Pulse width Modulation Control a Switched-Capacitor Dickson Charge Pumps for High Voltage High Power Applications

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ABSTRACT—Paper presents a switched-capacitor charge pumps circuit base on a Dickson charge pumps that focus on an output voltage controllable by PWM at power scale more than 50W and voltage above 200V. This research changes a Dickson’s digital switches by a full-bridge power MosFets switches in order to achieve an expected power. A 16 stages 50 kHz 300V output voltage PWM regulated Dickson charge pumps was designed and tested to supply the power under 500 mA pure resistive load condition. From experimental results, the maximum voltage conversion efficiency and voltage regulation are 62.5% and 2.66%. Then, the designer can be applied a Dickson charge pumps with PWM technique to a high voltage high power applications for another choices.

Keywords: Charge pumps circuits, Full-bridge power converter, MosFets switches, HVDC power supply.

I. INTRODUCTION

In high voltage power applications such as accelerator, laser power supply, insulation testing etc., a need of novel high voltage power supply becomes widely. In principle, voltages higher than that of the power supply input can be generated in electronics circuits using charge pumps that shown in Figure 1 [1]. Among many approaches to the charge pumps design, the switch-capacitor circuits such as Dickson charge pumps is a classic solution in many electronics application [2]-[4]. The Dickson charge pumps circuit is currently used for rewrite data and to switch MOS transistor in EEPROM’s memory cells [5] and usually operates at high frequency level in order to increase their output power and efficiency within a reasonable size of total capacitance that used for charge transfer.

Figure 1: Schematic representation of a voltage elevator.
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However, Most of Dickson circuits are normally designed for very low power applications [6]. There are a few researches that discuss about Dickson charge pumps with voltage higher than 100 V and the power more than 50W. Therefore, this research tries to use a basic structure of Dickson charge pumps to generate a high voltage at high power level. The principle of n-stages Dickson charge pumps circuit is shown in Figure 2 with voltage gain $A_V = n$ and having a driving clocks of the circuit in Figure 3. To increase the power of Dickson’s circuit in this paper, a digital INV switches in Figure 2 would be replaced with a full-bridge power MosFets switches as shown in Figure 4.

II. DICKSON CHARGE PUMPS ANALYSIS

The basic structure of n-stages of Dickson circuit in Figure 2 can rewrite to a practical circuit as shown in Figure 5 and its n-stages equivalent circuit is shown in Figure 6 [7]-[8].
The circuit in Fig. 5 consists of two pumping switches, SW\textsubscript{1} and SW\textsubscript{2}, which are out of phase and have a voltage of V\textsubscript{in}.

The charge pumps circuit operates by pumping a charge along the diode chain as the capacitors are successively charged and discharged during each cycle. When SW\textsubscript{1} goes low, diode D\textsubscript{1} conducts until the voltage of capacitor at node 1 becomes

\[ V_{C1} = V_{in} - V_{d} \]  

and when SW\textsubscript{1} switched to V\textsubscript{in}, the voltage at node 1 now becomes

\[ V_{C1} = V_{in} + (V_{in} - V_{d}) \]  

At this time, diode D\textsubscript{2} conduct until the capacitor’s voltage at node 2 equal to

\[ V_{C2} = V_{in} + (V_{in} - V_{d}) - V_{d} \]  

When SW\textsubscript{1} goes low again, the capacitor’s voltage at node 2 becomes

\[ V_{C2} = V_{in} + 2(V_{in} - V_{d}) \]  

For Dickson n-stages, the high-voltage output becomes

\[ HV_{out} = V_{in} + n(V_{in} - V_{d}) - V_{d} \]  

Under load condition I\textsubscript{out} and stray capacitance C\textsubscript{s}, the actual output voltage of Dickson charge pumps circuit becomes

\[ HV_{out} = V_{in} + n \left( \frac{C}{C + C_{s}} \cdot V_{in} - V_{d} - \frac{I_{out}}{(C + C_{s}) \cdot f_{SW}} \right) - V_{d} \]
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The voltage drop on a power diode can be neglected for high-voltage output. Hence, the output voltage under load condition now becomes

\[HV_{out} = V_n + n \left( \frac{C}{C + C_S} V_n - \frac{I_{out}}{(C + C_S) \cdot f_{SW}} \right)\]  

(7)

Consider from equivalent circuit in Fig.6, we can write

\[HV_{out} = V_o - I_{out} R_S\]  

(8)

and we found [2]

\[R_S = \frac{n}{(C + C_S) \cdot f_{SW}}\]  

(9)

and

\[V_o = V_n + n \left( \frac{C}{C + C_S} V_n - V_d \right) - V_d\]  

(10)

\(V_o\) and \(R_S\) are the open circuit output voltage and output series resistance of the multiplier respectively. Hence, the high-voltage output is equal to

\[HV_{out} = V_n + n \left( \frac{C}{C + C_S} V_n - \frac{n I_{out}}{(C + C_S) \cdot f_{SW}} \right)\]  

(11)

Equation (11) is similar to Equation (7) and we neglected the stray capacitance \(C_S\), we found [9]

\[HV_{out} = (n+1) V_n - \frac{n I_{out}}{C \cdot f_{SW}}\]  

(12)

From equivalent circuit Figure 6, \(C_{out}\) is sufficiently large for the ripple voltage \(V_R\) to be small compare to \(HV_{out}\), so that

\[V_R = \frac{I_{out}}{f_{SW} C_{out}} = \frac{HV_{out}}{f_{SW} R_C C_{out}}\]  

(13)

or

\[C_{out} = \frac{HV_{out}}{f_{SW} R_C V_R}\]  

(14)

The ripple voltage can be substantially reduced by increasing the frequency of the switches or using a large output capacitance. In the latter case, it would take the charge pumps significantly longer to reach steady state.

For switches section, In order to increase the power of Dickson charge pumps circuit, a pumping digital’s clock switches as shown in Figure 2 were replaced by full-bridge power MosFets switches as shown in Figure 4. Then, the maximum current handle of the MosFets main switches is equal to [10]

\[I_{peak,SW} = \frac{(1.6) P_{out}}{V_{CC}}\]  

(15)

As same as \(C_{out}\), a value of an input capacitor \(C_S\) to maintain energy transferred to the switches for minimum ripple voltage is [11]

\[C_S = \frac{2 \cdot t \cdot P_{out}}{V_R \cdot \eta \cdot V_{CC}}\]  

(16)

where \(t\) = charging time of a capacitor
III. PWM IN DICKSON CHARGE PUMPS CIRCUIT

PWM is a method for controlling the average output voltage by switching a voltage on and off at a constant frequency giving a switching time period as

$$T_s = t_{on} + t_{off} \quad (17)$$

By adjusting the $t_{on}$ and $t_{off}$ durations, it will create a switching ratio known as the duty-cycle ($D$) and defined as

$$D = \frac{t_{on}}{T_s} \quad (18)$$

The general form of a full-bridge converter with PWM controlling is shown in figure 7. With PWM controlling, the output voltage of a converter is

$$V_o = \frac{2D}{n} \times V_{CC} \quad (19)$$

where $n$ is a turn ratio of a high-frequency transformer.

For Dickson charge pumps circuit with PWM control, the turn ratio is in the form of number of stage. Then, the output voltage of the Dickson circuit becomes Equation (20) and the circuit diagram of PWM Dickson charge pumps circuit is shown in figure 8.

$$H V_{out} = \left( n + 1 \right) \cdot V_{in} - \frac{n I_{out}}{C \cdot f_{SW}} \times D \quad (20)$$
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Figure 8: PWM Dickson charge pumps circuit.

IV. EXPERIMENT AND RESULTS

The high-voltage high power Dickson charge pumps proposed in this paper has been designed on rating as follow.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>30 V.</td>
</tr>
<tr>
<td>Output voltage</td>
<td>300 V.</td>
</tr>
<tr>
<td>Output current</td>
<td>0.5 A.</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>50 kHz.</td>
</tr>
<tr>
<td>Output ripple voltage</td>
<td>200 mV.</td>
</tr>
<tr>
<td>Dickson’s pumping stage</td>
<td>16</td>
</tr>
</tbody>
</table>

For the data mention above, the minimum capacitance value on each stage of Dickson’s multiplied is 0.76µF: used 1µF and output capacitor of the multiplied circuit is 50µF. The peak current of power MosFets switches is 8A for an expectation rating. Figure 9 shows a drive signals waveform of main power MosFets switches. The high-voltage high power Dickson charge pumps circuit has been tested with pure resistive load. The time to steady-state of an output voltage of the circuit is shown in Figure 10 and the characteristics correlation between output current and high-voltage output and it efficiency are shown in Figure 11 and figure 12 respectively.

Figure 9: Drive signals of main MosFets switches.
CH1: 10V/div, CH2: 10V/div, Time: 5µS
Figure 10: Time to steady-state of $HV_{out}$.

CH1: 100V/div, Time: 250mS

Figure 11: characteristics correlation between output current and high-voltage output.

Figure 12: characteristics correlation between output current and efficiency.
The current of power MosFets main switches with no-load, 60% load and full load is shown in Figure 13, 14 and 15 respectively.

**Figure 13:** current of power MosFets main switches. (0%-load)
CH1: 2A/div, Time: 5μS

**Figure 14:** current of power MosFets main switches. (60%-load)
CH1: 10V/div CH2: 10A/div, Time: 5μS

**Figure 15:** Gate voltage and current of power MosFets main switches. (100%-load)
CH1: 10V/div CH2: 10A/div, Time: 5μS
V. CONCLUSIONS

The method for increasing the power of Dickson charge pumps and control a output voltage was presented and tested in this paper: the use of MosFets power switches instead of digital switches and PWM technique. An experimental data provide a confirmation of the theoretical. By means of both techniques, the Dickson charge pumps circuit was able to deliver more power to the load compared to the traditional Dickson charge pumps configurations. The maximum efficiency of a high-voltage high power Dickson charge pumps circuit with full-bridge power MosFets switches is 62.5% (for \( I_{out} = 0.5A \)) and The voltage regulation of the circuit is 2.66% with PWM control in this research. With these results, the future work will involve a research into the output high-voltage regulation at voltage above 1kV range for a high-voltage insulation testing applications.

REFERENCES


