

Chapter 2: Further Mains Power Supply Systems

Learning Objectives:

At the end of this topic you will be able to:

- distinguish between load regulation and line regulation;
- analyse and design a voltage regulator based upon a zener diode, a transistor emitter follower and a non-inverting amplifier;
- select and apply the gain equation

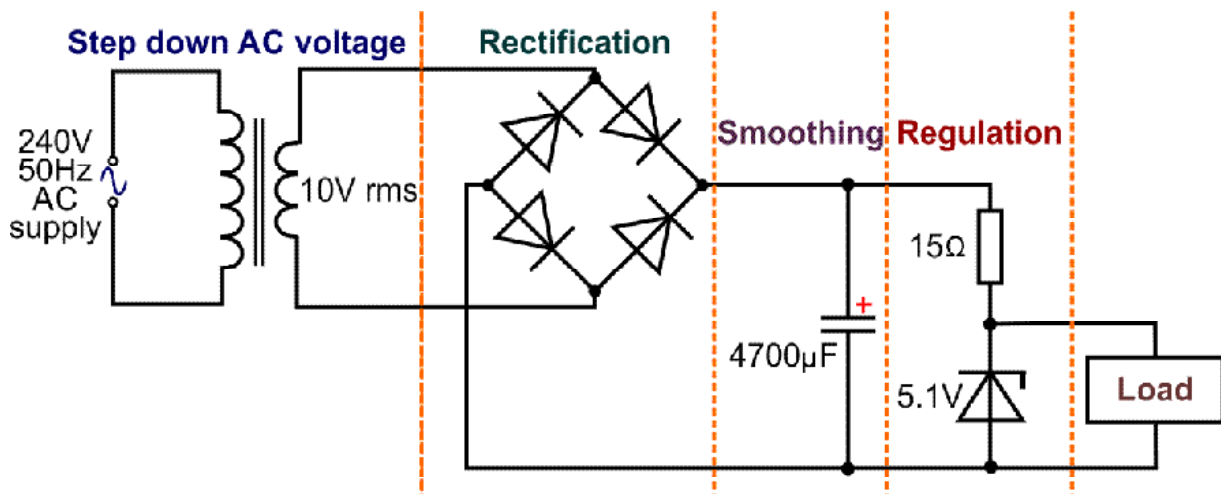
$$V_L \approx V_Z \left(1 + \frac{R_F}{R_1} \right)$$

- draw circuits for and recall the properties of the emitter follower sub-system;
- select and apply the equation

$$V_{OUT} = V_{IN} - 0.7 \text{ V}$$

Review:

In the AS E-book, we examined the role of rectification, capacitor smoothing, ripple voltage and zener diode regulation within the power supply shown below:

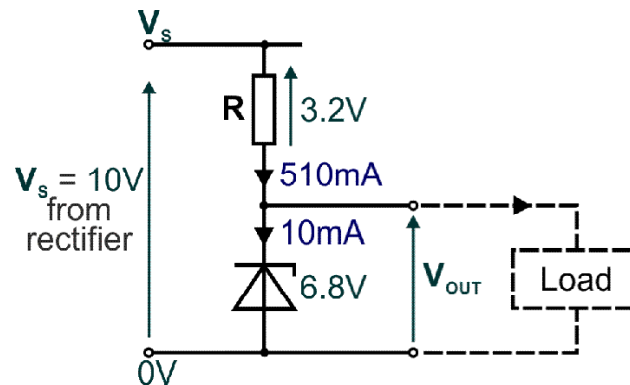


Several limitations of the power supply were identified. In this section we will consider ways of overcoming these limitations.

Example 1

A simple power supply is designed to deliver output currents up to **500 mA** at an output voltage of **6.8 V**.

- (a) The diagram shows the currents and voltages when the output current is at its maximum value, **500 mA**. A current of **10 mA** flows through the zener diode to keep it in zener breakdown.

**A reminder**

- The voltage across the zener diode remains fixed (at **6.8 V** in this case.)
- When $V_s = 10\text{ V}$, the voltage across $R = 10 - 6.8 = 3.2\text{ V}$.
- The current through $R = 500 + 10 = 510\text{ mA} = 0.51\text{ A}$.
- Using the Ohm's law formula, $R = \frac{3.2}{0.51} = 6.27\ \Omega$
- In practice, the nearest value in the E24 series is $6.2\ \Omega$. This is slightly smaller than the calculated value, and so allows a slightly larger current of **516 mA** to flow through it than the **510 mA** needed to meet the specification of the power supply.
- The load resistance R_{LOAD} which draws maximum current is:

$$R_{\text{LOAD}} = \frac{6.8\text{ V}}{0.5\text{ A}} = 13.6\ \Omega.$$

- (b) **First Limitation** - the effect of a **drop** in line voltage:

Assume that V_s drops by 10% to **9 V**.

The voltage across the $6.2\ \Omega$ resistor, $R = 9 - 6.8 = 2.2\text{ V}$.

The current through the $6.2\ \Omega$ resistor, $R, = \frac{2.2}{6.2} = 350\text{ mA}$.

- This is smaller than the current (**500 mA**) needed to create **6.8 V** across the load.
- The zener comes out of reverse breakdown and ceases to conduct.
- The circuit is effectively a voltage divider made from a $6.2\ \Omega$ resistor and a $13.6\ \Omega$ resistor so:

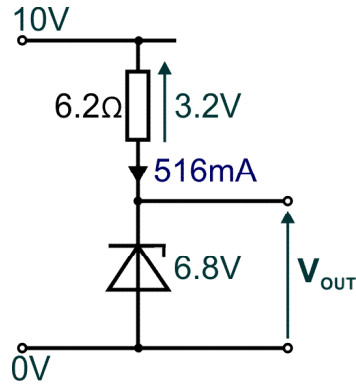
$$V_{\text{OUT}} = 13.6 \times \frac{9}{(13.6 + 6.2)} = 6.18\text{ V}$$

Although the zener diode works well for an **increase** in input line voltage it can be seen that it does not cope very well with a line voltage decrease of more than a few %.

(c) **Second Limitation** - the power ratings of the resistor and zener diode:

The zener diode dissipates most power when the output current is zero, i.e. when no load is connected to the power supply.

The next diagram shows this situation.



Now:

- The zener diode is still in zener breakdown and so has a voltage of **6.8 V** across it.
- This leaves **3.2 V** dropped across the 6.2 Ω resistor R.
- As a result, the current through R is

$$\frac{3.2}{6.2} = \mathbf{516 \text{ mA}} (= \mathbf{0.52 \text{ A}}).$$

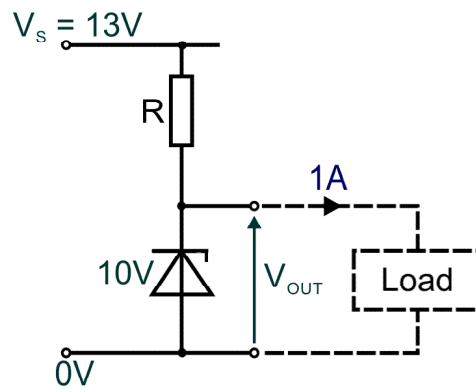
- As no current flows in the output, all this current flows through the zener diode.

As a result, using $\mathbf{P = I \times V}$:

- the power dissipated in the resistor = $0.52 \times 3.2 = 1.66 \text{ W}$;
- the power dissipated in the zener diode = $0.52 \times 6.8 = 3.54 \text{ W}$.

Exercise 2.1

The circuit diagram for a voltage regulator is shown below:



The voltage regulator must deliver output currents up to **1 A**, with a regulated output voltage of **10 V**.

The input voltage, from the rectifier sub-system, is **13 V**.

- (a) Calculate the resistance and power rating of the resistor **R**, and the power rating of the **10 V** zener diode used in the circuit.
(Assume that the zener diode requires a minimum current of **10 mA** to keep it in reverse breakdown.)

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- (b) The input voltage, **V_S**, from the rectifier sub-system drops to **12 V**.
Show by calculation whether **V_{OUT}** remains at **10 V**.

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Line and Load Regulation

Ideally, a power supply should deliver a constant output voltage regardless of any changes that take place in the input or output circuits.

It is not unusual for the nominal 240 V AC supply voltage to vary substantially throughout the day due to changes in demand. The average voltage in the UK is around 242 V.

In addition, changes in load current cause the ripple voltage produced by the rectification process to fluctuate.

The output voltage of the power supply should ignore both these effects.

Line regulation and load regulation measure how successfully the power supply does this.

Definition of line regulation:

Line regulation measures the ability of the power supply to maintain a steady output voltage when the input line voltage changes.

Definition of load regulation:

Load regulation measures the ability of the output voltage to remain constant when the output current changes due to a change in the load.

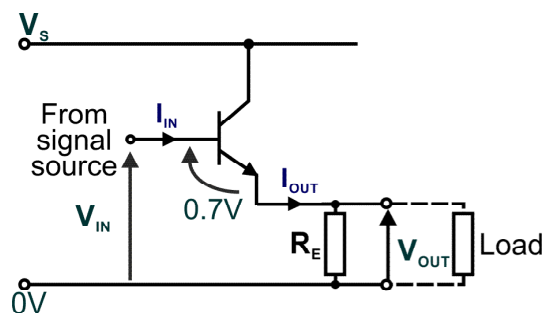
The emitter follower:

The performance of a zener voltage regulator can be improved by incorporating an emitter follower into the output circuit.

The emitter follower:

- is an example of a voltage follower circuit – the output voltage V_{OUT} **follows** (tries to equal) the input voltage V_{IN} ;
- is a current buffer – the output current I_{OUT} is much greater than the current I_{IN} drawn from the signal source;

The circuit diagram for the emitter follower, using an npn transistor, is shown below.



The npn transistor is conducting (but not saturated), so there is a 0.7 V drop between the base and the emitter.

As a result:

the output voltage is given by: $V_{OUT} = V_{IN} - 0.7$

and P , the power dissipated in the transistor, is:

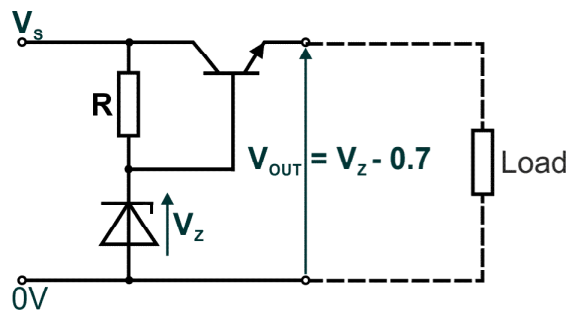
$$\begin{aligned} P &= V_{CE} \times I_{OUT} \\ &= (V_S - V_{OUT}) \times I_{OUT} \end{aligned}$$

Improvement 1:

The zener voltage regulator can be modified to include an emitter follower to reduce the power ratings of the zener diode and resistor.

In the diagram that follows, the transistor has been rotated through 90°.

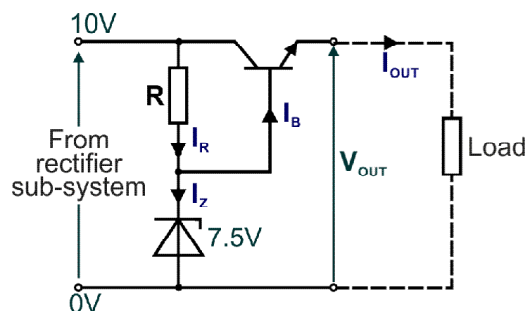
It is identifiable as an emitter follower, because the load is connected between the transistor emitter and 0 V.



Example 1:

A power supply delivers a maximum output current of 500 mA at a voltage of 6.8 V.

It includes a rectifier sub-system with an output voltage of 10 V DC. This is followed by a zener voltage regulator and an emitter follower output stage, included to reduce the power rating of the resistor and zener diode. The transistor has a current gain, h_{FE} , of 50.



Zener voltage choice:

Output voltage $V_{OUT} = V_z - 0.7$.

To maintain a output voltage of 6.8 V requires a 7.5 V zener diode.

Resistor R choice:

When the output current I_{OUT} is at its maximum value, 500 mA,

base current $I_B = \frac{I_{OUT}}{h_{FE}}$ (approximately)

$$I_B = \frac{500}{50} = 10 \text{ mA}$$

Assuming the zener diode needs a minimum current of 10 mA to keep it in zener breakdown:

current through R, $I_R = I_z + I_B$
 $= 20 \text{ mA} (= 0.02 \text{ A})$

Looking at the zener regulator,
 voltage across R

$$V_R = V_s - V_z = 10 - 7.5 = 2.5 \text{ V}$$

Using these values in the Ohm's law equation gives:

$$R = \frac{2.5}{0.02} = 125 \Omega$$

The nearest smaller preferred value is 120 Ω , giving a maximum current through **R** of:

$$\frac{2.5}{120} = 0.021 \text{ A (= 21 mA)}$$

Power dissipation:

At maximum output current,

$$I_R = 21 \text{ mA.}$$

Power dissipated in resistor

$$R = 21 \text{ mA} \times 2.5 = 52.5 \text{ mW.}$$

Current through zener diode,

$$\begin{aligned} I_Z &= I_R - I_B \\ &= 11 \text{ mA.} \end{aligned}$$

Power dissipated in zener diode

$$= 11 \text{ mA} \times 7.5 = 82.5 \text{ mW.}$$

At zero output current,

$$I_R = 21 \text{ mA (i.e. unchanged).}$$

Power dissipated in the resistor **R** remains unchanged at 52.5 mW.

Base current $I_B = 0$.

Current through zener diode,

$$\begin{aligned} I_Z &= I_R - I_B \\ &= 21 \text{ mA.} \end{aligned}$$

Power dissipated in zener diode

$$= 21 \text{ mA} \times 7.5 = 157.5 \text{ mW.}$$

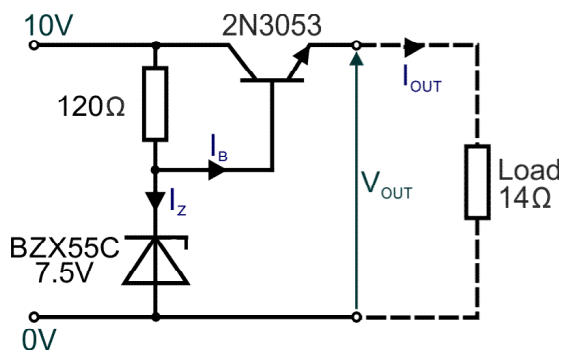
These power ratings are much lower than those obtained earlier for the voltage regulator without the emitter follower.

Note: Maximum power dissipated in the emitter follower:

$$\begin{aligned} &= (V_S - V_{OUT}) \times I_{OUT} \\ &= (10 - 7.5) \times 500 \text{ mA} \\ &= 1250 \text{ mW (=1.25 W)} \end{aligned}$$

Investigation 2.1

Set up the circuit analysed in example 1 earlier.



Note:

The 14 Ω load is chosen to replicate the load conditions when $V_{OUT} = 6.8\text{ V}$ and $I_{OUT} = 500\text{ mA}$.

(a) Measure the following values

I_Z I_B I_{OUT} V_{OUT}

(b) Compare each value with the corresponding value obtained in the example and comment on how well they agree.

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(c) (i) Reduce the supply voltage to 9 V and measure the new values of:

I_Z I_{OUT} V_{OUT}

- (ii) Compare these results with those obtained in example 1 part (b) (which considered the effect of reducing the supply voltage of a simple power supply by 1 V).

Comment on how well the power supply provides line regulation.

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- (d) Change the supply voltage to 10 V and reduce the load resistor to 7 Ω .

Measure the new value of V_{out} .

Comment on how well the power supply provides load regulation.

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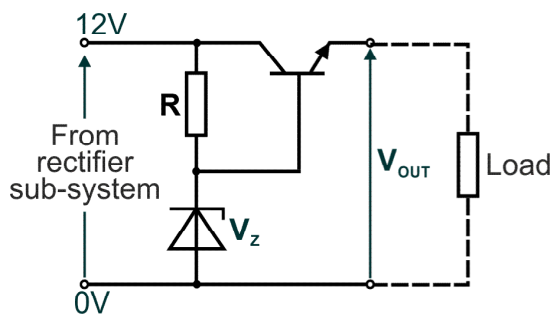
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Exercise 2.2

1. (a) Design a power supply to deliver a load current of 1 A at a voltage of 7.5 V. The emitter follower uses a transistor with a current gain, h_{FE} , of 40.



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- (b) Calculate the power dissipated in the zener diode, in the resistor **R** and in the transistor when the load current is 1 A.

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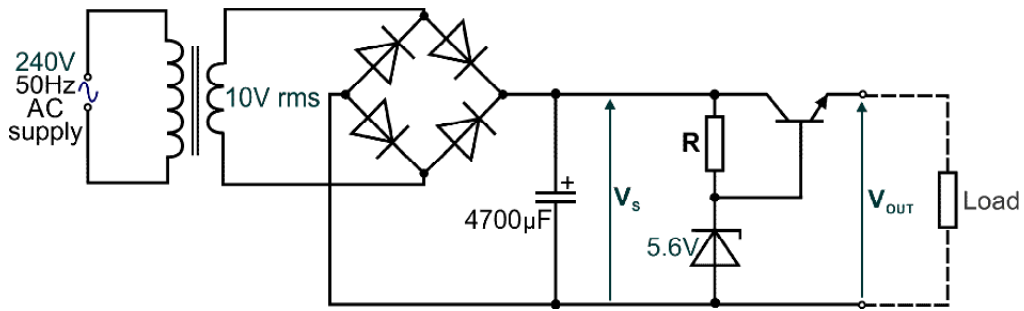
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2. An emitter follower is used as part of the voltage regulator in the power supply shown in the following circuit diagram:



- (a) Calculate the peak value of the secondary voltage V_s .

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- (b) Calculate the ripple voltage when the load current is 1 A.
(Assume that the current through resistor R is small enough to be ignored.)

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- (c) Calculate the output voltage, V_{OUT} , of the power supply.

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- (d) Calculate the power dissipated in the transistor when the load current is 1.2 A.

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- (e) Give one benefit of using an emitter follower in this circuit.

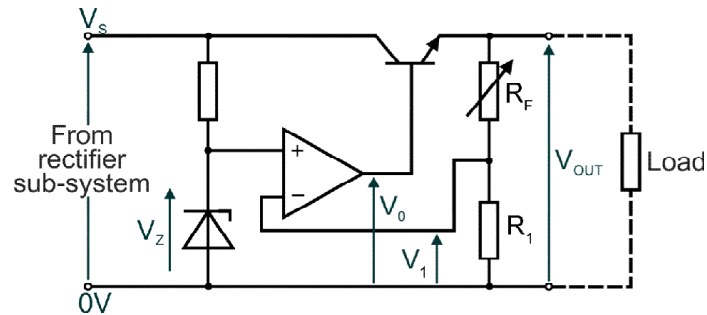
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Improvement 2:

This modification uses negative feedback to improve load regulation.
The modified circuit diagram is shown below.



The output voltage, V_{OUT} , is sensed by the voltage divider, made up of R_F and R_1 . This feeds back a signal to the inverting input of the non-inverting amplifier, i.e. uses negative feedback.

As always, the op-amp tries to keep the inverting and non-inverting inputs at the same voltage, and will do so unless the output saturates.

Hence:

- voltage at the non-inverting input = V_Z , the fixed voltage across the zener diode;
- voltage at the inverting input = V_1 , the voltage across resistor R_1 , i.e. the signal from the voltage divider sensing the output voltage.

The op-amp generates a voltage V_0 which depends on $(V_Z - V_1)$, the difference between its input voltages.

Providing the output does not saturate,

$$V_0 = A_0 (V_Z - V_1)$$

where A_0 = open-loop gain of the op-amp ($\approx 300\,000$ for a TL081 op-amp.)

The output voltage, V_{OUT} , of the power supply can be varied by adjusting variable resistor R_F .

Suppose that the loading of the power supply changes so that the output voltage starts to **fall**:

- the non-inverting input of the op-amp has a **fixed** voltage of V_Z applied to it;
- as V_{OUT} falls, the voltage V_1 , across R_1 , **falls**;
- as a result, the voltage difference $(V_Z - V_1)$ between inputs, **increases**.

The output of the op-amp is given by:

$$V_0 = A_0 (V_Z - V_1)$$

providing the output does not saturate.

As a result, V_0 and hence V_{OUT} start to **increase** countering the initial tendency to fall.

Calculating the output voltage:

Using the voltage divider formula:

$$V_1 = V_{\text{OUT}} \times \frac{R_1}{(R_F + R_1)}$$

Assuming that the output of the op-amp is not saturated:

$$\begin{aligned} V_1 &\approx V_Z \\ \text{SO } V_Z &\approx V_{\text{OUT}} \times \frac{R_1}{(R_F + R_1)} \end{aligned}$$

Re-arranging this gives:

$$V_{\text{OUT}} \approx V_Z \frac{(R_F + R_1)}{R_1}$$

$$\text{OR } V_{\text{OUT}} \approx V_Z \left(1 + \frac{R_F}{R_1} \right)$$

For example, suppose $V_Z = 7.5 \text{ V}$, $R_1 = 10\text{k } \Omega$ and $R_F = 5 \text{ k}\Omega$.

$$\begin{aligned} V_{\text{OUT}} &\approx 7.5 \times \left(1 + \frac{5}{10} \right) \\ &\approx 11.3 \text{ V} \end{aligned}$$

When R_F is a variable resistor, it can be used to adjust the output voltage V_{OUT} .For example, suppose R_F is a 10 k Ω variable resistor, and $R_1 = 10 \text{ k}\Omega$.

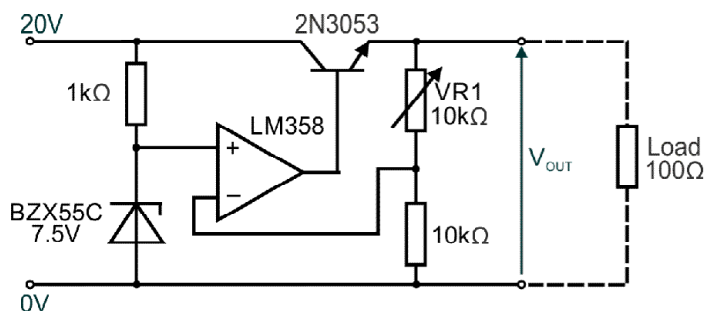
The output voltage can be changed from:

$$V_{\text{OUT}} \approx 7.5 \times \left(1 + \frac{0}{10} \right) \approx 7.5 \text{ V}$$

$$\text{to } V_{\text{OUT}} \approx 7.5 \times \left(1 + \frac{10}{10} \right) \approx 15 \text{ V}$$

Investigation 2.2

Set up the circuit shown below



Note:

If using **Circuit Wizard**, ensure that the “Automatically include hidden digital power supply” box is unticked in the **Project / Simulation / Power Supply** drop down menu.

For each value of VR1 listed in the table:

- (a) measure the value of V_{OUT} ;
- (b) calculate the theoretical value of V_{OUT} .

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Record all results in the table.

VR1 Setting	Measured value of V_{OUT}	Calculated value of V_{OUT}
10 k		
8 k		
4 k		
2 k		
0		

(c) Comment on how well the answers match.

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(d) (i) Set the supply voltage to 18 V and VR1 to 10 kΩ .
Measure the new value of V_{OUT} .

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(ii) Compare the result with those obtained in investigation 1 part (d) (which considered the effect of reducing the supply voltage of the emitter follower power supply by 1 V).

Comment on how well this power supply provides line regulation.

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(e) Set the supply voltage to 20 V, VR1 to 10 kΩ and reduce the load resistor to 50 Ω.
Measure the new value of V_{OUT} .

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Comment on how well the power supply provides load regulation.

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(f) Replace VR1 with a 20 kΩ fixed resistor.
Measure the new value of V_{OUT} .

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Explain why this value differs significantly from a calculated value of V_{OUT} .

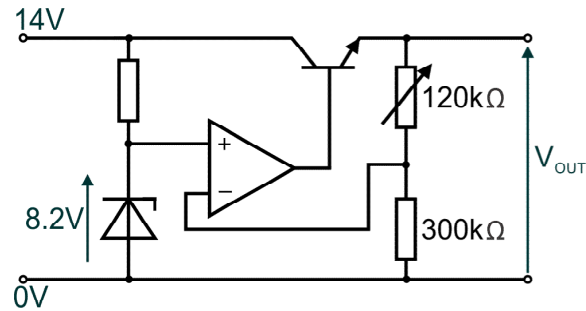
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Exercise 2.3

1. The diagram shows part of the circuit for a power supply. Calculate the range of output voltages available by adjusting the variable resistor.



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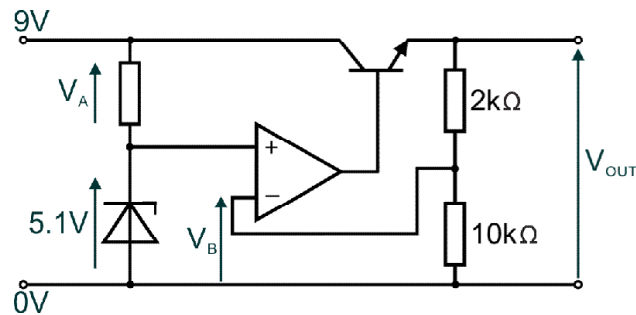
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2. Here is part of the circuit diagram for a regulated power supply.



Calculate:

- (a) V_A ;

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- (b) V_{OUT} ;

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- (c) V_B ;

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3. (a) A high quality power supply offers good **line** and **load** regulation.

Explain what is meant by, and distinguish between the terms line regulation and load regulation.

Line regulation:

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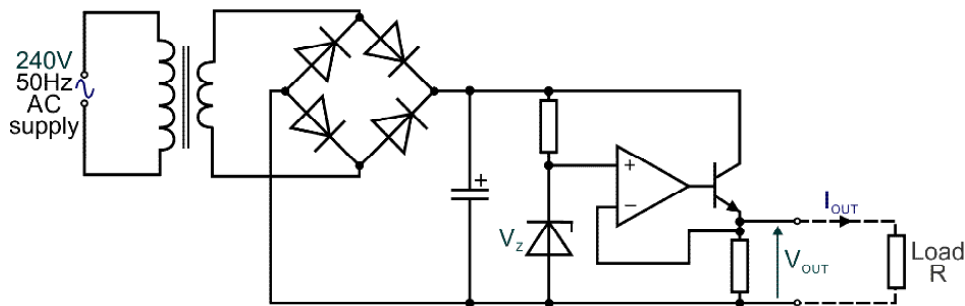
Load regulation:

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(b) A stabilised power supply circuit is shown below.



(i) Explain how this circuit keeps V_{OUT} constant as the load current I_{OUT} increases.

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(ii) Write down an equation to determine V_{OUT} in terms of V_Z and load resistor R .

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