Design of a High Voltage Multiplier with Series-Connected Bipolar Topology

Kei Eguchi, Kanji Abe, Hiroki Fujisawa, Ichirou Oota

Abstract—Recently, non-thermal food processing utilizing an underwater shockwave has been receiving much attention to provide nutritious and fresh foods at low cost. To generate the underwater shockwave, we propose a series-connected high voltage multiplier with bipolar structure. Unlike conventional Cockcroft-Walton voltage multipliers (CWVMs), the proposed multiplier amplifies the input voltage twice by connecting positive/negative multiplier blocks in series. Furthermore, these multiplier blocks are driven by high speed rectangular pulses. Owing to the series-connected bipolar topology, the proposed multiplier can achieve not only high conversion ratio but also high response speed. 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.

Keywords— bipolar topology, Cockcroft-Walton multipliers, high speed multipliers, non-thermal food processing, series-connected multipliers.

I. Introduction

In past studies, several attempts have been made to develop the efficient CWVM. For example, Wang et al. exhibited a cascade CWVM and its model of parasitic capacitances [6] in 2013. However, it requires a transformer with center-tapped secondary to perform its push-pull kind of operation. Iqbal and Besar proposed a bipolar CWVM [7] in 2007. Unlike a voltage multiplier using center-tapped transformers, the bipolar CWVM reported in [7] requires only one ac power source. Following this study, a hybrid symmetrical CWVM [8] was suggested by Iqbal in 2014. Owing to the hybrid symmetrical topology, the hybrid symmetrical CWVM reported in [8] can improve the voltage drop and transient response from the conventional converter reported in [7]. However, the response speed of these conventional CWVMs is still slow, because the diode switch is driven by a commercial ac power source. To improve the response speed of CWVMs, we proposed a parallel-connected high-speed voltage multiplier [9] in 2014. Using high/low side drivers, the diode switch of the CWVM reported in [9] is driven by high speed rectangular pulses. Therefore, the CWVM reported in [9] can achieve not only high step-up conversion ratio but also high response speed. However, the number of stages is still large.

In this paper, a novel CWVM with series-connected bipolar topology is proposed for non-thermal food processing. By connecting two positive/negative multiplier blocks in series, the proposed CWVM amplifies the input voltage twice. Owing to the series-connected bipolar topology, the proposed CWVM can achieve high conversion ratio with a small number of stages. In other words, the proposed CWVM can generate a high output voltage with small number of circuit components. To clarify circuit characteristics, simulation program with integrated circuit emphasis (SPICE) simulations and theoretical analysis are performed concerning the proposed CWVM.

II. Circuit Configuration

Fig.1 illustrates the block diagram of the CWVMs. Unlike conventional CWVMs, the proposed CWVM consists of a full-waveform rectifier and three voltage multiplier blocks (VMBs). Fig.2 shows an example of the circuit configuration of the proposed CWVM. As Figs.1 and 2 show, the proposed CWVM amplifies the input voltage twice.

The operation principle of the proposed CWVM is as follows: First, the AC input $V_{ac}$ is full-wave rectified by the full-wave rectifier (FWR). Next, the non-overlapped two-phase rectangular pulses $\Phi_1$ and $\Phi_2$ are provided by the clock pulse generator (CPG), where the full-wave rectified voltage $V_{ce}$ is used to generate $\Phi_1$ and $\Phi_2$. Then, the voltage $V_{ce}$...
doubles by the first VMB, where the output voltages of the 1st VMB are denoted by \( V_{o1} \) and \( V_{o2} \). Finally, by amplifying the voltage \( V_{cc} \) again in the 2nd VMBs, the proposed CWVM generates a high stepped-up voltage about 3.5kV. To reduce the ripple output voltage, the 2nd VMBs are connected in parallel.

Table 1 shows the comparison of output voltages between the proposed CWVM and conventional CWVMs. In Table 1, \( N (=1, 2, \ldots) \) is the number of stages of the VMB and \( V_{th} \) denotes the threshold voltage of the diode switch. As Table 1 shows, the step-up gain of the proposed CWVM is higher than that of the conventional CWVMs. Concretely, the gain of the proposed CWVM is about double of that of the conventional multipliers reported in [7] and [9]. In other words, the number of stages of the proposed CWVM is about a half of that of the conventional CWVMs if the step-up gain is same. Therefore, the proposed CWVM can reduce the number of circuit components and circuit volume.

### Table I. Comparison of Output Voltages

<table>
<thead>
<tr>
<th>Output Voltage</th>
<th>Proposed CWVM ((N=3))</th>
<th>Conventional CWVM ([5, 8])</th>
<th>Conventional CWVM ([7, 9])</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{out} )</td>
<td>( V_{out} = 2(2N+1)(V_{cc} - V_{th}) + 2(N)(V_{cc} - V_{th}) - V_{th} )</td>
<td>( V_{out} = 2N(V_{cc} - V_{th}) )</td>
<td>( V_{out} = (2N+1)V_{cc} - (2N+1)V_{th} + (2N)V_{cc} - (2N)V_{th} )</td>
</tr>
</tbody>
</table>

### III. Theoretical Analysis

To analyze the characteristics of the proposed CWVM, theoretical analysis is performed, where the equivalent circuit is assumed as a four-terminal equivalent circuit reported in...
Therefore, we have
\[ Δq_{l,T_1}^{(p)} = \left(\frac{3}{2}\right) Δq_{l,T_1}^{(n)} = 3Δq_{l,T_1}^{(p)} \] (8)
\[ = -Δq_{l,T_1}^{(n)} = \left(-\frac{3}{2}\right) Δq_{l,T_1}^{(p)} = -3Δq_{l,T_1}^{(p)} . \]

On the other hand, the following equations are satisfied in the negative converter blocks:
\[
\Delta q_{ij}^{m} = \Delta q_{ij}^{s} + \Delta q_{ij}^{o} , \quad (9)
\]

\[
\Delta q_{ij}^{s} = \Delta q_{ij}^{w} + \Delta q_{ij}^{l} - \Delta q_{ij}^{s,3,3} ,
\]

\[
\Delta q_{ij}^{o} = -\Delta q_{ij}^{s,3,3} = \Delta q_{ij}^{w} + \Delta q_{ij}^{l} - \Delta q_{ij}^{w,3,3} ,
\]

and \( \Delta q_{ij}^{s,3,3} = \Delta q_{ij}^{v,3,3} . \)

Therefore, we have
\[
\Delta q_{ij}^{s,3,3} = \left( \frac{3}{2} \right) \Delta q_{ij}^{s} = 3 \Delta q_{ij}^{s,3,3} . \quad (10)
\]

Using (3) – (6), the average input current and the average output currents can be obtained as
\[
I_{cc} = \frac{\Delta q_{Vcc}}{T} = \frac{1}{T} \sum_{i=1}^{4} \Delta q_{T_i, Vcc} , \quad (11)
\]
\[
I_{po} = \frac{\Delta q_{Vpo}}{T} = \frac{1}{T} \sum_{i=1}^{4} \Delta q_{T_i, Vpo} ,
\]
\[
I_{mo} = \frac{\Delta q_{Vmo}}{T} = \frac{1}{T} \sum_{i=1}^{4} \Delta q_{T_i, Vmo} ,
\]

and \( \Delta q_{Vc} = \Delta q_{Vpo} = -\Delta q_{Vmo} . \)

In (11), \( \Delta q_{Vcc}, \Delta q_{Vpo}, \) and \( \Delta q_{Vmo} \) are electric charges in \( V_{cc}, V_{po}, \) and \( V_{mo}, \) respectively. Substituting (3) – (10) into (11), we have the relation between the input current and the output currents as follows:
\[
I_{cc} = -14I_{po} + 12I_{mo} , \quad (12)
\]

where
\[
\Delta q_{Vc} = -14\Delta q_{Vpo} + 12\Delta q_{Vmo} = -26\Delta q_{Vc} .
\]

Next, let us consider the consumed energy \( W_f \) in one period. Using (1) – (10), the consumed energy \( W_f \) can be expressed as
\[
W_f = \sum_{i=1}^{4} W_i = 2W_i , \quad (13)
\]
where
\[
W_i = \frac{521}{2(1-2\delta)^{3/2}} R_j + \frac{1183}{2(1-2\delta)^{3/2}} R_m .
\]

In (13), \( W_f \) denotes the consumed energy in State-\( T_i \). Here, the consumed energy \( W_f \) of the four-terminal equivalent circuit is defined as
\[
W_f := \left( \frac{\Delta q_{Vmo}}{T} \right)^2 \cdot R_{sc} \cdot T . \quad (14)
\]

Therefore, from (13) and (14), we have the SC resistance as follows:
\[
R_{sc} = \left( \frac{521}{2(1-2\delta)^{3/2}} R_j + \frac{1183}{2(1-2\delta)^{3/2}} R_m \right) . \quad (15)
\]

By combining (12) and (15), the equivalent circuit of the proposed CWVM can be obtained as Fig.5. The equivalent circuit of Fig.5 is expressed by the following K-matrix:

\[
\begin{bmatrix}
V_{cc} - 27V_{th} \\
26V_{cc} - 27V_{th}
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 1 & V_{out}
\end{bmatrix} \cdot \begin{bmatrix}
I_{cc} \\
I_{po} \\
I_{mo}
\end{bmatrix} . \quad (16)
\]

From (16), the output voltage and power efficiency of the proposed CWVM are obtained as
\[
V_{out} = \begin{bmatrix}
R_i \over R_i + R_{sc}
\end{bmatrix} (26V_{cc} - 27V_{th}) , \quad (17)
\]

and
\[
\eta = \begin{bmatrix}
R_i \over R_i + R_{sc}
\end{bmatrix} \frac{26V_{cc} - 27V_{th}}{26V_{cc}} . \quad (18)
\]

Figure 5. Equivalent circuit of the proposed CWVM

Figure 6. Traditional CWVM

Figure 7. Simulated voltage of VMBs

iv. Simulation

To clarify circuit characteristics, SPICE simulations are performed concerning the proposed CWVM of Fig.2 and the traditional CWVM shown in Fig.6. Fig.7 shows the simulated output voltages of the VMBs in the proposed CWVM. In
Fig. 7, the SPICE simulation was performed under conditions that $N=3$, $V_{ac}=100V@60Hz$, $T=10\mu s$, $T_s=4.5\mu s$, $\delta=0.05$, $C_p^1=C_p^2=C_p^{m1}=C_p^{m2}=10\mu F$, and $C_{out}=100\mu F$. As Fig. 7 shows, the input voltage $V_{cc}$ is converted twice by the VMBs (see Fig. 2).

Fig. 8 shows the simulated output $V_{out}$ of the CWVM. In Fig. 8 (a), the output voltage of the proposed CWVM is 3.39kV. The settling time of the proposed CWVM is less than 80ms. On the other hand, the output voltage of the traditional CWVM is 3.38kV, where the parameter $N$ was set to 12. The settling time of the traditional CWVM is much shorter than that of the traditional CWVM. Obviously, the settling time of the proposed CWVM is less than 90s. The settling time of the proposed CWVM is less than 80ms.

**Acknowledgment**

This research is supported by a grant from Urakami Foundation for Food and Food Culture Promotion.

**References**


**iv. Conclusion**

For non-thermal food processing, a novel CWVM with series-connected bipolar topology has been proposed in this paper. Owing to the series-connected bipolar topology, the proposed CWVM can achieve higher step-up gain than conventional CWVMs.

The validity of circuit design was confirmed by SPICE simulations. By converting the input voltage 100V@60Hz, about 3.5kV was generated by the proposed CWVM. The proposed CWVM can offer about 3.5kV output with a smaller number of stages than the traditional CWVM. Furthermore, the proposed CWVM can achieve high response speed. The settling time of the proposed CWVM is less than 80ms.