High voltage switch-mode power supply for electron-beam technology with minimum load breakdown energy

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Abstract. This article deals with the calculation of unregulated energy stored in the output stage of a high-voltage power supply unit. For the classical topology of a bridge converter with an output LC filter, calculated dependences were been obtained that allow calculating the inductance and capacitance of a filter with a minimum stored energy, given the output voltage and the pulse factor. For sources with different voltage multiplier circuits, the calculated ratios for determining the stored energy, as well as recommendations for its reduction, are given.

Based on computer simulation, it is shown that the calculated dependencies obtained are comparable to real processes, and provide satisfactory results suitable for practical use.

1. Introduction

Additive technologies are currently a rapidly developing field of technology. The products obtained in this way are used in the production of aircraft, nuclear reactors, and space technology. One of the types of 3D metal printing technology is EBAM [1], in which the product is formed by fusing an electron beam of a metal wire in a vacuum chamber. The advantage of the technology is its high printing speed and the absence of metal oxidation in the melting zone. An important part of such printing plants are high-voltage pulse power supplies, the seam quality and dimensions of which depend on the stability and accuracy of voltage regulation. In the process of printing, emergency modes can occur in the form of breakdowns in the cathode tube, when the output power of the beam ceases to be limited, and during the time necessary for the control system to disable this mode, damage to the product (sinks, burnout, metal splashing) can occur. One of the ways to reduce the possible consequences of the breakdown is to select optimum parameters for the high-voltage power supply, providing a specified value of the minimum energy stored in its output stage. A review of scientific...
and technical literature on the design of high-voltage sources for cathode-ray tubes [2-7] showed that at present, such design techniques are not available.

2. Determination of the minimum filter energy for power supplies with a square pulse shape

Classic bridge / half-bridge converters with hard switching [8, 9] and phase-shifting bridges [10] with high output voltage have an output stage with a circuit shown in figure 1. In the event that the output stage is operating in the inductor continuous-current mode, the circuit can be simplified by replacing the transformer and diode bridge with a square-wave source.

![Figure 1. Output stage of bridge converter.](image)

The voltage amplitude of the power supply $V_1$ is equal to the voltage amplitude on the secondary winding of the transformer, and the frequency $f$ (period $T$) and pulse duty factor ($D$), respectively, to twice the frequency and PWM pulse duty factor. As any periodic signal, the voltage of the source $V_1$ can be decomposed into a series of harmonics:

$$U(t) = U_{DC} + \sum_{k=1}^{\infty} 2\frac{V_1}{\pi \cdot k} \sin(k \cdot \pi \cdot D) \cdot \cos(2 \cdot \pi \cdot f \cdot k \cdot t),$$

(1)

where $k$ is the number of harmonics, and $U_{DC} = D \cdot V_1$ is the constant component of the voltage.

The output voltage pulse coefficient is calculated as follows:

$$K_p = \frac{U_{1\omega}}{U_{DC}},$$

(2)

where $U_{1\omega}$ is the voltage amplitude of the first harmonic at the load.

For the worst case, when there is no load at the filter output, the transfer characteristic of the filter takes the form [11, p. 233] [12, p. 137]:

$$S = \frac{U_{m1}}{U_{1\omega}} = 1 - \left(2 \cdot \pi \cdot f\right)^2 \cdot L \cdot C,$$

(3)

where $U_{m1}$ is the amplitude of the first harmonic of the input voltage.

Hence, by calculating the pulse amplitude at the output, and substituting it in the formula for the pulse factor, we get:

$$K_p = \frac{U_{m1}}{D \cdot V_1 \cdot S} = -\frac{2 \cdot V_1 \cdot \sin(\pi \cdot D)}{\pi \cdot D \cdot V_1 \cdot (1 - (2 \cdot \pi \cdot f)^2 \cdot L \cdot C)} = -\frac{2 \cdot \sin(\pi \cdot D)}{\pi \cdot D - 4 \cdot \pi^2 \cdot f^2 \cdot L \cdot C \cdot D},$$

(4)

The required capacitance of the capacitor at the given frequency, pulse duty factor and inductance:

$$C(L) = \frac{U_{m1}}{D \cdot V_1 \cdot S} = -\frac{K_p \cdot \pi \cdot D - 2 \cdot \sin(\pi \cdot D)}{K_p \cdot 4 \cdot \pi^2 \cdot f^2 \cdot L \cdot D},$$

(5)
The total energy stored in the filter is calculated as follows:

$$W_{\text{sum}} = W_L + W_C = \frac{L \cdot I_m^2}{2} + \frac{C \cdot U^2}{2}.$$  \hspace{1cm} (6)

Since the voltage pulsations on the capacitor are small, it is possible to take:

$$U = D \cdot V_1.$$  \hspace{1cm} (7)

The maximum current value can be calculated using the formula [12]:

$$I_m = \frac{V_1 \cdot (1 - D) \cdot D}{2 \cdot f \cdot L} + \frac{V_1 \cdot D}{R}.$$  \hspace{1cm} (8)

Thus, the dependence of the energy stored in the output filter on the voltage of the output voltage, load resistance, frequency, pulse duty factor and inductance of the throttle takes the form:

$$W_{\text{sum}} = L \cdot \left( \frac{U_{\text{DC}} \cdot (1 - D)}{2 \cdot f \cdot L} + \frac{U_{\text{DC}}}{R} \right)^2 - \frac{K_p \cdot \pi \cdot D - 2 \cdot \sin(\pi \cdot D)}{K_p \cdot 4 \cdot \pi^3 \cdot f^2 \cdot L \cdot D} \cdot \frac{U_{\text{DC}}^2}{2}.$$  \hspace{1cm} (9)

For example, for the signal parameters $V_1 = 111$ V and $D = 0.9$ at the inlet of the filter, given load resistance $R = 20$ Ohm, the dependence graph $W_{\text{sum}}(L)$ has the form:

![Figure 2. Dependence of energy stored in filter on throttle inductance.](image)

In figure 2, the dashed line shows the graph obtained using the derived dependence, and the solid line shows the energy calculated using the symbolic method of calculating circuits with sinusoidal current. As can be seen from figure 2, the graphs coincide, which indicates that the accepted assumptions do not introduce a large error, which will increase with decreasing load resistance.

3. Calculation of minimum energy of voltage multipliers

When the output voltage of the power supply is more than ten kilovolts, the use of the classical topology of the PWM converter with a bridge output rectifier can become difficult. A step-up transformer with this voltage level must have a large number of turns, large insulating gaps and high-quality insulation with no gas inclusions. This leads to an increase in the leakage inductance and coil winding self-capacity, as well as an increase in the cost of the transformer [13]. In some cases, it is almost impossible to make such a transformer. To solve this problem, in many industrial high-voltage
power supplies, the output stage is made in the form of a voltage multiplier. Currently, several types of multiplier circuits are known, which are shown in figure 3 [14, p. 12] [15, p. 43] in the form of three groups:

a)  

b)  

c)  

d)  

e)
Figure 3. Variations of voltage multiplier circuits.

- half-wave multipliers: Cockcroft-Walton sequential multiplier (a) and Schenkel parallel multiplier (b),
- full-wave multiplier with midpoint: Halpern sequential multiplier (c) and parallel multiplier (d)
- full-wave multiplier with no mid-point: circuits (e) and (f).

The unregulated energy stored in the multiplier can be defined as the sum of the energies of each capacitor. Using the data on the capacitor voltages for each circuit, given in [15, p. 47], the following energy formulas for the corresponding circuits can be obtained:

\[
W_a = \frac{C \cdot U_{in}^2}{2} \cdot \frac{(8 \cdot n - 3)}{4 \cdot n^2},
\]

\[
W_b = \frac{C \cdot U_{in}^2}{2} \cdot \frac{1}{4 \cdot n^2} \sum_{k=1}^{n} k^2,
\]

\[
W_c = \frac{C \cdot U_{in}^2}{2} \cdot \frac{(6 \cdot n - 3)}{2 \cdot n^2},
\]

\[
W_d = \frac{C \cdot U_{in}^2}{2} \cdot \frac{1}{2 \cdot n^2} \sum_{k=1}^{n} \left(2 \cdot k - 1\right)^2 + 2 \cdot k^2,
\]

\[
W_e = \frac{C \cdot U_{in}^2}{2} \cdot \frac{(3 \cdot n - 2)}{n^2},
\]

\[
W_f = \frac{C \cdot U_{in}^2}{2} \cdot \frac{2 \cdot n - 2}{n^2} + 2,
\]

where \( n \) is the number of multiplication stages, \( U_{in} \) is the amplitude of the AC voltage at the input of the multiplier.

For comparison of the different multiplier circuits by the amount of unregulated energy stored in the output stage, the following forms of dependences must be obtained:

\[
W = f \left(U_{out}, R_{out}, f_{sw}, K_p, n\right),
\]

where \( R_{out} \) is the load resistance, \( f_{sw} \) is the frequency of the input sinusoidal voltage.

The derivation of the calculated relationships will be shown using the Cockcroft-Walton multiplier (circuit "a"). The pulse factor is determined using the formula [16, p. 61]:

\[
\]
From here, the required capacitance of the capacitor can be obtained for the given: frequency, load resistance, pulse factor and number of multiplication stages

\[ C = \frac{n \cdot (n + 2)}{4 \cdot f_{sw} \cdot K_p \cdot R_{out}}. \]  

Substituting this expression into the formula, we obtain the equation for calculating the stored energy:

\[ W_a = \frac{n \cdot (n + 2) \cdot U_{out}^2 \cdot (8n - 3)}{2 \cdot 4 \cdot f_{sw} \cdot K_p \cdot R_{out} \cdot 4n^3} = \frac{U_{out}^2 \cdot (8n - 3) \cdot (n + 2)}{32 \cdot f_{sw} \cdot K_p \cdot R_{out} \cdot n}. \]  

During designing, it is necessary to know the amplitude of the input voltage of the multiplier. This can be obtained from the following dependence [17, p. 257][18, p. 242]:

\[ \Delta U = \frac{I_{out}}{f_{sw} \cdot C} \cdot \left( \frac{2}{3} \cdot n^3 + \frac{1}{2} \cdot n^2 - \frac{1}{6} \cdot n \right) = \frac{U_{out}}{f_{sw} \cdot C \cdot R_{out}} \cdot \left( \frac{2}{3} \cdot n^3 + \frac{1}{2} \cdot n^2 - \frac{1}{6} \cdot n \right), \]  

where \( \Delta U \) is the drop in the output voltage of the multiplier under load, \( I_{out} \) is the load current.

Knowing the open-circuit voltage of the multiplier [15, p. 47] and the expression for capacitance, the dependence for calculating the output voltage can be obtained:

\[ U_{out} = 2 \cdot n \cdot U_{in} - \Delta U, \]  

\[ U_{out} = 2 \cdot n \cdot U_{in} - \frac{U_{out} \cdot 4 \cdot f_{sw} \cdot K_p \cdot R_{out} \cdot \left( \frac{2}{3} \cdot n^3 + \frac{1}{2} \cdot n^2 - \frac{1}{6} \cdot n \right)}{R_{out} \cdot f_{sw} \cdot n \cdot (n + 2)}. \]  

By converting and simplifying the given formula, the equation for the required amplitude of the input sinusoidal voltage can be obtained:

\[ U_{in} = \frac{U_{out}}{2 \cdot n} + \frac{2 \cdot U_{out} \cdot K_p \cdot R_{out}}{n \cdot (n + 2)} \cdot \left( \frac{2}{3} \cdot n^2 + \frac{1}{2} \cdot n - \frac{1}{6} \right). \]  

For the remaining circuits, the formulas can be derived the same way as for circuit "a", using the relations given in [15, p. 47] and [19, p. 26]. For circuit "f", the condition \( \lambda = 1 \) was accepted (that is, the capacitance value of the capacitors in the multiplier was assumed to be equal to the value of the output capacitance). Below are the calculated relationships for the corresponding multiplier circuits:

\[ C_b = \frac{1}{2 \cdot f_{sw} \cdot K_p \cdot R_{out}}, \]  

\[ C_c = \frac{n}{4 \cdot f_{sw} \cdot K_p \cdot R_{out}}. \]
\begin{align*}
C_d &= \frac{n}{4 \cdot f_{sw} \cdot K_p \cdot R_{out}}, \quad (26) \\
C_e &= \frac{n}{4 \cdot f_{sw} \cdot K_p \cdot R_{out}}, \quad (27) \\
C_f &= \frac{1}{4 \cdot f_{sw} \cdot K_p \cdot R_{out}}, \quad (28) \\
W_0 &= \frac{U_{out}^2}{16 \cdot f_{sw} \cdot K_p \cdot R_{out} \cdot n^2} \sum_{k=1}^{2n} k^2, \quad (29) \\
W_c &= \frac{U_{out}^2 \cdot (6 \cdot n - 3)}{16 \cdot f_{sw} \cdot K_p \cdot R_{out} \cdot n}, \quad (30) \\
W_d &= \frac{U_{out}^2}{16 \cdot f_{sw} \cdot K_p \cdot R_{out} \cdot n} \sum_{k=1}^{n} (2 \cdot k - 1)^2 + 2 \cdot k^2, \quad (31) \\
W_e &= \frac{U_{out}^2 \cdot (3 \cdot n - 2)}{8 \cdot f_{sw} \cdot K_p \cdot R_{out} \cdot n}, \quad (32) \\
W_f &= \frac{U_{out}^2}{8 \cdot f_{sw} \cdot K_p \cdot R_{out}} \left( \frac{2 \cdot n - 2}{n^2} + 2 \right), \quad (33) \\
U_{in b} &= \frac{U_{out}}{2 \cdot n} + \frac{U_{out} \cdot K_p}{n} \left( \frac{2 \cdot n - 1}{2} \right), \quad (34) \\
U_{in c} &= \frac{U_{out}}{2 \cdot n} + \frac{2 \cdot U_{out} \cdot K_p}{n} \left( \frac{1}{6} \cdot n^2 + \frac{1}{4} \cdot n + \frac{1}{3} \right), \quad (35) \\
U_{in d} &= \frac{U_{out}}{2 \cdot n} + \frac{2 \cdot U_{out} \cdot K_p}{n} \left( \frac{1}{6} \cdot n^2 + \frac{1}{4} \cdot n + \frac{1}{3} \right), \quad (36) \\
U_{in e} &= \frac{U_{out}}{n} + \frac{4 \cdot U_{out} \cdot K_p}{n} \left( \frac{1}{6} \cdot n^2 - \frac{1}{4} \cdot n + \frac{1}{3} \right), \quad (37) \\
U_{in f} &= \frac{U_{out} \cdot K_p}{n} \left( 2 \cdot n^3 - 3 \cdot n^2 + n + 3 - \left[ 2 \cdot n - \sqrt{2 \cdot (1 + n)} \right]^2 \right) \div \frac{3 \cdot n}{n}. \quad (38)
\end{align*}

To test the results obtained in the LTspiceIV software package, models of voltage multipliers were developed, the adequacy of which was confirmed in [20]. The models represent four multipliers with a number of steps equal to 3, 5, 7 and 10. In such a case, the frequency and magnitude of the load resistance were the same for all multipliers, and the capacitance of the capacitors and the amplitude of
the input voltage were assumed to be different. A controlled key was connected to each load resistance, which closed the output of the multiplier to a 1 mΩ resistor to which the stored energy was allocated. The initial data for verifying the dependencies obtained was given as the following: 

\[ U_{\text{out}} = 50 \text{ kV}; \quad I_{\text{out}} = 0.1 \text{ A}; \quad R_{\text{out}} = 500 \text{ kOhm}; \quad K_p = 0.1 \%. \]

The results of the calculation are given in figure 4. The stepped form of the graphs is explained by the fact that the number of multiplication steps can only be an integer.

![Figure 4](image)

**Figure 4.** Dependence of the energy of the stored multiplier on the frequency and the number of multiplication stages for circuits a) - f) (from left to right).

The verification of the calculation formulas was carried out at a frequency of 50 kHz. Table 1 – table 3 show the errors in calculating the parameters of the multipliers in relation to the results obtained in the simulation.

**Table 1.** Comparison of calculated data with data obtained in the simulation. Output voltage.

| Number of multiplication stages \( n \) | Circuit a  | Circuit b  | Circuit c  | Circuit d  | Circuit e  | Circuit f  |
|----------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 3                                      | -0.034    | 0.000     | 0.000     | 0.7798    | 0.006     | 23.628    |
| 5                                      | -0.020    | -0.006    | 0.012     | 2.0203    | 0.000     | 12.463    |
| 7                                      | -0.016    | -0.006    | 0.026     | 3.7165    | 0.010     | 4.441     |
| 10                                     | 0.000     | 0.002     | 0.044     | 7.0131    | 0.014     | -4.277    |

**Table 2.** Comparison of calculated data obtained by simulation. Pulse coefficient.

| Number of multiplication stages \( n \) | Circuit a  | Circuit b  | Circuit c  | Circuit d  | Circuit e  | Circuit f  |
|----------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 3                                      | -26.26    | -4.058    | -8.578    | -212.5    | -5.152    | -5.932    |
| 5                                      | -18.62    | -4.822    | -13.636   | -418.13   | -9.769    | -13.379   |
| 7                                      | -13.25    | -5.932    | -19.048   | -624.64   | -14.811   | -20.192   |
| 10                                     | -8.58     | -7.643    | -28.205   | -941.67   | -22.549   | -23.304   |

**Table 3.** Comparison of calculated data obtained by simulation. Energy breakdown.

| Number of multiplication stages \( n \) | Circuit a  | Circuit b  | Circuit c  | Circuit d  | Circuit e  | Circuit f  |
|----------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 3                                      | 0.540     | 0.189     | -0.537    | 1.408     | -1.588    | -3.907    |
| 5                                      | 0.280     | 0.163     | -0.506    | 3.942     | -1.587    | -39.349   |
4. Conclusions
Analysis of the dependence of stored energy on the parameters of the elements obtained for the LC filter allows to conclude that for inverters with a rectangular pulse shape, for a given voltage and load resistance, the PWM fill factor, pulse frequency and output voltage pulse factor, there are such quantities of inductance and capacitance for which the uncontrolled energy stored in them is minimal. The results of the calculation of the filter using the obtained formulas coincide with the calculation performed using the symbolic method, which confirms their correctness.

Analysis of the data provided in table 1 - table 3 allows to conclude that the dependences obtained for calculating the energy of the multipliers and their output voltage ensure that correct results are obtained with an error sufficient for practical use (less than 10%) (exception is the "f" circuit of a full-wave multiplier without an average point, where the error exceeds 100%, which does not allow using the results).

It should be noted that the error in calculating the pulse factor has a relatively high value for all circuits. However, since the actual pulse factor is smaller than the estimated, it does not lead to abnormal reproducible operating modes of the elements.

For the Cockcroft-Walton, Schenkel, Halpern circuits, in the case of a full-wave parallel multiplier with a mid-point and a half-period multiplier without an intermediate point (circuit "e"), the amount of stored energy in capacitors with constant parameters of the output stage grows with the number of multiplying steps and the frequency of the input voltage, which is confirmed by the graphs presented in Figure 4. An exception is the circuit of a full-wave multiplier without the middle point "f", where the increase in energy occurs with a decrease in the number of multiplication stages.

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