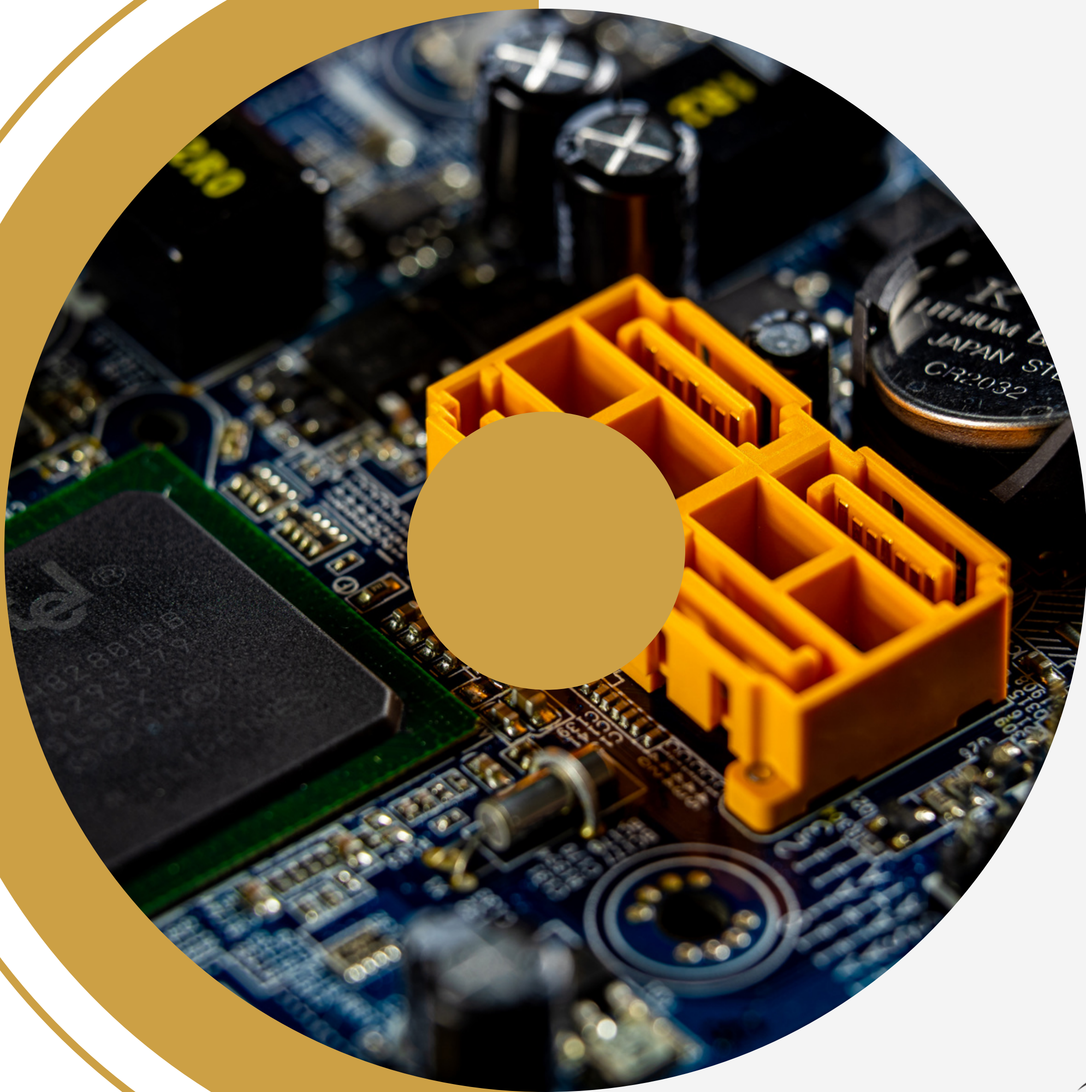
ELECTRONIC CIRCUITS



POLITEKNIK MALAYSIA
TUANKU SYED SIRAJUDDIN

AUTHORS

Sarah Jewahid
Mohamed Isa Osman
Noor Laila Ash'ari

Electronic Circuits

Polytechnic Series

Editor
Sarah Jewahid
Mohamed Isa Osman
Noor Laila Asha'ari

Writer
Azrini Idris
Mohamed Isa Osman
Sarah Jewahid
Noor Laila Asha'ari

Designer
Azrini Idris
Mohamed Isa Osman
Sarah Jewahid
Noor Laila Asha'ari

First published 2022

Published by :

POLITEKNIK TUANKU SYED SIRAJUDDIN

Pauh Putra

02600 Arau

Perlis1

ACKNOWLEDGEMENT

First of all, Alhamdulillah, thanks God Almighty for His guidance and blessing. We had succeeded in completing this Electronic Circuits E-Book. We want to express our utmost gratitude to our Head Department of Electrical Engineering, Mr Shaffie Bin Husin, who supported us in grabbing this opportunity . Without his support, we would not be able to produce this E-Book. Not to forget the E-Learning team because it provides us with this opportunity and guides us in making this E-Book.

Besides, we also extend our gratitude to all friends and our lovely families for their kindness and sincere assistance in adding us to finish up this E-Book. Indeed, we have appreciated them. Again, thanks for everything.

Our hopes are, may this E-Book helps students out there, especially engineering students in polytechnic, ease them to understand about electronic circuits. Nevertheless, we also need any comments from reads to help us improve our next debut. We hope this E-Book could ease everyone to understand and implement the technics and could fulfill everybody needs.

Thank you.

TABLE OF CONTENTS

1

LINEAR DC POWER SUPPLY

1.1 INTRODUCTION

- Electronic appliance use active components such as diode, transistor and etc. These components need DC voltage source to operate.
- Batteries can give constant voltage and easy to carry everywhere. But using batteries the power will not last longer after a certain period. Electronics appliances that using high power supply will shorter the batteries life.
- Electronics appliances that using high power supply will use more batteries. So, it's not economical if we using batteries.
- All power supply to public, factories and industries through output socket are AC power and in high value (1 phase = 240 V, 3 phase = 415 V). Therefore, it is importance to convert the AC input voltage to DC voltage because all the semiconductor devices require DC voltage source to operate.

1.1.1 DC POWER SUPPLY BLOCK DIAGRAM

- A dc power supply is used to convert alternating current (ac) signal to direct current (dc) signal. The signal need to pass through five stages to produce a purely dc signal. The stages is shown in Figure 1.1.

TRANSFORMER → RECTIFIER → FILTER → REGULATOR → VOLTAGE DIVIDER

Figure 1.1 : DC power supply block diagram

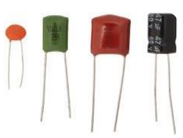
1.1.2 FUNCTION OF EACH BLOCK IN DC POWER SUPPLY

Transformer

- To change the 240V AC input voltage to the required value. In power supply portion, this transformer function is to step down the input line voltage.
- To isolate the rectifier from the voltage source to minimize the danger of electric shock.

Rectifier

- To converts the alternate current input signal to a pulsating direct current.

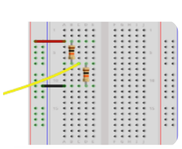


Filter

- To eliminate the fluctuations in the rectifier voltage and produce a relatively smooth DC voltage like voltage in battery.
- To reduce the ripple voltage.
- The output from rectifier is a pulsating dc voltage but the pulsating dc voltage from rectifier is still not enough to get pure DC voltage.

Voltage regulator

- Stabilise the output voltage, Vo even though there is a variation of the input current or the output current.
- Reduce the ripple at the output voltage of the filter circuit.



Voltage divider

- To divide the voltage following the circuit necessity.

1.2 TRANSFORMER

- A transformer is uses to increase (step up) or decrease (step down) the AC voltage level
- Most electronic circuits operate from voltages lower than the AC line voltage so the transformer normally steps the voltage down by its turns ratio to a desired lower level.

1.2.1 TRANSFORMER INPUT AND OUTPUT WAVEFORM

- Figure 1.2 show the effect of a step-down transformer.
- The amplitude of output voltage (Vo) has been reduced compare to input voltage (Vi). However the frequency remains.

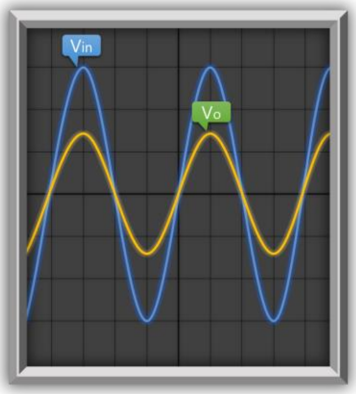


Figure 1.2 : Transformer input and output waveform

1.2.2 TRANSFORMER RATIO

- Transformer symbol is illustrated as in Figure 1.3. The transformer turns ratio determine the operation of the transformer either. The ratio is depends on the value of either number of primary and secondary winding, primary voltage and secondary voltage, or primary current and secondary current.
- Turns ratio can be calculated using formula:

$$\boxed{\frac{Ns}{Np} = \frac{Vs}{Vp}}$$

Where,

Np – No of turns at primary winding

Ns – No of turns at secondary winding

Vp – Voltage at primary winding

Vs – Voltage at secondary winding

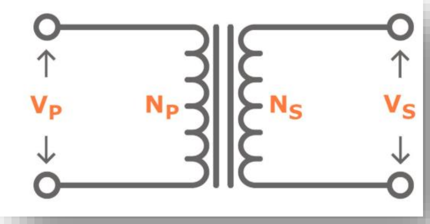
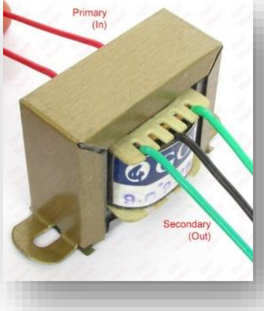


Figure 1.3: Transformer turns ratio

1.2.3 CENTER-TAPPED TRANSFORMER

- The center tap transformer is simply another wire which is typically connected somewhere in the middle of the secondary coil as shown in Figure 1.4.
- This concept is used in electronics to generate positive and negative voltages using the center tap as the ground.
- It is commonly use in a rectifier circuit.



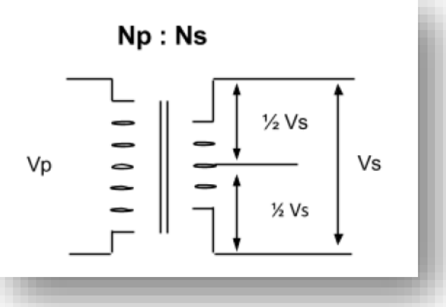


FIGURE 1.4 : CENTER TAPPED TRANSFORMER

1.3 DIODE AS WAVE RECTIFIER

- Most of the electronics circuit required DC power supply to operate. The most commonly used circuit to convert AC voltage to DC voltage is the rectifier circuit.
- There are two types of rectifier :
  a) Half wave rectifier
  b) Full wave rectifier

1.3.1 HALF-WAVE RECTIFIER

- Half-wave rectifier is made up of a diode and a resistor.
- It has the ability to conduct current in one direction (during positive half-cycle) and block current in the other direction (during negative half-cycle).

A) OPERATION OF HALF-WAVE RECTIFIER

During positive half-cycle :

- Diode is forward biased.
- Diode operates as a switch (act as a closed circuit) as in Figure 1.5 (a) and let the current flow through it
- A voltage with same magnitude to input signal is developed across RL (if we neglect the voltage drop at the diode

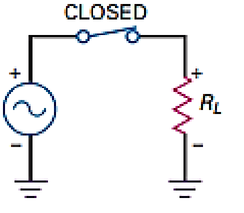


Figure 1.5 (a) : Half-wave rectifier circuit on positive half-cycle

During negative half-cycle :

- Diode is reverse biased.
- Diode operates as an opened switch (act as an open circuit) as in Figure 1.5 (b) . No current could flow through it.
- Since no current flow in the circuit, there will be no voltage drop across RL.

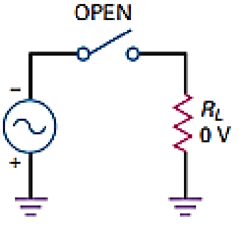


Figure 1.5 (b): Half-wave rectifier circuit on negative half-cycle

B) INPUT AND OUTPUT WAVEFORM OF A HALF-WAVE RECTIFIER

- The input signal of a half-wave rectifier is typically a sinusoidal waveform with peak value of Vp(in) as shown on Figure 1.6 (a).
- Half-wave voltage produce a unidirectional load current with peak value of Vp(out) as in Figure 1.6 (b). Ideally, value of Vp(out)=Vp(in)

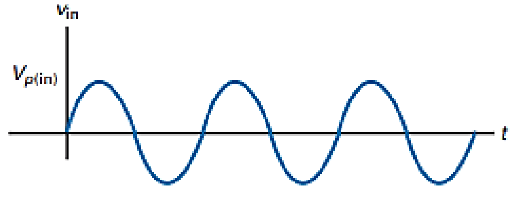


Figure 1.6 (a) : Half-wave rectifier input waveform

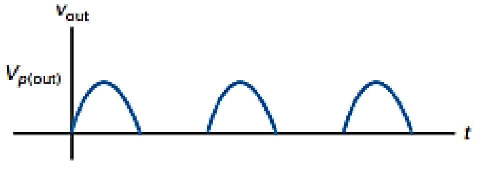


Figure 1.6 (b) : Half-wave rectifier output waveform

C) HALF-WAVE RECTIFIER OUTPUT VOLTAGE PROPERTIES

Peak Voltage	Vp(out) = Vp(in)-0.7V
Average Voltage	Vavg or Vdc = Vp(out)/π = 0.318Vp(out)
RMS Voltage	Vrms = 0.707Vp(out)
Frequency	Fout = Fin

EXAMPLE 1.1

Figure 1.7 shows a half-wave circuit with ac source of 10Vrms and 60Hz. Determine peak load voltage and dc load voltage (ignore voltage drop at diode).

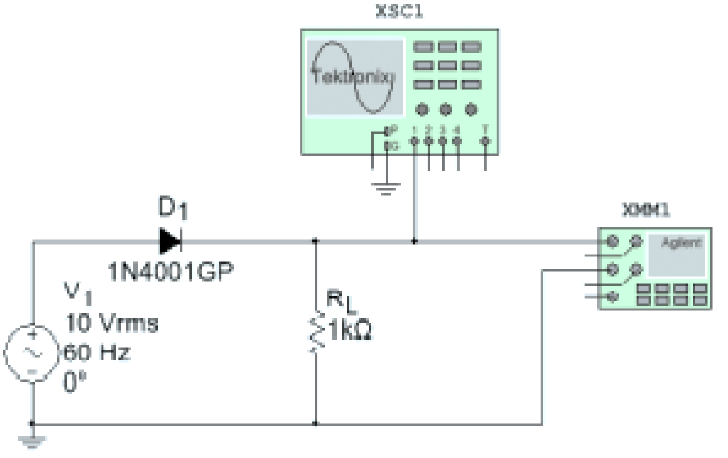


Figure 1.7

Solution Example 1.1:

$$V_{rms} = 0.707V_P$$

The peak source voltage :

$$V_p = \frac{V_{rms}}{0.707} = \frac{10V}{0.707} = 14.1V$$

With an ideal diode, the peak load voltage is:

$$V_{p(out)} = V_{p(in)} = 14.1V$$

The dc load voltage is :

$$V_{dc} = \frac{V_p}{\pi} = \frac{14.1}{\pi} = 4.49V$$

1.3.2 FULL-WAVE RECTIFIER

- Full wave rectifier allows bi-directional current to the load during the entire input cycle
- A full wave rectifier produces ripple voltage during both positive and negative input cycle.
- There are two types of full wave rectifiers:
  - i. Center tap transformer rectifier
  - ii. Bridge rectifier

I) FULL-WAVE CENTER TAP TRANSFORMER RECTIFIER (FWCT)

A full-wave rectifier is shown in Figure 1.8(a). It uses a center-tapped transformer secondary and two diodes. The transformer center tap is located at the electrical center of the secondary winding. If, for example, the entire secondary winding has 100 turns, then the center tap will be located at the 50th turn. The waveform across the load in Figure 1.8(a) is full-wave pulsating direct current with half the peak voltage of the secondary because of the center tap.

Both cycle of the ac input are used to energize the load. Thus, a full-wave rectifier can deliver twice the power of a half-wave rectifier.

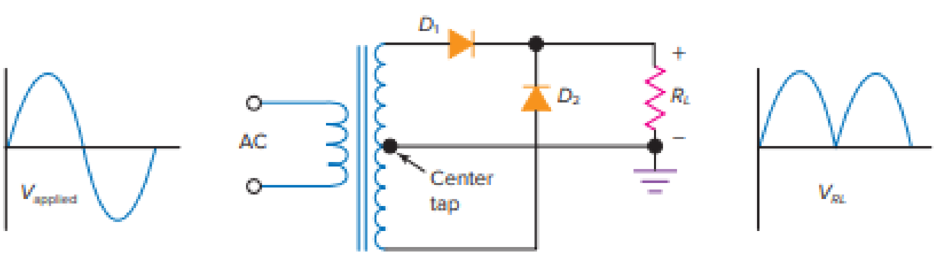


Figure 1.8 (a) : Full-wave center tap transformer rectifier

A) FWCT OPERATION

The positive cycle is shown in Figure 1.8(b). The induced polarity at the secondary is such that D1 is turned on. Electrons leave the center tap and flow through the load, through D1, and back into the top of the secondary. Note that the positive end of the load resistor is in contact with the cathode of D1.

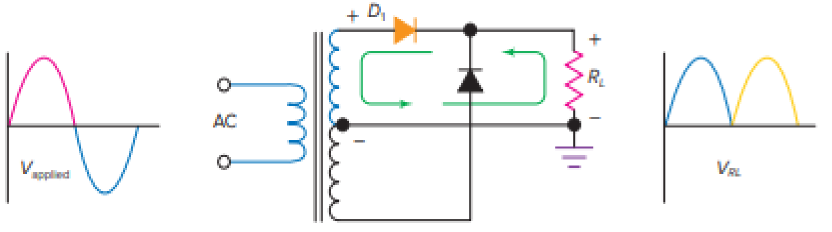


Figure 1.8 (b) : Positive cycle of FWCT

On the negative cycle, the polarity across the secondary is reversed. This is shown in Figure 1.8(c). Electrons leave the center tap and flow through the load, through D2 , and back into the bottom of the secondary. The load current is the same for both alternations: it flows up through the resistor. Since the direction never changes, the load current is direct current.

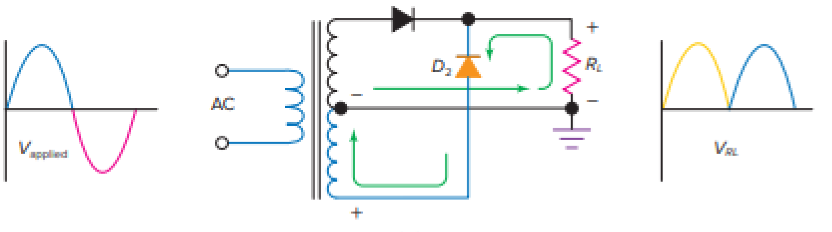


Figure 1.c (b) : Negative cycle of FWCT

B) FWCT OUTPUT VOLTAGE PROPERTIES

Peak Voltage	Vp(out) = (Vp(in)/2)-0.7V
Average Voltage	Vavg or Vdc = 2Vp(out)/π = 0.636Vp(out)
RMS Voltage	Vrms = 0.707Vp(out)
Frequency	Fout = 2Fin

EXAMPLE 1.2

Figure 1.9 shows a full wave center tapped circuit. Calculate the input and output voltages.

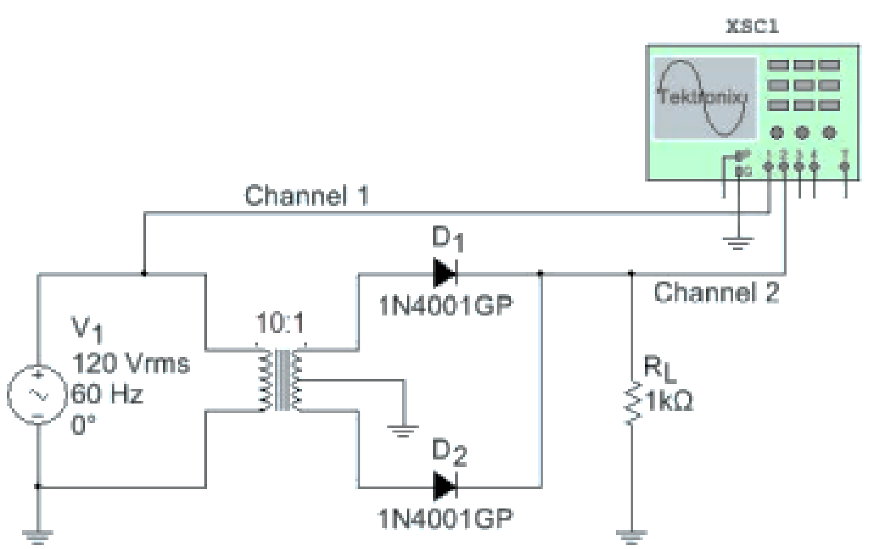


Figure 1.9

Solution Example 1.2 :

The peak primary voltage is:

$$V_{p(pri)} = \frac{Vrms}{0.707} = \frac{120}{0.707} = 170V$$

Because of the 10:1 step-down transformer, the peak secondary voltage is:

$$V_{p(sec)} = \frac{N_2}{N_1} \times V_{p(pri)} = \frac{1}{10} \times 170 = 17V$$

Because of the center tap, the input voltage foe each half-wave rectifier is only half the secondary voltage:

$$\mathrm{V_{p(in)}} = \frac{V_{p(sec)}}{2} = \frac{17\mathrm{V}}{2} = 8.5\mathrm{V}$$

Ideally, the output voltage is:

$$\mathrm{V_{p(out)}} = \mathrm{V_{p(in)}} = 8.5\mathrm{V}$$

Consider the voltage drop at diode:

$$\mathrm{V_{p(out)}} = \mathrm{V_{p(in)}} - 0.7V = 7.8\mathrm{V}$$

II) FULL-WAVE BRIDGE RECTIFIER

Figure 1.10 (a) shows a rectifier circuit that gives full-wave performance without the transformer. It is called a bridge rectifier. It uses four diodes to give full-wave rectification.

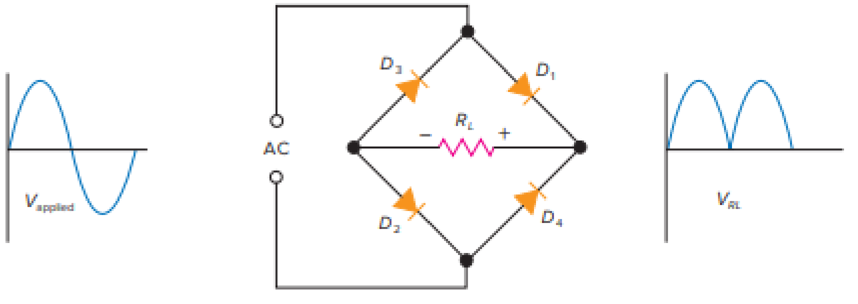


Figure 1.10 (a) : Full-wave bridge rectifier

A) FULL-WAVE BRIDGE RECTIFIER OPERATION

Figure 1.11 (a) traces the circuit action for the positive cycle of the ac input. The current moves through D2, through the load, through D1, and back to the source

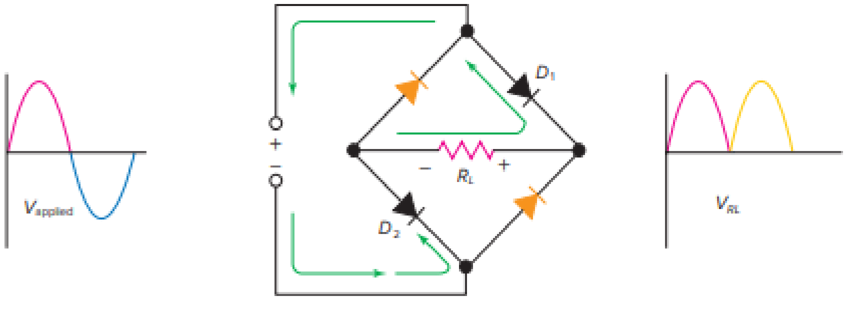


Figure 1.11 (a) : Positive cycle of full-wave bridge rectifier

The negative cycle is shown in Figure 1.11 (b). The current is always moving from left to right through the load. Again, the positive end of the load is in contact with the rectifier cathodes. This circuit could be arranged for either ground polarity simply by choosing the left or the right end of the load as the common point.

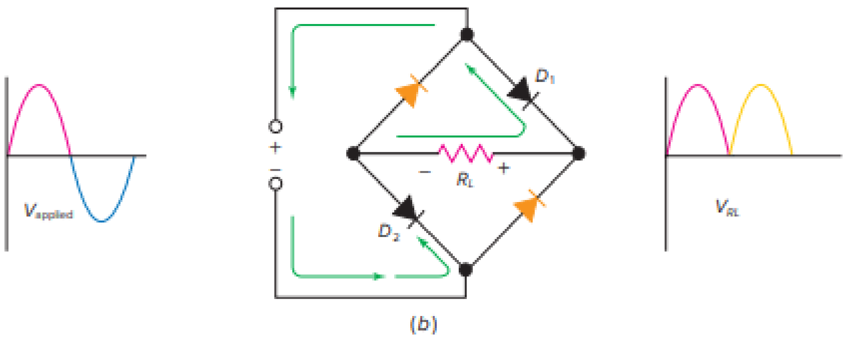


Figure 1.11 (b) : Negative cycle of full-wave bridge rectifier

B) FULL-WAVE BRIDGE RECTIFIER OUTPUT VOLTAGE PROPERTIES

Peak Voltage	Vp(out) = Vp(in)-1.4V
Average Voltage	Vavg or Vdc = 2Vp(out)/π = 0.636Vp(out)
RMS Voltage	Vrms = 0.707Vp(out)
Frequency	Fout = 2Fin

EXAMPLE 1.8

Figure 1.12 shows a full wave center tapped circuit. Calculate the input and output voltages.

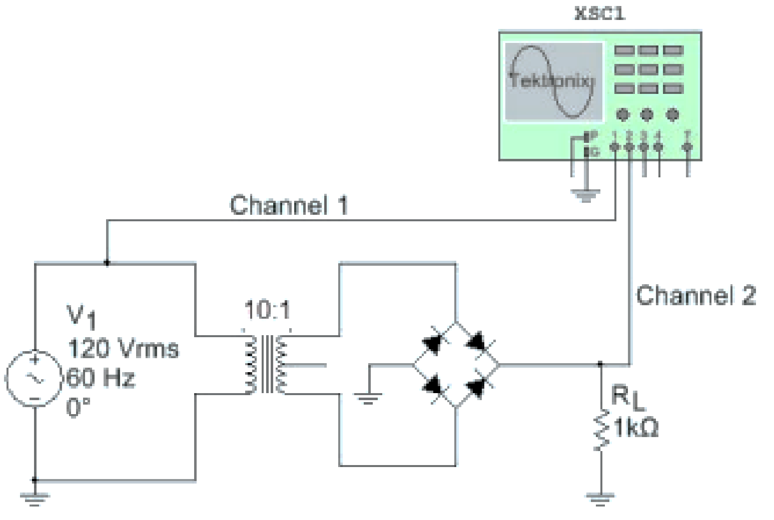


Figure 1.12

Solution Example 1.3 :

The peak primary voltage is:

$$V_{p(pri)} = \frac{Vrms}{0.707} = \frac{120}{0.707} = 170V$$

Because of the 10:1 step-down transformer, the peak secondary voltage is:

$$V_{p(sec)} = \frac{N_2}{N_1} \times V_{p(pri)} = \frac{1}{10} \times 170 = 17V$$

Solution Example 1.3 :

Because of the center tap, the input voltage for each half-wave rectifier is only half the secondary voltage:

$$V_{p(in)} = V_{p(sec)} = 17V$$

Ideally, the output voltage is:

$$V_{p(out)} = V_{p(in)} = 17V$$

Consider the voltage drop at diode:

$$V_{p(out)} = 17V - 1.4V = 15.6V$$

C) INTEGRATED CIRCUIT FULL-WAVE BRIDGE RECTIFIER

- The bridge rectifier is available in special packages (integrated circuit) containing the four diodes required.
- IC bridge rectifiers are rated by their maximum current and maximum reverse voltage.
- It has four leads or terminals: the two DC outputs are labelled + and , the two AC inputs are labelled.
- Figure 1.13 shows several examples of packaged bridge rectifiers.

Figure 1.13 : Bridge rectifiers packaging

- Typical integrated circuit bridge rectifier has four pin configuration as in Figure 1.14.

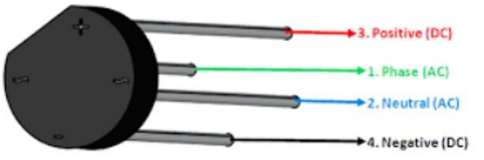


Figure 1.14 : IC Bridge rectifiers

Pin1 (Phase AC)	Pin 2 (Neutral AC)	Pin 3 (Positive DC)	Pin 4 (Negative DC)
Input pin where the phase wire of AC voltage supply is connected	Input pin where the neutral wire of the AC voltage supply is connected	Output pin from where the rectified DC signal is obtained	Output pin that sends out a ground voltage signal of a rectifier

1.4 FILTERS

- Pulsating direct current is not directly usable in most electronic circuits. Something closer to pure direct current is required. Batteries produce pure direct current. Battery operation is usually limited to low-power and portable types of equipment.
- Figure 1.15 (a) shows a battery connected to a load resistor. The voltage waveform across the load resistor is a straight line. There are no pulsations. Pulsating direct current is not pure because it contains an ac component.

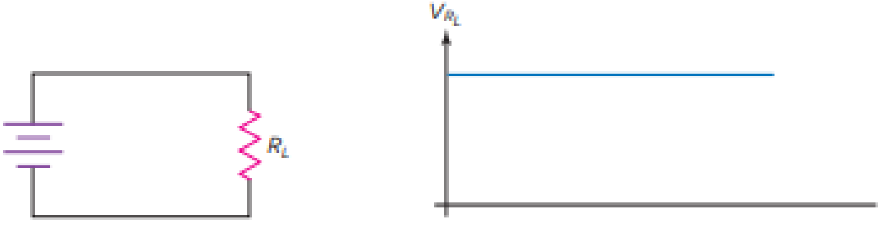


Figure 1.15 (a) : Pure direct current

Figure 1.15 (b) shows how both direct current and alternating current can appear across one load. An ac generator and a battery are series-connected. The voltage waveform across the load shows both ac and dc content. This situation is similar to the output of a rectifier. There is dc output because of the rectification, and there is also an ac component (the pulsations). The ac component in a dc power supply is called the ripple. Much of the ripple must be removed for most applications. The circuit used to remove the ripple is called a filter. Filters can produce a very smooth waveform that will approach the waveform produced by a battery.

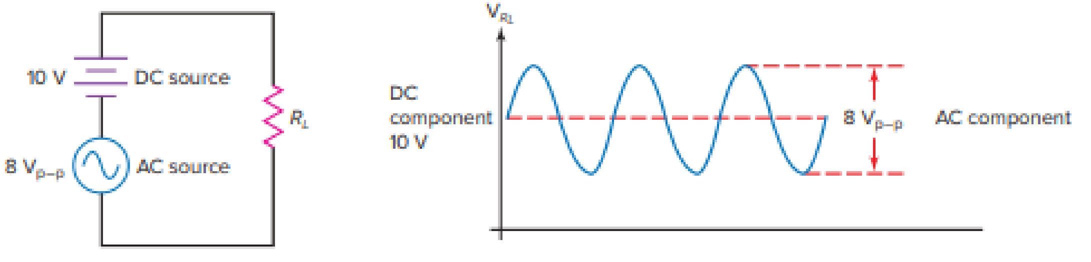


Figure 1.15 (b) : Alternating current with a dc component

- The most common technique used for filtering is a capacitor connected across the output. Figure 1.16 shows a simple capacitive filter that has been added to a full-wave rectifier circuit.
- The voltage waveform across the load resistor shows that the ripple has been greatly reduced by the addition of the capacitor.

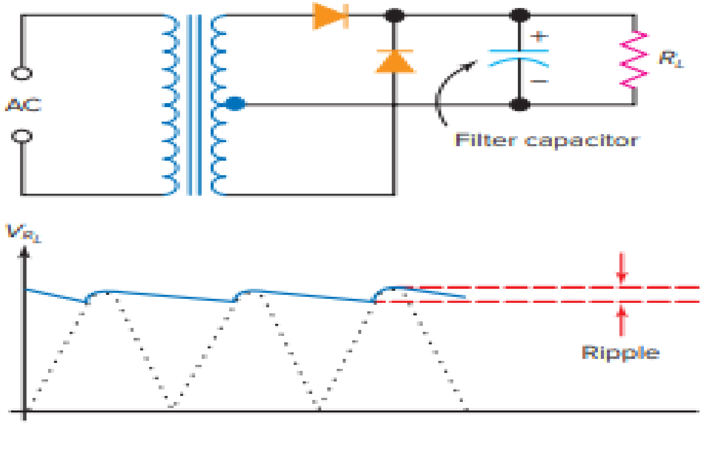


Figure 1.16 : Capacitor filter

Capacitors are energy storage devices. They can store a charge and then later deliver that charge to a load. In Figure 1.17(a) the rectifiers are producing peak output, load current is flowing, and the capacitor is charging.

Later, when the rectifier output drops off, the capacitor discharges and furnishes the load current Figure 1.17(b). Since the current through the load has been maintained, the voltage across the load will be maintained also. This is why the output voltage waveform shows less ripple.

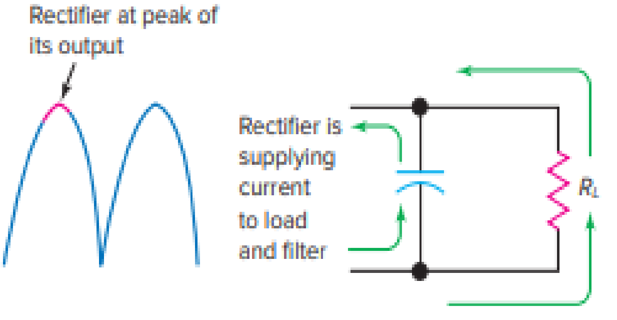


Figure 1.17 (a) : Rectifier output voltage

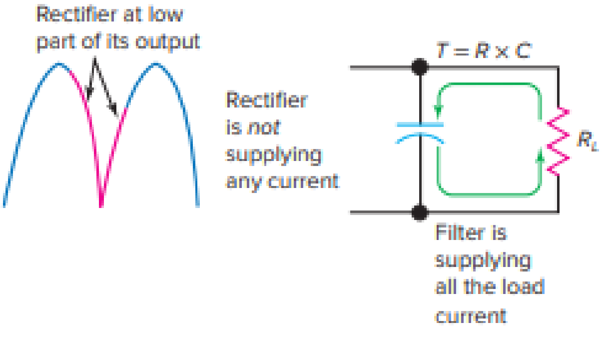


Figure 1.17 (b) : Filtered output voltage

The effectiveness of a capacitive filter is determined by three factors:

a) The size of the capacitor
b) The value of the load
c) The time between pulsations

These three factors are related by the formula :

$$\boxed{T = R \times C}$$

where T = time in seconds (s)
R = resistance in ohms (Ω)
C = capacitance in farads (F)

The product RC is called the time constant of the circuit. A charged capacitor will lose 63.2 percent of its voltage in T seconds. It takes approximately 5 × T seconds to completely discharge the capacitor.

To be effective, a filter capacitor should be only slightly discharged between peaks. This will mean a small voltage change across the load and, thus, little ripple. The time constant will have to be long when compared with the time between peaks. This makes it interesting to compare half-wave and full-wave filtering.

The time between peaks for full-wave and half wave rectifiers is shown in Figure 1.18. Obviously, in a half-wave circuit, the capacitor has twice the time to discharge, and the ripple will be greater. Full-wave rectifiers are desirable when most of the ripple must be removed. This is because it is easier to filter a wave whose peaks are closer together. Looking at it another way, it will take a capacitor twice the size to adequately filter a half-wave rectifier, if all other factors are equal.

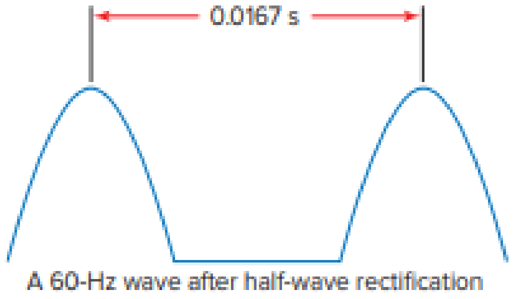


Figure 1.18 : Filter time constant

EXAMPLE 1.4

Estimate the relative effectiveness of 100-μF and 1,000-μF capacitors when they will be used to filter a 60-Hz half-wave rectifier loaded by 100 Ω.

Solution :

First, find both time constants:

$T = R \times C$

$T1 = 100\ \Omega \times 100\ \mu F = 0.01\ s$

$T2 = 100\ \Omega \times 1{,}000\ \mu F = 0.1\ s$

If we look at Figure 1.19. we see that the discharge time for 60-Hz half-wave circuits is in the vicinity of 0.01 s. This means that the smaller filter will discharge for about one time constant, losing about 60 percent, creating a significant amount of ripple. The larger capacitor has a 0.1-s time constant, which is long compared with the discharge time. The 1,000-μF capacitor will be a much more effective filter (a lot less ripple).

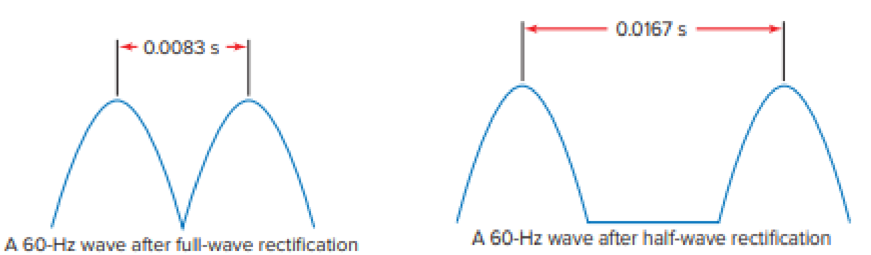


Figure 1.19

The choice of a filter capacitor can be based on the following equation:

$$\boxed{C=(1\ x\ T)/Vpp}$$

where C = the capacitance in farads (F)

I = the load current in amperes (A)

Vpp = the peak-to-peak ripple in volts (V)

T = the time in seconds (s)

EXAMPLE 1.6

By referring to Figure 1.19, choose a filter capacitor for a full-wave rectification, 60-Hz power supply when the load current is 5 A and the allowable ripple is 1 Vp-p

Solution :

The power supply operates at 60 Hz, but as Figure 1.19 shows, the ripple frequency is twice the input frequency for full-wave rectifiers:

Time constant :

$T=1/f$ = 1/2x60 = 8.33ms

Filter size :

C=(1 x T)/Vpp =(5 x 8.33 ms)/1=41.7mF=41,700µF

One way to get good filtering is to use a large filter capacitor. This means that it will take longer for the capacitor to discharge. If the load resistance is low, the capacitance will have to be very high to give good filtering. Inspect the time constant formula, and you will see that if R is made lower, then C must be made higher if T is to remain the same. So, with heavy current demand (a low value of R), the capacitor value must be quite high. Electrolytic capacitors are available with very high values of capacitance. However, a very high value in a capacitive-input filter can cause problems.

Figure 1.20 shows waveforms that might be found in a capacitively filtered power supply. The unfiltered waveform is shown in Figure 1.20 (a). In Figure 1.20 (b) the capacitor supplies energy between peaks. Note that the rectifiers do not conduct until their peak output exceeds the capacitive voltage. The rectifier turns off when the peak output ends. The rectifiers conduct for only a short time. Figure 1.20 (d) shows the rectifier current waveform. Notice the high peak-to-average ratio. In some power supplies, the peak-to-average current ratio in the rectifiers may exceed 100:1. This causes the rms rectifier current to be greater than eight times the current delivered to the load. The rms current determines the actual heating effect in the rectifiers. This is why diodes may be rated at 10A when the power supply is designed to deliver only 2A. The dc output voltage of a filtered power supply is higher than the output of a nonfiltered supply.

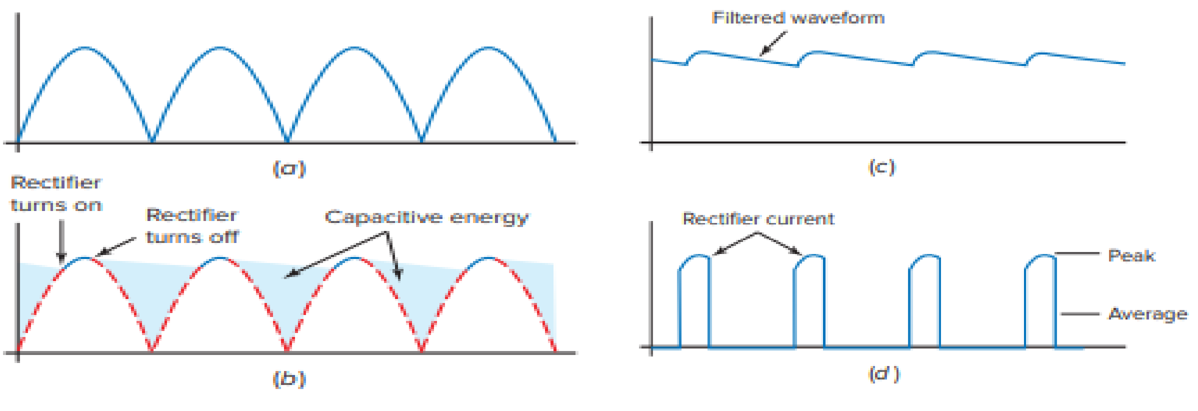


Figure 1.20 : Capacitive filter wavform

1.4.1 RIPPLE VOLTAGE

- Ripple voltage is the small variation in the dc voltage on the output of the filtered rectifier caused by the slight charging and discharging action of the filter capacitor as Figure 1.21 (a) and Figure 1.21 (b).
- The filtered output has dc value and some ac variation (ripple) after passing through filter circuit.
- Peak-to-peak value of ripple voltage can be measured using an oscilloscope.

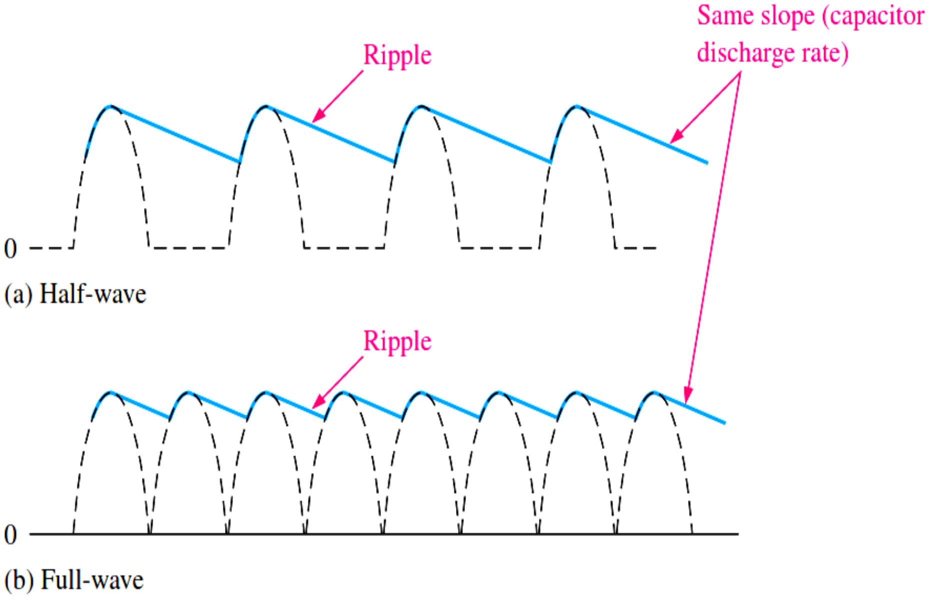


Figure 1.21 : Ripple voltage in filtered capacitor

- For filtered waveform in Figure 1.22, the ripple value can be calculated using formula :

$\boxed{\text{Vripple = Va - Vb}}$

Where,
Va – upper peak
Vb – lower peak

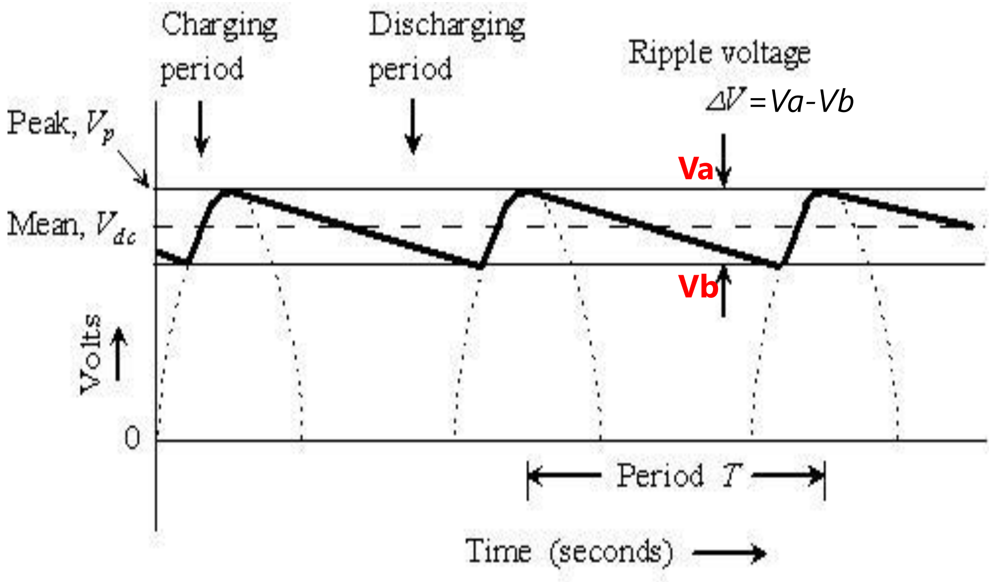


Figure 1.22 : Ripple value in filtered waveform

- Beside that, peak-to-peak ripple voltage can be estimated using formula :

$$\boxed{V_{\text{ripple}} = \frac{I}{fC}}$$

Where :

I - dc load current
f -ripple frequency
C -capacitance

A power-supply filter reduces ripple to a low level. The actual effectiveness of the filter can be checked with a measurement and then a simple calculation.

The formula for calculating the percentage of ripple is

$Ripple = (ac)/dc$ x 100% , where ac is the rms value.

For example, assume the ac ripple remaining after filtering is measured and found to be 1 V in a 20V dc power supply. The percentage of ripple is:

$Ripple = (ac)/dc$ x 100%

$Ripple = (1V)/20V$ x 100%

$Ripple = 5\%$

EXAMPLE 1.7

Find the percentage of ac ripple if the ac content is 0.5 V in a 20V supply.

$Ripple = (ac)/dc$ x 100%

$Ripple = (0.5V)/20V$ x 100%

$Ripple = 2.5\%$

Notice that the percentage is smaller when the ac content is less.

Ripple should be measured only when the supply is delivering its full rated output. At zero load current, even a poor filter will reduce the ripple to almost zero. Ripple can be measured with an oscilloscope or a voltmeter. The oscilloscope will easily give the peak-to-peak value of the ac ripple. Many meters will indicate the approximate value of the rms ripple content. It will not be exact since the ripple waveform is nonsinusoidal. In a capacitive filter, the ripple is similar to a sawtooth waveform. This causes an error with most meters since they are calibrated to indicate rms values for sine waves. There are meters that will read the true rms value of nonsinusoidal alternating current.

EXAMPLE 1.8

A half wave rectifier as shown in Figure 1.23 below produce a 34V dc load voltage. Calculate the ripple voltage.

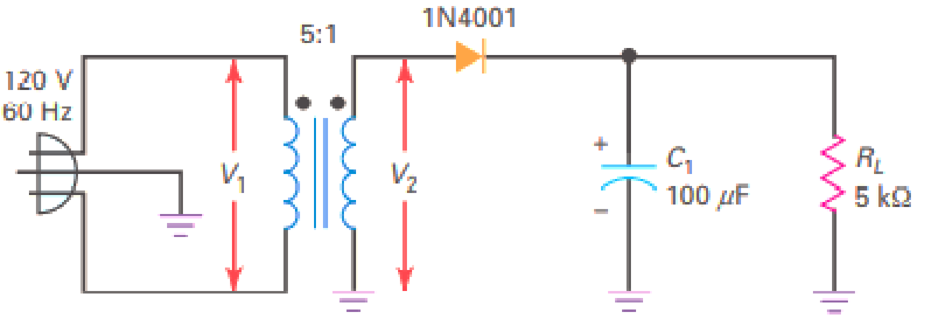


Figure 1.23

Solution :

To calculate the ripple, we first need to get the dc load current.

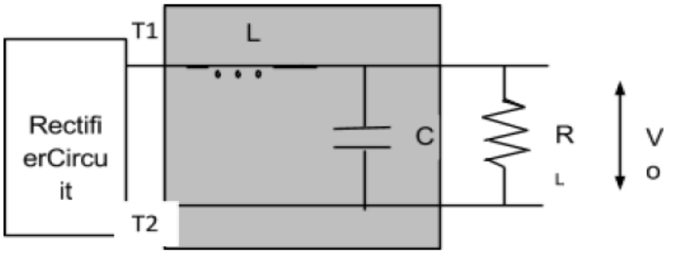
$$I_L = \frac{V_L}{R_L} = \frac{34V}{5k} = 6.8mA$$

Then, by using ripple voltage equation:

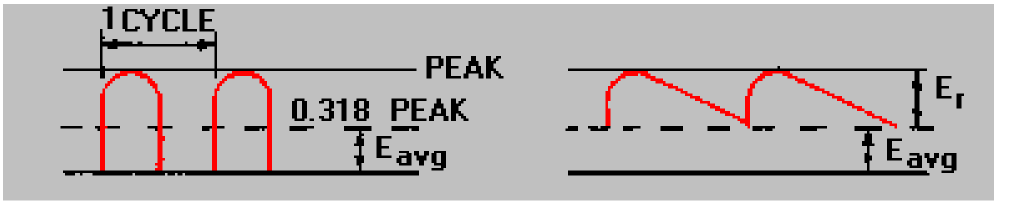
$$V_{ripple} = \frac{I}{fC} = \frac{6.8m}{(60)(100\mu)} = 1.13Vpp$$

1.4.2 LC FILTER

- The output of the full wave rectifier is applied across the terminals T1, T2, of the filter circuit as in Figure 1.24 (a).
- The rectifier output contains ac as well as dc component.
- The inductor L offers high resistance to the flow of ac component but allows the dc component to pass.
- As a result of which the ac component appears across the choke (inductor) while the entire dc component passes through it towards the load.
- At terminal T3, the rectifier output contains the dc component and the remaining part of ac component.
- The capacitor C offer low reactance and hence bypass the ac component but prevent the dc component to flow the through it.
- Therefore , only dc component reaches the load. In this way ac component has been filtered out by the choke input filter (LC filter) and only dc component is obtained across the load.



(a) LC filter circuit diagram



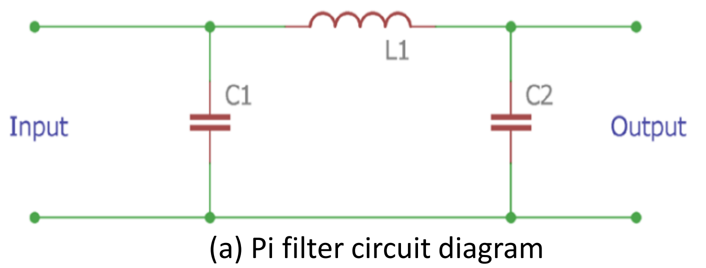
(b) Half wave rectifier waveform

(c) Waveform at C

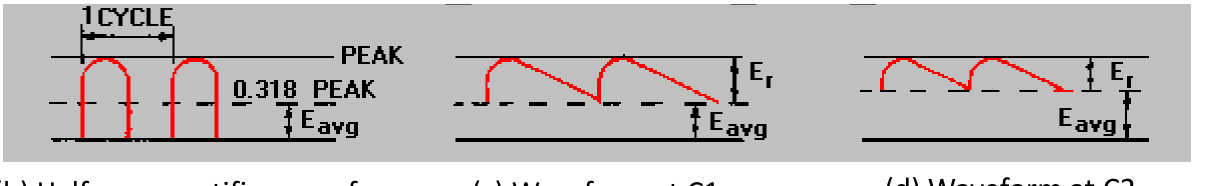
Figure 1.24 : LC filter

1.4.3 PI FILTER

- PI filter consists of a filter capacitor C1 connected across the rectifier output, a choke L in series and another filter capacitor C2 connected across the load as shown in Figure 1.25.
- The pulsating output from the rectifier is applied across the input terminals (i.e. terminals 1 and 2) of the filter.
- The filter capacitor C1 offers low reactance to a.c. component of rectifier output while it offers infinite reactance to the d.c. component. Therefore, capacitor C1 bypasses an appreciable amount of a.c. component while the d.c. component continues its journey to the choke L.
- The choke L offers high reactance to the a.c. component but it offers almost zero reactance to the d.c. component. Therefore, it allows the d.c. component to flow through it, while the unbypassed a.c. component is blocked.
- The filter capacitor C2 bypasses the a.c. component which the choke has failed to block. Therefore, only d.c. component appears across the load and that is what we desire



(a) Pi filter circuit diagram



(b) Half wave rectifier waveform (c) Waveform at C1 (d) Waveform at C2

Figure 1.25 : Pi filter

1.5 VOLTAGE REGULATOR

- The function of a voltage regulator is to:
  a) Stabilize the output voltage, Vo even though there is a variation of the input current or the output current
  b) Reduce the ripple at the output voltage of the filter circuit.

- Types of voltage regulator:
  a) Zener diode
  b) Serial transistor
  c) Integrated circuit (IC)

1.5.1 ZENER DIODE VOLTAGE REGULATOR

- The zener diode operates in the breakdown region and holds the load voltage constant. Even if the source voltage changes or the load resistance varies, the load voltage will remain fixed and equal to the zener voltage.
- To get breakdown operation, the source voltage VS must be greater than the zener breakdown voltage VZ.
- A series resistor RS is always used to limit the zener current to less than its maximum current rating. Otherwise, the zener diode will burn out, like any device with too much power dissipation.
- Figure 1.26 shows a zener diode voltage regulator connection in dc power supply circuit.

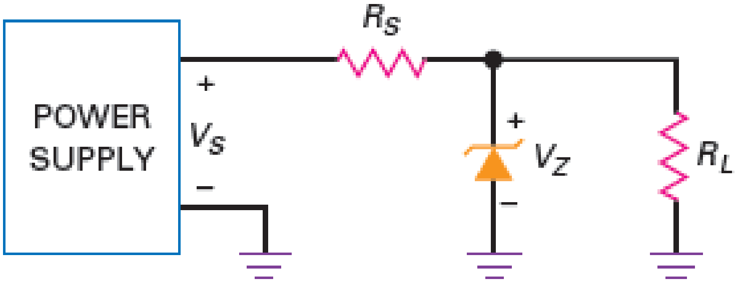


Figure 1.26 : Zener regulator

1.5.2 SERIAL TRANSISTOR VOLTAGE REGULATOR

- A series regulator comprises of a transistor and a zener diode as in Figure 1.27. Serial regulator has high efficiency .
- If the line voltage or load current changes, the zener voltage and base-emitter voltage will change only slightly.
- When the load current changes in a series regulator, the input current changes by the same amount.

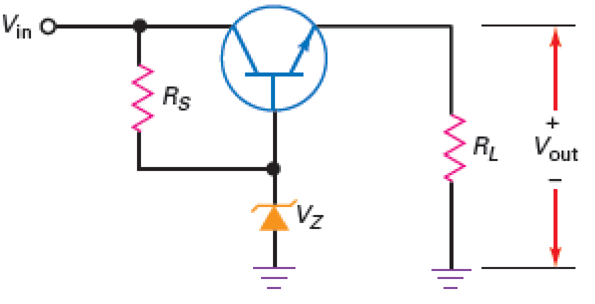


Figure 1.27 : Serial transistor regulator

1.5.3 INTEGRATED CIRCUIT VOLTAGE REGULATOR

- Integrated circuit (IC) voltage regulator can has either fixed positive, fixed negative or adjustable output voltage.
- Voltage regulator has 3 terminal which are input, ground and output as shows in Figure 1.28.
- The serial LM 78XX (where XX= 5,06,08,10,12,15,18 or 24).
- LM78XX will produce positive voltage.
- LM79XX will produce negative voltage.
- IC LM 7805 will produce the output voltage +5V .
- LM 7915 will produce the -15V output voltage.

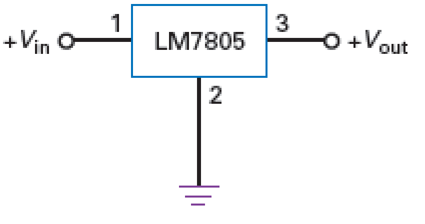
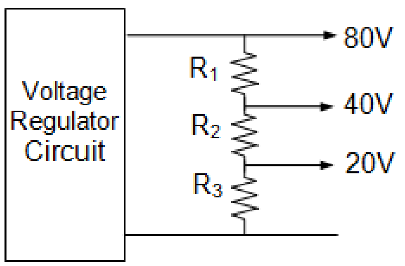


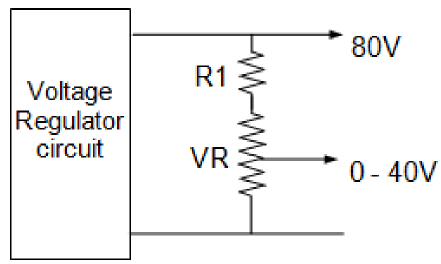
Figure 1.28 : IC voltage regulator

1.8 VOLTAGE DIVIDER

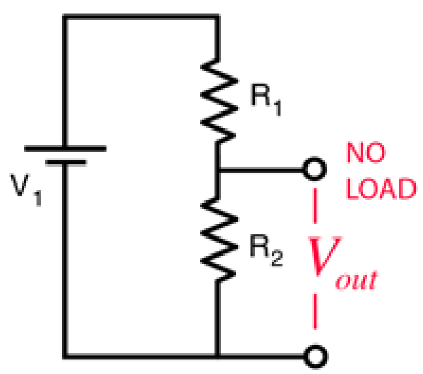
- Voltage divider is commonly used in a complicated electronic devices system that contains several circuit with different voltage level.
- There are constant voltage divider and variable voltage divider as shown in Figure 1.29 (a) and 1.29 (b). Constant voltage divider provide a fixed output voltage while variable voltage divider offer a certain range of output voltage.



(a) Constant voltage divider



(b) Variable voltage divider



(c) Loaded voltage divider

Figure 1.29 : Voltage divider

- Referring to Figure 1.29 (c), formula for output voltage, Vout is:

$$\boxed{V_{out} = V_1 \frac{IR_2}{I(R_1 + R_2)} = \frac{V_1 R_2}{(R_1 + R_2)}}$$

1.7 POWER SUPPLY SCHEMATIC DIAGRAM

- A complete dc power supply consist of stages in the dc power supply block diagram. Figure 1.30 shows a basic circuit of a linear dc power supply consists of transformer, half-wave rectifier circuit, pi-filter, zener diode voltage regulator. This configuration can vary depending on the selection of element in each stages.

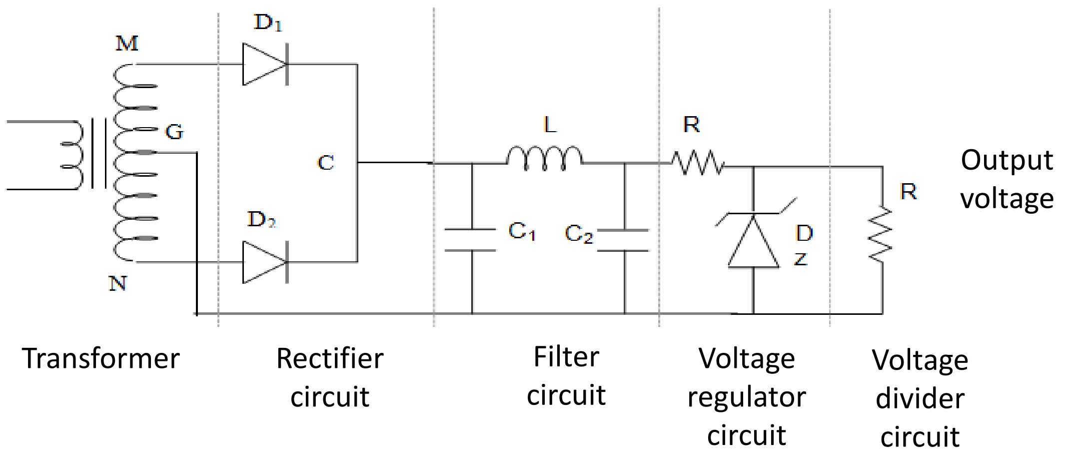


Figure 1.30 : Basic circuit of a linear dc power supply

Self test chapter 1

1. Power supplies will usually change alternating current to ……………..
2. A transformer secondary is center-tapped. If 50 V is developed across the entire secondary, the voltage from either end to the center tap will be ………………
3. A half-wave rectifier uses………………… diode(s).
4. A full-wave rectifier using a center-tapped transformer requires………………… diodes.
5. Each cycle of the ac input has two ……………..
6. In rectifier circuits, the load current never changes………………….. .
7. A bridge rectifier eliminates the need for a …………………..
8. A bridge rectifier requires……………………. diodes.
9. A transformer has five times as many primary turns as secondary turn. If 120 V ac is across the primary, the secondary voltage should be………………….. .
10. Suppose the transformer in Question 9 is center-tapped and connected to a full-wave rectifier. The average dc voltage across the load should be ……………………..
11. The average dc load voltage for the data in Question 10 will change to …………… if one of the rectifiers burns out (opens).
12. The ac input to a half-wave rectifier is 32 V. A dc voltmeter connected across the load should read……………… .
13. The ac input to a bridge rectifier is 20 V. A dc voltmeter connected across the load should read……………… .
14. In rectifier circuits, one can expect the output voltage to drop as load current…………….. .
15. Rectifier loss is more significant in……………. voltage rectifier circuits.
16. If each diode in a high-current bridge rectifier drops 1 V, then the total rectifier loss is……………. .
17. Pure dc contains no ……….

Self test chapter 1 (cont.)

18. Rectifiers provide ………… dc.
19. Power supplies use filters to reduce …….
20. Capacitors are useful in filter circuits because they store electric ………..
21. In a power supply with a capacitor filter, the effectiveness of the filter is determined by the size of a capacitor, the ac frequency, and the ……….
22. Half-wave rectifiers are more difficult to filter because the filter has more time to……….. .
23. Heating effect is determined by the ………..value of a current.
24. In a filtered power supply, the dc output voltage can be as high as ……….. times the rms input voltage.
25. The conversion factor that is useful when predicting the dc output voltage of a filtered supply is……. .
26. The conversion factors of 0.45 and 0.90 are useful for predicting the dc output of ……… supplies.
27. A filter capacitor's voltage rating must be greater than the ………..value of the pulsating waveform.
28. The dc output from a lightly loaded supply using a bridge rectifier with 15 V ac input and a filter capacitor at the output will be ……….. .
29. As the load current increases, the ac ripple tends to……….. .
30. As the load current increases, the dc output voltage tends to ……….
31. A power supply develops 13 V dc with 1-V ac ripple. Its percentage of ripple is …………..
32. A power supply develops 28 V under no-load conditions and drops to 24 V when loaded. Its percentage of regulation is…………………… .
33. A zener shunt regulator can provide voltage regulation and reduce…………………….. .

2

OSCILLATORS

2.1 INTRODUCTION

- An oscillator is a circuit that produces a repetitive signal (AC) from a DC voltage as in Figure 2.1.
- Oscillators can be designed to produce many kinds of waveforms such as sine, rectangular, triangular, or sawtooth.
- An electronic oscillator is a circuit which converts DC energy into AC at a very high frequency from less than 1 Hz to well over 10GHz .
- Depending on the waveform and frequency requirements, oscillators are designed in different ways.
- These signals serve a variety of purposes such as communications systems, digital systems including computers, and test equipment.

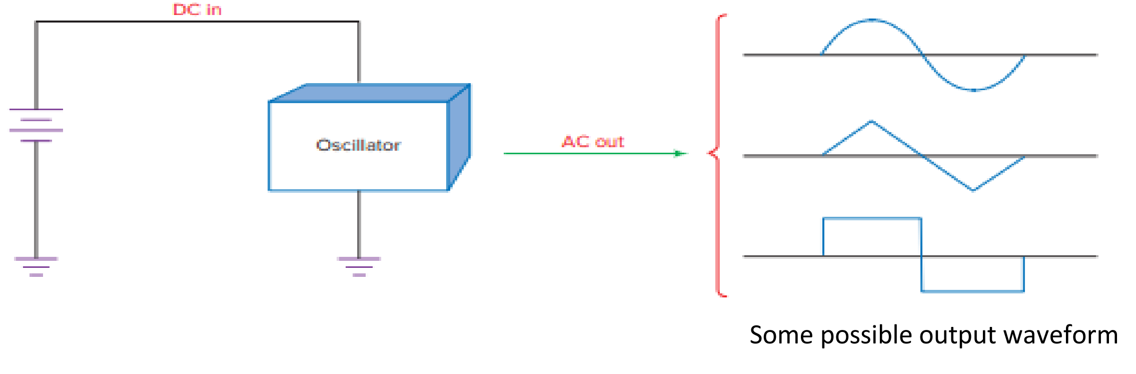


Figure 2.1 : Oscillators convert direct current to alternating current

2.2 OSCILLATOR APPLICATIONS

- Many digital devices such as computers, calculators, and watches use oscillators to generate rectangular waveforms that time and coordinate the various logic circuits.
- Signal generators use oscillators to produce the frequencies and waveforms required for testing, calibrating, or troubleshooting other electronic systems.
- Touch-tone telephones, musical instruments, and remote control transmitters can use oscillators to produce the various frequencies needed.
- Radio and television transmitters use oscillators to develop the basic signals sent to the receivers.
- Variable-frequency oscillators (VFOs)
- Voltage-controlled oscillators (VCOs)

2.3 BLOCK DIAGRAM OF AN OSCILLATOR

- In an oscillator circuit, an amplifier with positive feedback is used in place of the input signal as in Figure 2.2.
- If the feedback signal is large enough and has the correct phase, there will be an output signal even though there is no external input signal.
- The overall circuit gain is given by:

$$\boxed{A_f = \frac{A_V}{1 - A_V \beta}}$$

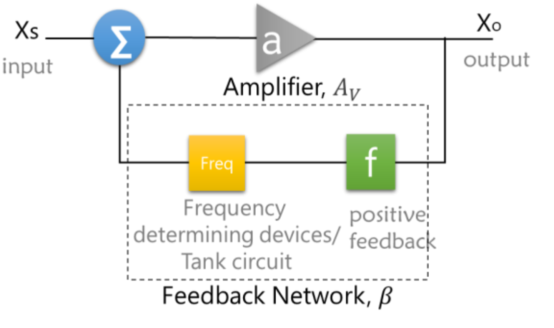


Figure 2.2 : Block diagram of an oscillator

2.4 REQUIREMENT OF AN OSCILLATOR CIRCUIT

- In order to oscillate a circuit, the voltage gain around the loop must be unity.

$\boxed{|A_V\beta|=1}$ A_V – gain of amplifier
β- gain of feedback network

- The phase shift around the positive feedback loop must be 0^o.
- The feedback oscillator relies on a positive feedback of the output to maintain the oscillations.
- The relaxation oscillator makes use of an RC timing circuit to generate a non-sinusoidal signal such as square wave.

2.4.1 FEEDBACK OSCILLATOR PRINCIPLES

- Referring to Figure 2.3, when switch at the amplifier input is open, no oscillation occurs.
- Consider Vi,, results in Vo=AVi (after amplifier stage) and Vf = β(AVi) (after feedback stage)
- Feedback voltage Vf = β(AVi) where βA is called the loop gain.
- In order to maintain Vf = Vi , βA must be in the correct magnitude and phase.
- When the switch is closed and Vi is removed, the circuit will continue operating since the feedback voltage is sufficient to drive the amplifier and feedback circuit, resulting in proper input voltage to sustain the loop operation.

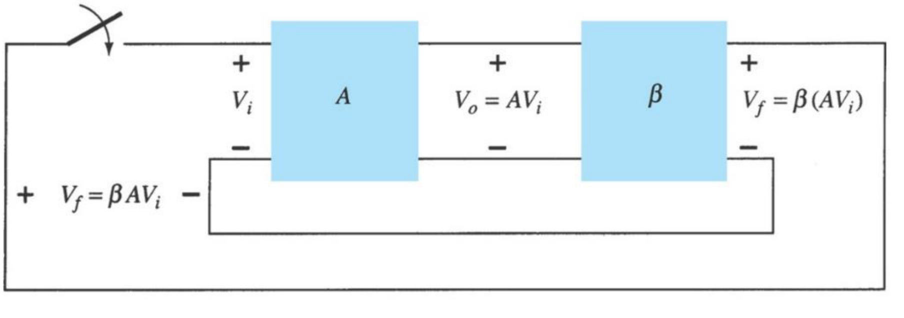


Figure 2.3 : Positive feedback circuit used as an oscillator

- An oscillator is an amplifier with positive feedback can be illustrated as in Figure 2.4.
- From the figure, we can derive the closed loop voltage gain, Af.

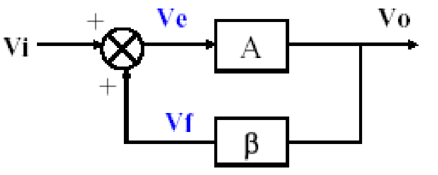


Figure 2.4 : Oscillator with positive feedback network

$V_e = V_i + V_f$ ....(1)

$V_o = AV_e$ ....(2)

$V_f = \beta(AV_e) = \beta V_o$ ....(3)

From (1), (2) and (3), we get $\boxed{A_f = \frac{V_O}{V_S} = \frac{A}{(1 - A\beta)}}$

In general ***A*** and ***β*** are functions of frequency and thus may be written as;

$$\boxed{A_f(s) = \frac{V_o}{V_s}(s) = \frac{A(s)}{1 - A(s)\beta(s)}}$$

$A(s)\beta(s)$ is known as **loop gain**

Writing $T(s) = A(s)\beta(s)$ the loop gain becomes;

$$A_f(s) = \frac{A(s)}{1 - T(s)}$$

Replacing *s* with *jω*;

$$A_f(j\omega) = \frac{A(j\omega)}{1 - T(j\omega)}$$

and $$T(j\omega) = A(j\omega)\beta(j\omega)$$

At a specific frequency ***f₀***;

$$T(j\omega_0) = A(j\omega_0)\beta(j\omega_0) = 1$$

At this frequency, the closed loop gain;

$$A_f(j\omega_0) = \frac{A(j\omega_0)}{1 - A(j\omega_0)\beta(j\omega_0)} = \frac{A(j\omega_0)}{(1-1)} = \infty$$

will be infinite, i.e. the circuit will have finite output for zero input signal – thus we have oscillation

2.5 FACTORS THAT DETERMINE THE FREQUENCY OF OSCILLATION

- Oscillators can be classified into many types depending on the feedback components, amplifiers and circuit topologies used.
- RC components generate a sinusoidal waveform at a few Hz to kHz range.
- LC components generate a sine wave at frequencies of 100 kHz to 100 MHz .
- Crystals generate a square or sine wave over a wide range, i.e. about 10 kHz to 30 MHz .

2.6 TYPES OF OSCILLATOR

- Sinusoidal oscillator can be divided into two categories : RC feedback oscillator and LC feedback oscillator.
- The classification of the oscillator is as shown in Figure 2.5.

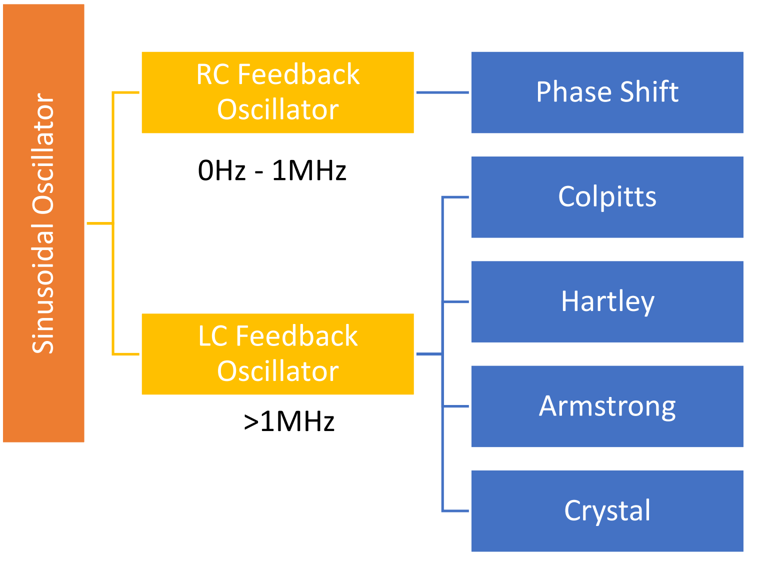
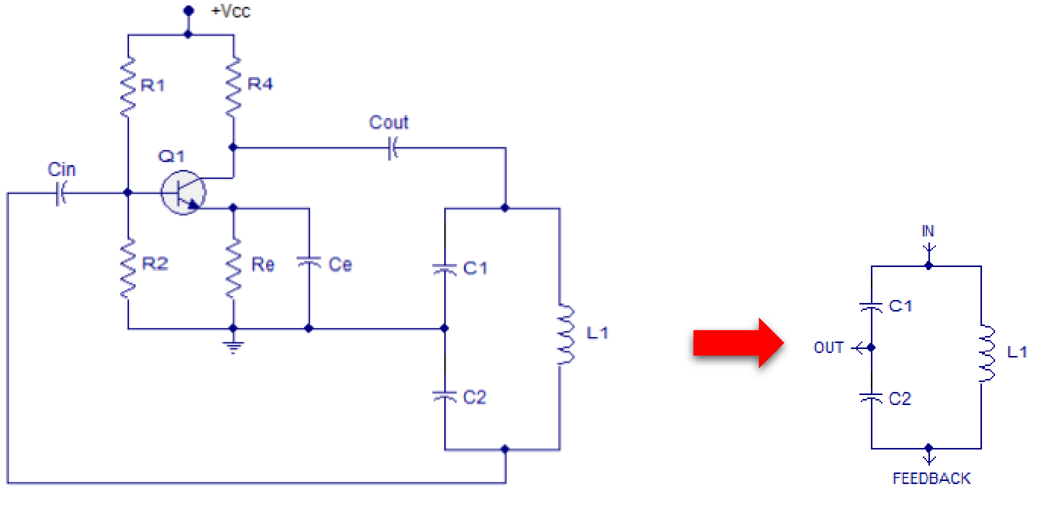


Figure 2.5 : Oscillator classification

2.6.1 COLPITTS OSCILLATOR

- In a Colpitts oscillator, two capacitors are connected in parallel to an inductor in the tank circuit as shown in Figure 2.6.
- When the circuit is turned on, C1 and C2 are charged.
- The capacitor discharge through L, setting up of the frequency determined by formula.
- The output voltage of the amplifiers appears across C1
- The feedback voltage is developed across C2. The voltage across it is 180° out of phase with the voltage developed across C1 (Vout).
- A phase shift of 180° is produced by the amplifier (transistor). Hence a proper positive fedback is obtained and produced continuous undamped oscillations.



(a) Colpitts Oscillator circuit diagram

(b) Tank circuit in Colpitts Oscillator

Figure 2.6 : Colpitts oscillator

Oscillator will oscillate at certain frequency. It is called frequency of oscillation, f_r. Colpitts oscillation frequency formula is :

$$f_r = \frac{1}{2\pi\sqrt{C_{eq}L}}$$

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

EXAMPLE 2.1

Calculate the operating oscillator frequency for Colpitts Oscillator. Given C1=0.003µF, C2=0.003 µF, and L1=50mH.

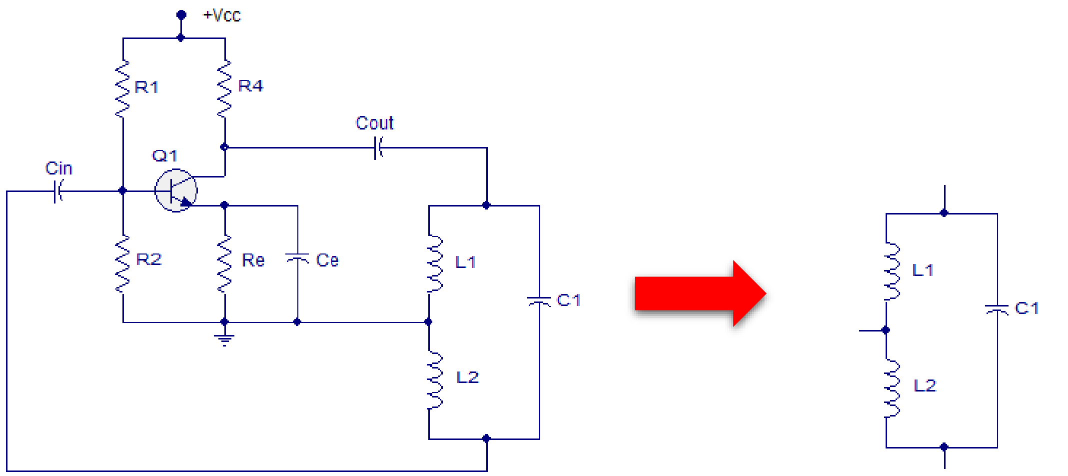
Solution :

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2} = \frac{(0.003\mu)(0.003\mu)}{0.003\mu + 0.003\mu} = 1.5nF$$

$$f_r = \frac{1}{2\pi\sqrt{C_{eq} L}} = \frac{1}{2\pi\sqrt{(1.5n)\,(50m)}} = 18.378\text{kHz}$$

2.6.2 HARTLEY OSCILLATOR

- In a Colpitts oscillator, two inductors are connected in parallel to an capacitor in the tank circuit as shown in Figure 2.7.
- When the circuit is turned on, the capacitor is charged.
- When this capacitor is fully charged, its discharges through coil L1 and L2 setting up oscillations.
- The output voltage of the amplifier appears across L1.
- The feedback voltage is developed across L2. The voltage across it is 180o out of phase with the voltage developed across L1 (Vout).
- A phase shift of 180o is produced by the amplifier (transistor). In this way, feedback is properly phased to produce continuous undamped oscillations.



(a) Hartley Oscillator circuit diagram

(b) Tank circuit in Hartley Oscillator

Figure 2.7 : Hartley oscillator

Hartley oscillation frequency f_r can be calculated using formula :

$$\boxed{\begin{gathered} f_r = \frac{1}{2\pi\sqrt{L_{eq}C}} \\ L_{eq} = L_1 + L_2 \end{gathered}}$$

EXAMPLE 2.2

Given the inductance values of a Hartley oscillator are L1=22µH and L2=70µH and the capacitor has a value of 20pF. Calculate the operating oscillator frequency.

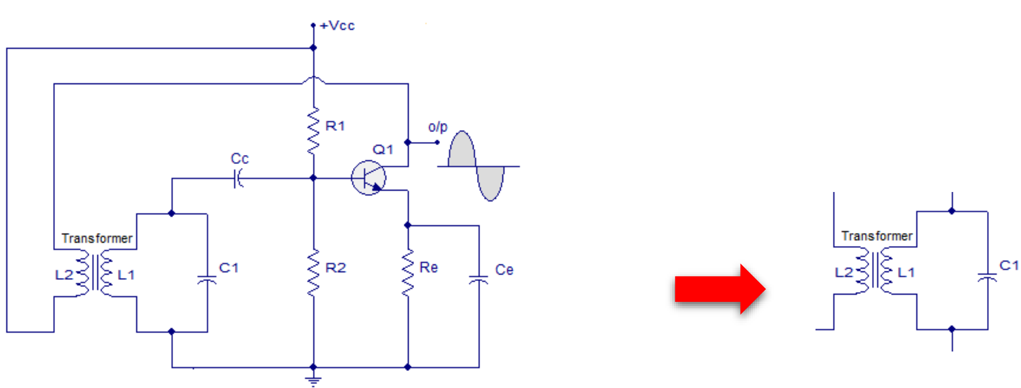
Solution :

$$L_{eq} = L_1 + L_2 = 22\mu + 70\mu = 92\mu H$$

$$f_r = \frac{1}{2\pi\sqrt{L_{eq}C}} = \frac{1}{2\pi\sqrt{(92\mu)(20p)}} = 3.710MHz$$

2.6.3 ARMSTRONG OSCILLATOR

- Armstrong oscillator is different from previous oscillator where it use transformer in the tank circuit as shown in Figure 2.8.
- When power supply is applied, the transistor Q1 starts conducting and its collector current starts to rise. From the circuit diagram, you can see that this collector current actually flows through secondary coil L2. This rise in current through the secondary induces some voltage across the primary coil L1 by virtue of mutual induction.
- The secondary coil L2 is also called "Tickler Coil". The induced voltage across L1 charges the capacitor C1 to the maximum. Now the energy stored in the coil L1 as electromagnetic field is transferred into the capacitor as electrostatic field. Now the capacitor starts discharging through L1 and the current through L1 starts increasing.
- When the capacitor is fully discharged, there will be no more EMF left across the capacitor to maintain the current through L1 and so the magnetic flux around the coil tends to collapse. The coil L1 produces a back EMF by virtue of self induction. This back EMF charges the capacitor C1 again.
- Then the capacitor discharges through L1 and the cycle is repeated. The repetitive charging and discharging cycles result in a series of oscillations in the tank circuit.



(a) Armstrong Oscillator circuit diagram

(b) Tank circuit in Armstrong Oscillator

Figure 2.8 : Armstrong oscillator

Armstrong oscillation frequency f_r can be calculated using formula :

$$\boxed{f_r = \frac{1}{2\pi\sqrt{L_{pri}C_1}}}$$

EXAMPLE 2.3

Determine the resonant frequency of an Armstrong oscillator circuit if the turns ratio of the transformer is 20 : 1 and the capacitor used in the tank circuit is 50µH.

Solution :

$$f_r = \frac{1}{2\pi\sqrt{L_{pri}C_1}} = \frac{1}{2\pi\sqrt{(20)(50\mu)}} = 5.033 \text{ Hz}$$

2.6.4 CRYSTAL OSCILLATOR

The crystal-controlled oscillator is the most stable and accurate of all oscillators. A crystal has a natural frequency of resonance. Quartz material can be cut or shaped to have a certain frequency. We can better understand the use of a crystal in the operation of an oscillator by viewing its electrical equivalent. The crystal oscillator is shown in Figure 2.9.

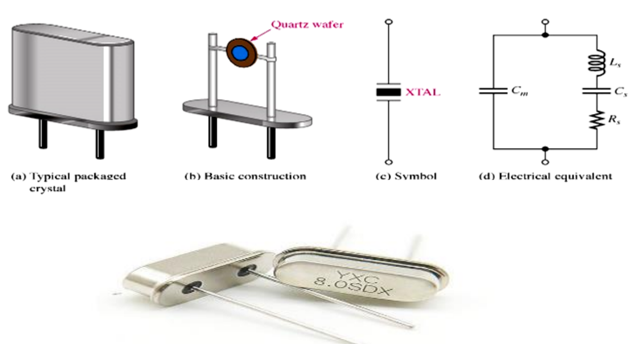


Figure 2.9 : Crystal oscillator

- When frequency accuracy is important, the quartz crystal as in Figure 2.10 is used to replace LC tanks in an oscillator circuit.
- The fundamental frequency (series resonance) is controlled by the quartz slab or quartz disk thickness.
- Higher multiples of the fundamental are called overtones.
- The electrode capacitance creates a parallel resonant frequency which is slightly higher.
- Typical frequency accuracy is measured in parts per million (ppm).

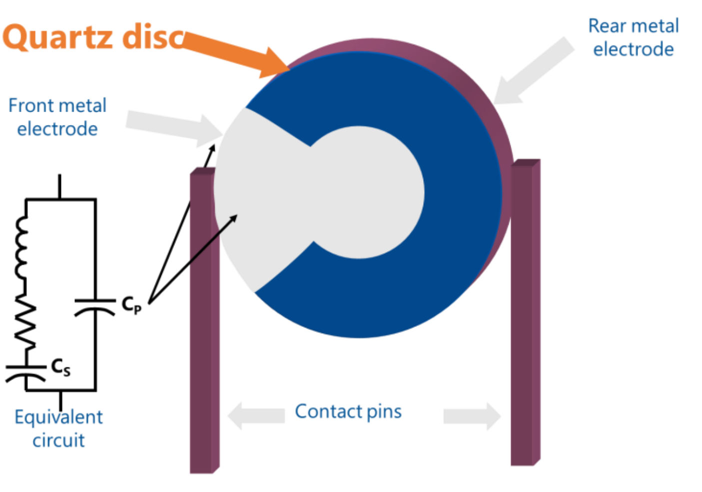


Figure 2.10 : Quartz crystal

- When a small voltage is applied to a small thin piece of quartz, it begins to change shape producing a characteristic known as the piezoelectric effect.
- The piezoelectric effect produces mechanical vibrations or oscillations which are used to replace the LC tank circuit in previous oscillators.

- Crystal oscillator can operate in either series or parallel resonance.
- At series resonant frequency, the inductive reactance is cancelled by the reactance of Cs. The remaining series resistor, Rs determines the impedance of the crystal.
- Parallel resonance occurs when the inductive reactance and reactance of parallel capacitance, Cm are equal. The parallel resonant frequency is usually 1KHz higher than the series resonant frequency

Series resonance formula :

$$\boxed{\mathrm{f}_{series} = \frac{1}{2\pi\sqrt{\mathrm{L_s}\mathrm{C}_s}}}$$

Parallel resonance formula :

$$\boxed{\mathrm{f}_{parallel} = \frac{1}{2\pi\sqrt{\mathrm{L_s}C}}} \qquad where, C = \frac{\mathrm{C}_P\mathrm{C}_s}{\mathrm{C}_P + \mathrm{C}_s}$$

EXAMPLE 2.4

A quartz crystal has the following values: Rs = 6.4Ω, Cs = 0.09972pF and Ls = 2.546mH. If the capacitance across its terminal, Cp is measured at 28.68pF, Calculate the series oscillating frequency of the crystal and its parallel resonance frequency.

Solution :

For series resonance :

$$\mathrm{f}_{series} = \frac{1}{2\pi\sqrt{\mathrm{L_s}\mathrm{C}_s}} = \frac{1}{2\pi\sqrt{(2.546m)(0.09972p)}} = 9.988MHz$$

For parallel resonance :

$$C = \frac{C_P C_S}{C_P + C_S} = \frac{(2.546m)(0.09972p)}{2.546m + 0.09972p} = 0.0997pF$$

$$f_{parallel} = \frac{1}{2\pi\sqrt{L_S C}} = \frac{1}{2\pi\sqrt{(2.546m)(0.0997p)}} = 9.989MHz$$

2.6.5 PHASE SHIFT OSCILLATOR

- Phase shift employ resistor and capacitor as the frequency determining device. Each of three RC circuits in the feedback loop will provide a phase shift as in Figure 2.11.
- Oscillation occurs at the frequency where the total phase shift through the three RC circuits is 180°.
- The amplifier has an additional 180° of phase shift because the signal drives the inverting input. As a result, the phase shift around the loop will be 360°, equivalent to 0°.
- If AvB is greater than 1 at this particular frequency, oscillations can start

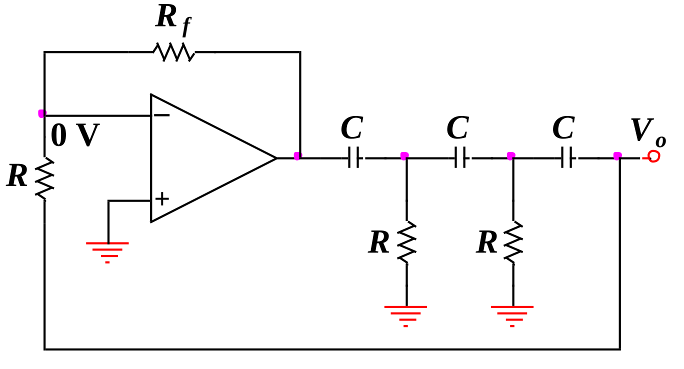


Figure 2.11 : Phase shift oscillator

- Phase shift employ resistor and capacitor as the frequency determining device. Each of three RC circuits in the feedback loop will provide a phase shift as in Figure 2.11.
- Oscillation occurs at the frequency where the total phase shift through the three RC circuits is 180^o.
- The amplifier has an additional 180° of phase shift because the signal drives the inverting input. As a result, the phase shift around the loop will be 360°, equivalent to 0°.
- If AvB is greater than 1 at this particular frequency, oscillations can start.
- The frequency for this type is similar to any RC circuit oscillator :

$$\boxed{f_r = \frac{1}{2\pi RC\sqrt{2N}}} \Rightarrow \boxed{f_r = \frac{1}{2\pi RC\sqrt{6}}}$$

Where,

β = 1/29 and the phase-shift is 180^o

N-the number of RC stages

- For the loop gain βA to be greater than unity, the gain of the amplifier stage must be greater than 29.
- If we measure the phase-shift per RC section, each section would not provide the same phase shift (although the overall phase shift is 180^o).
- In order to obtain exactly 60^o phase shift for each of three stages, emitter follower stages would be needed for each RC section.

$$\boxed{\text{The gain must be at least 29 to maintain the oscillation}}$$

EXAMPLE 2.5

Determine the frequency of the oscillation of a three-stage RC phase shift oscillator with resistor of 10kΩ and capacitors of 500pF.

Solution :

$N = 3,$

$$f_r = \frac{1}{2\pi RC\sqrt{2N}} = \frac{1}{2\pi(10K)(500p)\sqrt{2(3)}} = 12.994kHz$$

2.7 PERFORMANCE COMPARISON OF EACH OSCILLATOR

Oscillator	Output	Performance
Colpitt's	sine-wave output of constant amplitude and fairly constant frequency within the RF range	• has good frequency stability, is easy to tune, and can be used over a wide range of frequencies
Hartley	Sine wave output with constant amplitude and fairly constant frequency	• can be unstable in frequency due to inter-junction capacitance.
Armstrong	Sine wave output with constant amplitude and fairly constant frequency	• uses transformer coupling in the feedback loop. For this reason the Armstrong is not as popular. • can be unstable in frequency due to inter-junction capacitance.
Crystal	Sine wave output with constant amplitude and fairly constant frequency	• use a specially cut crystal to control the frequency. The crystal can act as either a capacitor or inductor, a series-tuned circuit, or a parallel-tuned circuit.
Phase Shift	Sine wave output of relatively constant amplitude and frequency.	• It uses RC networks to produce feedback and eliminate the need for inductors in the resonant circuit.

Self test chapter 2

1. Oscillators convert ………………… current to …………………… current.
2. Most oscillators are based on amplifiers with…………………feedback.
3. The oscillator is characterized by split capacitor in its tak circuit is…………………….
4. A Hartley Oscillator commonly used in…………………….
5. A/An ……………Oscillator uses a tapped inductor in the tank circuit.
6. The oscillator that gives good frequency stability and accurancy is…………………
7. If L1 = 1mH, L2 = 2mH and C = 0.1nF in Hartley oscillator, then f=………………..KHz.
8. RC Phase Shift Oscillator are commonly used circuits for generating ……………..waveform of a required frequency.
9. A Crystal Oscillator generates electrical oscillation of constant frequency based on the …………….effect.
10. Phase Shift Oscillator use the three RC networks, each giving a …………….phase angle.
11. A Hartley Oscillator circuit having two inductors of L1=0.5mH and L2=0.5mH which are connected in parallel with a capacitor. Given that the frequency of oscillations of the circuit is 503kHz. Calculate the value of capacitor used in the tank circuit.
12. Calculate the value of inductor in tank circuit of a Colpitts oscillator if oscillation frequency, fc is 1.592kHz and C1=C2=0.4μF.
13. Sketch the electrical equivalent of a Crystal Oscillator. Then, calculate the series and parallel resonant frequency of the crystal. Given the value of L=1H, CS=0.001pF, R=1kΩ and CP=20pF.
14. An oscillator has 3 stages with the same value of resistor and capacitor at each stage to provide a phase shift to the oscillation signal. Given the frequency of oscillation fr= 13kHz and C=1nF respectively. Calculate the value of the resistor. Then, draw the oscillator circuit completely.

3

OPERATIONAL AMPLIFIER

3.1 INTRODUCTION

- Integrated circuit amplifier with very high gain.
- It consists combination of many components such as transistor, resistor in a silicone chip.
- With a certain feedback, the op-amp can be used to do multiplication, summation, subtraction, differentiation, integration and etc.
- An ideal amplifier has infinite Gain and Bandwidth when used in the Open-loop mode with typical d.c. gains of 100,000, or 100 dB.
- The basic operational amplifier (op-amp) construction is of a 3-terminal device, 2-inputs and 1-output.
- An operational amplifier also has zero output impedance, (Z = 0).
- Op-amps sense the difference between the voltage signals applied to their two input terminals and then multiply it by some pre-determined Gain, (A).
- This Gain, (A) is often referred to as the amplifiers "Open-loop Gain".
- It operates from either a dual positive (+V) and an corresponding negative (-V) supply, or they can operate from a single DC supply voltage.
- Its applications has become so widely diversified.
- Op Amps are now used as a basic building block for;
    - ✓ phase shifting,
    - ✓ filtering,
    - ✓ signal conditioning,
    - ✓ multiplexing, detecting, etc.

The two main laws associated with the op- amp are that it has an infinite input impedance, (Z_{in} =∞) resulting in "**No current flowing into either of its two inputs**" and zero input offset voltage "$\mathbf{V_1 = V_2}$".

3.1.1 OPERATIONAL AMPLIFIER DESIGN

- IC XX741 is the identity of operational amplifier. It has 8 pins with two inputs and one output as in Figure 3.1.

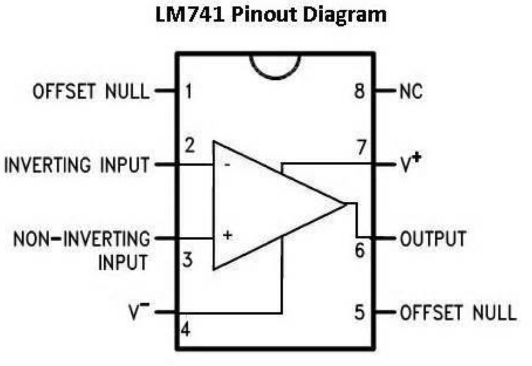


Figure 3.1 (a) : 741 Dual-In-Line pinouts

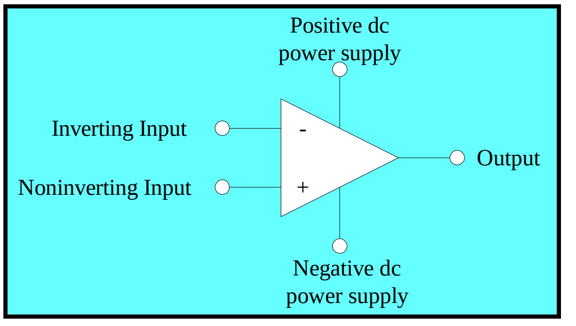


Figure 3.1 (b) :Op-Amp Symbol

- Inverting input – Produces 180˚ out of phase (opposite polarity) signal at the output.
- Non inverting input – ac signal or dc voltage applied to this terminal produces as in phase (same polarity) signal at the output

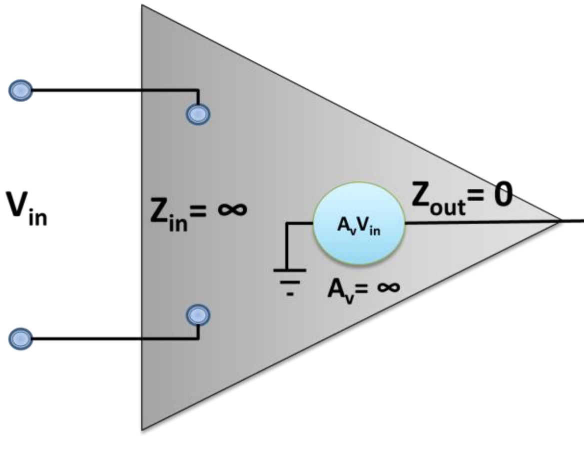
3.1.2 BLOCK DIAGRAM OF AN OP-AMP

- Basically, op-amp has three stages as in Figure 3.2.
- Input stage is differential amplifier. It provide high input impedance to input signal while provide low gain to common mode signal such as humming and noise.
- Gain amplifier state provide high voltage gain to drive current level to drive output stage.
- Push pull amplifier is the output stage. It has an output stage that can drive a current in either direction through the load.

Figure 3.2 :Op-Amp stage

3.2 CHARACTERISTIC OF AN IDEAL OP-AMP

- **Voltage Gain**: The primary function of an amplifier is to amplify, so the more gain the better. It can always be reduced with external circuitry, so we assume gain to be infinite.
- **Input Impedance**: Input impedance is assumed to be infinite. This is so the driving source won't be affected by power being drawn by the ideal operational amplifier.
- **Output Impedance**: The output impedance of the ideal operational amplifier is assumed to be zero. It then can supply as much current as necessary to the load being driven.
- **Input Offset Voltage :** The voltage difference between the input terminal when the input voltage is 0V.
- **Offset Current**: Output offset current: It is the current that flows through the output terminal of op-amp when both the input terminals(inverting and non-inverting) are precisely grounded
- **Bandwidth** : The ideal op-amp will amplify all signals from DC to the highest AC frequencies
- The ideal op-amp is represented as in Figure 3.3.



Voltage gain, A_v = infinity
Input impedance, Z_{in} = infinity
Output impedance, Z_{out} = 0
Input offset voltage = 0
Offset current = 0
Bandwidth = infinity

Figure 3.3 :Equivalent circuit of op-amp

3.3 DC ANALYSIS OF A DIFFERENTIAL AMPLIFIER

- Two very important concepts follow from these basic characteristics: Since the voltage gain is infinite, any output signal developed will be the result of an infinitesimally small input signal.
- Therefore: 1. The differential input voltage is zero. Also, if the input resistance is infinite: 2. There is no current flow into either input terminal.
- These two properties are the basics for op amp circuit analysis and design.

3.3.1 DIFFERENTIAL AMPLIFIER

Figure 3.4 shows the dc equivalent circuit for a differential amplifier. The circuit consists of :

- V1 and V2 - two inputs
- VOUT – one output
- TR1 and TR2
  - two identical transistors
  - both are biased at the same operating point
  - their emitters connected together and returned to the common rail, -Vee by way of resistor Re.

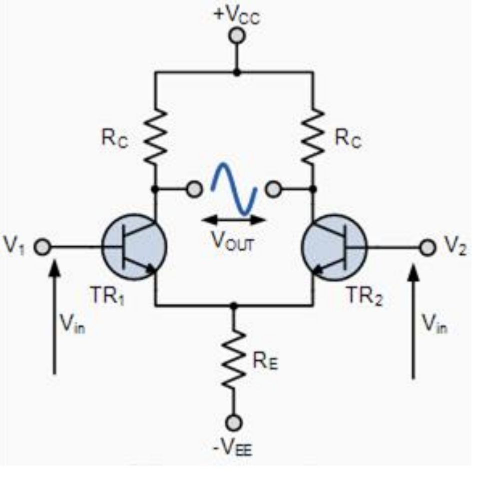


Figure 3.4 : DC equivalent circuit for a differential amplifier

- +VCC & -VEE = a dual constant supply.
- VOUT = the difference between the two input signals as the two base inputs are in anti-phase with each other.
- As the forward bias of transistor, TR1 is increased, the forward bias of transistor TR2 is reduced and vice versa.
- Then if the two transistors are perfectly matched, the current flowing through the common emitter resistor, RE will remain constant.

3.3.2 THE ANALYSIS

- For the purpose of DC analysis, assume both input are grounded, transistors are identical and collector resistors are equal as in Figure 3.5.
- The emitter of each transistor are connected together and returned to the common rail (VEE) through a common emitter resistor, RE.
- The current flow through RE is known as tail current, IT.

- By neglecting the voltage drops across the emitter of transistors, VBE, the top of the emitter resistor is now behave like a dc ground point. Therefore, tail current can be calculated by :

$$\boxed{I_T = \frac{V_{EE}}{R_E}}$$

- Ideal emitter current, **IE** for each transistor is :

$$\boxed{I_E = \frac{I_T}{2}}$$

- The dc voltage on each of transistor collector is :

$$\boxed{V_C = V_{CC} - I_C R_C} \Rightarrow I_c = I_E$$

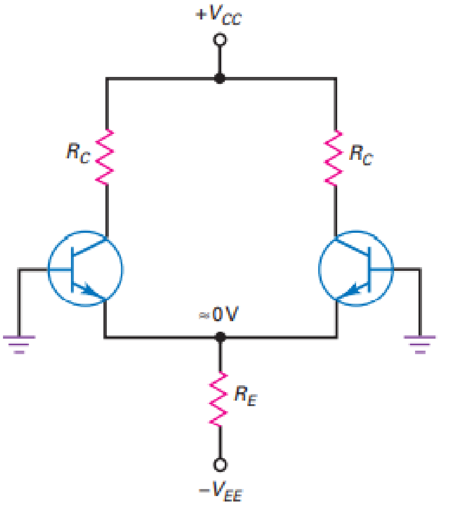


Figure 3.5 : DC equivalent circuit for a differential amplifier

EXAMPLE 3.1

What are the tail current (IT), ideal emitter current (IE) and collector voltage (VC) in Figure 3.6?

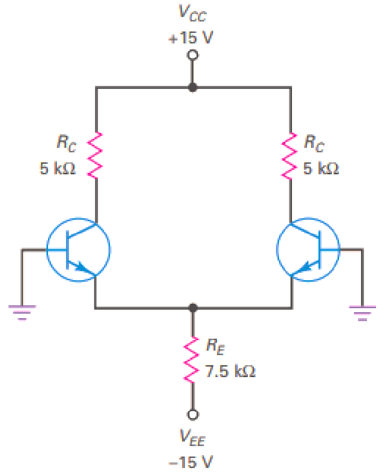


Figure 3.6

Solution :

Tail current,

$$I_T = \frac{V_{EE}}{R_E} = \frac{15V}{7.5k\Omega} = 2mA$$

Emitter current,

$$I_E = \frac{I_T}{2} = \frac{2mA}{2} = 1mA$$

Collector voltage,

$$V_C = V_{CC} - I_C R_C = 15V - (1mA)(5k\Omega) = 10V$$

3.4 INPUT CHARACTERISTICS OF AN OP-AMP

- In real applications, the assumption of two halves of a differential amplifier as identical cannot be used since it is not perfectly symmetrical in actual condition.
- Three input characteristics which are input bias current, input offset current and input offset voltage must be considered to get more accurate analysis.
- These characteristics can be eliminated by adding a compensating resistor in the circuit (pin 1 or pin 5) .

3.4.1 INPUT BIAS CURRENT, IIN(BIAS)

- Input bias current is an average of the dc base currents flowing into or out of input terminals of op-amp as in Figure 3.7.
- It is typically in the range up to hundreds nanoampere (nA).
- Input bias current, Iin(bias) formula is:

$$\boxed{I_{in(bias)} = \frac{I_{B1} + I_{B2}}{2}}$$

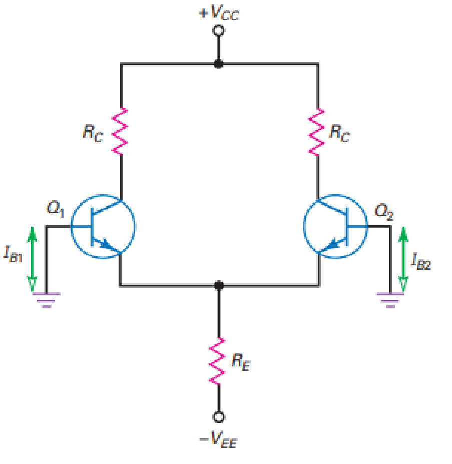


Figure 3.7: Input bias current

EXAMPLE 3.2

If IB1=90nA and IB2=70nA, what is the input bias current?

Solution :

$$I_{in(bias)} = \frac{I_{B1} + I_{B2}}{2} = \frac{90nA + 70nA}{2} = 80nA$$

3.4.2 INPUT OFFSET CURRENT, IIN(OFF)

- Input offset current, Iin(off) is the difference of the dc base currents:

$$\boxed{I_{iO} = |I_{B1} - I_{B2}|}$$

- It indicate the degree of mismatching between the base current of two transistors.
- The input offset current is zero for identical transistors. However, typically both of the transistor are slightly different and the two base currents are not equal.

EXAMPLE 3.3

If IB1=90nA and IB2=70nA, what is the input offset current?

Solution :

$$I_{in(offset)} = I_{B1} - I_{B2} = 90nA - 70nA = 20nA$$

The Q1 transistor has 20nA more base current than Q2 transistor. This can cause a problem when large base resistance are used.

3.4.3 INPUT OFFSET VOLTAGE, VIN(OFF)

- Input offset voltage, Vin(off) is the difference between the base-emitter voltages, VBE in a differential amplifier that produces an output offset voltage when the signals inputs are grounded.
- In other word, input offset voltage is the input voltage that would produce the same output error voltage in a perfect differential amplifier.

$$\boxed{V_{in(off)} = \frac{V_{error}}{A_V}}$$

- The input offset voltage occurs due to the error voltage. This error is contributed by:
  a) The different collector resistances, RC in the difference amplifier as shown in Figure 3.8 (a)
  b) The different VBE curves for each transistors as shown in Figure 3.8 (b)
  c) Other slightly different parameters in both transistors could lead to error as well.

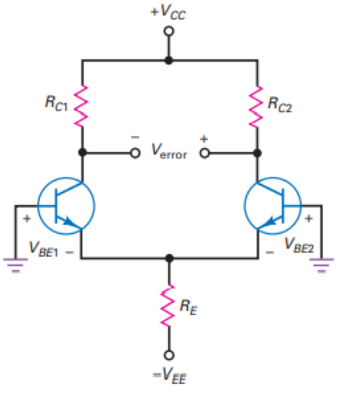


Figure 3.8 (a) : Different collector resistors produce error when bases are grounded

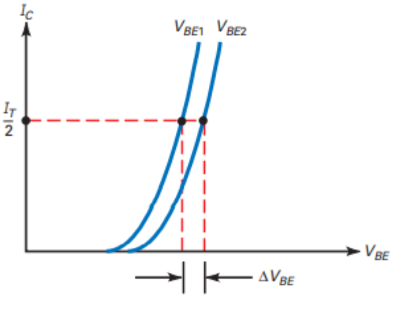
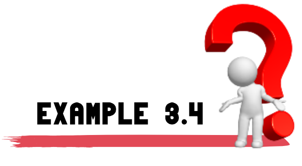


Figure 3.8 (b) : Different base-emitter curves added to error



If a differential amplifier has an output error voltage of 0.6V and a voltage gain of 300, what is the input offset voltage?

Solution :

$$V_{in(off)} = \frac{V_{error}}{A_V} = \frac{0.6V}{300} = 2mV$$

Figure 3.9 illustrate when an input offset voltage, Vin(off)=2mV will produce an error voltage of 0.6V when the voltage gain of the differential amplifier is 300.

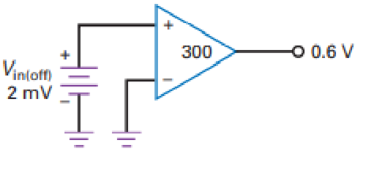


Figure 3.9 : Input offset voltage effect

3.4.4 COMMON-MODE GAIN (A_{CM})

- Differential amplifier has ability to discriminates against the common-mode signals.
- Common-mode voltage gain (ACM) will ensure that differential amplifier not amplify any common-mode signals. Common-mode gain is usually less than 1.
- Common-mode gain can be calculated by :

$$\boxed{A_{V(CM)} = \frac{R_C}{2R_E}}$$

EXAMPLE 3.5

Determine the common-mode voltage gain and output voltage for the circuit in Figure 3.10.

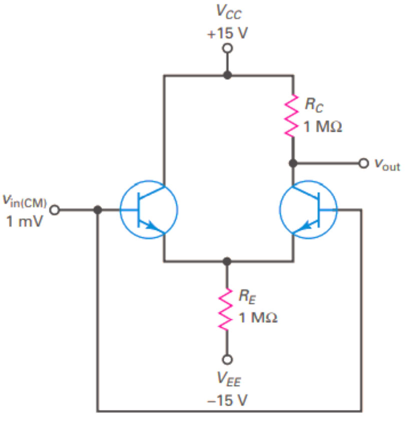


Figure 3.10

Solution :

Common-mode voltage gain,

$$A_{V(CM)} = \frac{R_C}{2R_E} = \frac{1M}{2M} = 0.5$$

Output voltage,

$$V_{out} = A_{V(CM)}V_{in} = 0.5(1mV) = 0.5mV$$

The output voltage (0.5mV) is less than input voltage (1mV). It shows that the differential amplifier has attenuates the common-mode signal rather than amplifying it.

3.4.5 COMMON-MODE REJECTION RATIO (CMRR)

- Common-mode gain -The ratio of the output voltage of a differential amplifier to the common-mode input voltage.
- Common-mode Rejection Ratio (CMRR) - The ratio of op-amp differential gain, Ad to common-mode gain, ACM. A measure of an op-amp's ability to reject common-mode signals such as noise.

- In equation :

$$\boxed{\mathrm{CMRR} = \frac{\mathrm{A_V}}{\mathrm{A_{V(CM)}}}}$$

- CMRR is usually measured in decibels using decibel conversion formula :

$$\boxed{CMRR(dB) = 20logCMRR}$$

- A higher CMRR indicates that differential amplifier has great ability to amplify the useful signal while eliminating the common mode signal such as hum and noise. In other word, the higher the CMRR, the better.

EXAMPLE 3.6 

A differential amplifier has voltage gain, $A_V = 200$ and $A_{V(CM)} = 0.5$. Determine CMRR and express it in decibel (dB).

Solution :

$$\mathrm{CMRR} = \frac{\mathrm{A_V}}{\mathrm{A_{V(CM)}}} = \frac{200}{0.5} = 400$$

$\mathrm{CMRR(dB)} = $ 20logCMRR=20log(400)=52dB

EXAMPLE 3.7

An operational amplifier has $A_V = 200{,}000$ and CMRR(dB)=90dB. Determine :

a) Common-mode voltage gain.

b) The output voltage (if both the desired input voltage and common-mode signal have a value of 1μV).

Solution :

a)

$$\mathrm{CMRR} = \mathrm{antilog}\frac{\mathrm{CMRR(dB)}}{20}$$

$$= \mathrm{antilog}\frac{90\mathrm{dB}}{20}$$

$$= 31{,}600$$

b)

$$\frac{\mathrm{A_V}}{\mathrm{CMRR}} = \mathrm{A_{V(CM)}} = \frac{200{,}000}{31{,}600} = 6.32$$

Output voltage for desired signal :

$$\mathrm{V_{out(desired)}} = \mathrm{A_V V_{in}} = (200{,}000)(1\mu\mathrm{V}) = 0.2\mathrm{V}$$

Output voltage for common-mode signal :

$$\mathrm{V_{out(CM)}} = \mathrm{A_{V(CM)} V_{in}} = (6.32)(1\mu\mathrm{V}) = 6.32\mu\mathrm{V}$$

From the calculation, we can see that the desired output voltage is larger than the common-mode output.

3.5 COMPLEMENTARY AMPLIFIER

- Complementary amplifier circuit employs a PNP transistor and a NPN transistor which are made with the same material and same maximum rating as in Figure 3.11. These transistors are connected in a single stage.
- Both transistors are complementary symmetry. They will alternately conduct for every half of the amplifier cycle (class B) to produce constant output.
- Current flow in the output circuit is completed through the collector-emitter junctions of the transistors.

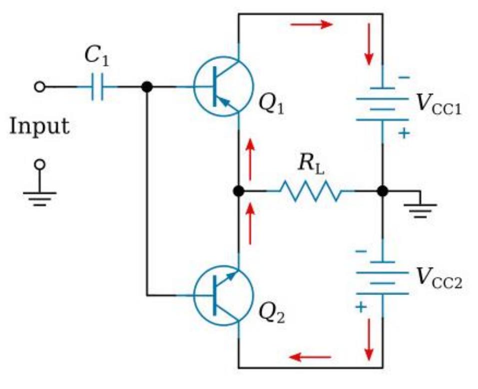


Figure 3.11 : Zero bias complementary circuit.

Complementary amplifier operated on full cycle of waveform. The operations are as in Figure 3.12

During positive cycle of input :

- Q1 is forward bias (conducts) and Q2 is reverse bias (not conducts)
- The current flows through Q1 and develop output voltage across the load, RL

+

During negative cycle of input :

- Q1 is reverse bias (not conducts) and Q2 is forward bias (conducts)
- The current flows through Q2 and develop output voltage across the load, RL

=

For complete cycle of input:

- A complete cycle of output will be developed.

Figure 3.12 : Operation of complementary amplifier circuit

3.8 PUSH-PULL AMPLIFIER

- A push-pull amplifier or Class B is made up by two symmetrical transistors connected in a push-pull arrangement as in Figure 3.13.
- This configuration allow the circuit to operates in two stages (push stage and pull stage).
- The NPN transistor will act as a push amplifier where the positive cycle of the input signal is amplified.
- The PNP transistor will act as a pull amplifier where the negative cycle of the input signal is amplified.
- A push-pull amplifier is commonly used in situation where low distortion, high efficiency and high output power is required.

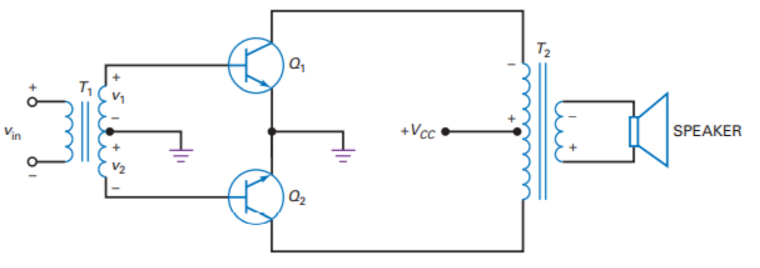


Figure 3.13 : Class B push-pull amplifier.

The operation of push-pull amplifier is as in Figure 3.14

During positive half-cycle of input :

- Q1 is forward bias (conducts) and Q2 is reverse bias (not conducts).
- The collector current through Q1 flows through the upper half of the primary winding.
- An amplified and inverted voltage appears at the loudspeaker.

+

During negative half-cycle of input :

- Q2 is forward bias (conducts) and Q1 is reverse bias (not conducts).
- The collector current through Q2 flows through the lower half of the primary winding.
- The alternate half-cycle appears across the loudspeaker.

=

For complete cycle of input:

- Each transistor amplifies input signal alternately for every half-cycle
- The loudspeaker will receive a complete cycle of the amplified signal

Figure 3.14 : Operation of push-pull amplifier circuit

3.7 OP-AMP CONFIGURATION

Op-amp configuration depends on the way an op-amp is connected in circuit. The configuration is :

a) Non-inverting amplifier
b) Inverting amplifier
c) Summing amplifier
d) Subtractor amplifier
e) Integrator amplifier
f) Differentiator amplifier
g) Comparator amplifier

3.7.1 NON-INVERTING AMPLIFIER

- Non-inverting amplifier, - the output signal is not inverted.
- In this circuit, the input voltage is applied to the positive input of the op amp, and a fraction of the output signal is applied to the negative input from the Rf - Rin voltage divider as in Figure 3.15.
- The gain of the noninverting amplifier is:

$$\boxed{A_V = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}}$$

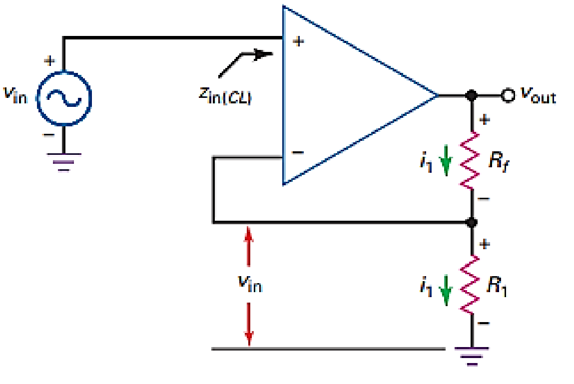


Figure 3.15 : Non-inverting amplifier

EXAMPLE 3.8

Determine voltage gain and output voltage for circuit in Figure 3.16:

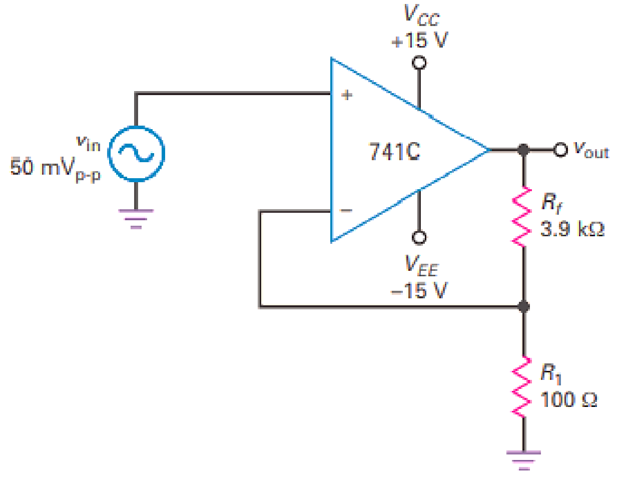


Figure 3.16

Solution :

Voltage gain :

$$A_V = 1 + \frac{R_f}{R_i} = 1 + \frac{3.9\text{k}\Omega}{100\Omega} = 40$$

Output voltage :

$$V_{out} = A_V V_{in} = 40\left(50\text{m}V_{p-p}\right) = 2V_{p-p}$$

3.7.2 INVERTING AMPLIFIER

- The inverting amplifier uses negative feedback to stabilize the closed-loop voltage gain.
- Input is applied to the inverting (-) input and the non-inverting input (+) is grounded. Resistor R_f is the feedback resistor connected from the output to the inverting (-) input (negative feedback) as in Figure 3.17.
- The amplified output voltage produces by inverting amplifier is 180^o out of phase from the input signal.
- The gain of the inverting amplifier is:

$$\boxed{A_V = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1}}$$

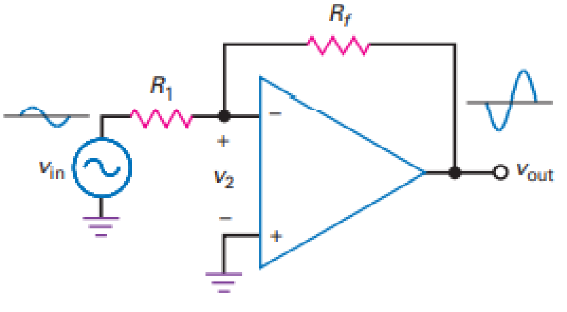


Figure 3.17 : Inverting amplifier

EXAMPLE 3.9

Determine voltage gain and output voltage for circuit in Figure 3.18:

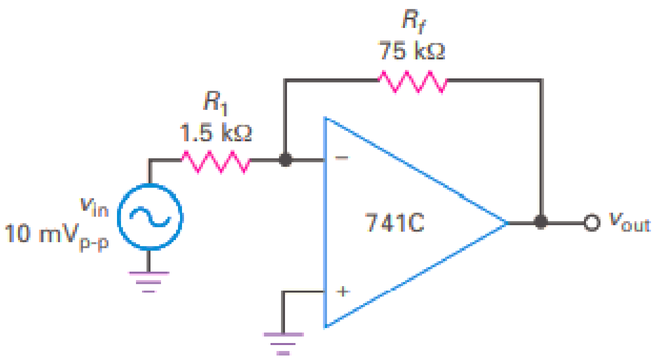


Figure 3.18

Solution :

Voltage gain :

$$A_V = 1 + \frac{R_f}{R_i} = 1 + \frac{3.9k\Omega}{100\Omega} = 40$$

Output voltage :

$$V_{out} = A_V V_{in} = 40\left(50mV_{p-p}\right) = 2V_{p-p}$$

3.7.3 SUMMING AMPLIFIER

- Summing amplifier is useful to combine two or more analog signal into a single input.
- Circuit in Figure 3.18 shows a summing amplifier with two input signals. However, we can add as many input as needed depending on our application.

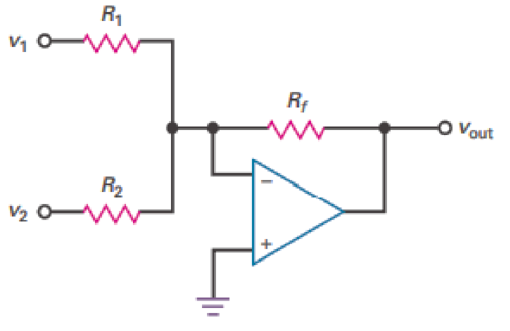


Figure 3.18 : Summing amplifier

- For a two input summing amplifier, the output voltage formula is:

$$\boxed{V_O = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right) = -R_f \sum_{j=a}^{c} \frac{V_j}{R_j}}$$

EXAMPLE 3.10

Determine the output voltage for circuit in Figure 3.19.

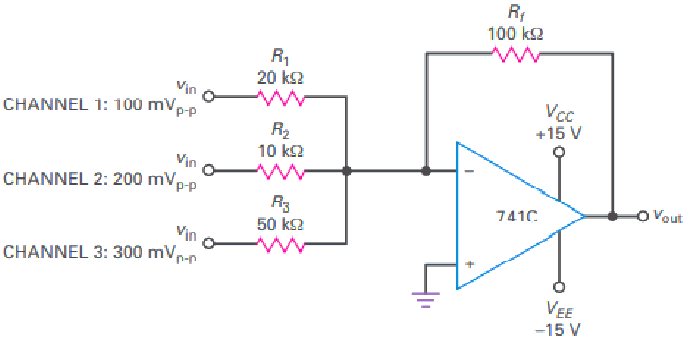


Figure 3.19

Solution :

Output voltage:

$$V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)$$

$$V_{out} = -100k\Omega\left(\frac{100mV_{p-p}}{20k\Omega} + \frac{200mV_{p-p}}{10k\Omega} + \frac{300mV_{p-p}}{50k\Omega}\right)$$

$$V_{out} = -3.1mV_{p-p}$$

3.7.4 SUBTRACTOR AMPLIFIER

- Substractor amplifier subtracts two input voltages to produce an output voltage equal to the difference in the input voltages ($V1$ and $V2$) as in Figure 3.20.

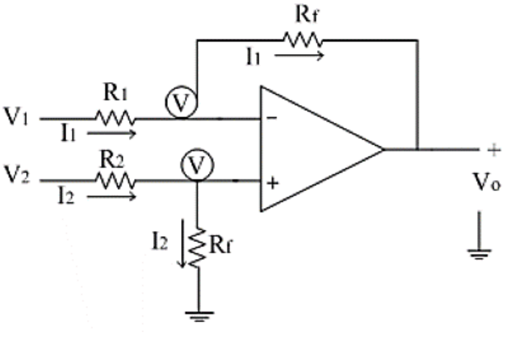


Figure 3.20 : Subtractor amplifier

- It is also called as a difference amplifier, since the output is an amplified one. The output voltage of subtractor amplifier:

$$\boxed{V_O = \frac{R_f}{R_1}(V_2 - V_1)}$$

EXAMPLE 3.11

Determine the output voltage for circuit in Figure 3.21:

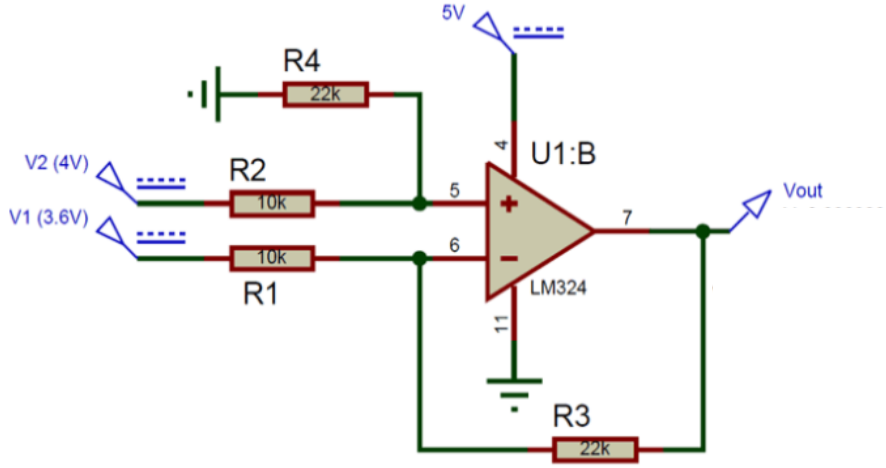


Figure 3.21

Solution :

Output voltage:

$$V_{out} = \frac{R_f}{R_1}(V_2 - V_1)$$

$$V_{out} = \frac{22k\Omega}{10k\Omega}(4V - 3.6V) = 0.88V$$

3.7.5 DIFFERENTIATOR AMPLIFIER

- A differentiator amplifier is a circuit that perform differentiation operation. The output voltage of this circuit is proportional to the instantaneous rate of change of the input voltage.
- The feedback component in the circuit is a resistor while the input component is a capacitor.

- Differentiator is commonly used to detect the leading and trailing edges of a rectangular pulse or to produce a rectangular output from a ramp input as in Figure 3.22.

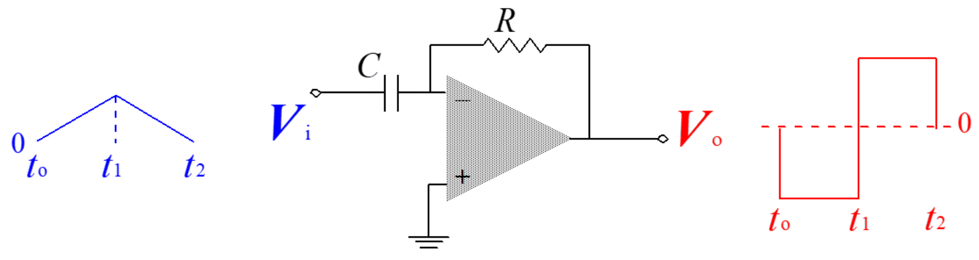


Figure 3.22 : Differentiator amplifier

- The output voltage of the differentiator is given by:

$$\boxed{v_o = -RC\left(\frac{dV_i}{dt}\right)}$$

EXAMPLE 3.12

An input voltage, V_in=3.5 cos(100πt)V is fed into a differentiator circuit. The time constant of the circuit, RC=1.5ms. Determine the output voltage.

Solution :

$$V_{out} = -RC\frac{dV_{in}}{dt}$$

$$= -1.5m\left[\frac{d}{dt}[3.5\cos(100\pi t)]\right]$$

$$=-1.5m[-3.5(100\pi)sin(100\pi t)]]$$

$$= 1.65\, sin(100\pi t)\, V$$

3.7.6 INTEGRATOR AMPLIFIER

- An integrator amplifier is a circuit that perform integration operation.
- The feedback component in the circuit is a capacitor while the input component is a resistor.
- Differentiator is commonly used to produce a ramp output voltage which is linearly increasing or decreasing voltage as in Figure 3.23 .

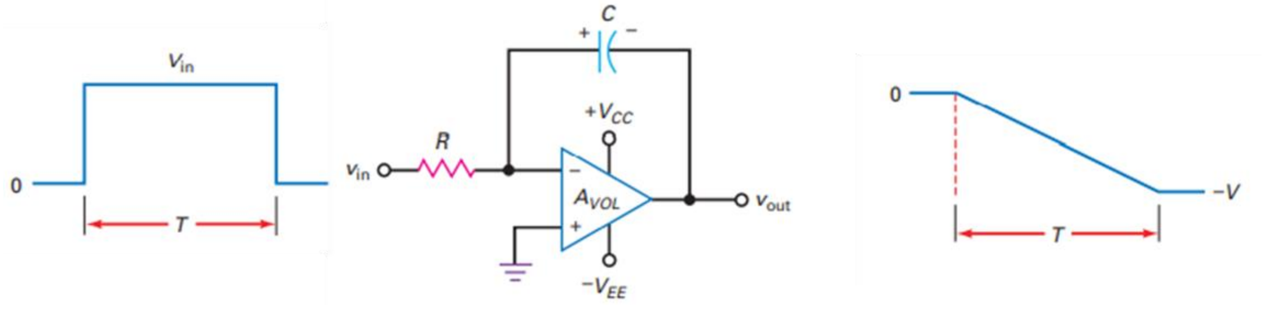


Figure 3.23 : Integrator amplifier

- The output voltage of the differentiator is given by:

$$\boxed{v_o(t) = \frac{-1}{RC}\int v_i(t)dt}$$

EXAMPLE 3.13

An integrator circuit in Figure 3.24 consists of step input voltage, Vin=-2V, R=20kΩ, C=10μF . Determine the output voltage produce by the circuit at time t=5ms.

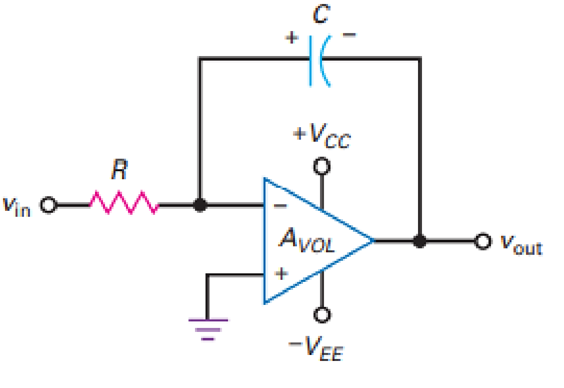


Figure 3.24

Solution :

$$V_{out} = -\frac{1}{RC}\int V_{in}dt$$

$$= -\frac{1}{(20k\Omega)(10\mu)}\int_0^{5m}(-2)dt$$

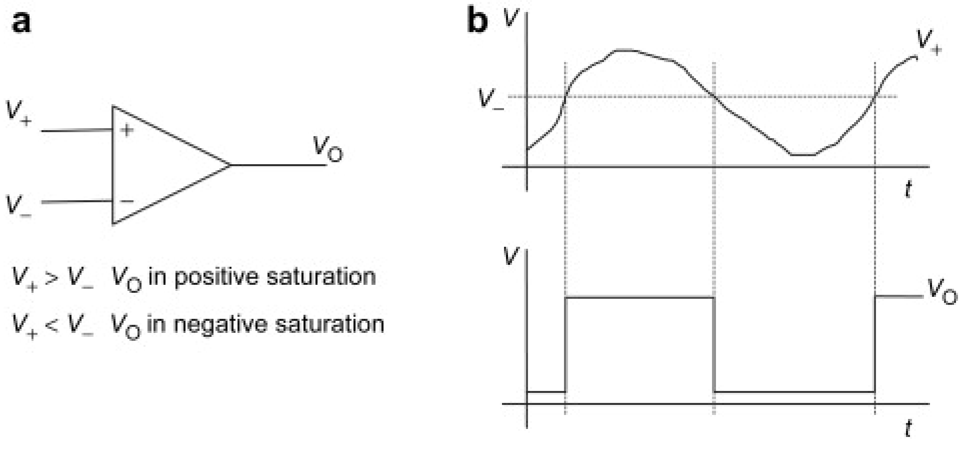
$$= -5[-2t]_0^{5m}$$

$$= -5[-2(5m) - 0]$$

$$= 50mV$$

3.7.7 COMPARATOR

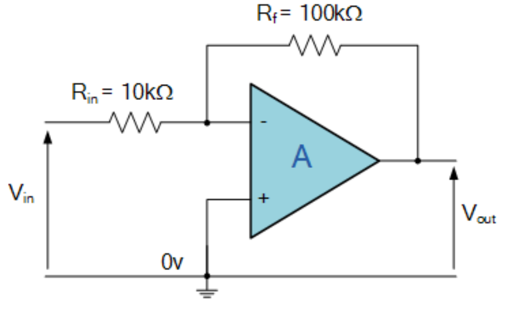
- The comparator simply compares its two inputs, shown in the diagram as V+ and V– in Figure 3.25.
- If V+ is greater than V–, then the comparator output goes to a positive voltage value, usually the maximum 'saturated' voltage level.
- If V+ is less than V–, then the output goes to a negative or zero voltage value.
- One application of comparator is in analog sensor.



V− has been set to a fixed voltage, shown by the dotted line, while V+ is varying. Whenever V+ is greater than V–, the output goes to Logic 1; when it is less, the output goes to Logic 0.ma

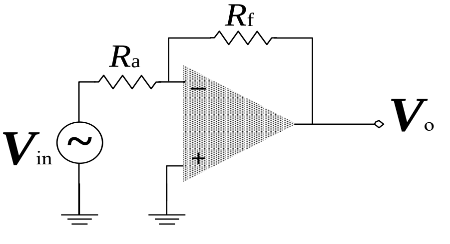
Figure 3.25 : Comparator

1. Find the closed loop gain of the following inverting amplifier circuit.



2. The gain, Av of an inverting amplifier is set to 50. Find the value of required input resistance if Rf=20kΩ.

3. Refer to figure below:



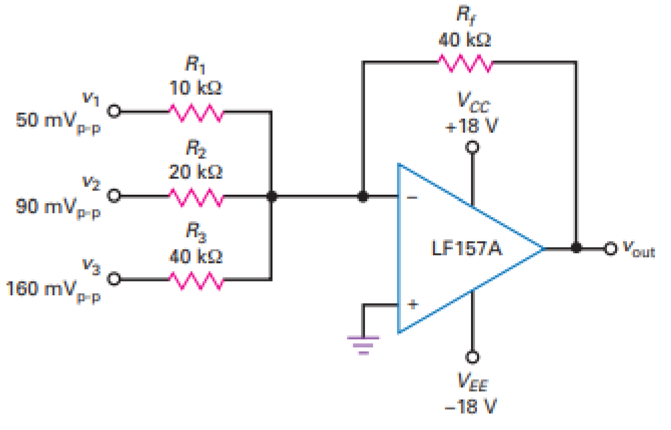
Given, Ra = 33 kΩ , Rf = 330 kΩ

a) Determine the closed loop gain.

b) If a signal voltage of 1mVp is applied, determine the output voltage.

c) Draw the phase relationship of input and output voltages.

4. Based on figure below:

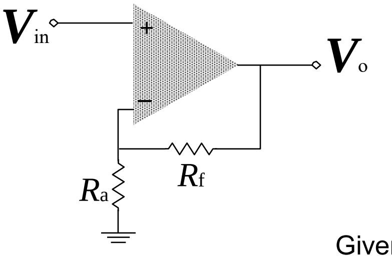


a) Calculate the output voltage, Vout

b) Draw input voltages and output voltage waveform

c) If the feedback resistor in figure is changed to a 100-kΩ variable resistor, what is the maximum and minimum output voltage?

5. Based on the following circuit diagram, calculate CMRR and express it in decibels. Given the common mode gain, A_{CM} is 0.001.



Given, Ra = 15kΩ , Rf = 100kΩ

REFERENCES

Albert Malvino, D. B. (2016). *Electronic principles (8th edition).* New York: McGraw-Hill Education.

Schuler, C. A. (2019). *Electronic Principles and Applications (Ninth Edition).* New York: Mc Graw Hill Education.

e ISBN 978-967-2258-98-8

9 7 8 9 6 7 2 2 5 8 9 8 8

Electronics Circuits