A Switched-Capacitor Dickson Charge Pumps for High-voltage High Power Applications

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ABSTRACT—This paper presents a switched-capacitor charge pumps circuit base on a Dickson charge pumps that focus on a power scale more than 10W and voltage above 100V. This research replaces a Dickson’s digital switches with a full-bridge power MosFets switches in order to achieve an expected power. A 16 stages 50 kHz 330V output voltage unregulated Dickson charge pumps from 20V input was designed and tested to supply the power under 100mA pure resistive load condition. From experimental results, voltage conversion efficiency and voltage regulation are 44.5% and 21.3% respectively. Although the voltage is not as good as it should at full load because it was not regulate an output voltage, but it is the one that can be applied a Dickson charge pumps circuit to a high-voltage high power applications.

Keywords—Charge pumps circuits; Full-bridge power 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 Fig.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.

Fig. 1. Schematic representation of a voltage elevator.

However, Most of Dickson circuits are normally designed for very low power applications [6]. 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 Fig.2 with voltage gain $A_V = n$ and having a driving clocks of the circuit in Fig.3. To increase the power of Dickson’s circuit in this paper, a digital INV switches in Fig.2 would be replaced with full-bridge power MosFets switches as shown in Fig.4.

Fig. 2. The principle of n-stages Dickson charge pumps.

Fig. 3. Timing diagram of Dickson circuit.

Fig. 4. High-voltage high power Dickson circuit proposed in this paper.
II. Dickson Charge Pumps Analysis

The basic structure of n-stages of Dickson circuit in Fig. 2 can rewrite to a practical circuit as shown in Fig. 5 and its n-stages equivalent circuit is shown in Fig. 6 [7]-[8].

Fig. 5. Practical circuit of Dickson charge pumps.

![Practical circuit of Dickson charge pumps.](image)

The circuit in Fig. 5 consists of two pumping switch, \( SW_1 \) and \( SW_2 \), which are out of phase and have a voltage of \( V_{in} \). The charge pumps operates by pumping a charge along the diode chain as the capacitors are successively charged and discharged during each cycle.

When \( SW_1 \) goes low, diode \( D_1 \) conducts until the voltage of capacitor at node1 becomes

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

(1)

and when \( SW_1 \) switched to \( V_{in} \), the voltage at node1 now becomes

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

(2)

At this time, diode \( D_2 \) conduct until the capacitor’s voltage at node2 equal to

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

(3)

when SW1 goes low again, the capacitor’s voltage at node2 becomes

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

(4)

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

\[
HV_{out} = V_{in} + n \left( V_{in} - V_d \right) - V_d
\]  

(5)

Under load condition \( I_{out} \) and stray capacitance \( C_S \), the actual output voltage of Dickson charge pumps circuit becomes

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

(6)

The voltage drop on a power diode can be neglected for high-voltage output. Hence, the output voltage under load condition now becomes

\[
HV_{out} = V_{in} - I_{out} R_S
\]  

(8)

and we found [2] \n
\[
R_S = \frac{n}{(C + C_S) \cdot f_{SW}}
\]  

(9)

and

\[
V_o = V_{in} + n \left( \frac{C}{C + C_S} V_{in} - \frac{I_{out}}{(C + C_S) \cdot f_{SW}} \right) - V_d
\]  

(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

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

(11)

Equation (10) is similar to Equation (7) and we neglected the stray capacitance \( C_S \), we found [9]

\[
HV_{out} = \left( n+1 \right) \cdot V_{in} - \frac{nI_{out}}{C \cdot f_{SW}}
\]  

(12)

Since the energy stores in capacitor is proportional to the product of the capacitance value and square of the voltage across the capacitance. Then, the total energy delivered to an \( (n-I) \) stage including the energy stored in the load capacitor is
\[ W = \frac{1}{2} CV^2 \quad (13) \]

For Dickson charge pumps \( n \) stages, the energy of circuit becomes

\[ W_{\text{Dickson}} = \sum_{i=1}^{n-1} \frac{1}{2} C[V_{in}]^2 + \frac{1}{2} C_{\text{load}}(nV_{in})^2 \quad (14) \]

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

\[ V_R = \frac{I_{\text{out}}}{f_{\text{SW}}C_{\text{out}}} = \frac{HV_{out}}{f_{\text{SW}}R_{\text{L}}C_{\text{out}}} \quad (15) \]

or

\[ C_{\text{out}} = \frac{HV_{out}}{f_{\text{SW}}R_{\text{L}}V_R} \quad (16) \]

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 Fig.2 were replaced by full-bridge power MosFets switches as shown in Fig.4. The maximum current handle of the MosFets main switches is equal to [10]

\[ I_{\text{peak,SW}} = \frac{(1.6)P_{\text{out}}}{V_{CC}} \quad (17) \]

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

\[ C_S = \frac{2 \cdot t \cdot P_{\text{out}}}{V_R \cdot \eta \cdot V_{CC}} \quad (18) \]

where \( t \) = charging time of a capacitor

III. Experiment and Result

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

- Input voltage: 20V.
- No-load Output voltage: 330V.
- Output current: 0.1A.
- Switching frequency: 50kHz.
- Output ripple voltage: 10V.
- Dickson’s pumping stage: 16

For the data mention above, the minimum capacitance value on each stage of Dickson’s multiplied is 2.2 \( \mu \)F and output capacitor of the multiplied circuit is 2 \( \mu \)F. The peak current of power MosFets switches is 3.11A for an expectation rating. Fig.7 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 Fig.8 and the characteristics correlation between output current and high-voltage output is shown in Fig.9.

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**Fig. 7.** Drive signals of main MosFets switches.

CH1: 10V/div, CH2: 10V/div, Time: 5\( \mu \)S

**Fig. 8.** Time to steady-state of \( HV_{out} \).

CH1: 100V/div, Time: 250mS

**Fig. 9.** Characteristics correlation between output current and high-voltage output.
The current of power MosFets main switches with no-load, half load and full load rating is shown in Fig. 10, 11 and 12 respectively.

![Fig. 10. no-load current of power MosFets main switches. CH1: 2A/div, Time: 5μS](image)

![Fig. 11. half-load current of power MosFets main switches. CH1: 5A/div, Time: 5μS](image)

![Fig. 12. full-load current of power MosFets main switches. CH1: 5A/div, Time: 5μS](image)

IV. Conclusions

The method for increasing the power of Dickson charge pumps was presented and tested in this paper: the use of MosFets power switches instead of digital switches. Experimental data provide a confirmation of the theoretical. By means of this technique, the Dickson charge pumps circuit was able to deliver more power to the load compared to the traditional Dickson charge pumps configurations. The efficiency of a high-voltage high power Dickson charge pumps circuit with full-bridge power MosFets switches is 44.5% (for $I_{out} = 0.1A$). The voltage regulation of the circuit is 21.3% because no voltage control in this designed but the future work will involve a research into the output high-voltage regulation at voltage in the kV range for a high-voltage insulation applications.

References


