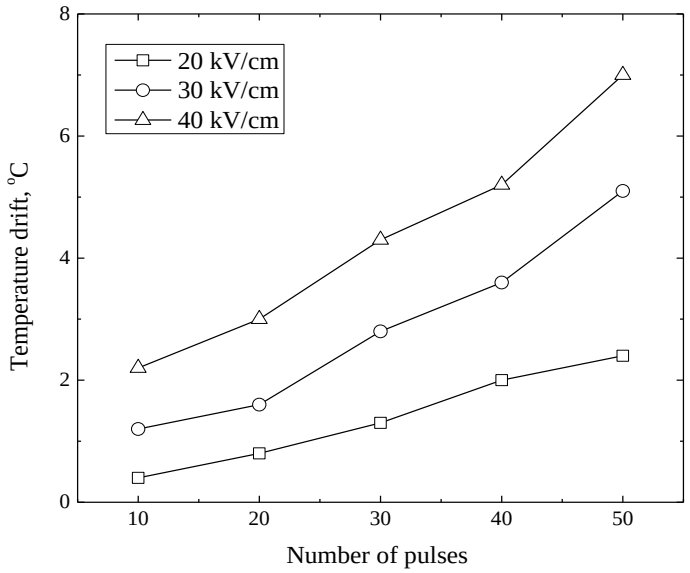


Figure 17. Variations in temperature drift and pulse number at different electric field strengths.

Another key variable in PEF treatment is energy and pulse number. Figure 18, shows the variations in energy drift and pulse numbers at different electric field strengths. An increase in the pulse number and electric field strength produced an increase in energy drift. At electric field strength of 20 kV/cm, the energy drifts were about 40, 65, 100, 146, and 155 kJ/L for 10, 20, 30, 40, and 50 pulses, respectively. At electric field strength of 30 kV/cm, the energy drifts were about 66, 150, 225, 305, and 400 kJ/L for 10, 20, 30, 40, and 50 pulses, respectively. At electric field strength of 40 kV/cm, the energy drifts were 146, 265, 405, 546, and 670 kJ/L for 10, 20, 30, 40, and 50 pulses, respectively.

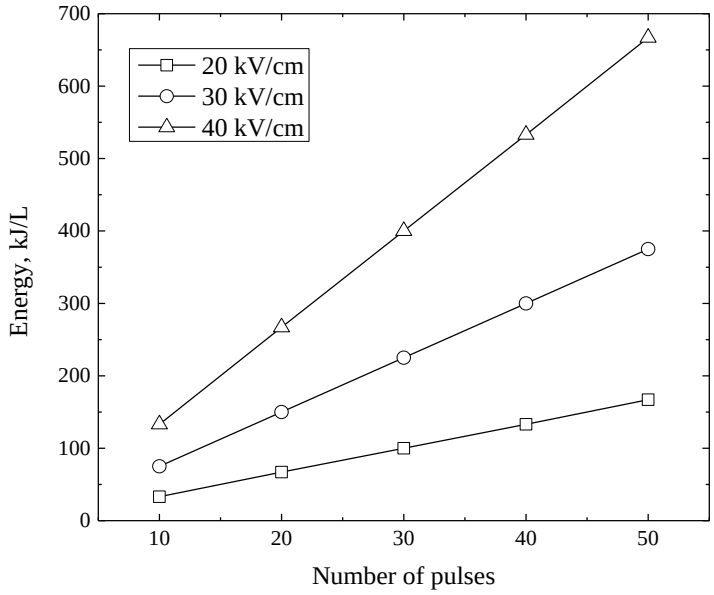


Figure 18. Variations in energy and pulse number at different electric field strengths.

As shown in Figure 19, the variations in electrical energy and pulse number at different electric field strengths. A digital multimeter, Fluke model 289 True-rms Industrial Logging, and a high voltage probe, Fluke model 80K-40, were used to measure the input and output high voltage power in this study. An increase in the pulse number and electric field strengths produced an increase in electrical energy. The electrical energy from each electric field strength increases the temperature of the product to which it is applied. As the pulse number increases, the temperature of the food product will also increase. At electric field strength of 20 kV/cm, the temperature drifts were about 33, 67, 100, 133, and 167 kJ/L for 10, 20, 30, 40, and 50 pulses, respectively. At electric field strength of 30 kV/cm, the temperature drifts were 75, 150, 225, 300, and 375 kJ/L for 10, 20, 30, 40, and 50 pulses, respectively. At electric field strength of 40 kV/cm, the temperature drifts were 133, 267, 400, 533, and 667 kJ/L for 10, 20, 30, 40, and 50 pulses, respectively.

Table 3. Comparison between the present work and the existing research works in PEF treatment.

	McDonald et al. [13]		Gupta et al. [14]	Qin et al. [15]	This work
Type of foods	Orange	Orange	Apple	Milk	Orange
Type of treatment chamber	Co-axial	Co-axial	Parallel plate	Co-axial	Parallel plate
Electric field (kV/cm)	30	50	40	60	30
Pulse width (μs)	2	2	1 – 2	10	10
Pulse number	10	4	100	50	30
Log cycle reduction (CFU/mL)	5	5	5	8	5
Temperature (°C)	65	62	Drift of about 2	40	31

Table 3 depicts the comparison between the present work and existing PEF research works. Notably, the present work agreed with the research works of McDonald et al. (2000), Gupta et al. (2003), and Qin et al. (1998). Further, a comparison between the present work and the existing non-thermal pasteurization processes, namely, high pressure Linton (1999), ultrasound Char (2010) and ultraviolet radiation process Char (2010), are shown in Table 4. Notably, the food and drug administration suggests a minimum 5-log reduction of microorganisms in juice processing FnBnews.com (2025).

Table 4. Comparison between the present work and the existing non-thermal pasteurization processes

	High Pressure [18]	Ultrasound [19]	Ultraviolet Radiation [19]	This work
Type of juices	Orange	Orange	Apple	Orange
Operating conditions	500 MPa 5 min 30 °C	20 kHz 95 μm	Lamp 100 W 90 cm.	30 kV/cm 10 μs 20 pulses
Treatment time	300 sec	20 min	15 min	300 μs.
Log cycle reduction	5 CFU/mL	2.2 CFU/mL	4.9 CFU/mL	5 CFU/mL
Temperature	30 °C	40 °C	30 °C	31 °C

4. Conclusion

In this study, a pilot-scale pulsed electric field processing system for the inactivation of microorganisms in orange juice was designed, developed and experimentally investigated. The developed system consisted of an AC power input, a rectifier circuit, a DC high-voltage power, an energy storage capacitor, a pulse controller to control the number and frequency of the pulse, a discharge switch to discharge energy from the capacitor across the food juice, and a sterilization chamber. The 3-phase pulse high-voltage source circuit was

simulated in the MATLAB/Simulink. It could generate a high-voltage unipolar exponential decaying pulse of approximately 22 kV with a pulse width of approximately 10 μs. In this study, the inactivation of microorganisms (*E.coli*) in orange juice was experimentally investigated by the total plate count method for electric field strengths between 20 and 40 kV/cm and pulse numbers between 10 and 100, respectively. Both PEF and thermal treatments reduced the population of *E. coli* inoculated in orange juice. No viable cells were observed after thermal processing of orange juice. However, PEF treatment achieved 5 logarithmic reductions in microbial viability at an electric field strength of up to 30 kV/cm for approximately 20 pulses.

Acknowledgments

The authors gratefully acknowledge the National Science and Technology Development Agency (NSTDA) for their financial support and providing the research contract (no. P-14-50757). The authors thank Dr. Rainer Zawadzki of Governor State University for their valuable contribution during the preparation of the manuscript.

References

[1] Chan, M. M., and Martinelli, C. K. (1997). The effect of color on perceived flavor intensity and acceptance of foods by young adults and elderly adults. *Journal of the American Dietetic Association*, 97(6), 657 – 9. doi: https://doi.org/10.1016/S0002-8223(97)00165-X.

[2] Michelle, K. B., Katherine, Z., Howe, E., Goicoechea, D., Paramanandhan, P., Stockman, R., Sellahewa, J., Szabo, E. A., Johnson, R. A. and Stewart, C. M. (2004). The effect of high pressure processing on the microbial, physical and chemical properties of Valencia and Navel orange juice. Innovative Food Science and Emerging Technologies, 5(2), 135-149. doi: https://doi.org/10.1016/j.ifset.2003.11.005.

[3] Cortes, C., Esteve, M. J., and Frígola, A. (2008). Color of orange juice treated by high intensity pulsed electric fields during refrigerated storage and comparison with pasteurized juice. Food Control, 19 (2), 151 – 158. doi: https://doi.org/10.1016/j.foodcont.2007.03.001.

[4] Sale, A. J. H., and Hamilton, W. A. (1968). Effects of high electric fields on microorganisms. III. Lysis of erythrocytes and protoplasts. Biochimical et Biophysica Acta, 163(1), 37 – 43. doi: https://doi.org/10.1016/0005-2736(68)90030-8.

[5] Hulsheger, H., Potel, J., and Niemann, E. G. (1981). Killing of bacteria with electric pulses of high field strength. Radiation and Environmental Biophysics, 20, 53 – 65. doi: https://doi.org /10. 1007 /BF01323926.

[6] Fleischman, G. J. (2014). HEAT TREATMENT OF FOODS | Action of Microwaves, *Journal of ELSEVIER,* 2, 1036-1041, https://doi.org/10.1016/B978-0-12-384730-0.00160-9.

[7] Jeyamkondan, S., Jayas, D. S., and Holley, R. A. (1999). Pulsed electric field processing of foods: A review. *Journal of National Library of Medicine,* 62(9), 1088 – 1096. doi: https://doi.org /10.4315/0362-028X-62.9.1088

[8] Ohshima, T.,Tamura, T., and Sato, M. (2007). Influence of pulsed electric field on various enzyme activities. *Journal of Electrostatics*, 65 (3), 156 – 161. doi: https://doi.org /10.1016/j.elstat.2006.07.005.

[9] Ohshima, T., Sato, K., Terauchi, H. and Sato, M. (1997). Physical and chemical modifications of high-voltage pulse sterilization. *Journal of Electrostatics*, 42 (1–2), 159 – 166. doi: https://doi.org /10.1016/S0304-3886(97)00152-6.

[10] Sen-in, P., Pinchai, P., Chaekoe, O., Yawootti, A. and Intra, P. (2012). Design of a pulsed electric field treatment chamber for a liquid foods pasteurization process. *KMUTT Research and Development Journal*, 35 (2), 253 – 267.

[11] Panyamuangjai, V., Janthara, S., Kusuya, R., Yawootti, A., & Intra, P. (2012). Application of pulsed electric field for milk pasteurization. *KMUTT Research and Development Journal*, 35 (4), 469 – 484.

[12] Intra, P., Manopian, P., Pengmanee, C., Yawootti, A., Asanavijit, V., and Somsri, N. (2015). Inactivation of E. coli for milk tea pasteurization by pulsed electric field. *Journal of KMUTNB*, 25, 425 – 437.

[13] Mcdonald, C., Lloyd, S., Vitale, M., Petersson, K. and Innings, F. (2000). Effects of pulsed electric fields on microorganisms in orange juice using electric field strengths of 30 and 50 kV/cm. *Journal of Food Science*, 65, 984 – 989. doi: https://doi.org/10.1111/j.1365-2621.2000.tb09404.x.

[14] Gupta, B. S., Masterson, F. and T. R. A. Magee, (2003). Inactivation of E. coli K12 in apple juice by high voltage pulsed electric field. European Food Research and Technology, 217, 434 – 437. doi: https://doi.org/10.1007/s00217-003-0756-6.

[15] Qin, B. - L., Barbosa-Canovas, G.V., Swanson, B.G., Pedrow, P. D., and Olsen, R. G. (1998). Inactivating microorganisms using a pulsed electric field continuous treatment system. *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*, 34(1), 43 – 50. doi: 10.1109/28.658715.

[16] Min, S., Jin, Z. T. and Zhang, Q. H. (2003). Commercial scale pulsed electric field processing of tomato juice. *Journal of Agricultural and Food Chemistry*, 51 (11), 3338 – 3344. doi: https://doi.org/10.1021/jf0260444.

[17] Min, S., Jin, Z.T., Min, S.K., Yeom, H. and Zhang, Q.H. (2003). Commercial-scale pulsed electric field processing of orange juice. *Journal of Food Science*, 68 (4), 1265 – 1271. doi: https://doi.org/10.1111/j.1365-2621.2003.tb09637.x.

[18] Linton, M., Mcclements, J.M.J. and Patterson, M.F. (1999). Inactivation of Escherichia coli O157:H7 in orange juice using a combination of high pressure and mild heat. *Journal of Food Protection*, 62(3), 277 – 279. doi: https://doi.org/10.4315/0362-028X-62.3.277.

[19] Char, C. D., Mitilinaki, E., Guerrero, S. N., and Alzamora, S. M. (2010). Use of high-intensity ultrasound and UV-C light to inactivate some microorganisms in fruit juices. Food and Bioprocess Technology, 3(6), 797 – 803. doi: https://doi.org/10.1007/s11947-009-0307-7.

[20] FnBnews.com 2025. Available Source: https://www.fnbnews.com /Top – News / customization - of-flavours – to – gain - prominence-in-fruit-juice-market-82472.