Chapter 6
Signal Conditioning Circuit
Power Supplies and Amplifiers
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6.1 An electronic instrumentation system consists of:

![Block Diagram Showing Components of Instrumentation System](image)

6.1.2 Power Supplies:
(1) Batteries.
(2) Line voltage power supply.

6.1.2.1 Batteries:
(1) Less expensive (Main advantage)
(2) Decay with time (Main disadvantage)
(3) Difficulty of voltage variation can be eliminated by zener diode
### Table (6-1) Types of Batteries

<table>
<thead>
<tr>
<th>Lead calcium Recharger (LCR)</th>
<th>Nickel cadmium</th>
<th>Lithium Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Voltage ranging: 4-12 volt&lt;br&gt;-Capacity: 16 VAh/lb&lt;br&gt;- Storage life: 6 months at 300° K (room temperature)&lt;br&gt;- Recharging: 500 times&lt;br&gt;- Advantages: Easy to use</td>
<td>- Cell: 1.2 volt&lt;br&gt;- Capacity: 16 VAh/lb&lt;br&gt;- Rechargeable: 500 times</td>
<td>- Lithium Iodine&lt;br&gt;OR&lt;br&gt;- Lithium manganese oxide (MnO&lt;sub&gt;2&lt;/sub&gt;)&lt;br&gt;- High individual cell voltage (20-30v)&lt;br&gt;- Not rechargeable&lt;br&gt;- Low decay under load&lt;br&gt;- Long shelf life&lt;br&gt;- High capacity (110 VAh/lb)</td>
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#### 6.1.2.2 Line Voltage Supply:
- **Main**: 110 → 220V (Input Voltage)
- **Line voltage consists of:**
Fig (6-2) Circuit Diagram of Power Supply System
6.2 Zener Diode:

- When a diode is reverse biased with a large enough voltage, the diode allows a large reverse current to flow. This is called diode breakdown. For most diodes the breakdown value is at least 50 V and may extend to kilovolts. A special class of diodes is designed to exploit this characteristic. They are known as zener, avalanche, or voltage-regulator diodes. This family of diodes exhibits steep breakdown curves with well-defined breakdown voltages, thus they can maintain a nearly constant voltage over a wide range of currents as shown in fig (6-3). This characteristic makes them good candidates for building simple voltage regulators, because they can maintain a stable DC voltage in the presence of a variable supply voltage and variable load resistance.

- To properly use the zener diode in a circuit, the zener should be reverse biased with a voltage kept in excess of its breakdown or zener voltage \( V_z \).

- Using a zener diode in series with a resistor as shown in Figure.4 results in a simple circuit known as a voltage regulator. The output voltage of the circuit \( V_{\text{out}} \), is maintained or regulated by the zener diode at the zener voltage \( V_z \).

- Even when the current through the zener diode changes (\( \Delta I_Z \) in the figure (6-3), the output voltage remains relatively constant (i.e., \( \Delta V_Z \) is small).
The narrowness of the voltage range for a given current change is a measure of the voltage regulation of the circuit. If the input voltage and load do not change much, this circuit is effective in obtaining steady and lower DC voltage values from a source, even if the source is not well regulated.

Since the load applied to the voltage regulator will change with time in most applications and the voltage source will exhibit fluctuations, careful consideration must be paid to the effect on the regulated voltage $V_Z$. For the circuit shown in Figure. 6-3, the zener current is related to the circuit voltages according to

$$I_z = \frac{(V_{in} - V_z)}{R}$$

(1)
To determine how changes in current are related to changes in voltage, we take the finite differential of Equation 1, which yields

$$\Delta I_z = \frac{I}{R} (\Delta V_{in} - \Delta V_z)$$  \hspace{1cm} (2)

The zener diode is a nonlinear circuit element, and therefore $\Delta V_z$ is not directly proportional to $I_z$. However, it is useful to define a dynamic resistance $R_d$ that is the slope of the zener characteristic curve at a particular operating point. This allows us to express the zener current change in terms of the zener voltage change:

$$\Delta I_z = \frac{\Delta V_z}{R_d}$$  \hspace{1cm} (3)

Normally a manufacturer specifies the nominal zener current $I_{zt}$, and the maximum dynamic impedance ($R_d$) at the nominal zener current. In a circuit design using a zener diode the zener current must exceed $I_{zP}$, otherwise the zener may operate near the "knee" of the characteristic curve where regulation is poor (i.e., where there is a large change in voltage with a small change in zener current).

By substituting Equation 3 into Equation 2 and solving for $\Delta V_z$, we can express changes in the regulator output voltage $V_{out}$ in terms of fluctuations in the source voltage $\Delta V_{in}$:
\[ \Delta V_{\text{out}} = \Delta V_z = \frac{R_h}{R_d + R} \Delta V_{\text{in}} \] (4)

- Therefore, the circuit acts like a voltage divider (for a change in voltage) with the zener diode represented by its dynamic resistance at the operating current of the circuit.

### 6.3 Zener Regulation Performance:
- To determine the regulation performance of the zener diode circuit shown in Figure. (6-4)(a) for a voltage source \( V_{\text{in}} \) whose value ranges between 20 and 30 V. For the zener diode we select a 1N4744A manufactured by National Semiconductor from the family 1N4728A to 1N4752A (having different zener voltage values). It is a 15 V, 1W zener diode. We select a value of \( R \) based on the specifications of this diode.

![Zener Diode Voltage Regulator](image)
To limit the maximum power dissipation to less than 1W, the current through the diode must be limited to

\[ I_{z\text{max}} = \frac{1W}{15V} = 66.7mA \]

Therefore, using Equation 1, the value for resistance \( R \) should be chosen to be at least.

\[ R_{\text{min}} = \frac{(V_{\text{in\text{max}}} - V_z)}{I_{z\text{max}}} = \frac{(30V - 15V)}{66.7mA} = 225\Omega \]

The closest acceptable standard resistance value is 240 \( \Omega \). From the manufacturer's specifications for this zener diode, its dynamic resistance \( R_d \) is 14 \( \Omega \) at 17mA. The current \( I_Z \) in this example is larger than this value, so the operating point of the zener diode is on the well-regulated portion of the characteristic curve. Using the given value for \( R_d \) in Equation 3 we can approximate the resulting output voltage range:

\[ \Delta V_{\text{out}} = \Delta V_z = \frac{R_d}{R_d + R} \Delta V_{\text{in}} = \frac{14}{14 + 240} (30 - 20) = 0.55V \]

which is a measure of regulation of this circuit. This can be expressed as a percentage of the output voltage for a relative measure:

\[ \frac{\Delta V_{\text{out}}}{V_{\text{out}}} \times 100\% = \frac{0.55V}{15V} \times 100\% = 3.7\% \]

### 6.4 Effects of Load on Voltage Regulator Design:

Figure (6-4)(a) illustrates a simple voltage regulator circuit where \( R_L \) is a load resistance and \( V_{\text{in}} \) is an unregulated source whose value exceeds the zener voltage \( V_z \). The purpose of this circuit is to provide a constant DC voltage \( V_z \) across the load with a corresponding constant current through the load. Providing a stable regulated voltage to a system containing digital integrated circuits is a common application.
If we assume the zener diode is ideal (i.e., its breakdown current-voltage curve is vertical), we can draw some conclusions about the regulator circuit. First, the load voltage will be \( V_Z \) as long as the zener diode is subject to reverse breakdown. Therefore, the load current \( I_L \) is

\[
I_L = I_{in} - I_Z
\]  

(5)

Second, the load current will be the difference between the unregulated input current \( I_i \) and the zener diode current \( I_Z \):

\[
I_L = I_{in} - I_Z
\]  

(5)

As long as \( V_Z \) is constant and the load does not change, \( I_L \) remains constant. This means that the diode current changes to absorb changes from the unregulated source.

Third, the unregulated source current \( I_{in} \) is given by

\[
I_{in} = \frac{(V_{in} - V_Z)}{R}
\]  

(6)
R is known as a current-limiting resistor since it limits the power dissipated by the zener diode. If $I_Z$ gets too large, the zener diode fails.

6.5 Zener Diode Voltage Regulator Design:

- To design a regulated 15 V DC source mechatronic system, and we would like to use the voltage regulator circuit shown in Figure (6-4). Furthermore, suppose we have access to only a poorly regulated DC source $V_{in}$ whose nominal value is 24 V.

- As the load $R_L$ changes, the zener current $I_Z$ increases for larger $R_L$ and decreases for smaller $R_L$. If we know the maximum possible load resistance (assuming that the output never is an open circuit), we can size the zener diode with regard to its power dissipation characteristics and select a current-limiting resistor. Combining Equations 5 and 6 and using the maximum value of the load $R_{L_{\text{max}}}$ gives

$$I_{Z_{\text{max}}} = \left( I_{in} - \frac{V_z}{R_{L_{\text{max}}}} \right)$$

This is the largest current the zener experiences. The power dissipated by the zener diode is

$$P_{z_{\text{max}}} = I_{Z_{\text{max}}} V_z = \left( I_{in} - \frac{V_z}{R_{L_{\text{max}}}} \right) V_z$$
I_{in} is controlled by the current-limiting resistor R. Substituting Equation 7 in 8 yields

\[ P_{z_{\text{max}}} = \left(\frac{V_{\text{in}} - V_z}{R}\right)V_z - \frac{V_z^2}{R_{\text{L_{max}}}} \]  (9)

Furthermore, for this design problem, we assume that R_{L_{\text{max}}} is 240Ω and we wish to select a 1 W zener. Therefore,

\[ I W = \frac{24V - 15V}{R_{\text{min}}} (15V) - \frac{225V^2}{240Ω} \]

We can now solve for the minimum required current-limiting resistance R:

\[ R_{\text{min}} = 69.7Ω \]

The closest acceptable standard resistance value is Ω

6.6 Advantages:

- Zener diodes are useful in circuits where it is necessary to derive smaller regulates' voltages from a single higher-voltage source. When designing zener diode circuits, one must select appropriate current-limiting resistors given the power limitations of the diodes.
- Although the zener diode voltage regulator is cheap and simple to use, it has some drawbacks: The output voltage cannot be set to a precise value, and regulation against source ripple and changes in load is limited.
6.7 Voltage Regulators:

- The present chapter introduces the operation of power supply circuits built using filters, rectifiers, and then voltage regulators. (Refer to Chapter 2 for the initial description of diode rectifier circuits.) Starting with an ac voltage, a steady dc voltage is obtained by rectifying the ac voltage then filtering to a dc level and, finally, regulating to obtain a desired fixed dc voltage. The regulation is usually obtained from an IC voltage regulator unit, which takes a dc voltage and provides a somewhat lower dc voltage, which remains the same even if the input dc voltage varies or the output load connected to the dc voltage changes.

- A block diagram containing the parts of a typical power supply and the voltage at various points in the unit is shown in Fig. (6-5). The ac voltage, typically 120V rms, is connected to a transformer, which steps that ac voltage down to the level for the desired dc output. A diode rectifier then provides a full-wave rectified voltage that is initially filtered by a simple capacitor filter to produce a dc voltage. This resulting dc voltage usually has some ripple or ac voltage variation. A regulator circuit can use this dc input to provide a dc voltage that not only has much less ripple voltage but also remains the same dc value even if the input dc voltage varies somewhat or the load connected to the output dc voltage changes. This voltage regulation is usually obtained using one of a number of popular voltage regulator IC units.
6.8 General Filter Considerations:

- A rectifier circuit is necessary to convert a signal having zero average value into one that has a nonzero average. The output resulting from a rectifier is a pulsating dc voltage and not yet suitable as a battery replacement. Such a voltage could be used in, say, a battery charger, where the average dc voltage is large enough to provide a charging current for the battery. For dc supply voltages, as those used in a radio, stereo system, computer, and so on, the pulsating dc voltage from a rectifier is not good enough. A filter circuit is necessary to provide a steadier dc voltage.
6.9 Filter Voltage Regulation and Ripple Voltage:

➢ Before going into the details of a filter circuit, it would be appropriate to consider the usual methods of rating filter circuits so that we can compare a circuit's effectiveness as a filter. Figure (6-6) shows a typical filter output voltage, which will be used to define some of the signal factors the filtered output of Fig. (6-6) has a dc value and some ac variation (ripple). Although a battery has essentially a constant or dc output voltage, the dc voltage derived from an ac source signal by rectifying and filtering will have some ac variation (ripple). The smaller the ac variation with respect to the dc level, the better the filter circuit's operation.

➢ Consider measuring the output voltage of a filter circuit using a dc voltmeter and an ac (rms) voltmeter. The dc voltmeter will read only the average or dc level of the output voltage. The ac (rms) meter will read only the rms value of the ac component of the output voltage (assuming the ac signal is coupled through a capacitor to block out the dc level).
**Definition: Ripple**

\[
    r = \frac{\text{Ripple voltage}(\text{rms})}{\text{Dc voltage}} = \frac{V_r(\text{rms})}{V_{dc}} \times 100\% \tag{10}
\]

**Example (1):**

- Using a do and ac voltmeter to measure the output signal from a filter circuit, we obtain readings of 25 V do and 1.5 V rms. Calculate the ripple of the filter output voltage.

**Solution:**

\[
    r = \frac{V_r(\text{rms})}{V_{dc}} \times 100\% = \frac{1.5V}{25V} \times 100\% = 6\%
\]

**6.10 Voltage Regulation:**

- Another factor of importance in a power supply the amount the dc output voltage changes over a range of circuit operation. The voltage provided at the output under no-load condition (no current drawn from the supply) is reduced when load current is drawn from the supply (under load). The amount the dc voltage changes between the no-load and load conditions is described by a factor called voltage regulation.

**Definition: Voltage regulation**
Voltage regulation:  

\[ \text{no load voltage} - \text{full load voltage} \]  
\[ \text{full load voltage} \]  

\[ \%V.R. = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% \]  

(11)  

(12)

Example (2):

- A dc voltage supply provides 60 V when the output is unloaded. When connected to a load, the output drops to 56 V calculate the value of voltage regulation.

Solution:

\[ \%V.R. = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% = \frac{60V - 56V}{56V} \times 100\% = 7.1\% \]

If the value of full-load voltage is the same as the no-load voltage, the voltage regulation calculated is 0%, which is the best expected. This means that the supply is a perfect voltage source for which the output voltage is independent of the current drawn from the supply. The smaller the voltage regulation, the better the operation of the voltage supply circuit.

6.11 Ripple Factor of Rectified Signal:

- Although the rectified voltage is not a filtered voltage, it contains a dc component and a ripple component. We will see that the full-wave rectified signal has a larger dc component and less ripple than the half-wave rectified voltage.
For a half-wave rectified signal, the output dc voltage is

\[ V_{dc} = 0.318 \text{ V} \]  \hspace{1cm} (13)

The rms value of the ac component of the output signal can be calculated (see Appendix B) to be

\[ V_r (\text{rms}) = 0.385 \text{ V} \]  \hspace{1cm} (14)

The percent ripple of a half-wave rectified signal can then be calculated as

\[
 r = \frac{V_r (\text{rms})}{V_{dc}} \times 100\% = \frac{0.385V_m}{0.318V_m} \times 100\% = 121\%
\]  \hspace{1cm} (15)

For a full-wave rectified voltage the dc value is

\[ V_{dc} = 0.636 \text{ V} \]  \hspace{1cm} (16)

The rms value of the ac component of the output signal can be calculated (see Appendix B) to be

\[ V_r (\text{rms}) = 0.308 \text{ V} \]  \hspace{1cm} (17)

The percent ripple of a full-wave rectified signal can then be calculated as
In summary, a full-wave rectified signal has less ripple than a half-wave rectified signal and is thus better to apply to a filter.

6.12 Capacitor Filter:

A very popular filter circuit is the capacitor-filter circuit shown in Fig. (6-7). A capacitor is connected at the rectifier output, and a dc voltage is obtained across the capacitor. Figure (6-7) (a) shows the output voltage of a full-wave rectifier before the signal is filtered, while Fig (6-7) (b) shows the resulting waveform after the filter capacitor is connected at the rectifier output. Notice that the filtered waveform is essentially a dc voltage with some ripple (or ac variation).

$$r = \frac{V_{r(m)}}{V_{dc}} \times 100\% = \frac{0.308V_m}{0.636V_m} \times 100\% = 48\%$$

Figure (6-7) Simple Capacitor Filter
ac input, Figure (6-8)(a) shows a full-wave bridge rectifier and the output waveform obtained from the circuit when connected to a load ($R_L$). If no load were connected across the capacitor, the output waveform would ideally be a constant dc level equal in value to the peak voltage ($V_p$) from the rectifier circuit.
However, the purpose of obtaining a dc voltage is to provide this voltage for use by various electronic circuits, which then constitute a load on the voltage supply. Since there will always be a load on the filter output, we must consider this practical case in our discussion.

6.13 Output Waveform Times:
- Figure (6-8) (b) shows the waveform across a capacitor filter. Time $T_1$ is the time during which diodes of the full-wave rectifier conduct, charging the capacitor up to the peak rectifier voltage, $V_m$. Time $T_2$ is the time interval during which the rectifier voltage drops below the peak voltage, and the capacitor discharges through the load. Since the charge-discharge cycle occurs for each half-cycle for a full-wave rectifier, the period of the rectified waveform is $T/2$, one-half the input signal frequency. The filtered voltage, as shown in Fig (6-9), shows the output waveform to have a dc level $V_{dc}$ and a ripple voltage $V_r$ (rms) as the capacitor charges and discharges. Some details of these waveforms and the circuit elements are considered next.

![Figure (6-9) Approximate Output Voltage of Capacitor Filter Circuit](image-url)
6.14 Ripple Voltage, \( V_r \) (RMS):

- Appendix B provides the details for determining the value of the ripple voltage in terms of the other circuit parameters. The ripple voltage can be calculated from

\[
V_{r,(rms)} = \frac{I_{dc}}{4\sqrt{3}fC} = \frac{2.41I_{dc}}{C} = \frac{2.4V_{dc}}{R_L C}
\]  

(19)

Where \( I_{dc} \) is in mill amperes, \( C \) is in microfarads, and \( R_L \) is in kilohms.

**Example (3):**

- Calculate the ripple voltage of a full-wave rectifier with a 100-\( \mu \) F filter capacitor connected to a load drawing 50 mA.

**Solution:**

\[
Eq.(19): V_{r,(rms)} = \frac{2.7(50)}{100} = 1.2V
\]

6.15 Dc Voltage, \( V_{dc} \):

- From Appendix B, we can express the dc value of the waveform across the filter capacitor as

\[
V_{dc} = V_m - \frac{I_{dc}}{4fC} = V_m - \frac{4.17I_{dc}}{C}
\]  

(20)
Where \( V_m \) is the peak rectifier voltage, \( I_{dc} \) is the load current in mill amperes, and \( C \) is the filter capacitor in microfarads.

**Example (4):**
- If the peak rectified voltage for the filter circuit of Example (4) is 30V, calculate the filter dc voltage.

**Solution:**

\[
Eeq_{dc} \approx V_{ms, w} \quad \text{can obtain the expression for the output waveform ripple of a full-wave rectifier and filter-capacitor circuit.}
\]

\[
r = \frac{V_{rms}}{V_{dc}} \times 100\% = \frac{2.4I_{dc}}{CV_{dc}} \times 100\% = \frac{2.4}{R_L C} \times 100\%
\]

where \( I_{ds} \) is in mill amperes, \( C \) is in microfarads, \( V_{dc} \) is in volts, and \( R_L \) is in kilohms.
Solution:

\[ Eq.(21): r = \frac{2.4I_{dc}}{CV_{dc}} \times 100\% = \frac{2.4(50)}{100(27.9)} \times 100\% = 4.3\% \]

We could also calculate the ripple using the basic definition

\[ r = \frac{V_{r (rms)}}{V_{dc}} \times 100\% = \frac{1.2V}{27.9V} \times 100\% = 4.3\% \]

6.17 Diode Conduction Period and Peak Diode Current:

- From the previous discussion, it should be clear that larger values of capacitance provide less ripple and higher average voltage, thereby providing better filter action. From this one might conclude that to improve the performance of a capacitor filter it is only necessary to increase the size of the filter capacitor. The capacitor, however, also affects the peak current drawn through the rectifying diodes, and as will be shown next, the larger the value of the capacitor, the larger the peak current drawn through the rectifying diodes.

- Recall that the diodes conduct during period \( T_1 \) (see Fig.6-10), during which time the diode must provide the necessary average current to charge the capacitor. The shorter time interval the larger the amount of the charging current. Figure (6-10) shows this relation for a half-wave rectified signal (it would be the same basic operation for full-wave).
Notice that for smaller values of capacitor, with $T_1$ larger, the peak diode current is less than for larger values of filter capacitor.

Since the average current drawn from the supply must equal the average diode current during the charging period, the following relation can be used (assuming constant diode current during charge time):

$$I_{dc} = \frac{T_1}{T} I_{peak}$$

From which we obtain

$$I_{peak} = \frac{T}{T_1} I_{dc}$$

Where $T_1$ = diode conduction time

$T = \frac{1}{f} (f = 2 \times 60 \text{ for full-wave})$
$I_{dc} = \text{average current drawn from filter}$

$I_{peak} = \text{peak current through conducting diodes}$

### 6.18 RC Filter:
- It is possible to further reduce the amount of ripple across a filter capacitor by using an additional RC filter section as shown in Fig. (6-11) the purpose of the added RC section is to pass most of the dc component while attenuating (reducing) as much of the ac component as possible.

![Figure (6-11) RC Filter Stage](image)

- Rectifier output Figure (6-12) shows a full-wave rectifier with capacitor filter followed by an RC filter section. The operation of the filter circuit can be analyzed using superposition for the dc and ac components of signal.
6.19 Dc Operation of RC Filter Section:

- Figure (6-13) (a) shows the dc equivalent circuit to use in analyzing the RC filter circuit of Fig. (6-13)(b). Since both capacitors are open-circuit for dc operation, the resulting output dc voltage is

\[ V_{dc} = \frac{R_L}{R + R_L} V_{dc} \]
**Example (6):**
- Calculate the dc voltage across a 1-kΩ load for an RC filter section (R = 120Ω, C = 10 μF). The dc voltage across the initial filter capacitor is $V_{dc} = 60$ V.

**Solution:**

$$ V_{dc} = \frac{R}{R + R_L} V_{dc} = \frac{1000}{120 + 1000} (60V) = 53.6V $$

**6.20 Ac Operation of RC Filter Section:**
- Figure (6-14)(b) shows the ac equivalent circuit of the RC filter section. Due to the voltage-divider action of the capacitor ac impedance and the load resistor, the ac component of voltage resulting across the load is

$$ V \cdot r(rms) \approx \frac{X_c}{R} V_r(rms) \tag{22} $$

- For a full-wave rectifier with ac ripple at 120 Hz, the impedance of a capacitor can be calculated using

$$ X_c \frac{1.3}{C} \tag{23} $$

- Where C is in microfarads and $X_c$ is in kilohms.
Example (7):
- Calculate the dc and ac components of the output signal across load $R_L$ in the circuit of Fig.(6-14). Calculate the ripple of the output waveform.

![Figure (6-14) RC Filter Circuit for Example (7)](image)

Solution:

**DC Calculation:**

$\begin{align*}
V_{dc} &= \frac{R_L}{R + R_L} V_{dc} = \frac{5k\Omega}{500 + 5k\Omega} (150V) = 136.4V
\end{align*}$

**AC Calculation:**

The RC section capacitive impedance is

$\begin{align*}
Eeq.(22) : X_c &= \frac{1.3}{C} = \frac{1.3}{10} = 0.13k\Omega = 130\Omega
\end{align*}$

The ac component of the output voltage, calculated using Eq.(10), is

$\begin{align*}
V_r^{\prime}(rms) &= \frac{X_c}{R} V_r^{\prime}(rms) = \frac{130}{500}(15V) = 3.9V
\end{align*}$
The ripple of the output waveform is then

\[ r = \frac{V_{i\text{rms}}}{V_{dc\text{}} \times 100} = \frac{3.7V}{136.4V} \times 100\% = 2.86\% \]

6.21 Discrete Transistor Voltage Regulation:
- Two types of transistor voltage regulators are the series voltage regulator and the shunt voltage regulator. Each type of circuit can provide an output dc voltage that is regulated or maintained at a set value even if the input voltage varies or if the load connected to the output changes.

6.22 Series Voltage Regulation:
- The basic connection of a series regulator circuit is shown in the block diagram of Fig. (6-15). The series element controls the amount of the input voltage that gets to the output. The output voltage is sampled by a circuit that provides a feedback voltage to be compared to a reference voltage.

![Series Regulator Block Diagram](image)
1. If the output voltage increases, the comparator circuit provides a control signal to cause the series control element to decrease the amount of the output voltage thereby maintaining the output voltage.

2. If the output voltage decreases, the comparator circuit provides a control signal to cause the series control element to increase the amount of the output voltage.

**6.23 Series Regulator Circuit:**

1. A simple series regulator circuit is shown in Fig. (6-16). Transistor Q₁ is the series control element, and Zener diode Dₖ provides the reference voltage. The regulating operation can be described as follows:

2. If the output voltage decreases, the increased base-emitter voltage causes transistor Q₁ to conduct more, thereby raising the output voltage—maintaining the output constant.

3. If the output voltage increases, the decreased base-emitter voltage causes transistor Q₁ to conduct less, thereby reducing the output voltage—maintaining the output constant.

![Figure (6-16) Series Regulator Circuit](image-url)
Example (8):

- Calculate the output voltage and Zener current in the regulator circuit of Fig. (6-17) for $R_L = 1 \, \text{k\Omega}$.

![Figure (6-17) Circuit for Example (8)]

Solution:

$$V_o = V_z - V_{BE} = 12\, V - 0.7\, V = 11.3\, V$$

$$V_{CE} = V_i - V_o = 20\, V - 11.3\, V = 8.7\, V$$

$$I_R = \frac{20\, V - 12\, V}{220\, \Omega} = \frac{8\, V}{220\, \Omega} = 36.4\, mA$$

For $R_L = 1 \, \text{k\Omega}$

$$I_L = \frac{V_o}{R_L} = \frac{11.3\, V}{1\, \text{k\Omega}} = 11.3\, mA$$

$$I_B = \frac{I_c}{\beta} = \frac{11.3\, mA}{50} = 226\, \mu A$$

$$I_z = I_R - I_a = 36.4\, mA - 226\, \mu A$$
6.24 Improved Series Regulator:

- An improved series regulator circuit is that of Fig. (6-18). Resistors \( R_1 \) and \( R_2 \) act as a sampling circuit, Zener diode \( D_Z \) providing a reference voltage, and transistor \( Q_2 \) then controls the base current to transistor \( Q_1 \) to vary the current passed by transistor \( Q_1 \) to maintain the output voltage constant.

- If the output voltage tries to increase, the increased voltage sampled by \( R_1 \) and \( R_2 \) increased voltage \( V_2 \), causes the base-emitter voltage of transistor \( Q_2 \) to go up since \( V_Z \) remains fixed. If \( Q_2 \) conducts more current, less goes to the base of transistor \( Q_1 \), which then passes less current to the load, reducing the output voltage thereby maintaining the output voltage constant. The opposite takes place if the output voltage tries to decrease, causing less current to be supplied to the load, to keep the voltage from decreasing.
The voltage $V_2$ provided by sensing resistors $R_1$ and $R_2$ must equal the sum of the base-emitter voltage of $Q_2$ and the Zener diode, that is,

$$V_{BE2} + V_z = V_2 = \frac{R_z}{R_1 + R_2} V_o \tag{24}$$

Solving Eq. (23) for the regulated output voltage, $V_o$,

$$V_o = \frac{R_1 + R_2}{R_2} (V_z + V_{BE2}) \tag{25}$$

**Example (9):**

What regulated output voltage is provided by the circuit of Fig (6-18) for the following circuit elements: $R_1 = 20 \, k\Omega$, $R_2 = 30 \, k\Omega$, and $V_Z = 8.3 \, V$?

**Solution:**

From Eq. (24), the regulated output voltage will

$$V_o = \frac{20k\Omega + 30k\Omega}{30k\Omega} (8.3V + 0.7V) = 15V$$

**6.25 Op-Amp Series Regulator:**

Another version of series regulator is that shown in Fig. (6-19). The op-amp compares the Zener diode reference voltage with the feedback voltage from sensing resistors $R_1$ and $R_2$. If the output voltage varies, the conduction of transistor $Q_1$ is controlled to maintain the output voltage constant. The output voltage will be maintained at a value of
Example (10):
>- Calculate the regulated output voltage in the circuit of Fig. (6-20)

Solution:
6.26 Current Limiting Circuit:
- One form of short-circuit or overload protection is current limiting, as shown in Fig. (6-21) as load current $I_L$ increases, the voltage drop across the short circuit sensing resistor $R_{sc}$ increases. When the voltage drop across $R_{sc}$ becomes large enough, it will drive $Q_2$ on, diverting current from the base of transistor $Q_1$, thereby reducing the load current through transistor $Q_1$, and preventing any additional current to load $R_L$. The action of components $R_{SV}$ and $Q_2$ provides limiting of the maximum load current.

![Figure (6-21) Current-limiting Voltage Regulator](image)

6.27 Fold Back Limiting:
- Current limiting reduces the load voltage when the current becomes larger than the limiting value. The circuit of Fig (6-22) provides fold back limiting, which reduces both the output voltage and output current protecting the load from over current, as well as protecting the regulator.
Fold back limiting is provided by the additional voltage-divider network of $R_4$ and $R_S$ in the circuit of Fig. (6-22) (over that of Fig) the divider circuit senses the voltage at the output (emitter) of $Q_1$. When $I_L$ increases to its maximum value, the voltage across $R_{sc}$ becomes large enough to drive $Q_2$ on, thereby providing current limiting. If the load resistance is made smaller, the voltage driving $Q_2$ on becomes less, so that $I_L$ drops when $V_L$ also drops in value—this action being fold back limiting. When the load resistance is returned to its rated value, the circuit resumes its voltage regulation action.
6.28 Shunt Voltage Regulation:

- A shunt voltage regulator provides regulation by shunting current away from the load to regulate the output voltage. Figure (23) shows the block diagram of such a voltage regulator. The input unregulated voltage provides current to the load. Some of the current is pulled away by the control element to maintain the regulated output voltage across the load. If the load voltage tries to change due to a change in the load, the sampling circuit provides a feedback signal to a comparator, which then provides a control signal to vary the amount of the current shunted away from the load. As the output voltage tries to get larger, for example, the sampling circuit provides a feedback signal to the comparator circuit, which then provides a control signal to draw increased shunt current, providing less load current, thereby keeping the regulated voltage from rising.

![Figure (6-23) Block Diagram of Shunt Voltage Regulator](image-url)
6.29 Basic Transistor Shunt Regulator:

- A simple shunt regulator circuit is shown in Fig. (6-24). Resistor \( R_s \) drops the unregulated voltage by an amount that depends on the current supplied to the load, \( R_L \). The voltage across the load is set by the Zener diode and transistor base-emitter voltage.

![Transistor Shunt Voltage Regulator](image)

- Figure (6-24) Transistor Shunt Voltage Regulator

- If the load resistance decreases, a reduced drive current to the base of \( Q_1 \) results, shunting less collector current. The load current is thus larger, thereby maintaining the regulated voltage across the load. The output voltage to the load is

\[
V_L = V_z + V_{BE}
\]
Example (11):
- Determine the regulated voltage and circuit currents for the shunt regulator of Fig (6-25).

![Figure (6-25) Circuit for Example (11)]

**Solution:**
The load voltage is

\[ V_L = 8.2V + 0.7V = 8.9V \]

For the given load,

\[ I_L = \frac{V_L}{R_L} = \frac{8.9V}{100\Omega} = 89mA \]

With the unregulated input voltage at 22 V the current through \( R_S \) is

\[ I_s = \frac{V_i - V_L}{R_s} = \frac{22V - 8.9V}{120} = 109mA \]

so that the collector current is

\[ I_c = I_s - I_L = 109mA - 89mA = 20mA \]
(The current through the Zener and transistor base-emitter is smaller than $I_c$ by the transistor beta.)

### 6.30 Improved Shunt Regulator:

- The circuit of Fig (6-26) shows an improved shunt voltage regulator circuit. The Zener diode provides a reference voltage so that the voltage across $R_1$ senses the output voltage. As the output voltage tries to change, the current shunted by transistor $Q_1$ is varied to maintain the output voltage constant. Transistor $Q_2$ provides a larger base current to transistor $Q_1$ than the circuit of Fig.(6-26), so that the regulator handles a larger load current. The output voltage is set by the Zener voltage and that across the two transistor base-emitters,

$$V_o = V_L = V_Z + V_{BE2} + V_{BE1} \quad (28)$$

![Figure (6-26) Improved Shunt Voltage Regulator Circuit](image)
6.31 Shunt Voltage Regulator Using op-Amp:

- Figure (6-27) shows another version of a shunt voltage regulator using an op-amp as voltage comparator. The Zener voltage is compared to the feedback voltage obtained from voltage divider R₁ and R₂ to provide the control drive current to shunt element Q₁. The current through resistor Rₛ is thus controlled to drop a voltage across Rₛ so that the output voltage is maintained.

6.32 Switching Regulation:

- A type of regulator circuit that is quite popular for its efficient transfer of power to the load is the switching regulator. Basically, a switching regulator passes voltage to the load in pulses, which are then filtered to provide a smooth dc voltage: Figure (6-28) shows the basic components of such a voltage regulator. The added circuit complexity is well worth the improved operating efficiency obtained.
6.33 IC Voltage Regulators:

- Voltage regulators comprise a class of widely used ICs. Regulator IC units contain the circuitry for reference source, comparator amplifier, control device, and overload protection all in a single IC. Although the internal construction of the IC is somewhat different from that described for discrete voltage regulator circuits, the external operation is much the same. IC units provide regulation of either a fixed positive voltage, a fixed negative voltage, or an adjustably set voltage.

- A power supply can be built using a transformer connected to the ac supply line to step the ac voltage to desired amplitude, then rectifying that ac voltage, filtering with a capacitor and RC filter, if desired, and finally regulating the output voltage using an IC regulator. The regulators can be selected for operation with load currents from hundreds of mill amperes to tens of amperes, corresponding to power ratings from mill watts to tens of Watts.
6.34 Three-Terminal Voltage Regulators:

- Figure (6-29) shows the basic connection of a three-terminal voltage regulator IC to a load. The fixed voltage regulator has an unregulated do input voltage, $V_i$, applied to one input terminal, a regulated output do voltage, $V_o$, from a second terminal, with the third terminal connected to ground. For a selected regulator, IC device specifications list a voltage range over which the input voltage can vary to maintain a regulated output voltage over a range of load current. The specifications also list the amount of output voltage change resulting from a change in load current (load regulation) or in input voltage (line regulation).

6.35 Fixed Positive Voltage Regulators:

- The series 78 regulators provide fixed regulated voltages from 5 to 24 V. Figure (6-29) shows how one such IC, a 7812, is connected to provide voltage regulation with output from this unit of +12V dc. An unregulated input voltage $V_i$ is filtered by capacitor $C_1$ and connected to the IC's IN terminal. The IC's OUT terminal provides a regulated +12V which is filtered by capacitor $C_2$ (mostly for any high-frequency noise).
The third IC terminal is connected to ground (GND). While the input voltage may vary over some permissible voltage range and the output load may vary over some acceptable range, the output voltage remains constant within specified voltage variation limits.

These limitations are spelled out in the manufacturer's specification sheets. A table of positive voltage regulator ICs is provided in Table (6-2).

Table (6-2): Positive Voltage Regulators in 7800 Series

<table>
<thead>
<tr>
<th>IC Part</th>
<th>Output Voltage(V)</th>
<th>Minimum Vi (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7805</td>
<td>+5</td>
<td>7.3</td>
</tr>
<tr>
<td>7806</td>
<td>+6</td>
<td>8.3</td>
</tr>
<tr>
<td>7808</td>
<td>+8</td>
<td>10.5</td>
</tr>
<tr>
<td>7810</td>
<td>+10</td>
<td>12.5</td>
</tr>
<tr>
<td>7812</td>
<td>+12</td>
<td>14.6</td>
</tr>
<tr>
<td>7815</td>
<td>+15</td>
<td>17.7</td>
</tr>
<tr>
<td>7818</td>
<td>+18</td>
<td>21.0</td>
</tr>
<tr>
<td>7824</td>
<td>+24</td>
<td>27.1</td>
</tr>
</tbody>
</table>

The connection of a 7812 in a complete voltage supply is shown in the connection of Fig. (6-30) the ac line voltage (120 V rms) is stepped down to 18 V rms across each half of the center-tapped transformer. A full-wave rectifier and capacitor filter then provides an unregulated dc voltage, shown as a dc voltage of about 22V with ac ripple of a few volts as input to the voltage regulator. The 7812 IC then provides an output that is a regulated +12 V dc.
6.36 Positive Voltage Regulator Specifications:

- The specifications sheet of voltage regulators is typified by that shown in Fig. (6-31) for the group of series 7800 positive voltage regulators. Some consideration of a few of the more important parameters should be made.

<table>
<thead>
<tr>
<th>Nominal output voltage</th>
<th>Regulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 V</td>
<td>7805</td>
</tr>
<tr>
<td>6 V</td>
<td>7806</td>
</tr>
<tr>
<td>8 V</td>
<td>7808</td>
</tr>
<tr>
<td>10 V</td>
<td>7812</td>
</tr>
<tr>
<td>15 V</td>
<td>7815</td>
</tr>
<tr>
<td>18 V</td>
<td>7818</td>
</tr>
<tr>
<td>24 V</td>
<td>7824</td>
</tr>
</tbody>
</table>
Absolute maximum ratings:
Input voltage 40 V
Continuous total dissipation 2 W
Operating free-air temperature range -65 to 150°C

IC 7812 Electrical Characteristics:

Table (6-3): specification sheet data for voltage regulator ICs. 7812

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage</td>
<td>11.5</td>
<td>12</td>
<td>12.5</td>
<td>V</td>
</tr>
<tr>
<td>Input regulation</td>
<td>3</td>
<td>120</td>
<td>MV</td>
<td></td>
</tr>
<tr>
<td>Ripple rejection</td>
<td>55</td>
<td>71</td>
<td>120</td>
<td>DB</td>
</tr>
<tr>
<td>Output regulation</td>
<td>4</td>
<td>100</td>
<td>mV</td>
<td></td>
</tr>
<tr>
<td>Output resistance</td>
<td>0.018</td>
<td></td>
<td>Ω</td>
<td></td>
</tr>
<tr>
<td>Dropout voltage</td>
<td>2.0</td>
<td></td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Short-circuit output current</td>
<td>350</td>
<td></td>
<td>mA</td>
<td></td>
</tr>
<tr>
<td>Peak output current</td>
<td>2.2</td>
<td></td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

Output voltage:
- Table (6-3) shows the specification for the 7812 that the output voltage is typically +12 V but could be as low as 11.5 V or as high as 12.5 V.

Output regulation:
- The output voltage regulation is seen to be typically 4 mV to a maximum of 100 mV (at output currents from 0.25 to 0.75 A). This information specifies that the output voltage can typically vary only 4 mV from the rated 12 V dc.
Short-circuit output current:
- The amount of current is limited to typically 0.35 A if the output were to be short-circuited (presumably by accident or by another faulty component).

Peak output current:
- While the rated maximum current is 1.5 A for this series of IC, the typical peak output current that might be drawn by a load is 2.2 A. This shows that although the manufacturer rates the IC as capable of providing 1.5 A, one could draw somewhat more current (possibly for a short period of time).

Dropout voltage:
- The dropout voltage, typically 2 V is the minimum amount of voltage across the input-output terminals that must be maintained if the IC is to operate as a regulator. If the input voltage drops too low or the output rises so that at least 2 V is not maintained across the IC input-output, the IC will no longer provide voltage regulation. One therefore maintains an input voltage large enough to assure that the dropout voltage is provided.

6.37 Fixed Negative Voltage Regulators:
- The series 7900 ICs provide negative voltage regulators, similar to those providing positive voltages. A list of negative voltage regulator ICs is provided in Table (4). As shown, IC regulators are available for a range of fixed negative voltages; the selected IC providing the rated output voltage as long as the input voltage is maintained greater than the minimum input value. For example, the 7912 provides an output of -12 V as long as the input to the regulator IC is more negative than -14.6 V.
TABLE (6-4): Negative Voltage Regulators in 7900 Series

<table>
<thead>
<tr>
<th>IC Part</th>
<th>Output Voltage (V)</th>
<th>Minimum $V_i$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7905</td>
<td>-5</td>
<td>-7.3</td>
</tr>
<tr>
<td>7906</td>
<td>-6</td>
<td>-8.4</td>
</tr>
<tr>
<td>7908</td>
<td>-8</td>
<td>-10.5</td>
</tr>
<tr>
<td>7909</td>
<td>-9</td>
<td>-11.5</td>
</tr>
<tr>
<td>7912</td>
<td>-12</td>
<td>-14.6</td>
</tr>
<tr>
<td>7915</td>
<td>-15</td>
<td>-17.7</td>
</tr>
<tr>
<td>7918</td>
<td>-18</td>
<td>-20.8</td>
</tr>
<tr>
<td>7924</td>
<td>-24</td>
<td>-27.1</td>
</tr>
</tbody>
</table>

Example (12):
- Draw a voltage supply using a full-wave bridge rectifier, capacitor filter, and IC regulator to provide an output of +5 V.

Solution
- The resulting circuit is shown in Fig. (6-32).

![Figure (6-32) + 5-V Power Supply]
Example (13)

- For a transformer output of 15 V and a filter capacitor of 250 μF, calculate the minimum input voltage when connected to a load drawing 400 mA.

Solution:

- The voltages across the filter capacitor are

\[ V_r(\text{peak}) = \sqrt{3} \frac{2.41I}{C} = \sqrt{3} \frac{2.4(400)}{250} = 6.65V \]

\[ V_{dc} = V_m - V_r = 15V - 6.65V = 8.35V \]

- Since the input swings around this do level, the minimum input voltage can drop to as low as

\[ V_i(\text{low}) = V_{dc} - V_r(\text{peak}) = 15V - 6.65V = 8.35V \]

- Since this voltage is greater than the minimum required for the IC regulator (from Table (6-3), \( V_i = 7.3 \) V), the IC can provide a regulated voltage to the given load.

Example (14):

- Determine the maximum value of load current at which regulation is maintained for the circuit of Fig. (6-32).

Solution:

- To maintain \( V_i(\text{min}) \geq 7.3 \) V,

\[ V_r(\text{peak}) \leq V_m - V_i(\text{min}) = 15V - 7.3V = 7.7V \]
so that

\[ V_{r}(\text{rms}) = \frac{V_{r}(\text{peak})}{\sqrt{3}} = \frac{7.7V}{\sqrt{3}} = 4.4V \]

The value of load current is then

\[ I_{dc} = \frac{V_{r}(\text{rms})C}{2.4} = \frac{(4.4V)(250)}{2.4} = 458mA \]

Any current above this value is too large for the circuit to maintain the regulator output at +5 V.

**6.38 Adjustable Voltage Regulators:**

- Voltage regulators are also available in circuit configurations that allow the user to set the output voltage to a desired regulated value. The LM317, for example, can be operated with the output voltage regulated at any setting over the range of voltage from 1.2 to 37 V Figure (6-33) shows how the regulated output voltage of an LM317 can be set.
- Resistors R₁ and R₂ set the output to any desired voltage over the adjustment range (1.2 to 37 V). The output voltage desired can be calculated using.

\[
V_o = V_{ref}\left(1 + \frac{R_2}{R_1}\right) + I_{adj}R_2
\]  

(29)

With typical IC values of

\[ V_{ref} = 1.25 \text{ V} \quad \text{and} \quad I_{adj} = 100\mu \text{ A} \]
Example (15)
Determine the regulated voltage in the circuit of Fig. (6-33) with $R_1 = 240 \, \Omega$ and $R_2 = 2.4 \, \Omega$.

Solution:

Eq. (28):

\[ V_o = V_o = 1.25V \left( 1 + \frac{2.4k\Omega}{240\Omega} \right) + (100\mu A)(2.4k\Omega) \]

\[ = 13.75V + 0.24V = 13.99V \]
Example (16):
Determine the regulated output voltage of the circuit in Fig. (6-34).

Solution:
The output voltage calculated using Eq. (28) is

\[ V_o = 1.25V \left( 1 + \frac{1.8k\Omega}{240\Omega} \right) + (100\mu A)(1.8k\Omega \approx 10.8V) \]

A check of the filter capacitor voltage shows that an input-output difference of 2 V can be maintained up to at least 200 mA load current.

6.39 Performance Characteristics of Power Supplies:
For the range \((o \rightarrow 40v), (o \rightarrow 3A)\)

1. Load Effect:
   a) For constant voltage source: 0.01 \% + 200 \(\mu V\)
   b) For constant current source: 0.02\% + 500 \(\mu V\)

EX \(\text{i} : \)
If the voltage of regulator = 20 volt
Solution: \[ 20 \pm \left( \frac{0.01}{100} \times 2 \times 20 + 200 \times 10^{-6} \right) = 20 \pm 0.0022 \]

EX2: If the current is 2 AMP

Solution: \[ 2 \pm \left( \frac{0.02}{100} \times 2 \times 2 + 500 \times 10^{-6} \right) = 2 \pm 0.0045 \]

2. Source Effect:
Source effect is the change in output for change in line voltage (input)
   a) Constant voltage source: 0.01 % + 200 μV
   b) Constant current source: 0.02% + 500 μV

3. Temperature Effect:
It is the change in the output voltage or current per degree centigrade (°C) following the warm-up period of 30 minutes.
   a) Constant voltage source: 0.01 % + 200 μV
   b) Constant current source: 0.01% + 1 μV

4. Drift Stability:
It is a change in the output under constant load over an 8 hours period following the 30min warm-up period is:
   a) For Constant voltage source: 0.03% + 500 μV
   b) For Constant current source: 0.03% + 3 μV
5. The output Impedance of the power supply:

Typical values of the output impedance
L=1μH
r =2 mΩ

6.40 Amplifiers:

- An amplifier increases the amplitude of a signal without affecting the phase relationships of different components of the signal. When choosing or designing an amplifier, we must consider size, cost, power consumption, input impedance, output impedance, gain, and bandwidth. Physical size depends on the components used to construct the amplifier.
- Generally, we model an amplifier as a two-port device, with an input and output voltage referenced to ground, as illustrated in Figure.(6-35). The voltage gain of an amplifier is defined as the ratio of the output and input voltage amplitudes:

\[ A_v = \frac{V_{out}}{V_{in}} \]  

- Normally we want an amplifier to exhibit amplitude linearity, where the gain is constant for all frequencies. However, amplifiers may be designed to intentionally amplify only certain frequencies, resulting in a filtering effect. In such cases, the output characteristics are governed by the amplifier's bandwidth and associated cutoff frequencies.
The input and output impedances of an amplifier, $Z_{in}$ and $Z_{out}$, are found by measuring the ratio of the respective voltage and current:

$$V_{in} = \frac{V_{in}}{I_{in}}$$

(31)

$$Z_{out} = \frac{V_{out}}{I_{out}}$$

(32)

For the operational amplifiers, $Z_{in}$ is larger than 100 kΩ and $Z_{out}$ is a few ohms or less.

In amplification the work inside the linear region.

Figure (6-35) Amplifier Model
6.41 The Ideal Operational Amplifier:

- The schematic symbol for an ideal op amp as shown in Fig (6-3)(1). It is a differential input, single output amplifier that is assumed to have infinite gain. The - symbol is sometimes used in the schematic to denote the infinite gain and the assumption that it is an ideal op amp. The voltages are all referenced to a common ground. The op amp is connection to an external power supply, usually plus and minus 15 V.

![Fig. (6-36)(a) Op amp Terminology and Schematic Representation](image)

![Fig. (6-36)(b) [Op-amp feedback]](image)
As illustrated in Figure 6-36-b an op amp circuit usually includes feedback from the output to the negative (inverting) input. This so-called closed loop configuration results in stabilization of the amplifier and control of the gain. When feedback is absent in an op amp circuit, the op amp is said to have an open loop configuration. This configuration results in considerable instability due to the infinite gain, and it is seldom used. The utility of feedback will become evident in the examples presented in the following sections.

Figure (6-37) illustrates an ideal model that can aid in analyzing circuits containing op amps. This model is based on the following assumptions that describe an ideal op amp:

1. **It has infinite impedance at both inputs** hence no current is drawn from the input circuits. Therefore,

\[ L_+ = L = 0 \quad (33) \]
2. **It has infinite gain.** As a consequence, the difference between the input voltages must be 0; otherwise, the output would be infinite. This is denoted in Figure 10 by the shorting of the two inputs.

\[ V_+ = V_- \]  

(34)

![741 op amp pin-out](image)

Therefore, Even though we indicate a short between the two inputs, we assume no current may flow through this short.

3. **It has zero output impedance.** Therefore, the output voltage does not depend on the output current.

   - Note that \( V_{\text{out}}, V_+, \) and \( V_- \) are all referenced to a common ground. Also, for stable linear behavior, there must be feedback between the output and the inverting input.
We need only Kirchhoff's laws and Ohm's law to completely analyze op amp circuits. Actual op amps are usually packaged in eight-pin dual in-line package (DIP) integrated circuit (IC) chips. The designation for a general purpose op amp produced by many IC manufacturers is 741. It is illustrated in Figure (38) with its pin configuration (pin-out). As with all ICs, one end of the chip is marked with an indentation or spot, and the pins are numbered counterclockwise and consecutively starting with 1 at the left side of the marked end. For a 741 series op amp, pin 2 is the inverting input, pin 3 is the non-inverting input, pins 4 and 7 are for the external power supply, and pin 6 is the op amp output. Pins 1, 5, and 8 are not normally connected. Figure (38) illustrates the internal design of a 741 IC available from National Semiconductor. Note that the circuits are composed of transistors, resistors, and capacitors that are easily manufactured on a single silicon chip. The most valuable details for the user are the input and output parts of the circuit having characteristics that might affect externally connected components.

### 6.42 Inverting Amplifier:

- An inverting amplifier is constructed by connecting two external resistors to an op amp as shown in Figure (6-39). As the name implies, this circuit inverts and amplifies the input voltage. Note that the resistor $R_f$ forms the feedback loop. This feedback loop always goes to the inverting input of the op amp, implying negative feedback.
We now use Kirchhoff's laws and Ohm's law to analyze this circuit. First, we replace the op amp with its ideal model shown within the dashed box in Figure (6-40). Applying Kirchhoff's current law at node C and utilizing assumption 1, that no current can flow into the inputs of the op amp,

\[ I_{in} = -i_{out} \]  

(35)

Fig (6-39) Inverting Amplifier

Fig (6-40) Equivalent Circuit for Inverting Amplifier
Also, since the two inputs are assumed to be shorted in the ideal model, C is effectively at ground potential:

\[ V_c = 0 \] (36)

Since the voltage across resistor \( R \) is \( V_{\text{in}} - V_c = V_{\text{in}} \), from Ohm's low,

\[ V_{\text{in}} = i_{\text{in}} R \] (37)

And since the voltage across resistor \( R_F \) is \( V_{\text{out}} - V_c = V_{\text{out}} \),

\[ V_{\text{out}} = i_{\text{out}} R_F \] (38)

Substituting Equation.34 into Equation.37 gives

\[ V_{\text{out}} = i_{\text{in}} R_F \] (39)

Dividing Equation.38 by Equation.36 yields the input/ output relationship:

\[ \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{R_F}{R} \] (40)
Therefore, the voltage gain of the amplifier is determined simply by the external resistors $R_F$ and $R$, and it is always negative. The reason this circuit is called an inverting amplifier is that it reverses the polarity of the input signal. This results in a phase shift of $180^\circ$ for periodic signals. For example, if the square wave $V_{in}$ shown in Figure (6-41) is connected to an inverting amplifier with a gain of -2, the output $V_{out}$ is inverted and amplified, resulting in a larger amplitude signal $180^\circ$ out of phase with the input.

6.43 Non-inverting Amplifier:

- The schematic of a non-inverting amplifier is shown in Figure (42). As the name implies, this circuit amplifies the input voltage without inverting the signal. Again, we can apply Kirchhoff's laws and Ohm's law to determine the voltage gain of this amplifier.
- The voltage at node C is $V_{in}$ since the inverting and non-inverting inputs are at the same voltage. Therefore, applying Ohm's law to resistor $R$, 

$$I_{in} = \frac{-V_{in}}{R}$$

(41)
and applying it to resistor $R_F$,

$$i_{out} = -\frac{V_{out} - V_{in}}{R_F}$$  \hspace{1cm} (42)
Solving Equation.41 for $V_{out}$, gives

$$V_{out} = i_{out}R_F + V_{in} \quad (43)$$

Applying KCL at node C gives Fig (43)

$$i_{in} = -i_{out} \quad (44)$$

So Equation.40 can be written as

$$V_{in} = i_{out}R \quad (45)$$

Using Equations.42 and 44, the voltage gain can be written as

$$\frac{V_{out}}{V_{in}} = \frac{i_{out} + V_{in}}{V_{in}} = \frac{i_{out}R_F + i_{out}R}{i_{out}R} = 1 + \frac{R_F}{R} \quad (46)$$

Therefore, the non-inverting amplifier has a positive gain greater than or equal to 1. This is useful in isolating one portion of a circuit from another by transmitting a scaled voltage without drawing appreciable current. If we let $R_F = 0$ and $R = \infty$, the resulting circuit can be represented as shown in Figure 44. This circuit is known as a buffer or follower since $V_{out} = V_{in}$. It has high input impedance and low output impedance. This circuit is useful in applications where you need to couple to a voltage signal without loading the source of the voltage. The high input impedance of the op amp effectively isolates the source from the rest of the circuit.
6.44 Difference Amplifier (Dual inputs):-

The difference amplifier circuit shown in Figure (6-45) is used to subtract analog signals. In analyzing this circuit, we can use the principle of superposition, which states that, whenever multiple inputs are applied to a linear system (e.g., an op amp circuit), we can analyze the circuit and determine the response for each of the individual inputs independently.

Fig (6-45) Difference Amplifier Circuit

Fig (6-46) Difference Amplifier with V2 Shorted
The sum of the individual responses is equivalent to the overall response to the multiple inputs. Specifically, when the inputs are ideal voltage sources, to analyze the response due to one source, the other sources are shorted. If some inputs are, current sources, they are replaced with open circuits.

The first step in analyzing the circuit in Figure (6-45) is to replace \( V_2 \) with a short circuit, effectively grounding \( R_2 \). As shown in Figure (6-46), the result is an inverting amplifier.

Therefore, from Equation (39), the output due to input \( V_1 \) is

\[
V_{\text{out}} = \frac{R_F}{R_1} V_1
\]  
(47)

The second step in analyzing the circuit in Figure 45 is to replace short circuit, effectively grounding \( R_1 \) as shown in Figure 47a. This equivalent to the circuit shown in Figure (6-20) (b) where the input voltage is since \( V_2 \) is divided between resistors \( R_2 \) and \( R_F \).

\[
V_3 = \frac{R_F}{R_2 + R_F} V_2
\]  
(48)

The circuit in Figure 47b is a non-inverting amplifier. Therefore, the output due to input \( V_2 \) is given by Equation 45

\[
V_{\text{out2}} = \left(1 + \frac{R_F}{R_1}\right) V_3
\]  
(49)
By substituting equation 47, in equation 48.

\[ V_{out2} = \left( 1 + \frac{R_F}{R_1} \right) \left( \frac{R_F}{R_2 + R_F} \right) V_2 \]  

(50)

Fig (6-47) Difference Amplifier with V1 Shorted

- The principle of superposition states that the total output \( V_{out} \) is the sum of the outputs due to the individual inputs:

\[ V_{out} = V_{out1} + V_{out2} = \left( \frac{R_F}{R_1} \right) V_1 + \left( 1 + \frac{R_F}{R_1} \right) \left( \frac{R_F}{R_2 + R_F} \right) V_2 \]  

(51)

- When \( R_1 = R_2 = R \), the output voltage is an amplified difference of the input voltages:

\[ V_{out} = \frac{R_F}{R} (V_2 - V_1) \]  

(52)
6.45 Integrator:

- The result is an integrator circuit. It is shown in Figure 6-48 referring to the analysis for the inverting amplifier. The relationship between voltage and current for a capacitor:

\[
\frac{dV_{\text{out}}}{dt} = \frac{i_{\text{out}}}{C}
\]  

Integrating gives

\[
V_{\text{out}}(t) = \frac{1}{C} \int_{0}^{t} i_{\text{out}}(\tau) d\tau
\]  

Where \( \tau \) is a dummy variable of integration. Since \( i_{\text{out}} = -i_{\text{in}} \) and \( i_{\text{in}} = V_{\text{in}}/R \),

\[
V_{\text{out}}(t) = \frac{1}{C} \int_{0}^{t} V_{\text{in}}(\tau) d\tau
\]  

Therefore, the output signal is an inverted, scaled integral of the input signal.

Fig (6-48) Ideal Integrator
6.46 Differentiator:
- If the input resistor of the inverting op amp circuit is replaced by a capacitor, the result is a differentiator circuit. It is shown in Figure (6-49). Referring to the analysis for the inverting amplifier, Equation (34) is replaced by the relationship between voltage and current for a capacitor:

\[
\frac{dV_{in}}{dt} = \frac{i_{in}}{C}
\]  

(56)

Since \( i_{in} = -i_{out} \) and to \( i_{out} = V_{out}/R \),

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

(57)

Therefore, the output signal is an inverted, scaled derivative of the input signal. Differentiation is a signal processing method that tends to accentuate the effects of noise whereas integration smoothes signals over time.
6.47 Comparator:

- The comparator circuit illustrated in Figure (6-50) is used to determine whether one signal is greater than another.

![Figure (6-50) Comparator](image)

The comparator is an example of an op amp circuit where there is no negative feedback and the circuit exhibits infinite gain. The result is that the op amp saturates. Saturation implies that the output remains at its most positive or most negative output value. Certain op amps are specifically designed to operate as comparators. The output of the comparator is defined by

\[
V_{\text{out}} = \begin{cases} 
+V_{\text{sat}} & V_{\text{in}} < V_{\text{ref}} \\
-V_{\text{sat}} & V_{\text{in}} > V_{\text{ref}} 
\end{cases}
\]  

(58)
Where $V_{sat}$ is the saturation voltage of the comparator and $V_{ref}$ is the reference voltage to which the input voltage $V_{in}$ being compared. The positive saturation value is slightly less than the positive supply voltage, and the negative saturation value is slightly greater than the negative supply voltage.

Some comparators (e.g., LN1339) have open-collector outputs, where the output states are controlled by an output transistor operating at cutoff or saturation. This type of output, illustrated in Figure (6-51), is called an open collector output since the collector of the output transistor is not connected internally and requires an external powered circuit. The output transistor is ON (at saturation) and the output is effectively grounded when $V_{in} > V_{ref}$, and the output transistor is OFF (at cutoff) and the output is open circuit when $V_{in} < V_{ref}$.

6.48 The Real op Amp:

- An actual operational amplifier deviates somewhat in characteristics from an ideal op amp. As the ideal operational amplifier model implies, real op amps have very high input impedance, so very little current is drawn at the inputs.

- At the same time, there is very little voltage difference between the input terminals. However, the input impedance of a real op amp is not infinite, and its magnitude is an important terminal characteristic of the op amp.

- Another important terminal characteristic of any real op amp is the maximum output voltage that can be obtained from the amplifier. Consider an op amp circuit with a gain of 100 set by the external resistors in a non-inverting amplifier configuration.
For a 1V input you would expect a 100 V output. In reality, the maximum voltage output will be about 1.4 V less than the supply voltage to the op amp for large load impedance. So if a ±15 V supply is being used, the maximum voltage output would be approximately 13.6 V and the minimum would be -13.6 V.

Two other important characteristics of a real op amp are associated with its response to a square wave input. When you apply a square wave input to an amplifier circuit you ideally would expect a square wave output. However, as illustrated in Figure. (6-52), the output cannot change infinitely fast; instead, it exhibits a ramp from one level to the next. In order to quantify the op amp step response, two parameters are defined:

- **Slow rate**—The maximum time rate of change possible for the output voltage:

\[ SR = \frac{\Delta V}{\Delta t} \] (59)
• Rise time-The time required for the output voltage to go from 10% to 90% of its final value. This parameter is specified by manufacturers for specific load and input parameters.

• Frequency response. An ideal op amp exhibits infinite bandwidth. In practice, however, real op amp has a finite bandwidth, which is a function of the gain established by external components. To quantify this dependence of bandwidth on the gain, another definition is used: the gain bandwidth product (GBP). The GBP of an op amp is the product of the open-loop gain and the bandwidth at that gain. The GBP is constant over a wide range of frequencies because, as shown in Figure (6-53), typical op amps exhibit a linear log relationship between open-loop gain and frequency. Note how the op amp's gain decreases with input signal frequency. Higher-quality op amps have larger GBPs. The open-loop gain is a characteristic of the op amp without feedback. The closed-loop gain is the overall gain of an op amp circuit with feedback.

Fig (6-53) Typical op amp open - and closed- loop Response
The closed-loop gain is always limited by the open-loop gain of the op amp. For example, a non-inverting amplifier with a closed-loop gain of 100 would have a bandwidth of 0 Hz to approximately 10,000 Hz as illustrated in Figure (6-53). The frequency where the open-loop gain curve first starts to limit the closed-loop gain is called the fall-off frequency. As you increase the gain of a circuit, you limit its bandwidth. Likewise, if your application requires only a small bandwidth (e.g., in a low-frequency application), larger gains can be used without signal attenuation or distortions.

6.49 Cascaded Amplifiers:

\[
\begin{align*}
V_1 &= V_i \cdot \frac{Z_i}{Z_1 + Z_i} \\
V_2 &= C \cdot V_1 \\
\text{Sub with } V_1 \text{ value} \\
V_2 &= V_i \cdot \frac{Z_i}{Z_1 + Z_i} \cdot G \\
V_3 &= V_2 \cdot \frac{Z_i}{Z_0 + Z_i}
\end{align*}
\]
Sub with $V_2$ value

$$V_3 = V_i \frac{Z_i}{Z_i + Z_1} \frac{Z_i}{Z_o + Z_i} * G$$

$$V_4 = V_3 * G$$

Sub with $V_3$ value

$$V_4 = \frac{V_i (Z_i G)^2}{(Z_i + Z_1)(Z_o + Z_i)}$$

$$V_5 = V_4 * \frac{Z_i}{Z_o + Z_i}$$

$$V_6 = V_5 * G$$

$$= \frac{V_i (Z_i G)^2}{(Z_i + Z_1)(Z_i + Z_o)} \frac{Z}{(Z_o + Z_2)} * G$$

$$V_o = G^3 \left( \frac{Z_i}{Z_i + Z_o} \right)^2 * \left( \frac{Z_i}{Z_i + Z_1} \right) * \left( \frac{Z_2}{Z_2 + Z_o} \right) V_i$$

(60)

6.50 Amplifier Classifications:

1. Single Input:
\[ V_o = G \cdot V_i \]  \hfill (61)

- Both input output are referenced to the ground.

2. **Dual Inputs:** (Differential)

\[ V_o = G \cdot (V_1i - V_2i) \]  \hfill (62)

- Both inputs and output are referenced to the ground

* It will amplify the difference between two input signals.

\[
\begin{align*}
V_1 &= V \\
V_2 &= v + \Delta v \\
V &= \text{Common mode voltage} \\
\Delta v &= \text{Is the small change voltage difference to be amplified.}
\end{align*}
\]

\[ V_o = G(v_1i - V_2i) \]  
For more accurate results, we use
\[ V_o = Gd \Delta v + Gc V \]  \hspace{1cm} (63)

**Where**
- \( Gd \) = Gain for the difference voltage (Difference mode)
- \( Gc \) = Gain for the common voltage (common mode)
- \( Cmrr \) = Common mode rejection Ratio

\[ CMRR = \frac{Gd}{Gc} \]  \hspace{1cm} (64)

Very high value for CMRR is preferred, so \( Gc \) is minimized.

6.51 **Amplifier Characteristics:**

**It has the following characteristics:**

1. Very high input impedance.
2. Large common mode rejection ratio (CMRR). The CMRR is the ratio of the difference mode gain to the common mode gain. The difference mode gain is the amplification factor for the difference between the input signals, and the common mode gain is the amplification factor for the average of the input signals. For an ideal difference amplifier, the common mode gain is 0, implying an infinite CMRR. When the common mode gain is nonzero, the output is nonzero when the inputs are equal and nonzero. It is desirable to minimize the common mode gain to suppress signals such as noise that are common to both inputs.
3. Capability to amplify low-level signals in a noisy environment, often a requirement in differential output sensor signal conditioning applications.

4. Consistent bandwidth over a large range of gains.

5. Signal to Noise Ratio: (S/N) or (SNP)

\[
\left( \frac{S}{N} \right)_i = \left( \frac{V_i}{V_{ni}} \right)^2
\]

Power not voltage

SNR = Power

Where:

V_{ni} = Signal or voltage super imposed on the input signal by noise

6. Input / output noise Figure (Fn)

\[
Fn = 10 \log \left[ \frac{((S/V)_i)}{(S/N)_o} \right]
\]  

Fn = 10 Log [NF]

NF = Noise factor = \( \frac{(S/N)_i}{(S/N)_o} \)

\[
(S / N) = \left( \frac{V_o}{V_{no}} \right)^2 = \frac{Gp*V_i^2}{Gp*V_{ni}^2 + V_{nA}^2}
\]
Where:

\( G_p \) = power gain of Amplifier
\( V_{ni} \) = Input signal noise
\( V_{nA} \) = noise of the amplifier

\[
NF = \left( \frac{S}{N} \right)_i = \frac{V_i}{V_{ni}}^2 \frac{G_p V_i^2}{G_p V_n^2 + V_n A^2}
\]

\[
NF = 1 + \frac{V_{n}^2 A}{V_{ni}^2 \cdot C_p} = \left( \frac{S}{N} \right)_i \frac{(S \, / \, N)_i}{(S \, / \, N)_o}
\]

(67)