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A NOVEL AIR-INSULATION RELAY WITH HIGH WITHSTAND VOLTAGE CHARACTERISTICS FOR SHOCKWAVE NON-THERMAL FOOD PROCESSING SYSTEMS

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Abstract. *For shockwave non-thermal food processing systems, a novel air-insulation relay with high withstand voltage characteristics is proposed in this paper. In the proposed relay, insulation is achieved by air pumped into a submerged bowl with an air pump. The proposed switch is turned on by controlling an electromagnet to rotate the bowl and fill it with water. Unlike conventional air-insulation relays, the proposed technique can provide 1) low-cost realization of shockwave non-thermal food processing and 2) effective non-thermal food processing by suppressing energy loss due to arc discharge caused by the conventional air-insulation relays, because the expensive relay with high withstand voltage characteristics is not required. The feasibility and effectiveness of the proposed relay are confirmed by laboratory experiments using a prototype shockwave non-thermal food processing system. In the experiment, the proposed technique achieves 2.2kA higher output current than the conventional technique. The experimental result reveals that the proposed technique can provide a low-cost and effective non-thermal food processing system.*
Keywords: High withstand voltage switch, Air-insulation, No mechanical connection, Non-thermal food processing, Underwater shockwaves

1. **Introduction.** Non-thermal food processing [1] is one of the most promising technologies for providing nutritious softened foods. Recently, several non-thermal food processing technologies have been proposed, such as high hydrostatic pressure technology [2], high voltage arc discharge technology [3], pulsed electric field technology [4], and cold plasma technology [5]. Among others, non-thermal food processing unitizing underwater shockwaves [6] is an attractive technology, because it can provide low-cost non-thermal food processing. In the shockwave non-thermal technology, the internal tissue of target foods is destroyed by underwater shockwaves generated by using the energy stored in a large output capacitor with high withstand voltage characteristics. Generally, high voltage switches and relays, such as vacuum relays [7], reed relays [8], electro-mechanical relays [9], high-speed high-voltage (HV) switches [10], and solid-state relays [11], are used for high current and high voltage isolation. However, for example, shockwave non-thermal food processing requires approximately 3.5kV/15kA of power to process target foods such as apples. Therefore, in the conventional shockwave non-thermal food processing systems

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[12-14], an expensive air-insulation relay with withstand voltage characteristics, such as EA12-NC-20-1-100-BD [15], is necessary to discharge the energy stored in the output capacitor. Needless to say, this expensive air-insulation relay is an obstacle to further cost reduction of the shockwave non-thermal food processing systems.

To solve this problem, a novel air-insulation relay with high withstand voltage characteristics is proposed in this paper. Unlike conventional air-insulation relays with withstand voltage characteristics, the proposed switch utilizes air stored in a submerged bowl to achieve isolation. The proposed relay is turned on by rotating the bowl and filling it with water. The shockwave non-thermal food processing system using the proposed relay has the following advantages: 1) low-cost non-thermal food processing can be achieved, because no expensive relay is used and 2) effective non-thermal food processing can be realized, because energy loss due to arc discharge can be suppressed. The feasibility and effectiveness of the proposed technique are confirmed by laboratory experiments using a prototype shockwave non-thermal food processing system.

This paper is organized by the following sections. First, Section 2 describes the system configuration of the shockwave non-thermal food processing system using the proposed relay. Next, Section 3 verifies the proposed design experimentally and confirms the effectiveness of the proposed technique through comparison. Finally, Section 4 summarizes the result of this work.

2. Shockwave Non-Thermal Food Processing System.

2.1. Problem formulation. Figure 1 shows the general structure of a shockwave non-thermal food processing system [12-14]. As Figure 1 shows, the shockwave non-thermal food processing system consists of a high voltage generator, a switch with high withstand voltage characteristics, an output capacitor with high withstand voltage characteristics, a pair of electrodes, and a pressure vessel filled with water. Therefore, unlike other non-thermal food processing technologies, such as cold plasma, the shockwave non-thermal food technology can provide low-cost food processing.

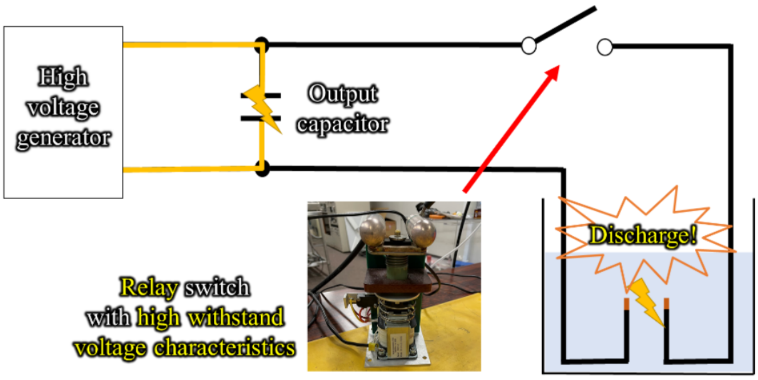


Figure 1. Configuration of the shockwave non-thermal food processing system [12-14]

The operation principle of the shockwave non-thermal food processing system shown in Figure 1 is as follows: Firstly, by converting a 100V@60Hz AC input, the high voltage generator, such as Dickson multipliers [16], Cockcroft-Walton multipliers [17], hybrid Cockcroft-Walton/Dickson multipliers [18,19], and Bipolar Cascade Voltage-Doubler [20], provides the following high voltage V_{high}:

$$V_{high} = G \times V_{in}, \tag{1}$$

where G is a voltage gain of the high voltage generator and V_{in} is the amplitude of the AC input. For example, V_{high} is set to about 3.5kV to process apples. Since the output capacitor C_{out} is charged by V_{high}, the voltage of C_{out}, $V_{cout}(t)$, is expressed as a function of time as follows:

$$V_{cout}(t) = V_{high}\left(1 - e^{-t/\tau}\right), \tag{2}$$

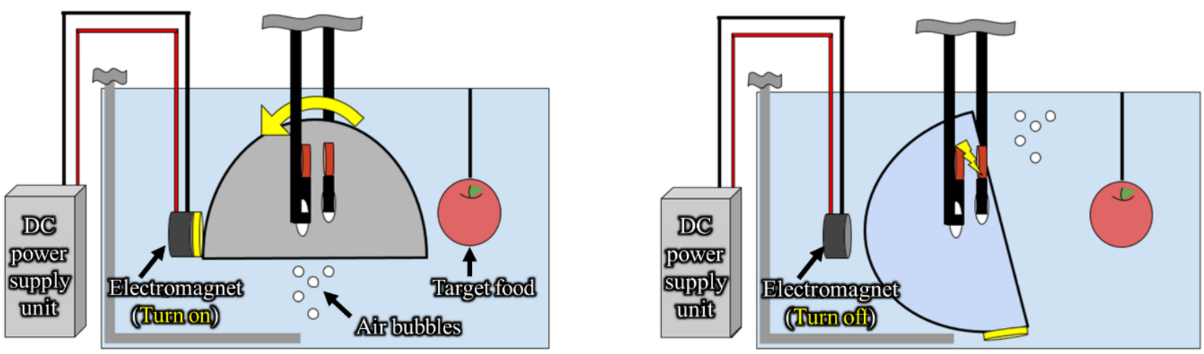
where τ is a time constant which is expressed as the product of C_{out} and the internal resistance of the high voltage generator. Therefore, the energy $E(t)$ stored in C_{out} is given by

$$E(t) = C_{out}V_{cout}^2(t)/2. \tag{3}$$

Next, by turning on the switch with high withstand voltage characteristics, the energy $E(t)$ is discharged and the large current I_{out} flows between the electrodes. Therefore, an underwater shockwave is generated by evaporating the water between the electrodes with I_{out}. Namely, the strength of the shockwave is determined by I_{out}. Finally, the underwater shockwave destroys only the inside of the target food submerged in water.

In the conventional shockwave non-thermal food processing system, the air-insulation relay with high withstand voltage characteristics is usually used. However, in the air-insulation relay, the considerable energy loss is caused by arc discharge. Furthermore, the air-insulation relay is expensive. For example, the price of the air-insulation relay [15] is more than USD1,000. In other words, the shockwave non-thermal food processing system can be made significantly cheaper by not using the relay with high withstand voltage characteristics. For this reason, we attempt to realize the shockwave non-thermal food processing system without expensive conventional relays.

2.2. **Structure of the proposed relay.** Figure 2 illustrates the mechanism of the proposed high withstand voltage relay. Unlike the conventional system shown in Figure 1, the electrodes are covered with a bowl. In the proposed technique, air is pumped into a submerged bowl with an air pump. In other words, the electrodes are electrically disconnected by filling the bowl with air. At this time, the electromagnet is on and is attracted to a steel plate on the edge of the bowl. The electromagnet turns off when the output capacitor is fully charged. At this time, the steel plate acts as a weigh and the bowl rotates. The electrodes are electrically connected by the water in the bowl. Therefore, unlike the traditional air-insulation relay, the proposed relay can avoid the energy loss caused by arc discharge, because the proposed technique does not use the mechanical connection



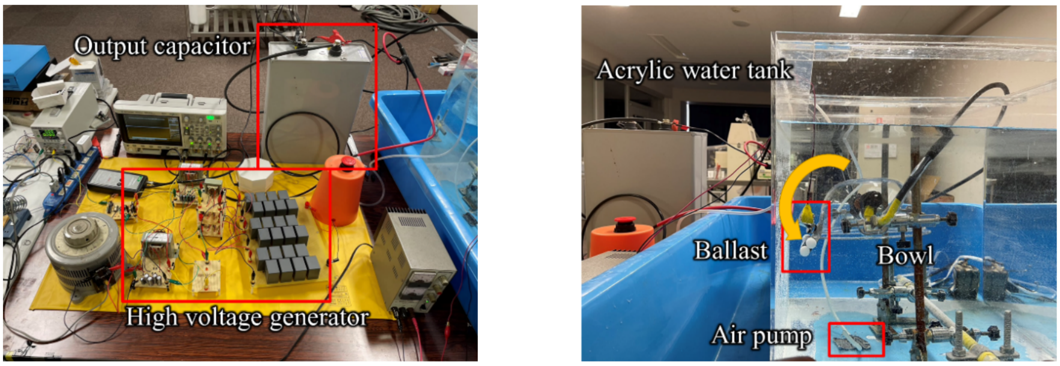
(a) (b)

FIGURE 2. Mechanism of the proposed relay with high withstand voltage characteristics: (a) Turn on and (b) turn off

of relay terminals. That is, the proposed technique can provide effective shockwave non-thermal food processing, because the output current of the shockwave non-thermal food processing system using the proposed relay becomes larger than that using the traditional air-insulation relay. The shockwave non-thermal food processing requires approximately 3.5kV/15kA of power to process apples, but the proposed relay could potentially reduce the output voltage. Moreover, low-cost realization of the air-insulation relay can be achieved by the proposed technique, because the proposed relay consists only of an air pump, a bowl, and a small electromagnet. Specifically, the materials cost to assemble the proposed relay is only less than USD30. In other words, the proposed technique can reduce the cost of the air-insulation relay to less than 1/30 compared to the conventional relay [15].

3. Experimental Verification.

3.1. Experimental setup. Figure 3 demonstrates the experimental setup of the prototype shockwave non-thermal food processing system. The experimental system consists of the instruments shown in Table 1. Figure 3(a) shows the high voltage generator and an output capacitor that stores the high voltage. In this experimental system, about 3.5kV is generated by the stacked hybrid Cockcroft-Walton/Dickson multipliers [18]. Figure 3(b) depicts the water tank and the proposed relay. In this proposed relay, the bowl shown in Figure 4 was used to fill the air. The bowl has a diameter of 19cm, a volume of



(a) (b)

FIGURE 3. Experimental setup: (a) High voltage generator and an output capacitor and (b) water tank and the proposed relay

TABLE 1. Instruments used in the experiment

Instrument	Name
DC power supply unit	Kikusui PMX35-1A
Output capacitor	TOEI SH CAPACITOR 200µF/4000VDC
Oscilloscope	Agilent Technologies DSO-X 3014A
High voltage probe	Iwatsu SS-0170
High voltage rely	Comcraft EA12-NC-20-1-100-BD
Rogowski coil type current measuring instrument	Power Electronic Measurements CWTHF600
Acrylic water tank	600mm × 450mm × 450mm
Electromagnet	DC12V/φ25mm/150N
Armature plate	φ25 × 3mm/M3 EA984CM-31

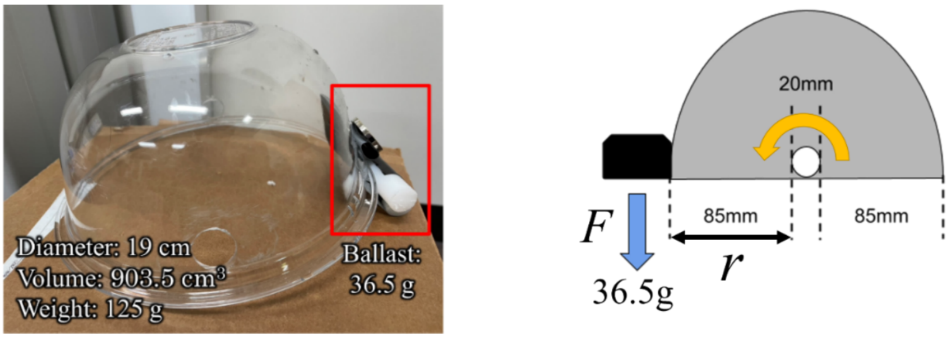


FIGURE 4. Bowl to fill air

TABLE 2. Attraction force of the electromagnet in air gap

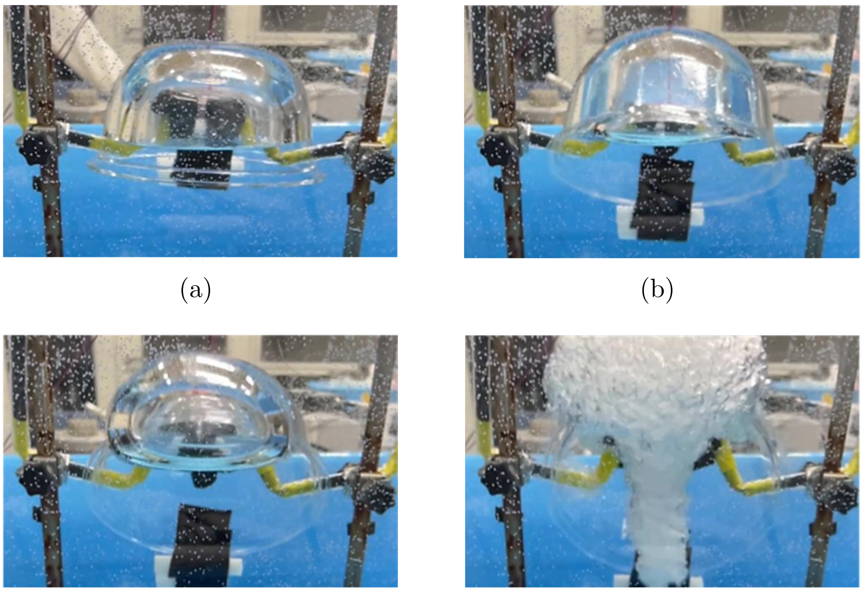
Gap between electromagnet and iron plate (mm)	0	0.09	0.18	0.27
Attraction force (N)	150	51	22	12

903.5cm^3, and a weight of 125g, where a 36.5g of ballast is attached to the edge of the bowl. Therefore, the moment of a force, M, can be calculated as

$$M = F \times r = 0.365 \times 0.085 \doteqdot 0.03 \text{ [Nm]} \tag{4}$$

According to the specifications of the electromagnet, the attraction force of the electromagnet is as shown in Table 2. In this experiment, the gap between the electromagnet and the iron plate is 0mm. Therefore, the attraction force of the electromagnet is 15kg if 1N = 100g. For this reason, the force to hold the tilt of the bowl is sufficient.

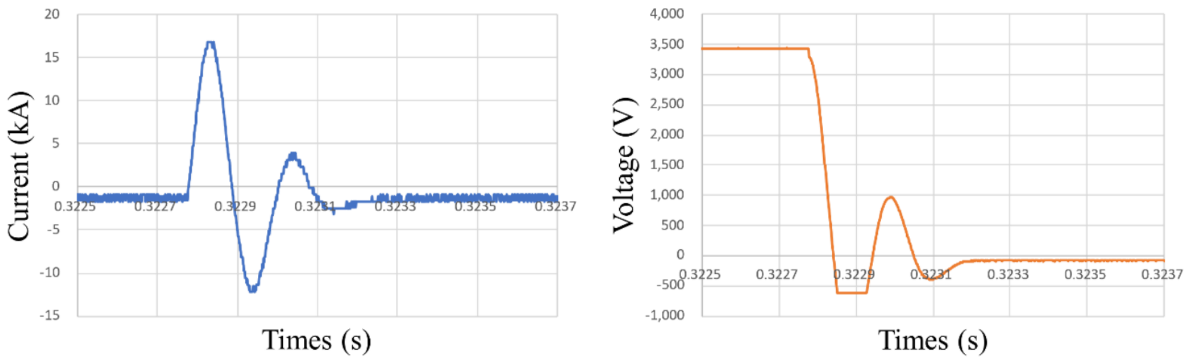
3.2. **Measured characteristics.** Figure 5 demonstrates the operation of the proposed relay. As this figure shows, the proposed technique functions as a high withstand voltage switch due to air-insulation. Figure 6 shows the measured outputs of the shockwave



(a) (b)

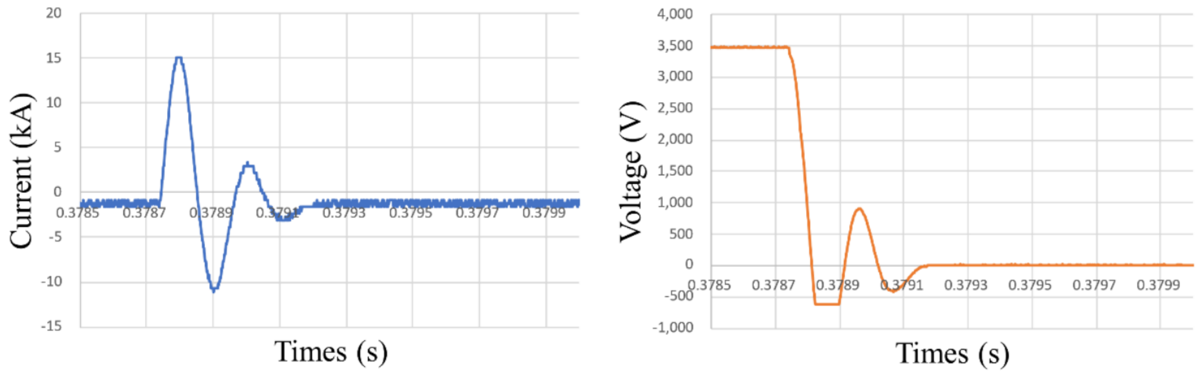
(c) (d)

FIGURE 5. Discharging process: (a) Initial state, (b) turn off process, (c) rotation process, and (d) discharge process



(a) (b)

FIGURE 6. Measured results when using the proposed air-insulation relay: (a) Output current and (b) output voltage



(a) (b)

FIGURE 7. Measured results when using the conventional air-insulation rely EA12-NC-20-1-100-BD: (a) Output current and (b) output voltage

non-thermal food processing system using the proposed air-insulation relay. On the other hand, Figure 7 depicts the measured outputs of the shockwave non-thermal food processing system using the conventional air-insulation relay [15]. As these figures show, both systems have approximately the same output voltage. However, the output current of the system using the proposed relay is higher than that using the conventional relay. This is because the proposed relay can suppress the reduction of stored energy in the output capacitor due to arc discharge.

Table 3 illustrates the average value of three output currents. As this table shows, the system using the proposed relay can achieve 2.2kA higher output current than the system using the conventional air-insulation relay. In other words, the system using the proposed relay can provide effective non-thermal food processing without expensive relays.

TABLE 3. Average value of the output currents

Type	1st	2nd	3rd	Average
Proposed	16.8kA	17.3kA	17.6kA	17.2kA
Conventional	14.8kA	15.2kA	15.0kA	15.0kA

4. **Conclusions.** For shockwave non-thermal food processing systems, we proposed a novel air-insulation relay with high withstand voltage characteristics. Unlike the conventional air-insulation relays, the proposed technique can suppress the reduction of stored energy in the output capacitor due to arc discharge. The effectiveness and validity of the proposed relay were confirmed by experiments. In the experiment, the system using the proposed relay obtained 2.2kA higher output current than the system using the conventional air-insulation relay. Moreover, the materials cost to assemble the proposed switch was only less than USD30. From the experimental result, a low-cost and effective non-thermal food processing system can be realized by employing the proposed switch, because expensive conventional relays are not required. Miniaturization of the proposed relay is left for future research.

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REFERENCES

[1] M. Stoica, L. Mihalcea, D. Borda and P. Alexe, Non-thermal novel food processing technologies – An overview, *Journal of Agroalimentary Processes and Technologies*, vol.19, no.2, pp.212-217, 2013.

[2] C. Y. Wang, H. W. Huang, C. P. Hsu and B. B. Yang, Recent advances in food processing using high hydrostatic pressure technology, *Crit. Rev. Food Sci. Nutr.*, vol.56, no.4, pp.527-540, DOI: 10.1080/10408398.2012.745479, 2016.

[3] N. Boussetta, J. L. Lanoisellé, C. Bedel-Cloutour and E. Vorobiev, Extraction of soluble matter from grape pomace by high voltage electrical discharges for polyphenol recovery: Effect of sulphur dioxide and thermal treatments, *Journal of Food Engineering*, vol.95, no.1, pp.192-198, DOI: 10.1016/j.jfoodeng.2009.04.030, 2009.

[4] N. Grimi, F. Mamouni, N. Lebovka, E. Vorobiev and J. Vaxelaire, Impact of apple processing modes on extracted juice quality: Pressing assisted by pulsed electric fields, *Journal of Food Engineering*, vol.103, no.1, pp.52-61, DOI: 10.1016/j.jfoodeng.2010.09.019, 2011.

[5] B. A. Niemira, Cold plasma decontamination of foods, *Annu. Rev. Food Sci. Technol.*, vol.3, pp.125-142, DOI: 10.1146/annurev-food-022811-101132, 2012.

[6] K. Shimojima, Y. Miyafuji, K. Naha, O. Higa, R. Matsubara, K. Higa, Y. Higa, T. Matsui, A. Takemoto, S. Tanaka, H. Maehara and S. Itoh, Development of the rice-powder manufacturing system using underwater shock wave, *Int. J. Multiphys.*, vol.6, no.4, pp.355-364, DOI: 10.1260/1750-9548.6.4.355, 2012.

[7] C. W. Miller, A vacuum relay, *Journal of Scientific Instruments*, vol.15, no.8, 263, DOI: 10.1088/0950-7671/15/8/303, 1938.

[8] M. Ahosan Ul karim, S. Chung, E. Alon and V. Subramanian, Stress-tolerant fully inkjet-printed Reed Relays, *2015 Transducers – 2015 18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS)*, Anchorage, AK, USA, pp.568-571, DOI: 10.1109/TRANSDUCERS.2015.7180987, 2015.

[9] M. Sakata, An electrostatic microactuator for electro-mechanical relay, *IEEE Micro Electro Mechanical Systems, Proceedings, 'An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots'*, Salt Lake City, UT, USA, pp.149-151, DOI: 10.1109/MEMSYS.1989.77980, 1989.

[10] S. Young, D. Kim and D. Kim, A new 1200V IGBT technology optimized for high speed switching, *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, Hefei, China, pp.1607-1610, DOI: 10.1109/IPEMC.2016.7512533, 2016.

[11] M. S. W. Cheung and U. Y. N. Cheung, Design of solid state relays for control circuitry on railway cars, *Proc. of the IEEE 1999 International Conference on Power Electronics and Drive Systems. PEDS'99 (Cat. No.99TH8475)*, Hong Kong, China, vol.1, pp.180-185, DOI: 10.1109/PEDS.1999.794557, 1999.

[12] K. Eguchi, F. Asadi, A. Shibata, H. Abe and I. Oota, Reduction of inrush current in a shockwave non-thermal food processing system using an exponential clock pulse generator, *Sustainability*, vol.12, no.15, 6095, DOI: 10.3390/su12156095, 2020.

[13] K. Eguchi, D. Nakashima and T. Ishibashi, Experimental study on discharging current to reduce voltage stress during underwater shock wave generation, *Energy Reports*, vol.8, supplement 10, pp.113-120, DOI: 10.1016/j.egyr.2022.05.143, 2022.
[14] D. Nakashima and K. Eguchi, Design of a high-speed bipolar Cockcroft-Walton voltage multiplier for non-thermal food processing systems suitable for low output voltage conditions, *International Journal of Innovative Computing, Information and Control*, vol.19, no.1, pp.299-306, DOI: 10.24507/ijicic.19.01.299, 2023.
[15] *https://www.rossengineeringcorp.com/products/control/hv-relays/e-series-12kv-60kv.html*, Accessed on May 1, 2023.
[16] D. Nakashima, Y. Kino and K. Eguchi, Design of a bipolar Dickson voltage multiplier suitable for low output voltage conditions to provide efficient food processing, *Energy Reports*, vol.9, supplement 8, pp.207-213, DOI: 10.1016/j.egyr.2023.04.304, 2023.
[17] A. Jaiwanglok, K. Eguchi, K. Smerpitak and A. Julsereewong, Modification of Cockcroft-Walton-based high-voltage multipliers with 220 V and 50 Hz input for non-thermal food processing apparatus, *Sustainability*, vol.12, no.16, 6330, DOI: 10.3390/su12166330, 2020.
[18] K. Eguchi, D. Nakashima, T. Ishibashi and F. Asadi, A high voltage multiplier using stacked hybrid Cockcroft-Walton/Dickson multipliers, *J. Phys.: Conf. Ser.*, 012019, DOI: 10.1088/1742-6596/2022/1/012019, 2022.
[19] S. Park, J. Yang and J. Rivas-Davila, A hybrid Cockcroft-Walton/Dickson multiplier for high voltage generation, *IEEE Transactions on Power Electronics*, vol.35, no.3, pp.2714-2723, DOI: 10.1109/TPEL.2019.2929167, 2020.
[20] W. Do, A. Shibata and K. Eguchi, Design of a bipolar cascade voltage-doubler for a non-thermal food processing system using underwater shockwave, *ICIC Express Letters, Part B: Applications*, vol.12, no.5, pp.453-459, DOI: 10.24507/icicelb.12.05.453, 2021.

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