Electricity and electronics - 2

BASIC ELECTRONICS

THEORY, PRACTICE AND SOLVED AND PROPOSED EXERCISES

ALBEIRO PATIÑO BUILES

XALAMBO
Engineering

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Editorial Direction: Albeiro Patiño Builes
Technical Review and Layout: David Esteban Londoño Patiño
Cover design: David Esteban Londoño Patiño
Translation: David Esteban Londoño Patiño

Edited in Medellín, Colombia
Xalambo Editorial
www.xalambo.com
Tel.: (+57) 302 827 35 13

“Technology alone is not enough. We also have to put our heart into it.”

Jane Goodall
Considered the greatest expert on chimpanzees.

INDEX

Chapter 1
SEMICONDUCTORS

We can say, without fear of being wrong, that the fundamental raw material of all electronics is semiconductors. Diodes, transistors, and integrated circuits are made based on these components, which are, electronically speaking, between conductors and insulators. Conductors are all those elements that offer low opposition to the flow of electrical current. Insulators are those elements that present remarkably high opposition. Semiconductors, on the other hand, are neither good nor bad conductors of electricity. They have exactly four electrons in the valence orbit (last energy level), while the best conductors have one and insulators have eight valence electrons.

Germanium is an example of a semiconductor, meaning that it has four electrons in the valence shell. The most widely used semiconductor material is Silicon, which contains 14 protons and 14 electrons, four of which are in the outermost shell.

Intrinsic Semiconductors

An intrinsic integrated semiconductor is a pure semiconductor. It has equal positive and negative charge, as shown in figure 1.1, and these positive and negative charges move in opposite directions, transporting the net charge from one place to another.

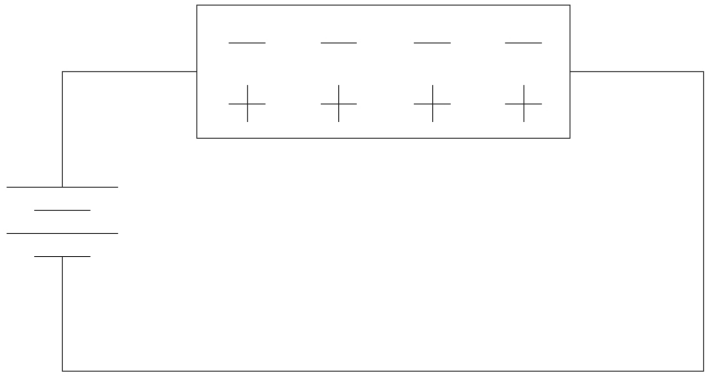


Figure 1-1. Intrinsic Semiconductor.

Doping of a semiconductor

Doping is a way of increasing the conductivity of a semiconductor. This is achieved by adding impurities to the intrinsic semiconductor. The doped semiconductor is called an extrinsic semiconductor.

Doping increases the number of free electrons, and this is achieved by adding pentavalent atoms (5 valence electrons) such as arsenic, antimony, or phosphorus to the melted silicon. These elements donate an electron to the silicon atom.

Doping can also be done by adding trivalent impurities to molten silicon, that is, atoms that have 3 valence electrons, such as Gallium, Boron, and Aluminum. The trivalent atom ends up accepting an electron, and the silicon is left with a positive charge or a hole that can accept a free electron during recombination.

Types of extrinsic semiconductors

As previously mentioned, a semiconductor can be doped to have an excess of electrons or an excess of holes. This in turn gives rise to two types of doped semiconductors.

N type Semiconductor

When the Silicon semiconductor is doped with a pentavalent impurity, it is left with an excess of electrons with respect to the holes, and due to this predominant negative charge, it is called an n-type semiconductor. The electrons, which are the majority carriers, are called majority carriers, and the holes are called minority carriers. In figure 1.2, the diagram of an n-type semiconductor can be observed.

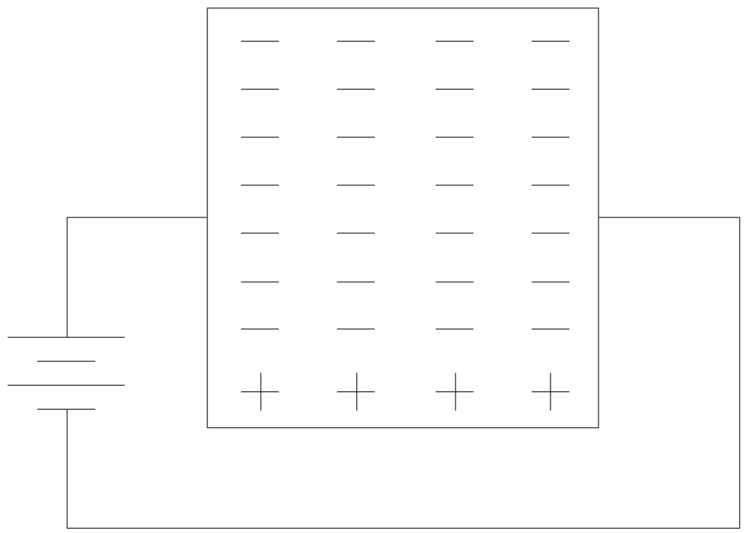


Figure 1-2. N type Semiconductor.

P type Semiconductor

When Silicon is doped with a trivalent impurity, it ends up with an excess of holes with respect to electrons, and due to this predominant positive charge, this element is called a p-type semiconductor, where "p" stands for positive. Holes, in greater quantity, are called majority carriers. Figure 1.3 shows the diagram of a p-type semiconductor.

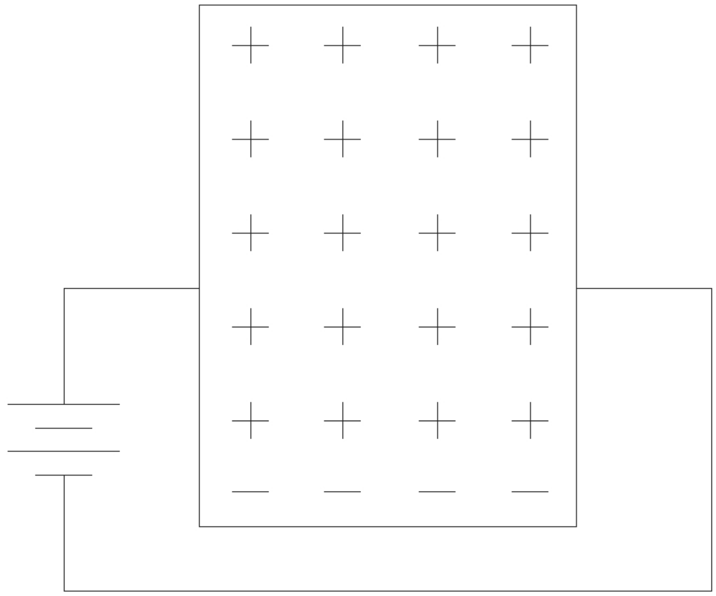


Figure 1-3. P type Semiconductor.

REVIEW

Concepts

Define or discuss the following:

- ☐ Semiconductor element.
- ☐ Intrinsic semiconductor.
- ☐ Doping of a semiconductor.
- ☐ Extrinsic semiconductor.
- ☐ N-type semiconductor.
- ☐ P-type semiconductor.
- ☐ Impurities.
- ☐ Minority carrier.
- ☐ Majority carrier.

Chapter 2
DIODES

If we consider separately a layer of p-type or n-type semiconductor, it will behave like a simple carbon resistor. However, if we study the junction composed of a p-type and an n-type semiconductor, special results are obtained. The element thus obtained is called a diode, and its application is wide in the field of electronics in general. See figure 2.1.

Figure 2-1. Pn junction or diode.

Direct polarization

Figure 2.2 shows a direct current source connected to a pn junction. The form shown in this connection corresponds to directly biasing the diode. In forward bias, the diode behaves ideally as a short circuit, allowing the flow of electric current through it. A real diode has a small resistance in forward bias, and for calculations of not much precision, this resistance can be considered negligible.

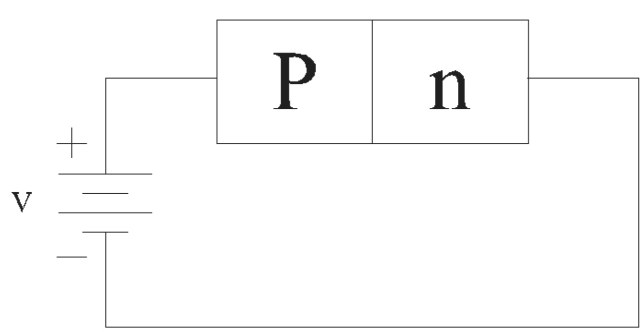


Figure 2-2. Direct diode polarization.

Note in figure 2.2, how the positive of the source is connected to the p-junction, while the negative is connected to the n-junction.

It is worth repeating that in a diode biased in the forward direction, the current flows easily through it. But for the diode to enter into conduction, the voltage of the source must be greater than or equal to 0.7V for a silicon diode. If a germanium diode is used, the minimum voltage required for the diode to enter into conduction is 0.3V.

Reverse polarization

If the polarity of the source in the previous circuit is reversed, so that the positive terminal of the battery is connected to the n-terminal of the diode and the negative terminal of the battery is connected to the p-terminal of the diode, as shown in figure 2.3, a reverse bias will be present.

In reverse bias, the diode behaves as an open circuit, ideally. However, in reality, there is a high resistance between its terminals, typically in the order of megaohms. Ideally, therefore, no current should flow through the diode. However, in practice, a small current flows through the element. The reverse current generated by minority carriers is called *saturation current*, and it can be in the order of nanoamperes. From now on, we will denote this saturation current as I_s

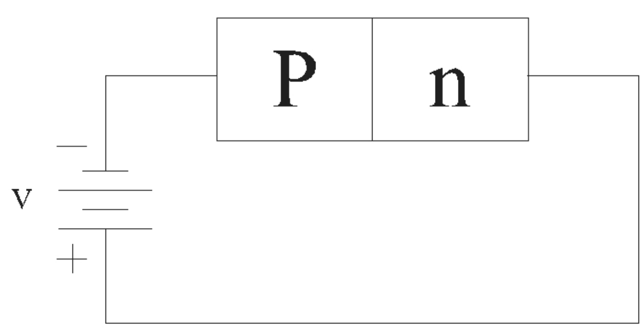


Figure 2-3. Reverse polarization.

Now, every diode has a maximum value for the reverse voltage applied to it. Normally, values higher than 50V. If this limit is exceeded (the technically specified voltage for each diode, called the *breakdown voltage*), the device would enter into avalanche, that is, it would behave as a conductor in both directions; that is, it would be a useless short circuit. In conclusion, exceeding the breakdown voltage implies destroying the diode.

Physical appearance and electrical symbol of the diode

In figure 2.4(c), the electrical symbol used to represent a diode is shown. The p-terminal is called the anode, and the n-terminal is called the cathode. The symbol for the diode is an arrow pointing from the anode to the cathode. In the direction in which the arrow points, current flow is possible, while in the opposite direction it is not. The physical shape of the diode, on the other hand, is that of a small dark-colored tank, marked at the cathode end with a silver-colored band. This can be seen in figure 2.4(b), while in figure 2.4(a) the physical composition of the diode is shown, indicating its anode (A) and cathode (K) terminals.

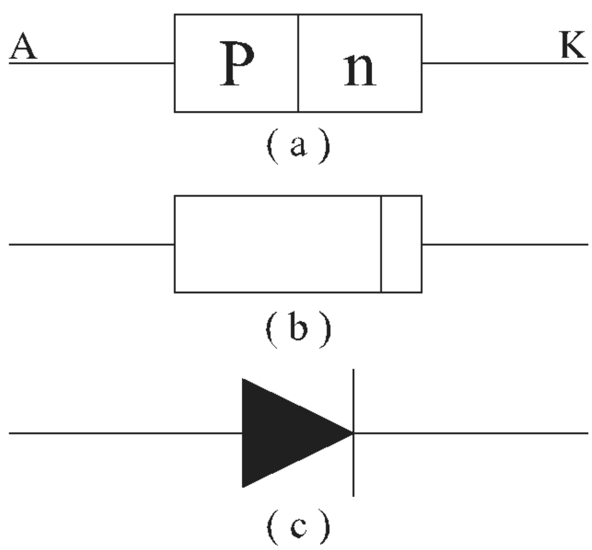


Figure 2-4. (a) Diode construction (b) physical appearance and (c) symbol.

Analogy for the diode

The discussions in the preceding sections indicate that the diode behaves like an intelligent switch. When forward biased, it automatically closes and takes a value of zero resistance, while when reverse biased, it opens and takes a value of infinite resistance. These aspects are shown in figure 2.5.

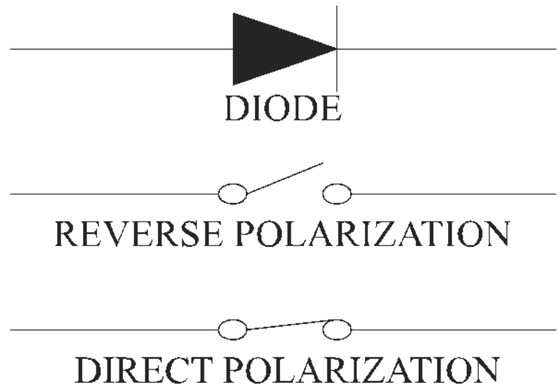


Figure 2-5. The diode as a switch.

Diode check and fault detection

To determine if a diode is in good condition, an ohmmeter can be used. The diode's resistance should be measured in both directions (this is achieved by reversing the leads in a measurement with respect to the previous one), so that one of the diode measurements will be forward-biased by the internal battery of the meter and will show a low resistance, while in the reversal of the measurement, the diode will be reverse-biased and therefore will show a high resistance. In general, what is expected is to obtain a remarkably high inverse to direct resistance ratio, usually greater than 100:1. However, the important thing in this test is not so much the value of the resistance, but determining if the diode conducts in one direction and not the other. The following cases are possible failures in diodes: if the resistance is small in both directions, it is a sign that the diode is short-circuited; if, on the other hand, the resistance is very high in both directions, it is indicative that the diode is open; if the resistance in the reverse direction is relatively small, then we say that we have a diode with leaks. The tests are performed with the diode out of the circuit, and it is recommended that they be performed on the Rx10 scale.

A practical tester shown in figure 2.6 can also be used to check diodes. When the tester's points are placed so that tip A touches the anode and tip C touches the cathode, the LED will light up indicating that current is flowing through the diode. If the tips are reversed, no current will flow through the diode and therefore it will not light up. If these steps are conducted with such results, the diode is in good condition, otherwise, there is something wrong with the device.

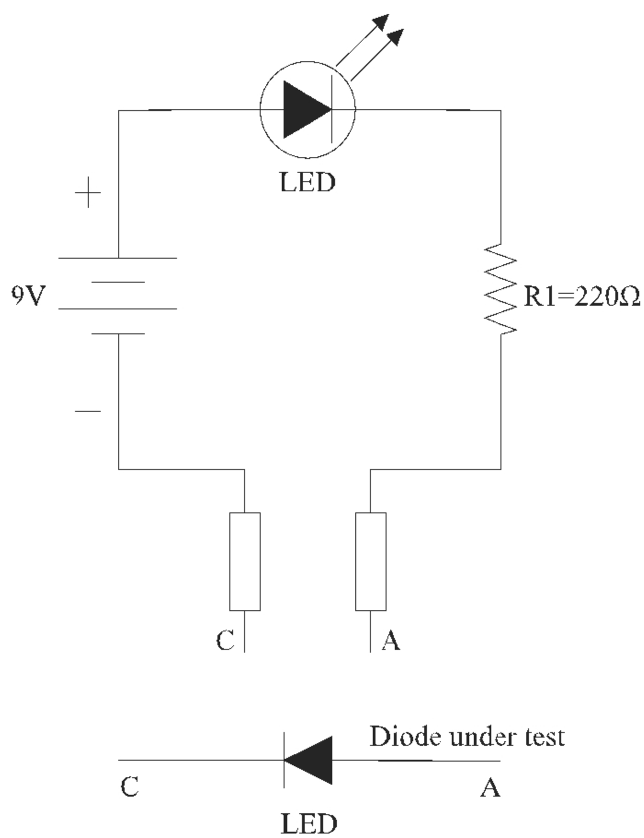


Figure 2-6. Diode tester.

Technical specifications

Manufacturers of semiconductor devices provide technical specifications about different components in their datasheets. These specifications are often complex for the average user who may not be able to interpret them properly, but they are especially useful for circuit designers. Many of these characteristics can also be studied in so-called replacement manuals, which describe parameters of interest for technicians and designers. In these datasheets or technical specifications, the elements must be located according to their references, and diodes, for example, are normally identified by a number that differentiates them and is always preceded by the prefix 1N. Thus, for example, references can be found from 1N4001 to 1N4007, from 1N746 to 1N759, from 1N957 to 1N984, or from 1N4370 to 1N4372. Each reference has its own technical specifications.

ECG manual review

Replacement manuals for semiconductor devices have become a useful tool for technicians in electronics and related areas nowadays.

The most popular one is perhaps the ECG replacement manual, which in a single volume provides complete information on the wide variety of devices available in the market, such as diodes, transistors, SCRs, Triacs, integrated circuits, and other elements.

Through the ECG manual, you can obtain information about the characteristics of devices, such as physical shape and terminal identification.

To use it, you look up the component reference in the second part of the book. For example, if we want to know the characteristics of the 2N3904 transistor, we search for the reference 2N3904 in the list under the heading "***to be replaced***".

To the right of it, the ECG number 123AP appears; this is its replacement. With this information, we go to the first part of the manual, where the ECG components are listed in numerical order. For our example, the 123AP tells us that it is an NPN transistor and refers us to page 1-40 and figure T-16. On page 1-40, we find a complete set of voltage-current characteristics for this transistor, while on the inside cover, a message refers us to page 1-76, where we can find a figure of the physical package with indications of size and terminals.

As it can be seen, this is a straightforward way to know all the components and their characteristics, without having to resort to manufacturers' catalogs.

REVIEW

Concepts

Define or discuss the following:

- ☐ Semiconductor diode.
- ☐ Direct polarization.
- ☐ Reverse polarization.
- ☐ Analogy of the diode and the switch.
- ☐ Checking diodes and detecting faults.
- ☐ Diode specification.
- ☐ Locating components in the ECG manual.

Chapter 3
DIODE CIRCUITS

Before starting the study of circuits with diodes, it is convenient to review some concepts related to the step-down transformer, which is necessary for managing the low voltages required in electronic circuits.

The step-down transformer

The power outlets available in residential areas provide users with a nominal voltage of 120V_RMS at a frequency of 60 Hz. However, this value is not constant, but fluctuates depending on the time, the area, and various other factors. At peak hours, for example, it can drop to a level of approximately 105V, and during resting hours it can rise to around 125V. Remember that the relationship between the RMS value and the peak value of a sine wave is given by:

$$V_{RMS} = \frac{V_m}{\sqrt{2}} \quad (3.1)$$

Which can also be expressed as:

$$V_{RMS} = 0.707V_m \quad (3.2)$$

According to this equation, the RMS voltage is 70.7% of the maximum voltage of the waveform. The RMS value of a signal is the equivalent DC voltage that would produce the same power as the sine wave over one complete cycle. However, the voltage obtained from the power outlets is too high to be applied to electronic circuits;

for this reason, almost all electronic equipment uses a transformer to reduce this signal from the power grid to a lower value, more appropriate for use in devices such as diodes and transistors.

Figure 3.1 shows the electronic symbol of a transformer.

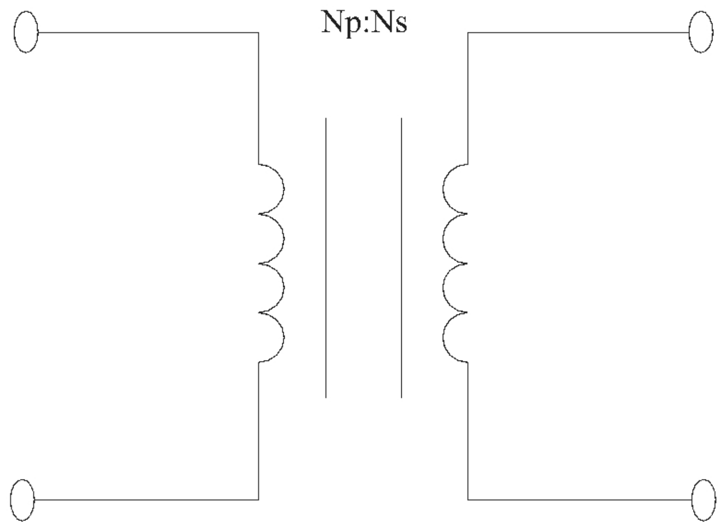


Figure 3-1. Transformer symbol.

And in figure 3.2 the diagram of a transformer with a load is shown.

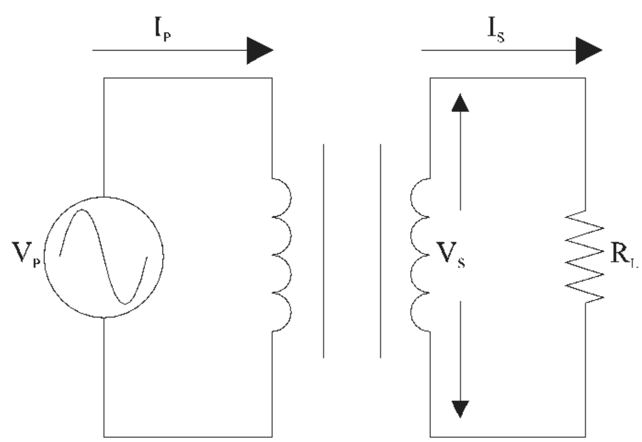


Figure 3-2. Transformer with load.

The left coil is called the primary winding and the right one is called the secondary winding. The number of turns in the primary winding is N_p and in the secondary winding is N_s. The vertical lines between the primary and secondary windings indicate that the conductor is wound around an iron core.

If the number of wires turns in the secondary is greater than the number of turns in the primary, the transformer will be step-up; if, on the other hand, the number of wires turns in the primary is greater than the number of turns in the secondary, the transformer will be step-down.

The first relationship of importance in transformer handling is that input power is equal to output power (for ideal transformers where there are no losses of any kind). This can be expressed as:

$$P_P = P_S$$

As power is the product of voltage and current, we will have:

$$V_P I_P = V_S I_S$$

This brings us to the first important relationship, which is:

$$\frac{V_P}{V_S} = \frac{I_S}{I_P} \qquad (3.3)$$

The second relationship is obtained from the fact that the product of amperes per turn for both windings remains constant.

$$I_P N_P = I_S N_S$$

Which we can express as:

$$\frac{N_P}{N_S} = \frac{I_S}{I_P} \qquad (3.4)$$

From the transitivity observed between equations (3.3) and (3.4) we conclude that:

$$a = \frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P} \qquad (3.5)$$

Where "*a*" is called "*transformation ratio*".

EXAMPLE 3.1

The voltage measured at a mains socket is 120V_{rms}.
Calculate the maximum value of the signal.

SOLUTION

According to equation (3.2) the rms voltage is given by the expression:

$$V_{RMS} = 0.707V_m$$

From where:

$$V_m = \frac{V_{rms}}{0.707}$$

Replacing we obtain:

$$V_m = \frac{120V}{0.707} = 170V$$

EXAMPLE 3.2

A step-down transformer has a transformation ratio of 4:1 if the primary voltage is 120V, determine the value of the secondary voltage.

SOLUTION

By the expression given in equation (3.5) we have that:

$$a = \frac{V_P}{V_S}$$

From where:

$$V_S = \frac{V_P}{a}$$

With $V_P = 120V$ and $a = 4/1 = 4$ we have:

$$V_S = \frac{120V}{4} = 40V$$

EXAMPLE 3.3

Assume that in the transformer of the previous exercise the current in the primary is $2A$. Determine the secondary current.

SOLUTION

For the transformer in the above exercise the transformation ratio is $a = 4$. With $Ip = 2A$ and the relationship obtained from equation (3.5) we have:

$$a = \frac{I_S}{I_P}$$

Or:

$$Is = aI_p = 4(2A) \ = 8A$$

Half-wave rectifier

Ideally, a rectifier diode is a device that allows the passage of current with direct polarization, and blocks, preventing it, when reverse polarization is applied. For this reason, it is a useful element for converting alternating current into direct current. The simplest circuit to achieve this conversion of alternating current into direct current is the half-wave rectifier, which can be seen in Figure 3.3. The primary of the transformer is supplied with the mains voltage by means of an electrical plug. Some plugs, especially those intended for electronic applications, have a third terminal intended to make the conversion to ground of the equipment.

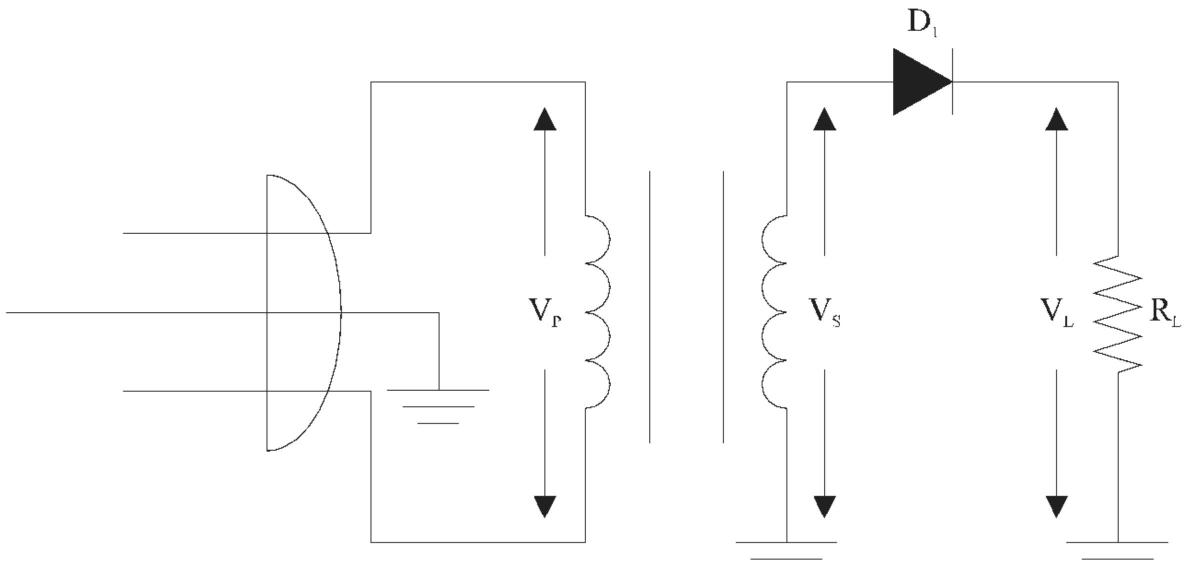


Figure 3-3. Half-wave rectifier.

The operation of the circuit is as follows:

During the positive half cycle of the voltage in the primary, the secondary will also have, by virtue of the way both windings have been wound, a positive half cycle. For this reason, the diode will be positively biased, and the same signal given by the secondary will appear on the load resistor. (See Figure 3.4). In the negative half cycle, on the other hand, the diode will be reverse biased and will not allow current to flow. Therefore, there will be no voltage across the load resistor, and the complete signal across it will be a half-wave signal.

Note that the voltage in the load is only of one half-cycle; the positive one; which means that this voltage is unidirectional. In this case, we say that the load current is pulsating direct current, with a value of zero during the time when the negative half-cycle appears in the secondary.

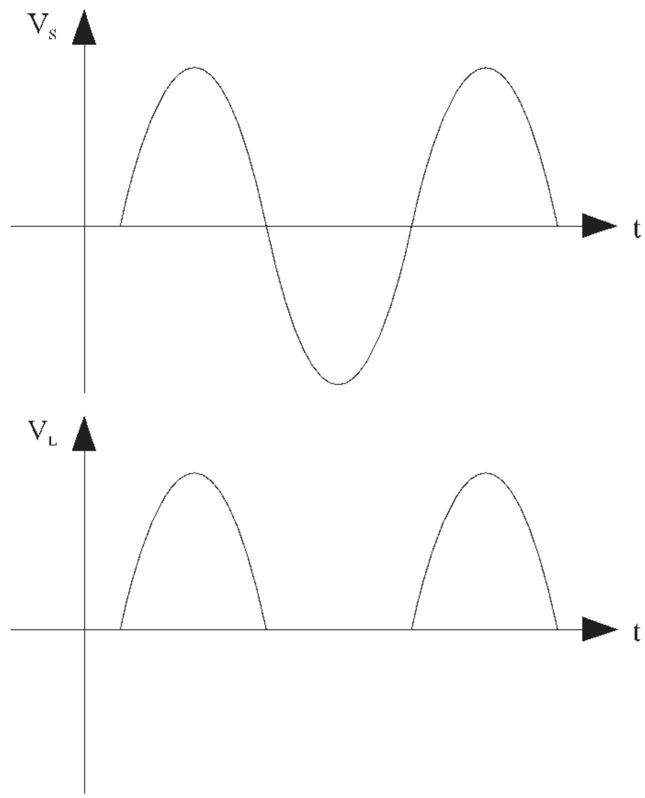


Figure 3-4. Sine-wave signal on the secondary (top) and half-wave signal on the load (bottom).

Half-wave signal period

In America, the frequency of the mains voltage is 60Hz. In Europe, it is 50Hz. The period, according to physical relationships, is equal to the inverse of the frequency, which is:

$$T = \frac{1}{f} \tag{3.6}$$

Where: T: Period
f: Frequency

EXAMPLE 3.4

Calculate the period of the sine signals captured in the power grids in America and Europe and explain what the period is in a wave.

SOLUTION

We have seen that in America, $f = 60Hz$, while in Europe, $f = 50Hz$.

Using equation (3.6), we arrive at:

$$T = \frac{1}{f} = \frac{1}{60Hz} = 16.7ms$$

Similarly:

$$T = \frac{1}{f} = \frac{1}{50Hz} = 20ms$$

That is to say, in America the signals in the power outlets have a period of 16.7ms, while in Europe they have a period of 20ms.

Answering the second question, the period is the time elapsed between the beginning of a positive half-cycle and the beginning of the next positive half-cycle.

Mean value of the half-wave signal

The average value of the half-wave signal is the value that would be measured with a voltmeter if it were read with its terminals connected to the ends of the load. The average value for the half-wave signal is given by the expression:

$$V_{CC} = \frac{V_m}{\pi} \quad (3.7)$$

Where: V_{CC}: Mean value of the signal.

V_m: Mean value of the signal.

EXAMPLE 3.5

The primary of a transformer is connected to a network that has a voltage level of 440V. If the transformation ratio is 16:1, determine the voltage in the transformer secondary. If a half-wave rectifier circuit is fed with the secondary, determine the average value of the signal that will be applied to the load.

SOLUTION

By the expression given in equation (3.5)):

$$V_S = \frac{V_P}{a} = \frac{440V}{16} = 27.5V$$

The half-wave rectified signal will have a peak value $V_m = 27.5V$, Then, by equation (3.7):

$$V_{CC} = \frac{V_m}{\pi} = \frac{27.5V}{\pi} = 8.75V$$

Full wave rectifier

The circuit diagram of a full-wave rectifier is shown in figure 3.5. A center tap on the transformer's secondary is required for this circuit to be grounded, and to provide a return for the current in the circuit. As can be seen, this circuit is basically the combination of two half-wave rectifier circuits.

The operation of the circuit is as follows: in the positive half cycle, diode D_1 is forward-biased while diode D_2 is reverse-biased. Therefore, the current flows through the load towards ground. In the negative half cycle, diode D_2 is forward-biased while diode D_1 is reverse-biased. Then, there will be a path for the current to flow through the load in the same direction towards ground. The signal across the load will be a full-wave signal, as shown in figure 3.6.

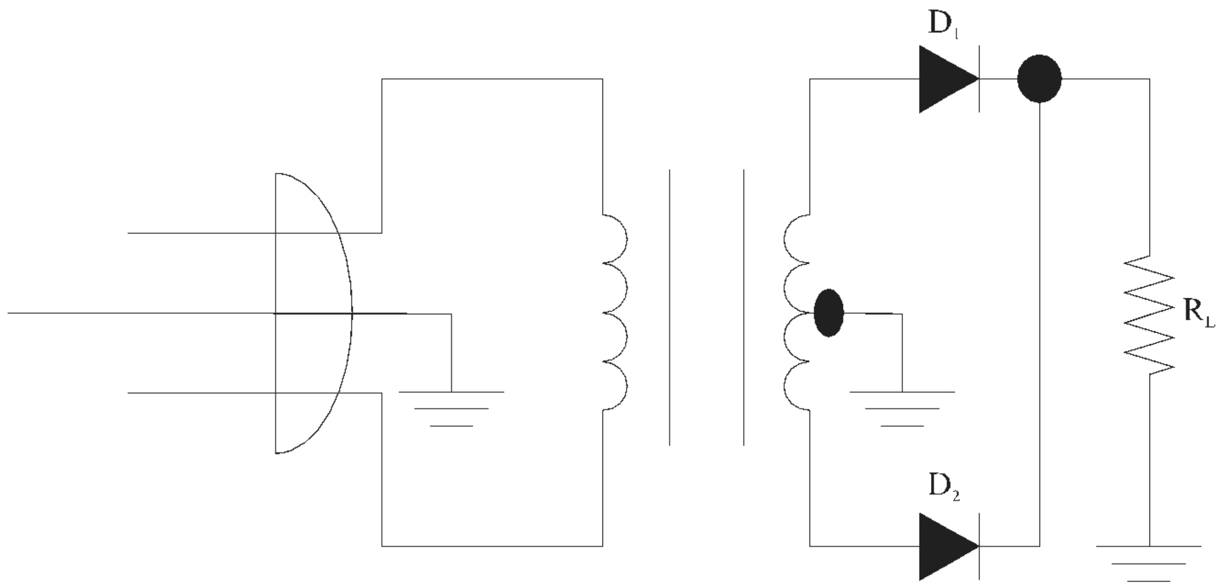
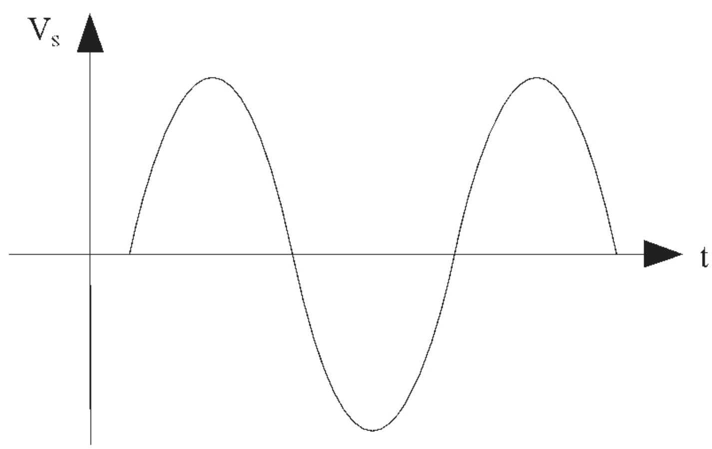


Figure 3-5. Full wave rectifier.

Specifically, diode D_1 conducts during the positive half cycle, and diode D_2 conducts during the negative half cycle. Therefore, current flows through the load in both half cycles, and always in the same direction.



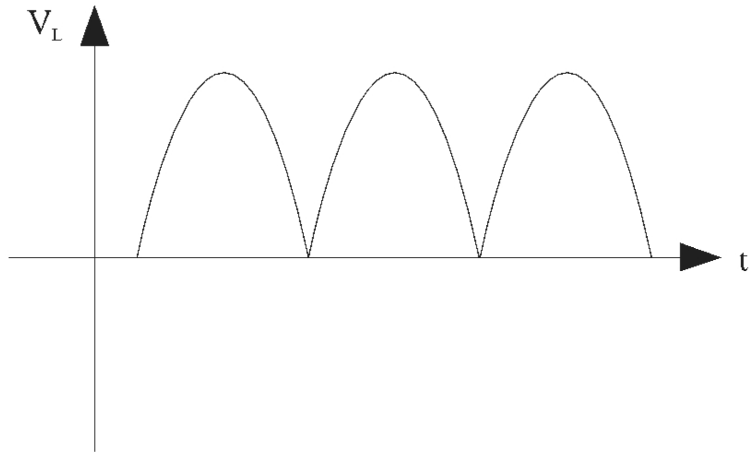


Figure 3-6. Waveform at transformer secondary (top) and at load (bottom).

Signal frequency

The frequency of the full-wave signal is twice the frequency of the input signal.

One complete cycle is when the signal starts to repeat. That is to say, in the full wave rectified signal, shown in figure 3.6, the wave starts to repeat after half a cycle of the voltage in the primary.

EXAMPLE 3.6

Determine the relationship between the frequencies of the input and output signals of a full-wave rectifier. (Considering figure 3.6).

SOLUTION

The frequency of the input voltage provided by the power grid is:

$$f_{ent} = 60Hz$$

The period of the input voltage will then be given by:

$$T_{ent} = \frac{1}{f_{ent}} = \frac{1}{60Hz} = 16.7ms$$

The period of the output voltage in the load will be:

$$T_{sal} = \frac{16.7ms}{2} = 8.33ms$$

Therefore, the frequency of the voltage at the load is equal to:

$$f_{sal} = \frac{1}{T_{sal}} = \frac{1}{8.33ms} = 120Hz$$

This means that the frequencies will be in a relation given by:

$$f_{sal} = 2f_{ent}$$

Mean value of the full-wave signal

If a DC voltmeter is connected to the load resistor in figure 3.5, the reading will be equal to the average value of the output voltage:

$$V_{CC} = \frac{2V_m}{\pi} \qquad (3.8)$$

This voltage is the average value of the full-wave signal because the voltmeter indicates the average voltage of a complete cycle.

EXAMPLE 3.7

The secondary of a transformer has a peak value of 48V. If it is connected to a full-wave rectifier, determine the average value of the signal that will appear at the load.

SOLUTION

If the signal from the secondary has a peak value of 48V, the peak value of the full-wave signal across the load will also be 48V. Using equation (3.8), we obtain that the average value of this waveform will be:

$$V_{CC} = \frac{2V_m}{\pi} = \frac{2(48)}{3.1416} = 30.55V$$

The bridge rectifier

The bridge rectifier uses four diodes instead of two, but with this design, a center-tapped transformer is not required. This has an advantage: ***the rectified voltage at the load is double what would be obtained with the circuit seen in the previous section***. Figure 3.7 shows the circuit diagram of the bridge rectifier.

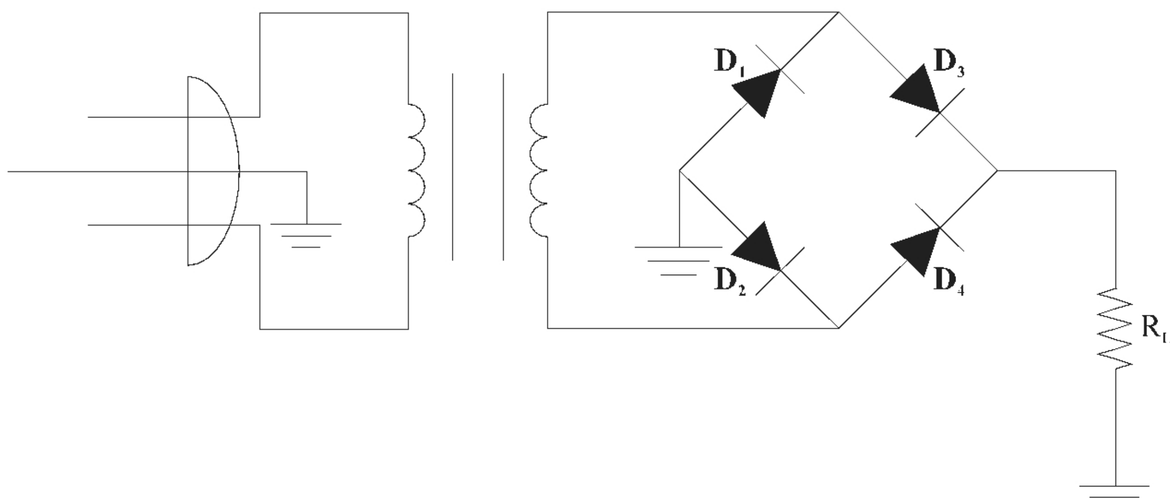


Figure 3-7. Bridge rectifier.

Its operation is as follows: during the positive half-cycle of the mains voltage, diodes D_2 and D_3 are forward-biased and conduct, producing a voltage half-cycle across the load. During the negative half-cycle of the mains voltage, diodes D_1 and D_4 conduct, similarly producing another positive half-cycle. The result is a full-wave signal across the load.

EXAMPLE 3.8

In Figure 3.7, assuming the secondary voltage has a peak value of 24V and the load resistance, R_L, is 100Ω, determine the peak current through the load.

SOLUTION

Since the signal over the load will be a full-wave waveform, the value of the voltage will be:

$$V_L = V_{CC} = \frac{2V_m}{\pi} = \frac{2(24)}{\pi} = 15.27V$$

And by Ohm's law, since:

$$V_L = I_L R_L$$

Then:

$$I_L = \frac{V_L}{R_L} = \frac{15.27V}{100\Omega} = 0.15A$$

Other diode circuits

Voltage multipliers

These are circuits that consist of the proper connection of diodes and capacitors in order to obtain an input voltage multiplied by a constant value: ($2V_P$, $3V_P$, $4V_P$, etc.). In the end, voltage multipliers constitute sources of high voltage and low current, of great usefulness in devices such as cathode ray tubes and image tubes in television receivers, oscilloscopes, and computer screens.

Half-wave voltage doubler

In Figure 3.8, the circuit of a half-wave voltage doubler can be seen. During the negative half-cycle, diode D_1 is forward-biased, and diode D_2 is reverse-biased. As a result, capacitor C_1 charges to the peak voltage, V_P, with the polarity shown. During the positive half-cycle, D_1 is reverse-biased, and D_2 is forward-biased. Since C_1 and the source are in series, C_2 charges to twice the voltage level, $2V_p$.

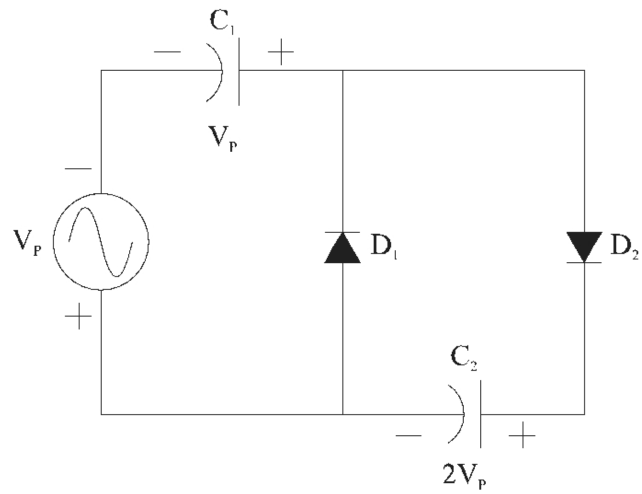


Figure 3-8. Half-wave voltage doubler.

The circuit is useful when a transformer with a secondary of hundreds of volts is required, as in these cases, such transformers tend to be bulky.

The circuit is called a half-wave voltage doubler because the output capacitor C_2 is charged only once during each cycle. Consequently, the ripple has a frequency of 60Hz.

Full-wave voltage doubler

The circuit of a full-wave voltage doubler is shown in figure 3.9. During the positive half-cycle of the source, capacitor C_1 charges to peak voltage with the polarity shown; during the negative half-cycle, capacitor C_2 charges to peak voltage with the polarity shown. Thus, the final output voltage is approximately equal to $2V_P$.

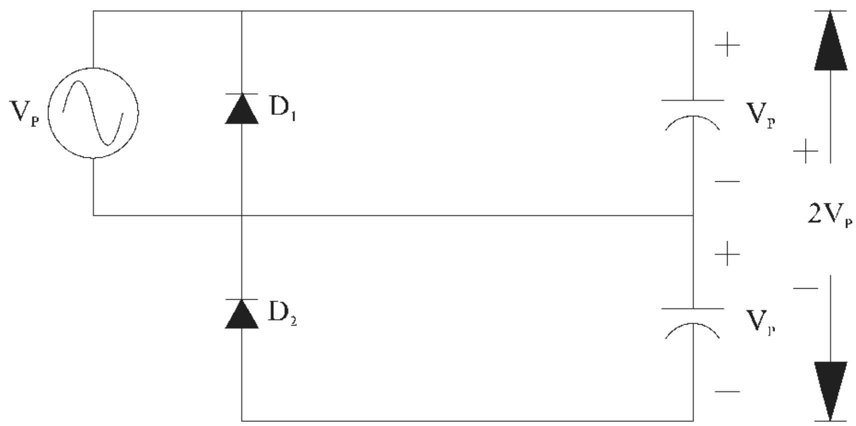


Figure 3-9. Full-wave voltage doubler.

The name of full-wave voltage doubler is due to the fact that one of the output capacitors charges during one half-cycle and the other during the following half-cycle. Therefore, the ripple of the output signal is 120Hz.

It should be noted that the half-wave doubler works better with high load resistances, while the full-wave voltage doubler works better with low-value load resistances.

You can find more advanced books to learn about circuits for voltage triplers, voltage quadruplers, etc.

Limiters (trimmers)

Rectifier diodes can manage power greater than 0.5W and operate optimally at 60Hz.

The limiting or clipping circuits use diodes that we call small-signal diodes: their power limitations are less than 0.5W with currents in milliamperes, not amperes, and are generally operated at frequencies above 60Hz.

The positive limiter circuit is shown in Figure 3.10, which eliminates the positive parts of the signal. As can be seen, the output voltage signal has all the positive half-cycles clipped. The operation of the circuit is as follows:

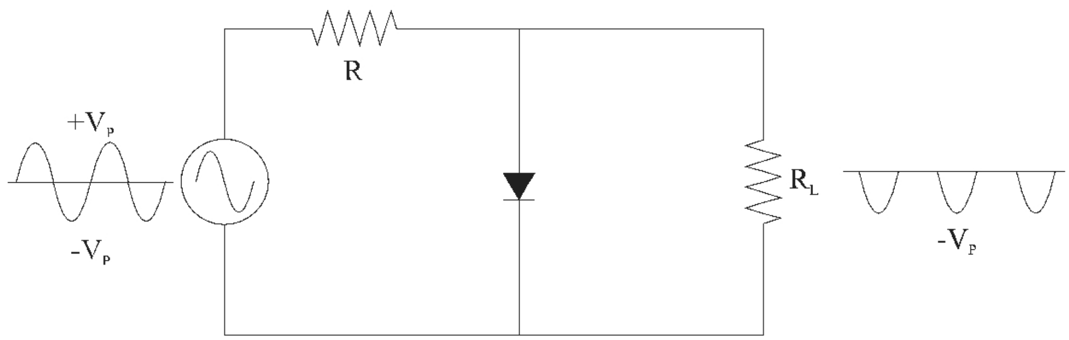


Figure 3-10. Positive limiter.

During the positive half-cycle of the input signal, the diode conducts and the voltage across it is around 0.7V, which can be considered as zero. During the negative half-cycle, the diode is reverse biased and open; the voltage of the negative half-cycle then appears across the load resistor.

If the diode is reversed, a positive limiter is achieved, which eliminates the negative half-cycle, and the positive half-cycle appears on the load.

Polarized limiter

In figure 3.11, the circuit of a biased positive limiter is shown. When the input voltage is greater than V+0.7, the diode conducts, and the output is maintained at V+0.7. If the input voltage is less than V+0.7, the diode opens, and the circuit operates as a voltage divider.

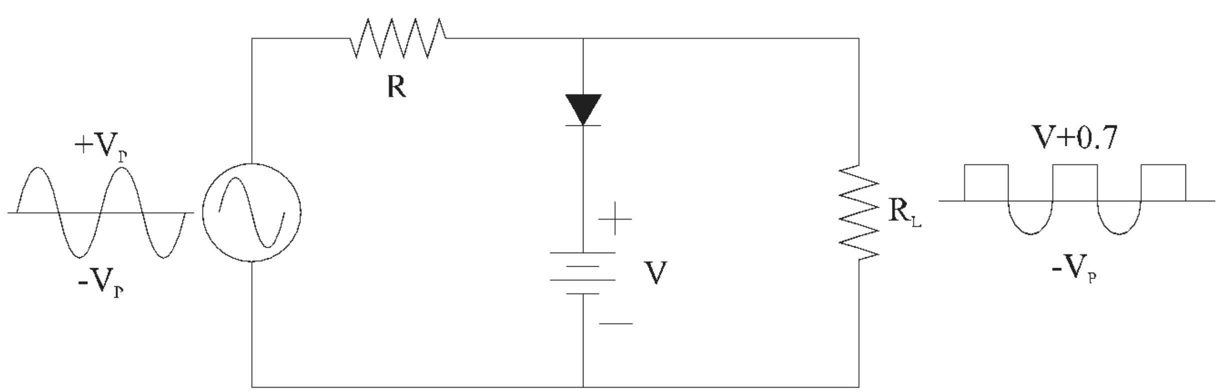


Figure 3-11. Positive polarized limiter.

The positive and negative limiters can be swapped to obtain clipped waves in both half cycles, thus achieving an approximately square wave. To do this, a circuit with a source and a diode with opposite polarity is connected in parallel with the load, as shown in the circuit of Figure 3.12.

Other types of diodes

The rectifier diode seen so far is of great practical usefulness; however, it is not the only type of diode; there are also special diodes that are used in particular applications, such as the Zener diode, Schottky diodes, Varicaps, etc.

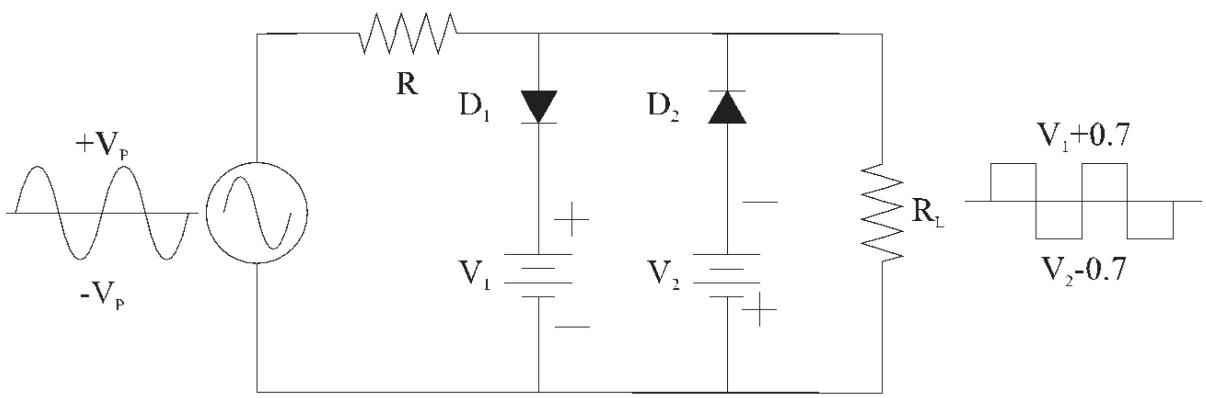


Figure 3-12. Combination of limiters.

The Zener diode

As seen in previous sections, rectifier diodes and small-signal diodes are often used in the forward and reverse bias regions, but it is not common to use them in the breakdown region, as this can destroy them.

The same does not happen with a Zener diode: the Zener diode is designed to operate in the breakdown region, even better.

The Zener diode is a practical and essential voltage regulator, which can maintain the voltage almost constant regardless of the variations that occur in the lin.

In figure 3.13(a) the electrical symbol of a Zener diode is shown, and in figure 3.13(b) an alternate symbol for it is represented. In both cases, the lines of the cathode resemble the letter Z of Zener.

Manufacturers produce Zener diodes with breakdown voltages ranging from 2 to 200V. These diodes can operate in all three regions: forward, reverse, and breakdown.

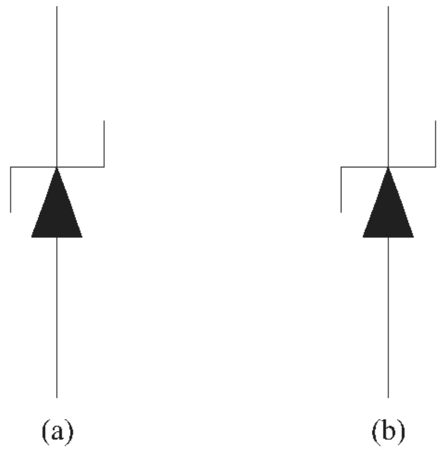


Figure 3-13. Zener electrical symbol.

The current vs. voltage characteristic curve of a Zener diode is shown in Figure 3.14. The graph itself is the same as for a regular rectifier diode, the only difference being the operating zone between the two.

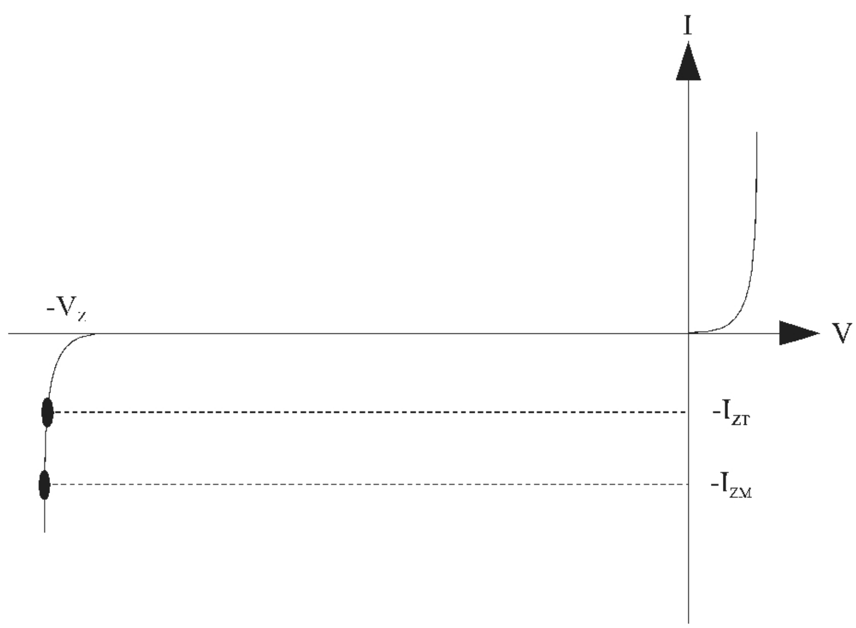


Figure 3-14. I - V curve for the diode.

In the forward region, both the Zener diode and a conventional rectifier diode behave similarly, starting to conduct at around 0.7V. In the reverse region, which is between 0V and the Zener voltage, $-V_Z$, a small reverse current flow, both for the Zener diode and the regular silicon diode. At the Zener voltage point, there is a very sharp knee and an almost vertical increase in current.

The minus sign at the Zener voltage point indicates that at that point the characteristic has a negative value. However, when referring to the Zener voltage, we can do it in terms of positive absolute value. For example, we can say that a diode has a Zener voltage of 100V, not -100V.

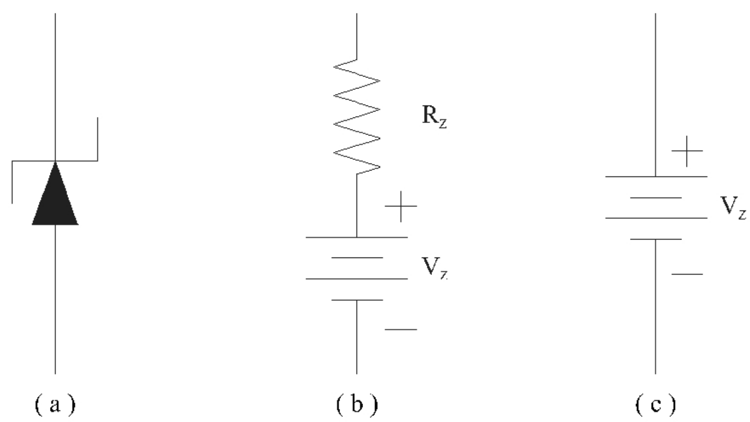


Figure 3-15. Zener voltage and Zener resistor.

Zener voltage and Zener resistor

The Zener diode is sometimes called a Zener regulator, because it performs the function of maintaining a constant voltage between its terminals, even if there are changes in current through it. Additionally, due to its composition based on doped p-n semiconductors, it is normal for it to have a resistance between its terminals. This resistance is commonly of incredibly low value. Figure 3.15(b) shows the equivalent representation of the Zener diode as a source and a resistance. Due to the low value of the Zener resistance compared to the load resistance, it can be neglected; Figure 3.15(c) shows a simplified representation as a voltage source only. Figure 3.15(a) shows the symbol and real and approximate equivalent circuits of the Zener.

EXAMPLE 3.9

The Zener diode in the circuit of figure 3.16 has a Zener voltage of 15V, determine the maximum and minimum currents flowing through the circuit.

SOLUTION

The input voltage can vary from 20 to 40V. With this input voltage, the voltage across the Zener diode will remain at 15V, as shown in Figure 3.16(b).

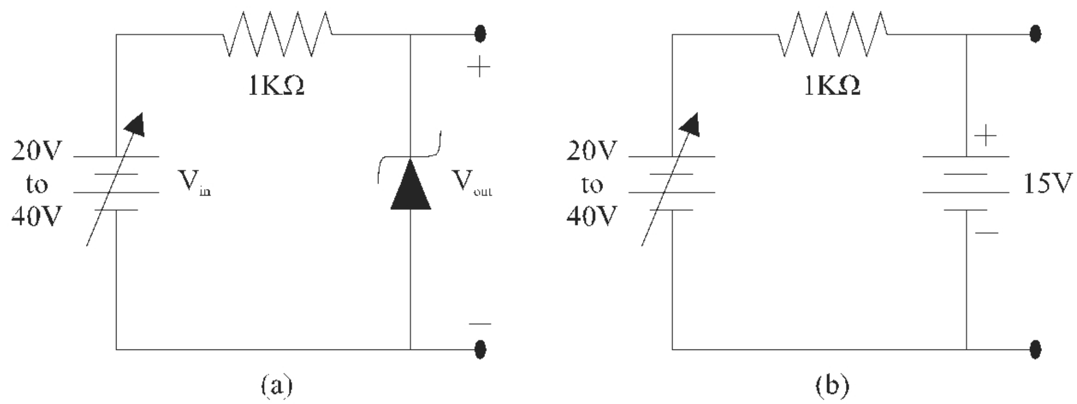


Figure 3-16. Circuit (a) given and (b) equivalent of example 3.9.

By summing up the voltages around the loop, we can determine the maximum and minimum currents as follows:

For the maximum value:

$$I_{máx} = \frac{(40 - 15)V}{1K} = 25mA$$

For the minimum value:

$$I_{mín} = \frac{(20 - 15)V}{1K} = 5mA$$

EXAMPLE 3.10

Explain the operation of the circuit shown in Figure 3.17.

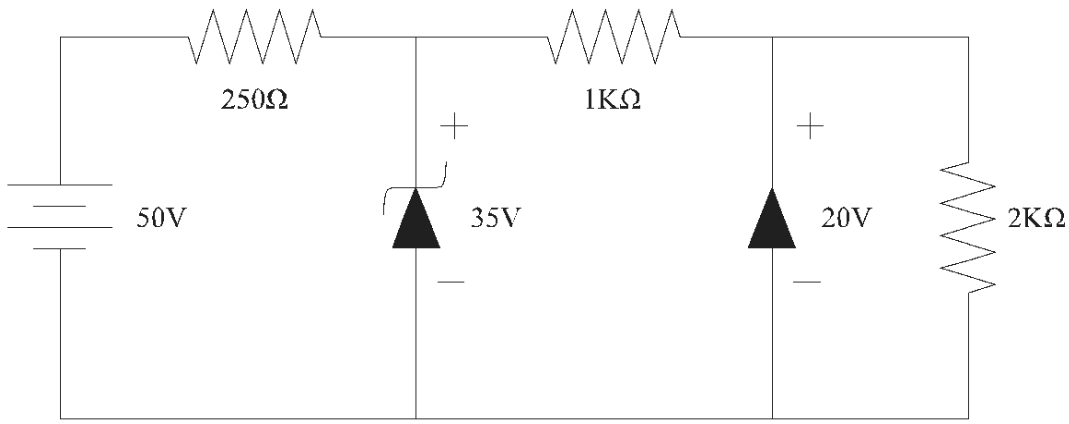


Figure 3-17. Circuit of example 3.10.

SOLUTION

The input voltage is divided between the 250Ω resistor and the 35V Zener, making the first Zener a pre-regulator for the system. The voltage of the first Zener, 35V, is divided between the 1kΩ resistor and the 20V Zener. The first regulator provides a well-regulated input and thus the final output will be well adjusted. As the load resistor is in parallel with the second Zener, its voltage will be 20V.

The Schottky diode

Normal rectifier diodes can switch from forward to reverse bias and vice versa, but their performance becomes deficient at high frequencies.

For managing high frequencies, Schottky diodes are used; a Schottky diode can switch (activate or toggle) faster than a normal diode. In fact, these diodes can rectify frequencies above 300 MHz with ease.

Their main application is found in digital computers, where the speed depends on how quickly the diodes and transistors can be activated. It is at this moment that Schottky diodes come into play.

The Varicap

The figure 3.8 shows (a) the symbol, (b) the equivalent circuit, and (c) the characteristic curve of a varicap.

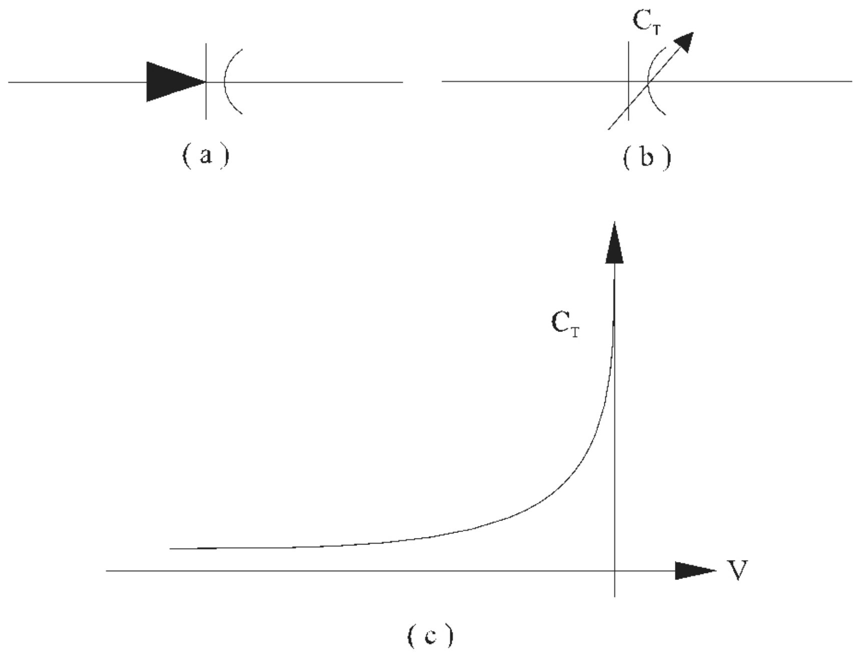


Figure 3-18. (a) Symbol (b) Equivalent circuit and (c) Characteristic curve of a varicap.

The varicap is a diode due to its p-n composition, but at high frequencies it acts as a variable capacitance. The characteristic curve of the varicap shows how the capacitance becomes smaller as the reverse voltage becomes larger. In summary, the reverse voltage controls the capacitance. This phenomenon is the principle of remote control. A varicap can also be connected in parallel with an inductance to obtain a resonant circuit. Thus, by changing the reverse voltage, the resonance frequency can be changed. And this is the principle of tuning a radio transmitter, a TV channel, etc. Figure 3.8 shows (a) the symbol, (b) the equivalent circuit, and (c) the characteristic curve of a varicap.

The varicap is especially useful in television receivers, FM receivers, and other communication circuits.

REVIEW

Concepts

Define or discuss the following:

- ☐ Step-down transformer.
- ☐ Turns ratio.
- ☐ Half-wave rectifier.
- ☐ Period of the half-wave signal.
- ☐ Average value of the half-wave signal.
- ☐ Full-wave rectifier.
- ☐ Frequency of the full-wave signal.
- ☐ Average value of the full-wave signal.
- ☐ The power supply rectifier.
- ☐ Voltage multiplication.
- ☐ Half-wave voltage doubler.
- ☐ Full-wave voltage doubler.
- ☐ Voltage limiter or clipper.
- ☐ Bias voltage limiter.
- ☐ The Zener diode.
- ☐ Zener voltage and Zener resistance.
- ☐ The Schottky diode.
- ☐ The varicap.

EXERCISES

3.1. A transformer has a nominal voltage of 150V in the primary, and a secondary with taps of 9V, 18V, 30V, and 50V. If these values are effective (RMS), determine the peak values of each.

3.2. A step-down transformer has a turns ratio of 8:1. If the primary voltage is 220V, determine the voltage in the secondary. If the secondary current is 3A, determine the power of the primary, the current and power of the secondary. If the primary has a winding of 1200 turns, how many turns does the secondary winding have?

3.3. From a certain circuit, signals of frequency 100Hz, 1000Hz, and 10000Hz can be obtained. Calculate the periods of the respective signals.

3.4. If the secondary voltages of the transformer in exercise 3.1 are rectified into (a) half-wave signals and (b) full-wave signals, determine the average values of the obtained signals.

3.5. If loads of 100Ω are connected in the circuits mentioned in the previous exercise, determine the current, IL, for each circuit.

3.6. The Zener diode in figure 3.19 has a Zener voltage of 20V. Determine the voltage that falls across each of the load resistors.

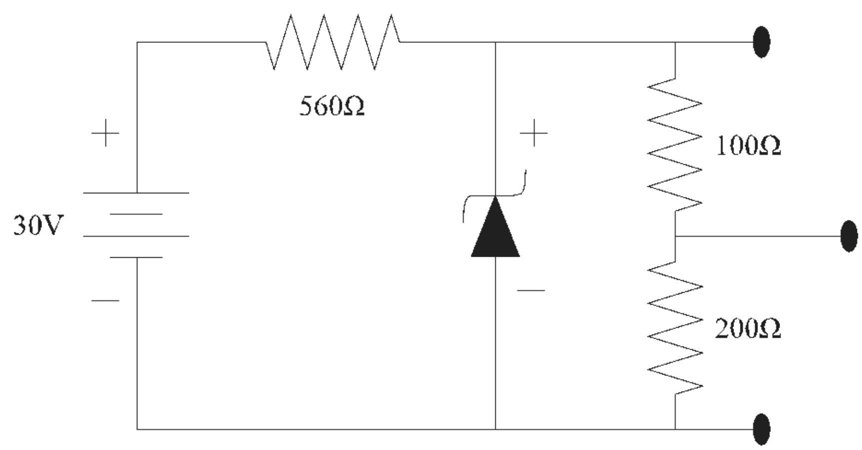


Figure 3-19. Circuit of exercise 3.6.

Chapter 4
BIPOLAR TRANSISTORS (BJT)

Composition and symbology

A bipolar transistor (bipolar meaning it has two polarities) is a semiconductor device composed of two p-type layers separated by an n-type layer, or two n-type layers separated by a p-type layer. In the first case, a pnp transistor is obtained, and in the second case, a npn transistor is obtained. Figure 4.1 shows the composition diagram of both elements.

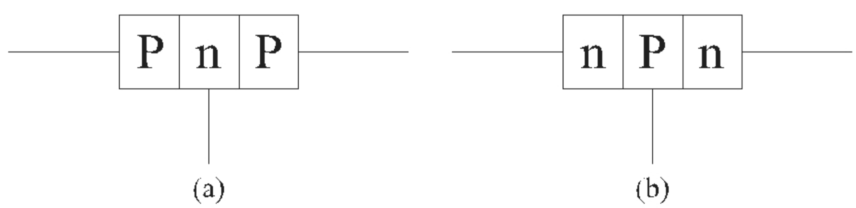


Figure 4-1. Composition of a (a) pnp and (b) npn transistor.

In Figure 4.2 the symbol used for both types of transistors is shown, as well as the names assigned to each terminal.

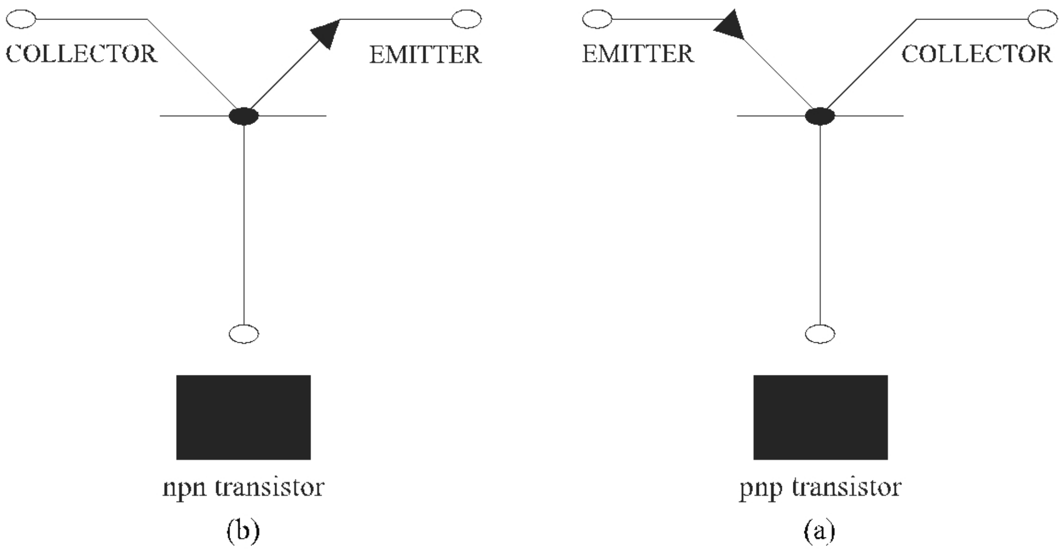


Figure 4-2. Symbol of a transistor (a) pnp and (b) npn.

For both types of transistors, the emitter is the terminal with the arrowhead and the base corresponds to the doped semiconductor material layer that separates the two ends.

Note in figure 4.1 how a transistor can be considered as the union of two diodes, one p-n and one n-p, in figure 4.1(a); and one n-p juxtaposed with another p-n in figure 4.1(b). This graphical consideration can be seen in figure 4.3.

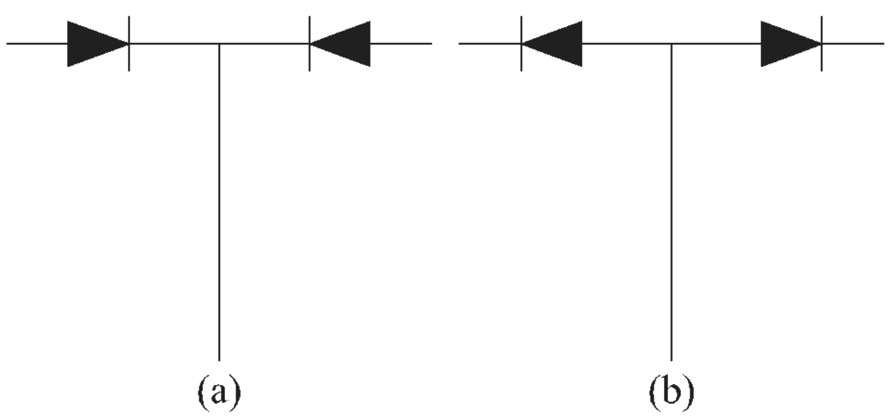


Figure 4-3. Representation of a transistor by diodes (a) npn transistor (b) npn transistor.

Transistor polarization

While the representation of the transistor by means of two diodes is practical, especially in checking and identifying terminals, it is not a good approximation when the transistor is biased, since in this case new and different results are obtained from those expected with such an assumption. These unexpected results, however, are what make the transistor a component of great applications.

In figure 4.4, the polarization of a transistor is shown.

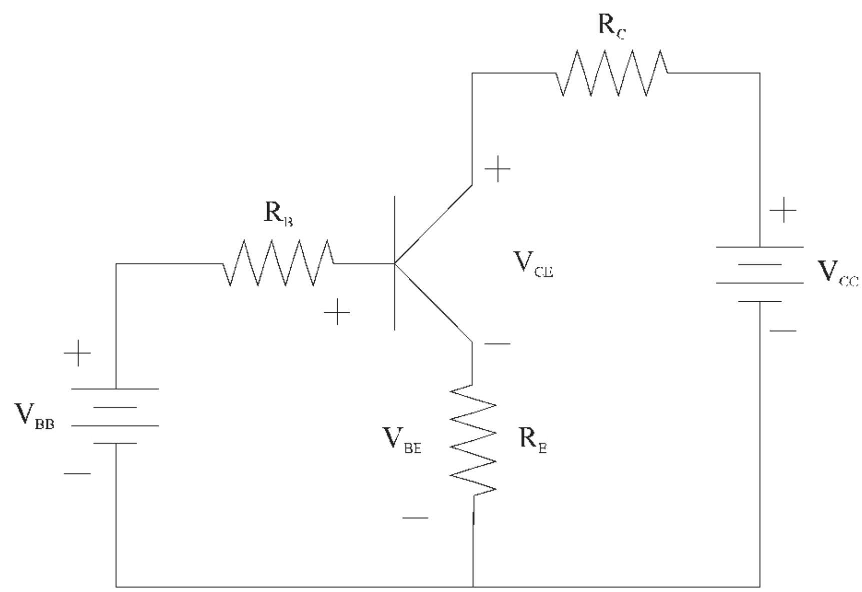


Figure 4-4. Polarization of a transistor.

The behavior of the circuit can be summarized as follows: V_{BB} causes the emitter diode to be forward biased, forcing the emitter electrons to enter the base. Since the base is a very thin layer, it takes little time for almost all electrons to diffuse into the collector through Rc and towards the positive terminal of the voltage source Vcc. In most transistors, about 95% of the electrons flow from the emitter to the collector, while the remaining 5% flow towards the outer part of the base. Figure 4.5 shows the same biasing, but it shows the electrons flowing from the emitter to the collector in the transistor composition diagram. The arrow indicates the direction of electron flow.

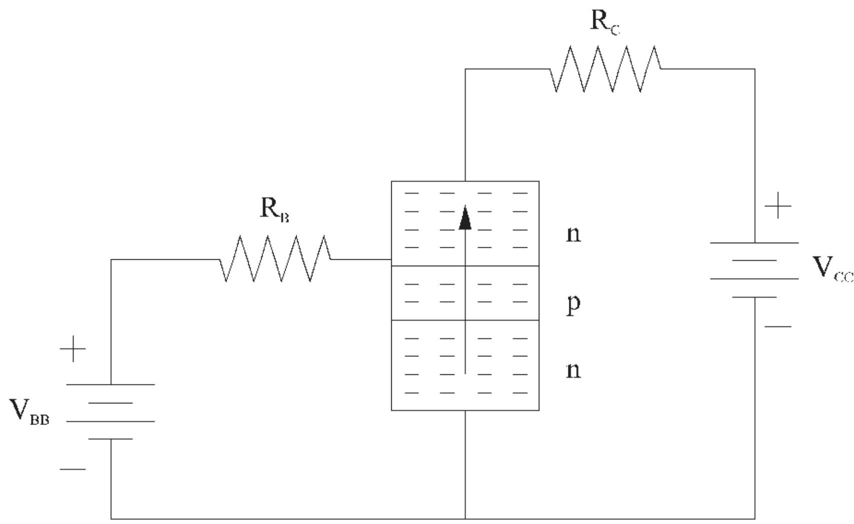


Figure 4-5. Electrons from the emitter to the collector.

Transistor configurations

The polarization applied to a transistor is the energy it requires for its operation. It is equivalent to connecting the power cord of a TV to a 110V outlet before turning it on. If the power cord of the TV is not connected to the outlet, it does not turn on. If the transistor is not properly polarized, it does not work.

Once the transistor is biased, different signals can be applied to it to amplify them, either in current, voltage or power. Depending on which terminals are taken as input and output for these signals, a specific configuration will be obtained. There are three possible configurations: common emitter configuration, common base configuration, and common collector configuration. Figures 4.6(a), (b) and (c) show the corresponding circuits for these configurations and their respective forms of biasing.

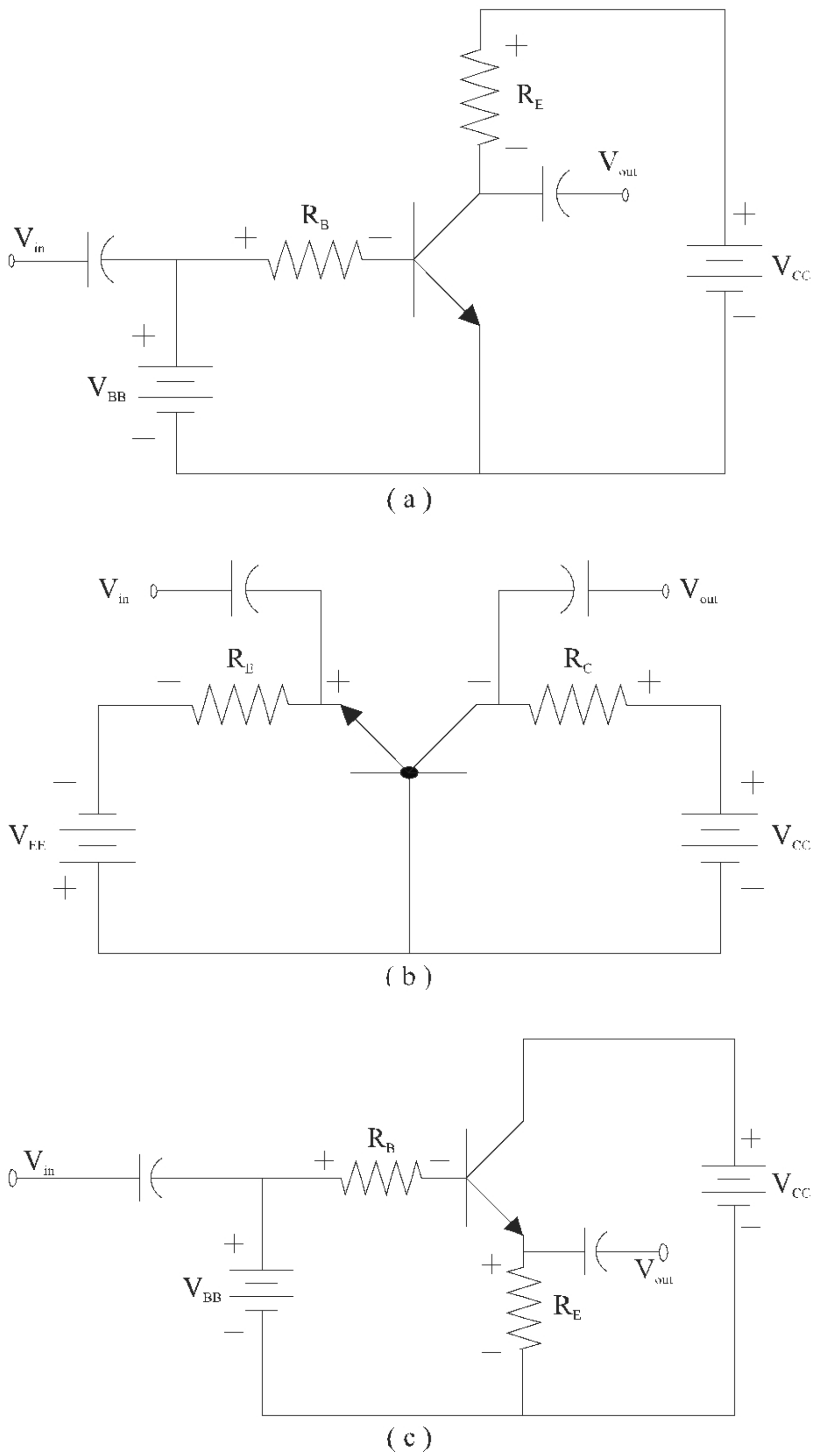


Figure 4-6. Configuration of (a) Common Emitter (b) Common Base and (c) Common Collector.

For the proper operation of the transistor, the goal is to achieve the transfer of energy from a low-resistance circuit to a high-resistance one. This is what allows the device to amplify signals, and to achieve it, the transistor is considered as a pair of opposed diodes, as shown in Figure 4.3(a) and (b). The base-emitter junction behaves like a normal diode with forward biasing (low resistance), and the base-collector junction behaves like a Zener diode, so it must be reverse biased (high resistance). For this reason, the base-collector junction requires greater power dissipation, and therefore it is constructed with a larger collector area.

As can be seen in figures 4.6(a), (b), and (c), the polarizations shown correspond to npn-type diodes. For pnp transistors, it is only necessary to change the polarity of the different batteries to obtain their correct polarization.

Common emitter

In this configuration, the base is taken as input and the collector as output (Figure 4.7), while the emitter is taken as the common terminal for both input and output.

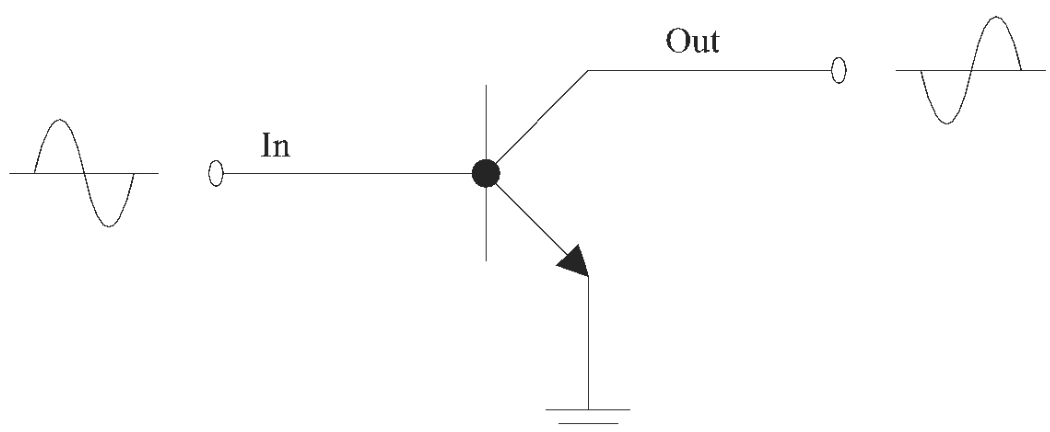


Figure 4-7. Signals to be applied and output for common emitter configuration.

The signals applied to bipolar transistors are current signals, not voltage signals. As can be seen in Figure 4.7, the output signal is amplified and inverted with respect to the input signal. The current amplification (A_i) is determined by the ratio of output current to input current. This is known as the transistor's Beta, β, and is expressed as:

$$A_i = \beta = \frac{I_C}{I_B} \quad (4.1)$$

For the transistor in this configuration, it also amplifies voltage due to voltage gain, as there is a multiplication of impedance and current. The voltage gain (A_V) is given by:

$$A_V = \frac{V_C}{V_B} \quad (4.2)$$

Where both the base voltage and the collector voltage are taken with respect to ground.

As the output signal is inverted in phase with respect to the input signal, it is customary to place a negative sign indicating such phase inversion.

The product of current gain and voltage gain allows to obtain the power gain. Thus:

$$A_P = A_i A_V \quad (4.3)$$

Common collector

As shown in figure 4.8, in this configuration, the base is taken as input and the emitter as output. The collector is the common terminal for the base and emitter.

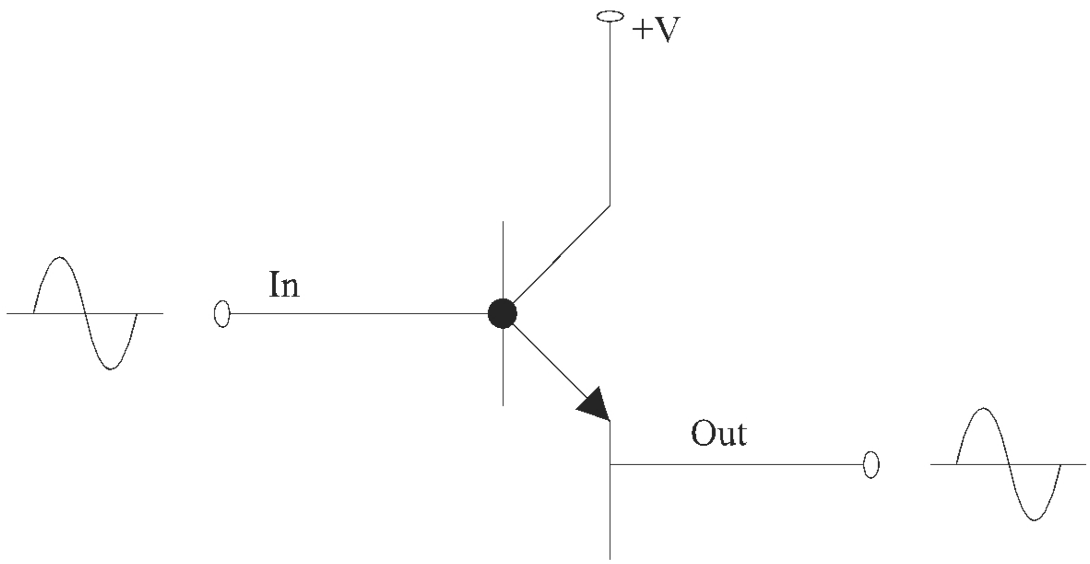


Figure 4-8. Input and output signals for common collector configuration.

This circuit is commonly known as an emitter follower, as shown in Figure 4.8. Its characteristics are it does not present a phase inversion of the output signal with respect to the input signal, it does not amplify voltage, it has a high input impedance and a low output impedance. The latter characteristic makes it ideal for impedance matching between circuits.

The gain observed in the output current (emitter) with respect to the input current (base) is called gamma (γ) and is expressed as:

$$A_i = \gamma = \frac{I_E}{I_B} \qquad (4.4)$$

Common base

In figure 4.9, the bipolar transistor is shown indicating the input and output terminals for the common base configuration.

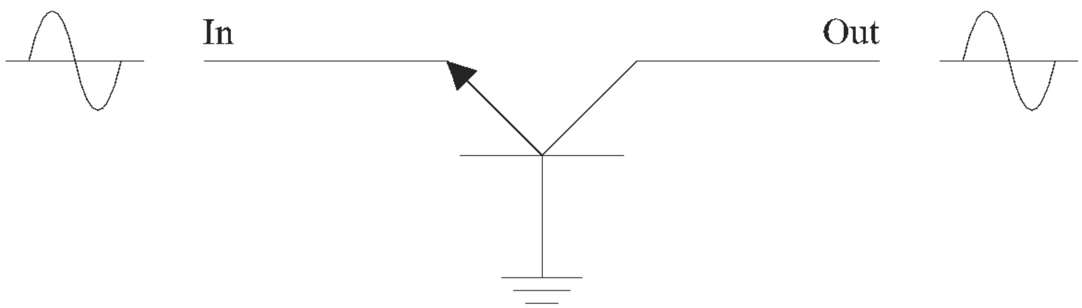


Figure 4-9. Input and output signals for common base configuration.

The transistor in this configuration has a low input capacitance, which allows its use at high frequencies.

For the common base configuration, the input is the emitter, and the output is the collector.

Its characteristics are it does not exhibit phase inversion of the input signal with respect to the output signal, it has low input impedance, high output impedance, and it does not amplify current but does amplify voltage and power. The ratio of collector current to emitter current is called alpha (α). This is expressed as:

$$A_i = \alpha = \frac{I_C}{I_E} \quad (4.5)$$

The input current is high due to its high input impedance; the output voltage is high, and the output current remains the same as the input current; for this reason, the output impedance is high. The input voltage is low, and the output voltage is high, that is, there is voltage amplification.

EXAMPLE 4.1

In an emitter common configuration transistor, an input signal of 10μA is applied and an output signal of 2.5mA is obtained. Determine the β of the transistor.

SOLUTION

In the common emitter configuration, the input is the base, and the output is the collector. If β is defined as the ratio between the output current and the input current, we can calculate β, according to equation (4.1), as:

$$\beta = \frac{I_C}{I_B} = \frac{2.5mA}{10\mu A}$$

From the previous exercise, it can be inferred that a small base current is controlling a high collector current. The process of controlling a high current with a low current is called **AMPLIFICATION**. In this case, it is observed that the base current is translated into an amplified collector current 250 times. In general, β, also known as h_{FE}, is the amplification factor of the transistor in common emitter configuration.

EXAMPLE 4.2

A transistor is connected in common collector configuration. If the γ of the transistor is 300 and an input signal of $8\mu A$ is applied to the base, determine the emitter current of the transistor.

SOLUTION

According to equation (4.4), the gain γ is calculated as:

$$\gamma = \frac{I_E}{I_B}$$

From where we have that:

$$I_E = \gamma I_B$$

Replacing:

$$I_E = 300(8)\left(10^{-6}\right) = 2.4mA$$

As can be observed in the preceding discussions, there are three different gains, one for each configuration. Of the three, γ is the least common, perhaps because the common collector configuration is not frequently used. β (Or h_{FE}) is the most commonly encountered, not only in textbooks dealing with transistors, but also in technical manuals and datasheets of electronic devices. α will also be frequently encountered; in fact, some authors use it in their calculations with equal or greater frequency than β. However, both α and β will be incredibly useful in many of the calculations performed in studies involving transistor circuits, especially because there exists an expression that relates them (which we will see later).

EXAMPLE 4.3

A common base transistor manages a collector current of 2.8mA. If α is 0.95, determine the emitter current.

SOLUTION

According to equation (4.5):

$$\alpha = \frac{I_C}{I_E}$$

From where:

$$I_E = \frac{I_C}{\alpha}$$

Replacing, we have:

$$I_E = \frac{2.8mA}{0.95} = 2.95mA$$

In the previous exercises, the difference in values for the parameters α, β, and γ can be observed. While the latter two are expressed as hundreds of units, the former is less than one. Generally, the values for β and γ are typically between 20 and 300, although values outside this range may be found. As for α, typical values range from 0.9 to 0.995. As noted earlier, however, in a large number of transistors, α is close to 0.95.

Currents in a transistor

In Figure 4.10, the directions for the flow of currents in PNP and NPN transistors are shown. Note that there are three currents in each component: emitter current (I_E), collector current (I_C), and base current (I_B). Since the emitter is practically the current source, it is where the highest flow of electrons occurs, which largely circulate towards the collector. For this reason, the emitter and collector currents are approximately equal. The difference in current between the emitter and collector is the current flowing through the base.

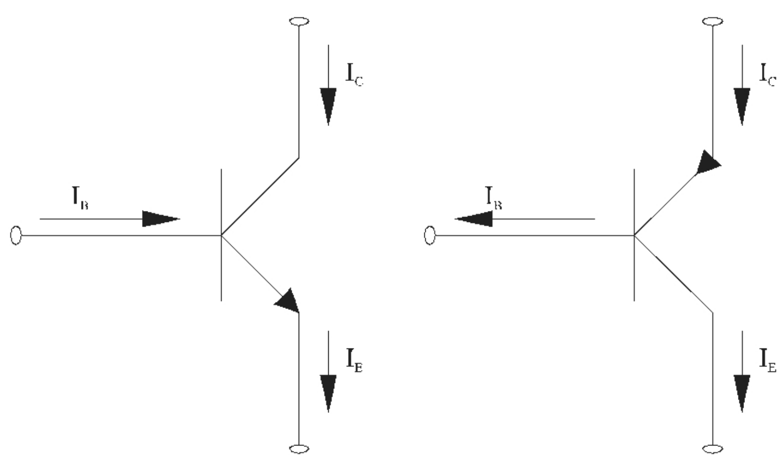


Figure 4-10. Current flow in transistors.

If we apply Kirchhoff's current law to the diagrams in Figure 4.10, we obtain an important relationship for transistors. Kirchhoff's current law states, as one can recall, that the sum of all the currents entering a node is equal to the sum of all the currents leaving the node. Thus:

$$I_E = I_C + I_B \qquad (4.6)$$

The emitter current is equal to the sum of the collector and base currents. And as it has been stated that the base current is minor compared to the emitter and collector currents, in some cases it will be a good approximation to say that the emitter current is equal to the collector current. This is:

$$I_E \approx I_C \qquad (4.7)$$

EXAMPLE 4.4

A transistor in common emitter configuration has a gain of $\beta = 250$, and a collector current of 2.3mA. Let us find the other currents.

SOLUTION

From equation (4.1) it follows that:

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

Substituting, we have, with $Ic = 2.3mA$ and $\beta = 250$.

$$I_B = \frac{2.3(10^{-3})}{250} = 9.2(10^{-6}) = 9.2\mu A$$

With the known values of collector and base currents, we can use equation (4.6) to calculate:

$$I_E = I_C + I_B = 2.3mA + 9.2\mu A$$

That is to say:

$$I_E = 2.31mA$$

EXAMPLE 4.5

A common base transistor has an α of 0.93. If the current flowing through its emitter is 3mA, determine the other currents in the device.

SOLUTION

According to equation (4.5):

$$\alpha = \frac{I_C}{I_E}$$

From which we have, with $I_E = 3mA$ and $\alpha = 0.93$.

$$I_C = \alpha I_E = 0.93(3mA) = 2.79mA$$

Substituting the values $I_E = 3mA$ and $Ic = 2.79mA$ into equation (4.6), we obtain that:

$$I_B = I_E - I_C = 3mA - 2.79mA = 0.21mA$$

Relationship between α and β

By manipulating the equations (4.1), (4.4), (4.5), and (4.6) mathematically, it is possible to derive expressions that relate the different gains of a transistor and calculate α in terms of β or γ, β in terms of α or γ, or γ in terms of α or β. Out of the six equations that can be obtained in this way, only two of them will be presented with their respective derivations (α and β). The process for obtaining the remaining equations is similar to what will be shown for these two; however, they are not practically applicable.

From equation (4.6) we know that:

$$I_E = I_C + I_B$$

Dividing the entire expression by I_C, we have:

$$\frac{I_E}{I_C} = 1 + \frac{I_B}{I_C}$$

Or also:

$$\frac{1}{\frac{I_C}{I_E}} = 1 + \frac{1}{\frac{I_C}{I_B}}$$

This can be expressed as:

$$\frac{1}{\alpha} = 1 + \frac{1}{\beta}$$

And by rearranging this expression, we arrive at the following equations for α and β:

$$\alpha = \frac{\beta}{\beta + 1} \qquad (4.8)$$

And also:

$$\beta = \frac{\alpha}{1 - \alpha} \qquad (4.9)$$

EXAMPLE 4.6

A transistor in common emitter configuration has a $\beta = 200$. Determine the α of the transistor if it is connected in common base configuration.

SOLUTION

Since we know β and want to calculate α, we use the expression in equation (4.8).

$$\alpha = \frac{\beta}{\beta + 1} = \frac{200}{201} = 0.995$$

EXAMPLE 4.7

It is known that the α of a transistor is 0.98. Calculate its β.

SOLUTION

Using equation (4.9), we have:

$$\beta = \frac{\alpha}{1 - \alpha} = \frac{0.98}{1 - 0.98} = 49$$

Other polarization circuits

As it is only logical, it is not practical to use two sources to perform the biasing of transistors, as shown in figures 4.6(a), (b), and (c). In order to conduct the polarization of the devices using only one source, circuits that allow the correct polarization of the different terminals must be used. Such circuits are called biasing circuits.

Fixed polarization

In the circuits shown in figure 4.11(a) and (b), this type of biasing is presented for the common emitter and common collector configurations.

As noted in previous sections, for a transistor to operate correctly, the base-emitter junction must be forward biased, and the base-collector junction must be reverse biased.

As can be seen in Figure 4.11, once the circuit is energized, the collector, base, and emitter currents will flow in the positive direction. Consequently, both the collector and base resistors (Figure 4.11(a)) will have a voltage drop, with the collector being positive relative to the negative emitter, both voltages measured with respect to ground. The goal is to have a greater voltage drop across the base resistor than the collector resistor, so the base resistor, R_B, must be larger than the collector resistor, R_C.

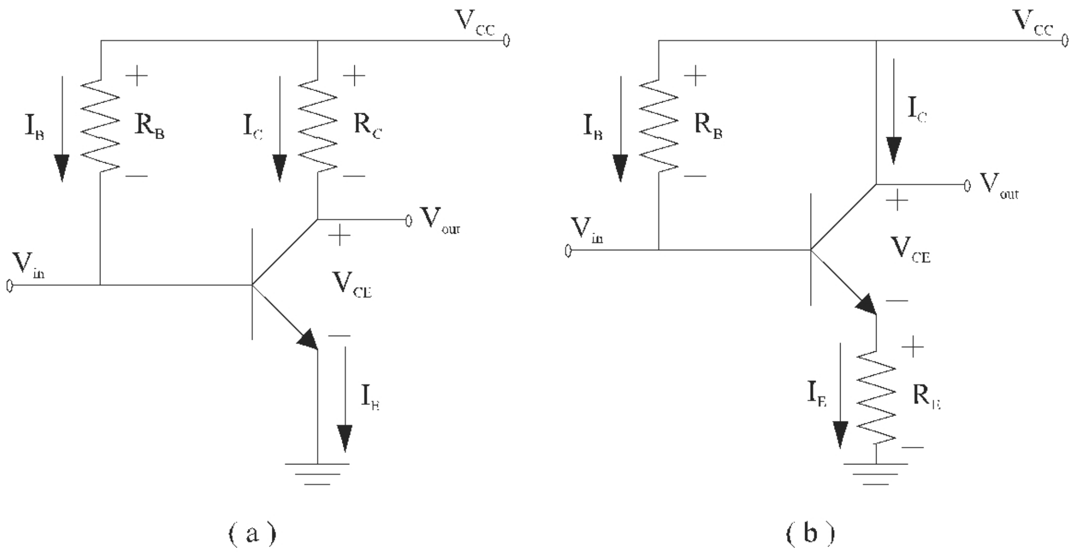


Figure 4-11. Fixed polarization of a transistor at (a) common emitter and (b) common collector.

The voltage V_{BE} (base-emitter junction) is around 0.2 to 0.3V for a Germanium transistor, and 0.4 to 0.8V for a Silicon transistor. Thus, the base is left with a small positive voltage relative to the emitter, but at the same time, it becomes negative relative to the collector, which has a higher positive voltage. In this way, the base-emitter junction is forward biased, and the base-collector junction is reverse biased for a npn transistor. For a pnp transistor, the battery would need to be reversed to achieve the same biasing.

Although the circuit is quite simple, it presents the drawbacks of instability, temperature increase, and signal variation.

For the circuit in Figure 4.11(b), the same effect is achieved, but the resistance R_C is replaced by R_E; the voltages across the junctions remain unchanged.

Automatic polarization

The name "automatic bias" is due to the fact that the bias is subject to variations in the collector voltage. The circuit is stable, but it presents signal variations, which reduces its gain.

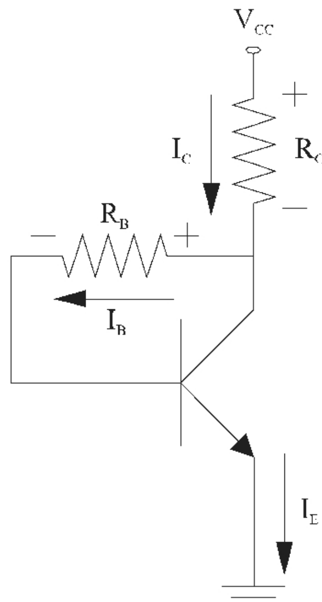


Figure 4-12. Automatic polarization of the transistor.

The automatic biasing circuit in common emitter configuration is shown in Figure 4.12. The currents through the transistor flow conventionally; however, the collector current has a bypass through the base resistor.

The junctions are polarized in the same way as seen in the case of fixed bias. R_B has a lower voltage drop compared to the previous case; therefore, R_B will also be lower. Note that if the collector voltage changes, the base current will change as well. In the case of fixed bias, this does not happen, as the base current is directly dependent on the fixed voltage of the source.

Voltage divider polarization

In Figure 4.13, the basic voltage divider configuration circuit can be seen. It is perhaps the most used, since it does not present polarization variations with the signal, improving the gain. In addition to this, technically it is less stable than the previous one, although this inconvenience is improved by placing a low-value resistor in the emitter.

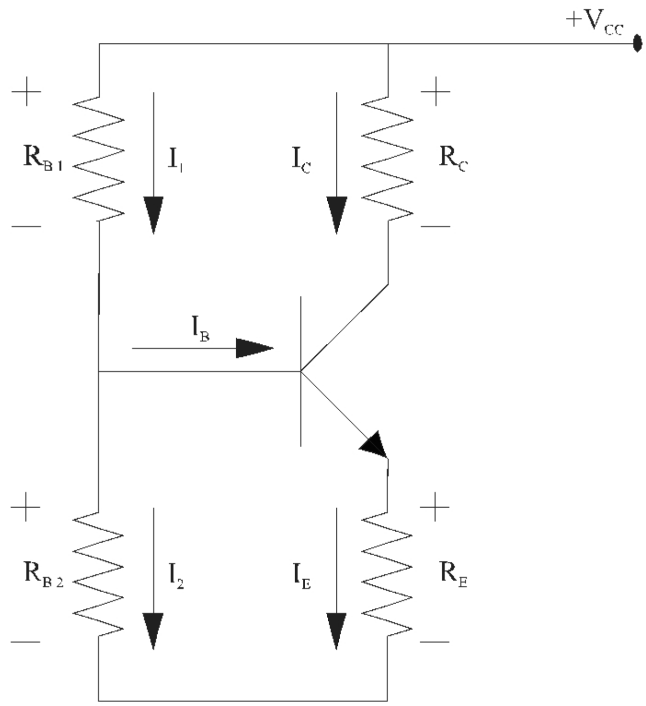


Figure 4-13. Voltage division transistor polarization.

The currents in the transistor do not vary compared to the previous cases. However, both I_B and I_2 flow through R_{B1}. The goal is to make I_1 greater than I_B by a factor of 10 to 20.

Transistor testing and terminal identification

At the beginning of this chapter, we saw that a transistor can be considered, for certain purposes, as two opposing diodes; if the transistor is npn, the diodes are connected by the anodes, and if the transistor is pnp, the diodes are connected by the cathodes. Now, the practicality of approximating the transistor as two diodes is that it allows for a check of the device and identification of its terminals.

In fact, if you want to know information about a transistor, such as whether the device is npn or pnp, or to identify which one is the base, you can proceed as follows: the first thing is to see if you have a schematic diagram of the device. In this case, if the arrowhead points to the base, the device is pnp; otherwise, that is, if the arrowhead points away from the base, the device is npn. Thus, the emitter is always the terminal indicated by the arrowhead; the base is where the arrowhead points towards or away from, and the remaining terminal will be the collector.

In a test like this, however, the possibility that the schematic diagram is incorrect is not taken for granted. To verify it, the next step would be to check the polarities of the voltage at the collector and emitter.

If the collector voltage is positive relative to the emitter voltage, we are dealing with a npn device; if the collector voltage is negative relative to the emitter voltage, the device is pnp. In other words, if $V_{CE} > 0$, the transistor is npn. With the device powered with DC, another test can be performed: determining whether the transistor is made of Silicon or Germanium. To do this, the DC voltage between the emitter and the base is measured. If the base-emitter voltage, V_{BE}, is 0.2V or less, the device is likely made of Germanium. Now, if the V_{BE} voltage is 0.4V or higher, the device is most likely made of Silicon. It should be noted that the main difference between Germanium and Silicon transistors is that the former are much more temperature-sensitive and unstable compared to the latter, which is why Silicon transistors are more commonly used.

To identify the type of transistor using an ohmmeter, as it may occasionally be necessary, the following procedure is followed: the ohmmeter test leads are placed between the base and one of the other two terminals. If a low resistance reading is obtained when the negative terminal is placed on the base, the transistor is of the pnp type, as shown in figure 4.14 (a). If, on the other hand, a low resistance reading is obtained when the base is positive, the transistor is of the npn type, as shown in figure 4.14 (b).

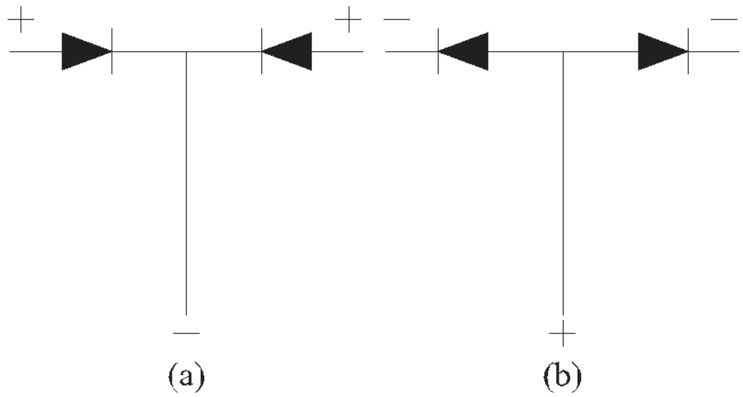


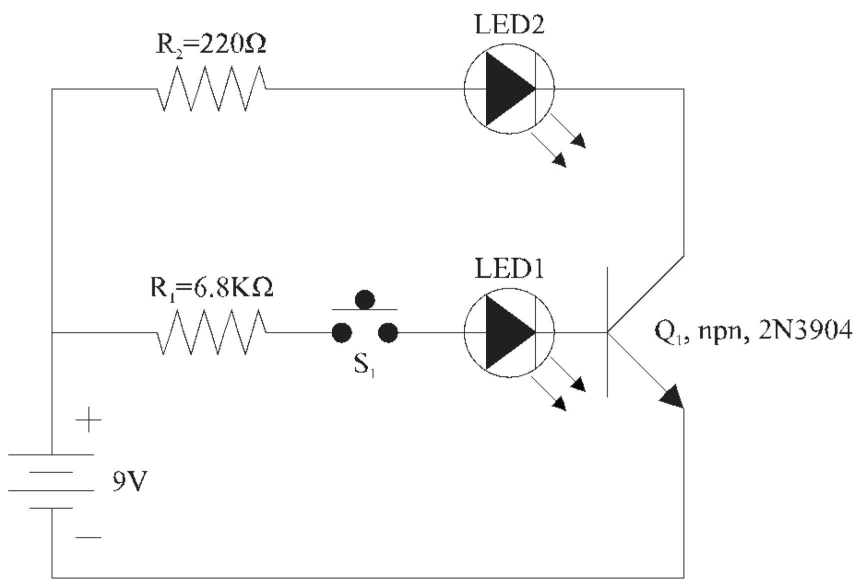
Figure 4-14. Determine the type of transistor using an ohmmeter (a) pnp (b) npn.

When making these ohmic measurements, it is possible, in about 80% of cases, to determine which is the emitter terminal and which is the collector terminal, since in this percentage, the base-emitter junction has a higher resistance than the base-collector junction.

Transistor checker circuits

Due to the correct polarization that must be applied to transistors for their operation, some circuits have been designed to observe how a transistor works, controlling a large collector current with a small base current. Figure 4.15(a) shows the tester circuit for npn transistors, and figure 4.15(b) shows the tester circuit for pnp transistors.

Both circuits (figure 4.15(a) and (b)) will be observed to have both LEDs light up when push button S_1 is pressed, and once the button is released, both LEDs will turn off again. However, when the switch is pressed, the LED connected to the transistor collector is brighter than the LED connected to its base. This is because the collector resistor is much smaller than the base resistor, and therefore there will be more current to excite the collector LED than the base LED. The operation of both circuits obeys the correct polarization of the device. A npn transistor is correctly polarized when the collector is positive, the emitter negative, and the base slightly positive. A pnp transistor is correctly polarized when its collector is negative, its emitter positive, and the base slightly negative.



(a)

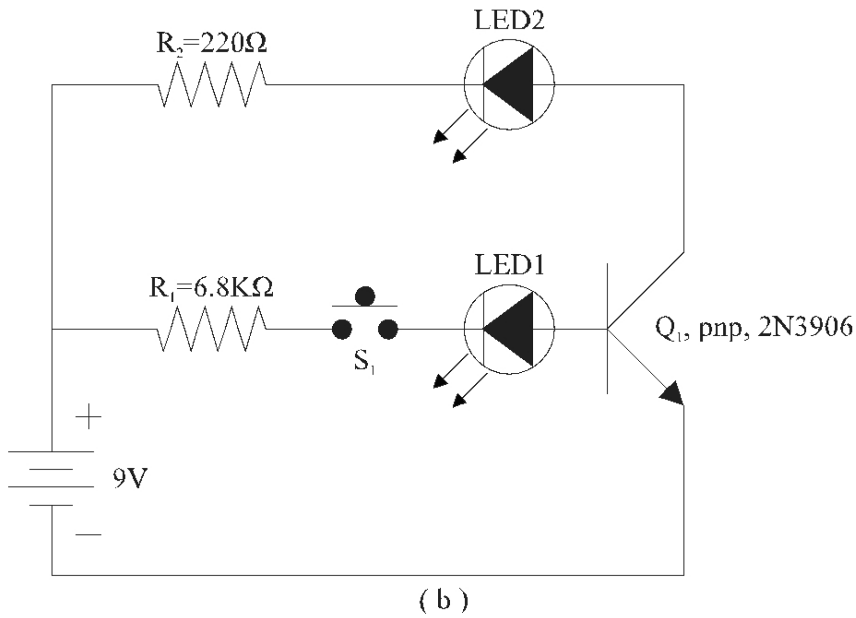


Figure 4-15. Transistor checker circuit (a) npn and (b) pnp.

The base current, which is small, controls the collector current, which is large. Remember that we had already mentioned that the phenomenon of controlling a high current with a low current is called *amplification*.

Characteristic curves

In bipolar transistors, there are basically four variables that are:

The collector-emitter voltage [V_{CE}].

The collector current [I_C].

The base-emitter voltage [V_{BE}].

The base current [I_B].

Graphically, in figure 4.16, the relationship between these parameters allows obtaining several types of curves. The most commonly used ones, however, are the ones that relate I_C to V_{CE} for different values of I_B and V_{BE} to I_B for different values of V_{CE}, known as output characteristic curves and input characteristic curves respectively, for the common emitter configuration. Less frequently used are the curves obtained from the relationship between the parameters I_C and I_B or I_C and V_{BE}, known as transfer curves.

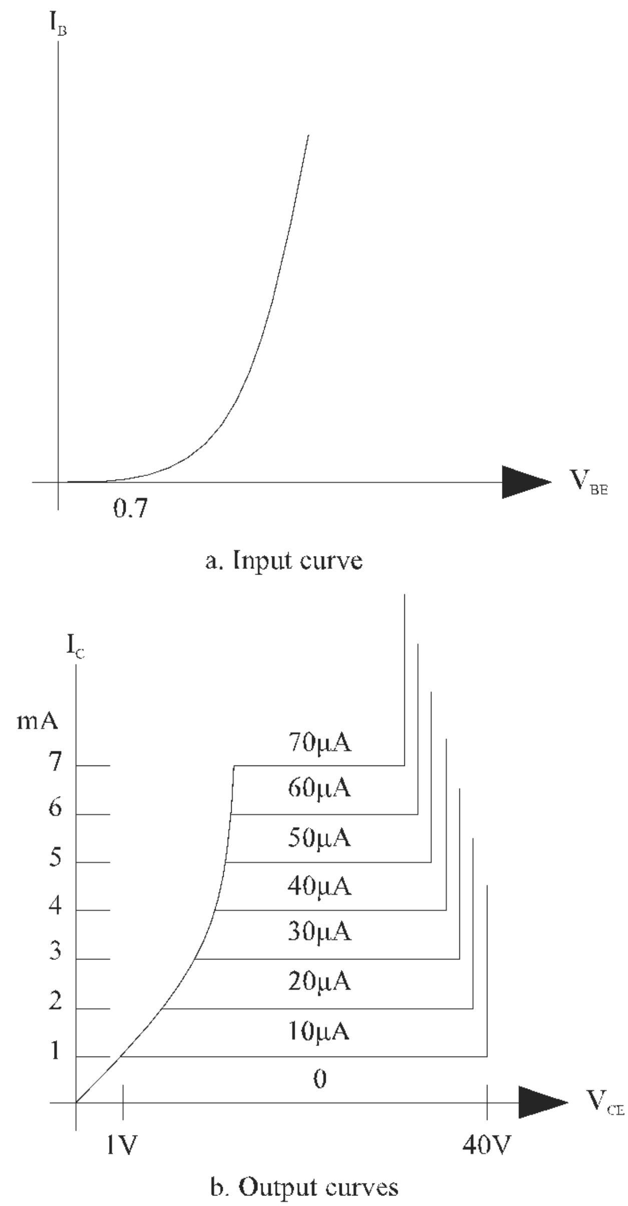


Figure 4-16. Transistor characteristic curves.

Input characteristic curve

Note in figure 4.16(a) how the input curve of the transistor is like the curve of a normal rectifier diode.

Remember that the voltage $V_{BE} = 0.7V$.

Output characteristic curve

In figure 4.16(b), you can precisely see a family of output curves. Notice how each curve is obtained by fixing I_B, which is taken as a parameter, and varying the applied bias voltage to measure and graph the resulting values of I_C and V_{CE}.

It should be noted that the characteristic curves shown in Figure 4.16 correspond to a widely used transistor, the 2N3904.

Transistor voltage, current and power calculations

Consider the circuit in common emitter configuration shown in Figure 4.17.

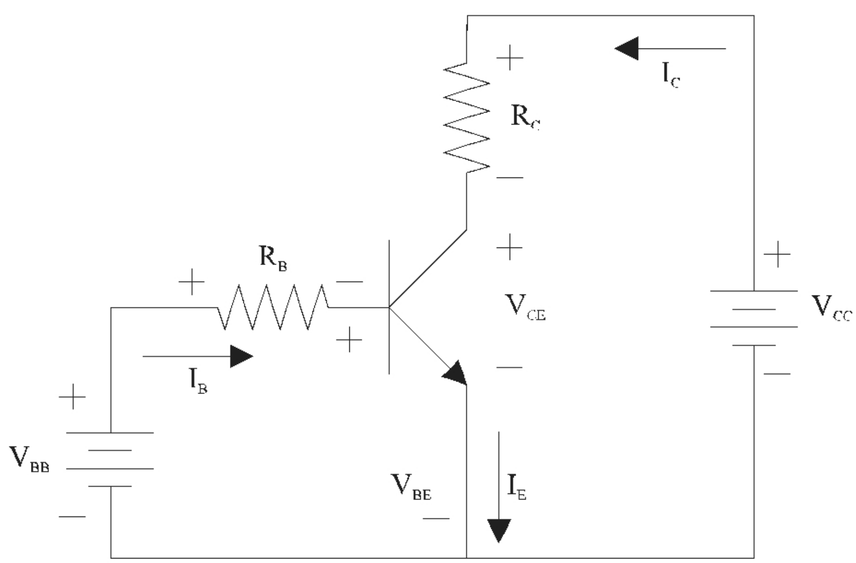


Figure 4-17. Circuit in common emitter configuration.

As can be seen, the circuit has two loops; the left one is the base circuit and the right one is the collector circuit. The base circuit is the one that controls the collector circuit (recall the concept of **AMPLIFICATION** seen in previous sections).

Typically, the voltage V_{BB} is between 5 and 15V in low-power amplifications. By varying V_{BB} and/or R_B, the base current I_B can be adjusted.

The voltage source V_{CC}, which can have values up to 40V depending on the transistor, must bias the collector diode in reverse for the transistor to function properly. A typical range for V_{CE} is 1 to 15V in low-power amplifications.

Calculation of the base current

Applying Ohm's law and Kirchhoff's voltage law to the base circuit, we obtain:

$$- V_{BB} + I_B R_B + V_{BE} = 0$$

From where the base current is:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} \quad (4.10)$$

The power in the base of the transistor is calculated as:

$$P_B = V_{BE} I_B \quad (4.11)$$

EXAMPLE 4.8

In figure 4.17, with $V_{BB} = 12V$ and $R_B = 100K\Omega$, determine the value of the current and power at the transistor's base.

SOLUTION

Unless specified otherwise, the reader can assume that we are working with Silicon transistors, and therefore the voltage $V_{BE} = 0.7V$.

Thus, substituting the given values in equation (4.10), we have:

$$I_B = \frac{12V - 0.7V}{100K\Omega} = 113\mu A$$

And the power in the base, substituting into equation (4.11):

$$P_B = V_{BE}I_B = (0.7)(113)(10^{-6}) = 79.1\ \mu W$$

Transistor voltage

The voltages with a single subscript (V_C, V_B, V_E) refer to the voltages of one terminal of the transistor with respect to ground. The double subscripts (V_{BE}, V_{CE}, V_{CB}) refer to the voltage between two terminals of the transistor. A voltage with a double subscript can be calculated by subtracting the corresponding voltages with a single subscript, like this:

$$V_{CE} = V_C - V_E \quad (4.12)$$

$$V_{CB} = V_C - V_B \quad (4.13)$$

$$V_{BE} = V_B - V_E \quad (4.14)$$

EXAMPLE 4.9

For the circuit in Figure 4.17, the voltage at the emitter is 0V, the voltage at the base is 0.8V, and the voltage at the collector is 15V. Determine the voltages V_{CE}, V_{CB}, and V_{BE} of the transistor.

SOLUTION

With the given values, we use equations (4.12) to (4.14) and obtain:

$V_{CE} = 15V–0V = 15V$

$V_{CB} = 15V–0.8V = 14.2V$

$V_{BE} = 0.8V–0V = 0.8V$

Transistor voltage and power

Using the circuit of Figure 4.17 as a reference, and applying Ohm's and Kirchhoff's voltage laws in the collector circuit loop, we obtain:

$$- V_{CC} + I_C R_C + V_{CE} = 0$$

From where:

$$V_{CE} = V_{CC} - I_C R_C \quad (4.15)$$

The approximate power dissipation of the transistor is calculated as follows:

$$P_D = V_{CE} I_C \quad (4.16)$$

This power is what increases the temperature at the collector junction. The higher the power, the higher the temperature. If the temperature reaches too high values (150°C or more), the transistor will burn out. That is why the information on maximum power dissipated by the transistor is one of the most important parameters in the technical data sheets.

EXAMPLE 4.10

Find the value of the collector-emitter voltage in the circuit of Figure 4.17, if the collector current is 2mA, the collector resistor is 4.7KΩ, and the collector voltage source is 12V.

SOLUTION

If we use the given data and substitute in equation (4.15), we obtain:

$$V_{CE} = 12V - (2mA)(4.7K\Omega)$$

This is:

$$V_{CE} = 2.6V$$

EXAMPLE 4.11

For the circuit given in the previous example, calculate the power dissipated by the transistor:

SOLUTION

With the known values of $I_C = 2mA$ and $V_{CE} = 2.6V$, when we substitute them into equation (4.16), we have:

$$P_D = (2.6V)(2mA)$$

That is:

$$P_D = 5.2mW$$

This is the power in the collector, which is equal to the product of the collector-emitter voltage and the collector current. This response is fully accurate. The only error is that it does not include the base power, which is the product of V_{BE} and I_B. However, this power can be neglected because its value is minor compared to the power calculated at the collector junction, P_D.

Transistor limits

The transistors, like all other electronic components, have some limit values that we will see below:

V_{CEO}: Maximum collector-emitter voltage, without base current, that the transistor can withstand.

I_{Cmax} : Maximum collector current with V_{CE} saturation (close to 0V).

V_{BEO}: Reverse bias voltage that the transistor can withstand with I_C equal to zero.

P_{Dmax} : Maximum collector power dissipation, and it is given by the product of voltage V_{CE} and current I_C.

F_t**:** Frequency cut-off, i.e., the frequency at which the gain of the transistor is 1 (not amplifying). It gives an idea of the maximum operating frequency.

Transistor operating regions

A transistor has three operating regions, each of which has distinctive characteristics.

The first one is the central region in the output curve shown in Figure 4.18. In this region, the voltage varies from approximately 1 to 40V; it is considered the most important region, as it is where the normal amplification operation of the transistor occurs. It is called the active region, and in the graph, it can be specifically located on the horizontal part of the curve.

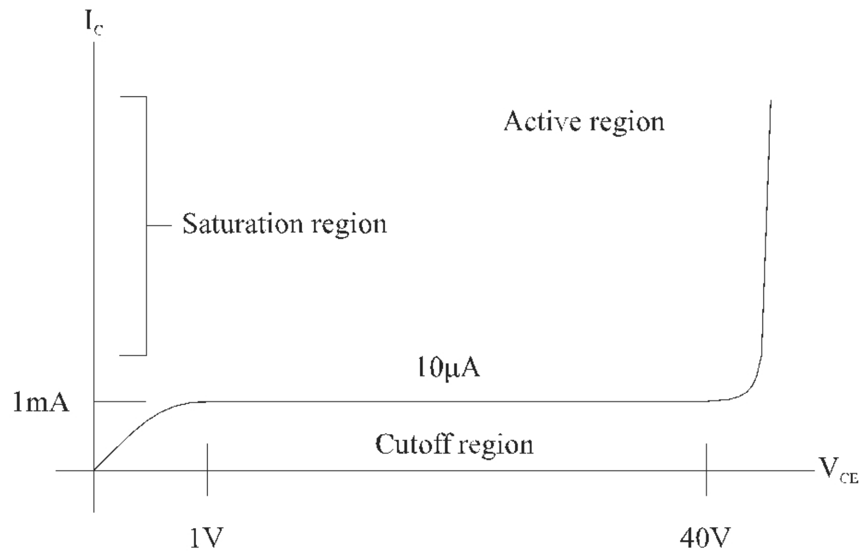


Figure 4-18. Output curve indicating transistor operation regions.

The second operating zone is called the saturation region. In the curve of figure 4.18, it is located in the collector-emitter voltage interval of 0 to 1V.

The third region is the cutoff region and occurs when the collector terminal is open; in this case, the base current becomes zero ($I_B = 0$). In Figure 4.18, the cutoff region is located just below the horizontal line of the curve.

The load line

A load line is a line drawn on the output curves to show each and every point at which the transistor can operate. Figure 4.19(a) shows a circuit in common emitter configuration and the family of output curves with the corresponding load line in Figure 4.19(b). The equation of this line is obtained by applying voltage summation (Kirchhoff's law) in the collector circuit and plotting I_C against V_{CE}:

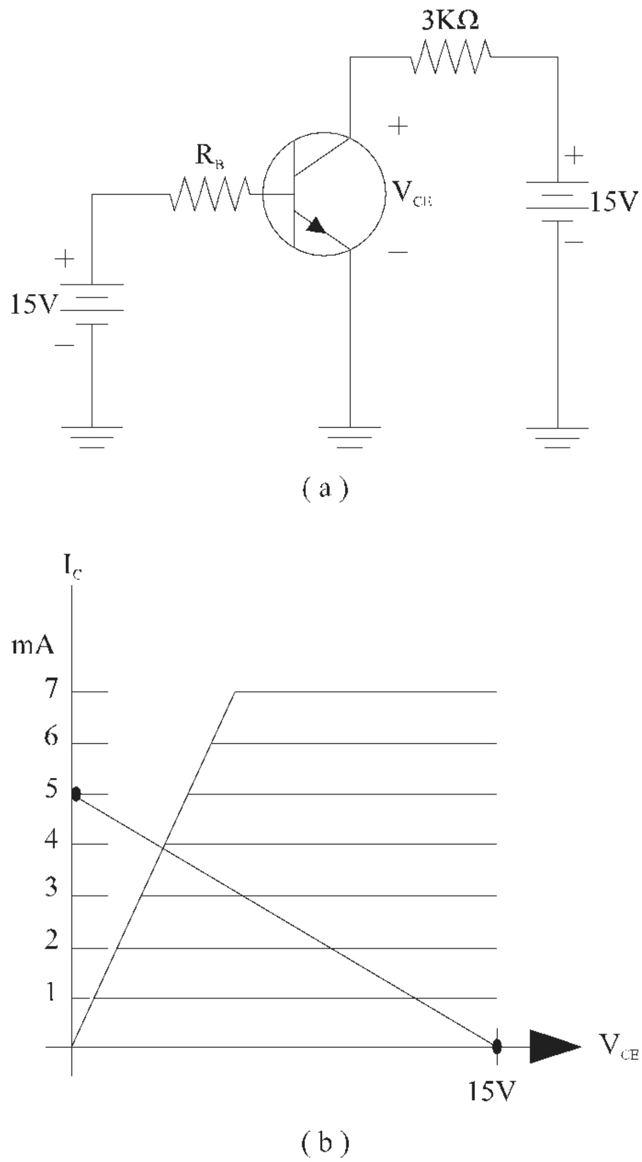


Figure 4-19. The load line.

$$-15 + 3000I_C + V_{CE} = 0$$

So:

$$I_C = \frac{15 - V_{CE}}{3000}$$

The saturation point

The saturation point is the point where the load line intersects the saturation region of the output curves.

In this case, it corresponds to a small collector-emitter voltage ($V_{CE} \approx 0$) and a collector current of 5mA; this current value is the maximum that can be reached in the circuit. Changing the value of the biasing source or the collector resistor will change the saturation point. In general, the saturation collector current can be calculated as follows:

$$I_{Csat} = \frac{V_{CC}}{R_C} \tag{4.17}$$

The cutoff point

The cutoff point is the point at which the load line intersects the cutoff region of the output curves. In this case, it corresponds to a collector current close to zero ($I_C \approx 0$) and a collector-emitter voltage of 15V. The cutoff point indicates the maximum collector-emitter voltage that can be applied in the circuit. By changing the collector bias voltage, the cutoff point can be varied. In general, the cutoff voltage can be obtained as follows:

$$V_{CEcorte} = V_{CC} \tag{4.18}$$

The operating point

Each transistor biasing circuit has its own load line.

Each transistor biasing circuit has its own load line. This, as such, determines the saturation current and the cutoff voltage. If the base resistance is known, the current and voltage for the operating point can also be calculated.

Figure 4.20(a) shows a circuit with base bias. The saturation current and cutoff voltage are calculated using the process described above, such that 5mA of saturation current and 15V of cutoff voltage are obtained. These values, along with the load line, are shown in the curves of Figure 4.20(b).

Let us now consider the base circuit. If we want to know the base current, we proceed with a Kirchhoff's loop equation, obtaining:

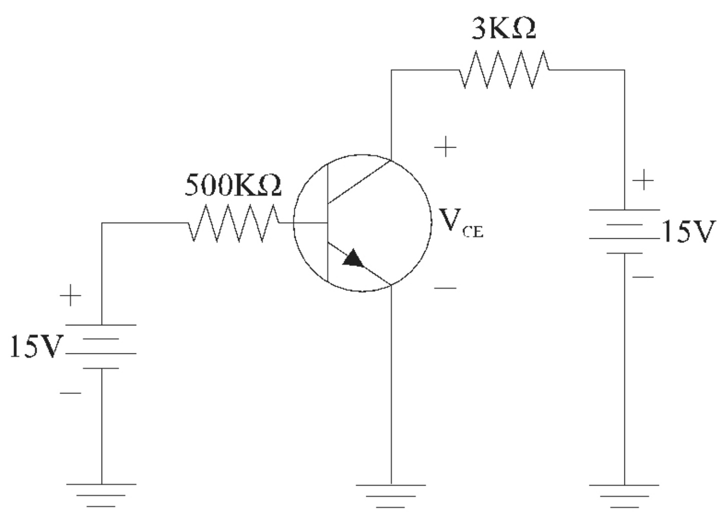
$$- 15V + 500K\Omega I_B + 0.7 = 0$$

From where:

$$I_B = \frac{(1.5 - 0.7)V}{500K\Omega} \approx 30\mu A$$

Considering now the base circuit. If we want to determine the base current, we use a Kirchhoff loop, obtaining:

$$- 15V + 500K\Omega I_B + 0.7 = 0$$



(a)

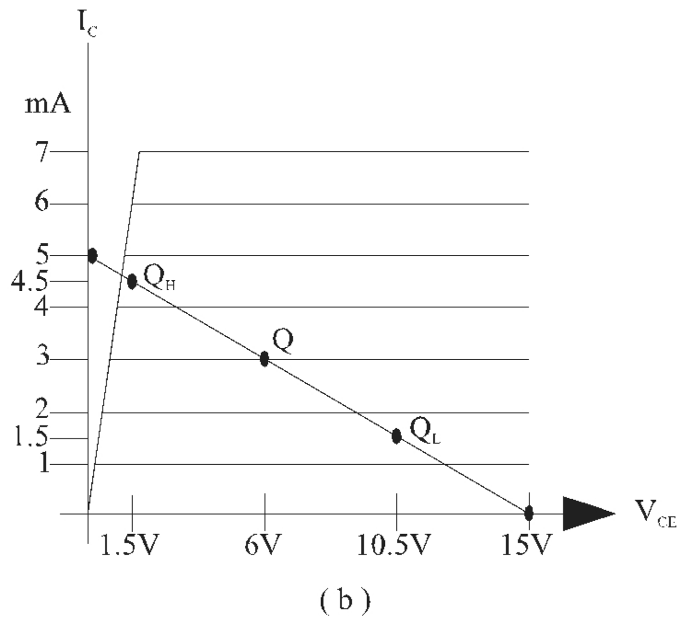


Figure 4-20. (a) Base-polarized circuit (b) Load line.

From where:

$$I_B = \frac{(1.5 - 0.7)V}{500K\Omega} \approx 30\mu A$$

Now, if we want to proceed, we need to know the transistor gain, β, as discussed in section 4.3 of this text. Let us choose a gain of $\beta = 100$ for this case. Then, the collector current will be:

$$I_C = \beta I_B = 100(30\mu A) = 3mA$$

This current causes a voltage drop across the $3K\Omega$ resistor of $9V$.

Now we can calculate the voltage across the transistor, V_{CE}, in the collector circuit:

$$- 15V + 9V + V_{CE} = 0$$

This is:

$$V_{CE} = 6V$$

If we plot these points (3mA and 6V), we obtain the operating point shown on the load line in figure 4.20(b). The operating point is typically represented by a Q.

In general terms, the formulas used are summarized in equations (4.19), (4.20), and (4.21).

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} \quad (4.19)$$

$$I_C = \beta I_B \quad (4.20)$$

$$V_{CE} = V_{CC} - I_C R_C \quad (4.21)$$

It should be noted that it is not important to memorize these formulas; what is enormously important is to understand and apply the Ohm's and Kirchhoff's laws well; with them, all these equations are easily obtained.

EXAMPLE 4.12

Given the circuit in Figure 4.21, determine the load line and the saturation, cutoff, and operating points. The transistor has a gain of $\beta = 100$.

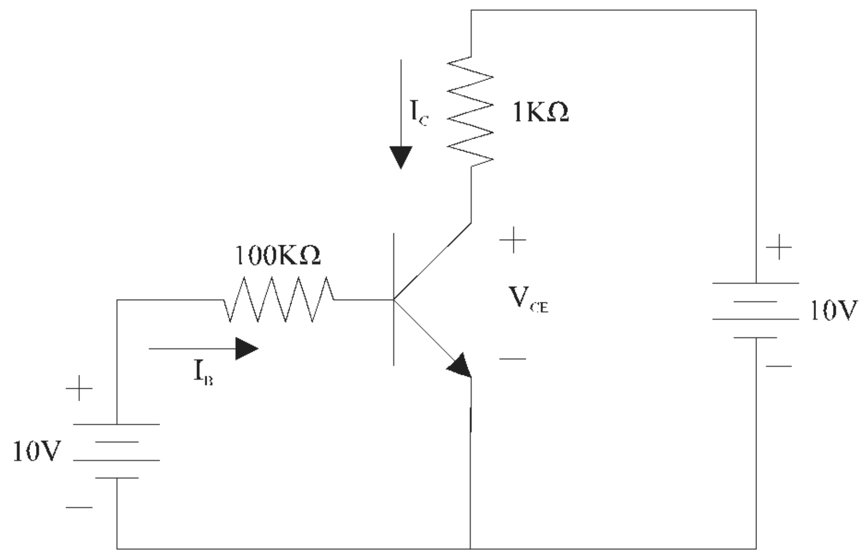


Figure 4-21. Circuit of example 4.12.

SOLUTION

First, we obtain the load line by applying Kirchhoff's voltage law to the collector circuit.

$$-10 + 1000I_C + V_{CE} = 0$$

And the load line is:

$$I_C = \frac{10 - V_{CE}}{1000}$$

The saturation collector current is found when $V_{CE} = 0$; thus:

$$I_C = 10mA$$

The cutoff collector-emitter voltage is found when the collector current $I_C = 0$; this occurs when:

$$V_{CE} = 10V$$

The load line is the one shown in figure 4.22.

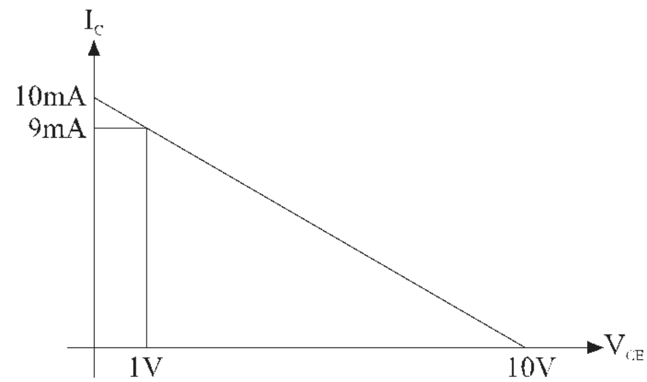


Figure 4-22. Load line for the circuit of example 4.12.

Once we have obtained the load line, we can determine the operating point. First, we calculate the base current. According to equation (4.19), we have:

$$I_B = \frac{10V - 0.7V}{100000\Omega} \approx 90\mu A$$

Knowing that $\beta = 100$, using equation (4.20), we have:

$$I_C = 100(90\mu A) = 9mA$$

And we calculate the voltage across the transistor, V_{CE}, using equation (4.21) as:

$$V_{CE} = 10V - (9mA)(1K\Omega)$$

This is:

$$V_{CE} = 1V$$

The operating point is also shown in figure 4.22.

Emitter polarization

Note in the circuits of the previous section, how a limiting resistor of the base current is always placed, while the emitter terminal is directly connected to ground.

In these circuits, it is worth noting that if the transistor gain, β, changes, the base current does not change as the gain has no effect on the base current. The same cannot be said for the collector current (see equation 4.20). However, if the collector current changes, the collector-emitter voltage also changes, and thus the operating point moves along the load line, as shown in figure 4.20(b).

In Figure 4.23, a circuit with emitter bias is shown. As can be seen, the resistor has been moved from the base circuit to the emitter circuit. That is the only change; however, it causes a significant difference because the operating point now remains fixed. When the current gain changes, for example, from 50 to 150, the operating point, Q, hardly moves on the load line.

The voltage at the base (base-ground) is 5V; the voltage between the base-emitter terminals is 0.7V; the voltage at the emitter (emitter-ground) will be:

$$V_E = V_{BB} - V_{BE} = 5V - 0.7V = 4.3V$$

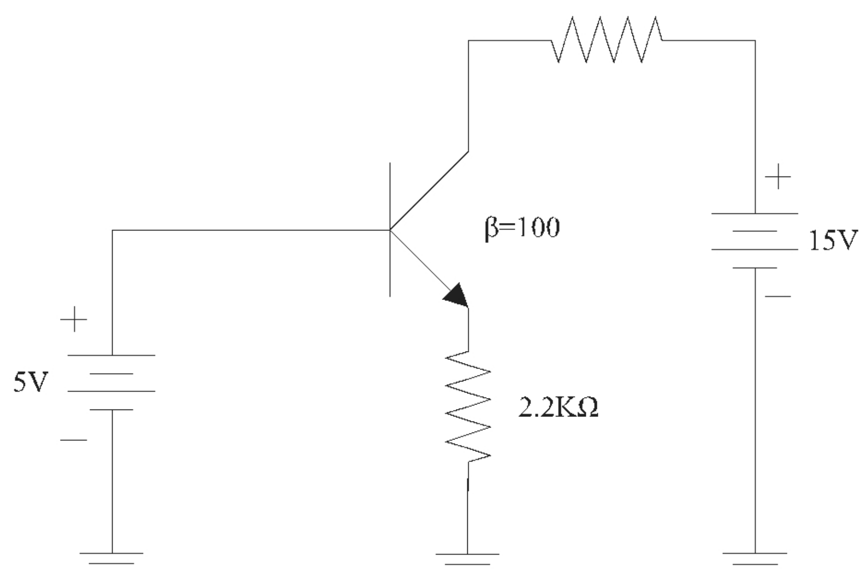


Figure 4-23. Circuit with emitter polarization.

Since this voltage is across the terminals of the emitter resistor, we can calculate the emitter current using Ohm's law as:

$$I_E = \frac{V_E}{R_E} = \frac{4.3V}{2.2K\Omega} = 1.95mA$$

For this case, it is a good approximation that:

$$I_C \approx I_E = 1.95mA$$

When this collector current flows through the resistor, it produces a voltage drop of 1.95V. To determine the collector voltage value, we subtract this value from the value of the collector bias voltage source, so:

$$V_C = 15V - (1.95mA)(1K\Omega)$$

That is:

$$V_C = 13.1V$$

And the collector-emitter voltage would be:

$$V_{CE} = 13.1V - 4.3V = 8.8V$$

With these values, the operating point for the circuit in figure 4.23 will have coordinates:

$$I_C = 1.95mA \text{ y } V_{CE} = 8.8V$$

The importance of emitter biasing lies in the process used to determine the operating point, namely:

a. Obtaining the emitter voltage.

b. Calculate the emitter current.

c. Find the collector voltage.

d. Obtain the collector-emitter voltage.

The current gain was not considered. Since it is not considered for any calculation, its exact value is no longer important.

Now, to determine the load line it is necessary to find the saturation and cutoff points. It is important to note that the emitter voltage remains at 4.3V, regardless of the value of the collector current.

The saturation collector current is obtained as:

$$I_{Csat} = \frac{V_{CC} - V_E}{R_C}$$

Note that the voltage V_{CE} is not considered ($V_{CE} = 0$), replacing it:

$$I_{Csat} = \frac{15V - 4.3V}{1K\Omega} = 10.7mA$$

The cutoff collector-emitter voltage is calculated as:

$$V_{CEcorte} = V_{CC} - V_E$$

Note that the collector current is not considered. This is due to the cutoff effect between collector and emitter ($I_C = 0$).

Replacing:

$$V_{CEcorte} = 15V - 4.3V = 10.7V$$

The cutoff voltage is shown in figure 4.24. The saturation current and the load line for the worked exercise are also displayed.

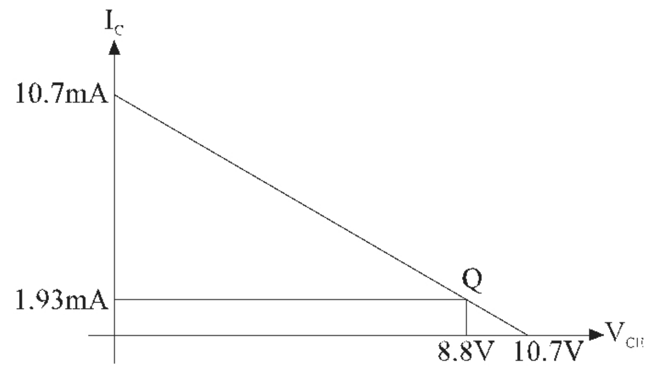


Figure 4-24. Load line for the circuit with emitter polarization.

In the treatment of the previous exercise, it should be remembered that the collector current was considered to be approximately equal to the emitter current. This approximation is due to the current gain α, defined in equation (4.5), which tends to approach 1 considerably. Section 4.4 also explains this fact, which concludes with the same approximation for these currents, given in equation (4.7).

EXAMPLE 4.13

Given the circuit in Figure 4.25, determine the load line and the saturation, cutoff, and operating points.

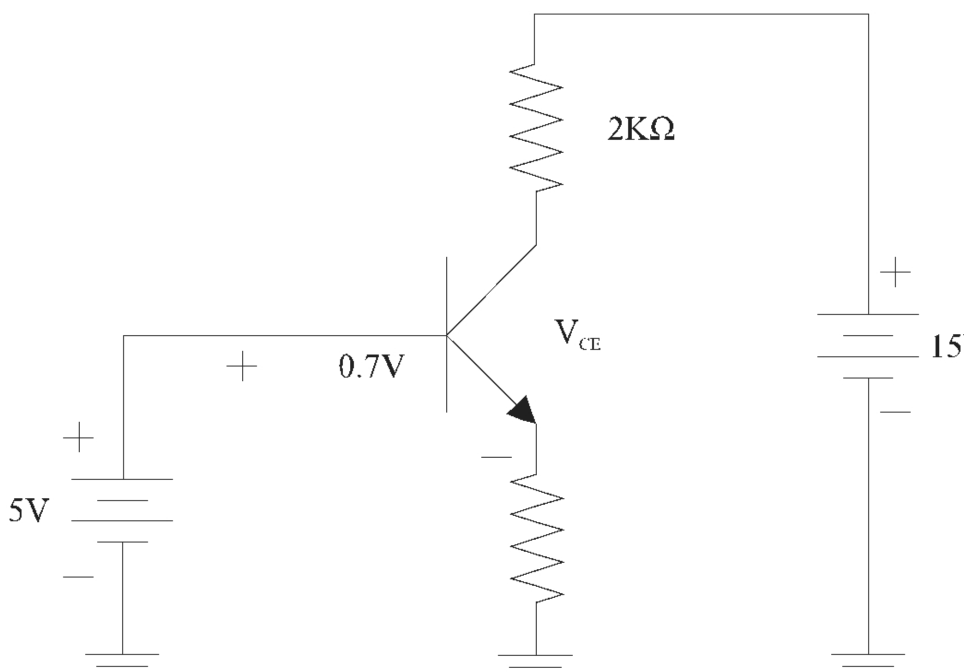


Figure 4-25. Circuit of example 4.13.

SOLUTION

The base voltage is 5V, the base-emitter voltage is 0.7V, and the emitter voltage is given by:

$$V_E = 5V - 0.7V = 4.3V$$

The emitter current is calculated as:

$$I_E = \frac{V_E}{R_E} = \frac{4.3V}{1K\Omega} = 4.3mA$$

The collector current is approximately equal to 4.3mA, thus, the collector voltage is given by:

$$V_C = 15V - (4.3mA)(2k\Omega)$$

That is:

$$V_C = 6.4V$$

It is convenient to remember that this voltage is the voltage between collector and ground.

It should also be noted that a voltmeter should not be connected between the collector and emitter because it could short-circuit the emitter to ground. If the value of V_{CE} is sought, the collector-to-ground voltage should be measured, then the emitter-to-ground voltage should be measured, and finally subtracted. In this case:

$$V_{CE} = 6.4V - 4.3V = 2.1V$$

The operating point is therefore located at the coordinates $I_C = 4.3mA$ and $V_{CE} = 2.1V$.

The saturation collector current will be:

$$I_{Csat} = \frac{15V - 4.3V}{2K\Omega} = 5.35mA$$

And the voltage collector-emitter of cut off is:

$$V_{CEcorte} = 15V - 4.3V = 10.7V$$

The load line with its specifications is shown in figure 4.26.

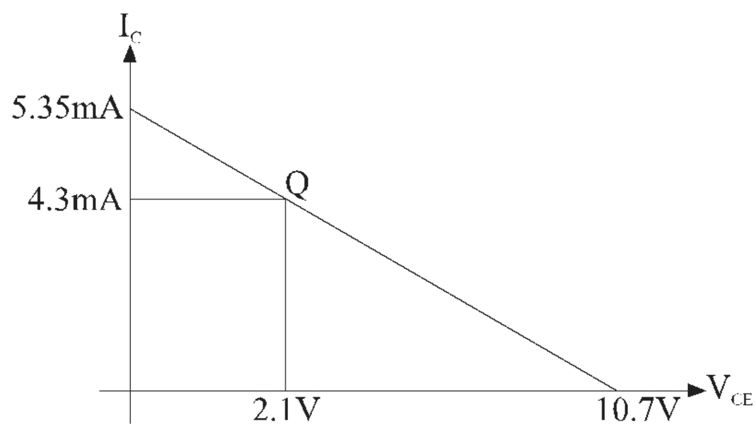


Figure 4-26. Load line for the circuit of example 4.13.

The transistor as a switch

When a transistor is biased so that its operating point is located near the midpoint of the load line, it can be treated as an amplification device. In this case, if a small alternating signal is applied to the transistor base, a large signal is obtained at the collector. The effect can be observed if an oscilloscope is available.

On the other hand, when the transistor is operated at points close to saturation or cut-off, it becomes an incredibly useful device for digital applications, because it presents a bi-stable output signal: high or low. In other words, the operating point is either the saturation point or the cut-off point.

In figure 4.27, the corresponding circuit of a transistor as a switch can be seen.

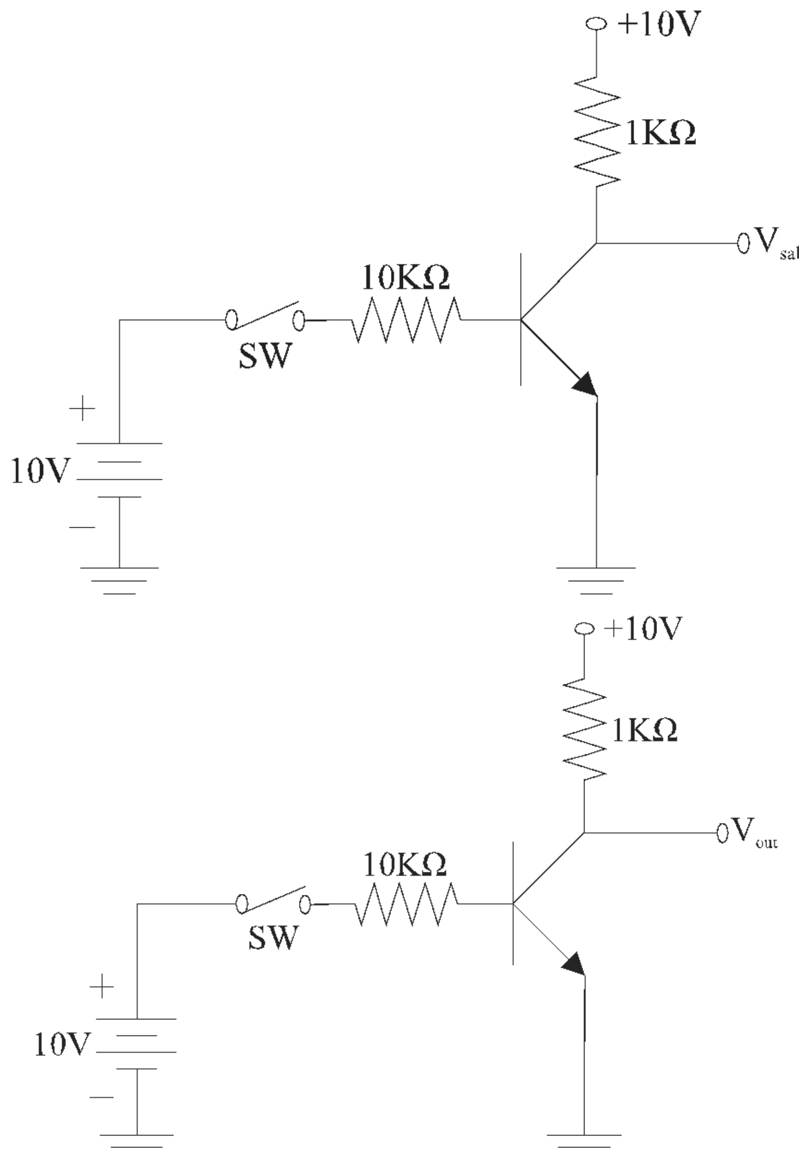


Figure 4-27. Transistor as a switch.

The operation of the circuit is as follows: if the switch, SW, in the base circuit is closed, as shown, a high current will be applied to the base of the transistor. This will cause the device to fall into the saturation region and therefore a 0V output will be measured at the collector-emitter. Due to saturation, there will be a short circuit, and therefore a voltage of 0V.

The situation is different when the switch, SW, is opened, cutting off the path for the current flow to the base of the transistor. With zero current at the base terminal, the device will operate in the cut-off region, which means that the transistor, literally, opens between the collector and the emitter. Under these circumstances, when measuring the collector voltage, it will be 10V, that is, the voltage of the biasing source in the collector circuit.

The circuit can only have two output voltages: 0V or +10V, and as a conclusion, if the transistor is saturated it acts as a closed switch from collector to emitter; if the transistor is in cutoff, it is like an open switch.

In figure 4.28 a switching circuit with a transistor excited by a step voltage is shown. When the input voltage is zero, the transistor is in cut-off, there is no current in the collector resistor and the output voltage is equal to +15V. When the input voltage is +15V, the base current is:

$$I_B = \frac{5V - 0.7V}{3K\Omega} = 1.43mA$$

There is a short circuit between the collector and emitter: the voltage V_{CE} drops to zero and the collector current will be:

$$I_{Csat} = \frac{15V}{1K\Omega} = 15mA$$

Base current is more than 10 times greater than the base current, and sufficient to produce saturation in the transistor. Thus, the output voltage will be approximately zero.

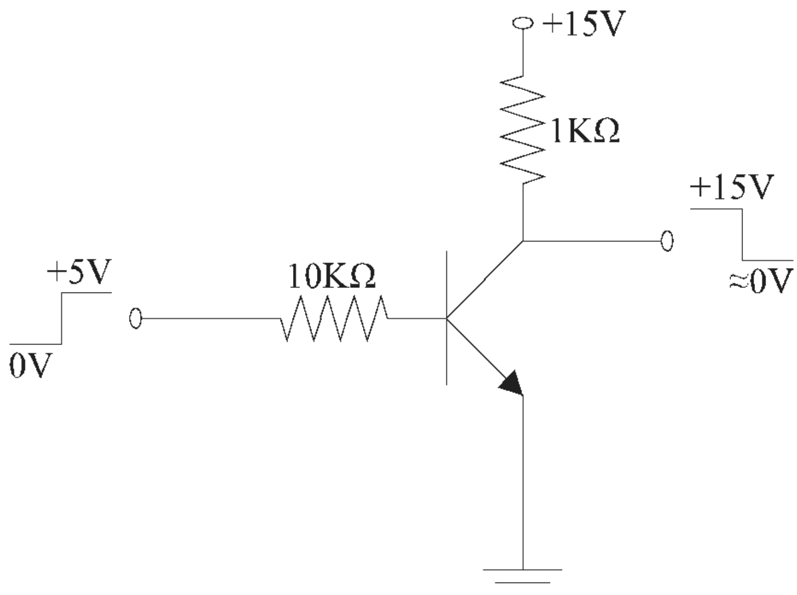


Figure 4-28. Transistor as a switch.

The transistor as a driver for LEDs

Figure 4.29 shows two ways to use a transistor operating as a switch to drive an LED. Note that in the first circuit, the LED is in series with the load resistor R_C, while in the second circuit, the LED takes the collector voltage but is connected with respect to ground. This difference in configuration causes the LEDs to turn on and off.

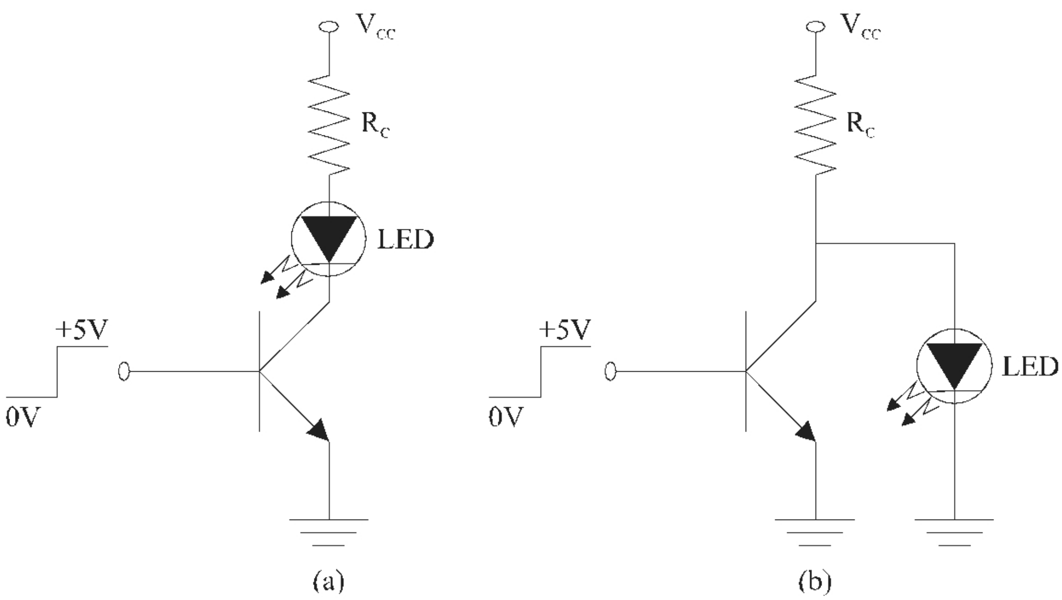


Figure 4-29. LED driver circuits.

The operation of the circuit is as follows: for the circuit in Figure 4.29(a), when the input voltage is zero, the transistor is cut off and as there is no current, the LED does not light up; when the input voltage is +15V, the transistor saturates, current flows through the collector resistor, and the LED lights up. For the circuit in Figure 4.29(b), the behavior of the circuit is the opposite; that is, when the input voltage is 0V, the transistor is cut off and the current is directed through the LED, then the LED lights up; when the input voltage is +15V, the transistor saturates, all the current flows through it, and therefore the LED remains off.

Calculation of the limiting resistance, Rc

The bias voltage, V_{CC}, should take a value that can vary depending on the technical specifications for each reference. Typical values, however, are around 10V or 15V. Such a voltage is sufficient and necessary to bias the transistor, but it is also enough to completely deteriorate the LED diode. To limit the voltage and thus the current through the LED, an appropriate value of collector resistor should be used. To determine the value of the resistor, the formula given in equation (4.22) is used, which is obtained by applying Kirchhoff's voltage law to the collector circuit. See figure 4.30.

$$R_C = \frac{V_{CC} - V_{LED}}{I_{LED}} \qquad (4.22)$$

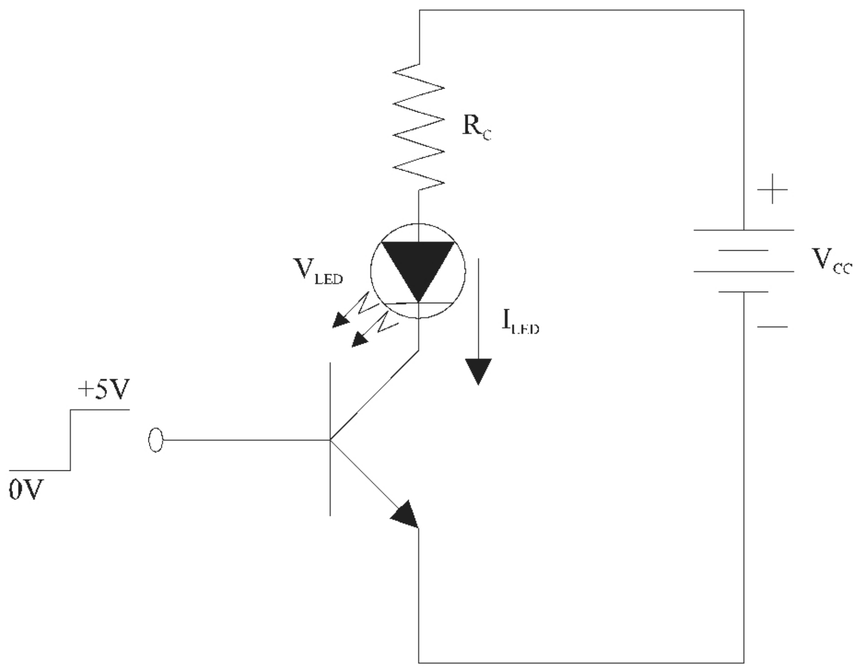


Figure 4-30. LED driver circuit.

The power for this resistor is calculated according to Joule's law as:

$$P_C = \left(I_{LED}^{2}\right)R_C \qquad (4.23)$$

EXAMPLE 4.14

For the circuit in figure 4.30, with $V_{CC} = 15V$, $V_{LED} = 3.0V$, and $I_{LED} = 25mA$, determine the value of R_C to protect the LED.

SOLUTION

If we substitute the data given by the problem into equation (4.23), we obtain:

$$R_C = \frac{15V - 3.0V}{25mA} = 480\Omega$$

480Ω is not a standard value, therefore, approximately round up to a higher standard value such as 560Ω.

With this value and the circuit current (LED current), we calculate the power for the resistor. Substituting in equation (4.23), we have:

$$P_C = (25mA)^2(560\Omega) = 0.35W$$

The highest commercial power rating for this value is 0.5W.

Therefore, we choose a 560Ω resistor with a power rating of 1/2W.

As we observed from everything seen previously, we can say that base bias circuits establish a fixed value for the base current and that emitter bias circuits establish a fixed value for the emitter current. Due to the problem of current gain, base bias circuits are commonly designed to operate in the saturation and cutoff regions, while emitter bias circuits are typically operated in the active region.

The concept of emitter follower

Consider the circuit shown in figure 4.13. The voltage across the emitter resistor is:

$$V_E = V_{BB} - V_{BE} \quad (4.24)$$

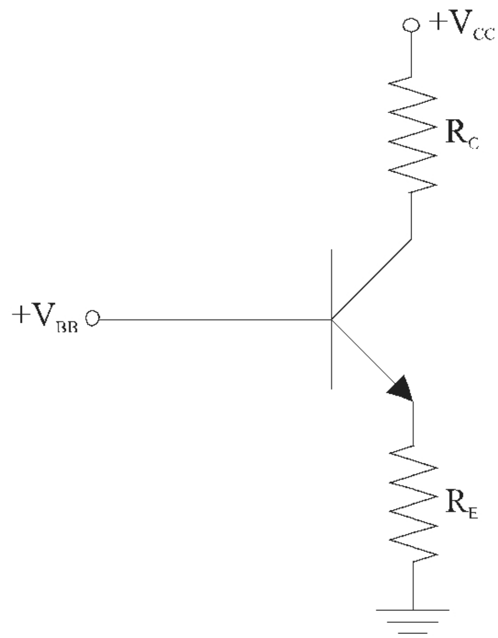


Figure 4-31. The emitter follower.

As V_{BE} remains fixed at approximately 0.7V, V_E will follow the changes in V_{BB}. For example, if V_{BB} increases from 2 to 10V, V_E increases from 1.3 to 9.3V. This type of "*obey the master*" action is called an ***emitter follower***.

Types of operation

Class A operation means that the transistor operates in the active region at all times; in other words, current flows through the device during the entire 360 degrees of the signal. This is the common way that transistors operate in linear circuits because it leads to the simplest and most stable biasing circuits. However, Class A is not the most efficient way to operate a transistor. In some applications, such as battery-powered systems, current consumption is a key factor for design.

The operation in class B of a transistor implies that the collector current flows only 180° of the signal cycle, then the Q point is located near the cutoff point, both in the DC and signal load lines. This has the advantage of lower power dissipation in the transistor and lower current consumption.

Darlington Connection

A Darlington connection is based on two cascaded emitter followers, as shown in figure 4.32.

The base current of the second transistor is provided by the base of the first transistor, and the total current gain is the product of the individual current gains, which is:

$$\beta_T = \beta_1 \beta_2 \tag{4.25}$$

The main advantage of this connection is the high input impedance seen at the base of the first transistor and the increased circuit gain.

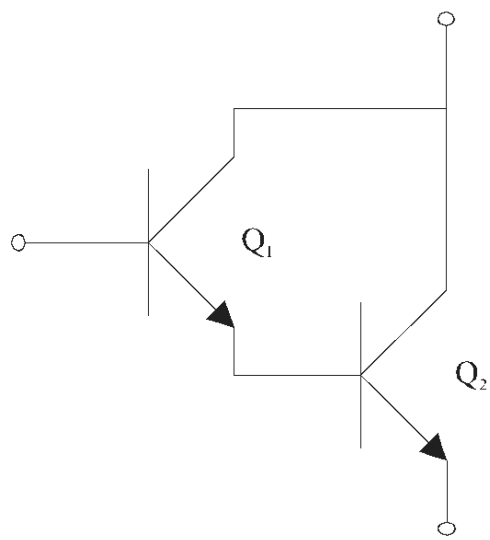


Figure 4-32. Darlington Connection.

REVIEW

Concepts

Define or discuss the following:

- ☐ Composition and symbology of a transistor.
- ☐ PNP transistor and NPN transistor.
- ☐ Terminals of a transistor.
- ☐ Polarization of a transistor.
    - Common emitter configuration.
    - Common collector configuration.
    - Common base configuration.
- ☐ Bias voltage and input/output voltages of a transistor.
- ☐ Current in a transistor.
- ☐ Current gain (α and β) for a transistor.
- ☐ Relationship between α and β.
- ☐ Fixed polarization.
- ☐ Automatic polarization.
- ☐ Polarization by voltage divider.
- ☐ Checking a transistor and identifying terminals.
- ☐ Transistor checker circuits.
- ☐ Input and output characteristics of a transistor.
- ☐ Regions of operation of a transistor.
    - Load line.
    - Active region.
    - Saturation region.
    - Cut-off region.
    - Operating point.
- ☐ Transistor as a switch.
- ☐ Transistor as an LED driver.

- ☐ Classes of operation of a transistor.
- ☐ Darlington connection.

EXERCISES

4.1. A transistor is in a common emitter configuration. A current of 5.2mA is applied to the base, and a current of 15mA appears at the collector. Determine the transistor's β.

4.2. The β of a transistor is 80. If the output current is 42mA, determine the input current.

4.3. The γ of a transistor is 250. If a current of 2.9mA is applied to the base, determine the emitter current.

4.4. The collector current in a common base transistor is 3mA. If the α of the transistor is 0.998, determine the emitter current.

4.5. The collector current for a transistor is 4.7mA. If the α is 0.95, determine the base and emitter currents, as well as the β of the transistor.

4.6. A common emitter transistor has a gain of $\beta = 300$, and a current of 3.4mA flows through its collector. Determine the remaining currents in the device.

4.7. A common base transistor has an α of 0.95. If the current flowing through its emitter is 5mA, determine the remaining currents in the device.

4.8. The α of a transistor is 0.93, determine the β.

4.9. The β of a transistor is 200, determine the α.

4.10. Find expressions relating γ to β and γ to α.

4.11. Use the ECG manual to determine the characteristics (terminals) of the following transistor references.

2N6553	BC307C	MPSA06	MPS-A13
PN3640	2N2222A	2N3906	PN3638A

4.12. Consider the circuit shown in figure 4.33.

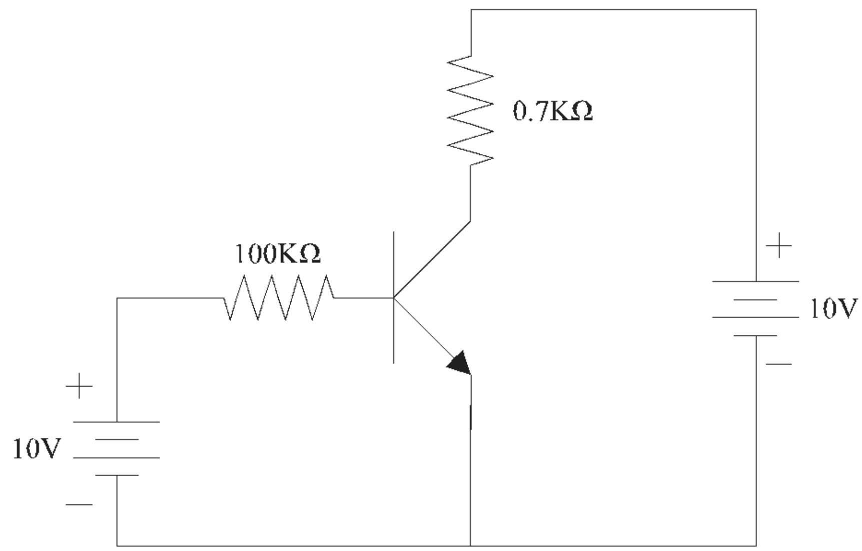


Figure 4-33. Circuit of exercise 4.12.

Determine the load line and the cut-off and saturation points. Also, determine the operating point (Q point) for $\beta = 100$.

4.13. If the base resistor in the circuit of Figure 4.33 is changed to $200\text{K}\Omega$, what would be the new operating point?

4.14. If the voltage V_{CC} in the circuit of Figure 4.33 is increased to 15V, how does the operating point change?

4.15. Repeat exercise 4.12, but with a transistor β of 50.

4.16. What happens in circuit 4.33 if β is 300?

4.17. What conclusions can you draw regarding the exercises performed in items 4.12 to 4.16?

4.18. Consider the circuit in Figure 4.34.

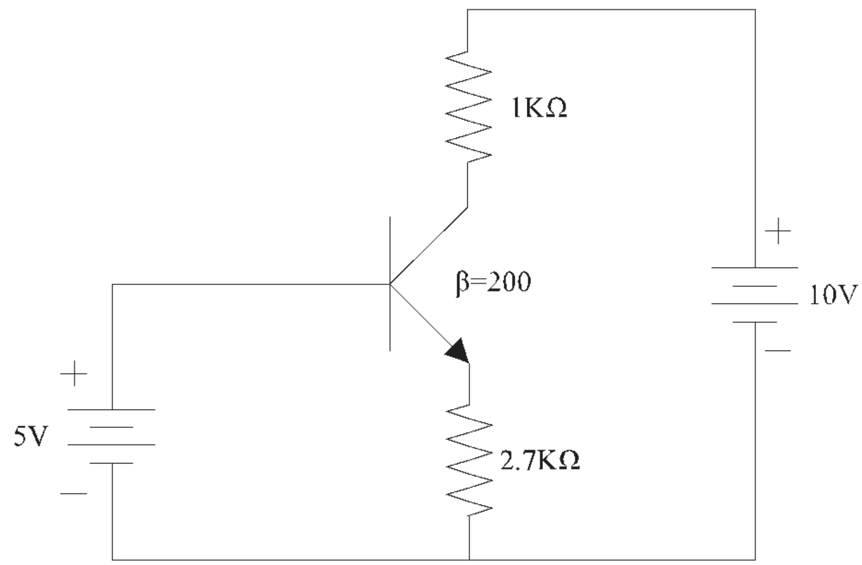


Figure 4-34. Circuit of exercise 4.18.

Determine the cutoff and saturation points and the load line with the respective operating point.

4.19. For the circuit shown in figure 4.35, determine the current-limiting resistor in the collector (ohmic value and power).

4.20. It is desired that the LED in the circuit of figure 4.35 remain on. Where should point B be connected?

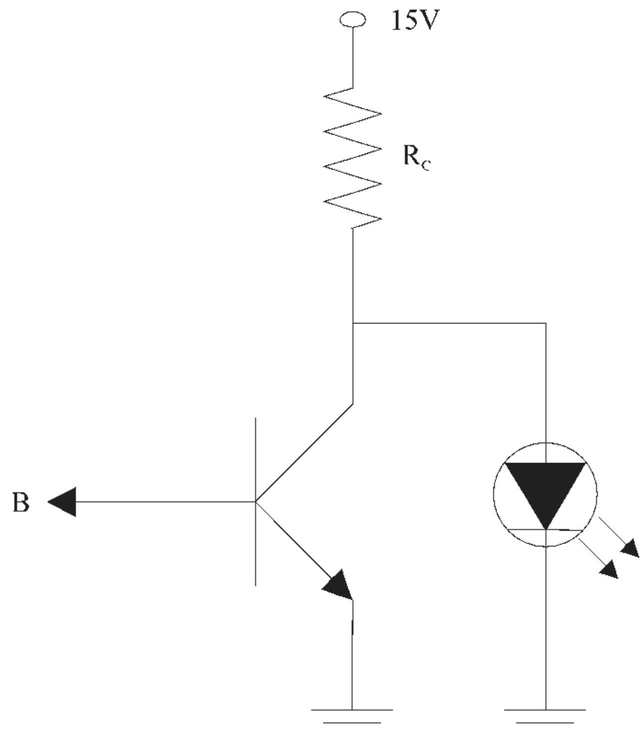


Figure 4-35. Circuit of exercise 4.19.

Chapter 5
OTHER ELECTRONIC COMPONENTS

Currently, there are many electronic components available to users in the technical market: some are extremely versatile in terms of their applications, while others may fulfill only a single but always particularly significant role. Next, we will see, although not in detail, some of these components: how they are symbolized, what function they perform within a circuit, and what letter they are normally represented with on electronic diagrams.

Battery

A battery is a device that stores electrical energy. There are those that, once they exhaust their potential, are discarded, and there are also those that can be recharged. In electronic schematics, it is usually represented by the letter B.

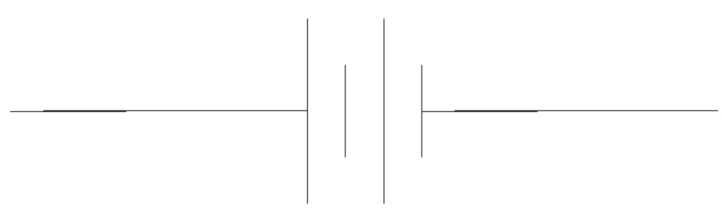


Figure 5-1. The battery (B).

Batteries

Essentially, a battery, as shown in figure 5.2, is the result of connecting several cells in series in order to increase the potential difference and fulfill a definitive purpose. Like a single cell, a battery is represented by the letter B in electronic diagrams.

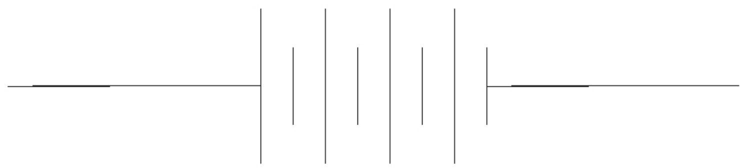


Figure 5-2. The battery (B).

Switches

An interrupter or switch, as shown in figure 5.3, is a device that opens or closes an electrical circuit. They come in various terminal configurations, although the most common ones have two. In a circuit, it is represented by an S.

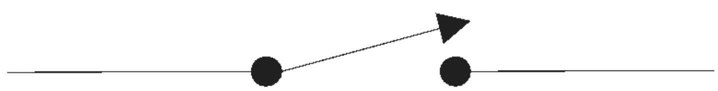


Figure 5-3. Switch (S).

Normally open and normally closed pushbuttons

A normally open push button is a device that prevents the flow of current, as shown in Figure 5.4, and only when it is pressed does the circuit close. Like a switch, it is represented in diagrams with an S.

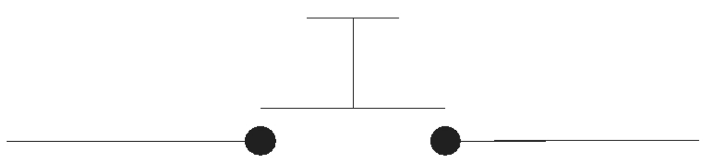


Figure 5-4. Normally open pushbutton (S).

There is another type of push-button that, unlike the previous one, is normally in a closed position, allowing the passage of current. When pressed (and only while pressed), the circuit is opened. It is also represented by an S on the diagrams.

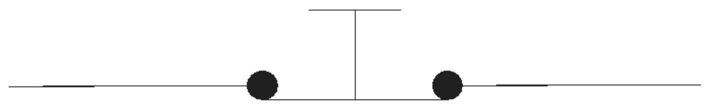
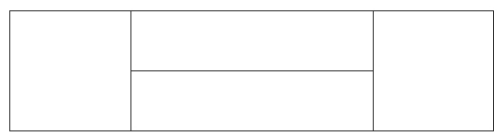


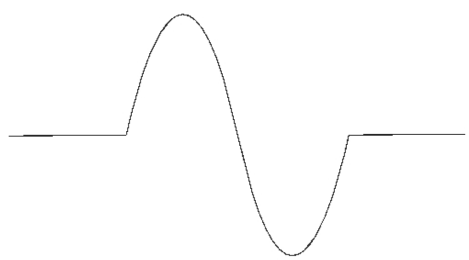
Figure 5-5. Normally closed pushbutton (S).

Fuses

A fuse, as shown in figure 5.6, is a component that, when connected in series in a circuit, allows a certain amount of current flow. If this limit is exceeded, the fuse breaks and the flow is interrupted. For this reason, it is a protective device against excessive current increases and is represented by an F in electrical diagrams.



(a) Physical form



(b) Symbol

Figure 5-6. Fuse (F).

Varistors

A varistor is a device that, when connected in parallel with a voltage line, absorbs voltage spikes or surges, as shown in Figure 5.7. As such, it is a component that serves only once when voltage spikes or surges are excessive. For this reason, it is said to be a "suicide element that is thrown onto the grenade". In an electrical circuit, it is represented by a V.

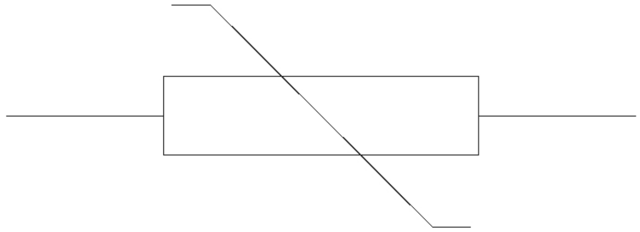


Figure 5-7. Varistor (V).

Resistors or resistors

A resistor is an electronic device that presents a voltage directly proportional to the current flowing through it between its terminals, as shown in figure 5.8. Its function is to oppose the passage of such current. In electrical diagrams, it is represented by an R.

Figure 5-8. Resistance (R).

Potentiometers

A potentiometer is essentially a variable resistor. Except for the fixed resistor with two terminals, the potentiometer has three, one of which is a sliding contact. This contact is what allows the resistance to be varied. It is represented in diagrams by an R.

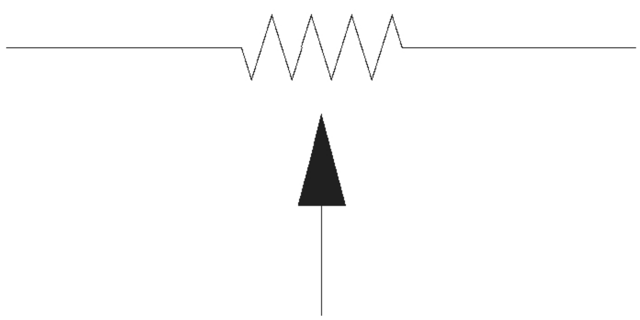


Figure 5-9. Potentiometer.

Ceramic capacitors

A ceramic capacitor, figure 5.10, is a device that stores lesser amounts of electricity. It does not have a defined polarity, so it does not matter how it is connected in a circuit. It is represented by C in electrical diagrams.

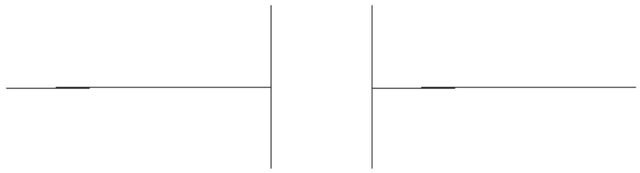


Figure 5-10. Ceramic condenser (C).

Electrolytic capacitors

An electrolytic capacitor stores relatively substantial amounts of electrical energy. They have a defined polarity, that is, one of the terminals is positive and the other negative; for this reason, care must be taken with their connection in a circuit, as connecting it with reverse polarity usually causes its explosion. The explosion of a capacitor of remarkably high capacity causes second-degree burns. In electrical diagrams, just like ceramic capacitors, it is represented by a C.

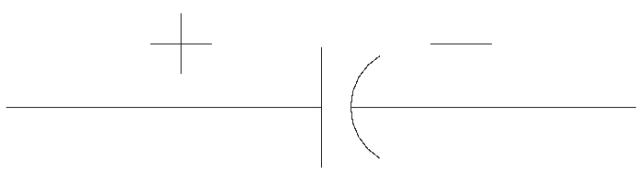


Figure 5-11. Electrolytic capacitors (C).

Coils or inductances

A coil, figure 5.12, is basically a wire winding over an air or iron core, like capacitors they have the property of storing insignificant amounts of energy. They have no defined polarity, but they do have a sense in the winding, which is important in some applications. Direct current should not be applied to them directly, as their low resistance makes them a short circuit. They are represented in electrical diagrams by an L.

Figure 5-12. Coil (L).

Light-emitting diodes (LEDs)

The symbol for an LED is shown in figure 5.13. An LED is a special type of diode that emits light when a current flows through it. It has two terminals called anode and cathode, just like conventional diodes. The cathode is indicated by a flat side on the plastic casing of the LED or by a shorter terminal than the anode. It is represented by the word LED in electrical diagrams.

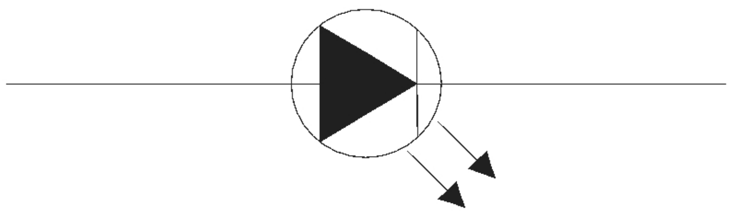


Figure 5-13. LED.

Photocells

A photocell is a special type of resistor that varies according to the intensity of light incident on its surface. It is represented by a P in electrical diagrams.

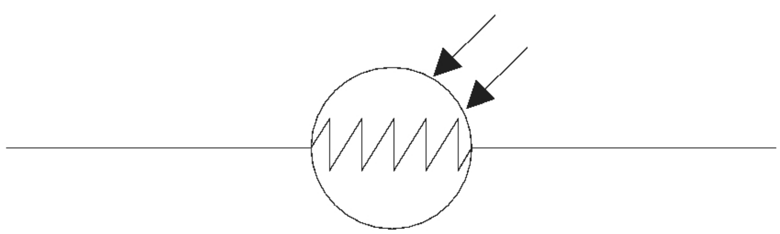


Figure 5-14. Photocell.

Integrated circuits (IC).

Integrated circuits (IC), shown in figure 5.15, contain many components (transistors, diodes, resistors, capacitors, etc.) placed inside a small package called a chip. Each type of integrated circuit performs a different function according to the components it has and how they are interconnected.

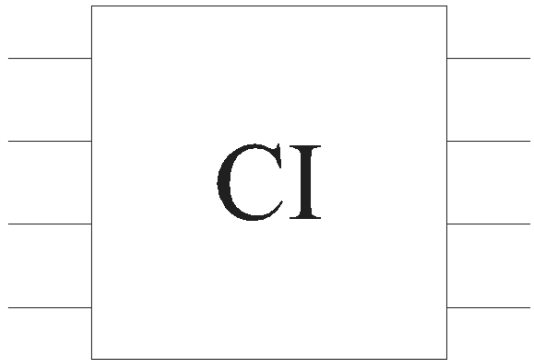


Figure 5-15. Integrated circuit (CI).

Speakers

A speaker, figure 5.16, is a device whose function is to convert the current flowing through it into sound waves. It is represented as SP in electronic diagrams.

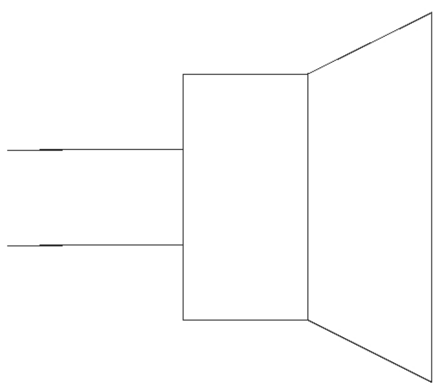


Figure 5-16. Speaker (SP).

Chapter 6
THE POWER SOURCE

A power supply is one of the tools that cannot be missing in a technician's laboratory. Its function is to supply the voltage required by a component or circuit for its proper operation. In electronics, the vast majority of devices require a DC bias. This is provided by the power supply after converting AC current. That is, the power supply is an element that takes the AC current and transforms it, through successive stages, into DC current. The process it performs is indicated in the block diagram shown in figure 6.1.

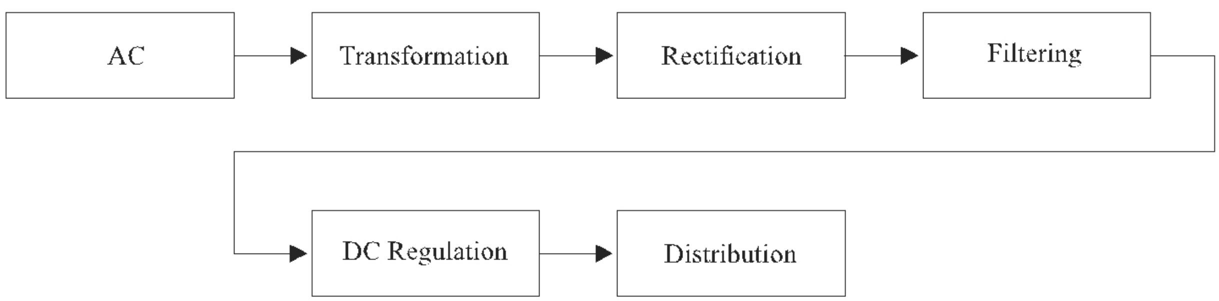


Figure 6-1. Block diagrams of a conventional power source.

The entry stage

The alternating current is captured from any household outlet, with a level of 110V or 220V. This signal must enter a transformer, which will lower the elevated level to one that is less harmful to electronic equipment. Remember that the transformer changes the signal level, but not its frequency. In section 3.1 of this text, the topic of transformers was discussed.

Signal rectification

Once the signal level has been reduced, its AC nature must be converted to DC. This is achieved through rectifiers based on diodes, a topic that was covered in section 3.2 of this text.

Signal filtering

The rectified signal must then be filtered to remove any noise it may contain; that is, any superimposed signal that should not naturally exist. For this purpose, capacitors are placed in parallel with the line to be filtered. Several capacitors of medium capacity can be used, or one of high capacity.

In this way, due to the slow discharge of the energy they have stored, the direct signal will be flattened and converted into a continuous signal with some ripple. Figures 6.2(a) and (b) show the effect of the capacitor on a half-wave and full wave rectified signal, respectively, and in Figure 6.3, the ripple can be seen, which is a small sinusoidal signal superimposed on the continuous signal, generating undesired effects. Ripple can be considered as noise.

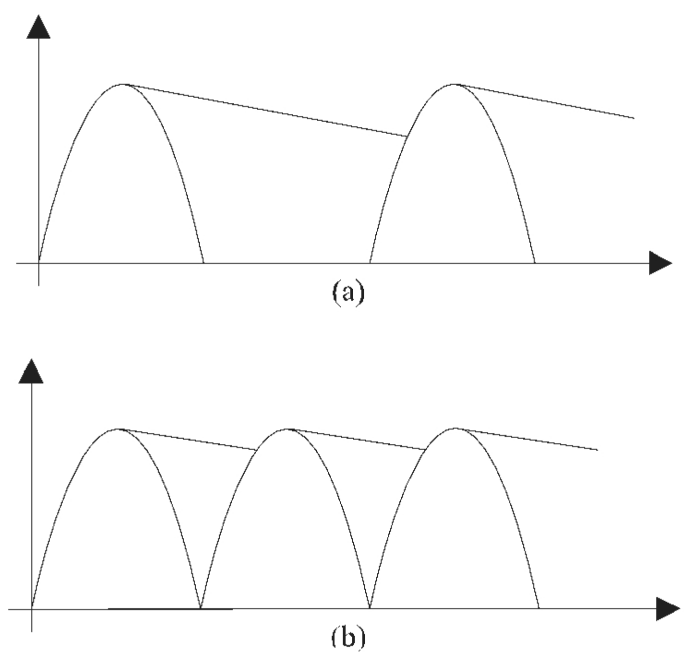


Figure 6-2. Effect of the capacitor on a rectified (a) half-wave (b) full-wave (a) signal.

The larger the capacitance of the capacitor, the flatter the signal will be, and therefore, the lower the ripple factor. It is recommended, therefore, to use capacitors with values greater than $1000\mu f$, with a voltage, obviously, higher than that of the line it will be connected to.

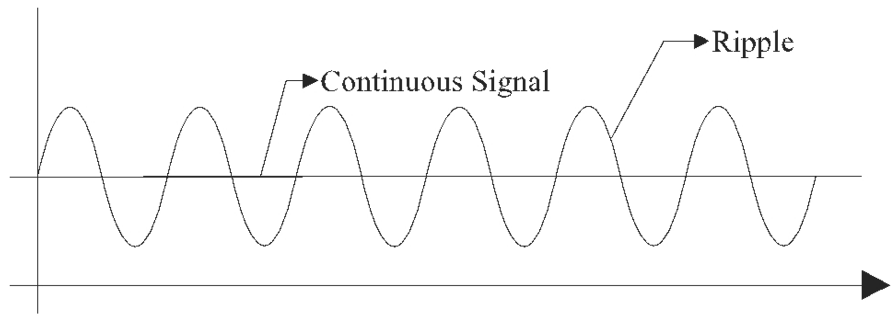


Figure 6-3. Ripple on a continuous signal.

Voltage regulation

According to what we have seen, ripple corresponds to a periodic change in the input voltage. Since regulators are devices that stabilize the output voltage against variations in the input voltage, a regulated power supply will be a source of continuous voltage with a fixed output, with a maximum attenuation of the ripple superimposed on the unregulated input voltage.

The latest generation of integrated voltage regulators has only three terminals: one for input, one for output, and a third for ground. The current supply of these elements' ranges from 100mA to over 5A. They are available in metal packages or external components, except for a couple of decoupling capacitors. The input decoupling capacitor prevents oscillations, and the output decoupling capacitor improves transient response. Figure 6.4(a) shows the connection for a fixed regulator, with its respective decoupling capacitors, and Figure 6.4(b) shows the corresponding connection for a variable regulator.

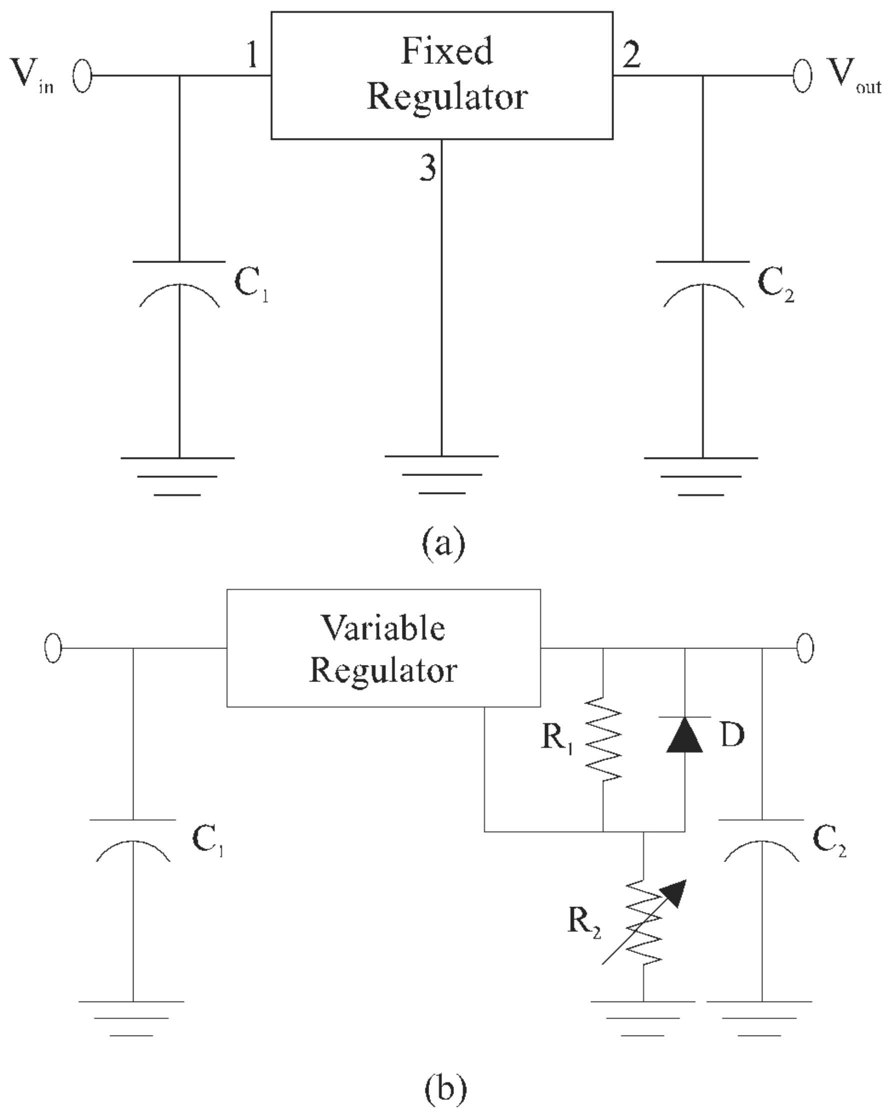


Figure 6-4. Connection for a (a) fixed and (b) variable regulator.

LM340 Serie

The LM340 series of regulators is available with output voltages of 5, 12, and 15V. They are the series of positive fixed voltages and are better known as the LM78XX reference. Thus, an LM7805 (LM340-05) produces an output of 5V, the LM7812 (LM340-12) produces an output of 12V, and the LM7824 (LM340-24) produces an output of 24V. To obtain these outputs, the respective inputs must have a few volts more than the expected output, 3 or 4, so that the device can regulate well.

LM320 Serie

It is a group of negative voltage regulators with fixed values of -5, -12, and -24V. They are commercially better known as LM79XX series. Thus, an LM7905 (LM320-05) produces an output of 5V, an LM7912 (LM320-12) produces an output of 12V, and an LM7924 (LM320-24) produces an output of 24V.

Both the LM340 and LM320 series include an output transistor that can manage more than 1.5A of load current if used with the appropriate heatsink. Additionally, they have thermal protection and current limiting. The thermal protection automatically disconnects the chip if the internal temperature becomes too high (around 175°C). Due to the thermal protection and current limiting, these integrated circuits are exceptionally durable.

Variable regulators

Some integrated regulators, such as the LM317, LM338, and LM350, are adjustable. Their maximum currents range from 1.5A to 5A. The LM317, for example, is a regulator with a current output of 1.5A and an adjustable voltage from 1.25V to 37V. The datasheet of an LM317 provides the formula given in equation (6.1) to determine the output voltage. The corresponding circuit is shown in Figure 6.4(b).

$$V_{sat} = \left(1 + \frac{R_2}{R_1}\right) \qquad (6.1)$$

Regulators with symmetrical output

Sometimes it is necessary to have a symmetrical (dual) voltage output for which a regulator such as the RC4194 and RC4195 is convenient. These regulators produce positive and negative voltage at the output.

RC4194 is adjustable from ±0.05 to ±32V, while RC4195 produces fixed ±15V outputs. Figure 6.5 shows the block diagram of the latter. The input must be from ±18 to ±30V and the current output is 150mA for each source.

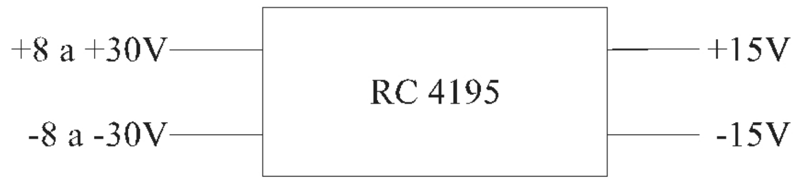


Figure 6-5. Regulator with symmetrical output.

EXAMPLE 6.1

For the circuit in figure 6.6, determine the value of each component, and explain the function of the distinct stages. Where it is necessary to choose a value without calculating it, explain the reason for the value.

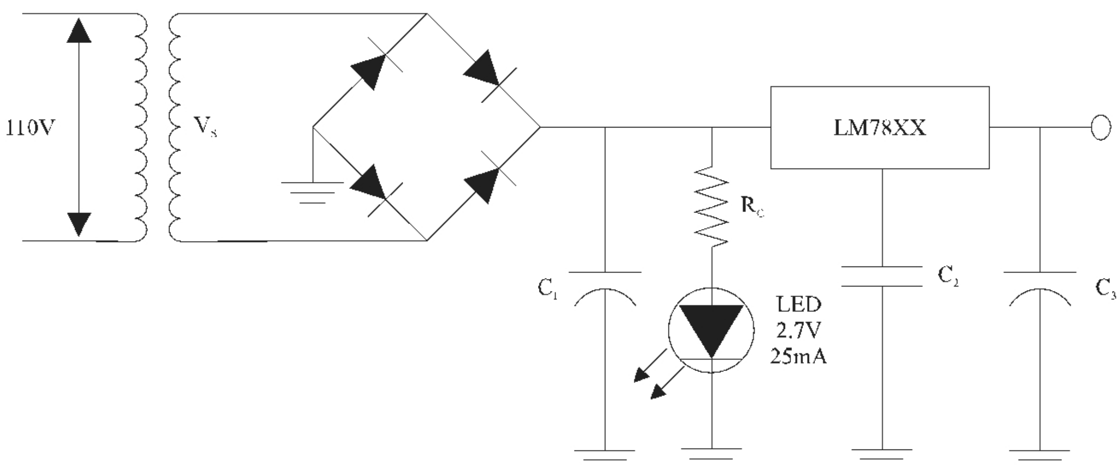


Figure 6-6. Circuit of example 6.1.

SOLUTION

As we have already mentioned, we take the 110V from a household outlet. With this voltage, we power the transformer, which lowers the voltage level in a 4:1 ratio. Therefore, the voltage in the secondary will be (equation (3.5)).

$$V_S = \frac{110V}{4} = 27.5V$$

The secondary voltage enters a full-wave rectifier, and the effect on the waveforms will be identical to that shown in Figure 3.6.

The capacitor C, which is the main filter, should be chosen with a high value, preferably greater than $1000\mu f$, and with a voltage higher than that supplied by the rectifier bridge. This voltage, according to equation (3.8), is:

$$V_{CC} = \frac{2V_m}{\pi} = \frac{2(27.5V)}{\pi} = 17.5$$

And the waveforms as shown in Figure 6.2(b). Remember that V_m is the same as the secondary voltage for a full-wave rectifier. The voltage rating for the capacitor should be higher than V_{CC}. In this case, we can choose 35V.

The LED diode is a pilot indicator for the secondary, and the resistor R_C serves to limit the current flowing through it and prevent it from burning out.

To calculate the limiting resistance, we proceed in an equivalent way as was done for the case of transistors in section 4.15, and for this purpose we can use the expression given in equation 4.22:

$$R_C = \frac{V_{CC} - V_{LED}}{I_{LED}} = \frac{17.5V - 2.7V}{25(10^{-3})A}$$

This is:

$$R_C = 592\Omega$$

We choose a commercial value higher than this. For example, 680Ω.

And the power:

$$P_{RC} = I_{LED}^2 R_C = \left(25\left(10^{-3}\right)\right)^2 (380)$$

That is to say:

$$P_{RC} = 0.425W$$

We can then place a 680Ω resistor with a power rating of ½W.

To have a fixed output and take advantage of the maximum input voltage, since it is necessary to leave a voltage of 3 or 4V on the input to ensure regulation, we choose an LM7812 regulator, thus ensuring a 12V output.

The input decoupling capacitor, C_2, prevents signal oscillations from entering the regulator and should be a low-capacitance type: $0.01\mu F$ to $0.1\mu F$ with a voltage rating higher than the line voltage. For example, $35V$; it can also be $25V$. The output decoupling capacitor, C_3, improves transient response, meaning it provides good regulation and fast response to sudden changes in load demand. It is recommended to use a tantalum capacitor with the same values as the input decoupling capacitor: $0.01\mu F$ to $0.1\mu F$ and $25V$ to $35V$.

To ensure the protection of the power supply and improve its operation, other devices can be added to its circuit. For example, an on/off switch and a fuse in series with the input. Additionally, a pilot light and a surge suppressor can be added at the input.

REVIEW

Concepts

Define or discuss the following:

- ☐ Power supply.
- ☐ Input stage of a power supply.
- ☐ Importance of rectification in a power supply.
- ☐ Capacitors as signal filters.
- ☐ Voltage regulators.
    - Fixed.
    - Variable.
    - Positive.
    - Negative.
    - Dual.

EXERCISES

6.1. For the circuit in figure 6.7, determine the value of each component, and choose the regulator that allows for maximum voltage utilization.

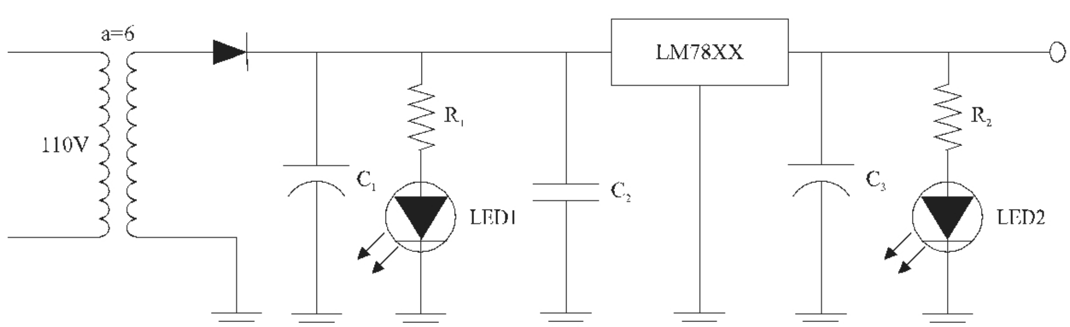


Figure 6-7. Circuit of exercise 6.1.

Does LED1 work with 3.1V and 30mA?
Does LED2 work with 2.7V and 24mA?
Does the circuit ensure good regulation?

6.2. Repeat the previous procedure, but for the circuit in figure 6.8.

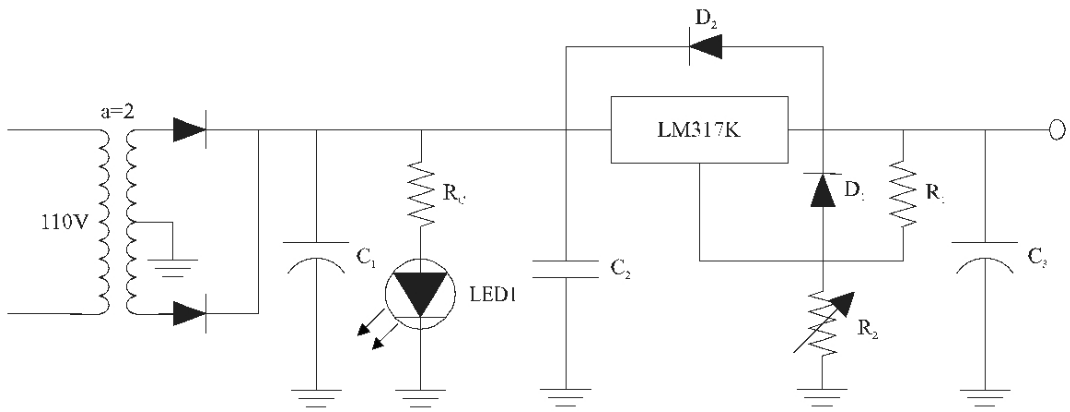


Figure 6-8. Circuit of exercise 6.2.

Does LED1 work with 2.5V and 22mA?

What is the purpose of placing diodes D_1 and D_2?

6.3. How could the circuit in Figure 6.7 be converted into a circuit with a variable output?

6.4. If the potentiometer R_2 is $5k\Omega$, what is the maximum output voltage that can be reached in the circuit of Figure 6.8?

6.5. In the circuit of Figure 6.8, what is the most recommended value for resistor R_1 at the regulator output?

6.6. What would be the value of potentiometer R_2 in the circuit of Figure 6.8 to obtain a minimum output voltage (1.25V)?

Chapter 7
ACADEMIC SUPPORT GUIDE

All theoretical knowledge should aim at some practical application, leading to the solution of real problems. Otherwise, it would run the risk of remaining in mere conceptual formulations, many of which would appear as abstract, without any use or applicability. Hence, it is important to work concretely, practically, if not with all, with the vast majority of devices seen during the course. When various devices have been manipulated individually, applications and projects that bring together several elements are more easily found, jointly fulfilling a special function.

This chapter aims to provide practical foundations to the student and, at the same time, to face them with the execution of a project, the power supply, of immense value in future work.

PRACTICE N°1

RECTIFIER CIRCUITS

GOALS

1. Verify the phenomenon of rectification, both half-wave and full wave.
2. Compare the results obtained theoretically with the results yielded by the experiment.

PROCEDURE

1. Assemble the circuit shown in figure 7.1.1

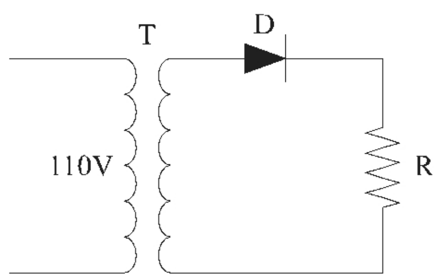


Figure 7-1-1. Half-wave rectifier circuit.

2. Using the oscilloscope, observe the signals in the secondary of the transformer, the diode, and the resistor.
3. Measure the values of the observed signals.
   i. Using the oscilloscope.
   ii. With a voltmeter.
4. Mount the circuits shown in Figure 7.1.2 and Figure 7.1.3 and repeat the procedure outlined in steps 2 and 3.

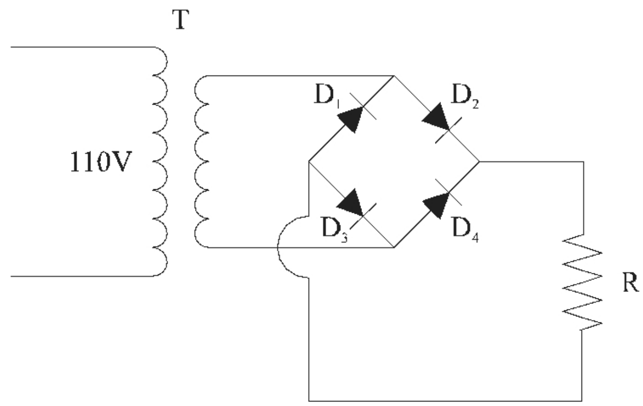


Figure 7-1-2. Full-wave rectifier circuit (bridge).

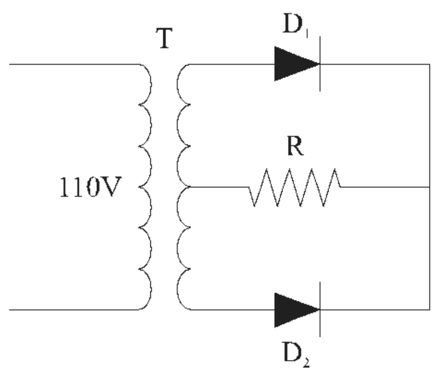


Figure 7-1-3. Full-wave rectifier circuit using center tapped transformer.

REPORT

1. Draw the observed waveforms for each of the circuits assembled.
2. Make a table with the results obtained in the different measurements.
3. Analyze the results.
4. Present your conclusions.

QUESTIONS

1. Do the measured values with different instruments match?

2. Which rectification setup do you consider to be the most convenient? Why?

PRACTICE N°2

VOLTAGE MULTIPLIERS

GOALS

Verify the voltage multiplier effect using diodes and capacitors.

PROCEDURE

1. Assemble the circuit shown in Figure 7.2.1 with $C_1 = C_2$ and observe the voltage across the diodes and capacitors terminals.

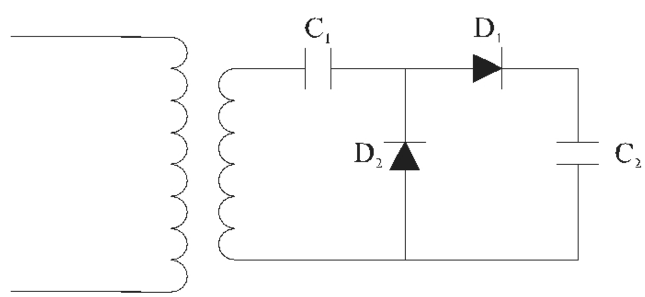


Figure 7-2-1. Voltage doubler circuit.

2. Connect a load resistor in parallel with C_2 and observe its voltage.

3. Assemble the circuit shown in figure 7.2.2(a) and repeat the procedure outlined for the previous circuit.

4. Assemble the circuit shown in Figure 7.2.2(b) and measure the voltages across the capacitors and the voltage between points A and B.

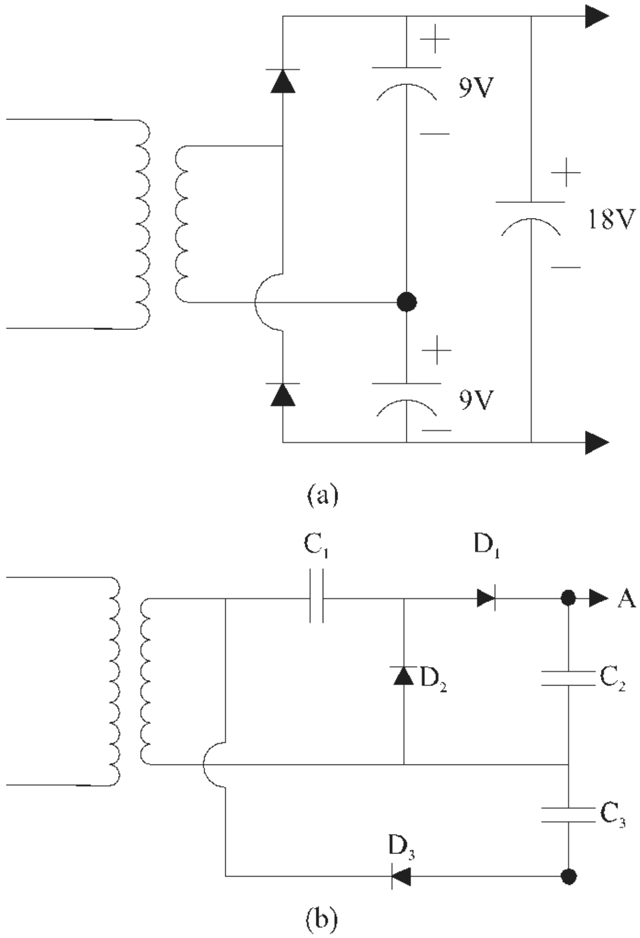


Figure 7-2-2. Voltage multiplier circuits.

5. Connect a load between points A and B and measure the voltage again.

REPORT

1. Create a table of results.
2. Analyze the results obtained.
3. Present your conclusions.

QUESTIONS

1. What effect does connecting different capacitors have on the circuit?

PRACTICE N°3

THE ZENER DIODE

GOALS

1. Characterize the Zener diode.
2. Observe the applications of the Zener diode.

PROCEDURE

1. Assemble the circuit shown in figure 7.3.1

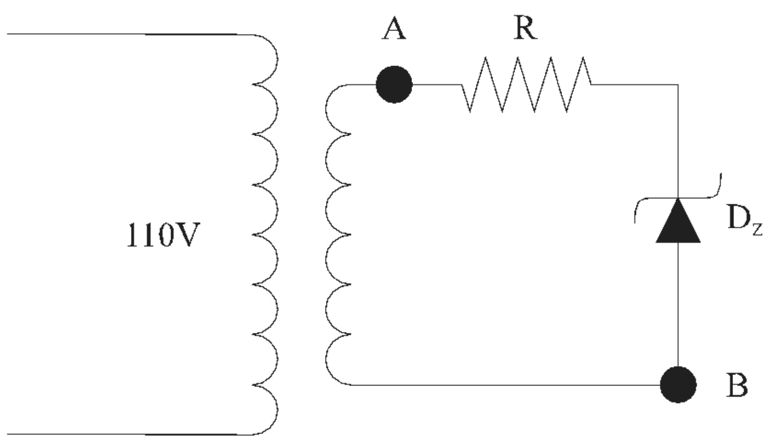


Figure 7-3-1. Zener diode amplification circuit.

2. Using an oscilloscope, observe the characteristics (waveforms) in the resistor, the Zener diode, and at points A and B shown in figure 7.3.1.
3. Assemble the circuit shown in figure 7.3.2

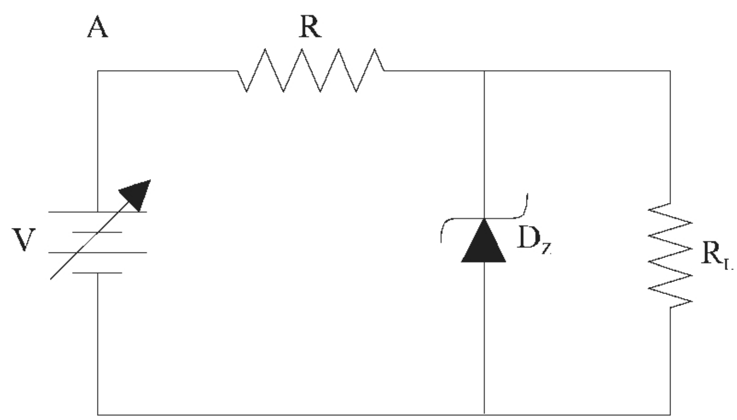
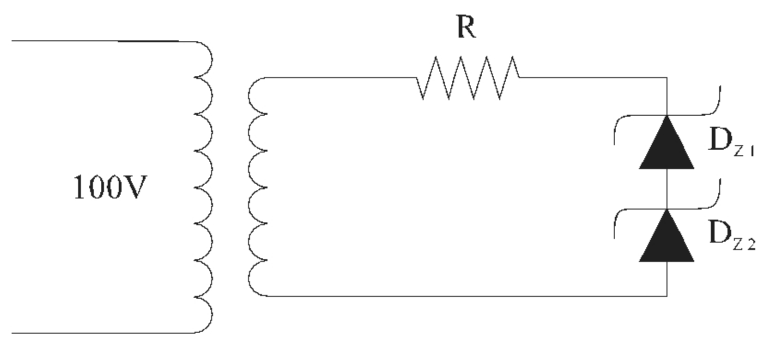


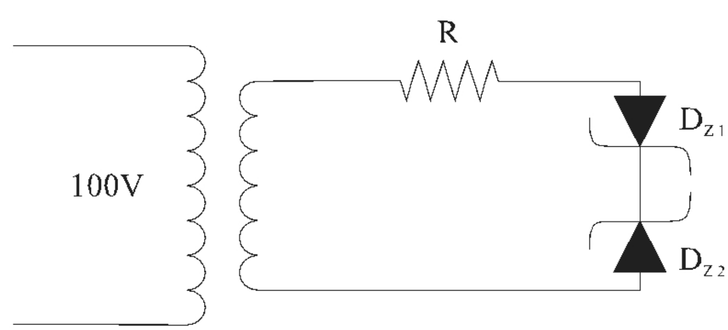
Figure 7-3-2. Circuit with Zener diode and load.

4. Vary the source voltage V at different values and establish the Zener's operating mode.

5. Assemble the circuits shown in Figures 7.3.3(a) and 7.3.3(b) and observe the output waveforms.



(a)



(b)

Figure 7-3-3. Zener diode application circuits.

REPORT

1. Draw the waveforms displayed with their respective measured values indicated.

2. Analyze the results obtained and discuss the signals observed in figures 7.3.3(a) and 7.3.3(b).

QUESTIONS

1. In what particular cases would you apply the results obtained in this experiment?

2. What other application do you find for the Zener diode?

PRACTICE N°4

BIPOLAR TRANSISTOR BIASING AND THERMAL STABILITY

GOALS

1. Determine the operating point of the bipolar transistor.
2. Determine changes in the operating point due to temperature changes.

PROCEDURE

1. Calculate the ohmic value and power of the resistors in the circuit shown in figure 7.4.1.

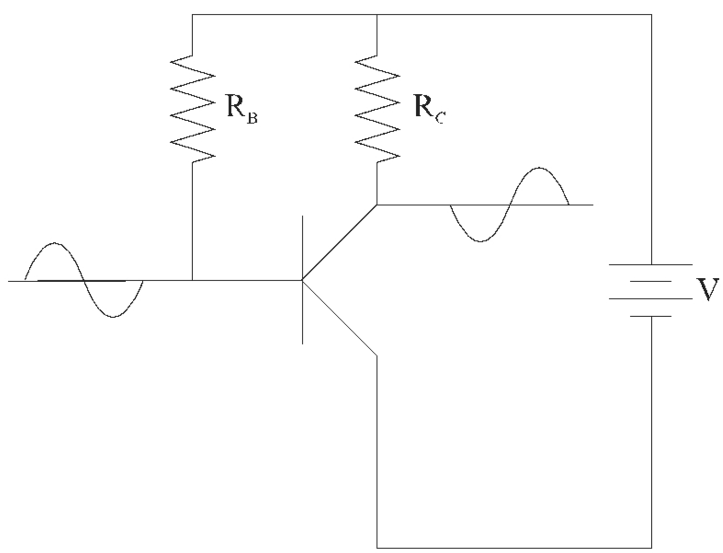


Figure 7-4-1. Circuits to determine transistor operating point.

2. Measure the currents and voltages in the transistor.
3. Using the soldering iron, increase the temperature on the transistor casing and measure the voltages and

currents again. Compare with the previous results.

4. Insert a 100Ω resistor in the emitter and repeat all the previous steps.

REPORT

1. Make a table with all the results obtained.
2. Analyze the results.
3. Present your conclusions.

QUESTIONS

1. What was the effect of temperature on the circuit?
2. What was the effect of the emitter resistor in the circuit?

PRACTICE N°5

BIPOLAR TRANSISTOR CHARACTERISTIC

GOALS

1. Determine the characteristics of bipolar transistors in their different configurations.
2. Graph the input-output signals of the bipolar transistor in its common emitter and common base configurations.

PROCEDURE

1. Use the ECG manual to determine the maximum allowable values for the transistors to be used.
2. Mount the circuit in figure 7.5.1.

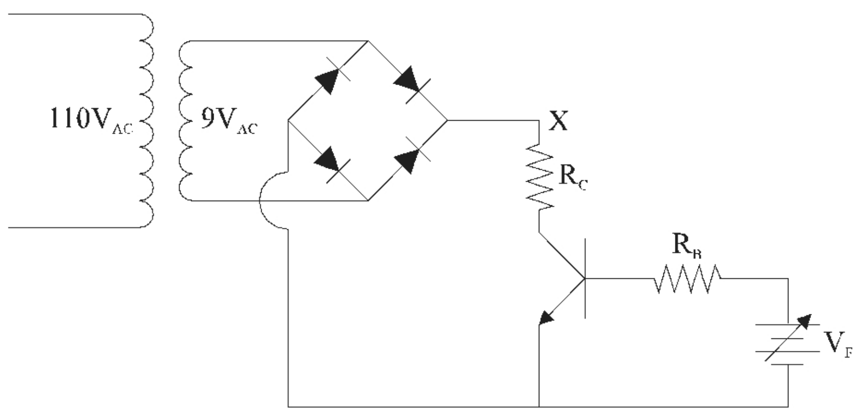


Figure 7-5-1. BJT common emitter configuration.

3. Set the time/div selector of the oscilloscope to $X - Y$ position and connect its terminals to points A and B of the circuit shown in Figure 7.5.1 and observe.
4. By varying the source V_f, obtain the maximum collector current possible and plot the graph.

5. Mount the circuit shown in figure 7.5.2.

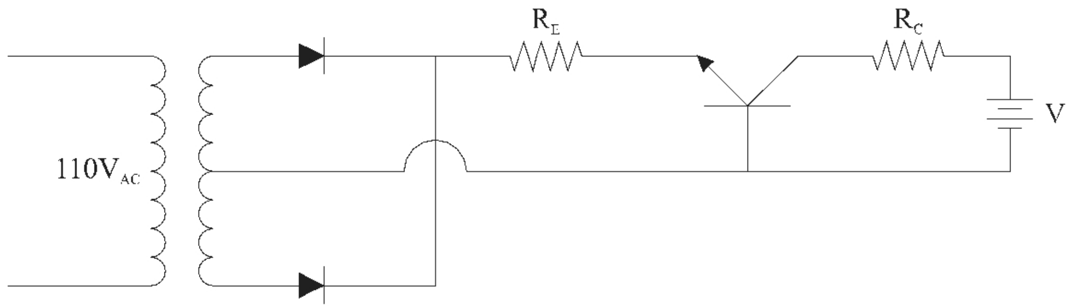


Figure 7-5-2. Common base BJT configuration.

6. By varying the voltage of the source V, obtain three curves of I_E versus V_{BE} for three different values of V_{CB}.

REPORT

1. Record the maximum values of the transistor obtained from the manual.
2. Draw the waveforms observed with the oscilloscope.
3. Draw the graphs you observed in section 6.
4. Analyze the results.
5. Present your conclusions.

PRACTICE N°6

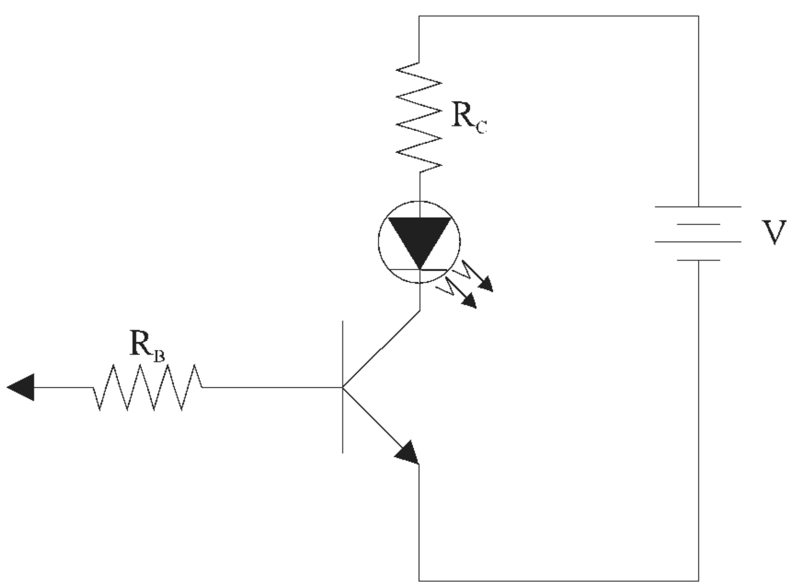
THE TRANSISTOR AS A SWITCH AND AS A COMMUTATOR

GOALS

1. Verify the operation of the transistor as a switching device.
2. Verify the operation of the transistor as a switching device.

PROCEDURE

1. Mount the circuit shown in figures 7.6.1(a) and 7.6.1(b).



(a)

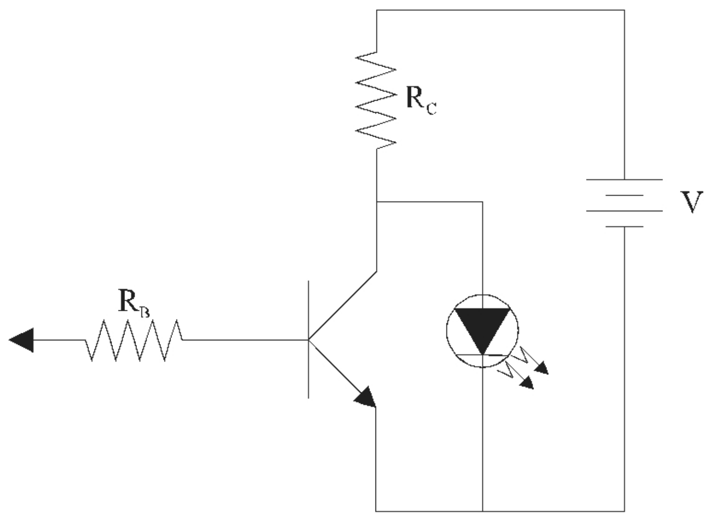


Figure 7-6-1. Circuits to verify transistor operation as a switch.

2. Vary the position of point B, first placing it at +V, and then at ground. Observe the operation of the diode.

3. Mount the circuit shown in figure 7.6.2.

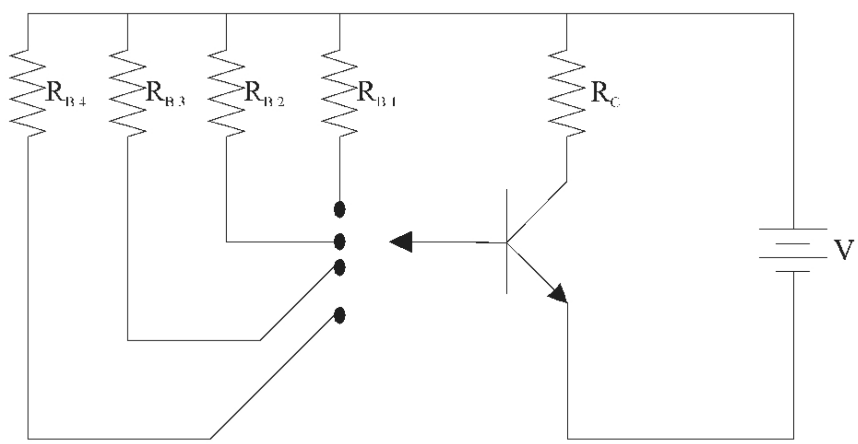


Figure 7-6-2. Circuit to verify the operation of the transistor as a switch.

4. Determine the operation by measuring voltages and currents of the transistor for each position of the switch connected to the base of the element.

5. Assemble the circuit shown in Figure 7.6.3 and apply a square wave signal to the input of the transformer.

6. Observe the output signal of the circuit in Figure 7.6.3.

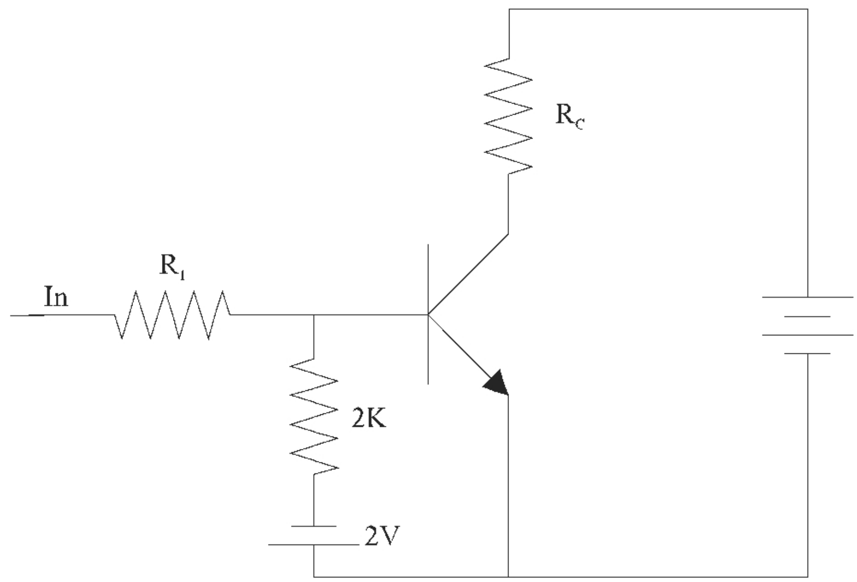


Figure 7-6-3. Bipolar transistor switching.

REPORT

1. Analyze the results obtained in each assembly.
2. Present your conclusions.

QUESTIONS

1. What application do you see for the transistor working as a switch?
2. What application do you see for the transistor working as an interrupter?

PRACTICE N°7

TRANSISTOR AMPLIFIERS

GOALS

Verify the amplification effect of the transistor, both in current and voltage.

PROCEDURE

1. Assemble the circuit shown in Figure 7.7.1 with $R = 5K\Omega$.

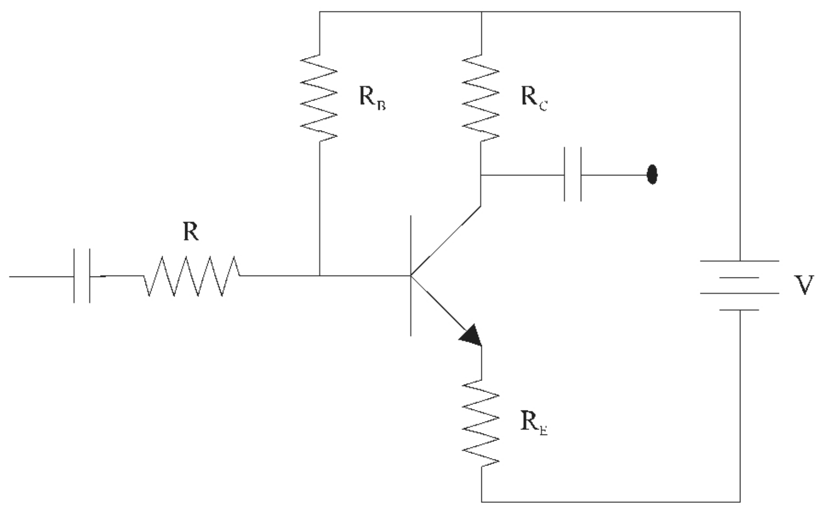


Figure 7-7-1. Transistor amplifier circuit.

2. Apply a 10KHz signal to the input, with an amplitude that does not produce distortion at the output.

3. Observe the input and output voltages and measure their values.

4. Measure the potentials in alternating current across R_C and across R_B to determine I_C and I_B, and the current gain.

REPORT

1. Draw the input and output signals with their respective DC values.

2. Make the necessary changes to determine the gains and show them.

QUESTIONS

1. In what specific practical case would you apply the results obtained in this practice?

PRACTICE N°8

DISCRETE VOLTAGE REGULATOR

GOALS

Verify voltage regulation using discrete circuit components.

PROCEDURE

1. Perform the assembly shown in figure 7.8.1 and measure the output voltage without load.

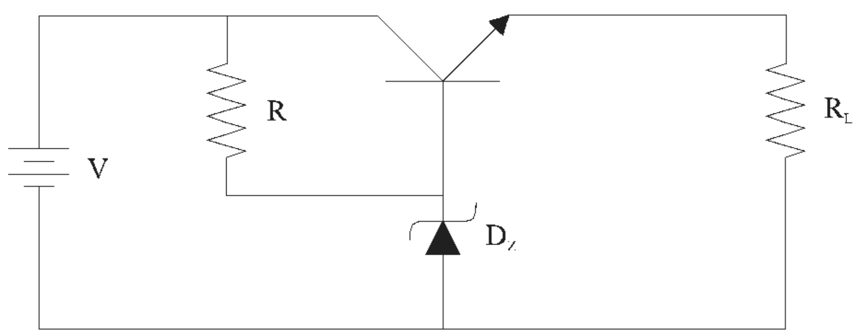


Figure 7-8-1. Discrete regulator.

2. Connect a load that requires the nominal current of the regulator and measure the output voltage again.

3. Build the circuit shown in figure 7.8.2 and measure the output voltage without load.

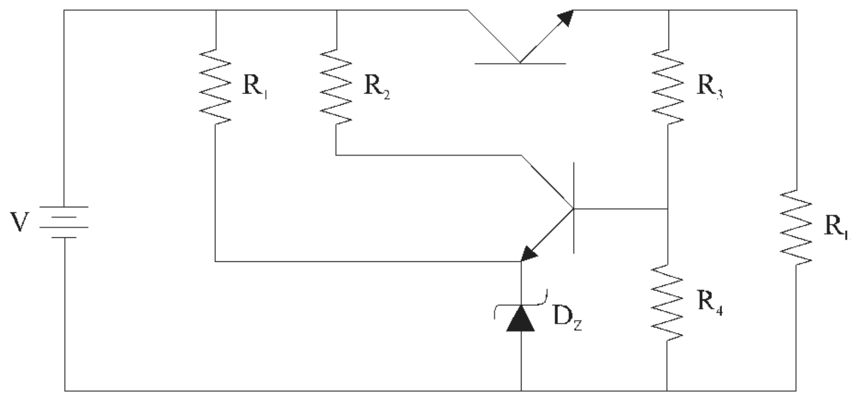


Figure 7-8-2. Discrete regulator with two transistors.

4. Repeat step 2.

5. Vary the voltage of the power supply and observe the output voltage.

REPORT

1. Make a table with the results obtained in the different assemblies.

2. Analyze the results.

3. Present your conclusions.

QUESTIONS

1. Which of the two circuits offers better regulation?

2. The variation in the output voltage with respect to the variation in the input voltage in the circuit of figure 7.8.2, is it large or small?

PRACTICE N°9

INTEGRATED VOLTAGE REGULATOR

GOALS

Verify the operation of integrated voltage regulators, both fixed and variable.

PROCEDURE

1. Assemble the circuits shown in figures 7.9.1(a) and (b) and measure the output voltages without load.

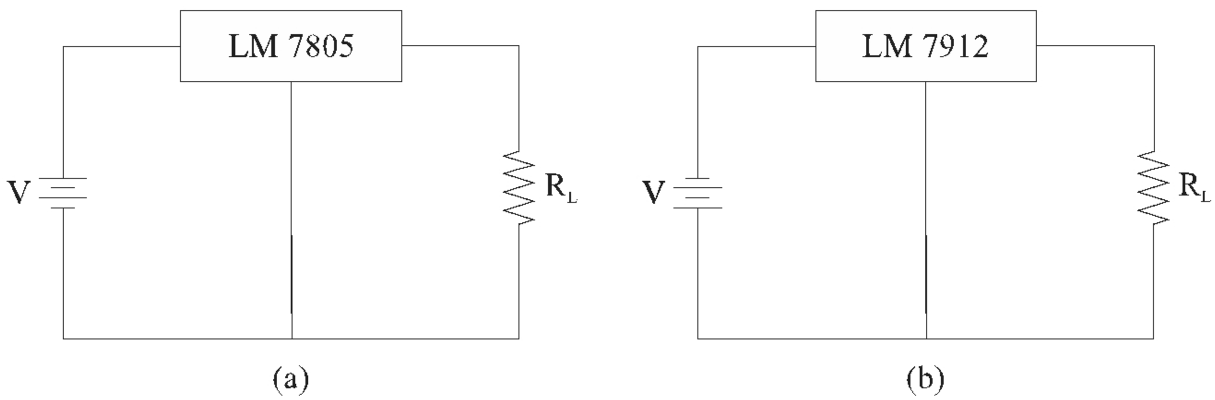


Figure 7-9-1. Built-in regulator (a) positive (b) negative.

2. Connect a load that demands the maximum ampere capacity of the regulators and measure the load voltage.

3. Assemble the circuit shown in Figure 7.9.2, use a 220Ω resistor for R_1, and a $5K\Omega$ potentiometer for R_2. Measure the voltage without load.

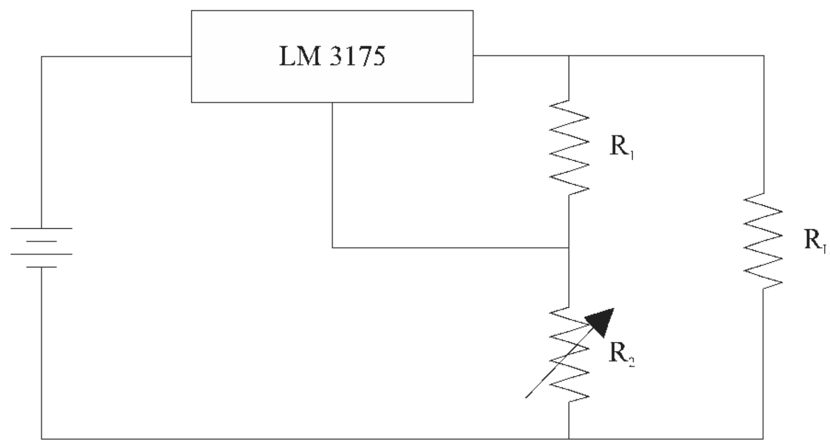


Figure 7-9-2. Integrated variable regulator.

4. For different loads in the circuit, verify the relationship:

$$V_L = 1.25\left(1 + \frac{R_2}{R_1}\right)$$

REPORT

1. Create a table containing all the values obtained during the experiment.

2. If the regulation of a circuit is defined as:

$$Reg = \frac{V_{SC} - V_{CC}}{V_{CC}} x100\%$$

Where: V_{SC} = Voltage without load.
V_{CC} = Voltage with load.

3. Calculate the regulation in the different circuits previously presented.

4. Determine the voltage range for the output of the circuit in figure 7.9.2.

PROJECT

VARIABLE REGULATED POWER SUPPLY

GOALS

Applying the above concepts in an accumulative process, aimed at the practical realization of a useful and didactic instrument.

PROCEDURE

1. Arrange the following list of elements:
   - ☐ 1 standard 110V plug (1 meter of duplex N°14 cable).
   - ☐ 1 1A, 250V fuse.
   - ☐ 1 Chassis fuse holder.
   - ☐ 1 Switch.
   - ☐ 1 $120V_{AC}$ pilot light.
   - ☐ 1 509 transformer.
   - ☐ 6 1N4004 diodes.
   - ☐ 1 Electrolytic capacitor of $3300\mu F$ at 35V.
   - ☐ 1 Tantalum capacitor of $0.1\mu F$ at 35V.
   - ☐ 1 Resistor of $1K\Omega$ at 0.5 watts.
   - ☐ 1 LED diode.
   - ☐ 1 LM317K$^{\Omega}$ regulator.
   - ☐ 1 $5K\Omega$ potentiometer.
   - ☐ 1 $0.1\mu F$ tantalum capacitor at 35V.
   - ☐ 2 terminals: 1 red and 1 black.
   - ☐ 1 #3 box.
   - ☐ 1 10x7 blank PCB.

- ☐ ½ pound of ferric chloride.
- ☐ 1 220Ω, 0.5-watt resistor.

2. With guidance from your instructor, design and etch your printed circuit board, corresponding to the circuit diagram shown in figure 1.

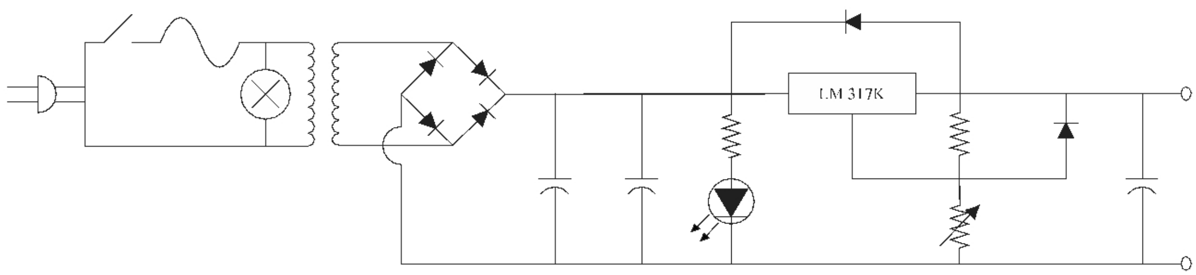


Figure 7-10-1. Variable regulated power supply.

3. Once you have performed the assembly on the circuit board, arrange the components that will go on the front of the chassis and fully assemble the power supply.

4. Before energizing the power supply, verify with a tester that the variation of the potentiometer is measured at the terminals. A quite common fault is that a zero resistance appears between the terminals, which implies that the power supply has a short circuit in the output stage. Correct this and energize. The pilot light should turn on, indicating that there is power in the primary, and the diode indicating that there is power in the secondary. With the tester set to DC volts, check which terminals show a voltage variation from 1.2 to approximately 24 volts. If so, you can load the power supply and start collaborating with it. Otherwise, identify and correct the fault.

GLOSSARY

Avalanche effect: phenomenon that occurs with high voltages in a pn junction. Free electrons are accelerated to such high speeds that they are capable of knocking valence electrons out of their orbitals.

Base: the middle part of a transistor. It is thin and lightly doped. Electrons flow through it from emitter to collector.

Base biasing: the most inconvenient way to bias a transistor to operate it in the active region. This biasing places a fixed value on the base current.

Bipolar transistor: a transistor that requires both electrons and holes for its operation.

Capacitor decoupling: capacitor used to connect a node to ground.

Class A operation: means that the transistor conducts throughout the entire cycle of the signal without entering saturation or cutoff.

Class B operation: polarization of a transistor so that it conducts only during half of a signal cycle.

Collector: the larger part of the transistor. It is called collector because it collects or gathers the charges from the base, sent by the emitter.

Collector cut-off current: small collector current that exists when the base current is zero in a common emitter connection. Theoretically, there should be no collector cut-off current. But it exists due to minority carriers and leakage currents of the collector diode.

Collector diode: a diode formed by the base and collector of a transistor.

Common emitter circuit: transistor circuit in which the emitter is grounded.

Coupling capacitor: capacitor used to transmit a signal from one node to another.

Cut-off point: it roughly corresponds to the lower end of the load line. The exact cut-off point occurs where the base current is almost zero.

Darlington transistor: two transistors connected to obtain a higher β. The emitter of the first transistor drives the base of the second transistor.

Diode: it is a pn junction. A device that conducts with forward bias and does not conduct with reverse bias.

Doping: addition of an impurity element to an intrinsic semiconductor to change its conductivity. Donor or pentavalent impurities increase the number of free electrons, and acceptor or trivalent impurities increase the number of holes.

Emitter: part of a transistor that serves as the source of charges. In npn transistors, the emitter sends free electrons towards the base. In a pnp, the emitter sends holes towards the base.

Emitter biasing: the best way to bias a transistor for operating in the active region. The key idea is to maintain the emitter current at a fixed value.

Emitter diode: diode formed by the emitter and base of a transistor.

Light Emitting Diode (LED). A diode that emits light of distinct colors such as red, green, yellow or even invisible light such as infrared.

Emitter follower: circuit in which the emitter signal follows the base signal.

Forward bias: application of an external voltage to overcome the potential barrier.

Gain: ratio between the output signal and the input signal in an amplifier device such as a transistor.

Germanium: one of the first semiconductor materials that were used. Like Silicon, it has four valence electrons.

Heat sink: a metallic mass attached to the package of a transistor, in order to allow heat to escape more easily.

Hole: absence of an electron in the valence orbit.

Intrinsic: Semiconductor in a pure state.

Leakage currents: total reverse current in a node.

LED driver: circuit that can produce enough current to turn on an LED.

Extrinsic: Semiconductor with impurities.

Load line: geometric locus of instantaneous operating points when a signal excites the transistor.

N-type semiconductor: a semiconductor in which there are more free electrons than holes.

Open: refers to a component or connection between whose terminals a resistance is measured that tends to infinity.

Power dissipation: the product of voltage and current in a resistor or another device.

P-type semiconductor: a semiconductor in which there are more holes than free electrons.

Rectifier diode: a diode that converts alternating current to direct current.

Reducing transformer: a transformer that has more turns in the primary coil than in the secondary coil. This results in a lower voltage in the secondary coil than in the primary coil.

Reverse bias: application of an external voltage to increase the potential barrier. The result is an almost zero current.

Ripple: in a filter with a capacitor at the input, this refers to the voltage saturation at the load, caused by the electric charging and discharging of the capacitor.

Saturation point: approximately equivalent to the upper end of the load line. At this point, the collector-emitter voltage is approximately zero.

Short circuit: occurs when a resistance is extremely small, almost zero. Due to this, the voltage in a short circuit tends to zero, although the current is high.

Schottky diode: a special-use diode with the ability to rectify high-frequency signals.

Silicon: most widely used semiconductor. It has atomic number 14 and 4 valence electrons.

Varicap: a diode adapted to exhibit a capacitance with reverse bias. The capacitance decreases as the reverse voltage increases.

Varistor: device that acts as two opposing Zener diodes. It is used or connected between the terminals of a power line to prevent power surges from entering the equipment.

Zener effect: effect that occurs when the intensity of the electric field is remarkably high and extracts valence electrons in a reverse-biased diode.

Zener resistance: internal resistance of a Zener diode.

Zener voltage: breakdown voltage in a Zener diode.

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ALBEIRO PATIÑO BUILES

Electrical engineer. With specializations in Literary Hermeneutics and High Management; also, Master in Strategic Management, Planning and Management Control of the IEE of Spain. He has received numerous awards, including first place in the II National Novel Award - National Culture Awards of the University of Antioquia (2006) and first place in the First Short Story Competition of the Association of Employees of the Colombian Industrial Bank (1996). His literary publications are: *Historias cruzadas* (short stories, 1994), *Bandidos y hackers* (novel, 2007), *Phishing* (novel, 2010), *Construir una novela. Cómo orientarse en el proceso de creación literaria* (essay, 2011), *Intimidación* (novel, 2014), *Galán, crónica de un magnicidio* (novel, 2014), *Las intermitencias del corazón I. Melancolía y enajenación* (novel, 2016), *La forja de un escritor* (essay, 2017), *Sombras en la Red* (novel, 2019) and *Las intermitencias del corazón II. Celos y dolor* (novel, 2019).

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