SOLID STATE POWER SUPPLY FOR KLYSTRONS

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ABSTRACT

The circuit of a solid state regulated power supply for the reflex klystron type 723 A/B along with its theoretical analysis is reported in this paper. The regulated DC voltage supply has been designed to provide an output voltage of 300 V and a maximum load current of 40 mA. The power supply is short circuit protected using SCR's and has high stabilization factor, low output impedance and good thermal stability. The circuit of a squarewave modulator for reflector voltage is also described.

Key words: Power supplies, Klystron power supplies, Voltage regulators.

1. INTRODUCTION

It is well known that the stability of the power output and frequency of reflex klystrons depends on the stability of the DC voltage sources. Situations do arise where the AC mains voltage may vary very widely. The solid state circuit described below, besides being compact, is capable of coping up with wide variations in the mains voltage. Approximate expressions for the stabilization factor, output impedance and the temperature coefficient have been derived by making use of the equivalent circuit of the regulator. It is found that the regulator keeps the output voltage variations to within 0·05% with AC mains voltage varying from 170 V to 240 V (nominal value being 220 V). Facility for squarewave modulation of the reflector voltage has also been provided in the power supply. Both the frequency and the amplitude of the modulating squarewave may be varied continuously over certain ranges.

2. DESCRIPTION AND ANALYSIS

The circuit diagram of the regulated power supply and its equivalent circuit are given in Figs. 1 and 2 respectively. The regulator derives the unregulated DC supply from a voltage doubler circuit consisting of the diodes D_1 and D_2 and the capacitors C_1 and C_2. The resistors R_2 are

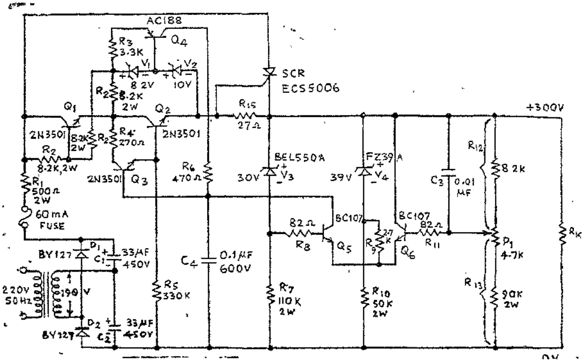

FIG. 1. Circuit diagram of the regulated power supply.

chosen such that the series transistors Q_1 and Q_2 share the voltage almost equally.[1] The transistor Q_3 is the driver for Q_2. The pre-regulator Q_4 supplies constant current to differential amplifier and the driver to help minimise the ripple voltage at the output. The capacitor C_4 is introduced to reduce noise voltages at the output. R_{15} is the overload sensing

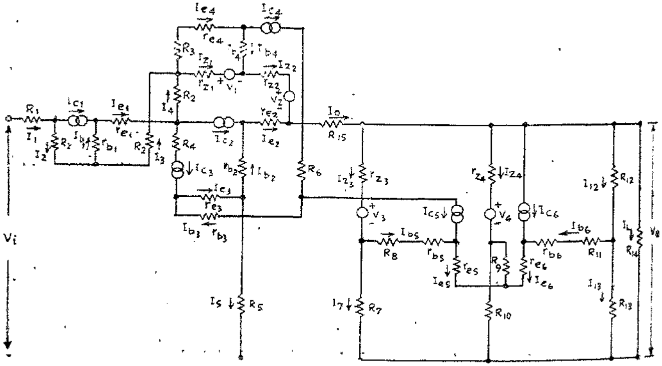

FIG. 2. Equivalent circuit of the regulator.

resistor. Under overload conditions the SCR is turned on and the load current is limited by the resistor R_1 and the output resistance of the doubler. An approximate analysis of the circuit is presented below.

The basic equation for the total change in regulator output voltage (V_0) with changes in the input voltage (V_i), the load current (I_L), and the temperature (T) is[2]

$$dV_0 = S dV_i - R_0\, dI_L + S_T\, dT, \tag{1}$$

where

$$\left.\begin{aligned} &\text{the stabilization factor,}\\ &\quad S = \frac{\partial V_i}{\partial V_0}\bigg|_{I_L,\,T},\\ &\text{output impedance,}\\ &\quad R_0 = -\frac{\partial V_0}{\partial I_L}\bigg|_{V_i,\,T},\\ &\text{and temperature coefficient,}\\ &\quad S_T = \frac{\partial V_0}{\partial T}\bigg|_{V_i,\,I_L}, \end{aligned}\right\} \tag{2}$$

From Fig. 2 the following equations are obtained:

$$I_{z_3}(r_{e_3} + R_7) - I_{b_5} R_7 = V_0 - V_3 \tag{3}$$

$$\begin{aligned} I_{z_4}(r_{z_4} + R_{10}) &+ I_{b_5}(1 + h_{FE_5}) R_{10} \\ &+ I_{b_6}\ (1 + h_{FE_6}) R_{10} = V_0 - V_4 \end{aligned} \tag{4}$$

$$\begin{aligned} I_{z_3} R_7 + I_{z_4} r_{z_4} &- I_{b_5}[R_7 + R_8 + r_{b_5} + (1 + h_{FE_5}) \\ &\times (r_{e_5} + R_9)] - I_{b_6}(1 + h_{FE_6}) R_9 = V_0 - V_4 \end{aligned} \tag{5}$$

$$\begin{aligned} I_{z_4} r_{z_4} - I_{b_5}(1 + h_{FE_5}) R_9 &- I_{b_6}[R_A + R_{11} + r_{b_6} + (1 + h_{FE_6}) \\ &\times (r_{e_6} + R_9)] \\ &= \frac{R_{12} V_0}{R_{12} + R_{13}} - V_4 \end{aligned} \tag{6}$$

where,

$$R_A = \frac{R_{12} R_{13}}{R_{12} + R_{13}}.$$

Making the assumptions that

$$
\begin{aligned}
&r_{z_3} \ll R_7 \quad ,\\
&I_{b_5} \ll I_{z_3} \quad ,\\
&r_{z_4} \ll R_{10} \quad ,\\
&h_{FE_5} = h_{FE_6} \gg 1,
\end{aligned}
$$

$h_{FE_5} R_9 \gg (r_{z_3} \,||\, R_7)$, $h_{FE_5} (r_{z_4} \,||\, R_{10})$, R_8, r_{b_5} and $h_{FE_5} r_{e_5}$, the following expressions for the various currents are obtained from equations (3) through (6)

$$I_{z_3} \approx \frac{V_0 - V_3}{R_7} \quad , \tag{7}$$

$$I_{z_4} \approx \frac{V_0 - V_4}{R_{10}} - I_{c_5} - I_{c_6} \tag{8}$$

$$\approx \frac{V_C - V_4}{R_{10}} - \frac{V_4 - V_3}{R_9} \quad , \tag{9}$$

$$I_{b_5} \approx \frac{V_4 - V_3}{h_{FE_5} R_9} - \frac{V_3}{R_A} + \frac{V_0}{R_{13}} \quad , \tag{10}$$

$$I_{b_6} \approx \frac{V_3}{R_A} - \frac{V_0}{R_{13}} . \tag{11}$$

The base current I_{b_4} of Q_4 is

$$I_{b_4} = \frac{I_{z_1} r_{z_1} + V_1}{r_{b_4} + (1 + h_{FE_4})(r_{e_4} + R_3)} . \tag{12}$$

Assuming that $I_{z_1} r_{z_1} \ll V_1$, $h_{FE_4} \gg 1$, and $r_{b_4} + h_{FE_4} r_{e_4} \ll h_{FE_4} R_3$,

$$I_{b_4} \approx \frac{V_1}{h_{FE_4} R_3} .$$

Hence

$$I_{c_4} \approx \frac{V_1}{R_3} . \tag{13}$$

The base current I_{b_3} of Q_3 is given by

$$I_{b_3} = I_{c_4} - I_{c_5} \tag{14}$$

$$\approx \frac{V_1}{R_3} - \frac{V_4 - V_3}{R_9} + \frac{h_{FE_5} V_3}{R_A} - \frac{h_{FE_5} V_0}{R_{13}} . \tag{15}$$

Also,

$$I_{b_4} \approx \frac{V_0 + I_0 R_{15}}{h_{FE_4} R_5} + \frac{I_{b_2}}{h_{FE_3}} \left(1 + \frac{r_{b_2} + (1 + h_{FE_2}) r_{e_2}}{R_5}\right) . \tag{16}$$

As

$$\frac{r_{b_3} + (1 + h_{FE_3})\, r_{e_3}}{R_5} \ll 1$$

and $I_0R_{15} \ll V_0$, equation (16) may be simplified to

$$I_{b_3} \approx \frac{V_0 + I_{b_2}R_5}{h_{FE_3}R_5}\,. \tag{17}$$

From equations (15) and (17) the base current I_{b_2} of Q_2 can be obtained and is given by

$$I_{b_2} \approx h_{FE_3}\left[\frac{V_1}{R_3} - \frac{V_4 - V_3}{R_9} + \frac{h_{FE_5}V_3}{R_A} - \frac{h_{FE_5}V_0}{R_{13}}\right] - \frac{V_0}{R_5}\,. \tag{18}$$

Since

$$I_{b_4} \ll I_{z_1}\,,$$

$$I_{z_1} \approx I_{z_2} = I_0 - I_{e_2}\,. \tag{19}$$

Now

$$\begin{aligned} I_0 &= I_{z_3} + I_{z_4} + I_{c_6} + I_{12} + I_L \\ &\approx \frac{V_0 - V_3}{R_7} + \frac{V_0 - V_4}{R_{10}} - \frac{V_4 - V_3}{R_9} \\ &\quad + h_{FE_5}\left(\frac{V_3}{R_A} - \frac{V_0}{R_{13}}\right) + \frac{V_3}{R_{12}} + \frac{V_0}{R_{14}}\,. \end{aligned} \tag{20}$$

From equations (18), (19) and (20), the zener currents I_{z_1} and I_{z_2} are obtained,

$$\begin{aligned} I_{z_1} \approx I_{z_2} \approx{} & \frac{V_0 - V_3}{R_7} + \frac{V_0 - V_4}{R_{10}} - \frac{V_4 - V_3}{R_9} \\ & + h_{FE_5}\left(\frac{V_3}{R_A} - \frac{V_0}{R_{10}}\right) + \frac{V_3}{R_{12}} + \frac{V_0}{R_{14}} - h_{FE_2}h_{FE_3} \\ & \times\left[\frac{V_1}{R_3} - \frac{V_4 - V_3}{R_9} + \frac{h_{FE_5}V_3}{R_A} - \frac{h_{FE_5}V_0}{R_{13}}\right] + \frac{h_{FE_2}V_0}{R_5}\,. \end{aligned} \tag{21}$$

Also,

$$I_3R_2 - I_4R_2 = V_{BE_1}.$$

Since $V_{BE_1} \ll I_4R_2$, the currents I_3 and I_4 are nearly equal. Therefore,

$$\begin{aligned} I_3 \approx I_4 &= \tfrac{1}{2}\,(I_{z_1} + I_{e_4}) \\ &\approx \tfrac{1}{2}\left(I_{z_1} + \frac{V_1}{R_3}\right). \end{aligned}$$

Since $I_{e_1} = I_4 + I_{c_2} + I_{c_3}$, the base current I_{b_1} of Q_1 is approximately given by

$$I_{b_1} \approx \frac{1}{2h_{FE_1}}\left(\frac{V_1}{R_3} + I_{z_1}\right) + \frac{h_{FE_2}}{h_{FE_1}}\, I_{b_2} + \frac{h_{FE_3}}{h_{FE_1}}\, I_{b_3}\,. \tag{22}$$

Assuming that

$$h_{FE_1} \gg 1,$$

$$I_{z_1} r_{z_1} \ll V_1,$$

$$I_{z_2} r_{z_2} \ll V_2,$$

and

$$I_0 R_{15} \ll V_0,$$

the input voltage V_i to the voltage regulator is

$$\begin{aligned} V_i &\approx I_1 R_1 + (I_2 + I_3) R_2 + V_1 + V_2 + V_0 \\ &\approx (h_{FE_1} R_1 + R_2) I_{b_1} + \frac{R_1 + 2R_2}{2} I_{z_1} \\ &\quad + V_1 \frac{(R_1 + 2R_2)}{2R_3} + V_1 + V_2 + V_0. \end{aligned} \tag{23}$$

Stabilization factor:

From equation (23),

$$\begin{aligned} S = \left.\frac{\partial V_i}{\partial V_0}\right|_{I_L,\, T} &= 1 + (h_{FE_1} R_1 + R_2) \frac{\partial I_{b_1}}{\partial V_0} \\ &\quad + \frac{R_1 + 2R_2}{2} \frac{\partial I_{z_1}}{\partial V_0} \end{aligned} \tag{24}$$

$$\begin{aligned} &\approx 1 + \left(\frac{h_{FE_1} R_1 + R_2}{2h_{FE_1}} + \frac{R_1 + 2R_2}{2}\right)\left(\frac{1}{R_7} + \frac{1}{R_{10}}\right. \\ &\quad \left. - \frac{h_{FE_3}}{R_{13}} + \frac{1}{R_{14}} + \frac{h_{FE_2} h_{FE_3} h_{FE_5}}{R_{13}} + \frac{h_{FE_2}}{R_5}\right) \\ &\quad - \frac{h_{FE_2}}{h_{FE_1}}\left(\frac{h_{FE_3} h_{FE_5}}{R_{13}} + \frac{1}{R_5}\right)(h_{FE_1} R_1 + R_2) - \frac{h_{FE_3} h_{FE_5}}{h_{FE_1} R_{13}}(h_{FE_1} R_1 + R_2) \\ &\approx h_{FE_2} h_{FE_3} h_{FE_5} \frac{R_2}{R_{13}} \end{aligned} \tag{25}$$

Output Impedance:

Substituting for I_{z_1} and I_{b_1} from equations (21) and (22) respectively in equation (23) and replacing $\frac{V_0}{R_{14}}$ in equation (21) by I_L,

$$V_i \approx \left(\frac{h_{FE_1}R_1 + R_2}{2h_{FE_1}} + \frac{R_1 + 2R_2}{2}\right) I_L + \left[\left(\frac{h_{FE_1}R_1 + R_2}{2h_{FE_1}} + \frac{R_1 + 2R_2}{2}\right)\right.$$

$$\times \left(\frac{1}{R_7} + \frac{1}{R_{10}} - \frac{h_{FE_5}}{R_{13}} + \frac{h_{FE_2}h_{FE_3}h_{FE_5}}{R_{13}} + \frac{h_{FE_3}}{R_5}\right) - \frac{h_{FE_1}R_1 + R_2}{h_{FE_1}}$$

$$\left.\times \left(\frac{h_{FE_2}h_{FE_3}h_{FE_5}}{R_{13}} + \frac{h_{FE_3}}{R_5} + \frac{h_{FE_3}h_{FE_5}}{R_{13}}\right)\right] V_0 + V_0$$

$+$ terms independent of V_0 and I_L.

$$R_0 = -\left.\frac{\partial V_0}{\partial I_L}\right|_{V_i,\, T}$$

$$\approx \left(\frac{h_{FE_1}R_1 + R_2}{2h_{FE_1}} + \frac{R_1 + 2R_2}{2}\right)\Big/ D$$

where

$$D = \left(\frac{h_{FE_1}R_1 + R_2}{2h_{FE_1}} + \frac{R_1 + 2R_2}{2}\right)\left(\frac{1}{R_7} + \frac{1}{R_{10}} - \frac{h_{FE_5}}{R_{13}} + \frac{h_{FE_2}h_{FE_3}h_{FE_5}}{R_{13}}\right.$$

$$\left. + \frac{h_{FE_3}}{R_5} + \frac{h_{FE_3}h_{FE_5}}{R_{13}}\right) + 1$$

or

$$R_0 \approx \frac{R_{13}\,(R_1 + R_2)}{h_{FE_2}h_{FE_3}h_{FE_5}R_2} = \frac{R_1 + R_2}{S}. \tag{26}$$

Temperature Coefficient:

In the analysis that follows, the temperature coefficients of the Zeners only are considered.

From equation (23)

$$V_0 \approx V_i - (h_{FE_1}R_1 + R_2)\, I_{b_1} - \frac{R_1 + 2R_2}{2} I_{Z_1}$$

$$- V_1\left(1 + \frac{R_1 + 2R_2}{R_3}\right) - V_2 \tag{27}$$

$$S_T = \left.\frac{\partial V_0}{\partial T}\right|_{V_i,\, I_L}$$

$$\approx \left(\frac{R_{13}}{R_A} + \frac{R_{13}}{h_{FE_3}R_9}\right)\frac{dV_3}{dT} - \frac{R_{13}}{h_{FE_3}R_9}\frac{dV_4}{dT}$$

$$+ \frac{R_{13}}{h_{FE_3}R_3}\frac{dV_1}{dT} - \frac{1}{S}\frac{dV_2}{dT}. \tag{28}$$

Since S is very large, the last term in equation (28) is negligible.

3. EXPERIMENTAL RESULTS

The theoretical values of stabilization factor, output impedance and temperature coefficient calculated for the circuit given in Fig. 1 are approximately 20,000, 0·5 Ω and + 1 mV/° C respectively. The temperature coefficient with 30 V zener in place of BEL 550A (Fig. 1) is about + 250 mV/° C. Experimentally it is found that due to the AC mains voltage variation from 170 V to 240 V (corresponding to a change of 200 V in the input DC voltage to the regulator) the regular output varies by 0·05 V. The output impedance is less than 1 Ω and the drift in output voltage after warm up period of 15 minutes is less than 0·1%.

4. SQUAREWAVE MODULATOR

For many laboratory experiments it is desirable to have AM microwave power of constant frequency. However, both the power output and frequency of a reflex klystron vary with its reflector voltage. Therefore, pure AM may be obtained only by using an on-off modulation; that is, by superposing a squarewave on the reflector DC voltage. The rise time of the squarewave should be small to avoid frequency modulation. The circuit of the squarewave modulator is shown in Fig. 3.

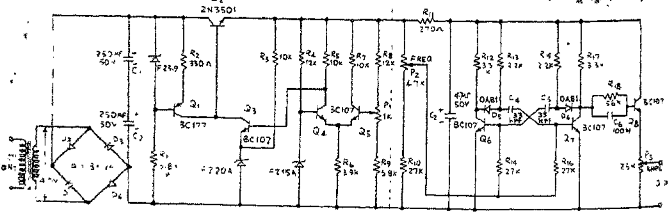

FIG. 3. Circuit diagram of the squarewave modulator.

The frequency of the symmetric squarewave is varied by returning the base resistors of the transistors Q_6 and Q_7 to a variable DC voltage (V_{bb}). The period of the squarewave is given by[3]

$$T = 2RC \ln \left(1 + \frac{V_{cc}}{V_{bb}}\right),$$

where V_{cc} is the collector supply voltage for the transistors Q_6 and Q_7 and $R_{14} = R_{16} = R$ and $C_4 = C_5 = C$. The squarewave amplitude may also be varied using the potentiometer P_3. For the circuit shown in Fig. 3 the squarewave amplitude may be varied from 0 V to 30 V and the frequency may be varied from about 900 to 1100 Hz.

5. PRACTICAL SYSTEM

The schematic diagram of the practical klystron power supply system is shown in Fig. 4. The beam voltage and the reflector voltage supply circuits employ similar solid state voltage regulators discussed above. The beam voltage supply provides a beam voltage of 300 V and a maximum

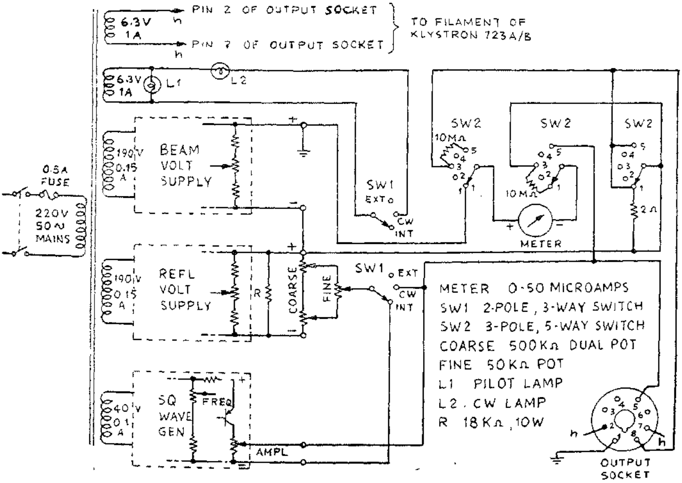

FIG. 4: Schematic diagram of the practical system.

beam current of about 40 mA. In the reflector voltage supply a load resistance R ($=18\ k\Omega$, 10 W) is introduced as shown (the reflector hardly takes any current) to improve line regulation. The reflector voltage may be varied from 0 to -300 V with the help of the 'COARSE' and 'FINE' controls. A modulation switch SW_1 selects CW operation, INTernal or EXTernal modulation of the klystron output. The CW operation is indicated on the front panel by lighting up of the lamp L_2. The monitor switch SW_2 permits the measurement of the beam voltage (SW_2 in position 1), the beam current (SW_2 in position 3), and the reflector voltage (SW_2 in position 5). From meter safety considerations, SW_2 is made to select the alternate outlets.

The circuits are assembled on four 15 cm × 10 cm printed circuit boards and are fixed inside a 25 cm × 20 cm × 15 cm aluminium casing. The complete klystron power supply system weighs about 4·8 kg and has a power consumption of about 60 watts. A conventional klystron power supply using vacuum tubes and having comparable characteristics has 50 cm × 30 cm × 25 cm overall dimensions and weighs about 10 kg and has a power consumption of about 80 watts. A photograph of the system is given in Fig. 5.

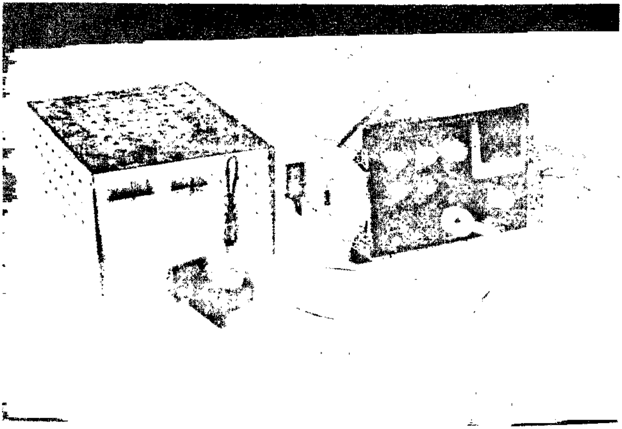

FIG. 5. Photograph of the practical system.

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