

Learning Objectives:

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

- ☑ explain what is meant by the terms load regulation and line regulation;
- ☑ draw the circuit diagram for an emitter follower based on an npn transistor;
- ☑ recall that for an emitter follower:
 - input impedance $\sim h_{FE} R_E$
 - $V_{OUT} = V_{IN} - 0.7V$
- ☑ design and analyse a voltage regulator based on a zener diode, an emitter follower and a non-inverting amplifier;
- ☑ select and use the following gain formula to calculate the output voltage:
$$V_L \approx V_Z (1 + R_F / R_1).$$

Introduction to Power Supplies

The national electricity distribution system uses AC (alternating current) delivered at high voltage.

Electronic systems usually require electrical energy delivered as DC (direct current) at relatively low voltages.

The mains power supply is one means of delivering electricity in a form suitable for electronic systems. This may involve a number of processes:

1. transforming the high AC input voltage to a lower AC output voltage;
2. rectifying the AC to DC;
3. smoothing the resulting DC supply;
4. providing line regulation;
5. providing load regulation;
6. providing over-voltage protection for the load system;
7. providing short-circuit protection for the power supply.

The first process uses a transformer, but this is outside the scope of this course.

The second process was covered in module ET2, section 2.4.2, which looked at both half-wave and full-wave rectification.

The third process uses a large value electrolytic capacitor, and was the subject of ET2 section 2.4.3.

Line regulation was introduced in ET2 section 2.4.4, though not explicitly. The focus of that section was voltage regulation using a zener diode. We will expand on what was said there shortly.

Load regulation will also be defined and covered in one of the following sections.

The remaining two processes, providing over-voltage protection and short-circuit protection, are outside the scope of the course.

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.

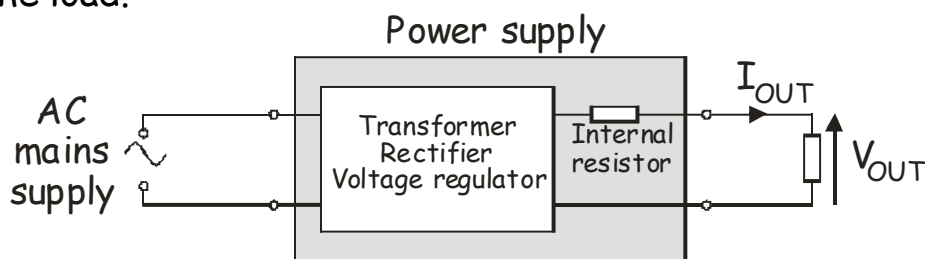
In particular, the mains supply voltage, (the *line* voltage,) increases and decreases significantly depending on national factors such as demand (weather conditions, 'Coronation Street', FA Cup Final, 'X Factor' etc.) The output voltage of the power supply should ignore these changes. Line regulation measures how successfully the power supply does this.

Here is a useful definition of line regulation:

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

It is expressed as the percentage change in the output voltage relative to the change in the input line voltage.

When the load attached to the output of a power supply is changed, the current through it changes, and this can cause a change in the power supply output voltage. When the power supply is used to deliver a steady voltage, it behaves as if there is an internal resistor in series with the load. When the output current, I_{OUT} , increases, the voltage dropped across this internal resistor increases, and the output voltage, V_{OUT} , seen by the load, decreases. Load regulation measures how successful the power supply is in ignoring changes in the load.



Now a useful definition of load regulation:

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

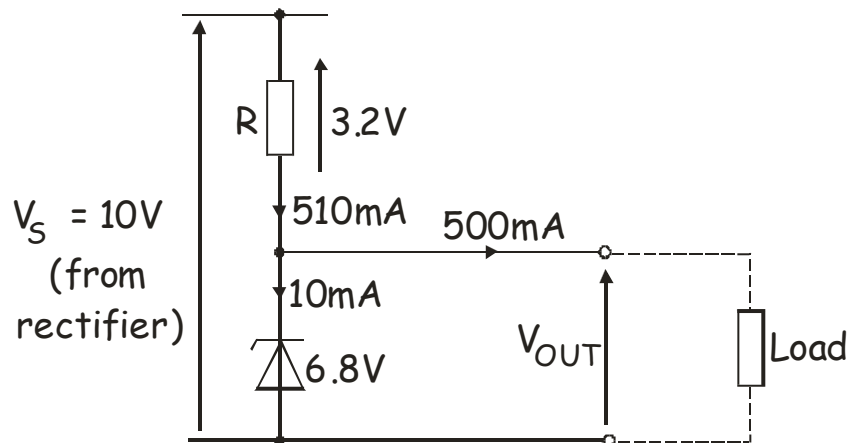
A reminder about the zener diode voltage regulator:

Section 2.4.4 of ET2 looked at the properties of the zener diode, and its use as a voltage regulator.

An example:

A simple power supply is designed to deliver output currents up to 500mA with an output voltage of 6.8V, (even if the line voltage, and so V_S , changes.)

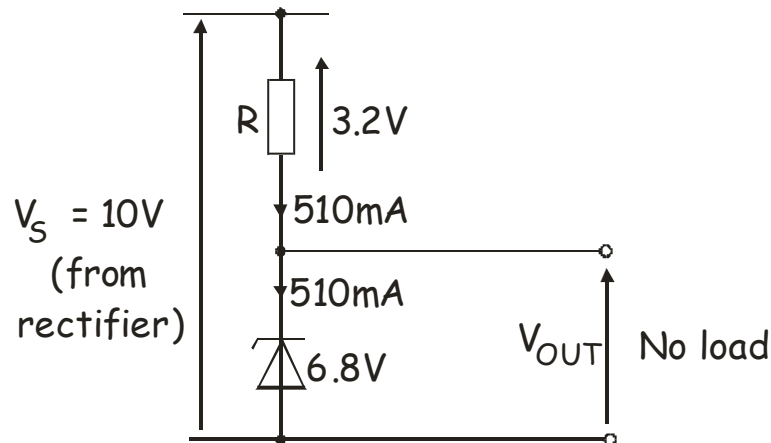
The diagram shows the currents and voltages when the output current is at its maximum value, 500mA. A current of 10mA flows through the zener diode to keep it in zener breakdown.



- The voltage across the zener diode remains fixed (at 6.8V in this case.)
- When the voltage from the rectifier section, $V_S = 10V$, the voltage across resistor $R = 10 - 6.8 = 3.2V$.
- The current through $R = 500 + 10 = 510mA = 0.51A$.
- Using the Ohm's law formula gives a value of $R = 3.2 / 0.51 = 6.27\Omega$.
- In practice, the nearest value in the E24 series is 6.2Ω . This is slightly smaller than the calculated value, and so allows a slightly larger current to flow through it than the 510mA needed to meet the specification of the power supply.

All this works quite well, but at a price - the power ratings of the resistor and the 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.



- The zener diode is still in zener breakdown and so has a voltage of 6.8V across it.
- This leaves 3.2V dropped across the 6.2 Ω resistor R .
- As a result, the current through R is $3.2 / 6.2 = 516mA$ ($= 0.52A$).
- As no current flows in the output, all this current flows through the zener diode.

As a result, using $P = I \times V$;

the power dissipated in the resistor = $0.52 \times 3.2 = 1.66W$.

the power dissipated in the zener diode = $0.52 \times 6.8 = 3.54W$.

Exercise 1 (The solutions are given at the end of the topic.)

Design a simple power supply, capable of delivering up to 1A, with an output voltage of 10V. The input voltage is 13V. You need to calculate the resistance and power rating of the resistor, and the power rating of the 10V zener diode used in the circuit.

The performance of this voltage regulator can be improved by incorporating an emitter follower into the output circuit. The next section introduces the emitter follower.

The emitter follower:

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;
- is often used as an impedance transformer, to interface a signal source having a high output impedance to a load with a low impedance. (We will use this property when we study audio systems in section 5.6;)
- is an example of a common-collector circuit.

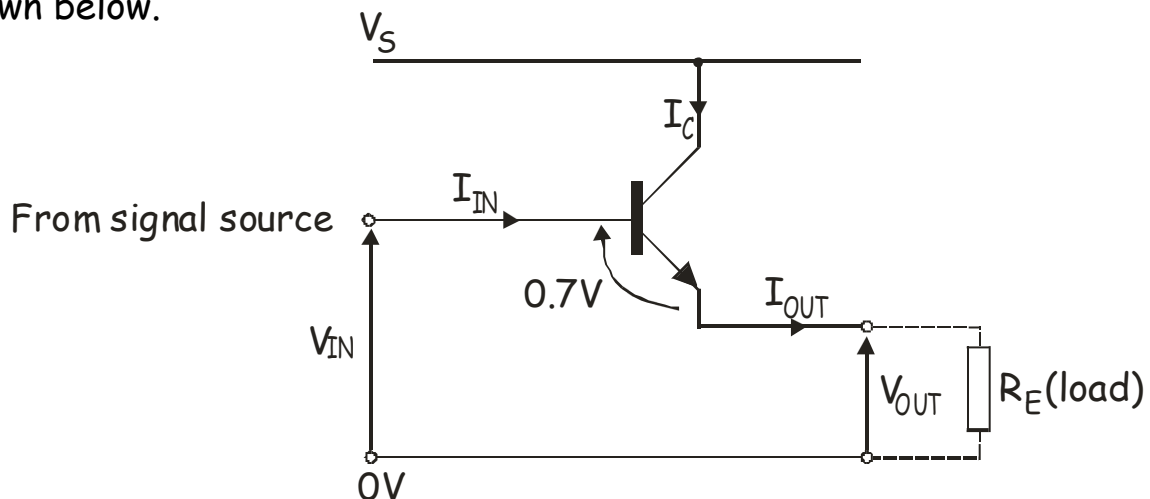
The specification requires that you can recall that for an emitter follower:

- input impedance $\sim h_{FE} R_E$
- $V_{OUT} = V_{IN} - 0.7V$

The next section is NOT examinable!

It shows you where these relationships come from. If you can follow this, it will help you to understand the way the emitter follower works.

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



The npn transistor is conducting and so there is a $0.7V$ drop between the base and the emitter.

As a result: $V_{OUT} = V_{IN} - 0.7$

The output current, I_{OUT} , is actually the emitter current I_E of the transistor.
The input current, I_{IN} , is the base current I_B .

Now $I_E = I_B + I_C$

and $I_C = h_{FE} \times I_B$

where I_C = collector current, and h_{FE} = current gain of transistor.

As $h_{FE} \gg 1$, $I_C \gg I_B$

and so $I_E \approx I_C$.

In other words, $I_E \approx h_{FE} \times I_B$

or $I_{OUT} \approx h_{FE} \times I_{IN}$

Input impedance of the emitter follower

Roughly speaking, the input impedance of the emitter follower, Z_{IN} , is given by:

$$Z_{IN} = V_{IN} / I_{IN}$$

Looking at the equations obtained above:

$$V_{OUT} = V_{IN} - 0.7$$

so $V_{OUT} \approx V_{IN}$

Also $I_{OUT} \approx h_{FE} \times I_{IN}$

so $I_{IN} = I_{OUT} / h_{FE}$

This means that we can re-write the input impedance equation as:

$$Z_{IN} \approx V_{OUT} / (I_{OUT} / h_{FE})$$

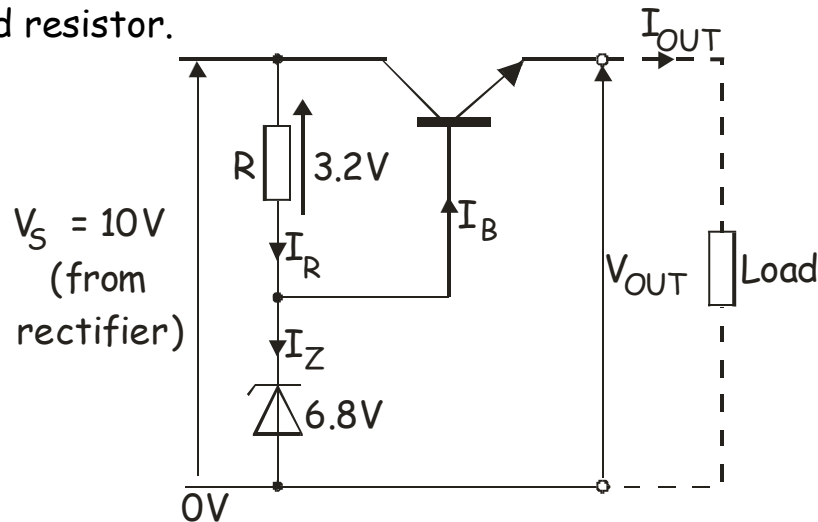
Looking at the output of the emitter follower, and the load resistor R_E ,

$$R_E = V_{OUT} / I_{OUT}$$

Finally then, $Z_{IN} \approx h_{FE} \times R_E$

Modified voltage regulator

Modification 1 - Add an emitter follower to reduce the power ratings of the zener diode and resistor.



To see the benefit, assume that:

- the power supply delivers a maximum output current of 500mA, as before;
- the transistor has a current gain, h_{FE} , of 50.

When the output current is at its maximum value, 500mA,
the base current I_B will be approximately equal to I_{OUT} / h_{FE} ,
or, in this case, $500 / 50 = 10\text{mA}$.

Allowing a current $I_Z = 10\text{mA}$ to keep the zener in zener breakdown, gives:

$$\begin{aligned} I_R &= I_Z + I_B \\ &= 20\text{mA} (= 0.02\text{A}) \end{aligned}$$

With a 3.2V drop across it, as before, the resistor now needs a maximum value of $3.2 / 0.02 = 160\Omega$, (which is a preferred value in the E24 series.)

When the output current is at maximum value, $I_R = 20\text{mA} (= 0.02\text{A})$ and $I_Z = 10\text{mA} (= 0.01\text{A})$.

The power dissipated in the resistor = $0.02 \times 3.2 = 0.064\text{W}$,
and the power dissipated in the zener diode = $0.01 \times 6.8 = 0.07\text{W}$.

When the output current is zero, $I_R = 20\text{mA}$ and $I_Z = 20\text{mA}$.

The power dissipated in the resistor = $0.02 \times 3.2 = 0.064\text{W}$,
and the power dissipated in the zener diode = $0.02 \times 6.8 = 0.14\text{W}$.

These power ratings are much lower than those obtained on page 5, for the voltage regulator without the emitter follower.

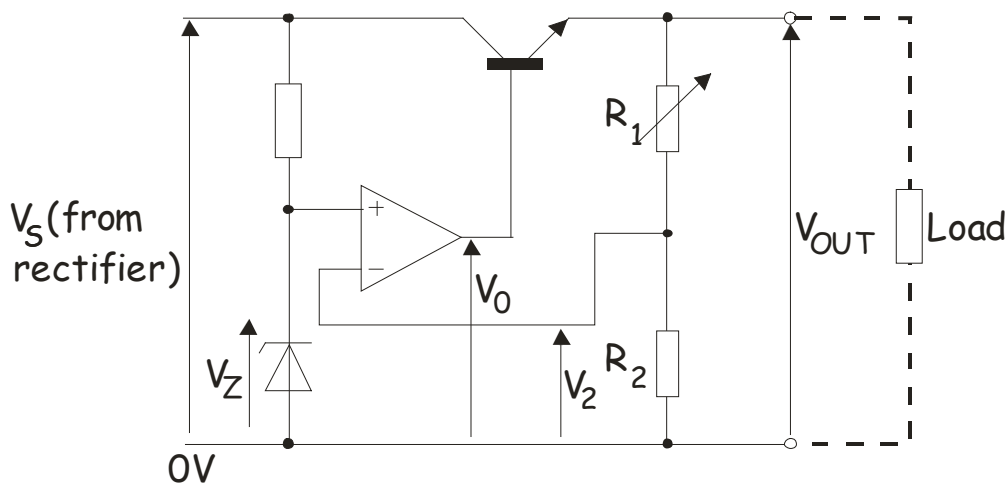
Exercise 2 (The solutions are given at the end of the topic.)

In exercise 1, you designed a simple power supply to deliver a current of 1A at a voltage of 10V. Now, an emitter follower is added to reduce power dissipation in the zener diode and resistor. The emitter follower uses a transistor with a current gain h_{FE} of 40.

Calculate the power dissipated in the zener diode and resistor in this new circuit.

Modification 2 - Add a non-inverting voltage amplifier to improve load regulation.

The final modification we need to consider uses negative feedback to control the output voltage. This results in improved load regulation. The modified circuit diagram is shown below.



The output of the power supply is sensed by the voltage divider, made up of R_1 and R_2 . The signal from this is fed back to the inverting input of the non-inverting amplifier - hence the use of 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.

The voltages around the circuit:

- Voltage at the non-inverting input = V_Z , the fixed voltage across the zener diode.
- Voltage at the inverting input = V_2 , the voltage across resistor R_2 , i.e. the voltage from the voltage divider sensing the output voltage.
- The op-amp generates a voltage V_0 which depends on the difference between the input voltages, $(V_Z - V_2)$.

Providing the output does not saturate,

$$V_0 = A_0 (V_Z - V_2)$$

where A_0 = open-loop gain of the op-amp (= 100 000 for a 741 op-amp.)

- The output voltage V_{OUT} of the power supply = $V_0 - 0.7V$, as a result of the emitter follower action.

Let's look at the sequence of events taking place if the loading of the power supply output starts to reduce the output voltage:

- 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_2 , across R_2 , falls;
- As a result, the difference in voltage between the inverting and non-inverting inputs, $(V_Z - V_2)$, increases;

- The output of the op-amp is governed by the following equation

$$V_0 = A_0 (V_Z - V_2)$$

(provided the output does not saturate,) so, as the voltage difference between the inputs increases, the output of the op-amp increases.

- The output V_{OUT} , of the power supply = $V_0 - 0.7V$.
- As a result, when V_0 starts to increase, V_{OUT} starts to increase, countering the initial tendency to decrease.

Calculating the output voltage:

Using the voltage divider formula:

$$V_2 = V_{OUT} \times R_2 / (R_1 + R_2)$$

If the output of the op-amp is not saturated, then to a good approximation,

$$V_2 \approx V_Z$$

$$\text{so } V_{OUT} \times R_2 / (R_1 + R_2) \approx V_Z$$

Re-arranging this:

$$V_{OUT} \approx V_Z (R_1 + R_2) / R_2$$

$$\text{or } V_{OUT} \approx V_Z (1 + R_1 / R_2)$$

You will be expected to use this expression, but you do not have to derive it!

For example, when $V_Z = 7.5V$, $R_2 = 10k\Omega$ and R_1 is set to $5k\Omega$,

$$V_{OUT} \approx 7.5 \times (1 + 5 / 10)$$

$$\approx 11.3V$$

When R_1 is a variable resistor, the output voltage V_{OUT} of the power supply can be changed by adjusting this variable resistor.

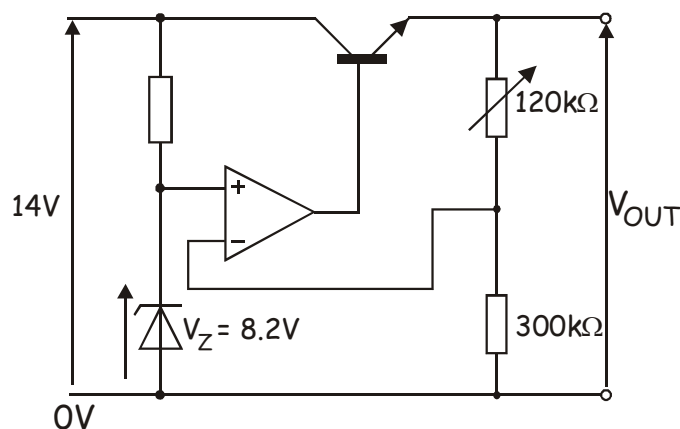
For example, if R_1 is a $10k\Omega$ variable resistor, and $R_2 = 10k\Omega$, the output voltage can be changed from:

$$V_{OUT} \approx 7.5 \times (1 + 0 / 10) \approx 7.5V$$

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

Exercise 3 (The solutions are given at the end of the topic.)

The diagram shows part of the circuit for a power supply. Calculate the range of output voltages which results from adjusting the variable resistor.



Practice Exam Questions:

1. (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. [2]

Line regulation

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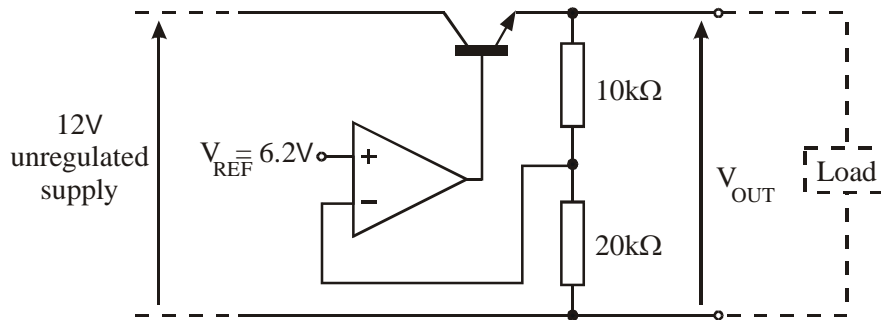
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Load regulation

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- (b) Here is part of the circuit diagram for a regulated power supply.



- (i) Calculate the output voltage V_{OUT} . [2]

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- (ii) What modification to the circuit is needed in order to make it possible to *vary* the output voltage produced by a fixed reference voltage V_{REF} of 6.2V? [1]

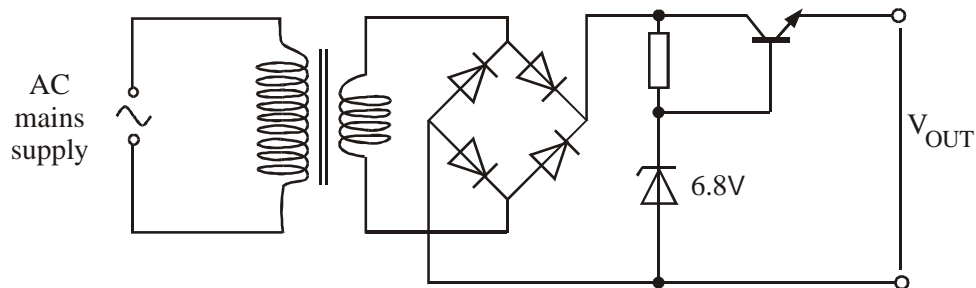
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Topic 5.3 - Power Supply Systems

2. An emitter follower is used as part of the voltage regulator in a power supply. Here is the circuit diagram for the power supply, containing a series regulator.



- (a) Calculate the output voltage, V_{OUT} , of the power supply. [1]

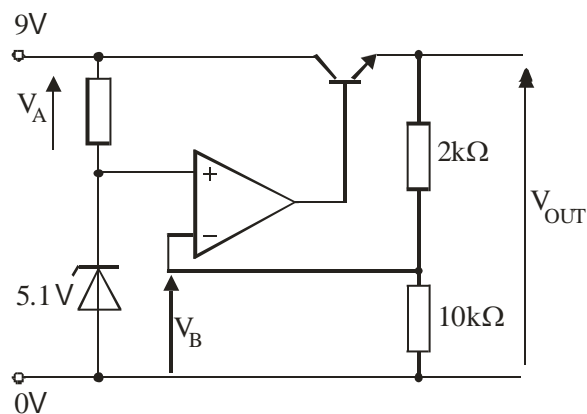
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- (b) Give one benefit of using an emitter follower in this circuit? [1]

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3. The following subsystem is part of a power supply unit.



- (a) Calculate:
the voltage V_A ; [1]

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- (b) the output voltage V_{OUT} ; [1]

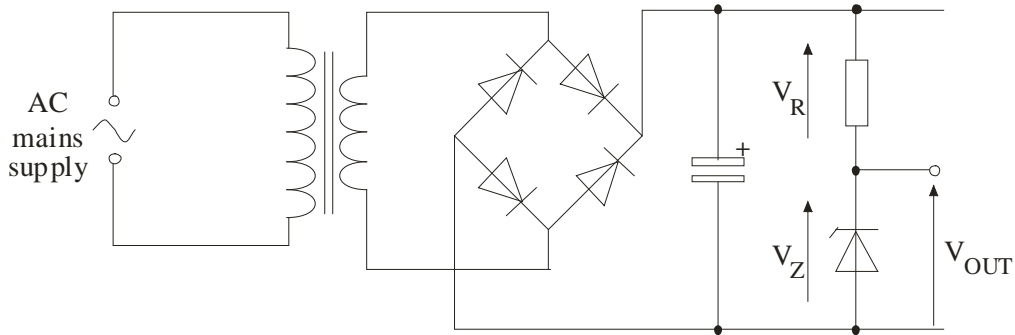
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- (c) the voltage V_B at the inverting input of the op-amp. [1]

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Module ET5
Electronic Systems Applications.

4. The power supply circuit shown below uses a zener diode to provide good line regulation.

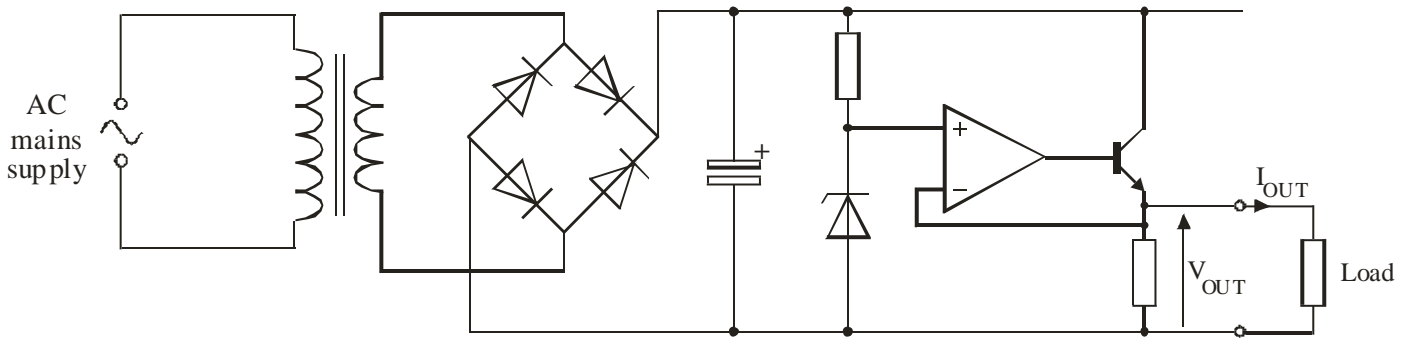


(a) Explain how the circuit provides line regulation. Your explanation should describe what happens to voltages V_R and V_Z when the AC mains supply voltage **increases**. [1]

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



Explain how this circuit keeps V_{OUT} constant as the load current I_{OUT} **increases**. [2]

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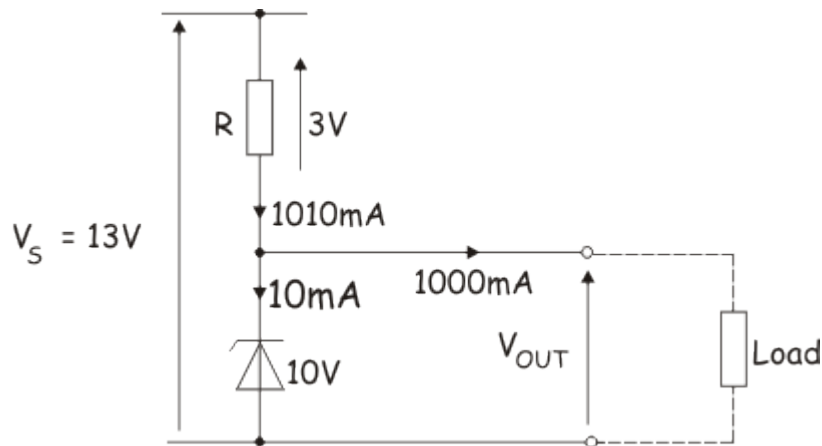
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Solutions to Exercises:

Exercise 1:

Here is the circuit diagram:



The design uses a 10V zener diode.

Voltage across resistor $R = 13 - 10 = 3V$.

Current through $R = 1.01A$.

Hence $R = 3 / 1.01 = 2.97\Omega$. (The nearest lower value is 2.7Ω .)

Using $P = I \times V$, the power rating for R is $1.01 \times 3 = 3.03W$

Under no load, all the current ($1010mA = 1.01A$) flows through the zener.

Hence power rating for the zener is $1.01 \times 10 = 10.1W$.

Exercise 2:

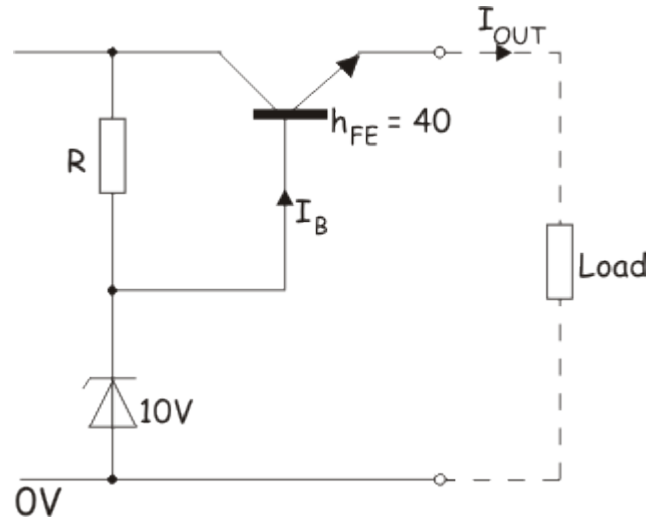
The output current $I_{OUT} = 1A = 1000mA$.
This is roughly equal to I_C , the collector current.

The base current, $I_B = I_C / h_{FE}$
so $I_B = 1000 / 40 = 25mA$.

Under no load, all the current flows through the zener, so max. current through zener = $25mA + 10mA = 35mA$, giving a power dissipation of $I \times V = 35 \times 10 = 350mW$.

As before, voltage across $R = 3V$.

Current through $R = 35mA$, so power dissipated in $R = 35 \times 3 = 105mW$.



Exercise 3:

Using the formula: $V_{OUT} \approx V_Z (1 + R_1 / R_2)$
when the variable resistor (R_1) is set to minimum resistance (0Ω),

$$V_{OUT} \approx 8.2 (1 + 0 / 300) \approx 8.2V$$

When the variable resistor is set to maximum resistance ($120k\Omega$),

$$V_{OUT} \approx 8.2 (1 + 120 / 300) \approx 11.5V$$