Analysis and design of voltage doubling circuit for 500kV 15mA high voltage supply

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Abstract. Among many important equipment and instruments, in order to obtain a stable HVDC output, a high voltage multiplier power supply is usually used. With the development of science and technology, higher requirements are put forward for the performance parameters of high voltage multiplier power supply. In this paper, the core part of the high voltage multiplier power supply - voltage doubling circuit as the focus of research. Firstly, the principle of various voltage doubling circuits are analyzed, the steady state analytical formula under ideal state is obtained and their advantages and disadvantages are analyzed. According to the above analysis and comparison, this paper proposes that the topological structure of the voltage doubling circuit for the 500kV HV power supply is the symmetrical CW multiplier circuit. Then the ripple expression of the symmetrical CW multiplier is deduced, the reason of voltage sag is analyzed, and the calculation expression is given. Finally, a simulation model of the voltage doubling circuit of the HV multiplier power supply was built in ANSYS Simplorer. The validity of the analytical design is verified by experimental simulation.

1. Introduction
In the ion implantation machine, particle accelerator, X-ray system, CT machine, ultrahigh voltage electron microscope, electrostatic system and other important instruments, high voltage or even ultra-high voltage DC power supply is often used[1]. This kind of high voltage power supply generally adopts the combination of transformer and voltage doubling circuit to produce the required high voltage. Reasonable design of voltage doubling circuit can reduce ripple and improve power supply precision. This helps to improve the performance of the entire device or instrument. Therefore, the voltage doubling circuit is the key process of this kind of power supply design [2].

The voltage doubling circuit is a network of capacitors and diodes. It makes use of the single guide pass of the diode and the energy storage of the capacitor. So that the output voltage of the output terminal is several times the input voltage of the input terminal. The circuit converts the AC input voltage $U(t)=E\sin(\omega t)$ to the DC output voltage $V_{out} = nE (n>2)$. Voltage doubling circuit has been widely used in many high voltage and small current occasions, it’s essence is the charge pump. The common voltage doubling circuits are: Schenkel voltage doubling rectifier circuit, half-wave Cockcroft-Walton voltage multiplier and symmetrical Cockcroft-Walton voltage multiplier[3].

The ripple refers to the AC component mixed in the direct current, which is an important parameter of high voltage multiplier power supply. It’s adverse effects are: generating harmonics, reducing
power efficiency, interference and so on. Voltage sag is another important parameter of a high voltage multiplier power supply, which describes the load capacity of the power supply. It is very necessary to analyze and calculate the ripple and voltage sag of the voltage doubling circuit in detail [4].

The steady-state and transient analysis of the voltage doubling circuit is necessary to design the voltage doubling circuit reasonably, so that the high-voltage power supply can output 500kV 15mA DC high voltage, and the ripple is less than 0.1%. Finally, a simulation model is established to verify the effectiveness of the designed voltage doubling circuit.

The organization of this paper is as follows. In the second section, the steady-state analysis under ideal state is carried out. The principle, advantages and disadvantages of various voltage doubling circuits are described. In the third section, the ripple and voltage sags of the symmetrical CW voltage multiplier circuit are analyzed and calculated. In the fourth section, according to the actual requirements of the project, the voltage doubling circuit of the high-voltage multiplier power supply with output up to 500kV 15mA is designed. Finally, in the fifth section, a simulation model is established for experimental verification.

2. The principle of voltage doubling circuit

The purpose of this paper is to analyze and design the voltage doubling circuit of 500kV 15mA high voltage multiplier power supply. However, in order to facilitate the description of the rationale of this section, it is assumed that the following three voltage doubling circuits are all five stages and ten times voltage doubling circuits. The basic characteristic of a simple voltage doubling rectifier circuit is shown in Fig. 1. Assuming that the capacitor is not initially charged, and $v_c = E \sin(\omega t)$, then the steady-state capacitor voltage is:

$$V_c = v_c(\infty) = E$$ (1)

![Figure 1. Simple rectifier circuit.](image)

Using the concept of equivalent voltage source above, we can now obtain the steady-state solution of the following kinds of voltage doubling circuits in ideal state by intuitive method.

2.1. The Schenkel voltage doubling rectifier circuit

The ten-times voltage Shinkel voltage doubling circuit is shown in Figure 2, it is assumed that when a capacitor in front of itself reaches a stable state, the next set of capacitors - diodes are connected; All the capacitors are not initially charged; Setting the input voltage as $E \sin(\omega t)$. According to the Equation (1) of the above equivalent voltage source, it can be obtained $V_{c1} = E$, then consider C1 as the voltage source. Looking at node 1 and node 2, we get an equivalent voltage source: $V_{1,2}(t) = E + E \sin(\omega t)$. Therefore, if diode D2 is reconnected after C1 reaches steady state, according to Eq. (1) of the equivalent voltage source, $V_{c2} = 2E$. As mentioned above, keep repeating this process and it's easy to get, under ideal conditions:

$$V_{c1} = E; V_{c2} = 2E; V_{c3} = 3E; \ldots; V_{c10} = 10E$$ (2)

Therefore, $V_{out} = V_{c10} = 10E$, under the assumed ideal condition, the circuit achieves 10 times output voltage, extended to N times voltage:

$$V_{out} = V_{cn} = nE$$ (3)

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The voltage sustained by the capacitor increases step by step with the increase of the multiple n, the reverse voltage to which the diode is subjected is also progressively increased. Therefore the Shinkel voltage doubling circuit can only be used in the case of low number n.

The advantage of the Shinkel voltage doubling circuit is that only the last level of the capacitor is used as the output capacitor and the output DC voltage ripple is small. However, the output of the high-voltage multiplier power supply designed in this paper is 500kV, and the voltage multiplier number n is large, so the Shinkel voltage multiplier circuit is not suitable.

2.2. The half-wave Cockroft-Walton voltage multiplier
A ten times voltage half-wave CW voltage multiplier circuit is shown in Fig. 3, assuming the same conditions as stated in 2.1. First, disconnect diode D2 and all the connections behind it, clearly \( V_{C1} = E \). Set it as a voltage source E, analyze node 1 and node 2, an equivalent voltage source can be obtained \( V_{Q1}(t) = E + E \sin(wt) \). After C1 reaches the steady state, the diode D2 is reconnected and \( V_{C2} = 2E \). After C2 reaches steady state, reconnect diode D3, analyze node 2 and node 3, easily obtained \( V_{C3} = 2E \). By repeating this process, the steady-state output voltage under ideal conditions can be obtained:

\[
V_{C1} = E; \quad V_{C2} = 2E; \quad V_{C3} = 2E; \quad \ldots \quad V_{C10} = 2E
\]

\[
V_{\text{out}} = V_{C2} + V_{C4} + V_{C6} + V_{C8} + V_{C10} = 10E
\]

The circuit realizes 10 times voltage output under ideal condition. Extended to n times voltage doubling circuit, where n is an even number greater than 4:

\[
V_{\text{out}} = V_{C2} + V_{C4} + \cdots + V_{Cn} = nE
\]

From the above analysis, it can be found that: Different from the difficulty of capacitor and diode selection in Schenkel voltage doubling circuit when n is large, the voltage on each capacitor of the half-wave CW voltage multiplier is less than 2U, which is more friendly to the selection of capacitor and diode. However, the output of the circuit is the voltage at both ends after several capacitors are connected in series, so the ripple is also the superposition of the ripple of a single capacitor output.
Therefore, the ripple of the output of the circuit is relatively large, and it is not suitable for this power supply.

2.3. The symmetrical Cockcroft-Walton voltage multiplier

The symmetrical CW circuit is based on the improvement of the half-wave CW circuit. Compared with the half-wave CW circuit, the symmetrical CW circuit can produce smaller ripple DC output voltage. The symmetrical CW circuit of ten times voltage is shown in Figure 4. Its working principle and analysis method are the same as the half-wave CW circuit in 2.2, which will not be described here. The difference is that the transformer of the AC input of the symmetrical CW circuit consists of two identical windings. It can be seen that the circuit is driven by two AC power sources, VL(t) and VR(t), which have a phase difference of 180°. They can also be obtained by using a high voltage transformer with a secondary winding with a center tap.

![Figure 4. The symmetrical Cockcroft-Walton voltage multiplier.](image)

The capacitor banks in the left and right columns of the circuit are called oscillating columns, while the middle column is called smoothing columns. The circuit works in a push-pull mode, with one AC power source pushing the charge into the smoothing column capacitors and the other power source pulling the charge into the smoothing column capacitors. The voltage at both ends of the smoothing column capacitors constitutes the high voltage output of the voltage doubling circuit. In the ideal condition, \( V_{\text{out}} = V_{C2} + V_{C5} + V_{C8} + V_{C11} + V_{C14} = 10E \), the circuit achieves a ten times voltage output. Generalized to n times voltage circuit:

\[
V_{\text{out}} = V_{C2} + V_{C5} + \cdots + V_{C(n+\frac{n+1}{2})} = nE
\] (7)

Using a symmetrical CW voltage multiplier effectively doubles the number of charging cycles per second, thereby reducing voltage sags and output ripple. To sum up, the power supply should adopt the symmetrical CW voltage multiplier.

3. The calculation of symmetrical CW voltage multiplier

However, the steady-state output analysis of the above principle is only based on the ideal state, the actual output voltage of the n times voltage circuit is less than nE, that is to say, the power supply efficiency F is always less than 1. In practical application, the output ripple of HVDC is also a very important parameter. The following is an in-depth analysis and calculation of the voltage sags and ripples of the symmetrical CW voltage multiplier. Due to the nonlinear characteristics of multi-stage cascade rectifier, it is impossible to obtain the analytical solution of steady state and transient operation, but the approximate solution can be obtained by analysis under some hypothetical conditions.
3.1. Voltage sags
The voltage efficiency of the circuit is determined by the various voltage drops due to the electrical properties of the voltage doubling rectifier element. Even under no-load conditions, the voltage doubling circuit can not reach its theoretical output voltage value, and with the increase of its voltage doubling stages, the power supply efficiency $F$ will decrease.

3.1.1. Voltage sags under no-load conditions. The half-wave CW voltage multiplier circuit introduces considerable stray capacitance between the oscillating column and the smoothing column, as well as to the ground, and produces a circulating current, namely reactive current. When the stages of voltage doubling circuit is high, the stray shunt capacitor diverts the AC current into the series capacitor. These currents have the effect of lower the output voltage and increase the ripple, even when no load is connected. The influence of stray capacitance has been confirmed by the iterative network theory and law of charge conservation [5-8].

The symmetrical CW voltage multiplier is an improvement of the half-wave CW circuit, it can be regarded as the composition of two half-wave CW circuits, the upper and lower halves of which have the same circulating current as the half-wave CW circuit, when passing through the smoothing column capacitors, the flow direction is opposite, and the effect cancels out, which can greatly reduce the influence of the circulating current. Therefore, the voltage sags affected by the circulating current of the symmetrical CW voltage multiplier under no load can be ignored.

3.1.2. Voltage sags with load connected. The use of a symmetrical CW voltage multiplier effectively doubles the number of charges for capacitors per cycle and works in a push-pull mode. Because the push-pull action occurs twice per cycle, the smoothing column capacitors are charged to peak twice per cycle.

It is assumed that the diodes are ideal, with no energy loss and no stray capacitance during charge transfer. There are two actions during the work of the symmetrical CW voltage multiplier: All capacitors of oscillating columns charge the capacitors of smoothing column through the diodes (resulting in an increase in the output voltage); The capacitors of smoothing column charge the capacitors of oscillating columns via diodes (causing a sudden drop in the output voltage). A more accurate description would be: At time $t_1$, the capacitor of the left oscillating column charges the capacitor of the next smoothing column, while the capacitor of smoothing column charges the capacitor of the next right oscillating column. At time $t_2$, the capacitor of smoothing column charges the capacitor of the next stage left oscillating column, and the capacitor of the right oscillating column charges the capacitor of the next stage smoothing column. Therefore, in the simulation, it is easy to find that the transient process, that is, the rising process of the output capacitor voltage, is a columnar rise and fall.

Assuming the charging times of $t_1$ and $t_2$ are infinitely short, and the diodes also conducts electricity simultaneously. In fact, the actual dynamic process is more complex, but the formulas derived from these assumptions can yield approximations. When the circuit is on load, some of the load current passes through the output of the voltage doubling circuit, and the capacitors of the oscillating column will produce a voltage drop. Therefore, the output voltage of the symmetrical CW voltage multiplier with load is [8-10]:

$$\Delta V_{\text{drop}} = \frac{l_0}{rC} \left( \frac{N^3}{6} + \frac{N^2}{4} + \frac{N}{3} \right)$$  \hspace{1cm} (8)

$$V_{xy}(t) = V_L(t) - V_R(t)$$ \hspace{1cm} (9)

$$V_L(t) = V_{in} \sin(\omega t)$$ \hspace{1cm} (10)

and

$$V_R(t) = V_{in} \sin(\omega t - 180)$$ \hspace{1cm} (11)
\[ V_{xy}(\text{max}) = 2V_{in} \]  
\[ V_{\text{out}} = 2N V_{in} - \frac{I_o}{fC} \left( \frac{N^3}{6} + \frac{N^2}{4} + \frac{N}{3} \right) \]  

where \( N \) is the stages of the voltage doubling circuit and \( N = \frac{n}{2} \); \( f \) is the working frequency; \( I_o \) is the output load current.

3.2. Ripple

In the symmetrical CW voltage multiplier, there are circulating currents in the upper and lower parts of the circuit. When these currents pass through the capacitors of smoothing column (\( C_2, C_5, C_8 \cdots C_{(n+n-2)} \)), they flow in opposite directions. Thus, in the case of a symmetrical CW voltage multiplier that is perfectly balanced, the net effect is cancelled out and the output does not include the harmonic component due to the circulating currents. The DC output voltage contains only the ripple components generated by the load.

Assume that the charge transferred to the load by a single output capacitor in each cycle is \( Q \), and the output current is:

\[ I_o = \frac{dQ}{dt} = \frac{Q}{t} = Qf \]  

and

\[ Q = C \times \delta V_{\text{out}} \]  
\[ \delta V_{\text{out}} = \frac{Q}{C} = I_o \frac{1}{f \times C} \]

Since the push-pull occurs twice per cycle, the capacitor of smoothing column is charged twice per cycle to reach the peak:

\[ \delta V_{\text{out}} = \frac{Q}{C} = \frac{I_o}{2 \times f \times C} \]  

There are \( N \) capacitors of the smoothing column, and the output voltage ripple generated by periodic charge and discharge of the load current is:

\[ \delta V_{\text{out}} = \frac{I_o N}{2fC} \]  

4. Voltage doubling circuit of 500kV high voltage doubling power supply

The symmetrical CW voltage multiplier is applied to the 500kV high voltage power supply in this paper. The simulation model is established as shown in Figure 5. Due to the huge size of the circuit, the picture can only show a part of the circuit, 20 layers are omitted, and each layer is the same as the circuit in the red frame.

Figure 5. The symmetrical Cockcroft-Walton voltage multiplier of the 500kV power supply.
The peak value of the AC input voltage $V_i$ is 350V and the frequency is 25kHz. The ratio of the transformer is 1:29. The peak value of $V_{in}$ is about 10kV. The output $V_o$ of the voltage doubling circuit is approximately 500kV. The voltage doubling circuit has 25 stages, for a total of 50 times voltage. Every four diodes and three capacitors are one stage, for a total of 100 diodes and 75 capacitors.

5. The result of simulation experiment
The simulation results are shown in the figure below, which verifies the validity of the proposed voltage doubling circuit. The parameters of the simulation experiment are as follows: all capacitors $C = 0.06uF$; output load resistance $R_L = 33.33M\Omega$; Working frequency $f = 25KHz$.

Fig.6 shows the steady-state output at 91.68ms without load, and the output voltage is 500kV.

![Figure 6. The steady-state output without load.](image)

Figure 7 and Figure 8 show the output voltage and current waveform of the voltage doubling circuit with load.

![Figure 7. The waveform of output ripple voltage with load.](image)

It can be seen from the output waveform that the output voltage is 496.3kV and the ripple is 125V. Meet the design requirements.
Figure 8. The waveform of output current with load.

It can be seen from the simulation results that the output voltage, current and ripple=125V≤500V of the voltage doubling circuit designed in this paper, which meets the design requirements of power supply.

6. Conclusion
Firstly, this paper analyzes the working principle of three voltage doubling circuits from the steady state process, and compares their advantages and disadvantages. Then, the topological structure of the voltage doubling circuit of the 500kV HV power supply is proposed. The ripple and voltage drop are analyzed and calculated. Finally, the validity of the proposed voltage doubling circuit is verified by experimental simulation.

References
[1] Edgar Everhart, Paul Lorrain. (1953) The Cockcroft-Walton Voltage Multiplying Circuit. Review of Scientific Instruments, 24: 221–226.
[2] G. Reinhold, K. Truempy, J. Bill. (1965) The symmetrical cascade rectifier: an accelerator power supply in the megavolt and milliampere range. IEEE Trans. Nucl. Sci, 12: 288–292.
[3] Melvin M, Weiner. (1969) Analysis of Cockcroft-Walton Voltage Multipliers with an Arbitrary Number of Stages. Review of Scientific Instruments, 40: 330-333.
[4] Maria D, Bellar, Edson H. (1992) Analysis of the Dynamic and Steady-State Performance of Cockcroft-Walton Cascade Rectifiers. IEEE TRANSACTIONS ON POWER ELECTRONICS, 7: 526-534.
[5] Palmín. (1977) Topological Generation and Analysis of Voltage Multiplier Circuits. IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS, 10: 517-529.
[6] S Iqbal. (2012) Elimination of odd harmonics in symmetrical voltage multipliers. Journal of Instrumentation, 04: 003-017.
[7] Christian G. H, Maennel. (2013) Improvement in the modelling of a half-wave Cockcroft-Walton voltage multiplier. Rev. Sci. Instrum, 84: 034-039.
[8] Zhanwen Ma, Xiaodong Su, Xiaolong Lu. etc. (2016) 250 kV 6 mA compact Cockcroft-Walton high-voltage power supply. Rev. Sci. Instrum, 87: 117-121.
[9] Guangyi Zhao, Xiangyang Liu, Cong Wu, Yanyun Chu. etc. (2020) 300 kV/6 mA integrated Cockcroft–Walton high-voltage power supply for a compact neutron generator. Rev. Sci. Instrum, 91: 004-008.