2016 International Conference on Applied Mathematics and Mechanics (ICAMM 2016)
ISBN: 978-1-60595-399-1

Theoretical Analysis of a High Step-up Bipolar Voltage Multiplier

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Keywords: Cockcroft-Walton multipliers, High voltage multipliers, High speed multipliers, Non-thermal food processing, Bipolar step-up voltage multipliers.

Abstract. In previous studies, we proposed the circuit topology of the high step-up bipolar voltage multiplier using level shift drivers for non-thermal food processing and demonstrated the proposed voltage multiplier by the experiments. Unlike a common high voltage multiplier, the proposed voltage multiplier can generate a high voltage at high speed with the small number of circuit components owing to its bipolar structure. In this paper, to clarify the detailed characteristics of the proposed voltage multiplier, theoretical analysis using a four-terminal equivalent circuit and simulation program with integrated circuit emphasis (SPICE) simulations are performed. The theoretical analysis shows the power efficiency and the output voltage as a handy theoretical equations. The validity of the theoretical results is confirmed by comparing with simulated results.

Introduction

In recent years, the non-thermal food processing attracts much researchers' attention [1], because it does not destroy nutrients of foods unlike a general cooking process. Among them, the non-thermal food processing by utilizing an underwater shockwave can be realized at relatively low cost and safety [2]. This non-thermal food processing system mainly consists of a pressure vessel, a high voltage multiplier which can generate more than 3.5kV and an output capacitor with 200μF. In this food processing, the high voltage multiplier has to discharge a high voltage repeatedly so that the underwater shockwave is generated in water. A Cockcroft-Walton voltage multiplier (CWVM) is famous as a traditional voltage multiplier [3]. The CWVM can be built easily, but its operation speed is too slow. Therefore, in order to generate a high voltage at high speed, we proposed the high step-up bipolar voltage multiplier using level shift drivers as a novel high voltage multiplier [4]. The usability of the proposed voltage multiplier has been already confirmed by the experiments, and it is reported in [4]. However, through it is important for non-thermal food processing to clarify the detailed characteristics of the high voltage multiplier, the detailed characteristics has not been clarified.

In this paper, in order to clarify the detailed characteristics of the proposed voltage multiplier in the case of an actual situation, theoretical analysis using a four-terminal equivalent circuit and detailed SPICE simulations are performed. The theoretical analysis shows the power efficiency and the output voltage. The validity of the theoretical results is confirmed by comparing with simulated results.

Circuit Configuration

Figure 1 shows the proposed voltage multiplier. As Figure 1 shows, the proposed voltage multiplier mainly consists of an AC-DC rectifier block, a driver circuit and bipolar voltage multiplier block. The output voltage of the proposed voltage multiplier is expressed as

$$V_{out} = 4N \cdot (4M+1) \cdot V_{in} - \{(4M+1) \cdot (4N+1) + 1\} \cdot V_{th} . \quad (1)$$

In Eq. 1, V_{in} is an input AC voltage, V_{th} is a threshold voltage of diode switches, N is the number of stages of the AC-DC rectifier and M is the number of stages of the bipolar voltage multiplier.

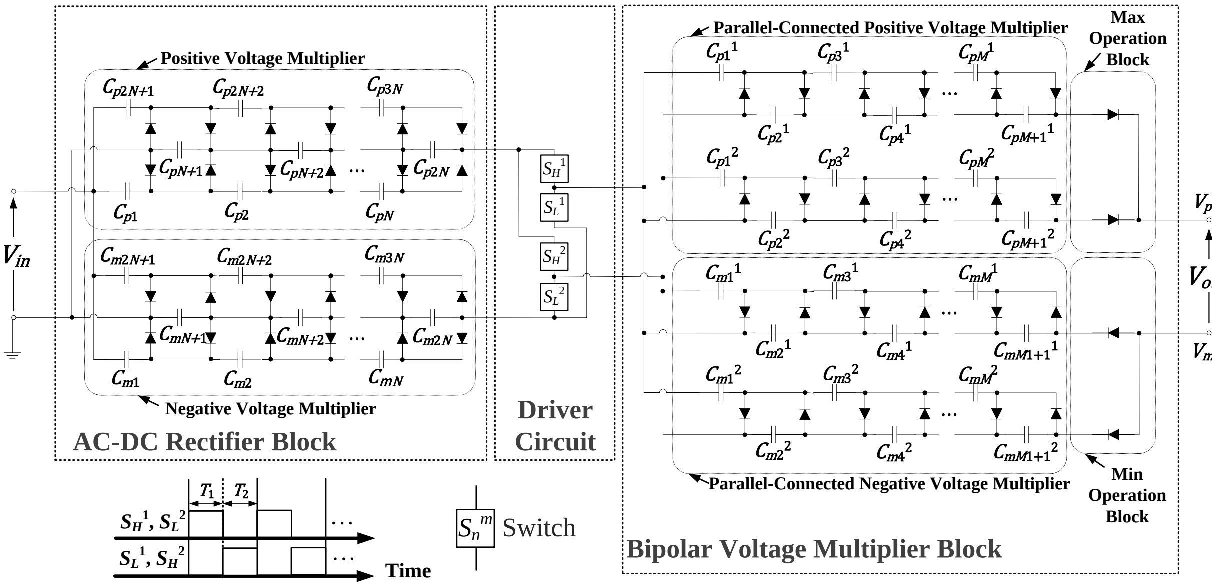


Figure 1. Proposed multiplier.

Owing to the features of the proposed voltage multiplier reported in [4], the proposed voltage multiplier can offer high voltage efficiency, high speed operation and the small number of circuit components when the proposed voltage multiplier generates more than 3.5kV.

Theoretical Analysis

To clarify the characteristics of the proposed voltage multiplier, theoretical analysis in is performed. The proposed voltage multiplier can be assumed as a four-terminal equivalent model reported in [5]. In the theoretical analysis, the AC-DC rectifier block are analyzed separately, because each block is controlled by different periods T_r and T_m, where T_r and T_m are the periods of clock pulses of the AC-DC rectifier block and the bipolar voltage multiplier block. To clarify the characteristics in the case of an actual situation, the number of stages of the proposed voltage multiplier is set to following conditions: the AC-DC rectifier block N = 1, the positive voltage multiplier M_p = 2 and the negative voltage multiplier M_m = 1.

Figure 2 and Figure 3 show the instantaneous equivalent circuits of each block. As Figure 3 shows, the AC-DC rectifier block has two states which are at T_{ri} (i= 1, 2). As Figure 4 shows, the bipolar voltage multiplier block has two states which are T_{mi}, as well. In steady state, the differential value of the electric charge in C_{pj} and C_{mj} (j= 1, 2, 3), which are in the AC-DC rectifier, and C_{pk}^{1}, C_{pk}^{2} (k= 1, 2, 3, 4), C_{ml}^{1} and C_{ml}^{2} (l= 1, 2), which are in the bipolar voltage multiplier block, satisfies

$$\sum_{i=1}^{2}\Delta q_{Tri}^{pj}=0,\quad \sum_{i=1}^{2}\Delta q_{Tri}^{mj}=0,\quad \sum_{i=1}^{2}\Delta q_{Tmi}^{1pk}=0,\quad \sum_{i=1}^{2}\Delta q_{Tmi}^{2pk}=0,\quad \sum_{i=1}^{2}\Delta q_{Tmi}^{1ml}=0 \quad \text{and} \quad \sum_{i=1}^{2}\Delta q_{Tim}^{2ml}=0$$

$$\text{where}\quad T_r=\sum_{i=1}^{2}T_{ri},\quad T_{r1}=T_{r2}=\frac{T_r}{2}\quad \text{and}\quad T_{m1}=T_{m2}=\frac{T_m}{2}. \tag{2}$$

In Eq. 2, Δq_{Tri}^{pj}, Δq_{Tri}^{mj}, Δq_{Tmi}^{1pk}, Δq_{Tmi}^{2pk}, Δq_{Tmi}^{1ml} and Δq_{Tmi}^{2ml} denote the electric charge of the j-th, the k-th or l-th capacitor in State-T_{ri} or State-T_{mi}. In the AC-DC rectifier block, the differential values of electric charges in the outer capacitors in each multiplier are same owing to the symmetrical structure. Then, the bipolar voltage multiplier has two same circuits, which are controlled by the opposite clock pulses. The differential values of electric charges in one capacitor is same as that of another circuit at opposite state. These are shown as follows:

$$\Delta q_{T_{ri}}^{p1}=\Delta q_{T_{ri}}^{p3},\quad \Delta q_{T_{ri}}^{m1}=\Delta q_{T_{ri}}^{m3},\quad \Delta q_{T_{m1}}^{1pk}=\Delta q_{T_{m2}}^{2pk},\quad \Delta q_{T_{m1}}^{2pk}=\Delta q_{T_{m2}}^{1pk},\quad \Delta q_{T_{m1}}^{1ml}=\Delta q_{T_{m2}}^{2ml}\quad \text{and}\quad \Delta q_{T_{m1}}^{2ml}=\Delta q_{T_{m2}}^{1ml}. \tag{3}$$

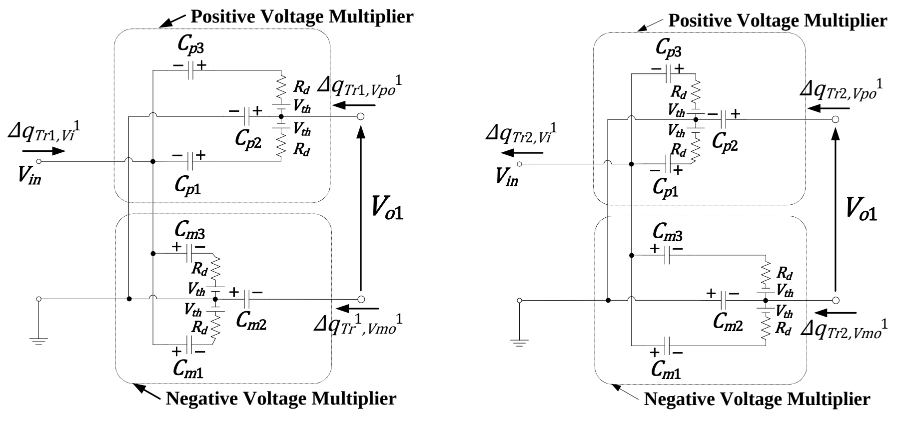


Figure 2. Instantaneous equivalent circuits of the AC-DC rectifier block; (a) State-T_{r1} and (b) State-T_{r2}.

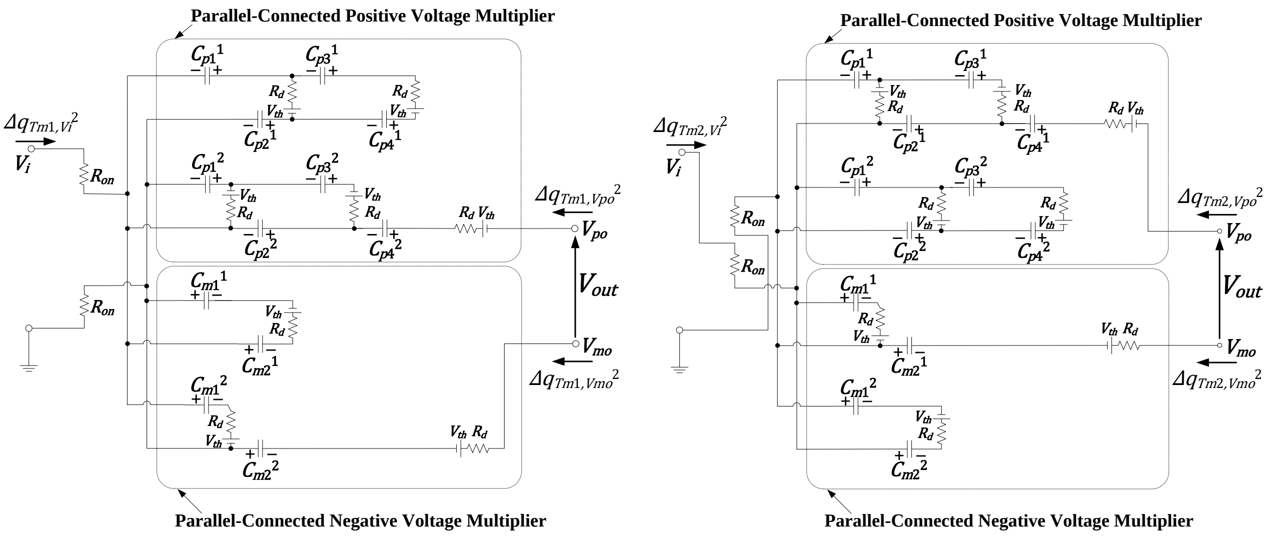


Figure 3. Instantaneous equivalent circuits of the bipolar voltage multiplier block; (a) State-T_{m1} and (b) State-T_{m2}.

From Figure 2 and Figure 3, the differential values of electric charges in V_{in}, V_{o1} (=V_{i2}) and V_{out}, $\Delta q_{Tri,Vin}$, $\Delta q_{Tri,Vpo}{}^1$, $\Delta q_{Tri,Vmo}{}^1$, $\Delta q_{Tmi,Vi}{}^2$, $\Delta q_{Tmi,Vpo}{}^2$ and $\Delta q_{Tmi,Vmo}{}^2$ are given as follows:

State-T_{r1}: $\Delta q_{T_{r1},V_i^1} = -\Delta q_{T_{r1}}^{p1} - \Delta q_{T_{r1}}^{p3} + \Delta q_{T_{r1}}^{m1} + \Delta q_{T_{r1}}^{m3}$,

$$\Delta q_{T_{r1},V_{po}{}^1} = \Delta q_{T_{r1}}^{p1} + \Delta q_{T_{r1}}^{p2} + \Delta q_{T_{r1}}^{p3} \quad \text{and} \quad \Delta q_{T_{r1},V_{mo}{}^1} = -\Delta q_{T_{r1}}^{m2}. \tag{4}$$

State-T_{r2}: $\Delta q_{T_{r2},V_i^1} = \Delta q_{T_{r2}}^{p1} + \Delta q_{T_{r2}}^{p3} - \Delta q_{T_{r2}}^{m1} - \Delta q_{T_{r2}}^{m3}$,

$$\Delta q_{T_{r2},V_{po}{}^1} = \Delta q_{T_{r2}}^{p2} \quad \text{and} \quad \Delta q_{T_{r2},V_{mo}{}^1} = -\Delta q_{T_{r2}}^{m1} - \Delta q_{T_{r2}}^{m2} - \Delta q_{T_{r2}}^{m3}. \tag{5}$$

State-T_{m1}: $\Delta q_{T_{m1},V_i^2} = -\Delta q_{T_{m1}}^{1p1} + \Delta q_{T_{m1}}^{2p1} - \Delta q_{T_{m1}}^{2p2} - \Delta q_{T_{m1}}^{2p3} + \Delta q_{T_{m1}}^{1m2} + \Delta q_{T_{m1}}^{2m1}$,

$$\Delta q_{T_{m1},V_{po}{}^2} = \Delta q_{T_{m1}}^{2p4} \quad \text{and} \quad \Delta q_{T_{m1},V_{mo}{}^2} = -\Delta q_{T_{m1}}^{2m2}. \tag{6}$$

State-T_{m2}: $\Delta q_{T_{m2},V_i^2} = \Delta q_{T_{m2}}^{1p1} - \Delta q_{T_{m2}}^{1p2} - \Delta q_{T_{m2}}^{1p3} - \Delta q_{T_{m2}}^{2p1} + \Delta q_{T_{m2}}^{1m1} + \Delta q_{T_{m2}}^{2m2}$,

$$\Delta q_{T_{2m},V_{po}{}^2} = \Delta q_{T_{m2}}^{1p4} \quad \text{and} \quad \Delta q_{T_{m2},V_{mo}{}^2} = -\Delta q_{T_{m2}}^{1m2} \tag{7}$$

In the equivalent model [5], the average input current and the average output current are expressed as

$$\overline{I_{in}} = \frac{1}{T}\left(\sum_{i=1}^{2}\Delta q_{T_i,V_{in}}\right) = \frac{\Delta q_{V_{in}}}{T} \quad \text{and} \quad \overline{I_{out}} = \frac{1}{T}\left(\sum_{i=1}^{2}\Delta q_{T_i,V_{out}}\right) = \frac{\Delta q_{V_{out}}}{T}. \tag{8}$$

where $\Delta q_{V_{in}}$ and $\Delta q_{V_{out}}$ are electric charges in the input and output of each block. In the each block, two output terminals are connected through the load. Therefore, $\Delta q_{V_{po}^{1}}$ equals to $\Delta q_{V_{mo}^{1}}$, and $\Delta q_{V_{po}^{2}}$ equals to $\Delta q_{V_{mo}^{2}}$. Substituting Eq. 2 to Eq. 5 into Eq. 8, and Eq. 2, Eq. 3, Eq. 6 and Eq. 7 into Eq. 8, we have the relation between the input current and output current as follows:

$$\overline{I_{i^1}} = -4\overline{I_o}^{1} \quad \text{and} \quad \overline{I_{i^2}} = -7\overline{I_{out}}, \quad \text{where} \quad \overline{I_{o^1}} = \overline{I_{po}}^{1} = -\overline{I_{mo}}^{1} \quad \text{and} \quad \overline{I_{out}} = \overline{I_{po}}^{2} = -\overline{I_{mo}}^{2}. \tag{9}$$

From Eq. 9, the parameter m_1 and m_2 are obtained as 4 and 7.

Next, in order to obtain the parameter R_{SC}, let us consider the consumed energy in one period. Using Eq. 2 to Eq. 7, the total consumed energy of each block can be expressed as

$$W_{T_r} = \sum_{i=1}^{2} W_{T_{ri}} = \frac{4R_d}{T_r}\left(\Delta q_{V_{po}^{1}}\right)^2, \quad \text{and} \quad W_{T_m} = \sum_{i=1}^{2} W_{T_{mi}} = \frac{8R_d + 98R_{on}}{T_m}\left(\Delta q_{V_{po}^{2}}\right)^2. \tag{10}$$

From Eq. 10, the parameters R_{SC1} and R_{SC2} are derived as $4R_d$ and $8R_d + 98R_{on}$, because the consumed energy W_T of the four-terminal equivalent model [5] is expressed as $R_{SC} \cdot (\Delta q_{V_{out}})^2 / T$. In the equivalent model, R_{SC1} is connected with primary side of the ideal transformer in the bipolar voltage multiplier block. By moving R_{SC1} into the secondary side of the ideal transformer in the voltage multiplier, R_{SC} is obtained as $204R_d + 98R_{on}$ (= $m_2^2 \times R_{SC1} + R_{SC2}$). Then, the parameter m is derived as 28 (= 4×7).

Finally, by combining m and R_{SC}, the four-terminal equivalent model of the proposed voltage multiplier can be expressed as follows:

$$\begin{bmatrix} \overline{V_{in}} \\ \overline{I_{in}} \end{bmatrix} = \begin{bmatrix} 1/28 & 0 \\ 0 & 28 \end{bmatrix} \begin{bmatrix} 1 & 204R_d + 98R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \overline{V_{out}} \\ -\overline{I_{out}} \end{bmatrix}. \tag{11}$$

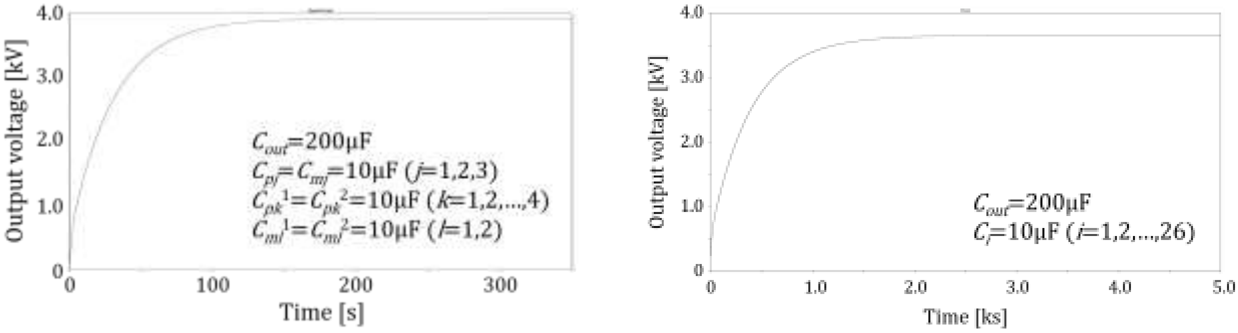
Therefore, we have the efficiency η and output voltage V_{out} as follows:

$$\eta = \frac{R_L}{R_L + (204R_d + 98R_{on})} \times \left(1 - \frac{9V_{th}}{7V_{in}}\right) \quad \text{and} \quad V_{out} = \frac{28R_L}{R_L + (204R_d + 98R_{on})} \times \left(V_{in} - \frac{9}{7}V_{th}\right). \tag{12}$$

Simulation

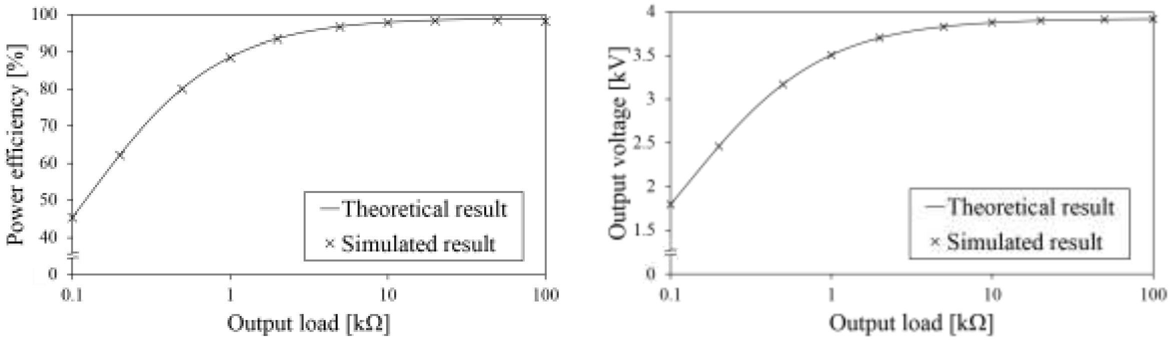
To clarify circuit characteristics, SPICE simulations are performed. Firstly, the property of the proposed voltage multiplier is compared with the conventional CWVM with thirteen stages [3] under the actual condition of the non-thermal food processing. The number of stages of the proposed voltage multiplier is set to the same stages as the theoretical analysis: N = 1, M_p = 2 and M_m =1. Figure 4 shows the simulated output voltages. In the Figure 4 (a), the SPICE simulations were performed under conditions: V_{in} = 100V@50Hz, T_m = 10µs, $C_{pj} = C_{mj} = C_{pk}^{1} = C_{pk}^{2} = C_{ml}^{1} = C_{ml}^{2}$ = 10µF and C_{out} = 200µF, because the capacitance of the output capacitor must be set to 200µF in the actual condition of the non-thermal food processing. As Figure 4 shows, the settling time of the proposed voltage multiplier is less than 250s. On the other hand, the settling time of the conventional CWVM is less than 3,000s. Therefore, the proposed voltage multiplier can generate a high voltage at high speed.

Next, the validity of the theoretical analysis described in Sect.3 is confirmed by SPICE simulations. Figure 5 shows the comparison between the simulated results and the theoretical results in the case of (a) the power efficiency and (b) the output voltage. In the simulation, the power switch modeled by an ideal switch and on-resistance R_{on} = 1Ω. The diode switch modeled by an ideal switch, an on-resistance R_d = 0.1Ω, and a threshold voltage V_{th} = 1V. As Figure 5 shows, the theoretical results are in good agreement with the simulated results. Therefore, the validity of the theoretical analysis was confirmed.



(a) (b)

Figure 4. Simulated output voltage; (a) proposed multiplier and (b) conventional Cockcroft-Walton voltage multiplier.



(a) (b)

Figure 5. Comparison between simulated results and theoretical results; (a) power efficiency and (b) output voltage.

Conclusion

In this paper, the detailed characteristics of a high step-up bipolar voltage multiplier, which was proposed for non-thermal food processing, were confirmed by the theoretical analysis and the SPICE simulations. The results of this study are as follows: (1) the operation speed of the proposed voltage multiplier was more than 10 times faster than that of the conventional CWVM in the actual situation of the non-thermal food processing and (2) the theoretical results were in good agreement with the simulated results. Therefore, the characteristics of the proposed voltage multiplier were confirmed.

Acknowledgement

This work was financially supported by Urakami Foundation for Food and Food Culture Promotion.

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