A High-Speed Bipolar Hybrid Cockcroft–Walton/Dickson Multiplier for Shockwave Non-thermal Food Processing

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Abstract. For the design of shockwave non-thermal food processing systems, a novel high-speed bipolar voltage multiplier is presented in this paper. Unlike conventional high voltage multipliers, the proposed voltage multiplier has bipolar topology employing hybrid Cockcroft-Walton/Dickson multipliers (HCWDMs), where the bipolar HCWDM is driven by a driver circuit generating high speed rectangular pulses. Therefore, the proposed multiplier can achieve high speed operation. Through simulation program with integrated circuit emphasis (SPICE) simulations and experiments, the validity of the proposed multiplier is confirmed. The SPICE simulations and experiments reveal that the proposed multiplier outperforms the conventional HCWDM.

1. Introduction
Recently, shockwave non-thermal food processing [1, 2] attracts many researchers’ attention to provide nutritious foods at low cost. In the design of the shockwave non-thermal food processing system, a high voltage multiplier is one of the most important components. For example, high voltages, such as 3.7 kV and 3.5 kV, are used to process rice powder and apple juice, respectively. For this reason, several types of high voltage multipliers have been designed in past studies, where the Cockcroft–Walton voltage multiplier (CWVM) [3] and its families, such as bipolar CWVM [4], hybrid symmetrical CWVM [5], series-connected CWVM [6], modified series-connected bipolar CWVM [7, 8], and high-speed bipolar voltage multiplier [9], are usually employed. However, it is known that the output voltage of the CWVM decreases as the number of multiplier stages increases. To overcome this problem, Park et al. proposed the hybrid Cockcroft–Walton/Dickson multiplier (HCWDM) [10], where low output voltage drop and low capacitor voltage stress are achieved by the combination of the CWVM and the Dickson multiplier [11, 12]. However, there is still room for improvement, because the response speed of the HCWDM is slow.

In this paper, we present a novel high-speed bipolar voltage multiplier to design shockwave non-thermal food processing systems. Unlike conventional multipliers, the proposed multiplier has the following features: i) bipolar topology employing HCWDMs and ii) high speed operation of the HCWDMs using a high-speed driver. These features enable the high-speed operation of the proposed multiplier. Concerning the proposed multiplier with the voltage gain of 28, simulations and experiments are performed to confirm the feasibility of the proposed multiplier.
2. Circuit configuration

Fig. 1 illustrates the circuit configuration of the conventional HCWDM [10]. As a simple example, \((2 \times N)\) HCWDM is shown in Fig. 1. Unlike CWVMs, the conventional HCWDM arranges some capacitors in parallel and others in series. However, the response speed is slow, because the conventional HCWDM is driven directly by a commercial power supply. Furthermore, the number of multiplier stages significantly increases, because high voltage gain is required for shockwave non-thermal food processing. To overcome these problems, a novel high-speed bipolar voltage multiplier is proposed as shown in Fig. 2. As this figure shows, the proposed multiplier is composed of an isolation transformer, two full waveform rectifiers (FWRs), a pulse generator, and a bipolar HCWDM. First, the dc voltages \(V_{\text{max}}\) and \(-V_{\text{max}}\) are generated by the full-wave rectifiers (FWRs), where \(V_{\text{max}}\) denotes the amplitude of the ac input. Next, high speed two-phase clock pulses with the amplitude of \(2|V_{\text{max}}|\) are provided to the bipolar HCWDM by driving IGBT switches by the clock pulses \(\Phi_1\) and \(\Phi_2\). Finally, the dc output voltages \(16|V_{\text{max}}|\) and \(-12|V_{\text{max}}|\) are produced by the positive and negative modules, respectively. By combining these output voltages, about 3.9 kV \((= 100\sqrt{2} \times 12)\) is offered to the output capacitor \(C_{\text{out}}\).

3. Analysis of voltage gain

In this section, the voltage gain of the proposed bipolar HCWDM will be analyzed theoretically, where we assume that the time constant is much larger than the period of \(\Phi_1\) and \(\Phi_2\). In a steady state condition, the instantaneous equivalent circuits of the proposed bipolar HCWDM can be expressed as Fig. 3. In this figure, the variation of electric charge in the capacitors \(C_{pi}(i = 1, \ldots, 16)\) and \(C_{mj}(j = 1, \ldots, 12)\) [13, 14] satisfies

\[ V_{\text{out}} = V_{\text{ac}} \]

\[ 1 : 1 \]

\[ \text{Isolation Trans.} \]

\[ \text{1st cell (2 stages)} \]

\[ \text{2nd cell (2 stages)} \]

\[ \text{N-th cell (2 stages)} \]

\[ \text{Vout} \]

\[ \text{Vac} \]

\[ 1 : 1 \]

\[ \text{Isolation Trans.} \]

\[ \text{FWR} \]

\[ \text{Pulse Generator} \]

\[ \Phi_1 \]

\[ \Phi_2 \]

\[ Q_1 \]

\[ Q_2 \]

\[ T_1 \]

\[ T_2 \]

\[ \ldots \]

\[ \text{C}_{p1} \]

\[ \text{C}_{p2} \]

\[ \text{C}_{p3} \]

\[ \text{C}_{p4} \]

\[ \text{C}_{p5} \]

\[ \text{C}_{p6} \]

\[ \text{C}_{p7} \]

\[ \text{C}_{p8} \]

\[ \text{C}_{p9} \]

\[ \text{C}_{p10} \]

\[ \text{C}_{p11} \]

\[ \text{C}_{p12} \]

\[ \text{C}_{p13} \]

\[ \text{C}_{p14} \]

\[ \text{C}_{p15} \]

\[ \text{C}_{p16} \]

\[ \text{C}_{m1} \]

\[ \text{C}_{m2} \]

\[ \text{C}_{m3} \]

\[ \text{C}_{m4} \]

\[ \text{C}_{m5} \]

\[ \text{C}_{m6} \]

\[ \text{C}_{m7} \]

\[ \text{C}_{m8} \]

\[ \text{C}_{m9} \]

\[ \text{C}_{m10} \]

\[ \text{C}_{m11} \]

\[ \text{C}_{m12} \]

\[ \text{C}_{m13} \]

\[ \text{C}_{m14} \]

\[ \text{C}_{m15} \]

\[ \text{C}_{m16} \]

\[ \text{Vout} \]

\[ \text{V}_{\text{pout}} \]

\[ \text{V}_{\text{mout}} \]

\[ \text{Positive Module} \]

\[ \text{Negative Module} \]

**Figure 1.** Conventional hybrid Cockcroft-Walton/Dickson multiplier [10].

**Figure 2.** Proposed high voltage multiplier.
Applying Kirchhoff's current law for Fig. 3, the variation of the electric charge in the input and output terminals, $\Delta q_{T_k,\text{pin}}$, $\Delta q_{T_k,\text{pout}}$ and $\Delta q_{T_k,\text{min}}$, and $\Delta q_{T_k,\text{mout}}$ ($k=1,2$) is obtained as

$$\Delta q_{T_1,\text{pin}} = -\Delta q_{T_1}^{p1} - \Delta q_{T_1}^{p3},$$

and

$$\Delta q_{T_2,\text{pin}} = \Delta q_{T_1}^{p15} + \Delta q_{T_1}^{p16},$$

where

$$\Delta q_{T_1}^{p1} + \Delta q_{T_1}^{p2} = \Delta q_{T_1}^{p5} + \Delta q_{T_1}^{p6}$$

$$= \Delta q_{T_1}^{p9} + \Delta q_{T_1}^{p10} = \Delta q_{T_1}^{p13} + \Delta q_{T_1}^{p14} = 0.$$  \hspace{1cm} (3)

and

$$\Delta q_{T_2,\text{pout}} = \Delta q_{T_2}^{p1} + \Delta q_{T_2}^{p3},$$

where

$$\Delta q_{T_2}^{p14} + \Delta q_{T_2}^{p15} = 0.$$  \hspace{1cm} (5)

and

$$\Delta q_{T_2,\text{min}} = \Delta q_{T_1}^{m1} + \Delta q_{T_1}^{m3}$$

and

$$\Delta q_{T_2,\text{mout}} = -\Delta q_{T_1}^{m12},$$

where

$$\Delta q_{T_1}^{m10} + \Delta q_{T_1}^{m11} = 0.$$  \hspace{1cm} (7)

$$\Delta q_{T_2,\text{min}} = -\Delta q_{T_1}^{m1} - \Delta q_{T_2}^{m3}$$

Figure 3. Instantaneous equivalent circuits of the proposed bipolar HCWDM: (a) State-$T_1$ ($\Phi_1$ is high and $\Phi_2$ is low); (b) State-$T_2$ ($\Phi_1$ is low and $\Phi_2$ is high).
and
\[ \Delta q_{T2,v_{\text{mout}}} = -\Delta q_{T2}^{m11} - \Delta q_{T2}^{m12}. \]  

Where
\[ \Delta q_{T2}^{m1} + \Delta q_{T2}^{m2} = \Delta q_{T2}^{m5} + \Delta q_{T2}^{m6} \]
\[ = \Delta q_{T2}^{m9} + \Delta q_{T2}^{m10} = 0. \]  

Furthermore,
\[ \Delta q_{T2}^{p2} + \Delta q_{T2}^{p3} = \Delta q_{T2}^{p5} + \Delta q_{T2}^{p7}, \]
\[ \Delta q_{T2}^{p6} + \Delta q_{T2}^{p7} = \Delta q_{T2}^{p9} + \Delta q_{T2}^{p11}, \]

and
\[ \Delta q_{T2}^{p10} + \Delta q_{T2}^{p11} = \Delta q_{T2}^{p13} + \Delta q_{T2}^{p15}. \]

And
\[ \Delta q_{T1}^{m2} + \Delta q_{T1}^{m3} = \Delta q_{T1}^{m5} + \Delta q_{T1}^{p7} \]
\[ \Delta q_{T1}^{m6} + \Delta q_{T1}^{m7} = \Delta q_{T1}^{m9} + \Delta q_{T1}^{m11}. \]  

Since the proposed bipolar HCWDM has symmetrical structure, the following conditions are satisfied:
\[ \Delta q_{T1}^{p1} = \Delta q_{T1}^{p5} = \Delta q_{T1}^{p9} = \Delta q_{T1}^{p13} \]
\[ = -\Delta q_{T1}^{p2} = -\Delta q_{T1}^{p6} = -\Delta q_{T1}^{p10} = -\Delta q_{T1}^{p14}. \]  

And
\[ \Delta q_{T1}^{p3} + \Delta q_{T1}^{p4} = \Delta q_{T1}^{p7} + \Delta q_{T1}^{p8} \]
\[ = \Delta q_{T1}^{p11} + \Delta q_{T1}^{p12} = \Delta q_{T1}^{p15} + \Delta q_{T1}^{p16} = 0. \]
\[ \Delta q_{T1}^{m1} = \Delta q_{T1}^{m5} = \Delta q_{T1}^{m9} = -\Delta q_{T1}^{m2} = -\Delta q_{T1}^{m6} = -\Delta q_{T1}^{m10} \]
\[ = \Delta q_{T1}^{m11} + \Delta q_{T1}^{m12} = 0. \]  

By rearranging (1) - (15), we have the relationship between the input and output currents, $I_{\text{pin}}$, $I_{\text{pout}}$, $I_{\text{min}}$, and $I_{\text{mout}}$, as
\[ I_{\text{pin}} = -16I_{\text{pout}} \quad \text{and} \quad I_{\text{min}} = 12I_{\text{mout}}, \]  

because the input and output currents [13, 14] can be expressed as
\[ TI_{\text{pin}} = \Delta q_{T1,v_{\text{pin}}} + \Delta q_{T2,v_{\text{pin}}}, \]
\[ TI_{\text{pout}} = \Delta q_{T1,v_{\text{pout}}} + \Delta q_{T2,v_{\text{pout}}}, \]
\[ TI_{\text{min}} = \Delta q_{T1,v_{\text{min}}} + \Delta q_{T2,v_{\text{min}}}, \]
\[ TI_{\text{mout}} = \Delta q_{T1,v_{\text{mout}}} + \Delta q_{T2,v_{\text{mout}}}. \]  

Figure 4. Comparison of simulated transient characteristics: (a) proposed multiplier; (b) conventional HCWDM [10].
In (17), $T$ denotes the period of $\Phi_1$ and $\Phi_2$. From (16), we get $I_{in} = -28I_{out}$, because

$$I_{in} = I_{pin} + I_{min} \quad \text{and} \quad I_{pout} = -I_{mout} = I_{out},$$

Therefore, the output voltage can be obtained as $V_{out} = 28 \mid V_{max} \mid$ when we assume that the proposed multiplier is a lossless circuit. In other words, the voltage gain is 28. To save space, the loss analysis of the proposed bipolar HCWDM is omitted. The loss analysis is left to a future study.

4. Simulation

To clarify the effectiveness of the proposed multiplier, the performance comparison was conducted between the proposed multiplier and the conventional HCWDM [10]. Fig. 4 demonstrates the simulated transient characteristics when the voltage gain is 12 and the voltage stress is $4V_{max}$. In this figure, the SPICE simulations were conducted under the conditions that $V_ac = 100$ V at 60 Hz, $C_{pj} = C_{mj} = 1 \mu F$, $C_{out} = 200 \mu F$, $T = 100 \mu s$, and $R_d = 0.1 \Omega$. As it can be seen from Fig. 4, the proposed multiplier is faster than the conventional HCWDM [10], because i) the number of multiplier stages of the proposed multiplier is smaller than that of the conventional HCWDM and ii) the proposed bipolar HCWDM is driven by high-speed clock pulses. Concretely, the rise time of the proposed multiplier is about 12 s. On the other hand, the rise time of the conventional HCWDM is about 4010 s.

5. Experiment

To confirm the feasibility of the proposed multiplier, experiments were conducted on the experimental circuit shown in Fig. 5. In this figure, the experimental circuit was built with the circuit components, such as the diode 1N4007, the driver IC IR2110PBF, the IGBT GT50JR22, and the film capacitor 1 $\mu F$.

Fig. 6 demonstrates the measured transient characteristic of the experimental circuit, where the input voltage was set to 100V at 60Hz and the frequency of the clock pulses was set to 10kHz. In this experiment, the output voltage is provided to the output capacitor produced by TOEI corporation, where the capacitance is 200$\mu$F and the rated voltage is 4000V DC. As it can be seen from Fig. 6, the output voltage reaches 3.94 kV and the rise time is 97.4 s. From these results, the feasibility of the proposed multiplier can be confirmed.

6. Conclusion

To design shockwave non-thermal food processing systems, a novel high-speed bipolar voltage multiplier has been designed by employing the HCWDMs. The characteristics of the proposed multiplier was evaluated by SPICE simulations and experiments. The simulated results demonstrated that the proposed multiplier is faster than the conventional HCWDM. In the performed experiments, the output voltage of the proposed multiplier with the voltage gain of 28 reached more than 3.9 kV, where the rise time was less than 98 sec.
7. References

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