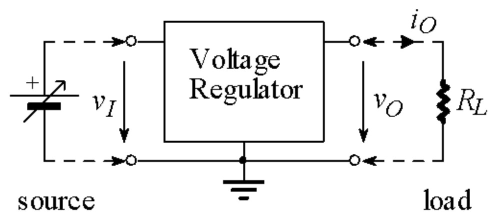
Voltage Regulators

The purpose of a voltage regulator is to provide a constant dc output that is practically independent on the variations of: the input voltage, output load current and temperature.
In Romanian the circuit is called “Stabilizator de tensiune”



The two fundamental classes of voltage regulators are:
- linear regulators and
- switching regulators.

Voltage Regulators Parameters

The two basic aspects of voltage regulation are: line regulation and load regulation.
Line regulation can be defined as the percentage change in the output voltage for one volt change in the input (line) voltage (measured in %/V): $LineRg = \frac{\Delta v_O}{V_O} \cdot \frac{100}{\Delta v_I}$.

Load regulation can be defined as the percentage change in output voltage for a given change in current (e.g. from no-load “NL” to full-load “FL”): $LoadRg = \frac{V_{NL} - V_{FL}}{V_{FL}} \cdot 100$.

For small variations of the output voltage the differentials can be used and:

$$dv_O = \frac{dv_I}{S} - R_o \cdot di_O + TC \cdot dT \,.$$

From this equation, the parameters of the voltage regulator can be found:

$S = \left.\frac{dv_I}{dv_O}\right|_{di_O, dT=0}$ - The S factor, regulation coefficient (Romanian: coeficient de stabilizare);

$R_o = -\left.\frac{dv_O}{di_O}\right|_{dv_I, dT=0}$ - The output resistance (or internal resistance of the source);

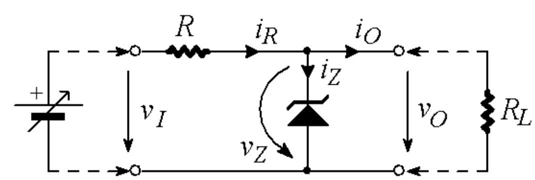
$TC = \left.\frac{dv_O}{dT}\right|_{dv_I, dv_O=0}$ - The thermal coefficient, (Romanian: S_T, coeficient de temperatură).

The small variation parameters of the regulator can be computed using the small signal equivalent circuit.

Linear Regulators

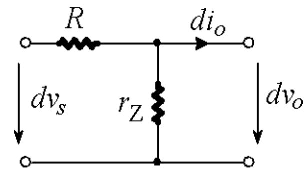
There are two basic types of linear regulators: series regulator and shunt regulator.

The Zener Diode Voltage Regulator



This is the simpler shunt regulator; it consists on a Zener diode in parallel with the load and a series resistor (between input and output).
Input voltage variations and output current variations are converted by the circuit in Zener current variations. As long as: $I_{Z\min} < i_Z < I_{Z\max}$, the Zener voltage is almost constant: $v_Z = \text{ct} = V_Z$ and $v_O = v_Z = \text{ct}$.

The small variation parameters of the voltage the regulator are computed based on the small signal equivalent circuit, where the Zener diode is replaced by its dynamic resistance:



$$S = \left.\frac{dv_I}{dv_O}\right|_{di_O=0} = \frac{R + r_Z}{r_Z} \cong \frac{R}{r_Z}$$ (the voltage divider rule);

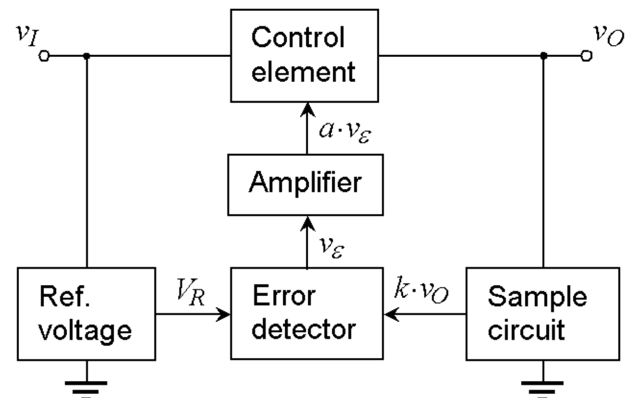
$$R_o = -\left.\frac{dv_O}{di_O}\right|_{dv_I=0} = r_Z \parallel R \cong r_Z$$; the approximations are correct for the usual case: $r_Z \ll R$.

The output resistance of the voltage regulator depends directly on the dynamic resistance of the Zener diode (de aceea în română circuitul se numeşte “Stabilizator parametric”).

The Series Voltage Regulator

The control element is in series with the load; between input and output. The sample circuit senses a change in the output voltage. The error detector compares the sampled voltage with a reference voltage and causes the control element to compensate in order to maintain a constant output voltage:

$v_\varepsilon = V_R - k \cdot v_O = 0$ and $v_O = V_R / k = \text{ct}$.

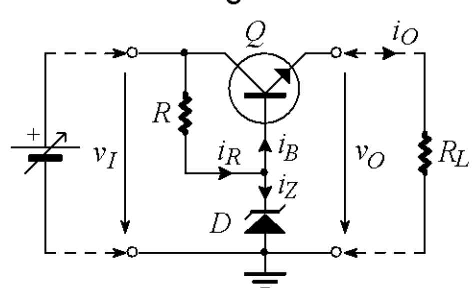


The Emitter-Follower Series Regulator

The simplest series regulator consists on an emitter-follower and a Zener diode regulator (that provides the reference voltage). The circuit is presented in the next figure.

The output voltage is constant: $v_O = V_Z - V_{BE} = \text{ct}$.

The emitter follower reduces the output current variation by a factor of β: $\Delta i_Z = \dfrac{-\Delta i_O}{\beta}$.



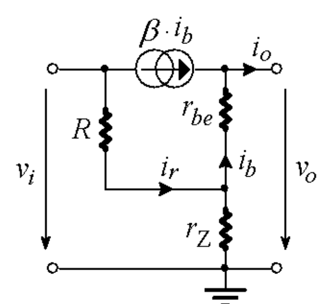
The load current pass through the series transistor, the voltage across the series transistor is: $v_{CE} = v_I - v_O$ and the power dissipation is: $P_D = v_{CE} \cdot i_E = (v_I - v_O) \cdot i_O$.

Q is a power transistor and it is often used with a heatsink.

The regulator parameters can be found from the small-signal equivalent circuit:

$$S = \left.\frac{dv_I}{dv_O}\right|_{di_O=0} = \left.\frac{v_i}{v_o}\right|_{i_o=0} = \frac{R + r_Z}{r_Z} \cong \frac{R}{r_Z};$$

$$R_o = -\left.\frac{dv_O}{di_O}\right|_{dv_I=0} = -\left.\frac{v_o}{i_o}\right|_{v_i=0} = \frac{(r_{be} + R \parallel r_Z) \cdot i_b}{(\beta + 1) \cdot i_b} \cong \frac{r_{be} + r_Z}{\beta + 1} = \frac{1}{g_m} + \frac{r_Z}{\beta}.$$



The S factor can be much greater than that of the zener regulator, because R can be much greater, beeing passed by the Zener current, that is much lower than the output current.

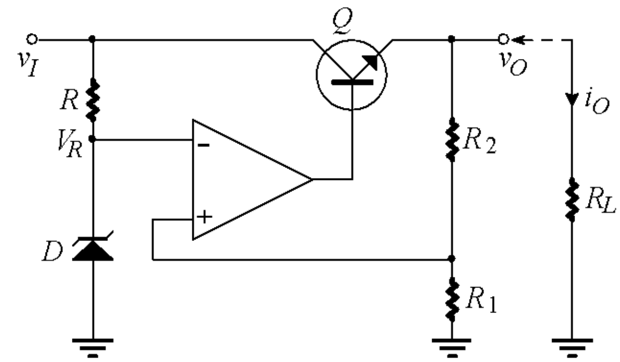
The output resistance is much smaller than for the zener regulator, the dynamic resistance of the zener beeing reduced by the high β factor (and $1/g_m = r_e$ has a very low value).

The Basic Op Amp Series Regulator

The reference voltage V_R is the input of the noninverting amplifier and the R_1/R_2 voltage divider forms the negative feedback network. The ideal closed loop gain is:

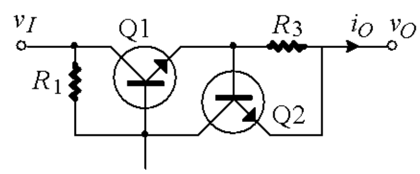
$$A = 1 + \frac{R_2}{R_1}.$$

Therefore the regulated voltage is a constant value determined by the Zener voltage and the resistor ratio: $v_O = \left(1 + \frac{R_2}{R_1}\right) \cdot V_R$.



The Short-Circuit or Overload Protection

If an excessive amount of load (output) current is drawn, the series-pass transistor Q_1 can be quickly destroyed. One method of current limiting to prevent overloads is the "constant current limiting"; it consists of transistor Q_2 and resistor R_3 of the circuit in the next figure.



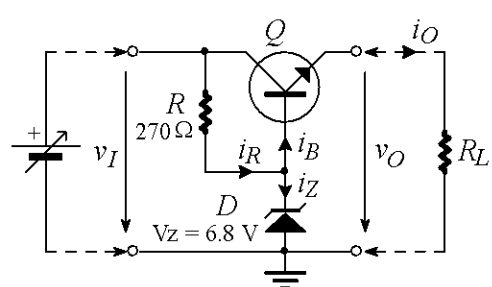
The voltage load through R_3 creates a voltage from base to emitter of Q_2. For normal load current the voltage drop across R_3 is small and Q_2 is off. When i_O reaches the limiting value, the voltage drop across R_3 is sufficient to turn on Q_2. Enough Q_1 base current is diverted into Q_2 so that i_O is limited to its maximum value:

$$I_{O\max} \cong \frac{V_D}{R_3} = \frac{0.7}{R_3}.$$

Since v_{BE} voltage is limited to about 0.7 V for a silicon transistor, the voltage drop across R_3 is held to this value and the load current is limited to $I_{O\max}$.

Application

VR – P1.



1. In the next figure consider $V_I = 10\text{ V}$ and $V_{BE} = 0.7\text{ V}$. What is v_O?
2. If $\beta = 50$ and $R_L = 22\ \Omega$ what is the base current and the zener current for $V_I = 10\text{ V}$?
3. If v_I varies from 10 to 15 V and R_L varies from $22\ \Omega$ to $500\ \Omega$ what is the maximum power dissipation in the transistor, in the Zener and in R?
4. R_L changes from $22\ \Omega$ to $500\ \Omega$. If $\beta = 50$ and $r_Z = 5\ \Omega$, what is the approximate change in output voltage and the load regulation (expressed in %)?

1. $V_O = V_Z - V_{BE} = 6.8 - 0.7 = 6.1\,\mathrm{V}$.

2. $i_R = i_Z + i_B$. $i_Z = i_R - i_B = \dfrac{v_I - V_Z}{R} - \dfrac{i_O}{\beta} = 11.9m - 5.5m = 6.4\,\mathrm{mA}$;

$$i_O = \frac{10 - 6{,}1}{270} = 11.9\,\mathrm{mA},\ i_O = \frac{V_O}{R_L} = \frac{6.1}{22} = 0.277\,\mathrm{A} = 277\,\mathrm{mA},\ i_B = \frac{i_O}{\beta} = \frac{277m}{50} = 5.5\,\mathrm{mA}.$$

3. The transistor power dissipation is: $P_{dQ} = v_{CE} \cdot i_E = (v_I - V_O) \cdot i_O$;

Its maximum power dissipation is: $P_{dQM} = (v_{IM} - V_O) \cdot i_{OM} = (15 - 6.1) \cdot 0.277 = 2.47\,\mathrm{W}$.

The zener diode power dissipation is: $P_{dZ} = V_Z \cdot i_Z \cong V_Z \cdot \left(\dfrac{v_I - V_Z}{R} - \dfrac{i_O}{\beta} \right)$; its maximum is:

$$P_{dZM} = V_Z \cdot \left(\frac{v_{IM} - V_Z}{R} - \frac{V_O}{\beta \cdot R_{LM}} \right) = 6.8 \cdot \left(\frac{15 - 6.8}{270} - \frac{6.1}{50 \cdot 500} \right) = 0.207\,\mathrm{W}.$$

The resistance power dissipation is: $P_{dR} = \dfrac{(v_I - V_Z)^2}{R}$;

Its maximum power dissipation is: $P_{dRM} = \dfrac{(v_{IM} - V_Z)^2}{R} = \dfrac{(15 - 6.8)^2}{270} = 0.25\,\mathrm{W}$.

4. With $V_{BE} = \mathrm{ct}$, the output voltage v_O is modified because of v_Z variation (produced by i_Z variation). To simplify the computing we will consider a constant $v_Z\ (= V_Z)$ when computing the zener current variation, Δi_Z. The limits of the zener current are given by the limits of the output current (load resistance limits); the minimum zener current has been computed for the maximum load current (minimum load resistance) at point 2. The maximum zener current results for the minimum load current (maximum load resistance):

$$i_{Z\max} = \frac{v_I - V_Z}{R} - \frac{i_{O\min}}{\beta} = i_R - \frac{V_O}{\beta \cdot R_{L\max}} = 11.9m - \frac{6.1}{50 \cdot 500} = 11.9m - 502m = 11.7\ \mathrm{mA},$$

$$\Delta v_Z = r_Z \cdot \Delta i_Z = 5 \cdot (11.7 - 6.4)m = 26.5\,\mathrm{mV}.\ LoadRg = \frac{\Delta v_O}{V_O} 100 = \frac{26.5m}{6.1} 100 = 0.43\,\%.$$