



## MODULE 1 (CONT.): OPERATIONAL AMPLIFIER



### OPERATIONAL AMPLIFIER (OP-AMP)

- An op-amp is a DC-coupled high-gain electronic voltage amplifier with
  - differential input and
  - single-ended output (Figure 16.1).
- An op-amp produces an output-voltage that is typically hundreds of thousands times larger than the voltage difference between its input terminals.
- Opamps are important building blocks for a wide range of electronic circuits.

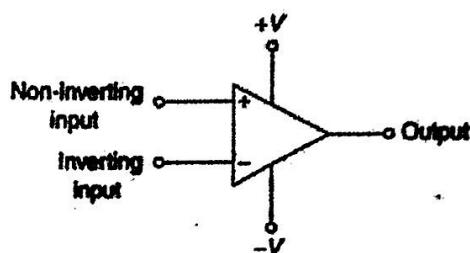


Figure 16.1: Circuit symbol for an op-amp

$$V_o = A(V_1 - V_2) \quad \text{--- (1)}$$

$$A = \frac{V_o}{V_d}$$

$V_d$  = differential input voltage

### IDEAL VERSUS PRACTICAL OPAMP

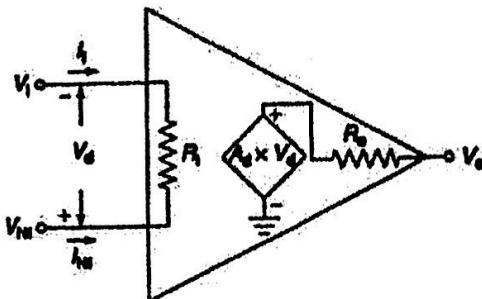


Figure 16.13: Model of practical opamp

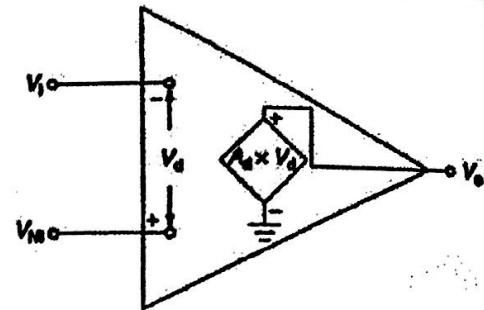


Figure 16.14: Model of ideal opamp

- Here,  $V_I$  = Inverting input.
- $V_{NI}$  = Non-inverting input.
- The ideal opamp model was derived to simplify circuit calculations (Figure 16.14).
- The Ideal opamp model makes 3 assumptions. They are:
  1. Input impedance,  $Z_i = \infty$ .
  2. Output impedance,  $Z_o = 0$ .
  3. Open-loop gain,  $A_d = \infty$ .
- From the above 3 assumptions, other assumptions can be derived. They are:
  1. Since  $Z_i = \infty$ ,  $I_I = I_{NI} = 0$ .
  2. Since  $Z_o = 0$ ,  $V_o = A_d \times V_d$ .
  3. Common mode gain = 0.
  4. Bandwidth =  $\infty$ .
  5. Slew Rate =  $\infty$ .
  6. Offset Drift = 0.
- Properties of ideal opamp are:
  1. Infinite open-loop differential voltage gain.
  2. Infinite input impedance.
  3. Zero output impedance.
  4. Infinite bandwidth.
  5. Zero DC input and output offset voltages.
  6. Zero input differential voltage.

Properties	Ideal opamp	Practical opamp
Voltage Gain.	Ideal opamps have infinite open-loop voltage gain (Figure 16.14).	Practical opamps have open-loop gain in the range of 10,000 to 100,000 (Figure 16.13).
Input Impedance.	Ideal opamps have infinite input impedance.	Input impedance varies from hundreds of $\text{K}\Omega$ for some low-grade opamps to $\text{T}\Omega$ for high-grade opamps.
Output Impedance.	Ideal opamps have zero output impedance.	Output impedance may be in the range of 10 to 100 $\text{K}\Omega$ .
Bandwidth.	Infinite bandwidth i.e. ideal opamp amplifies all signals from DC to highest AC frequencies.	Bandwidth is limited and is specified by gain-bandwidth product.
DC Input & output offset voltages.	An ideal opamp produces a zero DC output when both the inputs are grounded.	For real devices, there may be some finite DC output even when both the inputs are grounded. Output offset may vary from few nano-volts for ultra-low offset opamps to kw milli-volts for general-purpose opamps.
Input differential voltage.	Zero input differential voltage. Voltage appearing at 1 input also appears at the other input for linear mode of operation i.e. differential inputs stick together.	Practical Opamp exhibits offsets and non-linearity.

## **PERFORMANCE PARAMETERS**

### **1. Bandwidth**

- Bandwidth refers to range of frequencies the opamp can amplify for a given amplifier-gain.
- When the opamp is used in the closed-loop mode, the bandwidth increases at the cost of the gain.
- The bandwidth is usually expressed in terms of the unity gain crossover frequency (also called *gain-bandwidth product*).
- It is 1 MHz in the case of opamp 741.
- It is 1500 MHz in the case of high-bandwidth opamp.

### **2. Slew Rate**

- Slew-rate is defined as the rate of change of output-voltage with time.
- It gives us an idea about how well the output follows a rapidly changing waveform at the input.
- It limits the large signal bandwidth.
- For a sinusoidal signal,  
peak-to-peak output-voltage( $V_{o,t,p}$ ), slew rate & bandwidth are inter-related by following equation:  
$$\text{Bandwidth (highest frequency, } f_{MAX} \text{)} = \text{Slew rate} / (\pi \times V_{pp})$$

### **3. Open-loop Gain**

- Open-loop gain is the ratio of single-ended output to the differential input.
- This parameter has a great bearing on the gain-accuracy specification of the opamp.
- The ratio of the open-loop gain to the closed-loop gain is called the **loop-gain**.
- Accuracy depends on the magnitude of the loop-gain.
- The magnitude of loop-gain depends directly on the value of the open-loop gain, as the value of closed-loop gain is fixed.

### **4. Common Mode Rejection Ratio (CMRR)**

- CMRR is the ratio of the desired differential gain ( $A_d$ ) to the undesired common mode gain ( $A_c$ ).  
i.e.  $\text{CMRR} = 20 \log(A_d/A_c) \text{ dB}$

- It is a measure of the ability of the opamp to suppress common mode signals.

### **5. Power Supply Rejection Ratio (PSRR)**

- PSRR is defined as the ratio of change in the power supply voltage to corresponding change in the output-voltage.
- PSRR should be zero for an ideal opamp.

### **6. Input Impedance**

- Input Impedance is the ratio of input-voltage to input-current.
- It is the impedance looking into the input terminals of the opamp.
- It is expressed in terms of resistance.
- It is assumed to be infinite to prevent any current flowing from the source supply into the amplifiers input circuitry.

### **7. Output Impedance**

- Output Impedance is defined as the impedance between the output terminal of the opamp and ground.
- For ideal opamp, the output impedance is assumed to be zero.
- The opamp acts as a perfect internal voltage-source with no internal resistance so that it can supply as much current as necessary to the load.
- This internal resistance is effectively in series with the load thereby reducing the output-voltage available to the load.

### **8. Settling Time**

- Settling time is a parameter specified in the case of
  - high speed opamps or
  - opamps with a high value of gain-bandwidth product.

### **9. Offset Voltage ( $V_{IO}$ )**

- Output offset voltage is the voltage at the output with both the input terminals grounded.
- Real opamps have some amount of output offset voltage.
- In real opamps, we need to apply a DC differential voltage externally to get a zero output. This externally applied input is referred to as input offset voltage.

**Example 16.4**

Opamp LM 741 is specified to have a slew rate of  $0.5 \text{ V}/\mu\text{s}$ . If the opamp were used as an amplifier and the expected peak output-voltage were 10V, determine the highest sinusoidal frequency that would get satisfactorily amplified.

**Solution:**

1. Highest sinusoidal frequency  $f_{MAX}$  that would get satisfactorily amplified is given by

$$f_{MAX} = \text{slew rate}/2\pi V_p$$

where  $V_p$  is the expected peak output-voltage.

2. In the present case, slew rate =  $0.5 \text{ V}/\mu\text{s}$  and  $V_p = 10 \text{ V}$ .

$$3. \text{ Therefore, } f_{MAX} = (0.5*10^6)/(2\pi*10) = 7.96 \text{ KHz}$$

**Example 16.5**

Differential voltage gain and CMRR of an opamp when expressed in decibels are 110 dB and 100 dB respectively. Determine the common mode gain expressed as a ratio.

**Solution:**

$$1. \text{ CMMR (in dB)} = 20 \log (A_d/A_{CM})$$

where  $A_d$  = differential voltage gain

$A_{CM}$  = common mode gain

$$2. \text{ CMMR (in dB)} = 20 \log A_d - 20 \log A_{CM}$$

$$3. \text{ That is } 20 \log A_{CM} = 20 \log A_d - \text{CMMR} = 110 - 100 = 10 \text{ dB}$$

$$4. \text{ This gives } \log A_{CM} = 10/20 = 0.5$$

$$5. \text{ Therefore, } A_{CM} = \text{antilog}(0.5) = 3.16$$

**Example 16.6**

In the case of a certain opamp, 0.5 V change in common mode input causes a DC output offset change of  $5\mu\text{V}$ . Determine CMRR in dB.

**Solution:**

$$1. \text{ CMRR} = \Delta V_{CM}/\Delta V_{OS} = 0.5/(5*10^{-6}) = 10^5$$

$$2. \text{ CMRR in dB} = 20 \log 10^5 = 100 \text{ dB.}$$

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## MODULE 1 (CONT.): OPERATIONAL AMPLIFIER APPLICATION CIRCUITS

### **PEAK DETECTOR CIRCUIT**

- It is one of the applications of opamp (Figure 17.34).
- Peak detector circuit produces a voltage at the output equal to peak amplitude of the input signal.
- Essentially, it is a clipper-circuit with a parallel resistor-capacitor connected at its output.
- Here is how it works:
  - > The clipper reproduces the positive half cycles.
  - > During this period, the diode  $D_1$  is forward-biased.
  - > The capacitor rapidly charges to the positive peak from the output of the opamp.
  - > As the input starts decreasing beyond the peak, the diode gets reverse biased, thus isolating the capacitor from the output of the opamp.
  - > The capacitor can now discharge only through the resistor ( $R$ ) connected across it.
- The value of the resistor is much larger than the forward-biased diode's ON resistance.
- The buffer-circuit prevents any discharge of the capacitor due to loading effects of the circuit.
- The circuit can be made to respond to the negative peaks by reversing the polarity of the diode.

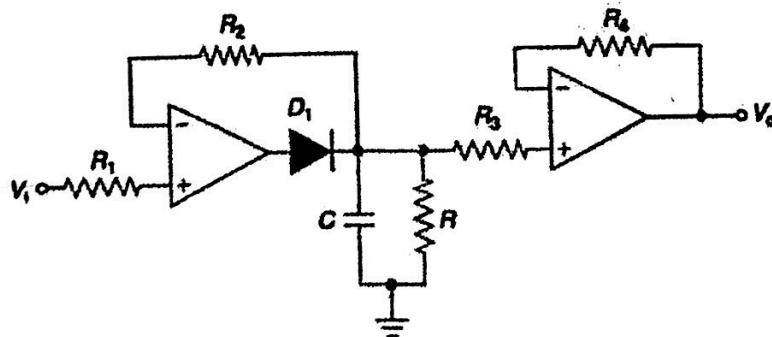


Figure 17.34: Peak Detector Circuit

- The parallel R-C circuit time constant is typically 100 times the time period corresponding to the minimum frequency of operation.
- The R-C time constant also controls the response time.
- Slew rate is the primary specification that needs to be looked into while choosing the right opamp for the clipper portion.

## ANALOG AND DIGITAL ELECTRONICS

### **COMPARATOR**

- A comparator circuit is a two input, one-output building block.
- It produces a high or low output depending upon the relative magnitudes of the 2 inputs.
- An opamp can be very conveniently used as a comparator when used without negative feedback.
- Because of very large value of open-loop voltage gain, it produces either positively saturated or negatively saturated output-voltage.
- The output-voltage depends on whether the amplitude of the voltage applied at the non-inverting terminal is more or less positive than the voltage applied at the inverting Input terminal.

### **ZERO CROSSING DETECTOR**

- The comparator has 2 inputs:
  - 1) First Input is connected to standard reference voltage.
  - 2) Second Input is connected to input-voltage that needs to be compared with the reference voltage.
- In special case, where reference voltage is 0, the circuit is referred to as **zero-crossing detector**.
- Here, we consider 2 cases: 1) Non-Inverting zero-crossing detector &  
2) Inverting zero-crossing detector.

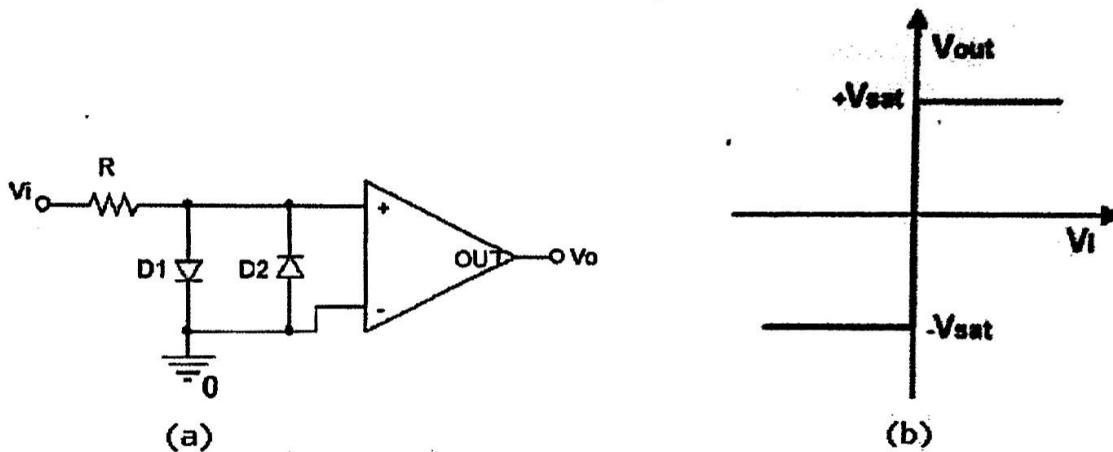


Figure 17.38: Non-inverting zero-crossing detector

- In **non-inverting zero-crossing detector**, input-voltage more positive than zero produces a positively saturated output-voltage (Figure 17.38).
- Diodes  $D_1$  and  $D_2$  connected at the input are to protect the sensitive input circuits inside the opamp from excessively large input-voltages.

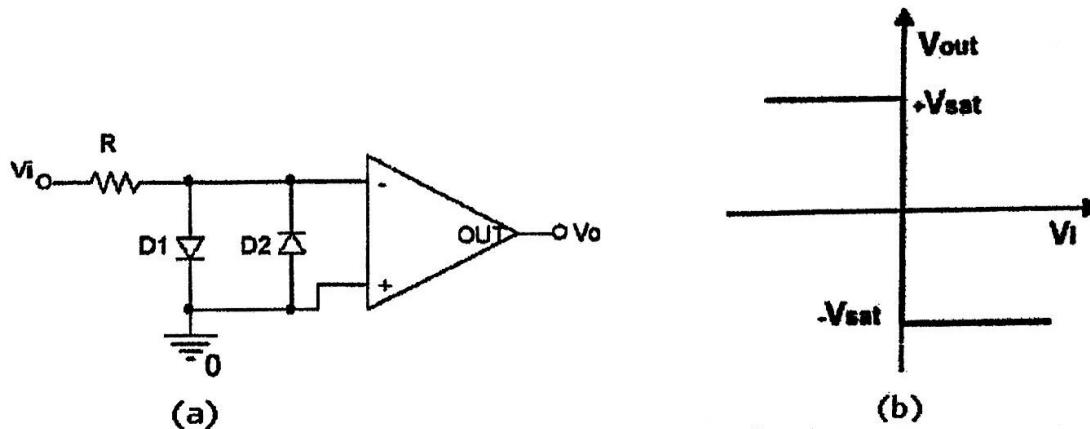


Figure 17.39: Inverting zero-crossing detector

- In **inverting zero-crossing detector**, input-voltage slightly more positive than zero produces a negatively saturated output-voltage (Figure 17.39).

- Common Application of zero-crossing detector: To convert sine wave signal to a square wave signal (Figure 17.40).

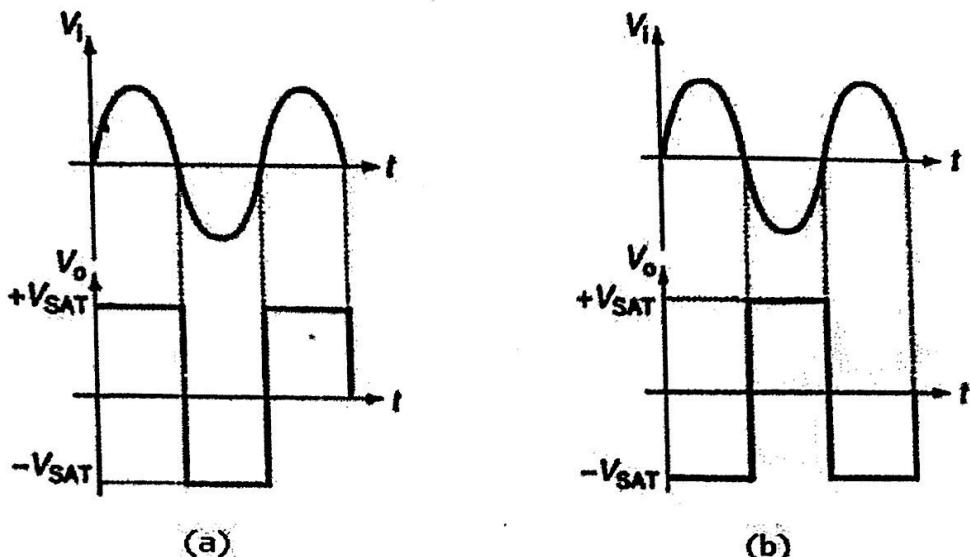


Figure 17.40: Waveform of (a) Non-inverting zero-crossing detector (b) Inverting zero-crossing detector

- In general, reference voltage may be
  - positive (Figure 17.41) or
  - negative voltage (Figure 17.42).

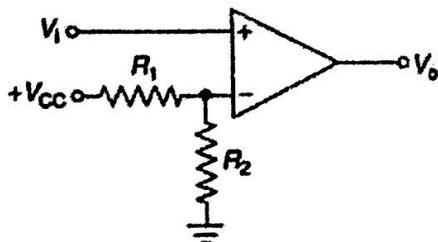


Figure 17.41: Non-inverting comparator with positive reference

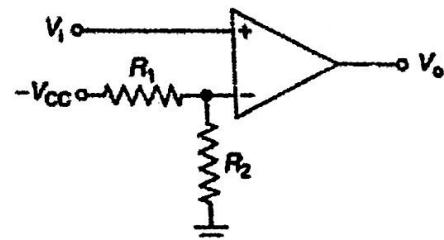


Figure 17.42: Non-inverting comparator with negative reference

- In case of non-inverting comparator,
  - A positive reference voltage, \$V\_{REF}\$ is given by  

$$+V_{CC} \times [R_2 / (R_1 + R_2)]$$
  - A negative reference voltage, \$V\_{REF}\$ is given by  

$$-V_{CC} \times [R_2 / (R_1 + R_2)]$$



## ANALOG AND DIGITAL ELECTRONICS

### **COMPARATOR WITH HYSTERESIS**

- Here we consider, 1) Inverting comparator & 2) Non-inverting comparator.

#### **1) Inverting Comparator with Hysteresis**

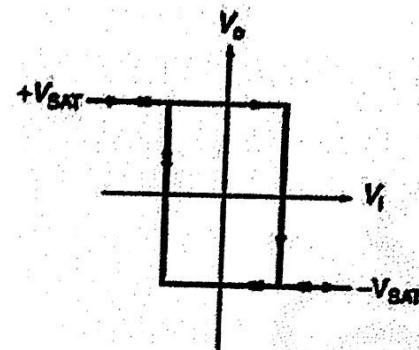
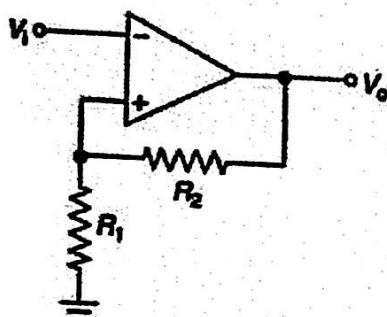


Figure 17.44: Inverting comparator with hysteresis

- Here is how it works:

➢ Let us assume that the output is in positive saturation ( $+V_{SAT}$ ). (Figure 17.44).  
➢ Voltage at non-inverting input is

$$V_{SAT} \times R_1 / (R_1 + R_2)$$

➢ Due to this small positive voltage at the non-inverting input, the output is reinforced to stay in positive saturation.

➢ Now, the input signal needs to be more positive than this voltage for the output to go to negative saturation.

➢ Once the output goes to negative saturation ( $-V_{SAT}$ ), voltage fed back to non-inverting input becomes

$$-V_{SAT} \times R_1 / (R_1 + R_2)$$

➢ A negative voltage at the non-inverting input reinforces the output to stay in negative saturation.

➢ In this manner, the circuit offers a hysteresis of

$$2V_{SAT} \times R_1 / (R_1 + R_2)$$

#### **2) Non-inverting Comparator with Hysteresis**

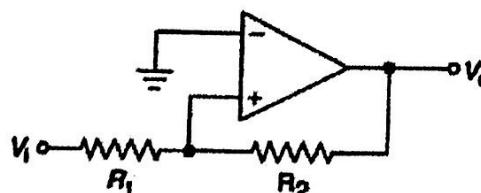


Figure 17.45: Non-inverting comparator with hysteresis

➢ Non-inverting comparator with hysteresis can be built by applying the input signal to the non-inverting input (Figure 17.45).

➢ Operation is similar to that of inverting comparator.

➢ Upper and lower trip points and hysteresis is given by

$$UTP = +V_{SAT} \times \frac{R_2}{R_1}$$

$$LTP = -V_{SAT} \times \frac{R_2}{R_1}$$

$$H = 2V_{SAT} \times \frac{R_2}{R_1}$$



## ANALOG AND DIGITAL ELECTRONICS

### WINDOW COMPARATOR

- In the case of a conventional comparator, the output changes state when the input-voltage goes above or below the preset reference voltage (Figure 17.46).
- There are 2 reference voltages called **lower and the upper trip points (LTP & UTP)**. (Fig 17.47).

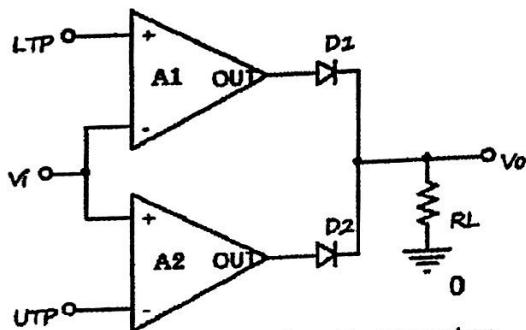


Figure 17.46: Window Comparator



Figure 17.47: Transfer characteristics of Window Comparator

- Here is how it works:

#### Case 1:

- When the input-voltage is less than the voltage-reference corresponding to the lower trip point (LTP), output of opamp A1 is at  $+V_{SAT}$  and the opamp A2 is at  $-V_{SAT}$ .
- Diodes D<sub>1</sub> and D<sub>2</sub> are respectively forward and reverse biased.
- Consequently, output across R<sub>L</sub> is at  $+V_{SAT}$ .

#### Case 2:

- When the input-voltage is greater than the reference voltage corresponding to the upper trip point (UTP), the output of opamp A1 is  $-V_{SAT}$  and that of opamp A2 is at  $+V_{SAT}$ .
- Diodes D<sub>1</sub> and D<sub>2</sub> are respectively reverse and forward biased.
- Consequently, output across R<sub>L</sub> is at  $+V_{SAT}$ .

#### Case 3:

- When the input-voltage is greater than LTP voltage and lower than UTP voltage, the output of both opamps is at  $-V_{SAT}$ .
- Both diodes D<sub>1</sub> and D<sub>2</sub> are reverse biased.
- Consequently, the output across R<sub>L</sub> is zero.

## ANALOG AND DIGITAL ELECTRONICS

### **Example 17.11**

Refer to the comparator circuit of figure 17.50. Determine the state of LED-1 and LED-2 (whether ON or OFF) when the switch SW-1 is in (a) position-A and (b) position-B. Assume diodes D<sub>1</sub> and D<sub>2</sub> to have forward biased voltage drop equal to 0.7 V each.

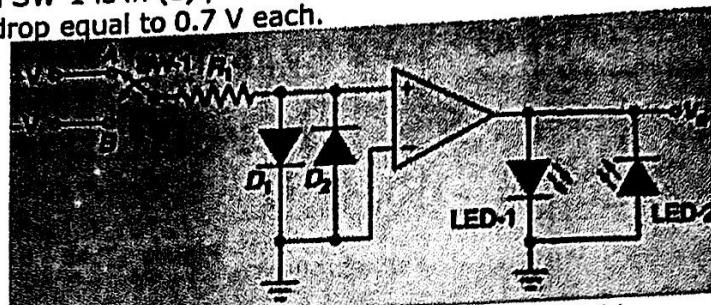


Figure 17.50: solution to Example 17.11

### **Solution:**

- When the switch SW-1 is in position-A, voltage appearing at non-inverting input is +0.7 V. (equal to forward biased voltage drop across D<sub>1</sub>). That is, voltage at non-inverting input is more positive with respect to voltage at inverting input. Therefore, opamp output goes to positive saturation with the result that LED-1 is ON and LED-2 is OFF.
- When the switch SW-1 is in position-B, voltage appearing at non-inverting input is -0.7 V. (equal to forward biased voltage drop across D<sub>2</sub>). That is, voltage at non-inverting input is more negative with respect to voltage at inverting input. Therefore, opamp output goes to negative saturation with the result that LED-1 is OFF and LED-2 is ON.

### **Example 17.12**

Figure 17.51 shows a non-inverting type of window comparator configured around comparator IV LM 339, which is a quad comparator. Determine the lower and upper trip points of the comparator and also draw the output-voltage V<sub>o</sub> versus input-voltage V<sub>i</sub> transfer characteristics.

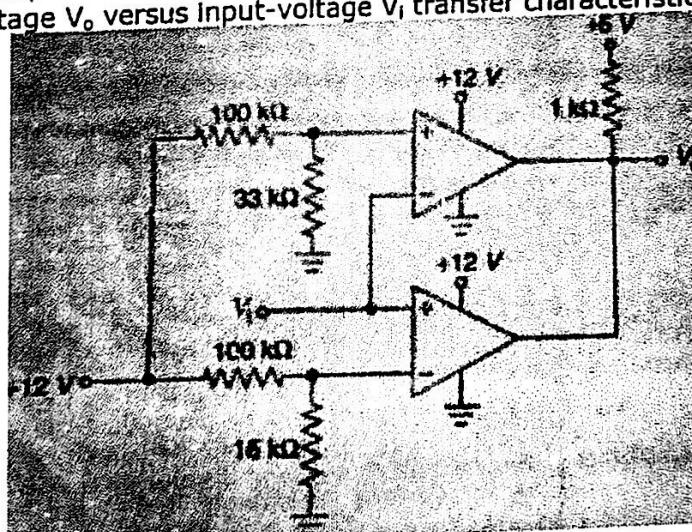


Figure 17.51: Example 17.12

### **Solution:**

- Lower trip point (LTP) is given by  $(12 * 15 * 10^3) / (115 * 10^3) = 1.565V$
- Upper trip point (UTP) is given by  $(12 * 33 * 10^3) / (133 * 10^3) = 2.977V$
- Transfer characteristics are shown in figure 17.52.

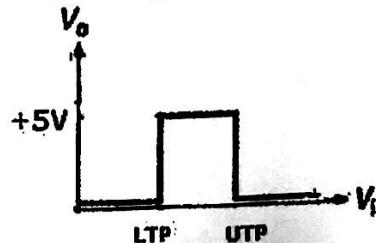


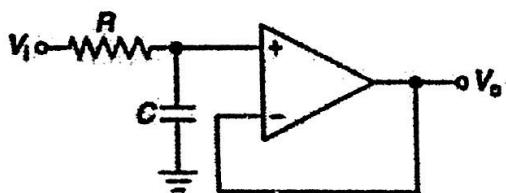
Figure 17.52: Solution to Example 17.12

## ACTIVE FILTERS

- Opamp circuits can be used to build:
  - 1) Low-pass filters.
  - 2) High-pass filters.
  - 3) Band-pass filters.
  - 4) Band-reject filters.
- Also, filters can be classified depending on their order like first-order and second-order.
- Order of an active filter is determined by number of RC sections used in the filter.

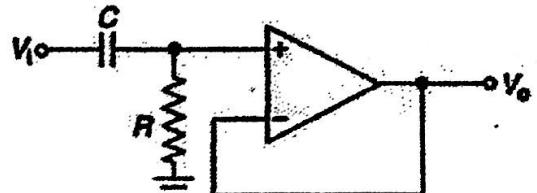
### FIRST-ORDER FILTERS

- A simple low-pass and high-pass active filters are constructed by connecting lag & lead type of RC sections, respectively, to the non-inverting input of the opamp (Fig 17.54).



(a)

Figure 17.54a: First-order low-pass active filter

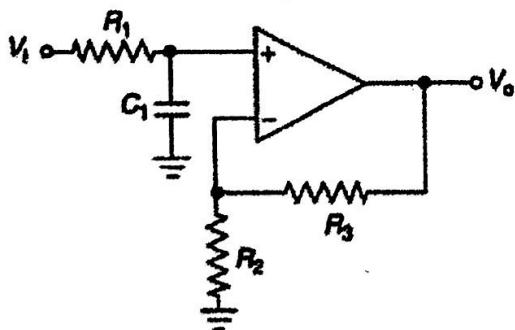


(b)

Figure 17.54b: First-order high-pass active filter

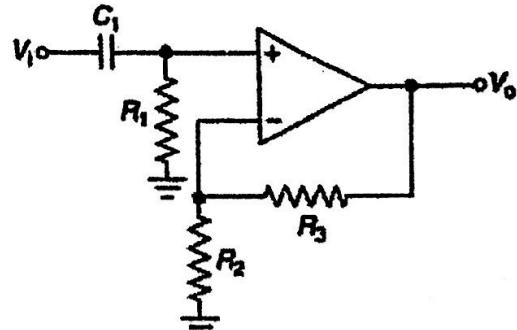
- Here is how the low-pass filter works (Figure 17.54a):
  - 1) At low frequencies, reactance offered by the capacitor is much larger than the resistance value. Therefore, applied input signal appears at the output mostly unattenuated.
  - 2) At high frequencies, the capacitive reactance becomes much smaller than the resistance value. Thus, forcing the output to be near zero.
- Here is how the high-pass filter works (Figure 17.54b):
  - 1) At high frequencies, reactance offered by the capacitor is much larger than the resistance value. Therefore, applied input signal appears at the output mostly unattenuated.
  - 2) At low frequencies, the capacitive reactance becomes much smaller than the resistance value. Thus, forcing the output to be near zero.
- Here, we consider 2 cases: 1) Inverting Filter & 2) Non-Inverting Filter.

#### Case 1: Non-Inverting Filter with gain



(a)

Figure 17.55a: Low-pass filter with gain



(b)

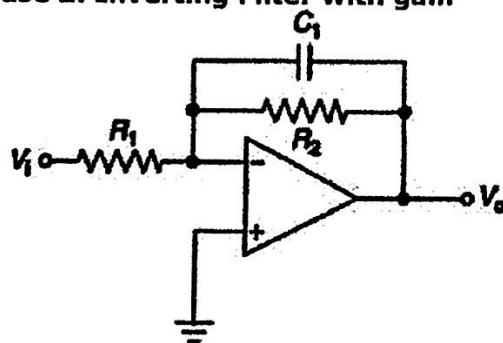
Figure 17.55b: High-pass filter with gain

➤ The cut-off frequency ( $f_c$ ) in both cases (Figure 17.55a & Figure 17.55b) is given by

$$f_c = \frac{1}{2\pi R C}$$

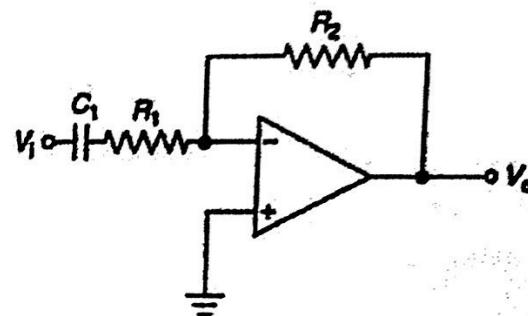
➤ The voltage gain ( $A_v$ ) in both cases is given by

$$A_v = 1 + \frac{R_3}{R_2}$$

**ANALOG AND DIGITAL ELECTRONICS****Case 2: Inverting Filter with gain**

(a)

Figure 17.56a: Inverting Low-pass filter with gain



(b)

Figure 17.56b: Inverting High-pass filter with gain

➤ In case of Inverting filters (Figure 17.56a &amp; Figure 17.56b).

The cut-off frequency ( $f_c$ ) & voltage gain ( $A_v$ ) is given by

$$f_c = \frac{1}{2\pi R_2 C_1} \quad A_v = -\frac{R_2}{R_1}$$

## **ANALOG AND DIGITAL ELECTRONICS**

### **SECOND ORDER FILTERS (BUTTERWORTH FILTER)**

- Butterworth filter is also called as **maximally flat filter**.
- It offers a relatively flat pass and stop band response.

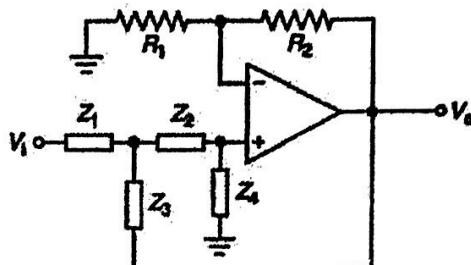


Figure 17.57: Generalized form of second-order Butterworth filter

- Here is how it works (Figure 17.57):
  1. If  $Z_1 = Z_2 = R$  and  $Z_3 = Z_4 = C$ , we get a second-order low-pass filter.
  2. If  $Z_1 = Z_2 = C$  and  $Z_3 = Z_4 = R$ , we get a second-order high-pass filter.
- The cut-off frequency( $f_c$ ) & pass band gain( $A_v$ ) is given by

$$f_c = \frac{1}{2\pi RC} \quad A_v = 1 + \frac{R_2}{R_1}$$

- Here, we consider 2 types of filters: 1) Band-pass filters & 2) Band-reject filters.

#### **1) Band-pass filters**

- Band-pass filters can be formed by cascading high-pass & low-pass filter sections in series.
- These filters are simple to design and offer large bandwidth.

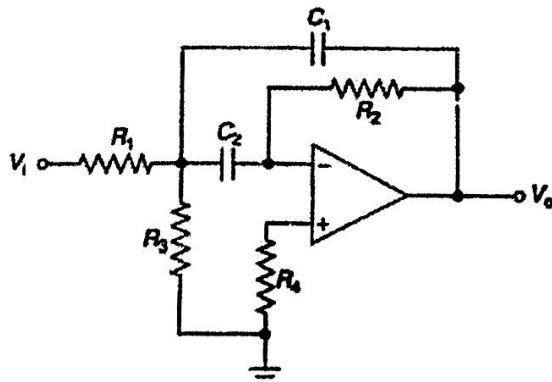


Figure 17.58: Narrow band-pass filter

➢ Here is how it works (Figure 17.58):

- 1) At very low frequencies,  $C_1$  and  $C_2$  offer very high reactance. As a result, the input signal is prevented from reaching the output.
  - 2) At very high frequencies, the output is shorted to the inverting input, which converts the circuit to an inverting amplifier with zero gain. Again, there is no output.
- At some intermediate band of frequencies, the gain provided by the circuit offsets the loss due to potential divider  $R_1-R_3$ . The resonant frequency is given by

$$f_R = 2Q/2\pi R_2 C$$

where Q is the quality factor

➢ For  $C_1 = C_2 = C$ , the quality factor and voltage gain is given by

$$Q = [R_1 R_2 / 2 R_3]^{1/2}$$

$$A_v = Q / 2\pi R_1 f_R C$$

## **ANALOG AND DIGITAL ELECTRONICS**

### **2) Band-reject filters**

- Band-reject filters can be implemented by summing together the outputs of the low-pass and high-pass filters.
- These filters are simple to design and have a broad reject frequency range.
- It uses a twin-T network that is connected in series with the non-inverting input of the opamp.

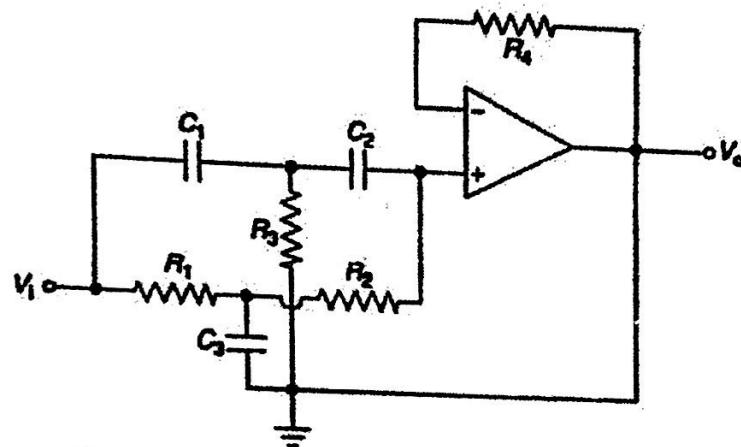


Figure 17.59: Second-order band-reject filter

➤ Here is how it works (Figure 17.59):

- 1) Very low frequency signals find their way to the output via the low-pass filter formed by  $R_1-R_2-C_3$ .
- 2) Very high frequency signals reach the output through the high-pass filter formed by  $C_1-C_2-R_3$ .

➤ Intermediate band of frequencies pass through both the filters, net signal reaching the non-inverting input and hence the output is zero.

➤ Component values are chosen by following equations:

$$R_1 = R_2 = R, R_3 = R/2$$

$$C_1 = C_2 = C, C_3 = 2C$$

$$0 \leq R_4 \leq (R_1 + R_2)$$

$$f_R = \frac{1}{2\pi RC}$$

**Example 17.14**

Refer to the first order low pass filter of figure 17.60. Determine the cut-off frequency and the gain value at four times the cut-off frequency.

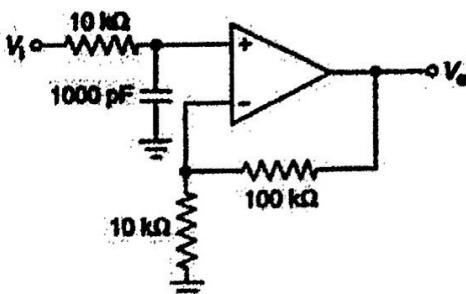


Figure 17.60: Example 17.14

**Solution:**

1. Cut-off frequency,  
 $f_c = 1/(2\pi \times 10 \times 10^3 \times 1000 \times 10^{-12}) = 10^3 / 2\pi \text{ Hz} = 15.915 \text{ kHz}$
2. Gain,  $A_v = (1 + 100 \times 10^3) / (10 \times 10^3) = 11 = 20.827 \text{ dB}$ .
3. Gain at cut-off point =  $20.827 - 3 = 17.827 \text{ dB}$ .
4. Gain at frequency four times the cut-off frequency will be 12 dB below the value of mid-band gain.
5. Therefore, gain at four times the cut-off frequency =  $20.827 - 12 = 8.827 \text{ dB}$ .

**Example 17.15**

Figure 17.61 shows a second-order low-pass filter built around a single opamp. Calculate the values of  $R_1$ ,  $R_2$ ,  $C_1$ ,  $C_2$  and  $R_3$  if the filter had a cut-off frequency of 10 kHz, Q-factor of 0.707 and input impedance not less than  $10\text{k}\Omega$ .

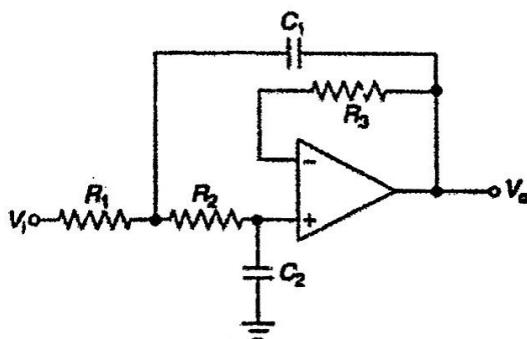


Figure 17.61: Example 17.15

**Solution:**

1. Q-factor is given by  $Q = \left(\frac{1}{2}\right) \times \sqrt{\frac{C_1}{C_2}}$
2. For  $Q = 0.707$ ,  $C_1 = 2C_2$ .
3. For input impedance of  $10\text{k}\Omega$ ,  $R_1 = 10\text{k}\Omega = R_3$ , also  $R_3 = R_1 + R_2$ ,  $\therefore R_3 = 20\text{k}\Omega$
4.  $f_c = \frac{1}{2\pi R\sqrt{C_1 C_2}}$ ,  $10 \times 10^3 = \frac{1}{2\pi \times 10 \times 10^3 \times C_2 \times \sqrt{2}}$ ,  $\therefore C_2 = 0.0011\mu\text{F}$
5.  $C_1 = 2C_2 = 0.0022\mu\text{F}$

**Example 17.16**

Design an opamp based twin-T band reject filter having a notch frequency of 100kHz. Specify the small-signal bandwidth of the chosen opamp if the highest expected frequency were 1 MHz.

**Solution:**

1. Figure 17.62 shows the circuit.

The notch frequency is given by  $f_R = 1/2\pi RC$

2. Let  $C_1 = C_2 = C$ . This gives  $R_1 = R_2 = R$ ,  $C_1 = C_2 = C$ ,  $R_3 = R/2$  and  $C_3 = 2C$ .
3. This gives  $C_1 = C_2 = 0.0001 \mu F$ , and  $C_3 = 0.0002 \mu F$
4.  $R_1 = R_2 = 15.92 \text{ k}\Omega$  and  $R_3 = (15.92 \times 10^3)/2 = 7.96 \text{ k}\Omega$
5.  $R_4 = R_1 + R_2 = (15.92 \times 10^3) + (15.92 \times 10^3) = 31.84 \text{ k}\Omega$

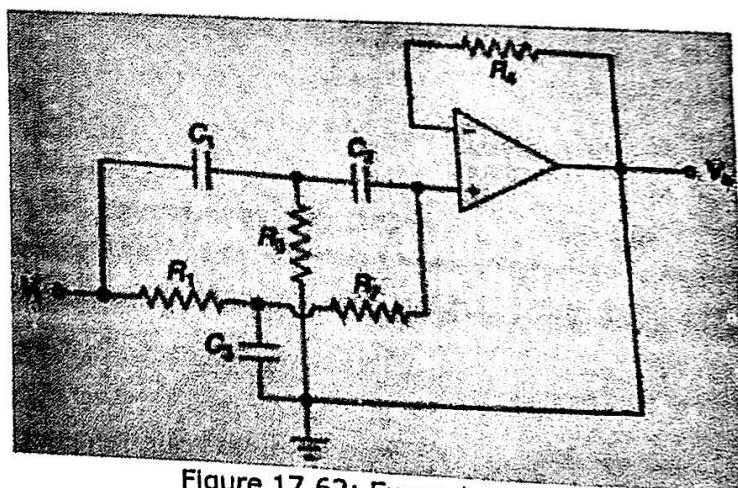


Figure 17.62: Example 17.16



## ANALOG AND DIGITAL ELECTRONICS

### NON-LINEAR AMPLIFIER

- Here, the gain value is a non-linear function of the amplitude of the signal applied at the input.
- For example, the gain may be
  - very large for weak input signals and
  - very small for large input signals.
- This implies that for a very large change in the amplitude of input signal, resultant change in amplitude of output signal is very small.

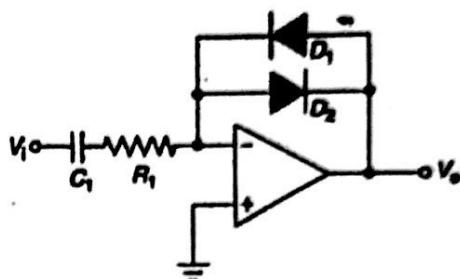


Figure 17.69: Non-linear amplifier

- For small values of input signal,
  - diodes act as open circuit and
  - gain is high due to minimum feedback (Figure 17.69).
- When the amplitude of input signal is large, diodes offer very small resistance and thus gain is low.
- Resistance  $R_1$  decides the compression ratio.  
Higher the value of resistor  $R_1$ , lesser is the compression ratio.

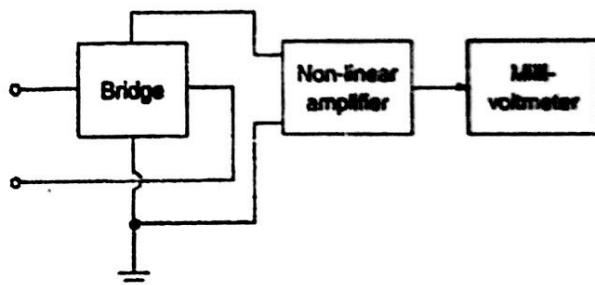


Figure 17.70: Application of non-linear amplifier in AC Bridge balance detector

- **Common Application:** AC Bridge balance detectors (Figure 17.70).
  - The output of bridge may vary over a wide range around its null point.
  - In order to achieve null, the output is usually applied to an AC millivoltmeter.
  - If the bridge output is applied to the non-linear amplifier, the output of the non linear amplifier will vary only in a small range.

## **ANALOG AND DIGITAL ELECTRONICS**

### **RELAXATION OSCILLATOR**

- Relaxation oscillator is an oscillator circuit.
- It produces a non-sinusoidal output whose time period is dependent on the charging time of a capacitor.
- The capacitor is connected as a part of the oscillator circuit.
- Here is how it works (Figure 17.71):
  - Let us assume that the output is initially in positive saturation.
  - As a result, voltage at non-inverting input of opamp is  $+V_{SAT} \times R_1/(R_1 + R_2)$
  - This forces the output to stay in positive saturation as the capacitor C is initially in fully discharged state.
  - Capacitor C starts charging towards  $+V_{SAT}$  through R.
  - The moment the capacitor voltage exceeds the voltage appearing at the non-inverting input, the output switches to  $-V_{SAT}$ .
  - The voltage appearing at non-inverting input also changes to  $-V_{SAT} \times R_1/(R_1 + R_2)$
  - The capacitor starts discharging after reaching zero, it begins to discharge towards  $-V_{SAT}$ .
  - Again, as soon as it becomes more negative than the negative threshold appearing at non-inverting input of the opamp, the output switches back to  $+V_{SAT}$ .
  - The cycle repeats thereafter.
  - The output is a rectangular wave.
- The expression for time period of output waveform can be derived from the exponential charging and discharging process and is given by

$$T = 2RC \ln\left(\frac{1+B}{1-B}\right)$$

where  $B = R_1/(R_1 + R_2)$

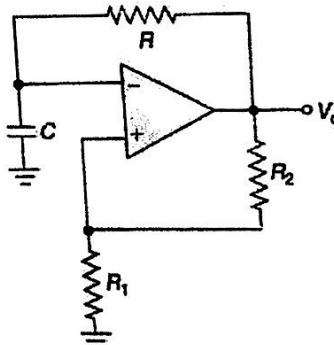


Figure 17.71: Relaxation oscillator

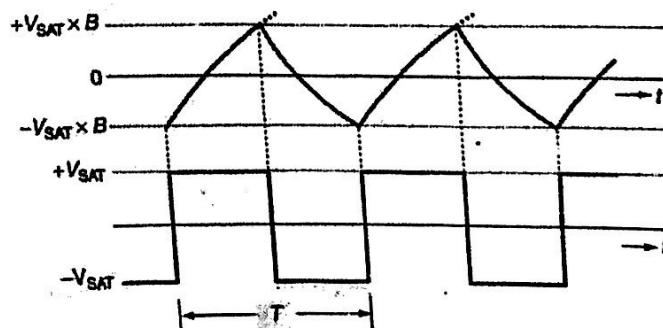


Figure 17.72: Relevant waveforms of Relaxation oscillator

**Example 17.19**

Refer to the relaxation oscillator circuit of figure 17.76. Determine the peak-to-peak amplitude and frequency of the square wave output given that saturation output-voltage of the opamp is +12.5 V at power supply voltages of +15V.

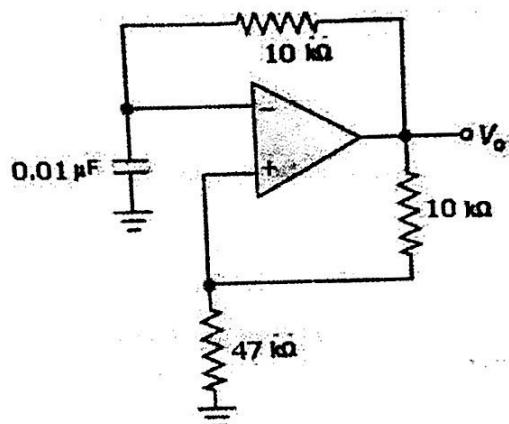


Figure 17.76: Example 17.19

**Solution:**

1. The feedback factor  $B$  is given by  $(47 \cdot 10^3) / (47 \cdot 10^3 + 10 \cdot 10^3) = 0.825$
2. Time period  $T$  of the output waveform is given by  $T = 2RC \ln [(1+B)/(1-B)]$
3. That is,  $T = 2 \cdot 10 \cdot 10^3 \cdot 0.01 \cdot 10^{-6} \ln [(1+0.825)/(1-0.825)] = 0.469 \text{ ms}$
4. Therefore,  $f = 1/T = 1/0.469 \text{ kHz} = 2.13 \text{ kHz}$
5. Peak-to-peak amplitude of output =  $2V_{\text{SAT}} = 25 \text{ V}$ .

### CURRENT-TO-VOLTAGE CONVERTER

- Current-to-voltage converter is a transimpedance amplifier (Figure 17.74).
- An ideal transimpedance amplifier makes a perfect current-to-voltage converter, as it has
  - zero input impedance &
  - zero output impedance.
- Opamp wired as transimpedance amplifier very closely approaches a perfect current-to-voltage converter.

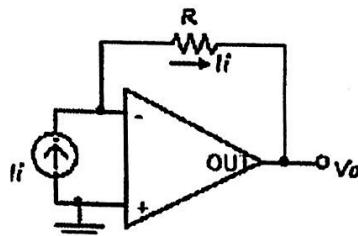


Figure 17.74: Current-to-Voltage converter

- The circuit is characterized by voltage shunt feedback with a feedback factor of unity.
- The output-voltage is given by

$$V_o = I_i \times R \times \left( \frac{A_{OL}}{1 + A_{OL}} \right).$$

For  $A_{OL} \gg 1$ , we have

$$V_o = I_i \times R$$

- Closed loop input impedance is given by

$$Z_{in} = \frac{R}{1 + A_{OL}}$$

- Closed loop output impedance is given by

$$Z_o = \frac{R_o}{1 + A_{OL}}$$

where  $R_o$  is the output impedance of the opamp.

### Example 17.20

For current-to-voltage converter circuit of figure 17.77, determine output-voltage, closed loop input and output impedance given that chosen opamp has open-loop transimpedance gain of 100,000 input impedance of  $1M\Omega$  and output impedance of  $100\Omega$ .

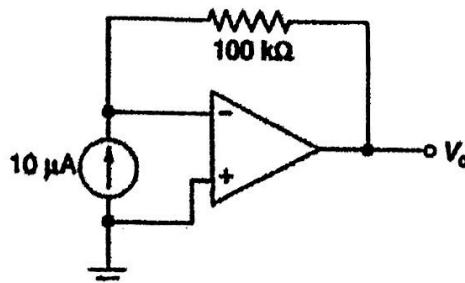


Figure 17.77: Example 17.20

### Solution:

1. Output voltage  $= 10 \times 10^{-6} \times 100 \times 10^3 = 1 V$ .
2. Closed-loop input impedance,  $Z_{in} = R/(1 + A_{OL}) = 100 \times 10^3 / (1 + 100,000) = 1 \Omega$ .
3. Closed-loop output impedance,  $Z_o = R_o/(1 + A_{OL}) = 100/(1 + 100,000) = 0.001 \Omega$ .



## ANALOG AND DIGITAL ELECTRONICS

### VOLTAGE-TO-CURRENT CONVERTER

- Voltage-to-current converter is a transconductance amplifier (Figure 17.75).
- An ideal transconductance amplifier makes a perfect voltage-controlled current source or a voltage-to-current converter.
- Opamp wired as transconductance amplifier very closely approaches a perfect voltage-to-current converter.

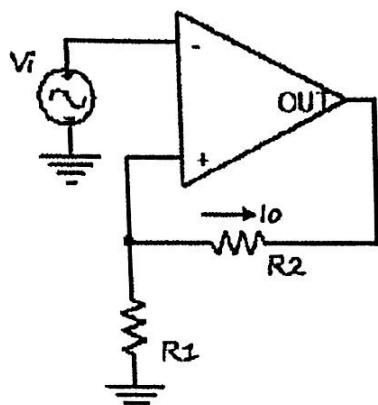


Figure 17.75: Voltage-to-Current converter

- The circuit is characterized by current series feedback.
- The output-voltage is given by

$$I_o = \frac{V_i}{R_1 + \left[ \frac{(R_1 + R_2)}{A_{OL}} \right]}$$

For  $A_{OL} \gg 1$ , we have

$$I_o = \frac{V_i}{R_1}$$

- Closed loop input impedance is given by

$$Z_{in} = R_i \times \left( 1 + A_{OL} \times \frac{R_1}{R_1 + R_2} \right)$$

where  $R_i$  is the input impedance of the opamp.

- Closed loop output impedance is given by

$$Z_o = R_1 \times \left( 1 + A_{OL} \times \frac{R_1}{R_1 + R_2} \right)$$