

Laboratório 10

Reguladores de Tensão

Referências

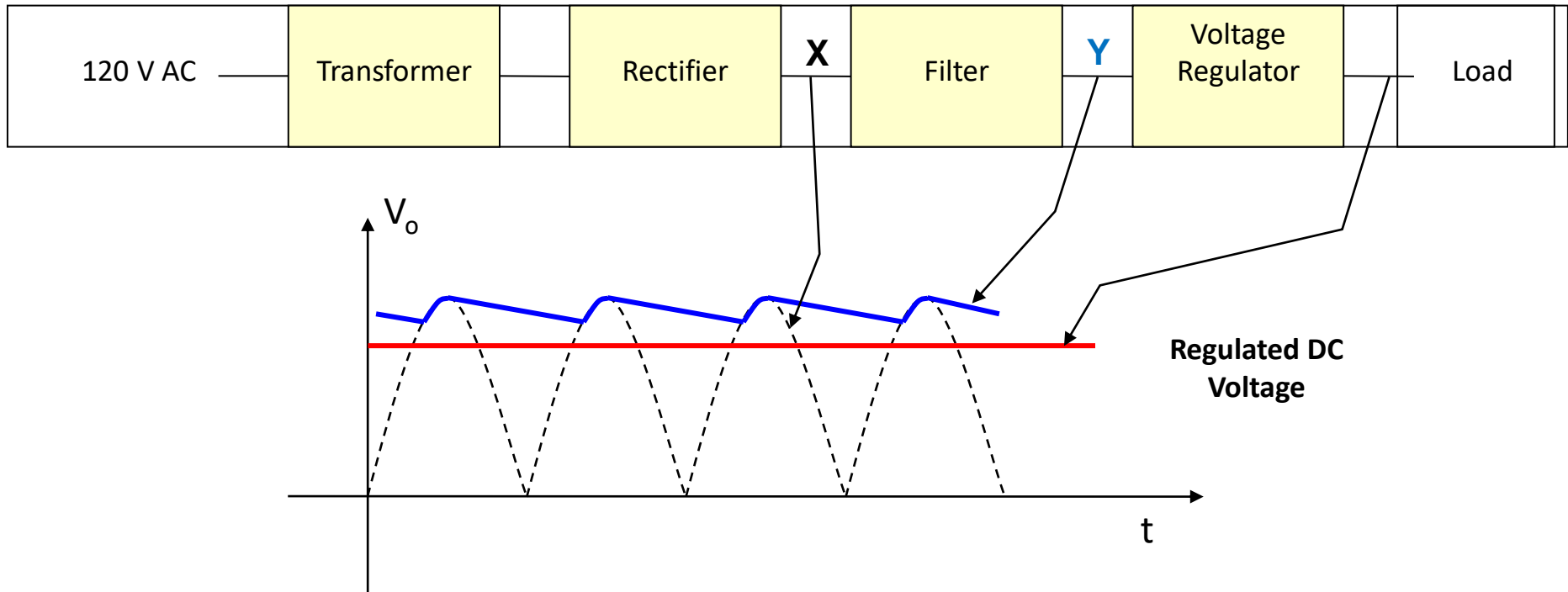
Kit ME3000 - ANALOG ELECTRONICS – Dream Catcher

Fundamentos Teóricos

- **Introduction**
- **Series Voltage Regulation**
 - Zener Regulation
 - Op-Amp Series Regulator
- **Shunt Voltage Regulation**
 - Zener Regulation
 - Op-Amp Shunt Regulator
- **Voltage Regulator IC**
 - Fixed Positive Voltage Regulation
 - Fixed Negative Voltage Regulation
 - Adjustable Voltage Regulation

Introduction

Basic Concept of Voltage Regulation

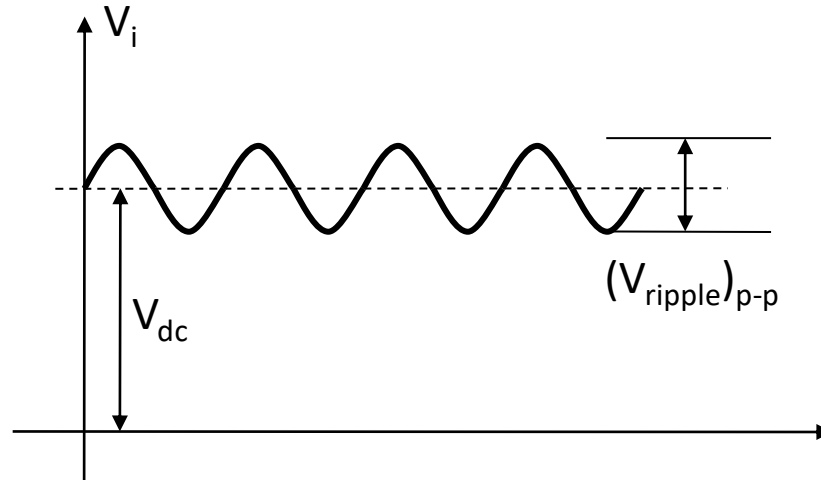


1

Starting with an AC voltage, a steady DC voltage is obtained by rectifying the AC voltage, filtering to a DC level and finally regulating to obtain a desired, regulated DC voltage.

2

Ripple



A typical filter output is shown. It has a DC value and some AC variation.

The smaller the ripple, the better the circuit performance.

$$\begin{aligned} \text{Ripple} &= \frac{\text{ripple voltage (rms)}}{\text{dc voltage}} \\ &= \frac{V_r (rms)}{V_{dc}} \times 100\% \end{aligned}$$

Line Regulation

When the DC input (line) voltage changes, the voltage regulator must maintain a nearly constant output voltage.

Line regulation: percentage of change in output voltage for a given change in the input (line) voltage.

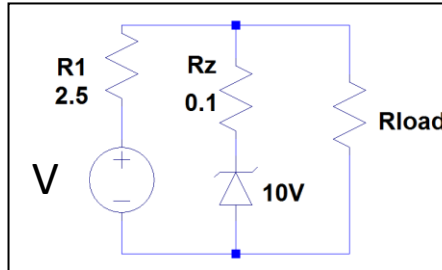
$$\text{Line Regulation} = \frac{\Delta V_{out}}{\Delta V_{in}} \times 100\%$$

Where ΔV_{out} = variation in the output voltage

ΔV_{in} = variation in the input voltage

Exemplo

In the circuit below with $R_{load} = 10\Omega$ calculate the line regulation if V varies from 13V to 17V.



If $V=17V$

$$I_s + I_z + I_{load} = 0 \quad \rightarrow \quad \frac{V_{load}-17}{2.5} + \frac{V_{load}-10}{0.1} + \frac{V_{load}}{10} = 0 \quad \rightarrow \quad V_{load} = 10.171 V$$

If $V=13V$

$$I_s + I_z + I_{load} = 0 \quad \rightarrow \quad \frac{V_{load}-13}{2.5} + \frac{V_{load}-10}{0.1} + \frac{V_{load}}{10} = 0 \quad \rightarrow \quad V_{load} = 10.019 V$$

$$\text{Line Regulation} = \frac{10.171 - 10.019}{17 - 13} = 0,0385$$

$$\frac{\Delta_{in}}{\Delta_{out}} \approx 26$$

Load Regulation

When the amount of current through a load changes due to a varying load resistance, the voltage regulator must maintain a nearly constant voltage across the load.

Load regulation: percentage of change in output voltage for a given change in the load current.

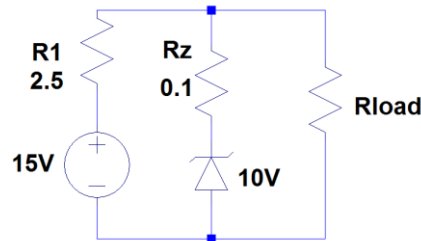
$$\text{Load Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

where V_{NL} = load voltage with no load current

V_{FL} = load voltage with full load current

Load Regulation

Calculate the load regulation considering R_{load} varying between no load and 10Ω .



■ If $R_{load} = \infty$

$$I_{total} = \frac{15 - 10}{2.6} = 1.925A$$

$$V_{load} = 15 - 2.5 \times 1.925 = 10.19V$$

■ If $R_{load} = 10\Omega$

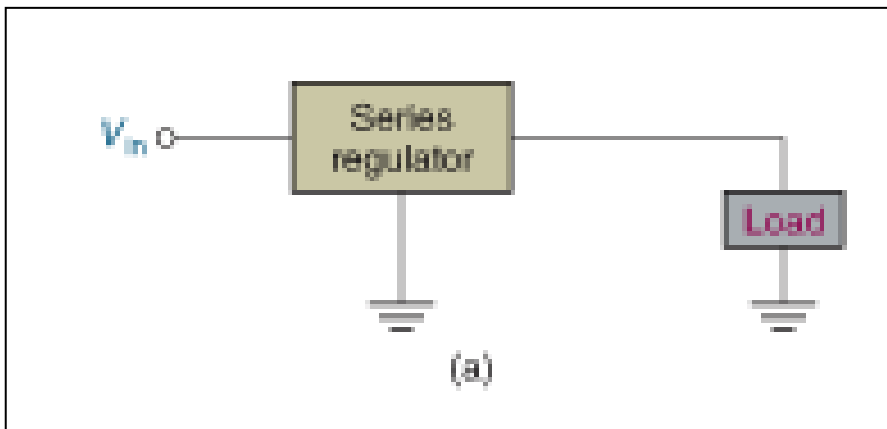
$$I_s + I_z + I_{load} = 0 \quad \rightarrow \quad \frac{V_{load} - 10}{0.1} + \frac{V_{load} - 10}{2.5} + \frac{V_{load}}{10} = 0 \quad \rightarrow \quad V_{load} = 10.10V$$

$$\text{Load Regulation} = \frac{10.19 - 10.1}{10.1} \times 100 = 0.89\% \quad \rightarrow \quad \boxed{\text{Load Regulation} = 0.89\%}$$

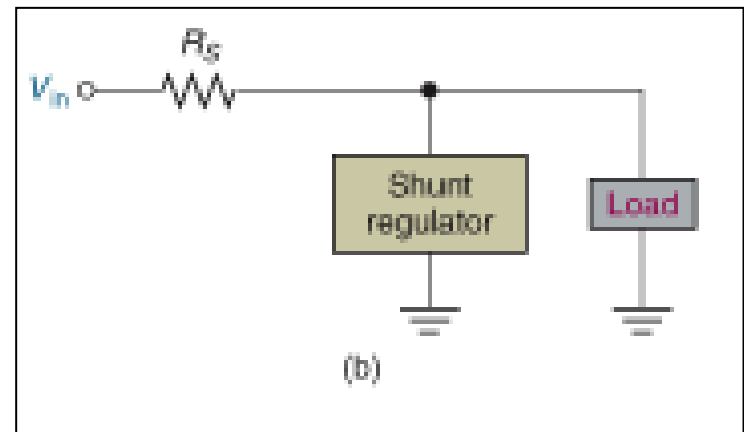
Voltage Regulators

There are two types of voltage regulators:

Series Voltage Regulator

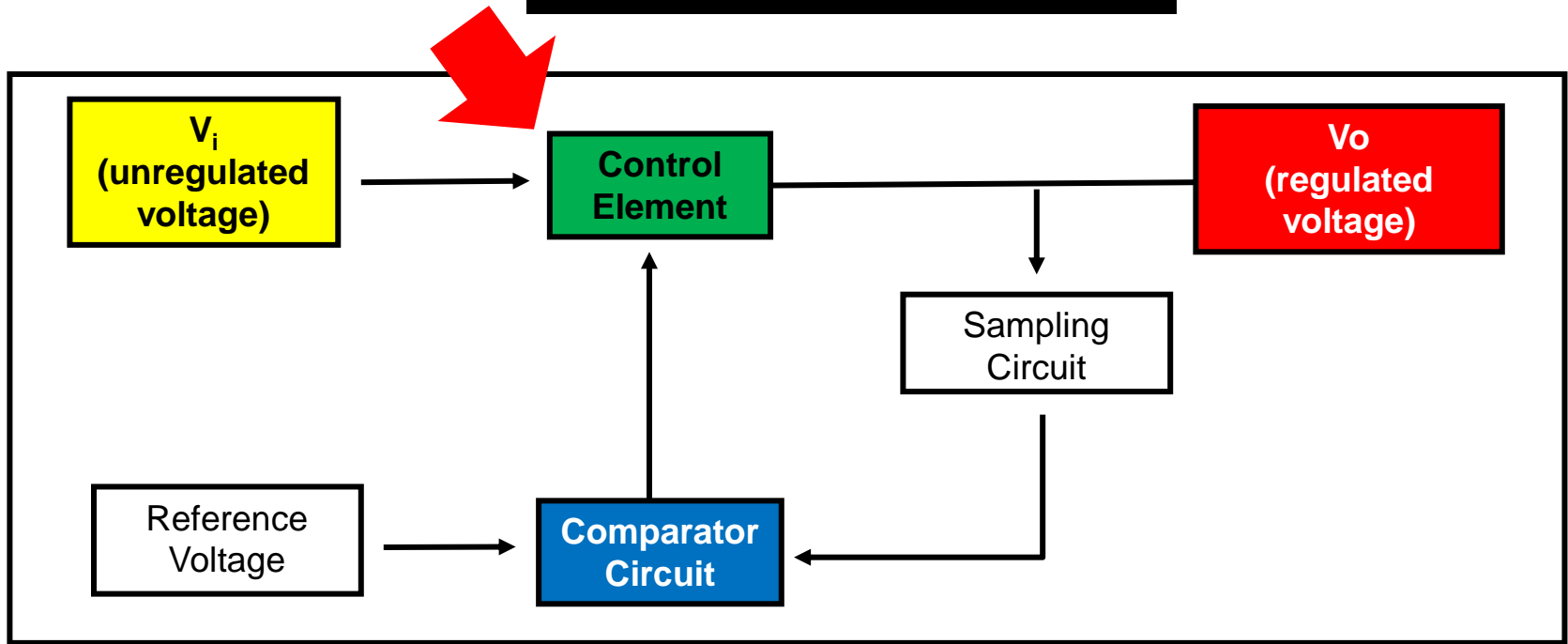


Parallel Voltage Regulator



Series Voltage Regulation

Basic Operation



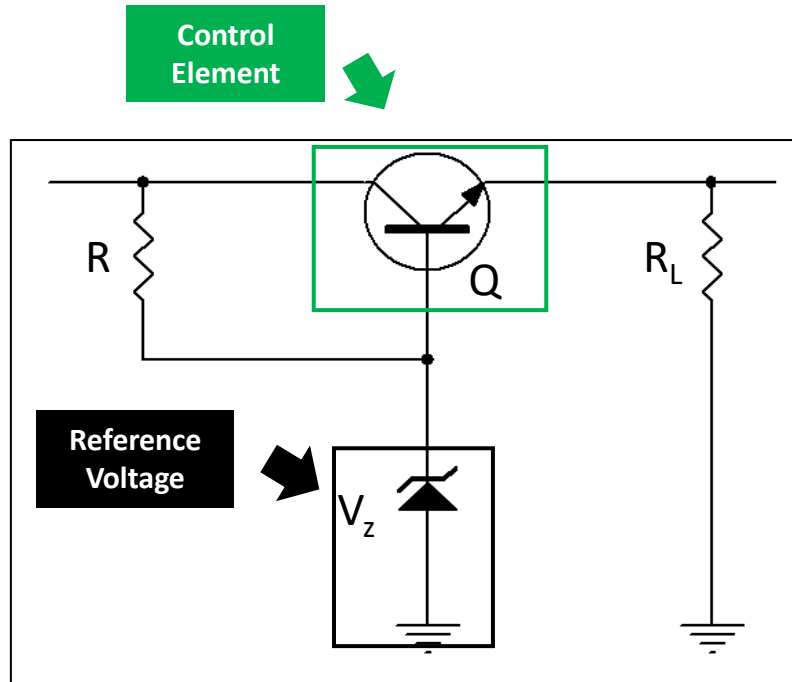
The **control element is in series** with the load between input and output.

The **sampling circuit** is used to sense a change in the output voltage.

The **comparator** compares the sample voltage with a reference voltage and causes the control element to compensate in order to maintain a constant output voltage.

Example

V_i
(unregulated
voltage)



V_o
(regulated
voltage)

$$V_o = V_Z - V_{BE}$$

$$V_{CE} = V_i - V_o$$

$$I_R = \frac{V_i - V_Z}{R}$$

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

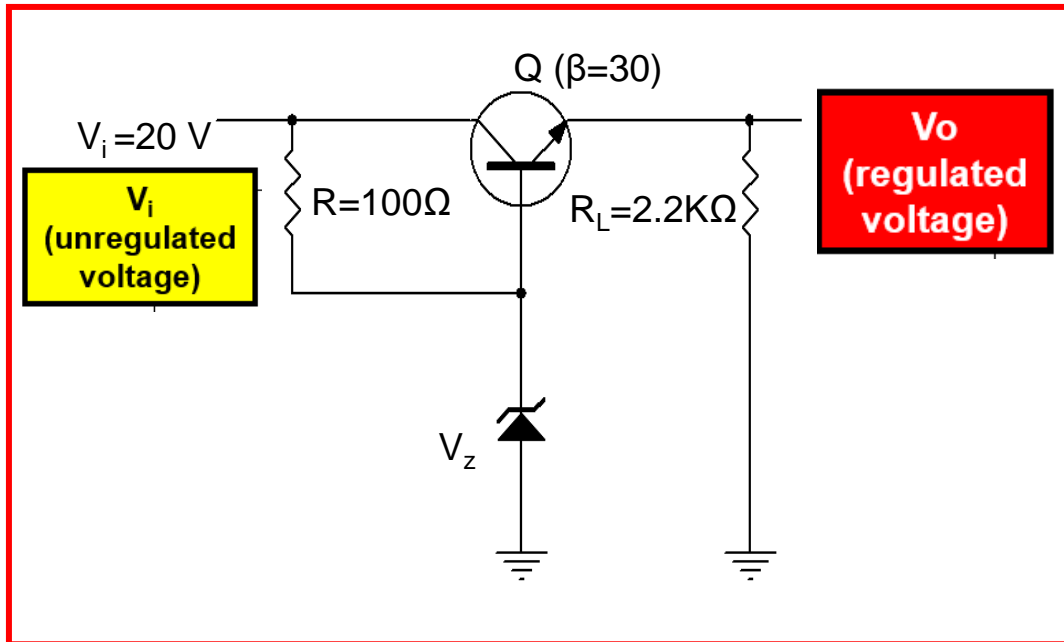
$$I_B = \frac{I_C}{\beta} = \frac{I_L}{\beta}$$

$$I_Z = I_R - I_B$$

- The transistor **Q is the series control element**, while **the zener diode provides the reference voltage**.
- If the output voltage decreases, base emitter voltage increases. This causes transistor Q to conduct more and raise the output voltage.
- If the output voltage increases, base emitter voltage decreases. This causes transistor Q to conduct less and reduce the output voltage.

Exercise

Referring to the following diagram, determine the output voltage and the Zener current.



Solution:

$$V_o = V_z - V_{BE} = 12 - 0.7 = 11.3\text{ V}$$

$$V_{CE} = V_i - V_o = 20 - 11.3 = 8.7\text{ V}$$

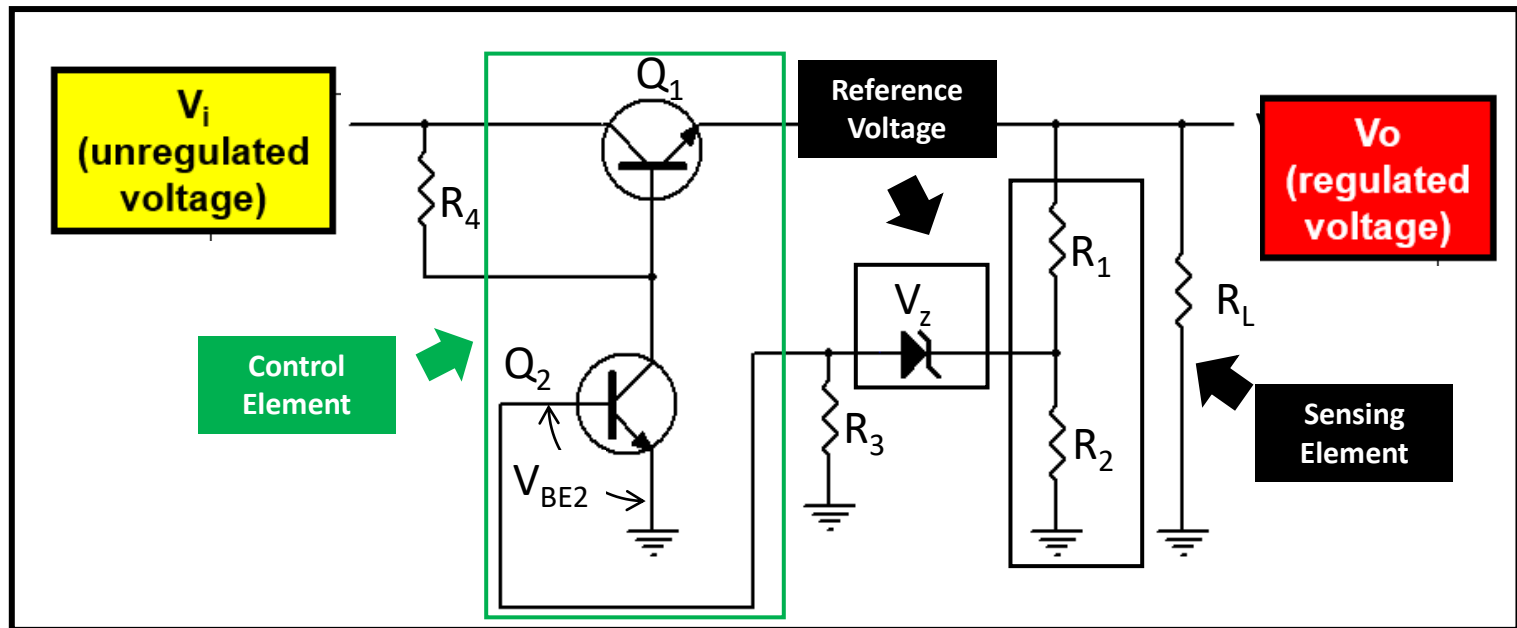
$$I_R = \frac{V_i - V_z}{R} = \frac{20 - 12}{100} = 80\text{ mA}$$

$$I_L = \frac{V_o}{R_L} = \frac{11.3}{2200} = 5.14\text{ mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{I_L}{\beta} = \frac{5.14}{30} = 171\text{ }\mu\text{A}$$

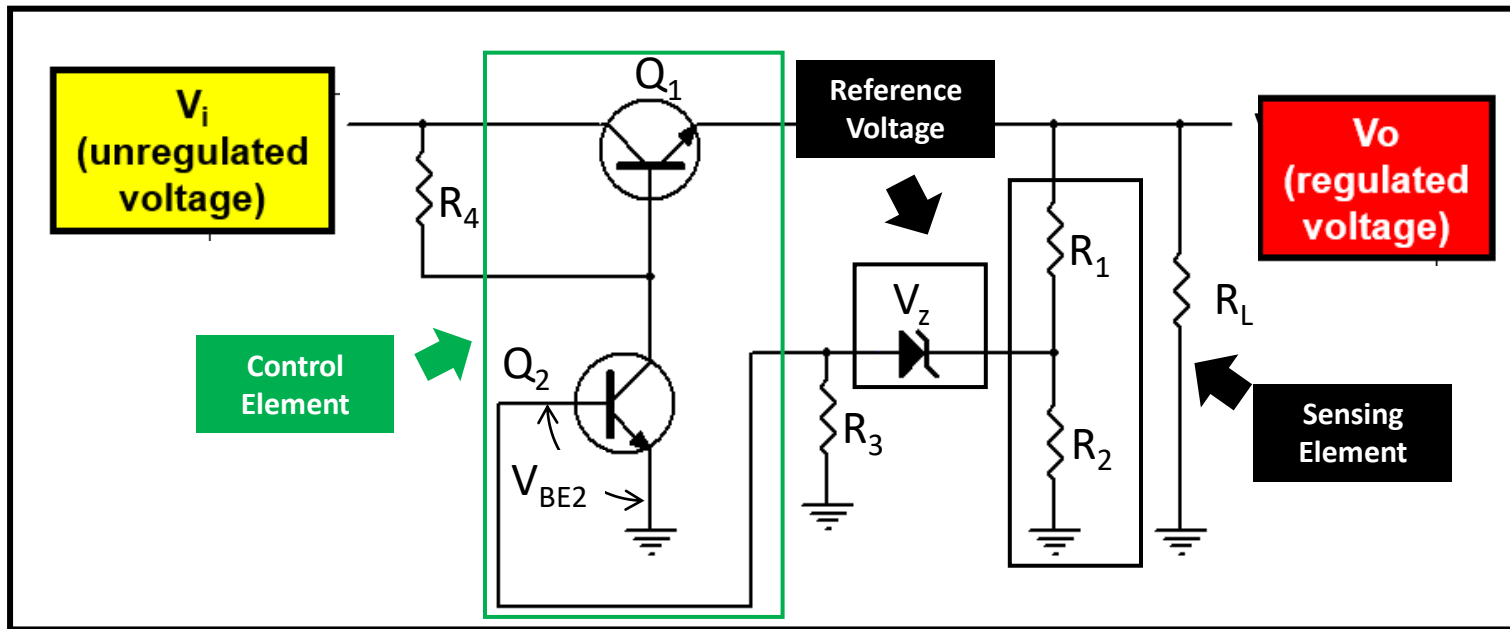
$$I_z = I_R - I_B = 79.8\text{ mA}$$

Improved Series Regulator



- In this configuration, R_1 and R_2 is the sampling circuit, while the Zener diode will provide the reference voltage.
- Q_2 controls the base current of Q_1 .
- If the output voltage increases, voltage across R_2 increases. This causes the base emitter voltage of Q_2 to increase since V_Z remains fixed. If Q_2 conducts more current, less goes to the base of transistor Q_1 , thus reducing output voltage.

Improved Series Regulator (cont.)



- The opposite process takes place if output voltage decreases.

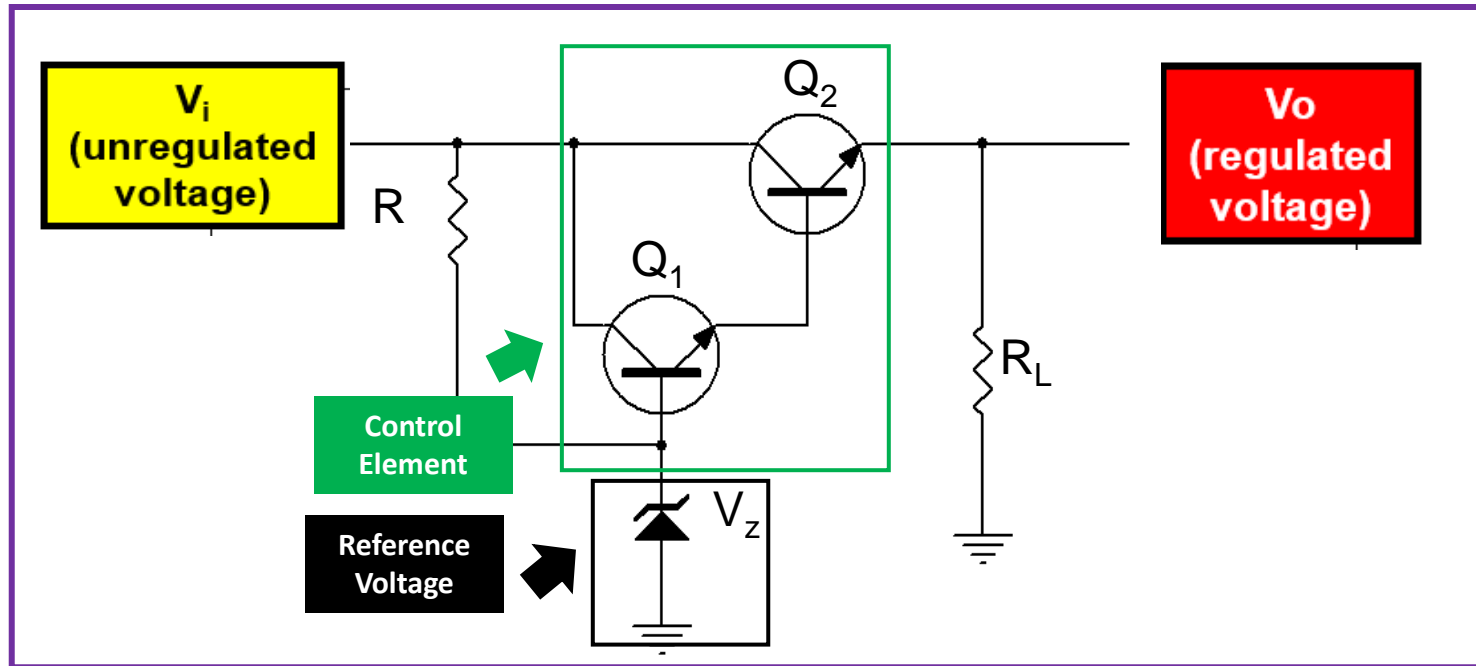
- The voltage across R_2 must equal to the sum of base emitter voltage of Q_2 , i.e.

$$V_{BE2} + V_Z = \frac{R_2}{R_1 + R_2} V_o$$

- The regulated output voltage is given by

$$V_o = \frac{R_1 + R_2}{R_2} (V_{BE2} + V_Z)$$

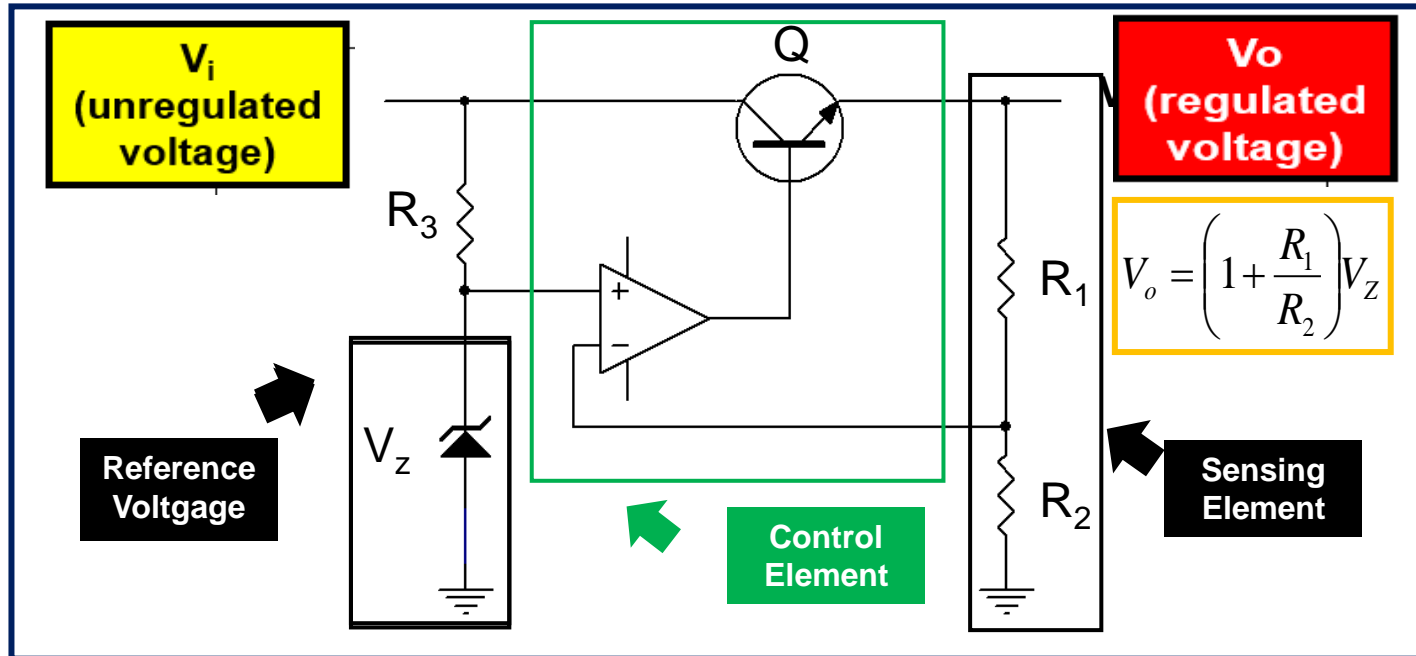
Darlington Pass Transistor Regulator



- In this configuration, **darlington pair is the series control element** while **Zener diode provides the reference voltage**.
- The output voltage will be maintained at a value of

$$V_o = V_Z - V_{BE1} - V_{BE2} = V_Z - 2V_{BE}$$

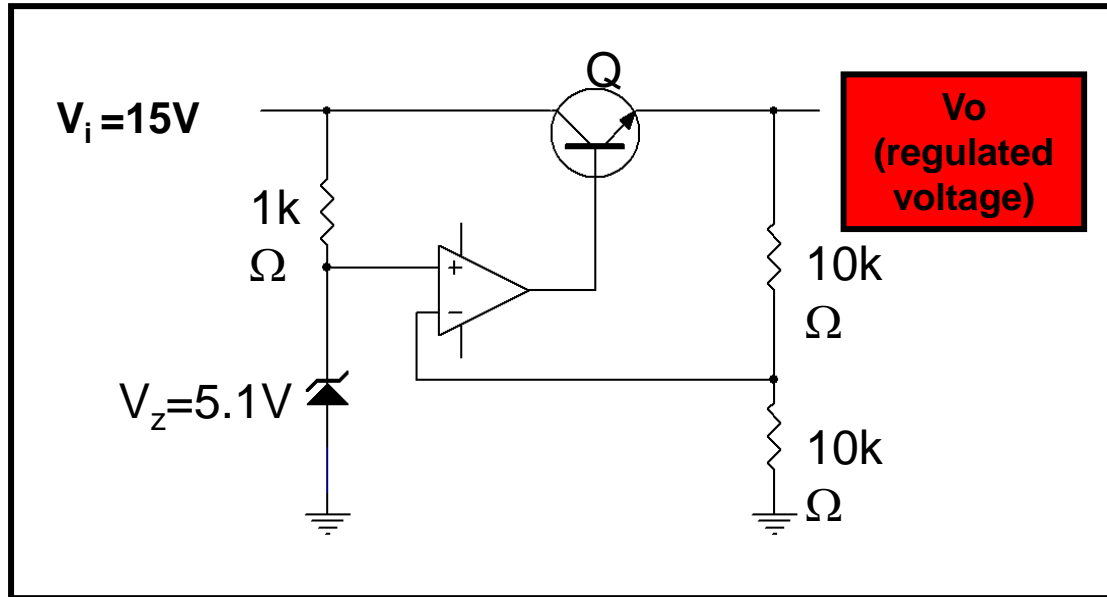
Op-Amp Series Regulator



- The op-amp compares the Zener diode reference voltage with the feedback voltage from **sensing resistor R_1 and R_2** .
- When the output voltage changes, the **conduction of Q is controlled by the op-amp** to maintain a constant output voltage.

Example

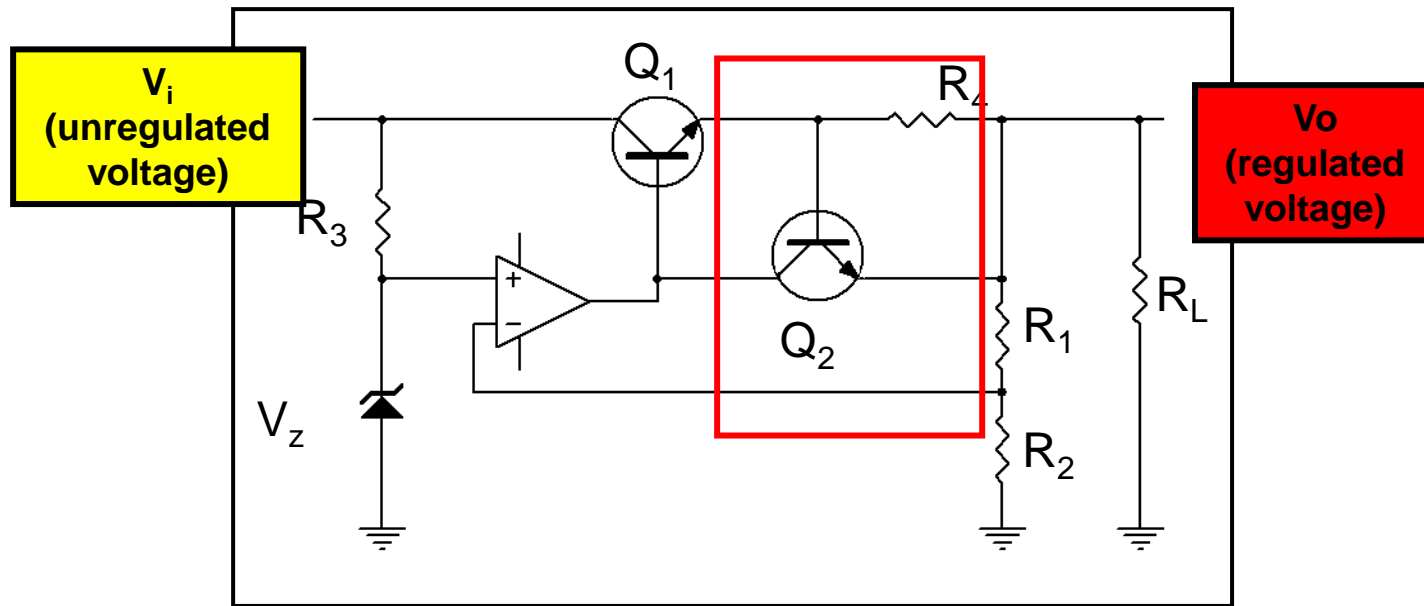
Determine the output voltage of the following regulator.



Solution:

$$\begin{aligned} V_o &= \left(1 + \frac{R_1}{R_2} \right) V_Z \\ &= \left(1 + \frac{10k}{10k} \right) 5.1 \\ &= 10.2V \end{aligned}$$

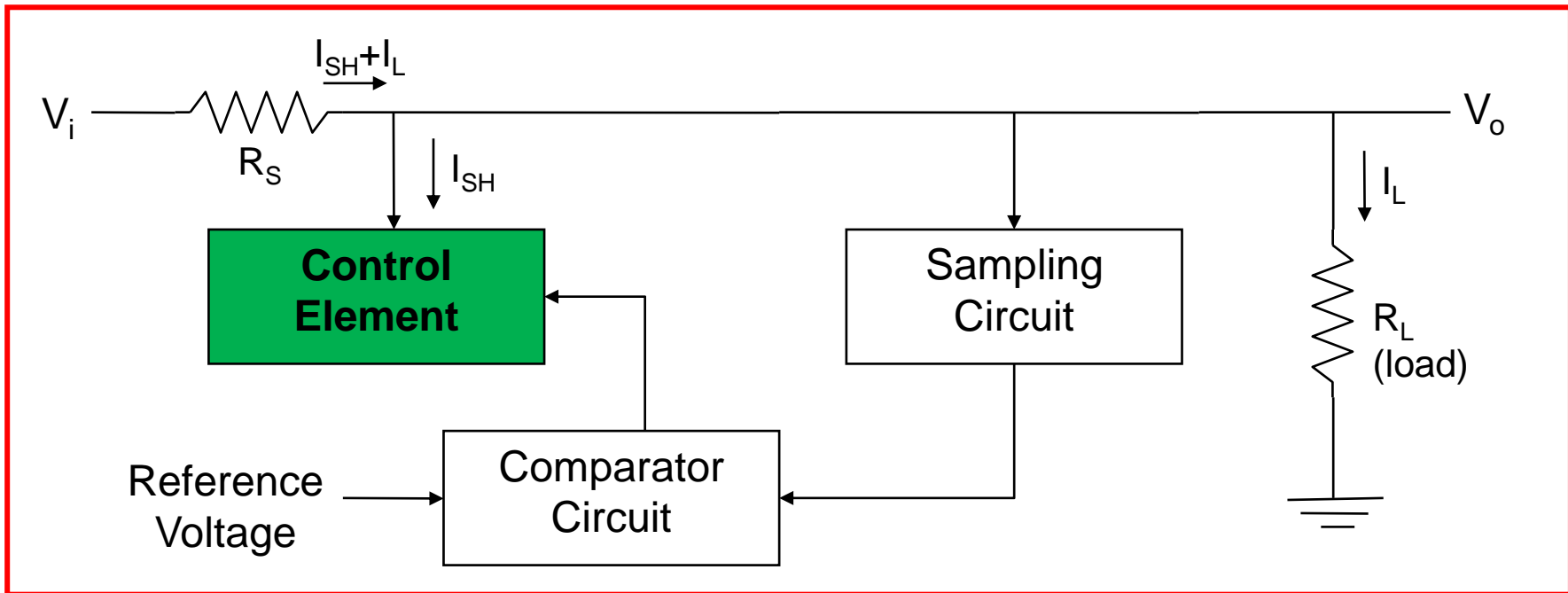
Current Limiting Circuit



- Additional short circuit or overload protection can be applied to the regulator to limit the current flow.
- **R_4 and Q_2 formed the overload or short circuit protection circuit.**
- When load current increases, the voltage drop across R_4 (V_{R4}) increases. If V_{R4} becomes large enough, it will turn on Q_2 , diverting current from base Q_1 and reducing load current through transistor Q_1 . This will prevent any additional current to flow through R_L .

Shunt Voltage Regulation

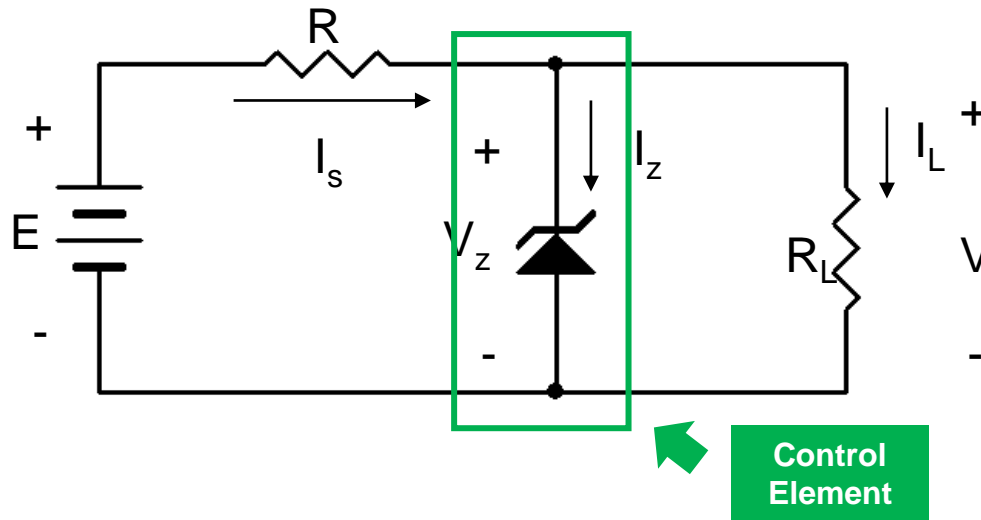
Basic Operation



- The basic block diagram of the shunt regulator circuit is shown here.
- The input unregulated voltage provides current to the load.
- Some current is pulled away by control element to maintain the regulated output voltage across the load.
- The sampling circuit provides a feedback signal to the comparator circuit.
- When the load voltage changes, a control signal is fed back to the control element to maintain the regulated voltage.

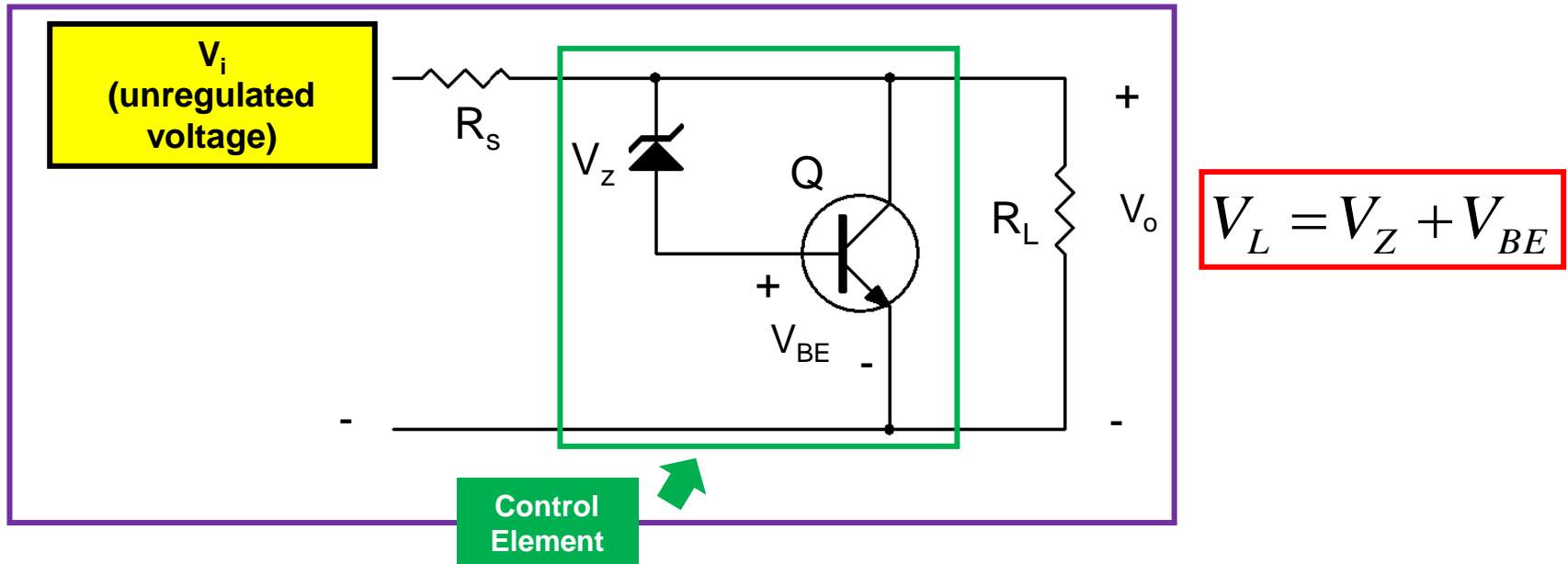
Zener Regulation

- In this configuration, the Zener diode operates in its breakdown region.
- The output voltage equals to the Zener voltage.
- It is a simple Shunt regulator.
- The Zener diode can be small in size but must be able to absorb current levels ranging from zero to maximum current delivered to the load.



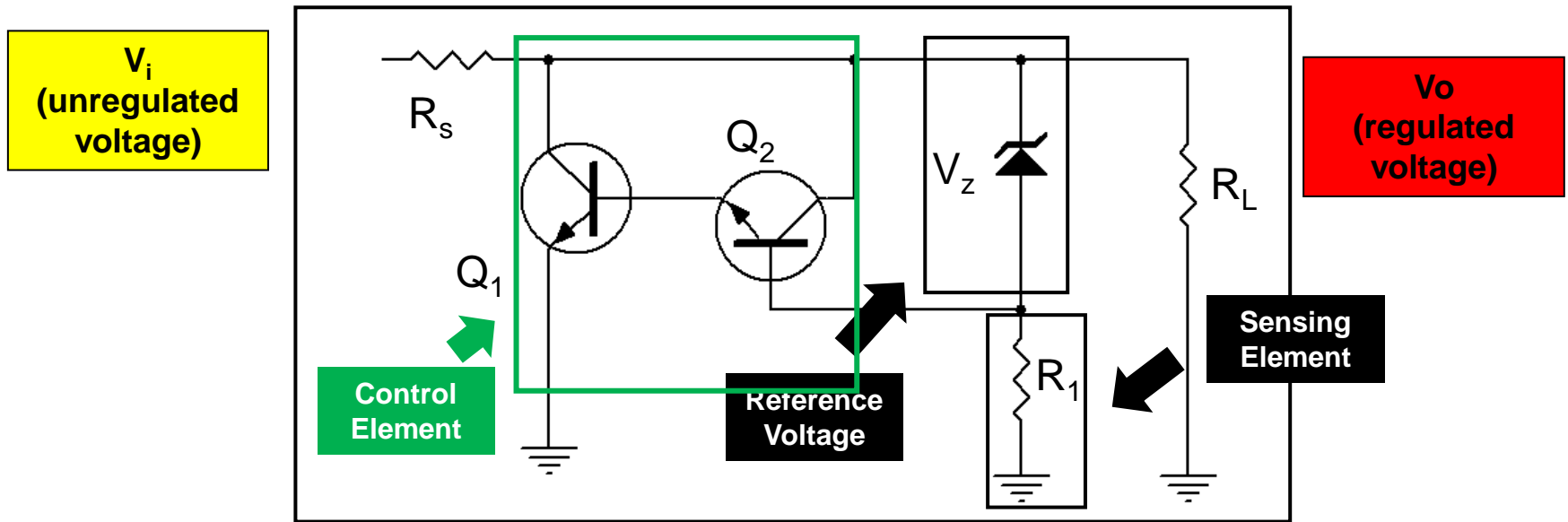
$$I_s = \frac{E - V_z}{R}$$
$$I_L = \frac{V_z}{R_L}$$
$$I_z = I_s - I_L$$

Zener Regulation with Transistor



- In this configuration, **the voltage across the load is set by a Zener diode and a transistor base-emitter voltage.**
- If the load resistance decreases, a reduced drive current to the base of transistor Q causes shunting less collector current. The load current is larger and hence, maintaining the regulated voltage across the load.

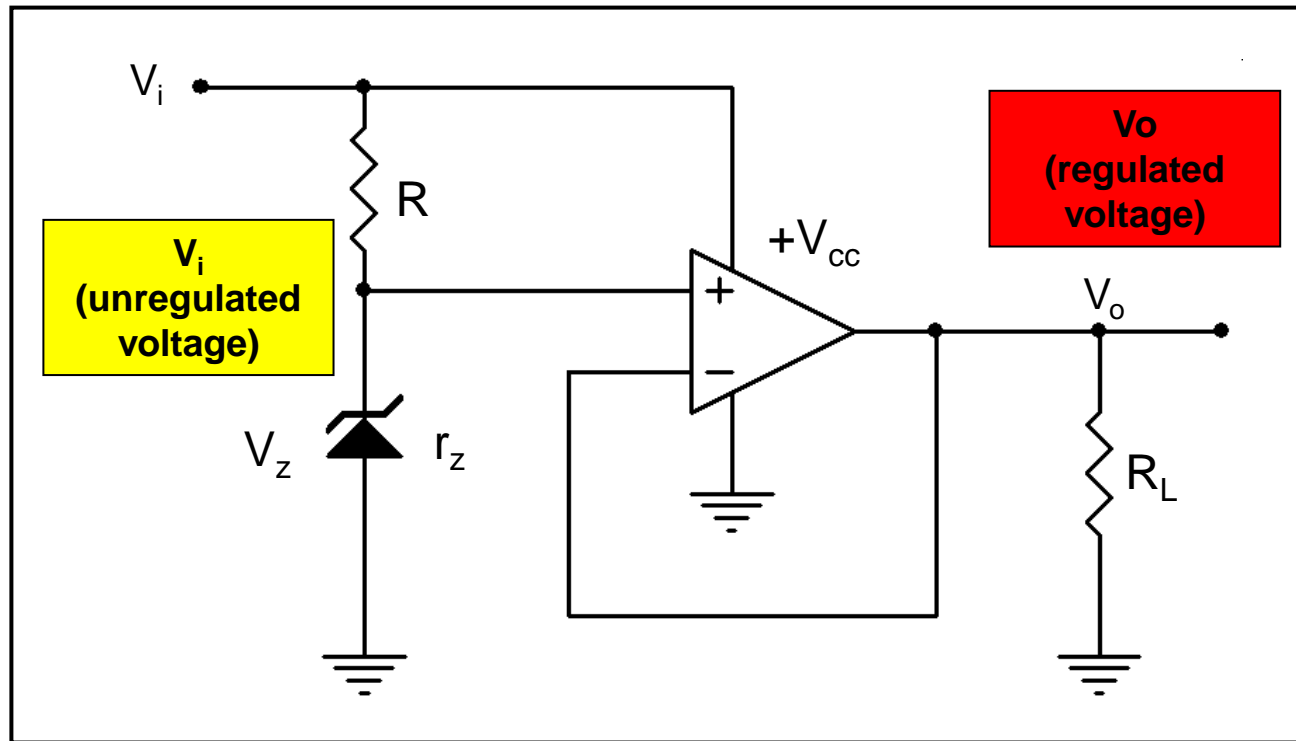
Improved Shunt Regulator



- The Zener diode provide a reference voltage so that the voltage across R_1 can sense the output voltage.
- If the output voltage changes, the current shunted by Q_1 is varied to maintain the output voltage.
- Q_2 provides a larger base current to Q_1 so that the regulator handles a larger load current.

$$V_o = V_L = V_Z + V_{BE1} + V_{BE2}$$

Op-Amp as an IC Regulator



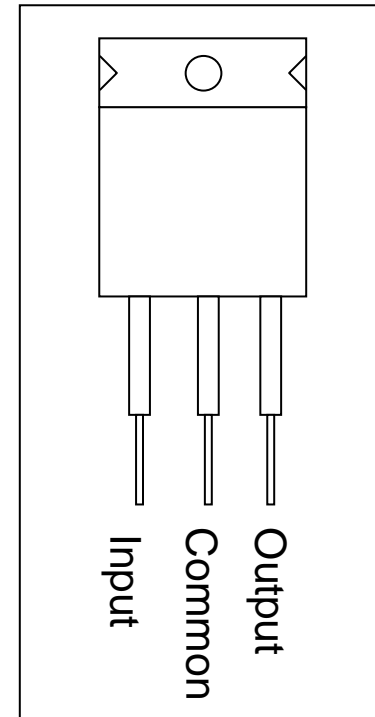
- Op-amp can be used as an IC regulator.
- In this configuration, there is almost no current into the op-amp. No current is drawn away from the Zener diode.
- **The load voltage is independent of the load.**

$$V_L = V_Z$$

Voltage Regulator IC

Voltage Regulator IC

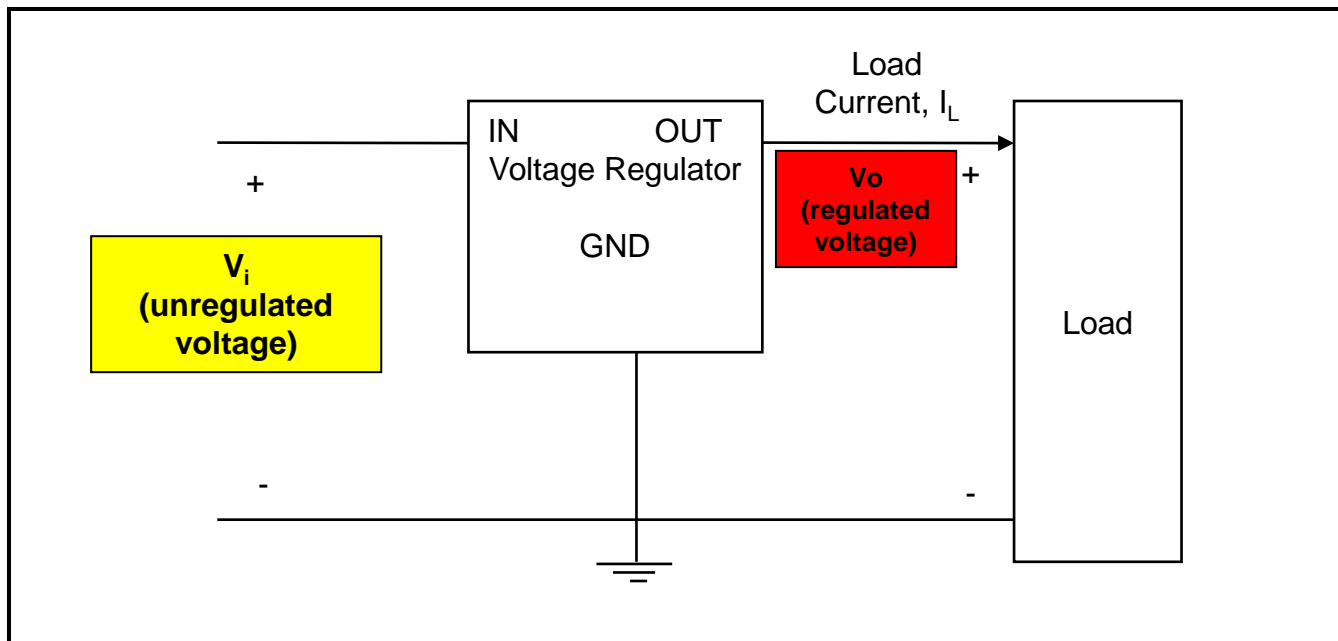
- Voltage regulator ICs are widely used in electronics appliances.
- It consists of circuitry with reference source, control device, and overload protection in a single IC package.
- The output of a voltage regulator IC can be:
 - Fixed positive voltage
 - Fixed negative voltage
 - Adjustable voltage



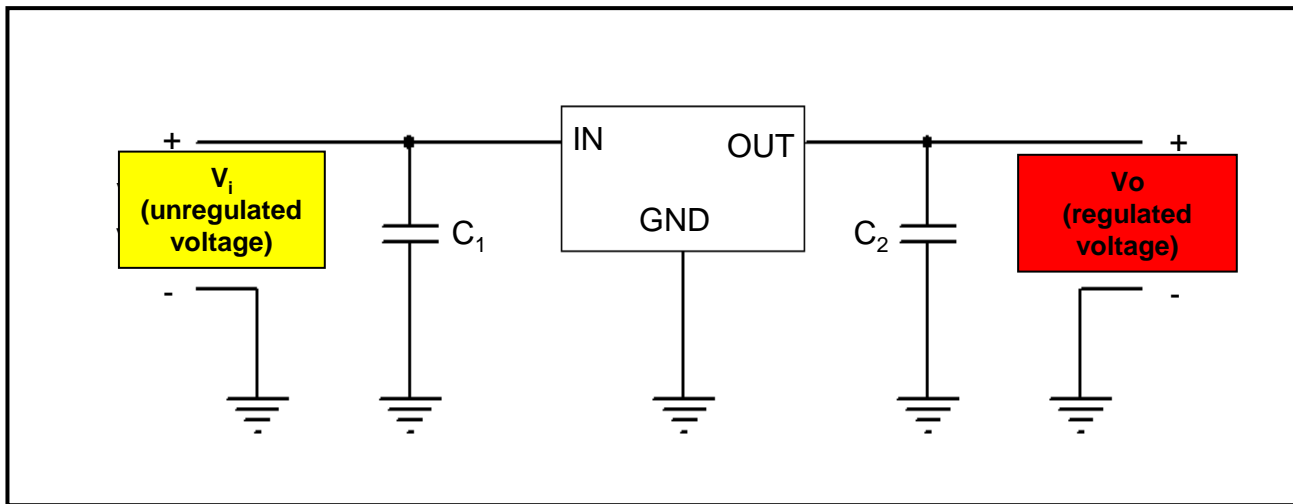
A three-terminal voltage regulator IC

Three Terminal Voltage Regulators

- A typical block diagram of three terminal voltage regulator is shown below.
- An unregulated DC input voltage is applied to the input terminal (IN), a regulated output DC voltage is obtained at the output terminal (OUT), and the third terminal (GND) is connected to the system ground.



Fixed Positive Voltage Regulation



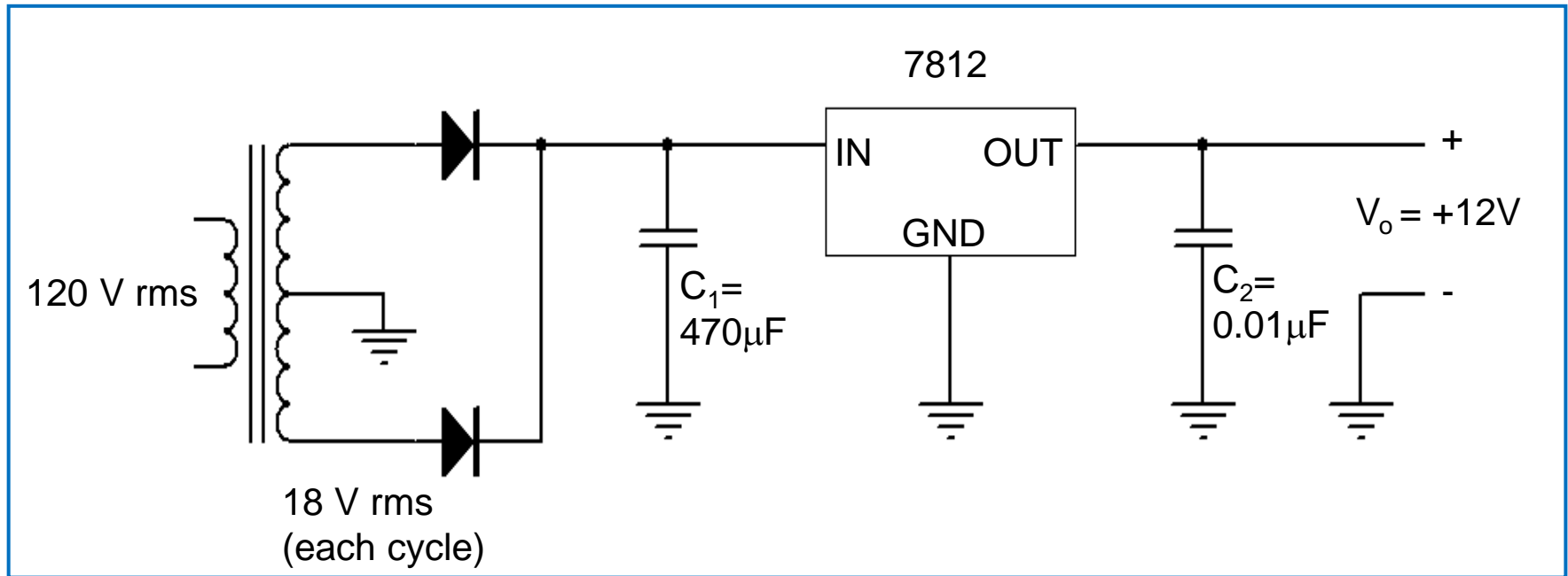
- The 78-series ICs provide fixed regulated voltages ranging from 5 V to 24 V.
- Typically, a capacitor C_1 is connected to the input terminal of the IC to filter high frequency noise.
- Capacitor C_2 is used to filter any high frequency noise appears at the regulated output.

78-series Positive Voltage Regulators

- Table below shows a list of positive voltage regulator ICs available in the market.
- The regulator IC will maintain the rated output voltage as long as the input voltage is greater than a minimum input value ($\sim 2-3$ V).

IC Part	Output Voltage (V)	Minimum V_i (V)
7805	+5	7.3
7806	+6	8.3
7808	+8	10.5
7810	+10	12.5
7812	+12	14.6
7815	+15	17.7
7818	+18	21.0
7824	+24	27.1

Example: +12V Power Supply



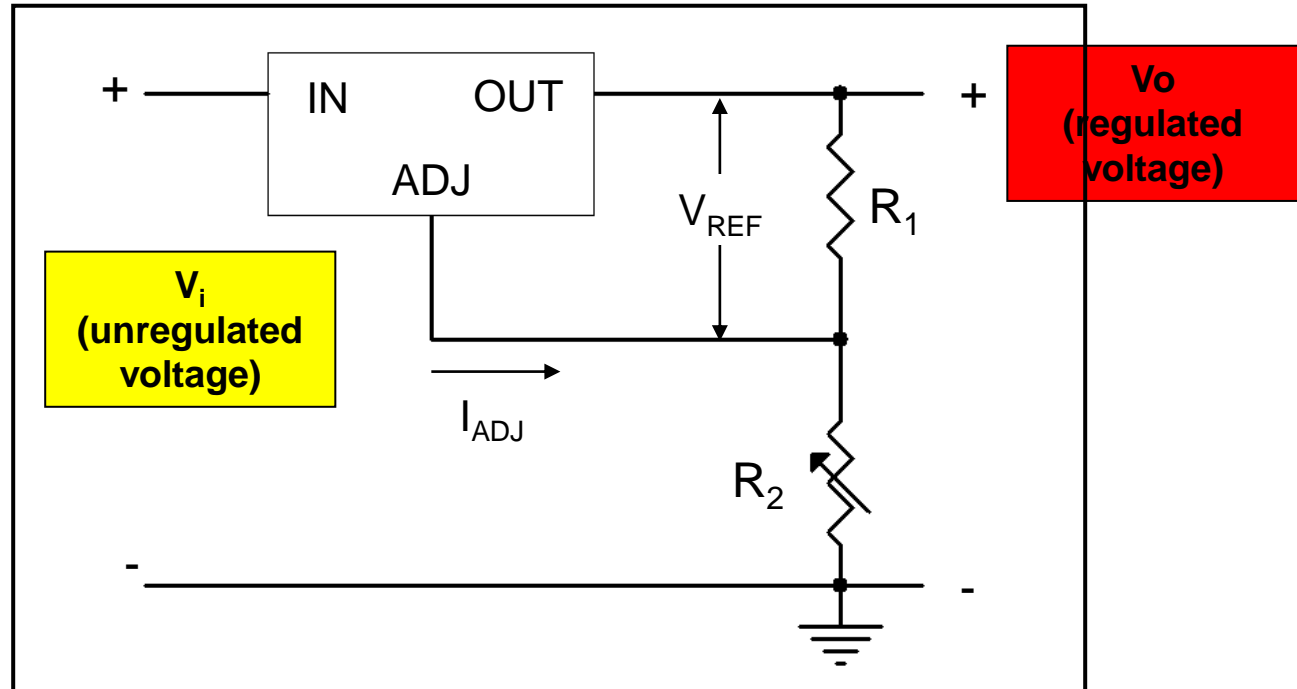
- This diagram shows a simple +12 V power supply by using a step-down transformer and a 7812 voltage regulator.
- The AC line voltage with 120 V rms is stepped down to 18 Vrms across each half by the center tapped transformer.
- A full wave rectifier and a capacitor filter provides an unregulated DC voltage of about 22 V with a ripple of few volts.
- In the final stage, the 7812 provides an output which is regulated at 12 V dc.

Fixed Negative Voltage Regulation

- The 79 series ICs provide fixed negative regulated voltages ranging from -5 V to -24 V .
- The regulator IC will maintain the rated output voltage as long as the input voltage is less than a minimum input value (more negative).

IC Part	Output Voltage (V)	Minimum V_i (V)
7905	-5	-7.3
7906	-6	-8.3
7908	-8	-10.5
7909	-9	-11.5
7912	-12	-14.6
7915	-15	-17.7
7918	-18	-20.8
7924	-24	-27.1

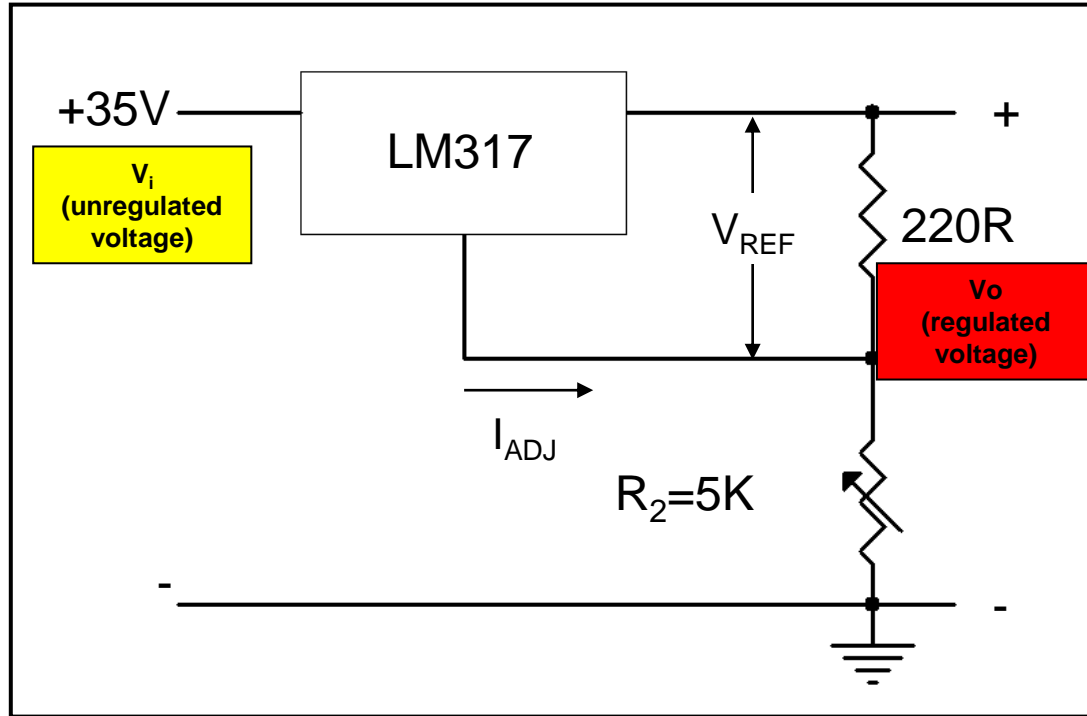
Adjustable Voltage Regulators



- It allows the output voltage to be set at a desired regulated value.
- For example, the LM317 can be adjusted to operate from 1.2 V to 37 V.
- Resistors R_1 and R_2 are used to set the desired output, where

$$V_o = V_{REF} \left(1 + \frac{R_2}{R_1}\right) + I_{ADJ} R_2$$

Example



Determine the minimum and maximum output voltages. $V_{REF} = 1.25V$

Assume $I_{ADJ} = 50\mu A$

When R_2 is at maximum of 5 k Ω :

$$V_o = V_{REF} \left(1 + \frac{R_2}{R_1}\right) + I_{ADJ} R_2 = 29.91V$$

When R_2 is at minimum of 0 Ω :

$$V_o = 1.25V$$

Regulador de Tensão de Alto Desempenho

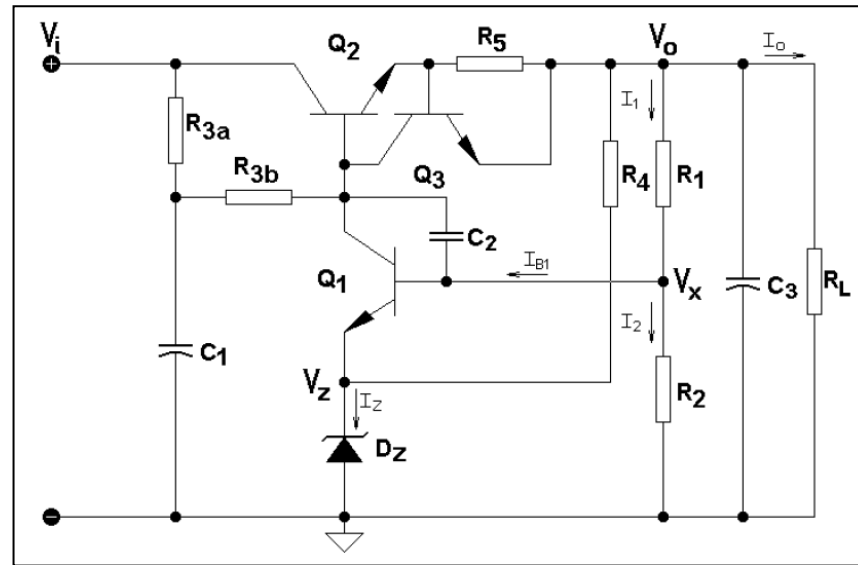
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Exercícios

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2020

22. Estabilizador de Tensão.



Estabilizador com Dispositivo de Proteção Contra Curtos-Circuitos e Sobrecargas.

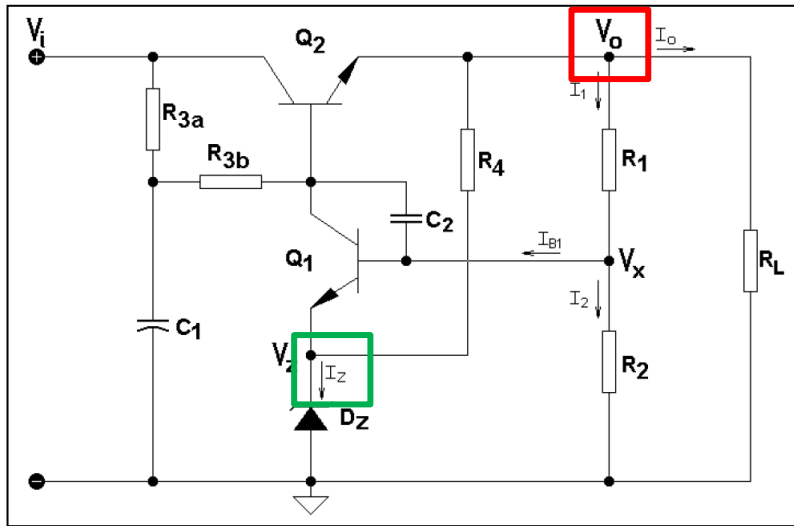
22.1. Proposição

Usando as leis de Ohm e de Kirchhoff, deduzir as equações que calculam os valores da tensão de saída (V_o) e da corrente no diodo Zener (I_z), no circuito da Figura 41. Usar, para o diodo Zener, um modelo linearizado com os parâmetros V_{rev} e R_{rev} e considerar: $I_2 \gg I_{B1}$.

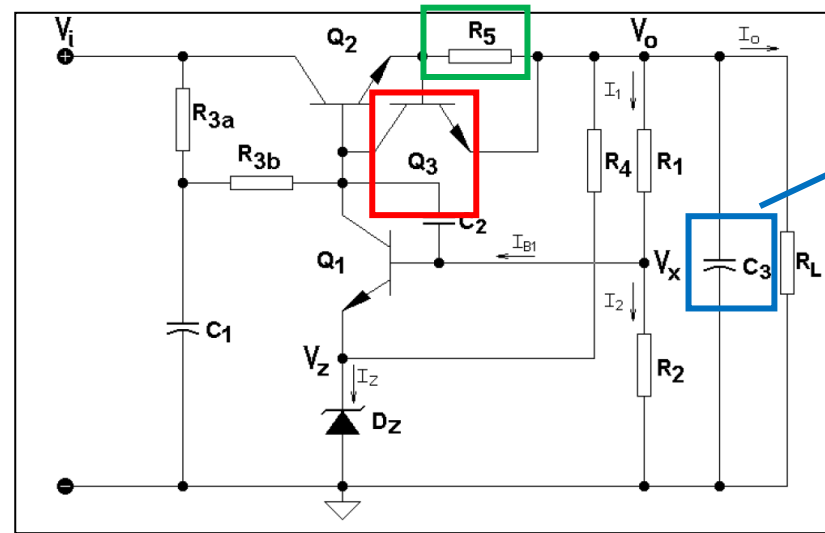
22.2. Resolução Literal

22.3. Resolução Numérica

22. Estabilizador de Tensão.



Estabilizador sem proteção contra curto circuito e sobrecarga



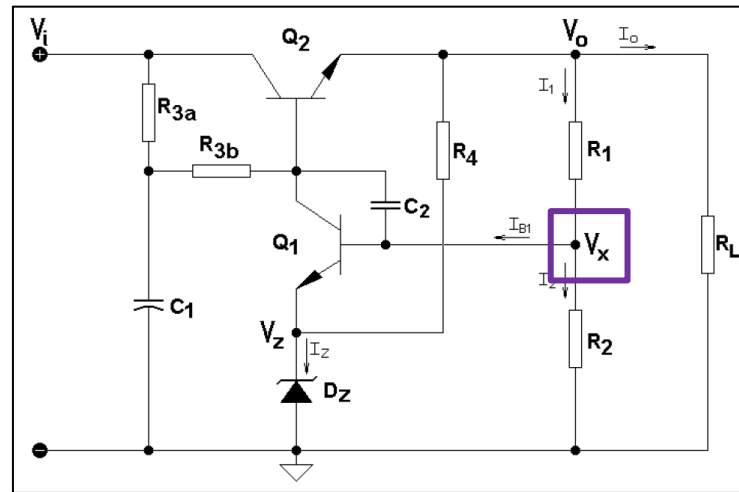
Estabilizador com proteção contra curto circuito e sobrecarga e filtro capacitivo

22.1. Proposição

Usando as leis de Ohm e de Kirchhoff, deduzir as equações que calculam os valores da tensão de saída (V_o) e da corrente no diodo Zener (I_Z), no circuito da Figura 41. Usar, para o diodo Zener, um modelo linearizado com os parâmetros V_{rev} e R_{rev} e considerar: $I_2 \gg I_{B1}$.

22.2. Resolução Literal

Tensão de Saída (V_o)



1 Usando-se o modelo linearizado, a tensão sobre o diodo Zener vale:

$$V_Z = V_{rev} + R_{rev} I_Z$$

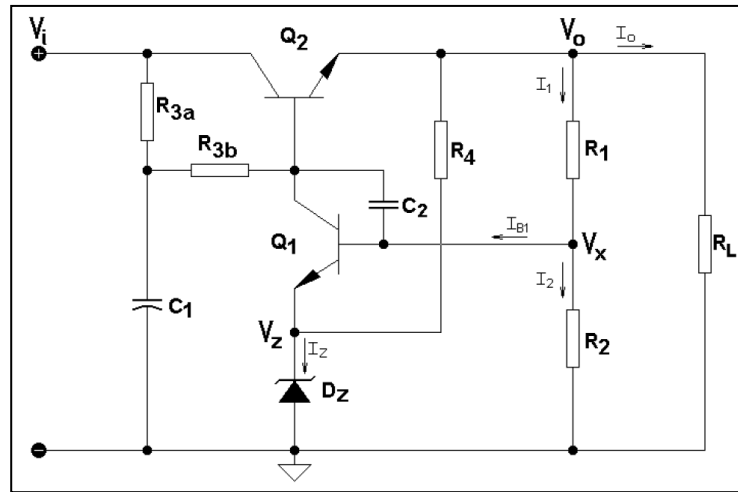
2 Analisando-se o circuito acima constata-se que:

$$V_X = V_{rev} + R_{rev} I_Z + V_{BE1}$$

$$\frac{V_o - V_X}{R_1} = \frac{V_X}{R_2} + \frac{I_{C1}}{\beta_1} \rightarrow V_o = \frac{R_1 + R_2}{R_2} \times V_X + \frac{R_1 I_{C1}}{\beta_1}$$

$$\rightarrow V_o = (V_{rev} + R_{rev} I_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2} + \frac{R_1 I_{C1}}{\beta_1}$$

Corrente de Coletor (I_{C1})



3

$I_2 \gg I_{B1}$, então $I_2 \cong I_1 = V_o / (R_1 + R_2)$.

$$\frac{V_i - V_o - V_{BE2}}{R_3} = I_{C1} + \frac{I_o + I_1 + I_{R4}}{\beta_2 + 1} = I_{C1} + \frac{V_o}{(\beta_2 + 1) \times R_L} + \frac{V_o}{(\beta_2 + 1) \times (R_1 + R_2)} + \frac{V_o - V_{rev} - R_{rev} I_Z}{R_4}$$

$$\rightarrow I_{C1} = \frac{V_i - V_{BE2}}{R_3} - \left[\frac{1}{R_3} + \frac{1}{(\beta_2 + 1)} \times \left(\frac{1}{R_L} + \frac{1}{R_1 + R_2} + \frac{1}{R_4} \right) \right] \times V_o + \frac{V_{rev} + R_{rev} I_Z}{(\beta_2 + 1) R_4}$$

Se β_2 for suficientemente grande, pode-se então aproximar a equação acima para:

$$\rightarrow I_{C1} \cong \frac{V_i - V_{BE2}}{R_3} - \left[\frac{1}{R_3} + \frac{1}{(\beta_2 + 1)} \times \left(\frac{1}{R_L} + \frac{1}{R_1 + R_2} + \frac{1}{R_4} \right) \right] \times V_o$$

5

As Equações de V_o , I_{C1} e I_Z resolvem, portanto, em um problema de análise, o sistema no qual as incógnitas são V_o , I_{C1} e I_Z .

Em um circuito como o da figura para que β_2 seja suficientemente grande, isto é, $\beta_2 > 1500$, o transistor Q_2 deve estar em uma configuração Darlington.

Nesse caso, a Equação de I_{C1} pode ser reescrita, de forma aproximada, como:

$$I_{C1} \cong \frac{V_i - V_{BE2}}{R_3} - \left[\frac{1}{R_3} + \frac{1}{(\beta_2 + 1)} \times \left(\frac{1}{R_L} + \frac{1}{R_1 + R_2} + \frac{1}{R_4} \right) \right] \times V_o \quad \longrightarrow \quad I_{C1} \approx \frac{V_i - V_{BE2}}{R_3}$$

Mas:

$$I_Z = \frac{\frac{\beta_1 + 1}{\beta_1} \times I_{C1} \times R_4 + V_o - V_{rev}}{R_4 + R_{rev}}$$

$$\longrightarrow I_Z \approx \frac{R_4 \times (V_i - V_{BE2}) + (V_o - V_{rev}) \times R_3}{(R_4 + R_{rev}) \times R_3} = \frac{R_4 \times (V_i - V_{BE2})}{(R_4 + R_{rev}) \times R_3} + \frac{V_o - V_{rev}}{R_4 + R_{rev}}$$

6

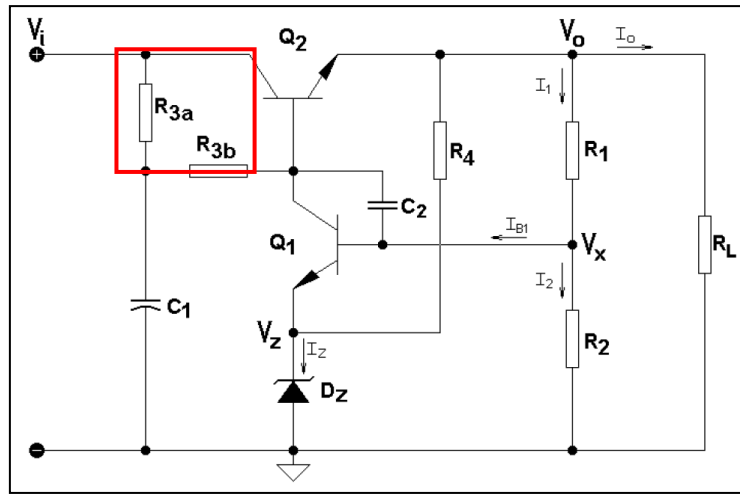
Mostrou-se que:

$$V_o = (V_{rev} + R_{rev}I_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2} + \frac{R_1 I_{C1}}{\beta_1}$$

Se $\beta_1 > 400$, a Equação de V_o pode ser reescrita como:

$$V_o \approx (V_{rev} + R_{rev}I_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2} = (V_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2}$$

Esta equação é normalmente usada para calcular a tensão de saída aproximada do circuito !



7

Mostrou-se que:

$$I_Z \approx \frac{R_4 \times (V_i - V_{BE_2}) + (V_o - V_{rev}) \times R_3}{(R_4 + R_{rev}) \times R_3} = \frac{R_4 \times (V_i - V_{BE_2})}{(R_4 + R_{rev}) \times R_3} + \frac{V_o - V_{rev}}{R_4 + R_{rev}}$$

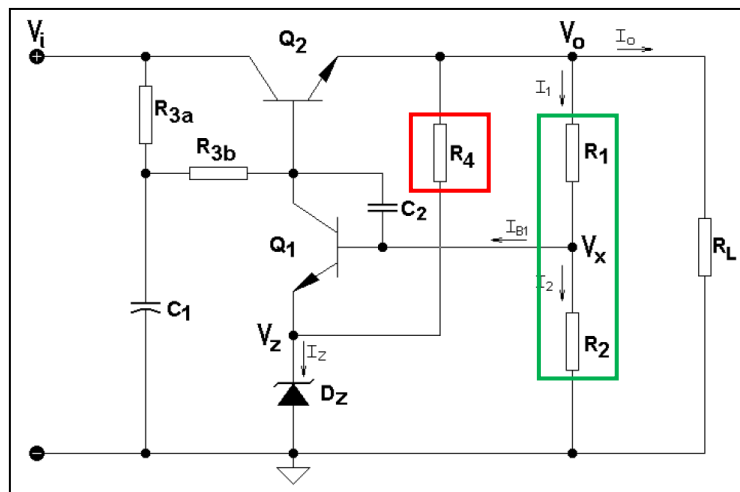
Se $R_3 \gg R_4$, então constata-se que a corrente do diodo Zener fica virtualmente independente de V_i e, então, o estabilizador passa a apresentar uma tensão de saída quase que totalmente independente da tensão de entrada e da carga e, portanto, constante !

8

A resistência R_3 no circuito foi dividida em duas, isto é, $R_3 = R_{3a} + R_{3b}$.

A adição do capacitor C_1 forma, com essas resistências, um filtro passa-baixos com $f_c \leq 2 \text{ Hz}$, que minimiza a injeção de ondulações (*ripple*) e de ruídos no circuito.

9



O resistor R_4 , que provê corrente de polarização para o diodo Zener, deve ser dimensionado para que: $3\text{ mA} \leq I_z \leq 6\text{ mA}$.

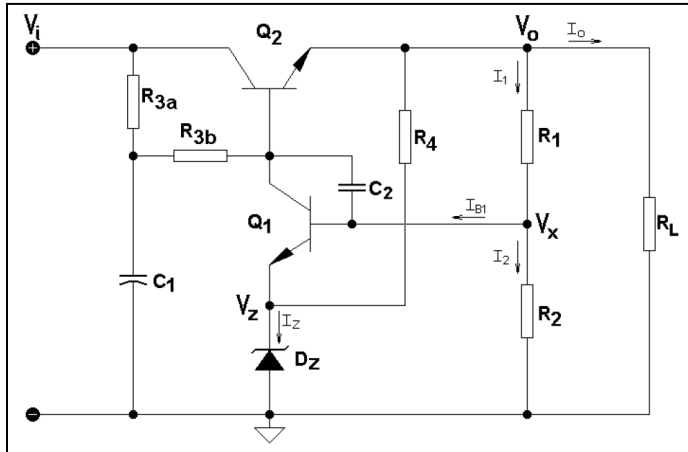
O resistor R_3 , que ainda provê uma parcelada da corrente de polarização do diodo Zener, deve ser dimensionado para que: $300\text{ mA} \leq I_{R3} \leq 1\text{ mA}$ se o transistor Q_2 possuir $\beta_2 > 1500$.

10 Os resistores R_1 e R_2 polarizam a base do transistor Q_1 e devem ser dimensionados para que $1\text{ mA} \leq I_1 \leq 10\text{ mA}$.

11 O transistor Q_1 deve possuir $\beta_1 > 400$ e, portanto, devem ser usados, para esse componente, transistores com sufixo C, como, por exemplo, o BC548C.

12 O transistor Q_2 deve possuir $\beta_2 > 1500$ e, portanto, devem ser usados transistores Darlington como, por exemplo, o 2N6039, o TIP41, o ZTX605, etc., dependendo da corrente de saída e do diferencial de tensão entre a entrada e a saída do estabilizador.

22.3. Resolução Numérica



Resolver o circuito para os seguintes componentes:

$$R_1 = 2,5 \text{ k}\Omega; R_2 = 1 \text{ k}\Omega$$

$$R_{3a} = R_{3b} = 10 \text{ k}\Omega; R_4 = 3,9 \text{ k}\Omega$$

$$R_{L(\text{tip})} = 160 \text{ }\Omega \text{ e } 118,706 \text{ }\Omega \leq R_L \leq \infty$$

A tensão de entrada vale: $V_{i(\text{tip})} = 35 \text{ V}$ e $28 \text{ V} \leq V_i \leq 42 \text{ V}$.

Dados:

Q1 ⇒

$$\beta_1 = 600$$

$$V_{BE1(\text{tip})} = 0,65705 \text{ V e } 0,58794 \text{ V} \leq V_{BE1} \leq 0,67574 \text{ V}.$$

Q2 ⇒

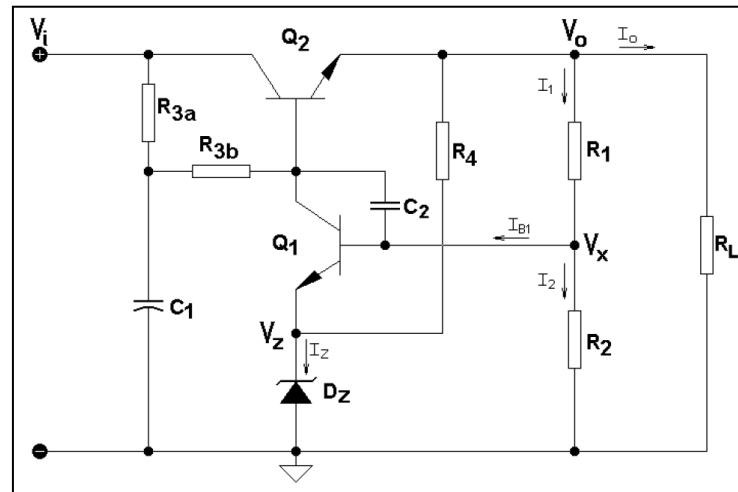
$$\beta_2 = 2000; V_{BE2(\text{tip})} = 1,358 \text{ V e } 1,2871 \text{ V} \leq V_{BE2} \leq 1,3676 \text{ V}.$$

Dz ⇒

$$V_{fwd} = 0,6 \text{ V}; R_{on} = 9 \text{ }\Omega; V_{rev} = 6,15 \text{ V}; R_{rev} = 10 \text{ }\Omega \text{ e } R_{off} = 1,33333 \text{ M}\Omega.$$

Solução Numérica

Valor Típico de V_o



1

Parâmetros:

$V_{itip} = 35 \text{ V}$; $\beta_1 = 600$; $V_{BE1tip} = 0,65705 \text{ V}$; $\beta_2 = 2000$; $V_{BE2tip} = 1,358 \text{ V}$; $R_3 = 20\text{k}\Omega$ e $R_{Ltip} = 160\Omega$.
Usando na equação de V_o :

$$V_o = (V_{rev} + R_{rev}I_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2} + \frac{R_1 I_{C1}}{\beta_1}$$

$$\rightarrow V_o = (V_{rev} + R_{rev}I_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2} + \frac{R_1 I_{C1}}{\beta_1} = (6,15 + 10I_Z + 0,65705) \times 3,5 + \frac{2,5\text{k} \times I_{C1}}{600}$$

2

$$I_{C1} \cong \frac{V_i - V_{BE2}}{R_3} - \left[\frac{1}{R_3} + \frac{1}{(\beta_2 + 1)} \times \left(\frac{1}{R_L} + \frac{1}{R_1 + R_2} + \frac{1}{R_4} \right) \right] \times V_o$$

$$\rightarrow I_{C1} \cong \frac{35 - 1,358}{20\text{k}} - \left[\frac{1}{20\text{k}} + \frac{1}{2001} \times \left(\frac{1}{160} + \frac{1}{3,5\text{k}} + \frac{1}{3,9\text{k}} \right) \right] \times V_o = 1,6821\text{m} - 53,394365\mu \times V_o$$

3

$$I_Z = \frac{\frac{\beta_1 + 1}{\beta_1} \times I_{C_1} \times R_4 + V_o - V_{rev}}{R_4 + R_{rev}}$$

$$\rightarrow I_Z = \frac{\frac{\beta_1 + 1}{\beta_1} \times I_{C_1} \times R_4 + V_o - V_{rev}}{R_4 + R_{rev}} = \frac{\frac{601}{600} \times (1,6821m - 53,394365\mu \times V_o) \times 3,9k + V_o - 6,15}{3,9k + 10}$$

4

Substituindo-se esses valores na equação de V_o , obtém-se:

$$V_o = 24 \text{ V}$$

5

Retornando-se esse valor às equações de I_{C_1} e de I_Z , calcula-se:

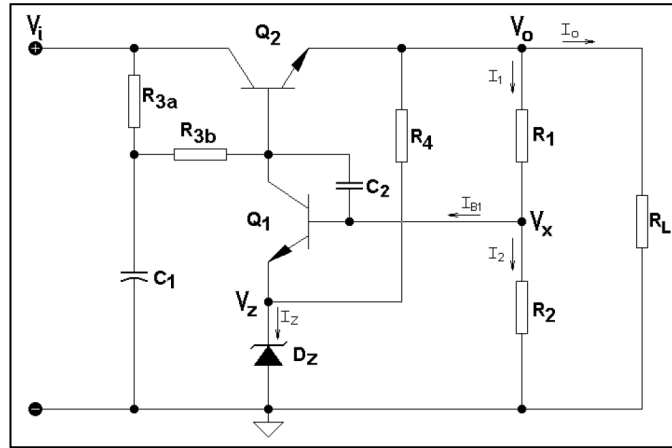
$$I_{C_1} = 400,6279 \mu\text{A}$$

$$I_Z = 4,96552 \text{ mA}$$

6

$$I_o = \frac{V_o}{R_L} = \frac{24}{160} \rightarrow I_o = 150 \text{ mA}$$

Valor Mínimo de V_o



7

A tensão de saída será mínima quando V_i for mínima e a carga for máxima. Parâmetros:

$V_{imin} = 28 \text{ V}$; $\beta_1 = 600$; $V_{BE1min} = 0.58794 \text{ V}$; $\beta_2 = 2000$; $V_{BE2max} = 1,3676 \text{ V}$; $R_3 = 20\text{k}\Omega$ e $R_{Lmax} = 118.706 \Omega$.

Usando-se a equação de V_o :

$$V_o = (V_{rev} + R_{rev} I_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2} + \frac{R_1 I_{C1}}{\beta_1}$$

$$\rightarrow V_o = (V_{rev} + R_{rev} I_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2} + \frac{R_1 I_{C1}}{\beta_1} = (6,15 + 10 I_Z + 0,58784) \times 3,5 + \frac{2,5k \times I_{C1}}{600}$$

8

$$I_{C1} \cong \frac{V_i - V_{BE2}}{R_3} - \left[\frac{1}{R_3} + \frac{1}{(\beta_2 + 1)} \times \left(\frac{1}{R_L} + \frac{1}{R_1 + R_2} + \frac{1}{R_4} \right) \right] \times V_o$$

$$\rightarrow I_{C1} \cong \frac{28 - 1,3676}{20k} - \left[\frac{1}{20k} + \frac{1}{2001} \times \left(\frac{1}{118,706} + \frac{1}{3,5k} + \frac{1}{3,9k} \right) \right] \times V_o = 1,33162m - 54,481\mu \times V_o$$

9

$$I_Z = \frac{\frac{\beta_1 + 1}{\beta_1} \times I_{C_1} \times R_4 + V_o - V_{rev}}{R_4 + R_{rev}}$$

$$\rightarrow I_Z = \frac{\frac{\beta_1 + 1}{\beta_1} \times I_{C_1} \times R_4 + V_o - V_{rev}}{R_4 + R_{rev}} = \frac{\frac{601}{600} \times (1,33162m - 54,481\mu \times V_o) \times 3,9k + V_o - 6,15}{3,9k + 10}$$

10

Substituindo-se esses valores na equação de V_o , obtém-se:

$$V_o = 23,7414 \text{ V}$$

11

Retornando-se esse valor às equações de I_{C_1} e de I_Z , calcula-se:

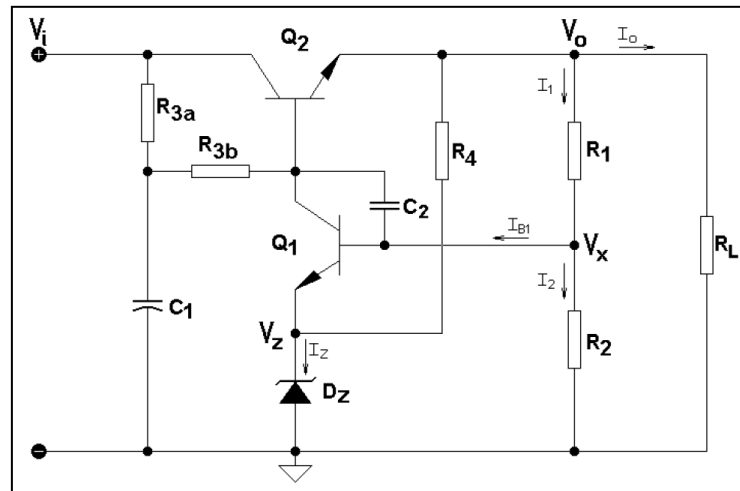
$$I_{C_1} = 38,167 \mu\text{A}$$

$$I_Z = 4,5372 \text{ mA}$$

12

$$I_o = \frac{V_o}{R_L} = \frac{23,7414}{118.7061} \rightarrow I_o = 200 \text{ mA}$$

Valor Máximo de V_o



13

A tensão de saída será máxima quando V_i for máxima e a carga for mínima. Parâmetros:

$V_{i_{max}} = 42 \text{ V}$; $\beta_1 = 600$; $V_{BE1min} = 0,58794 \text{ V}$; $\beta_2 = 2000$; $V_{BE2max} = 1,3676 \text{ V}$; $R_3 = 20k \Omega$ e $R_{Lmin} = \infty$.
Usando-se a equação de V_o :

$$V_o = (V_{rev} + R_{rev} I_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2} + \frac{R_1 I_{C1}}{\beta_1}$$

$$\rightarrow V_o = (V_{rev} + R_{rev} I_Z + V_{BE1}) \times \frac{R_1 + R_2}{R_2} + \frac{R_1 I_{C1}}{\beta_1} = (6,15 + 10 I_Z + 0,67574) \times 3,5 + \frac{2,5k \times I_{C1}}{600}$$

14

$$I_{C1} \cong \frac{V_i - V_{BE2}}{R_3} - \left[\frac{1}{R_3} + \frac{1}{(\beta_2 + 1)} \times \left(\frac{1}{R_L} + \frac{1}{R_1 + R_2} + \frac{1}{R_4} \right) \right] \times V_o$$

$$\rightarrow I_{C1} \cong \frac{42 - 1,2871}{20k} - \left[\frac{1}{20k} + \frac{1}{2001} \times \left(\frac{1}{3,5k} + \frac{1}{3,9k} \right) \right] \times V_o = 2,035645m - 50,271\mu \times V_o$$

15

$$I_Z = \frac{\frac{\beta_1 + 1}{\beta_1} \times I_{C_1} \times R_4 + V_o - V_{rev}}{R_4 + R_{rev}}$$

→
$$I_Z = \frac{\frac{\beta_1 + 1}{\beta_1} \times I_{C_1} \times R_4 + V_o - V_{rev}}{R_4 + R_{rev}} = \frac{\frac{601}{600} \times (2,035645m - 50,271\mu \times V_o) \times 3,9k + V_o - 6,15}{3,9k + 10}$$

16

Substituindo-se esses valores na equação de V_o , obtém-se:

$$V_o = 24,083 \text{ V}$$

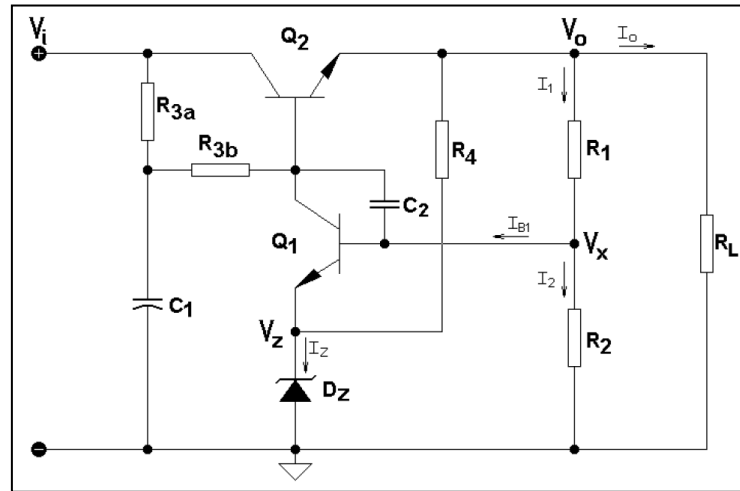
17

Retornando-se esse valor às equações de I_{C_1} e de I_Z , calcula-se:

$$I_{C_1} = 824,9753 \mu\text{A}$$

$$I_Z = 5,4107 \text{ mA}$$

$$I_o = 0$$



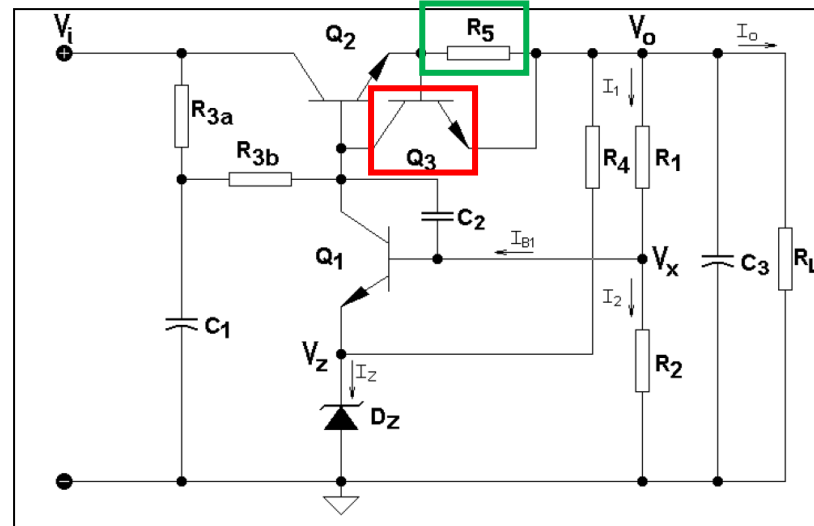
A potência dissipada sobre Q_2 pode atingir o valor: $P_{Q_2} = (42-24) \times 0.2 = 3,6W$.

Nesse caso, o transistor Q_2 deve ser escolhido adequadamente e um dissipador de calor deve ser dimensionado para ele.

O transistor Q_1 é um transistor de pequenos sinais de áudio.

Esse estabilizador apresenta uma variação de 1,42 % na tensão de saída para uma variação de 40 % na tensão de entrada, com uma variação de corrente de saída de 0 à 200 mA. É, portanto, um estabilizador de tensão de alto desempenho.

22.4. Proteção contra curtos-circuitos e sobrecargas:



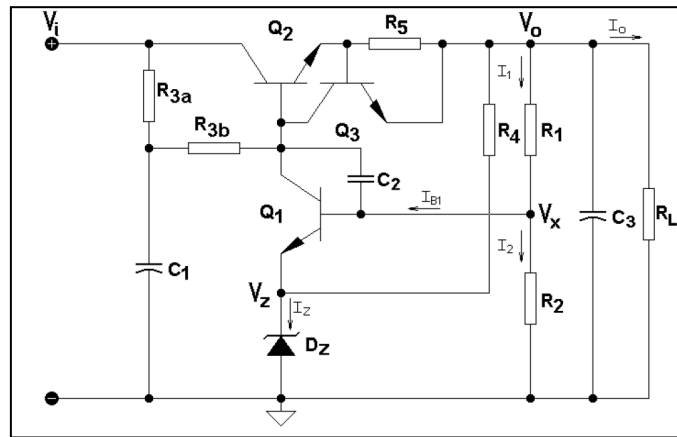
Se o estabilizador sofrer um curto-circuito em sua saída, o transistor Q_2 será irremediavelmente danificado por excesso de corrente. Para evitar isso, devem ser adicionados o **transistor Q_3** e o **resistor R_5** , como mostra a Figura acima.

Em funcionamento normal, isto é, quando $R_5 \times I_o < 0,6V$, o transistor Q_3 não conduz e, portanto, comporta-se como ausente do circuito.

Se a corrente I_o for excessiva, V_{BE} do transistor Q_3 ultrapassa a $0,6V$ e ele começa a conduzir, retirando corrente de base de Q_2 e levando-o ao corte.

Definem-se para o estabilizador, nesse caso, duas correntes de saída singulares:

a **corrente de saída limite ($I_{o(lim)}$)** e a **corrente de saída em curto-circuito ($I_{o(curto)}$)**.



Pode-se, então, escrever que:

$$I_{o(\text{lim})} \cong \frac{0,6}{R_5}$$

$$I_{o(\text{curto})} \cong \frac{0,7}{R_5}$$

Para $I_o > I_{o(\text{lim})}$ o circuito funciona aproximadamente como uma fonte de corrente, com

$$I_{o(\text{lim})} \leq I_o \leq I_{o(\text{curto})}$$

Deve-se lembrar, também, que, na situação de curto circuito, $P_{Q2} \cong V_i \times I_{o(\text{curto})}$.

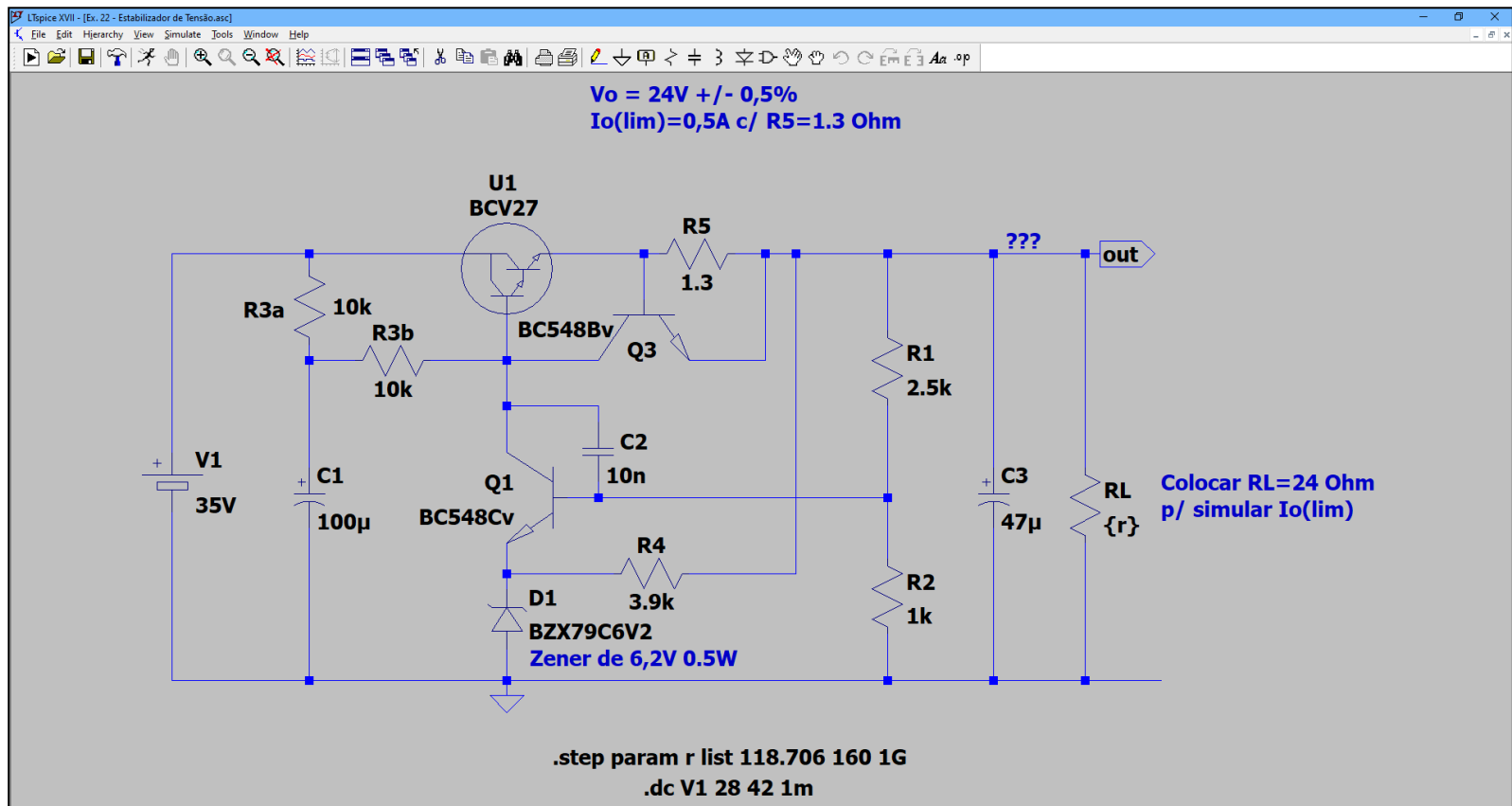
Se, por exemplo, $R_5 = 3,3\Omega$, então $I_{o(\text{curto})} = 0,7 \times 3,3 = 212,12 \text{ mA}$.

No exemplo numérico $P_{Q2} \cong 42 \times 0,21212 = 8,91 \text{ W}$. O transistor Q_2 e o seu dissipador de calor, conseqüentemente, devem ser dimensionados para essa potência.

O transistor Q_3 , assim como o transistor Q_1 , é um transistor de pequenos sinais de áudio.

No circuito foi acrescentado o capacitor C_3 que funciona como um filtro adicional de *ripple* e de ruídos na saída da fonte. Ele é do tipo eletrolítico e, normalmente não possui capacitância muito elevada ficando, em geral, na seguinte faixa de valores: $10 \mu\text{F} \leq C_3 \leq 100 \mu\text{F}$.

Simulação em LTSPice



Q₁ é BC548C

Q₂ é um Darlington que está na pasta Darlington. Foi usado o BCV27.

Q₃ é BC548B.

O Zener é de 6,2V.

O circuito de simulação c/ R5 está setado para Io(lim)= 0,5A.

Os resultados das simulações não batem totalmente com os cálculos teóricos porque o beta do Darlington é muito variável e imprevisível com a variação de V_{in} e de R_L, mas não fogem de +/- 5% dos valores desejados na prática. Isso é normal.

Um trimpot de 100R pode ser colocado entre R1 e R2, com o cursor ligado à base de Q1, para um ajuste mais preciso, se necessário.

Veronese

Roteiro Experimental

SEL393 – Laboratório de Instrumentação Eletrônica I
Departamento de Engenharia Elétrica e de Computação

Laboratório 7 – Reguladores de Tensão

Implemente em LTSpice o regulador de tensão de alto desempenho da Figura 1 e compare os resultados teóricos e de simulação.

- 1) Meça o intervalo de variação da tensão de saída para tensões de entrada no intervalo $28V \leq V_i < 42V$.
- 2) Meça a corrente na carga nas três condições analisadas teoricamente.
- 3) Acrescente um trimpot de 100Ω no nó entre R_1 e R_2 e determine o valor da resistência para que o valor máximo da tensão de saída seja 24V.
- 4) O limite de corrente deste circuito é 0,5A. Verifique para qual carga este limite é atingido.

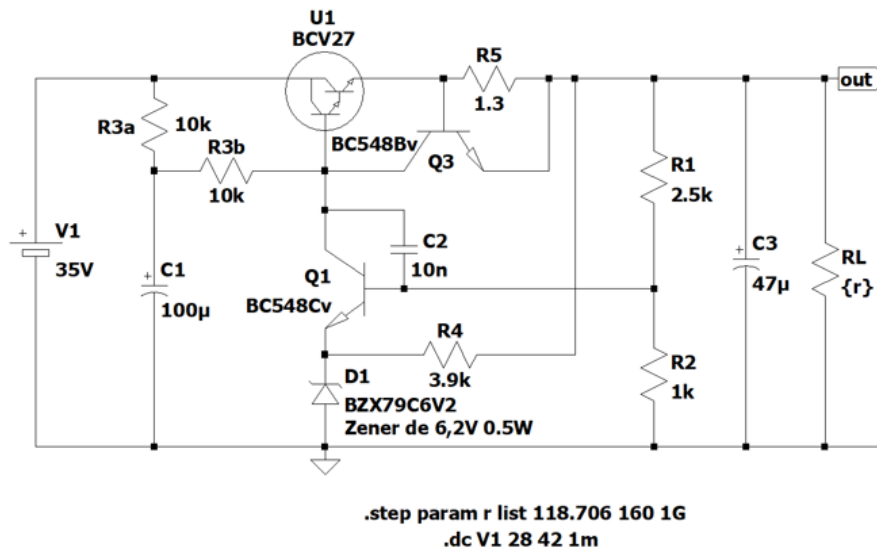


Fig. 1 – Regulador de Tensão de Alto Desempenho