PHOTOMULTIPLYER HIGH VOLTAGE POWER SUPPLY UNIT

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A photomultiplyer power supply producing output voltage from 0 to 1500 V at an output current from 0 to 2 mA is described. A stabilization factor of more than 1500 at mains variation is provided. The variation of the output voltage by output current alteration from 0 to 2 mA is less than 0,06%. The long term instability is under 0,05 % and the output voltage ripple less than 10 mVp-p. Two special protection circuits limit the output voltage and current either at an accidental output short circuit or at an interruption of the stabilizer feedback.

Keywords: photomultiplyer, high voltage, power supply.

1. INTRODUCTION

Photomultiplyers have a very large field of application – photometry, optical and nuclear researches, astronomy, cosmology etc. The main reasons are their high gain, very low noises and high speed. The successful use of these features significantly depends on the parameters of the high voltage power supply unit used. The device's requirements are rigorous:

- high stability of the output voltage;
- wide range of output voltage regulation;
- protection against output overload and internal failures;
- very low ripple voltage;
- compact construction, low weight and price.

A high voltage power supply unit satisfying many of these requirements is developed and will be described here.

2. DESCRIPTION OF THE CIRCUIT

The electric diagram of the device is shown in fig. 1. The output high voltage (U_O) is regulated by means of the potentiometer P_1. The voltage from it (U_P) is fed to the noninverting input of the operational amplifier *OA*. There it is compared with the voltage received at the *OA* inverting input from the stabilizer feedback (R_4). The difference between these two voltages is amplified by *OA* and its output voltage U_{OA} is fed to the emitter circuit of the transistor T_1.

The transistors T_1, T_2 and T_3 convert this low direct voltage into high voltage by using a timer 555 generator. The generator's output pulses, with amplitude of 12 V, control the transistor T_1 – at an output pulse level of 0 V T_1 is saturated and at 12 V it

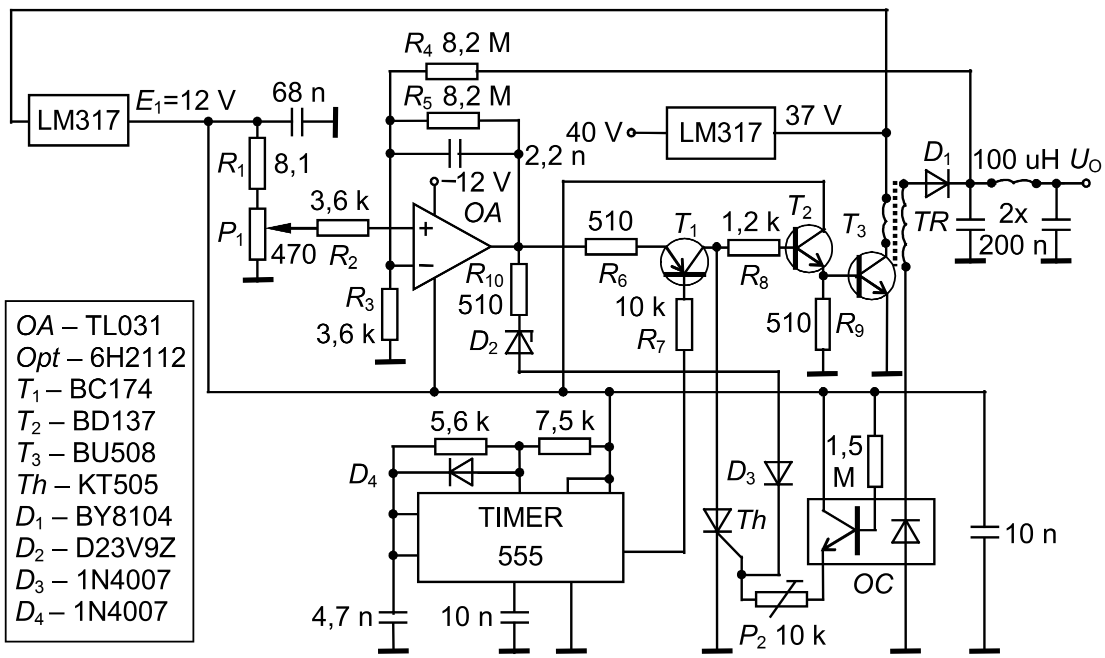

Fig. 1. Power supply unit electrical diagram.

is cut-off. For this reason the base current of the Darlington transistor T_2-T_3 flows only during the zero-level at the timer output. As can be seen from the diagram this current as well as the current through the T_3 collector circuit (i.e. the current through the transformer *TR* primary winding) and the output voltage U_O will be proportional to the *OA* output voltage, which is controlled by P_1.

The protection against output overload is provided by means of the optocoupler *OC* and the thyristor *Th*: the load current flows through the *OC* LED and when it value becomes over 2 mA the *OC* transistor opens; its current switches on the thyristor and through it the T_1 collector is connected to ground; as a results transistors T_2 and T_3 are cut-off and the output voltage drops to 0. When the overload disappears the output voltage restores immediately because the current through the thyristor ceases each time, when T_1 is cut-off by the generator 555.

The same thyristor by means of R_{10}, D_2 and D_3 circuit provides the protection against a dangerous output voltage exceeding due to an interruption of the feedback in the stabilizer (from the output to the *OA* input through R_4). For that purpose the break-down voltage of the Zener diode D_2 is chosen so (3,9 V), that for the normal operating values of *OA* output voltage U_{OA} it is cut-off. Only when does U_{OA} rises sharply D_2 breaks down and it's current through the diode D_3 switches on the thyristor *Th*. In such a case the thyristor controls the output voltage in the same way as at an output overload.

3. OPERATION ANALYSIS

The relation between the output voltage U_O and the control voltage U_P received from P_1 can be found taking into account that (for an ideal operational amplifier) the circuit will be in balance when the voltages at the *OA* inverting and noninverting input are equal –

(1) $$U_P = U_O R_3/(R_3+R_4).$$

When the output voltage range is fixed the corresponding value of the control voltage can be calculated from this equation. The control voltage depends on the supply voltage E_1 and the voltage divider formed by the resistor R_1 and P_1. Normally the voltage E_1 as well as the resistance of the helipot P_1 can be chosen and then the resistance R_1 has to be calculated to provide the maximal necessary value of the control voltage U_{Pmax} (produced at up position of P_1) –

(2) $$R_1 = (\frac{E_1}{U_{\text{Pmax}}} - 1)P_1.$$

Table 1

U_O, V	U_{PEXP}, mV	U_{PTH}, mV
100	41,0	43.9
200	84,0	87.8
300	127.2	131.6
400	169.1	175.5
500	213.5	219.4
600	255.4	263.3
700	301.7	307.2
800	344,0	351.1
900	387.8	394.9
1000	432.1	438.9
1100	477.5	482.7
1200	522.2	526.6
1300	568.1	570.5
1400	616.3	614.4
1500	662,0	658.2

For this unit the accepted range of the output high voltage is U_{Omin}=0, U_{Omax}=1500 V. With the resistance values of R_3 and R_4 shown on fig. 1, a voltage U_{Pmax}≈0,658 V is calculated from (1). Then at E_1=12 V and P_1=470 Ω a resistance R_1≈8,1 kΩ is obtained from (2). In Table 1 the measured (U_{PEXP}) and the calculated (U_{PTH}) from (1) control voltage values for a series of output voltages (from 0 to 1500 V) are given. In fig. 2 the theoretical relation is shown by continuous line and the measured values – by small triangles. As can be seen the differences between these two series of values are not considerable and most likely are due to the operational amplifier TL031 offset voltage.

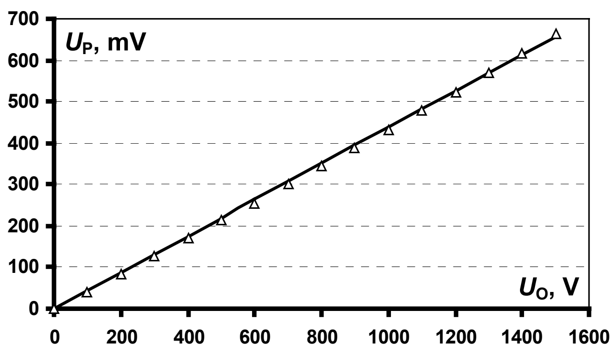

Fig. 2. Dependence between the control voltage (U_P) and the output voltage (U_O).

The transistors T_1, T_2 and T_3 operation can be analyzed using the equivalent circuit for the half period when T_1 is saturated as shown in fig. 3. In it the diodes D_{B1}, D_{B2} and D_{B3} represent the base-emitter PN-junctions of the transistors T_1, T_2 and T_3. This figure shows that the output current of *OA* (I_{OA}) splits between the base (I_{B1}) and the collector circuits of T_1 ($I_{C1} = I_{B2}$). Applying the first Kirhoff's law to the point *A* of the circuit the following equation can be written –

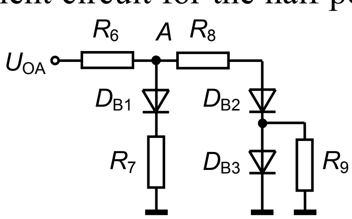

Fig. 3. T_1, T_2 and T_3 equivalent circuit.

(3) $$I_{OA} = I_{B1} + I_{B2}$$

or

(4) $$\frac{U_{OA} - U_A}{R_6} = \frac{U_A - \Delta U_1}{R_7} + \frac{U_A - (\Delta U_2 + \Delta U_3)}{R_8} = \frac{U_A - \Delta U}{R_7} + \frac{U_A - 2\Delta U}{R_8},$$

where U_A is the voltage in point A and $\Delta U_1 \approx \Delta U_2 \approx \Delta U_3 \approx \Delta U$ – the voltage drop at the PN-junction of the corresponding transistor.

From the equations

(5) $$I_{B1} = \frac{U_A - \Delta U}{R_7} \text{ and } I_{B2} = \frac{U_A - 2\Delta U}{R_8}$$

it can be seen that an increasing of the R_7 resistance with respect to R_8 will enhance the current I_{B2}, i.e. the part of I_{OA} controlling the output voltage U_O and will decrease the necessary OA output voltage (see (6)). In the same time the saturation condition of T_1 is $R_7/R_8 << \beta_1$, where β_1 is the static current gain of T_1. Taking into account these conflicting requirements the values of R_7 and R_8 shown in fig. 1 are chosen. The R_6 resistance (510 Ω) stabilizes the T_1 operation (due to the local negative feedback) and limits the maximal output current of OA.

The voltage in point A can be calculate from equation (4) –

(4a) $$U_A = \frac{U_{OA} + \Delta U R_6 (1/R_7 + 2/R_8)}{1 + R_6(1/R_7 + 1/R_8)}.$$

Replacing this value in equation (5) the following relations for the base currents of T_1 and T_2 are received –

(5a) $$I_{B1} = \frac{U_{OA} - \Delta U (1 - R_6/R_8)}{R_7 + R_6(1 + R_7/R_8)},$$

(5b) $$I_{B2} = \frac{U_{OA} - \Delta U (2 + R_6/R_7)}{R_8 + R_6(1 + R_8/R_7)}.$$

If the value of the necessary T_2 base current I_{B2} is known, the equation (5b) allows to calculate the operational amplifier OA output voltage which is needed –

(6) $$U_{OA} = I_{B2}[R_8 + R_6(1 + R_8/R_7)] + \Delta U(2 + R_6/R_7).$$

The relation between I_{B2} and output current I_O can be found by following reasoning. The mean value of T_3 collector current is

(7) $$I_{C3} = k_{TR} I_O + I_{0TR},$$

where k_{TR} is the transformer current ratio and I_{0TR} – the open-circuit current through the transformer primary winding. The corresponding base current is

(8) $$I_{B3} = I_{C3}/\beta_3 = (k_{TR} I_O + I_{0TR})/\beta_3.$$

To find the corresponding T_2 emitter current, the current through the resistor R_9 has to be added –

(9) $$I_{E2} = I_{B3} + I_{R9} = (k_{TR} I_O + I_{0TR})/\beta_3 + \Delta U/R_9$$

(ΔU as in (5)). Finally

(10) $$I_{B2} = I_{E2}/(\beta_2 + 1) = [(k_{TR} I_O + I_{0TR})/\beta_3 + \Delta U/R_9]/(\beta_2 + 1).$$

To calculate a concrete I_{B2} value β_2 and β_3 has to be taken for the real operating conditions of the corresponding transistors. For example, at U_O=1500 V and maximal output current I_{Omax} =2 mA the mean T_3 collector current is about 142 mA (k_{TR}=56 and I_{0TR}≈30 ma) at a voltage pulse amplitude of 32 V (in order to avoid T_3 saturation). Under these conditions the used T_3 transistor BU508 [2] has β_3≈15. Respectively T_2

(type BD 139) has $\beta_2 \approx 35$. Then for I_{B2} mean value from (10) can be received $I_{B2} \approx$ 0,285 mA ($\Delta U \approx$ 0,8 V).

Now the necessary *OA* output voltage providing this current can be calculated from equation (6). The result is $U_{OA} \approx 2{,}145$ V which is in good correspondence with the measured value of 2,17 V.

4. EXPERIMENTAL RESULTS

The basic parameters of the device were investigated in details by means of a prototype. The instability of the output voltage as a function of the mains voltage and load current is shown in Table 2. As can be seen variation in the mains voltage from 198 to 242 V (±10% of the nominal value $U_{M\text{-}nom}$=220 V) and at constant load current causes a maximal output voltage deviation of 0,0133% (from 1500,2 V to 1500,4 V at I_O=1 mA and from 1500,1 to 1500,3 V at I_O=2 mA). The corresponding minimal stabilization factor is

Table 2

$U_{O,HOM}$, V	I_O, mA	U_O, V at U_M		
		198 V	**220 V**	**242 V**
500	0	500,7	500,7	500,7
500	0,5	500,7	500,7	500,7
500	1	500,6	500,6	500,6
500	1,5	500,5	500,5	500,5
500	2	500,4	500,4	500,4
1000	0	1000,8	1000,9	1000,9
1000	0,5	1000,7	1000,8	1000,8
1000	1	1000,7	1000,7	1000,8
1000	1,5	1000,6	1000,7	1000,7
1000	2	1000,6	1000,6	1000,6
1500	0	1500,4	1500,4	1500,5
1500	0,5	1500,3	1500,4	1500,5
1500	1	1500,2	1500,3	1500,4
1500	1,5	1500,2	1500,2	1500,3
1500	2	1500,1	1500,1	1500,3

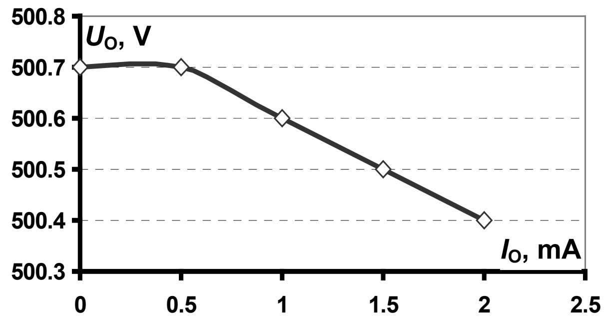

Fig. 4. Load characteristic at U_O= 500 V.

$$K_{\text{STmin}} = \frac{\Delta U_{\text{M}} / U_{\text{Mnom}}}{\Delta U_{\text{Omax}} / U_{\text{Onom}}} = \frac{20}{0{,}0133} = 1500 . \qquad (11)$$

The load characteristics of the device (Table 2) show that the full variation of the load current (from 0 to 2 mA) provokes a 0,3 V absolute decrease of the output voltage, independently of the output voltage rate. The maximum relative deviation is at U_O=500 V – 0,06% (from 500,7 to 500,4 V, fig. 4).

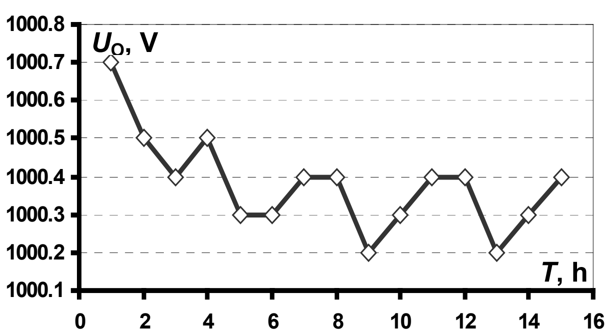

Fig. 5. Long term stability at U_O=1000 V

The long term stability investigation during a period of 15 hours (fig. 5) shows a deviation of 0,05% for the whole period and only 0,02% during the last 10 hours.

The maximal ripple voltage, measured at the heaviest operating conditions – U_O=1500 V, I_O=2 mA, is less than 10 mVp-p.

5. CONCLUSIONS

The described high voltage power supply unit, designed mainly for supplying photomultiplyers, satisfies most of the requirements indicated in the introduction: the output voltage can be regulated from 0 to 1500 V; it has very high stability at mains voltage variation and load current alteration, good long term stability and low output ripple; the unit contains very effective protection against a short circuit in the output or a break in the stabilizer feedback circuit; the high performance of the unit is achieved by a relatively simple and cheap original circuit design.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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