

## DESIGN OF A HIGH-SPEED BIPOLAR COCKCROFT-WALTON VOLTAGE MULTIPLIER FOR NON-THERMAL FOOD PROCESSING SYSTEMS SUITABLE FOR LOW OUTPUT VOLTAGE CONDITIONS

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**ABSTRACT.** *This paper proposes a high-speed bipolar Cockcroft-Walton voltage multiplier (CWVM) using underwater shockwaves suitable for low output voltage conditions. Unlike conventional high-voltage multipliers, the proposed multiplier is not only bipolar topology, but also has a high-speed driver. The theoretical analysis reveals that the voltage gain and internal resistance of the proposed multiplier are 6 and  $8R_d + 18R_{on}$ , respectively. Moreover, experimental results using a prototype of the proposed multiplier demonstrate that the output voltage of the proposed multiplier can be obtained more than 859 V within 26.7 seconds during the voltage gain of 6 and an input voltage of 100 V at 60 Hz.*

**Keywords:** High voltage multipliers, Shockwave non-thermal food processing, Cockcroft-Walton multipliers, Underwater shockwaves, High voltage gains, Bipolar topology

1. **Introduction.** Food processing in general has the problem that food nutrients are destroyed during processing. To solve this problem, several non-thermal food processing methods have been devised [1-8]. Among them, the method using underwater shockwaves generated by high voltage [7,8] has the advantage of low processing cost. However, this method has the weakness that it takes a long time for food processing because it is necessary to charge high voltage to output capacitors. To improve the efficiency of food processing, many voltage multipliers are studied by many researchers. Among them, one of the most popular high voltage multipliers is the Cockcroft-Walton voltage multiplier (CWVM) [9], for example, symmetrical CWVM [10], series-connected CWVM [11], hybrid CWDM [12], stacked DM [13], and stacked HCWDM [14]. However, it is necessary to generate high voltages, such as more than 3 kV for food processing. For this reason, custom-made capacitors with high withstand voltage and large capacitance must be used as output capacitors. Thereby, it increases the manufacturing cost of the processing system. In the method using underwater shockwaves generated by high voltage, the output voltage can be reduced by keeping the output energy constant [15]. Therefore, the manufacturing cost of the processing system can be reduced under low output voltage conditions because general capacitors can be used as output capacitors. However, the lower output voltage is, the larger capacity of output capacitors must be, resulting in a longer processing time.

In this paper, we present a high-speed bipolar CWVM using underwater shockwaves suitable for low output voltage conditions. This multiplier has the advantage of having fewer circuit stages than the conventional CWVM [9] because of its bipolar topology.

Moreover, the proposed multiplier is equipped with a high speed driver. This paper is organized by the following sections. In Section 2, the features of the proposed multiplier are presented and its circuit operation is explained. Section 3 presents the results of theoretical analysis of the proposed multiplier. Section 4 demonstrates the results of experiments conducted on a prototype of the proposed multiplier. Finally, Section 5 summarizes this paper.

**2. Circuit Configuration.** Figure 1 shows the circuit configuration of a conventional CWVM [9]. This multiplier has the advantage of a simple structure because it consists of only diodes and capacitors. However, the response speed of the conventional CWVM becomes slower as the number of multiplier stages increases. In addition, the conventional CWVM is directly driven by a commercial power supply. Therefore, we devised a multiplier that employs a bipolar Cockcroft-Walton topology, as shown in Figure 2. This topology can reduce the number of multiplier stages. In addition, this multiplier is equipped with the high-speed driver, which enables fast circuit drive. As shown in Figure 2, this multiplier is organized by an isolation transformer, two full-waveform rectifiers (FWRs), a high-speed pulse generator, and a bipolar CWVM. First, two full-wave rectifiers (FWRs) generate DC voltages  $|V_{\max}|$  and  $-|V_{\max}|$  from the AC input by the commercial power supply, where  $V_{\max}$  is the amplitude of  $V_{ac}$ . Next, the pulse generator consisting of IGBTs driven by the clock pulses  $\Phi_1$  and  $\Phi_2$  provides high-speed 2-phase rectangle pulses with the amplitude  $2|V_{\max}|$  to the bipolar CWVM. Finally,  $4|V_{\max}|$  and  $-2|V_{\max}|$  are generated

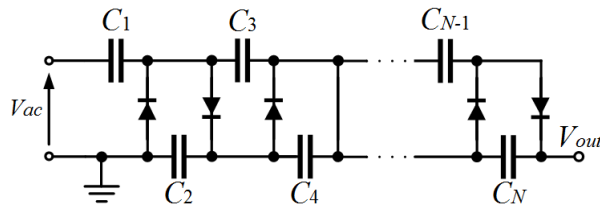


FIGURE 1. Conventional CWVM [9]

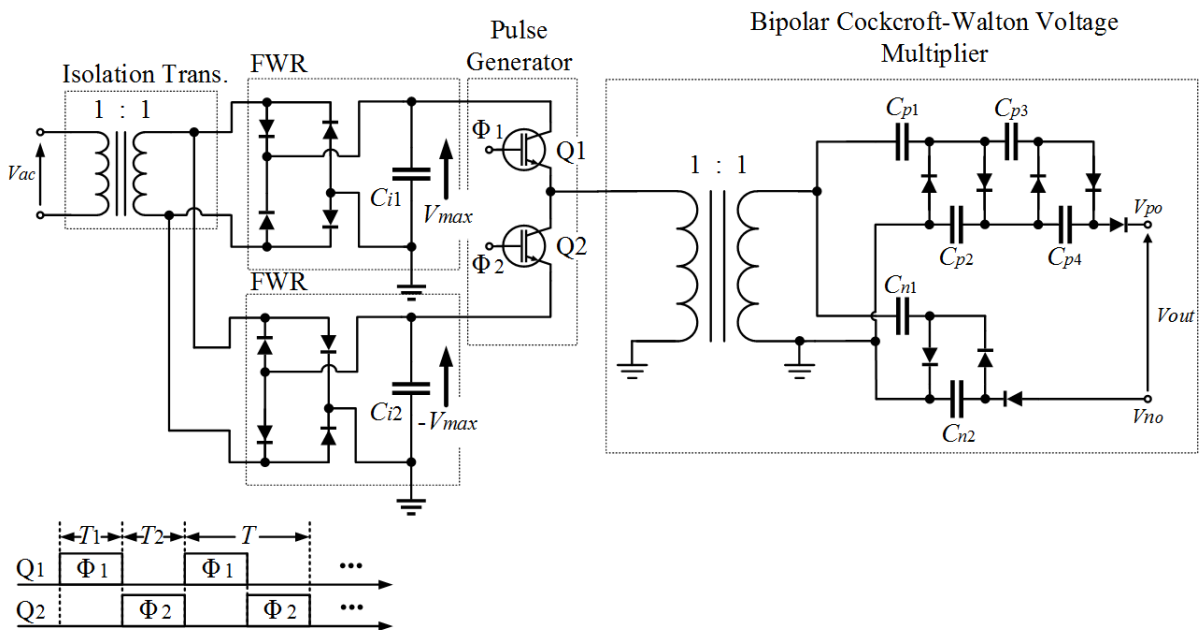


FIGURE 2. Proposed high voltage multiplier

as  $V_{po}$  and  $V_{no}$ , respectively, where  $V_{po}$  and  $V_{no}$  are DC output voltages of the positive and negative modules. The difference between  $V_{po}$  and  $V_{no}$ , approximately  $848\text{ V} (= 100\sqrt{2}\times 6)$  is supplied to the output capacitor  $C_{out}$ .

**3. Theoretical Analysis.** To clarify theoretically the output voltage gain  $m$  and the internal resistance of the proposed multiplier  $R_{SC}$ , a theoretical analysis is performed. Figure 3 illustrates the instantaneous equivalent circuit of the proposed multiplier. In this section, theoretical analysis is performed under the following conditions: 1) the time constant of the circuit is much larger than the clock pulse period  $T$ , 2) the equivalent resistance of diodes is  $R_d$ , and 3) the on resistance of IGBTs is  $R_{on}$ .

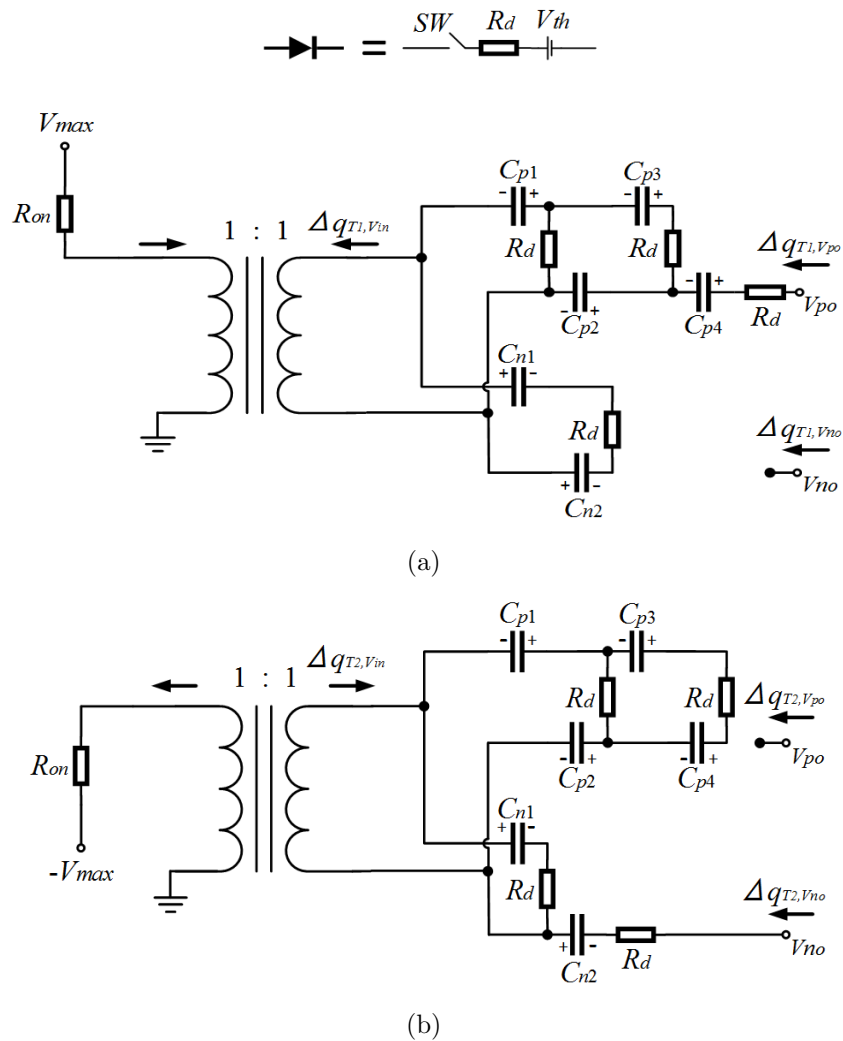


FIGURE 3. Instantaneous equivalent circuits of the proposed multiplier: (a) State- $T_1$  ( $\Phi_1$  is high and  $\Phi_2$  is low) and (b) State- $T_2$  ( $\Phi_1$  is low and  $\Phi_2$  is high)

In Figure 3, the variation of electric charge in  $C_{pi}$  ( $i = 1, 2, 3, 4$ ) and  $C_{nj}$  ( $j = 1, 2$ ) satisfies Equations (1) and (2):

$$\Delta q_{T1}^{pi} = -\Delta q_{T2}^{pi} \tag{1}$$

$$\Delta q_{T1}^{nj} = -\Delta q_{T2}^{nj} \tag{2}$$

First, applying Kirchhoff's current law to the instantaneous equivalent circuit in Figure 3(a), we obtain Equations (3) to (6):

$$-\Delta q_{T_1, V_{in}} = -\Delta q_{T_1}^{p1} + \Delta q_{T_1}^{n1} \quad (3)$$

$$\Delta q_{T_1, V_{po}} = \Delta q_{T_1}^{p4} \quad (4)$$

$$\Delta q_{T_1}^{p4} = \Delta q_{T_1}^{p2} + \Delta q_{T_1}^{p3} \quad (5)$$

$$\Delta q_{T_1}^{n1} = -\Delta q_{T_1}^{n2} \quad (6)$$

On the other hand, applying Kirchhoff's current law to Figure 3(b), we obtain Equations (7) to (9):

$$\Delta q_{T_2, V_{in}} = -\Delta q_{T_2}^{p1} + \Delta q_{T_2}^{n1} \quad (7)$$

$$\Delta q_{T_2}^{p4} = \Delta q_{T_2}^{p1} + \Delta q_{T_2}^{p2} - \Delta q_{T_2}^{p3} = -\Delta q_{T_2}^{p3} \quad (8)$$

$$\Delta q_{T_2, V_{no}} = -\Delta q_{T_2}^{n2} \quad (9)$$

The input variation of electric charge,  $\Delta q_{in}$ , is expressed as Equation (10):

$$\Delta q_{in} = \Delta q_{T_1, V_{in}} + \Delta q_{T_2, V_{in}} = 2 (\Delta q_{T_1}^{p1} - \Delta q_{T_1}^{n1}) \quad (10)$$

By rearranging Equations (1) to (10), we obtain Equations (11) to (15):

$$\Delta q_{T_1}^{p2} = -\Delta q_{T_1}^{p1} \quad (11)$$

$$\Delta q_{T_1}^{p3} = \frac{1}{2} \Delta q_{T_1}^{p1} \quad (12)$$

$$\Delta q_{T_1}^{p4} = -\frac{1}{2} \Delta q_{T_1}^{p1} \quad (13)$$

$$\Delta q_{T_1}^{n1} = -\frac{1}{2} \Delta q_{T_1}^{p1} \quad (14)$$

$$\Delta q_{T_1}^{n2} = \frac{1}{2} \Delta q_{T_1}^{p1} \quad (15)$$

From Equations (1) and (15), we get Equation (16),

$$\Delta q_{in} = 2 (2\Delta q_{T_1, V_{po}} - \Delta q_{T_2, V_{no}}) \quad (16)$$

Thereby, we obtained  $\Delta q_{in} = -6\Delta q_{T_1, V_{po}}$ , because of  $\Delta q_{T_1, V_{po}} = -\Delta q_{T_2, V_{no}}$ . From these equations, the output voltage of the proposed multiplier can be obtained as  $V_{out} = 6|V_{max}|$ . Therefore, the voltage gain  $m$  is 6.

Next, we calculate the power loss of the proposed multiplier in order to obtain the internal resistance  $R_{SC}$ . In Figure 3, the power loss of the proposed multiplier,  $W_T$ , is obtained as Equation (17):

$$W_T = W_{T_1} + W_{T_2} \quad (17)$$

where  $T$  expresses the time of the clock pluses,  $W_{T_1}$  and  $W_{T_2}$  are the power loss of State- $T_1$  and State- $T_2$ .  $W_{T_1}$  and  $W_{T_2}$  are expressed as Equations (18) and (19):

$$\begin{aligned} W_{T_1} = & \frac{R_d}{T_1} (\Delta q_{T_1}^{p3} - \Delta q_{T_1}^{p1})^2 + \frac{R_d}{T_1} (\Delta q_{T_1}^{p3})^2 + \frac{R_d}{T_1} (\Delta q_{T_1, V_{po}})^2 + \frac{R_d}{T_1} (\Delta q_{T_1}^{n1})^2 \\ & + \frac{R_{on}}{T_1} (\Delta q_{T_1, V_{in}})^2 \end{aligned} \quad (18)$$

$$\begin{aligned} W_{T_2} = & \frac{R_d}{T_2} (\Delta q_{T_2}^{p3} - \Delta q_{T_2}^{p1})^2 + \frac{R_d}{T_2} (\Delta q_{T_2}^{p3})^2 + \frac{R_d}{T_2} (\Delta q_{T_2}^{n1})^2 + \frac{R_d}{T_2} (\Delta q_{T_2, V_{no}})^2 \\ & + \frac{R_{on}}{T_2} (\Delta q_{T_2, V_{in}})^2 \end{aligned} \quad (19)$$

From Equations (17) to (19),  $W_T$  is obtained as Equation (20).

$$W_T = (8R_d + 18R_{on}) \frac{(\Delta q_{V_{po}})^2}{T} \tag{20}$$

where  $T = T_1 + T_2$ . From Equation (20), the internal resistance  $R_{SC}$  is calculated as  $8R_d + 18R_{on}$ . The equivalent model of the proposed multiplier shown in Figure 4 can be expressed by Equation (21) [16,17].

$$\begin{bmatrix} |V_{max}| - V_{th} \\ I_{in} \end{bmatrix} = \begin{bmatrix} 1/6 & 0 \\ 0 & 6 \end{bmatrix} \begin{bmatrix} 1 & 8R_d + 18R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_{out} \\ -I_{out} \end{bmatrix} \tag{21}$$

Finally, the maximum output voltage of the proposed multiplier,  $V_{out}$ , is obtained as Equation (22).

$$V_{out} = 6(|V_{max}| - V_{th}) \times \left( \frac{R_L}{R_L + 8R_d + 18R_{on}} \right) \tag{22}$$

where  $R_L$  is an output load. From this theoretical analysis, we were able to get that the voltage gain  $m$  and the internal resistance  $R_{SC}$  are 6 and  $8R_d + 18R_{on}$ , respectively. Therefore,  $V_{out}$  is about 848 V when input voltage of the proposed multiplier is 100 V AC.

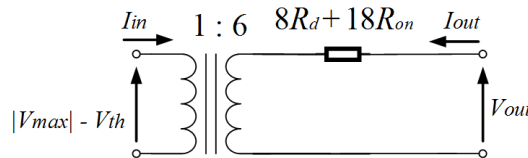


FIGURE 4. Equivalent circuit of the proposed voltage multiplier

**4. Experimental Results.** In this section, we experimentally confirm the feasibility of the proposed multiplier. Figure 5 shows the experimental prototype. The prototype circuit components consist of the diode 1N5408G-T, the capacitor 10  $\mu$ F, the isolation transformer TZ-100A, and the IGBT FGA60N65SMD. Figure 6 and Figure 7 show the measured output voltage and the output current during food processing using the proposed multiplier. From Figure 6(a), we confirm that the output voltage reaches 859 V with a rise time of 26.7 seconds, where the input voltage was 100 V at 60 Hz and the clock pulse frequency was 10 kHz. The output voltage was supplied to KEMET corporation capacitors with capacitances of 3300  $\mu$ F ( $1100 \mu$ F  $\times$  3) and rated voltages of 1100

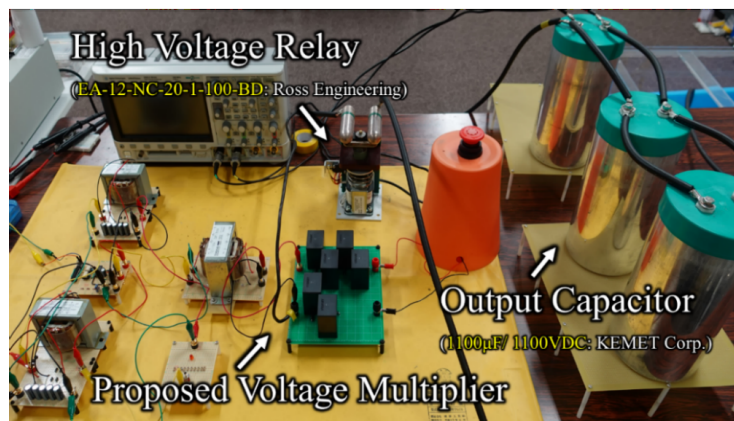


FIGURE 5. Prototype of the proposed multiplier



FIGURE 6. Measured output voltage of multipliers: (a) Proposed and (b) conventional [11]



FIGURE 7. Measured output current of multipliers: (a) Proposed and (b) conventional [13]

TABLE 1. Feature comparison of high voltage multipliers

	Topology	Gain	Speed	Voltage stress
Conventional [11] (2018)	Series-connected Cockcroft-Walton voltage multiplier	28	Fast	$8V_{\max}$
Conventional [12] (2020)	Hybrid Cockcroft-Walton/Dickson multiplier (2 stages $\times$ 6 cells)	24	Slow	$4V_{\max}$
Conventional [13] (2021)	Stacked Dickson multiplier	24	Fast	$4V_{\max}$
Proposed	Bipolar Cockcroft-Walton voltage multiplier	6	Very Fast	$2V_{\max}$

V DC. In contrast, in Figure 6(a), the conventional multiplier can be reached 3.93 kV within a rise time of which is 281 seconds. Therefore, we confirmed that it can reduce the rise time by using the proposed multiplier.

Next, in Figure 7(a), the maximum output current during the discharge process is 22.6 kA. On the other hand, in Figure 7(b) the maximum output current of the conventional multiplier is 23 kA. It is noteworthy that the output current of the proposed multiplier is the same as that of the conventional multipliers. In other words, the proposed multiplier can achieve non-thermal food processing similar to the conventional multipliers. Table 1 compares the output voltage gain, speed, and maximum voltage stress of the conventional and proposed multiplier, respectively. Table 1 indicates that speed of circuit drive of

the proposed multiplier is much faster and lower voltage stress of output capacitor than conventional multipliers. Thereby, we can confirm the feasibility of the proposed multiplier by these results.

**5. Conclusions.** A high-speed bipolar CWVM has been devised in order to develop a non-thermal food processing system utilizing underwater shockwaves suitable for low output voltage conditions. The proposed multiplier can reduce the number of circuit stages compared to conventional CWVM. Moreover, unlike conventional CWVMs, the proposed multiplier is equipped with a high-speed driver. The output gain of the proposed multiplier was clarified by theoretical analysis and experimental results. In the theoretical analysis, we were able to obtain the voltage gain  $m$  is 6 and the internal resistance  $R_{SC}$  is  $8R_d + 18R_{on}$ , respectively. In the experiment, the output voltage was more than 859 V with the voltage gain of 6 and the rise time of 26.7 seconds. In addition, the output current was 22.6 kA. These experimental results confirmed the feasibility of the proposed multiplier.

In future research, we are planning to design a voltage multiplier that can process more quickly under low output voltage conditions.

## REFERENCES

- [1] P. Hartyáni, L. Dalmadi, Z. Cserhalmi, D. B. Kántor, M. T. Markus and A. Sass-Kiss, Physical chemical and sensory properties of pulsed electric field and high hydrostatic pressure treated citrus juices, *Innovative Food Science and Emerging Technologies*, vol.12, no.3, pp.255-260, 2011.
- [2] L. G. Gonzalez, A. H. Geeraerd, S. Spilimbergo, K. Elst, L. V. Ginneken, J. Debevere, J. F. V. Impe and F. Devlieghere, High pressure carbon dioxide inactivation of microorganisms in foods: The past, the present and the future, *International Journal of Food Microbiology*, vol.17, no.1, pp.1-28, 2007.
- [3] 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.
- [4] B. A. Niemira, Cold plasma decontamination of foods, *Annual Review of Food Science and Technology*, vol.3, pp.125-142, 2012.
- [5] P. Sunka, Pulse electrical discharges in water and their applications, *Physics of Plasmas*, vol.8, no.5, 2001.
- [6] A. Oda, N. Okamoto and S. Itoh, Study on the relationship between some foods and underwater shock wave using the explosion of the detonating fuse, *Materials Science Forum*, vol.566, pp.197-202, 2008.
- [7] K. Naha, K. Shimojima, Y. Miyafuji and S. Itoh, Design and development of pressure vessel for improvement of manufacturing rice-powder efficiency using underwater shock wave, *Proc. of the ASME 2012 Pressure Vessels and Piping Conf.*, pp.15-19, 2012.
- [8] S. Shinzato, Y. Higa, T. Tamaki, H. Iyama and S. Itoh, Computational simulation of underwater shock wave propagation using smoothed particle hydrodynamics, *Materials Science Forum*, vol.767, pp.86-91, 2013.
- [9] A. Lamantia, P. Maranesi and L. Radrizzani, The dynamics of the Cockcroft-Walton voltage multiplier, *The 21st Annual IEEE Conference on Power Electronics Specialists*, pp.485-490, 1990.
- [10] S. Iqbal, A hybrid symmetrical voltage multiplier, *IEEE Trans. Power Electronics*, vol.29, no.1, pp.6-12, 2014.
- [11] K. Eguchi, A. Jaiwanglok, A. Julsereewong, F. Asadi, H. Abe and I. Oota, Design of a non-thermal food processing system utilizing wire discharge of dual electrodes in underwater, *International Journal of Innovative Computing, Information and Control*, vol.14, no.3, pp.847-860, 2018.
- [12] S. Park, J. Yang and J. R. Davila, A hybrid Cockcroft-Walton/Dickson multiplier for high voltage generation, *IEEE Trans. Power Electronics*, vol.35, no.3, pp.2714-2723, 2020.
- [13] K. Eguchi, D. Nakashima, T. Ishibashi and I. Oota, Design and experimental evaluation of a stacked Dickson multiplier for shockwave non-thermal food processing, *International Journal of Innovative Computing, Information and Control*, vol.17, no.5, pp.1801-1808, 2021.
- [14] K. Eguchi, D. Nakashima, T. Ishibashi and F. Asadi, A high voltage multiplier using stacked hybrid Cockcroft-Walton/Dickson multipliers, *Journal of Physics: Conference Series*, 2021.

- [15] 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, no.10, pp.113-120, 2022.
- [16] W. Do and K. Eguchi, Analysis of parallel connected Fibonacci switched capacitor converter, *Energy Reports*, vol.6, no.supplement 2, pp.362-367, 2020.
- [17] K. Eguchi, K. Kuwahara and T. Ishibashi, Analysis of an LED lighting circuit using a hybrid buck-boost converter with high gain, *Energy Reports*, vol.6, no.supplement 2, pp.250-256, 2020.

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