CHAPTER 3

VOLTAGE REFERENCE CIRCUITS

The voltage regulator diode is ideal for use in simple stabilising circuits because large changes in the diode current are accompanied by only small changes in the voltage across the diode, as shown in Fig. 1. For example, voltage regulator diode type BZY88–C9V1 has a nominal reference voltage of 9·1V at 5mA; changing the current through this diode from 4 to 64mA (1500%) produces a voltage change of only 0·1V (1·1%).

Basic Stabilising Circuit

The basic equation relating changes in the output of a stabilising circuit to changes in input, load current and temperature is

$$dV_o = \left(\frac{\partial V_o}{\partial V_i}\right)dV_i + \left(\frac{\partial V_o}{\partial I_L}\right)dI_L + \left(\frac{\partial V_o}{\partial T}\right)dT \qquad \ldots(5)$$

where

V_o = output voltage
V_i = input voltage
I_L = load current
T = temperature.

The *stabilisation factor* S is defined as

$$S = \left(\frac{\partial V_o}{\partial V_i}\right) \; I_L \text{ and } T \text{ constant} \qquad \ldots(6)$$

The ratio of the percentage change in output to the percentage change in input causing the change in output is the *fractional change coefficient* S_F. The fractional change coefficient is also known as the *regulation change factor*. Therefore,

$$S_F = \left(\frac{V_i}{V_o}\right)\left(\frac{\partial V_o}{\partial V_i}\right) \; I_L \text{ and } T \text{ constant} \qquad \ldots(7)$$

The *output resistance* is defined as

$$R_o = -\left(\frac{\partial V_o}{\partial I_L}\right) V_i \text{ and } T \text{ constant}$$

and the *temperature coefficient* is defined as

$$S_z = \left(\frac{\partial V_o}{\partial T}\right)_{V_i \text{ and } I_L \text{ constant}}$$

Hence, Eq.(5) can be rewritten as

$$dV_o = SdV_i - R_o dI_L + S_z dT. \qquad \ldots(8)$$

Simple Stabilising Circuit

The simplest stabilising circuit consists of a resistor and voltage regulator diode arranged as shown in Fig. 9a; the equivalent circuit is shown in Fig. 9b.

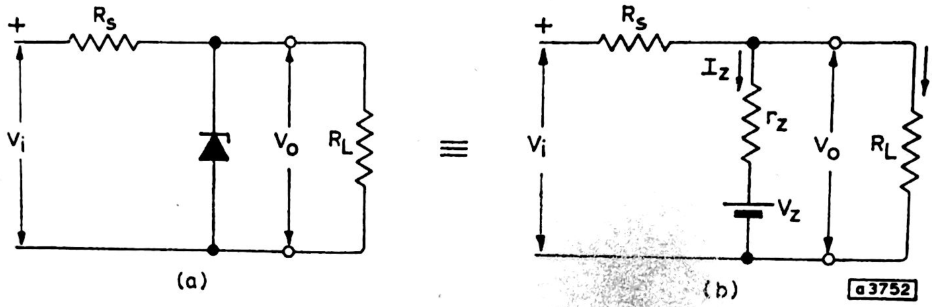

Fig. 9—Simple stabilising circuit and equivalent circuit

Stabilisation Factor

The input voltage in Fig. 9 is

$$V_i = (I_z + I_L)R_s + V_o \qquad \ldots(9)$$

where

I_z = current through the voltage regulator diode after breakdown
I_L = load current
R_s = series resistance including source resistance of the supply.

Therefore,

$$I_z = \frac{V_i - V_o}{R_s} - I_L. \qquad \ldots(10)$$

But

$$I_L = \frac{V_o}{R_L}.$$

Therefore,

$$I_z = \frac{V_i}{R_s} - V_o\left(\frac{1}{R_s} + \frac{1}{R_L}\right).$$

If the voltage across the voltage regulator diode is V_{zs} when the current through it is I_{zs}, the output voltage, V_o, at any other current, I_z, is given by

$$V_o = V_{zs}+(I_z-I_{zs})r_{zs} \qquad \ldots(11)$$

where the effect of junction temperature change is ignored.

Substituting for I_z gives

$$V_o = \frac{V_{zs} + \dfrac{V_i r_{zs}}{R_s} - I_{zs}r_{zs}}{1 + \dfrac{r_{zs}}{R_s} + \dfrac{r_{zs}}{R_L}}. \qquad \ldots(12)$$

Therefore, from Eq.(6),

$$S = \frac{\dfrac{r_{zs}}{R_s}}{1 + \dfrac{r_{zs}}{R_s} + \dfrac{r_{zs}}{R_L}}. \qquad \ldots(13)$$

That is, the stabilisation factor, S, for the single-stage stabilising circuit is given by

$$S = \frac{1}{1 + \dfrac{R_s}{r_{zs}} + \dfrac{R_s}{R_L}}. \qquad \ldots(14)$$

In a simple stabilising circuit, such as that shown in Fig. 10 which uses the BZY96–C7V5, a typical value for S would be 0·063.

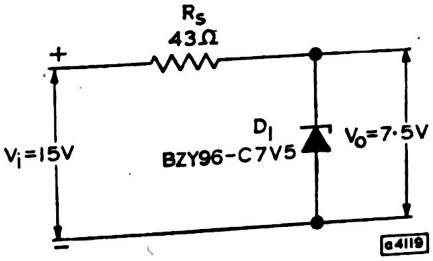

Fig. 10—Stabilising circuit with an output of 7·5V at 100mA

Fractional Change Coefficient

From Eqs.(7), (12) and (13), the fractional change coefficient is

$$S_F = \frac{\dfrac{r_{zs}}{R_s}}{\left(1 + \dfrac{r_{zs}}{R_s} + \dfrac{r_{zs}}{R_L}\right)} \times \frac{\left(1 + \dfrac{r_{zs}}{R_s} + \dfrac{r_{zs}}{R_L}\right)V_i}{\left(V_{zs} + \dfrac{V_i r_{zs}}{R_s} - I_{zs}r_{zs}\right)}.$$

That is,

$$S_F = \frac{1}{1 + \frac{V_{zs}R_s}{V_i r_{zs}} - \frac{I_{zs}R_s}{V_i}}. \qquad \ldots(15)$$

A typical value for the fractional change coefficient of a circuit similar to that in Fig. 10 is 0·124.

Output Resistance and Series Resistance

The output resistance, R_o, in Fig. 9 is

$$R_o = \frac{r_{zs}R_s}{r_{zs}+R_s}.$$

If r_{zs} is much smaller than R_s, the output resistance R_o is approximately equal to r_{zs}. Therefore, R_s should be as large as possible and r_{zs} as small as possible.

Substituting for S and R_o in Eq.(8) gives, for the circuit in Fig. 9,

$$dV_o = \frac{dV_i}{1 + \frac{R_s}{r_{zs}} + \frac{R_s}{R_L}} - \frac{r_{zs}R_s}{r_{zs}+R_s}\, dI_L + S_z dT.$$

From Eq.(9),

$$R_s = \frac{V_i - V_o}{I_z + I_L} \qquad \ldots(16)$$

and substituting the expression for V_o from Eq.(11) gives

$$R_s = \frac{V_i - V_{zs} - (I_z - I_{zs})r_{zs}}{I_z + I_L}.$$

A stabilising circuit similar to that in Fig. 9 is usually designed so that diode current I_z equals the specified reference current I_{zs}. Therefore,

$$R_s = \frac{V_i - V_{zs}}{I_{zs} + I_L}. \qquad \ldots(17)$$

This equation for R_s, however, gives the nominal value; the limit values of R_s are found by substituting the limits of V_i, V_{zs}, I_z and I_L in the equation.

Clearly, to ensure that the required load current is always available,

$$I_{zs}\text{min} + I_L\text{max} \leqslant \frac{V_i\text{min} - V_z\text{max}}{R_s}.$$

Hence, the upper limit for R_s is

$$R_s\text{max} \leqslant \frac{V_i\text{min} - V_z\text{max}}{I_{zs}\text{min} + I_L\text{max}}. \qquad \ldots(18)$$

When determining the upper limit of R_s, the worst possible conditions must be used of course; this means that $V_z$max must be the maximum value at the maximum diode current, which is

$$I_z\text{max} = I_z\text{min} + I_L\text{max} - I_L\text{min}.$$

The resistor R_s also serves to limit the current through the voltage regulator diode to ensure that its maximum permissible dissipation is not exceeded. Consequently, the lower limit of R_s is governed by the maximum permissible dissipation of the voltage regulator diode.

The power dissipated in the voltage regulator diode is

$$P_s = I_z V_z.$$

Substituting for I_z from Eq.(10) gives

$$P_s = \left(\frac{V_i - V_o}{R_s} - I_L\right) V_z$$

$$= \left(\frac{V_i - V_z}{R_s} - I_L\right) V_z$$

because V_z equals V_o.

Maximum dissipation in the diode occurs when the load current is a minimum and is given by

$$P_s\text{max} = \left(\frac{V_i - V_z}{R_s} - I_L\text{min}\right) V_z \qquad \ldots(19)$$

where no allowance has been made for tolerances in the input and output voltages. When the tolerances are taken into account, either

$$P_s\text{max} = \left(\frac{V_i\text{max} - V_z\text{max}}{R_s} - I_L\text{min}\right) V_z\text{max} \qquad \ldots(20)$$

or

$$P_s\text{max} = \left(\frac{V_i\text{max} - V_z\text{min}}{R_s} - I_L\text{min}\right) V_z\text{min}. \qquad \ldots(21)$$

The correct expression depends on the operating conditions of the circuit. It can be determined only by substituting precise values in each expression and comparing the results.

The dissipation of the voltage regulator diode, however, must not exceed its maximum permissible dissipation. Therefore, if $P_s$max is the maximum permissible dissipation,

$$P_s\text{max} > \left(\frac{V_i\text{max} - V_z\text{max}}{R_s} - I_L\text{min}\right)V_z\text{max} \qquad \ldots(22)$$

and
$$P_s\text{max} > \left(\frac{V_i\text{max} - V_z\text{min}}{R_s} - I_L\text{min}\right)V_z\text{min}. \qquad \ldots(23)$$

Both conditions must be satisfied.

From Eqs.(22) and (23), the lower limit of R_s is either

$$R_s\text{min} \geqslant \frac{V_i\text{max} - V_z\text{max}}{\dfrac{P_s\text{max}}{V_z\text{max}} + I_L\text{min}} \qquad \ldots(24)$$

or

$$R_s\text{min} \geqslant \frac{V_i\text{max} - V_z\text{min}}{\dfrac{P_s\text{max}}{V_z\text{min}} + I_L\text{min}}. \qquad \ldots(25)$$

The correct expression for a particular circuit must be determined by substituting precise values in each and comparing the results. The higher of the lower limits of R_s is the value to accept.

The expressions within the brackets in Eqs.(22) and (23) define the maximum diode current. Hence, $V_z$max and $V_z$min in Eqs.(22), (23), (24) and (25) are maximum and minimum values when the current through the diode is a maximum.

When a voltage regulator diode is to be used well within its ratings and in no danger of being overloaded, the value of R_s can be determined from Eqs.(17) and (18). However, a check should always be made with Eqs.(22) and (23) to ensure that the diode is not being overloaded.

When there is any uncertainty about the loading condition of the voltage regulator diode, Eqs.(24) and (25) must be used for determining the minimum value of R_s, and the greater value obtained must be the lower limit of R_s.

Design Procedure for Simple Stabilising Circuit

Usually, the only requirements specified for a simple stabilising circuit are the output voltage and load current. Sometimes the input voltage is also specified, but more often it has to be selected. A large input voltage is desirable for the series resistor will then have a high value (see Eq.(16)). This gives the circuit a good stability factor because

r_{zs}/R_s plus r_{zs}/R_L will be much less than unity and Eq.(13) becomes

$$S \simeq \frac{r_{zs}}{R_s}.$$

With an output of 7·5V and a load current of 100mA, a suitable input voltage is 15V.

As the load current increases, the current through the voltage regulator diode decreases and is a minimum when the load current is a maximum. To ensure stability, the minimum diode current must exceed the breakdown current. On the other hand, the current through the voltage regulator diode must not be too great as this would cause unnecessary dissipation that might damage the diode when the load current is a minimum. With this circuit, 20mA might be a suitable value for the minimum diode current.

The voltage across the diode is a nominal 7·5V. Therefore, the nominal value of the series resistor is, from Eq.(16),

$$R_s = \frac{15-7\cdot5}{20\times10^{-3}+100\times10^{-3}}$$
$$= 62\cdot5\Omega.$$

$\frac{25}{50}$

If the minimum load current is 20mA, the maximum dissipation of the voltage regulator diode is, from Eq.(19),

$$P_s\text{max} = \left(\frac{15-7\cdot5}{62\cdot5} - 20\times10^{-3}\right)7\cdot5$$
$$= 0\cdot75\text{W}.$$

From published data, it will be seen that voltage regulator diode type BZY96–C7V5 has adequate power and operating current ratings, and the required reference voltage. The minimum current value of 20mA was, therefore, quite suitable.

If the stabilising circuit has to cope only with changes caused by varying the load current, the nominal value of the series resistor is acceptable. However, if the circuit has to cope with changes in the input voltage, the limit value of R_s must be accurately determined to ensure that the circuit operates with the most adverse values of input voltage and diode reference voltage. Also, a check must be made to ensure that the voltage regulator diode is in no danger of being overloaded.

In this application the maximum diode current is 100mA. The published data for the BZY96–C7V5 show that when the current through the diode is 100mA the limits of its reference voltage are 7·3 and 8·2V.

Therefore, if the input voltage has a tolerance of ±10%, the series resistance is, from Eq.(18),

$$R_S \leqslant \frac{13{\cdot}5-8{\cdot}2}{120\times10^{-3}} = 44{\cdot}16\Omega.$$

The BZY96–C7V5 has a maximum permissible dissipation of 1·5W. Therefore, from Eq.(24),

$$R_S \geqslant \frac{16{\cdot}5-8{\cdot}2}{\dfrac{1{\cdot}5}{8{\cdot}2}+20\times10^{-3}} = 40{\cdot}9\Omega,$$

and, from Eq.(25),

$$R_S \geqslant \frac{16{\cdot}5-7{\cdot}3}{\dfrac{1{\cdot}5}{7{\cdot}3}+20\times10^{-3}} = 40{\cdot}7\Omega.$$

Hence, the value of R_S must be between 40·9 and 44·16Ω to ensure that the diode is not overloaded and that the output voltage is constant over the given range of input voltage. In the circuit shown in Fig. 10, a value of 43Ω±1% was chosen for the series resistor.

The typical value of r_z for the BZY96–C7V5 is 3Ω; R_L is V_o/I_L and equals 75Ω. Therefore, from Eq.(14),

$$S = \frac{1}{1+\dfrac{43}{3}+\dfrac{43}{75}} = 0{\cdot}063$$

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and, from Eq.(15),

$$S_F = \frac{1}{1+\dfrac{7{\cdot}5\times43}{15\times3}-\dfrac{50\times10^{-3}\times43}{15}} = 0{\cdot}124.$$

$3.63 \times 10^{-3} =$

Stabilised Supply of 27V at 500mA

Fig. 11 shows the circuit of a power supply of 27V at 500mA. A suitable input voltage is 50V, and a suitable value for the minimum current through the voltage regulator diode might be 100mA.

The nominal value of the series resistor is, from Eq.(16),

$$R_s = \frac{50-27}{100\times10^{-3}+500\times10^{-3}} = 38{\cdot}3\Omega.$$

If the minimum load current is zero, the maximum dissipation of the voltage regulator diode is, from Eq.(19),

$$P_s\max = \left(\frac{50-27}{38\cdot3} - 0\right)27 = 16\cdot2\text{W}.$$

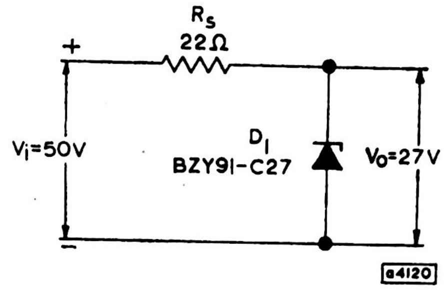

Fig. 11—Stabilising circuit with an output of 27V at 500mA

Published data show that the voltage regulator diode type BZY91–C27 has adequate power and operating current ratings, and the reference voltage required for use in this circuit. The minimum current of 100mA, therefore, was suitable.

The BZY93–C27 also has adequate ratings to meet the foregoing requirements. When the circuit has to accommodate an input voltage tolerance of 10%, however, the higher power rating of the BZY91–C27 is necessary.

The limits of the reference voltage of the BZY91–C27 are 25·1 and 28·9V. Therefore, if the input voltage has a tolerance of ±10%, from Eq.(18),

$$R_s \leqslant \frac{45-28\cdot9}{100\times10^{-3}+500\times10^{-3}} = 26\cdot8\Omega.$$

The maximum permissible dissipation of the BZY91–C27 is 75W. Therefore, from Eq.(24),

$$R_s \geqslant \frac{55-28\cdot9}{\dfrac{75}{28\cdot9} - 0} = 10\cdot08\Omega$$

and, from Eq.(25),

$$R_s \geqslant \frac{55-25\cdot1}{\dfrac{75}{25\cdot1} - 0} = 10\cdot4\Omega.$$

Hence, the value of R_s must be between 10·4 and 26·8Ω. In the circuit shown in Fig. 11, a value of 22Ω±10% was chosen for the series resistor.

The maximum value of r_z for the BZY91–C27 is 1Ω, and R_L is 54Ω. Therefore, from Eq.(14),

$$S = \frac{1}{1 + \frac{22}{1} + \frac{22}{54}} = 0{\cdot}037,$$

and, from Eq.(15),

$$S_F = \frac{1}{1 + \frac{27 \times 22}{50 \times 1} - \frac{0{\cdot}1 \times 22}{50}} = 0{\cdot}078.$$

The maximum power dissipated by the diode in Fig. 11 is, from Eq.(20),

$$P_s\max = \left(\frac{55 - 28{\cdot}9}{22} - 0\right) 28{\cdot}9 = 34{\cdot}3\text{W},$$

or, from Eq.(21),

$$P_s\max = \left(\frac{55 - 25{\cdot}1}{22} - 0\right) 25{\cdot}1 = 34{\cdot}1\text{W}.$$

If the maximum ambient temperature is 65°C, a heatsink will be needed to dissipate the heat generated in the diode. The thermal resistance of the heatsink is, from Eqs.(1) and (2),

$$R_{th\ h-a} = \frac{175 - 65}{34{\cdot}3} - (1{\cdot}47 + 0{\cdot}2) = 1{\cdot}54\text{degC/W}.$$

This, however, is a maximum value and to ensure safety the thermal resistance of the heatsink should be less than 1·54degC/W. Also, this value of thermal resistance is for steady-state dissipation and makes no allowance for any transients. Without knowing what surges can be expected it is impossible to give a more accurate design for the heatsink. However, if the maximum transient dissipation is about 8W, the maximum dissipation expected of the diode will be 43W. Consequently, a safe value for the thermal resistance of the heatsink would be 0·93degC/W. This can be provided by means of extruded heatsink type 56231 that is 4in (102mm) long.

Single-stage Stabilising Circuit with More than One Diode

A higher voltage, or perhaps a voltage nearer a desired value, can be obtained by means of two voltage regulator diodes as shown in Fig. 12. By selecting diodes with opposite temperature coefficients, this arrangement can be given a temperature coefficient of nearly zero.