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A Bipolar High-Voltage Multiplier Using Switched-Capacitor AC-AC Converters

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Abstract. To provide nutritious and fresh processed foods at low cost, an underwater shockwave has been utilized for non-thermal food processing in recent years. In this paper, we propose an efficient high voltage multiplier in order to generate the underwater shockwave. Unlike conventional Cockcroft-Walton voltage multipliers (CWVMs), the proposed multiplier amplifies the input voltage twice by combining a switched-capacitor (SC) ac-ac converter and a bipolar CWVM in series. The proposed multiplier can achieve smaller size than existing multipliers, because the proposed multiplier requires no full-bridge circuits. Furthermore, owing to the series-connected bipolar topology using an SC ac-ac converter, high step-up gain can be realized with a small number of stages. The operation principle and characteristic evaluation are described concerning the proposed multiplier. Simulation program with integrated circuit emphasis (SPICE) simulations demonstrate the feasibility and effectiveness of the proposed multiplier.

Introduction

Recently, non-thermal food processing is receiving much attention to provide nutritious and fresh foods at low cost. In the non-thermal food processing, the target food in a pressure vessel is destroyed by an underwater shockwave [1,2], where a high voltage multiplier [3-8] is employed to generate the underwater shockwave. Among others, the Cockcroft-Walton voltage multiplier (CWVM) [3] is one of the most promising multipliers, because the CWVM requires no transformer with high turn ratio. Therefore, the CWVM can achieve light and small circuit configuration. For this reason, several types of CWVMs have been proposed in past studies. For example, a bipolar CWVM [4,5] was suggested by Iqbal et al. and Eguchi et al. Unlike a voltage multiplier using center-tapped transformers, the bipolar CWVM [4,5] requires only one ac power source. Following this study, a hybrid symmetrical CWVM [6] was developed by Iqbal in 2014. Owing to the hybrid symmetrical topology, the hybrid symmetrical CWVM can improve the voltage drop and transient response from the conventional converter reported in [4]. However, the response speed of these conventional CWVMs is slow, because the diode switch is driven by a commercial ac power source. To improve the response speed of the hybrid symmetrical CWVM, Eguchi et al. proposed a parallel-connected high voltage multiplier with symmetrical structure [7]. By driving diode switches by high speed two-phase pulses, the CWVM reported in [7] can realize high response speed. However, due to the large number of stages, the CWVMs reported in [3-7] suffer from the voltage drop caused by diode switches. To reduce the number of stages, Eguchi et al. proposed a high voltage multiplier with series-connected bipolar topology [8]. By connecting positive/negative multiplier blocks in series, the CWVM reported in [8] amplifies the input voltage twice. Owing to high step-up gain, the CWVM reported in [8] can reduce the number of stages. However, there is still room for improvement in circuit topology.

In this paper, an efficient high voltage multiplier is proposed for non-thermal food processing. Unlike conventional CWVMs, the proposed CWVM amplifies the input voltage twice by combining a switched-capacitor (SC) ac-ac converter and a bipolar CWVM in series. Therefore, the proposed multiplier can achieve smaller size than existing multipliers, because the proposed multiplier requires no full-bridge circuits. Furthermore, owing to the series-connected bipolar topology using an SC ac-ac converter, high step-up gain can be realized with a small number of stages. To clarify circuit characteristics, simulation program with integrated circuit emphasis (SPICE) simulations and theoretical analysis are performed concerning the proposed CWVM.

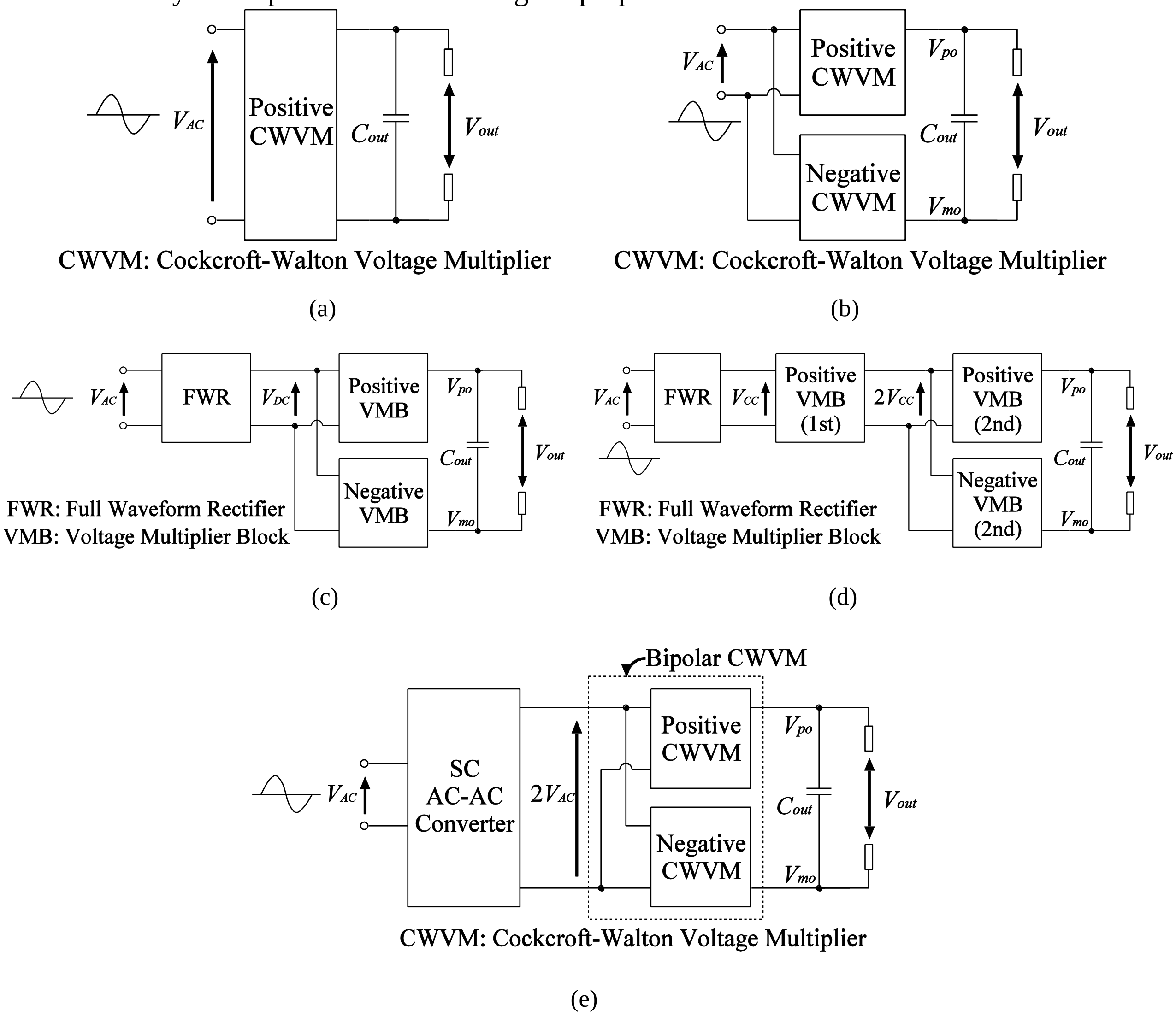

Figure 1. Comparison of block diagrams: (a) Conventional CWVM [3,6]; (b) Conventional CWVM [4,5]; (c) Conventional CWVM [7]; (d) Conventional CWVM [8]; (e) Proposed CWVM.

Proposed High-Voltage Multiplier

Block Diagram

Figure 1 shows the comparison of the block diagram between the proposed CWVM and conventional CWVMs. Unlike conventional CWVMs, the proposed CWVM consists of a switched-capacitor (SC) ac-ac converter and a bipolar CWVM composed of a positive CWVM and a negative CWVM. By connecting an SC ac-ac converter and a bipolar CWVM in series, the proposed CWVM achieves high step-up gain without a full waveform rectifier (FWR).

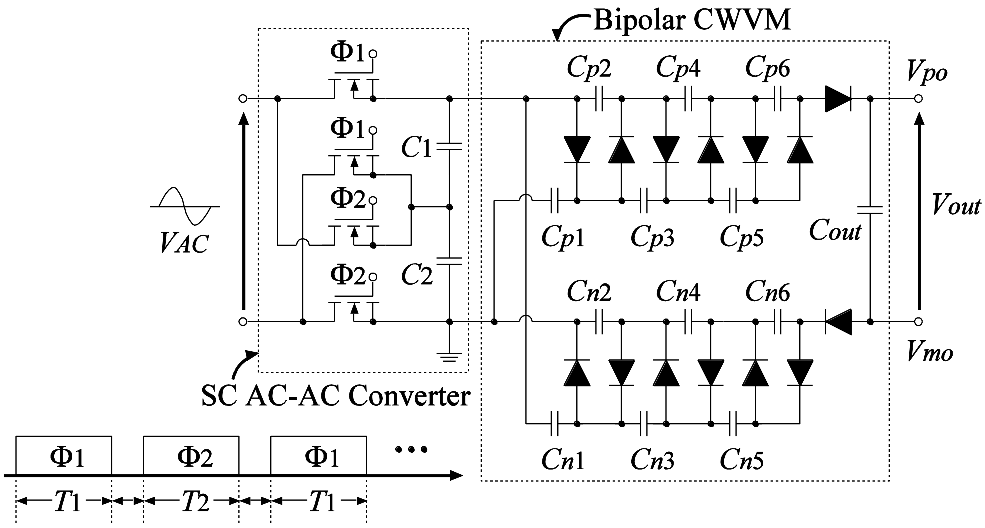

Figure 2. Circuit configuration of the proposed CWVM.

Table 1. Comparison of output voltages.

	Output Voltage
Conventional CWVM [3,6]	$V_{out}=2N(V_{\max}-V_{th})$
Conventional CWVM [4,5,7]	$V_{out}=2N(V_{\max}-V_{th})+(2N)V_{\max}-(2N+1)V_{th}$
Conventional CWVM [8]	$V_{out}=2(2N+1)(V_{\max}-V_{th})+2(2N)(V_{\max}-V_{th})-V_{th}$
Proposed CWVM	$V_{out}=(2N+1)(2V_{\max}-V_{th})+2N(2V_{\max}-V_{th})-V_{th}$

Circuit Configuration

Figure 2 illustrates the circuit configuration of the proposed CWVM. As Figs. 1 and 2 show, the proposed CWVM amplifies the input voltage twice. In the SC ac-ac converter, the input voltage V_{AC} (=100V@60Hz) is charged to C_1 and C_2 by controlling transistor switches by non-overlapped two-phase clock pulses Φ1 and Φ2. Therefore, the input voltage of the bipolar CWVM becomes $2V_{AC}$, because C_1 and C_2 are connected in series. In the bipolar CWVM, the input voltage is converted again. Thus, the outputs V_{po} and V_{mo} become about $14V_{max}$ and $-12V_{max}$, respectively, where V_{max} denotes the maximum value of V_{AC}. Therefore, the following output voltage is stored in the output capacitor C_{out}:

$$V_{out}=26V_{\max}-15V_{th}, \tag{1}$$

where V_{th} denotes the threshold voltage of the diode switch. In the proposed CWVM, the step-up gain is set to 26 in order to generate more than 3.5kV from 100V@60Hz. Because it is known that a 3.5kV output is required to destroy fruits such as apples, lemons, etc.

Table 1 shows the comparison of output voltages between the proposed CWVM and conventional CWVMs. In Table 1, N (=1, 2, …) is the number of stages of the VMB. As Table 1 shows, the proposed CWVM can achieve higher gain than others.

Simulation

To clarify circuit characteristics, SPICE simulations are performed concerning the proposed CWVM of Fig.2 and the traditional CWVM reported in [3]. Figure 3 shows the simulated output voltages of the proposed CWVM. In Fig.3, the SPICE simulation was performed under conditions that V_{AC}= 100V@60Hz, T= 10μs, T_1=T_2= 5μs, C_1= C_2= C_{p1}= ...= C_{p6}= C_{n1}=…= C_{n6}=10μF, and C_{out}=10μF. In Fig.3 (a), the output voltage of the proposed CWVM is 3.67kV. The settling time of the proposed CWVM is less than 7.17s. On the other hand, the output voltage of the traditional CWVM reported in [3] is 3.67kV, where the parameter N was set to 13. The settling time of the traditional CWVM is about 143s. Obviously, the proposed CWVM is much faster than the traditional CWVM reported in [3].

Table 2 shows the comparison of the number of circuit components between the proposed CWVM and conventional CWVMs reported in [3,7,8]. In Table 2, the conventional CWVMs reported in [4,5,6] were omitted, because these CWVMs require transformers. As Table 2 shows, the number of circuit components for the proposed CWVM is smaller than that for the conventional CWVMs [3,7,8] though the conventional CWVMs reported in [7,8] are faster than the proposed CWVM.

Table 2. Comparison of the number of circuit components.

	Number of diodes	Number of capacitors	Number of switches
Conventional CWVM [3]	26	26	0
Conventional CWVM [7]	62	43	4
Conventional CWVM [8]	34	29	8
Proposed CWVM	14	14	4

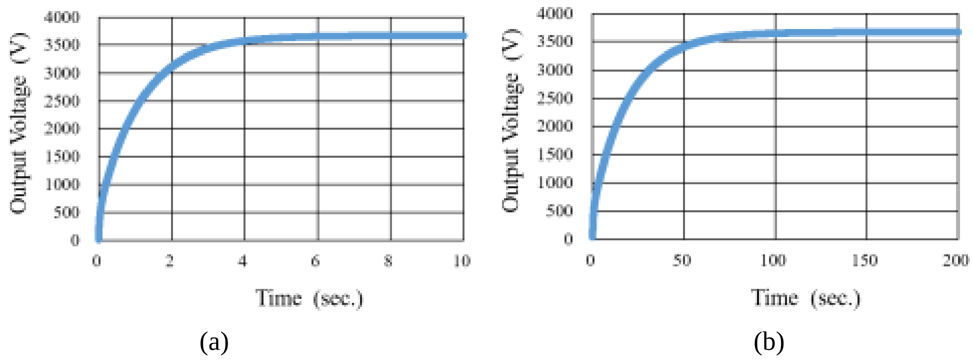

Figure 3. Simulated output voltages: (a) Proposed CWVM; (b) Conventional CWVM. [3]

Conclusion

To generate an underwater shockwave for non-thermal food processing, a bipolar high-voltage multiplier using a switched-capacitor (SC) ac-ac converter has been proposed in this paper. By combining an SC ac-ac converter and a bipolar CWVM in series, the proposed multiplier amplifies the input voltage twice with small number of circuit components.

The operation principle and characteristic evaluation demonstrated the following results. By converting the input voltage 100V@60Hz, about 3.67kV output was generated by the proposed CWVM. When the gain is 26, the number of circuit components for the proposed CWVM was smaller than that for the inductor-less conventional CWVMs. Concretely, the proposed CWVM can be constructed with 14 diodes, 14 capacitors, and 4 transistor switches. Furthermore, the proposed CWVM showed higher response speed than the traditional CWVM. The settling time of the proposed CWVM was less than 7.17 sec.

The detailed experiment of the proposed CWVM is left to a future study.

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