OPERATIONAL AMPLIFIERS

Operational amplifiers perform mathematical operations on input voltages to obtain desired output voltage characteristics by choosing the feedback/input impedance relationship of a high-gain d-c amplifier. This instruction leaflet will introduce the terminology, symbols and basic theory of operational amplifiers as outlined below.

Section I - Operational Amplifier Theory
Section II - High-Gain D-C Amplifiers
Section III - Checking Operational Amplifiers

I. OPERATIONAL AMPLIFIER THEORY

The operational amplifier is a high-gain voltage amplifier designed to remain stable with large amounts of negative feedback from output to amplifier input (SJ). Thus, it functions in the manner of a self-balancing bridge, providing through the feedback element whatever current is necessary to hold the summing junction (SJ) to virtual zero.

The present line of operational amplifiers provides a separate component board on which the input and feedback components are assembled. These components produce the output voltage characteristics of the operational amplifier which can be evaluated by obtaining the mathematical relationship of the feedback to input impedance ratio. This ratio is called the transfer function of the device.

To introduce the method used to obtain the transfer function of each operational amplifier, the following assumptions must be made:

1. Amplifier input current (i_g) = 0
2. Amplifier drift and offset = 0
3. Amplifier output voltage is 180° out of phase with the input voltage

A. To derive the mathematical relationship of the configuration given in Figure 1, we begin by summing the currents at SJ,

1. $i_1 + i_f - i_g = 0$

   Since $i_g = 0$

2. $i_1 = - i_f$

   Writing the current equation

3. $i_1 = \frac{E_1 - e_g}{Z_1}$

4. $i_2 = \frac{E_0 - e_g}{Z_f}$

5. $\frac{E_1 - e_g}{Z_1} = \frac{e_g - E_0}{Z_f}$

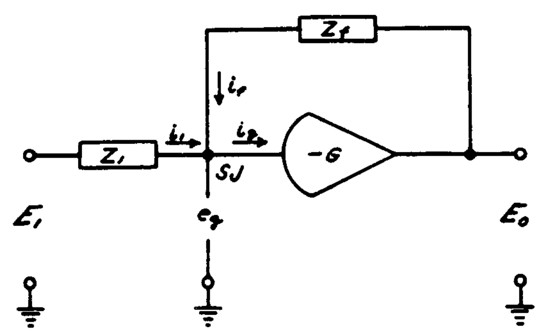


FIGURE 1 - BASIC OPERATIONAL AMPLIFIER

Effective January, 1965, supersedes I.L. 16-800-48

Since $E_0 = -G e_g$, where $-G$ is the gain of the amplifier, we can write $e_g = -E_0/G$ and rewrite equation 5.

6. $$\frac{E_1 + E_0/G}{Z_1} = \frac{-E_0/G - E_0}{Z_f}$$

7. $$E_1 Z_f + \frac{E_0}{G} Z_f = -E_0 Z_1 - \frac{E_0}{G} Z_1$$

8. $$E_0 \left[Z_1 + \frac{1}{G} (Z_f + Z_1) \right] = -E_1 Z_f$$

9. $$\frac{E_0}{E_1} = \frac{-Z_f}{Z_1 + \frac{1}{G} (Z_f + Z_1)}$$

10. $$\frac{E_0}{E_1} = \frac{-\frac{Z_f}{Z_1}}{1 + \frac{1}{G} \left(\frac{Z_f}{Z_1} + 1\right)}$$

Assuming $G \gg 1$

11. $$\frac{E_0}{E_1} = -\frac{Z_f}{Z_1} \quad \text{or} \quad E_0 = -\frac{Z_f}{Z_1} E_1$$

This analysis shows the output voltage characteristic is practically independent of amplifier gain, therefore, the derivation that follows will not include this term.

B. An expansion of the analysis given above to include additional inputs follows.

Summing the currents at SJ,

$$i_1 + i_2 \; . \; . \; . + i_n + i_f = 0$$

$$\frac{E_1}{Z_1} + \frac{E_2}{Z_2} \; . \; . \; . \; \frac{E_n}{Z_n} = -\frac{E_0}{Z_f}$$

$$E_0 = -\frac{Z_f}{Z_1} E_1 - \frac{Z_f}{Z_2} E_2 \; . \; . \; . - \frac{Z_f}{Z_n} E_n$$

In the case where,

$Z_f = R_f$, $Z_1 = R_1$, $Z_2 = R_2$ . . . $Z_n = R_n$

And,

$R_f = R_1 = R_2 = . . . R_n$,

the output voltage is the summation of the input voltages.

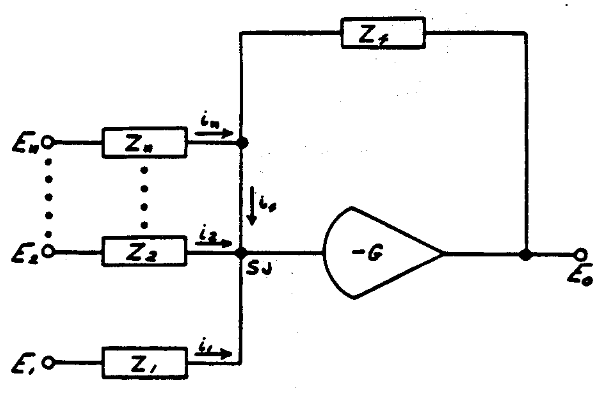


FIGURE 2 - MULTIPLE INPUTS

C. The analysis given above in terms of complex impedance indicates the versatility of operational amplifiers and precludes describing every possible configuration. However, to introduce the operator p*, the transfer function of the configurations given in Figure 3 and Figure 4 will be derived.

From the fundamental equation for the voltage and current relationship across a capacitor,

$$E_0 = \frac{1}{C_f} \int_0^t i_f dt$$

We can write the current equation for the feedback loop,

$$i_f = E_0 C_f p$$

Summing the currents at SJ,

$$i_1 + i_f = 0$$

$$\frac{E_1}{R_1} + E_0 C_f p = 0$$

$$\frac{E_0}{E_1} = \frac{1}{R_1 C_f p}$$

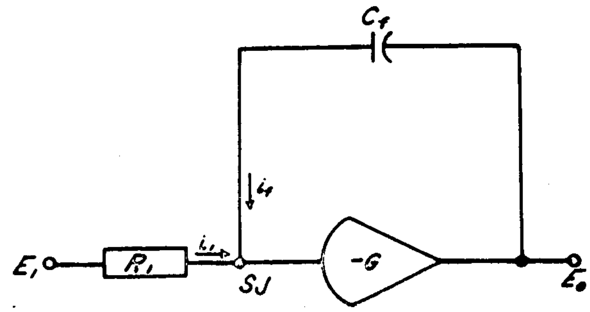


FIGURE 3 - INTEGRATOR

In Figure 4, the current is the same through both elements of the feedback loop, therefore,

$$E_0 = i_f \left(R_f + \frac{1}{C_f p}\right)$$

Summing the current at SJ,

$$i_1 + i_f = 0$$

$$\frac{E_1}{R_1} + \frac{E_0}{R_f + \frac{1}{C_f p}} = 0$$

$$\frac{E_0}{E_1} = \frac{R_f + \frac{1}{C_f p}}{R_1} = \frac{R_f C_f p + 1}{R_1 C_f p}$$

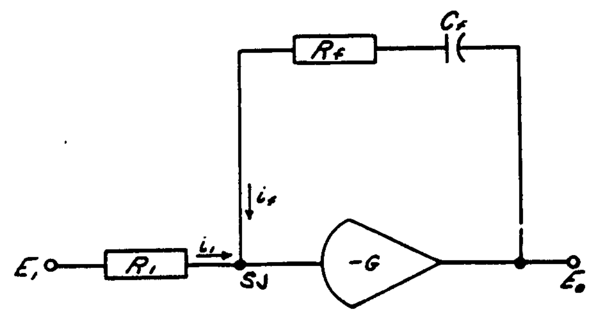


FIGURE 4 - PROPORTIONAL PLUS INTEGRAL

*The Laplace operator p is used extensively in describing the transfer function of operational amplifiers. The most commonly used terms are:

$$p = \frac{d}{dt} \quad , \quad \frac{1}{p} = \int_0^t dt$$

II. HIGH-GAIN D-C AMPLIFIERS

The analysis in Section I introduced assumptions required to evaluate the transfer function of operational amplifiers, based on the theory of an ideal amplifier. Since practical amplifier designs can only approach this criteria, predictable variations from the calculated transfer function is inherent in every amplifier design. It is the intent of this section to introduce the reader to solid state, high-gain voltage amplifiers without entering into a discussion of their design.

Operational amplifiers fall into two categories, chopper-stabilized and non-stabilized. The chopper-stabilized amplifier is a stable, high-gain, d-c voltage amplifier that automatically compensates for any drift of the output voltage signal. Non-stabilized amplifiers rely on component stability and amplifier design to limit the amplifier drift to a level that is acceptable in most operational amplifier applications.

The subjects to be discussed in this section are outlined below.

Section A	Chopper-Stabilized Amplifiers
Section B	Non-Stabilized Amplifiers
Section C	Output Limiters

A. Chopper-Stabilized Amplifiers

In chopper-stabilized amplifiers, drift-free amplification of d-c input voltages are obtained by using a chopper and an a-c voltage amplifier to supply drift-free amplification of low frequency signals to a high-gain d-c amplifier. This arrangement divides the drift voltage at the input of the d-c amplifier by the gain of the stabilizing amplifier, thus reducing the drift.

A connection diagram of the chopper-stabilized operational amplifier is given in Figure 5. A description of operation follows.

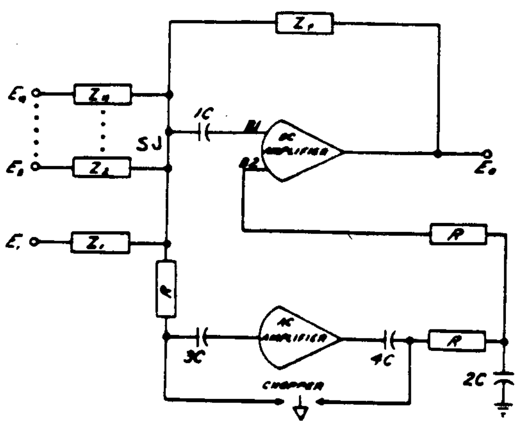


FIGURE 5 - CHOPPER STABILIZED AMPLIFIER

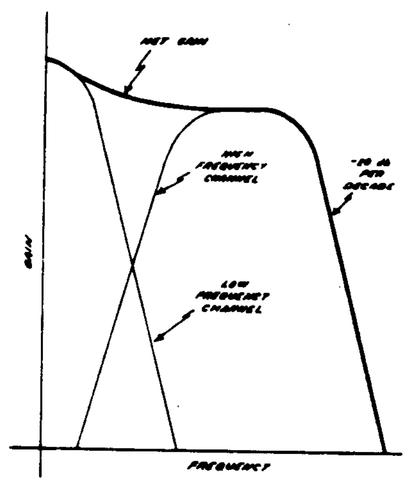


FIGURE 6 - AMPLIFIER OPEN LOOP RESPONSE

Any low frequency voltage signal at the summing junction of the amplifier is converted to a square wave of 60 cps by one contact of a single pole, double throw chopper. This signal is coupled to the a-c amplifier through capacitor 3C and amplified as a-c voltage.

The second contact of the chopper demodulates the a-c amplifier output, restoring a d-c voltage level that is proportional to the input signal. This voltage passes through a large time delay filter and is applied to the base of a differential input stage transistor of the d-c amplifier, B2. The filter eliminates chopper demodulation ripple and provides a sufficient time delay to allow stable operation with the amplifier loop closed.

Higher frequency signals at the summing junction of the operational amplifier are passed directly to the base of the other differential input stage transistor in the d-c amplifier, B1, providing direct access to the fast acting d-c amplifier. The resulting net gain of the completely stabilized amplifier is given in Figure 6.

An undesirable side effect of chopper stabilization is amplifier "hang-up" due to saturation of the a-c or d-c amplifier. This condition effectively opens the feedback loop, allowing the summing junction to deviate from virtual zero, charging capacitor 1C. The output of the amplifier is then driven to plus or minus saturation, remaining there (hang-up) until capacitor 1C can be discharged and loop control restored.

To avoid this condition, output limiters are placed between the output and summing junction of the operational amplifier. Limiting the output voltage retains the loop gain, thus preventing the summing junction from deviating from virtual zero.

B. Non-Stabilized Operational Amplifiers

Differential circuit symmetry in the input stages of non-stabilized d-c voltage amplifiers provides the low drift characteristic required in operational amplifier applications. Inherent with this approach, the source resistance as seen at the base of each differential input transistor (B1, B2), must be equal to complete the input circuit symmetry.

The resistance value from B2 to PSC is chosen in the amplifier design to provide optimum dynamic response of the amplifier. This value, given in the instruction leaflet describing each amplifier, restricts the source resistance required at the base of the other differential input transistor B1 to an equal value. The connection diagram given in Figure 7 will be used to demonstrate how this value can be calculated.

With the inputs connected to their source impedance, the net resistance looking out of B1 is determined as follows.

$$\frac{1}{R_T} = \frac{1}{R_1 + R_{S1}} + \frac{1}{R_2 + R_{S2}} \cdots\cdots \frac{1}{R_n + R_{SN}} + \frac{1}{R_f}$$

To obtain input circuit symmetry, $R_T = R_{B2}$ where R_{B2} is the resistance from B2 to PSC as specified in the instruction leaflet describing the amplifier.

If $R_T > R_{B2}$, a resistor (R_{B1}) can be added from B1 to PSC where $R_{B1} = \frac{R_T R_{B2}}{R_T + R_{B2}}$

If $R_T < R_{B2}$, the input and feedback resistor magnitudes must be increased to obtain the condition given above.

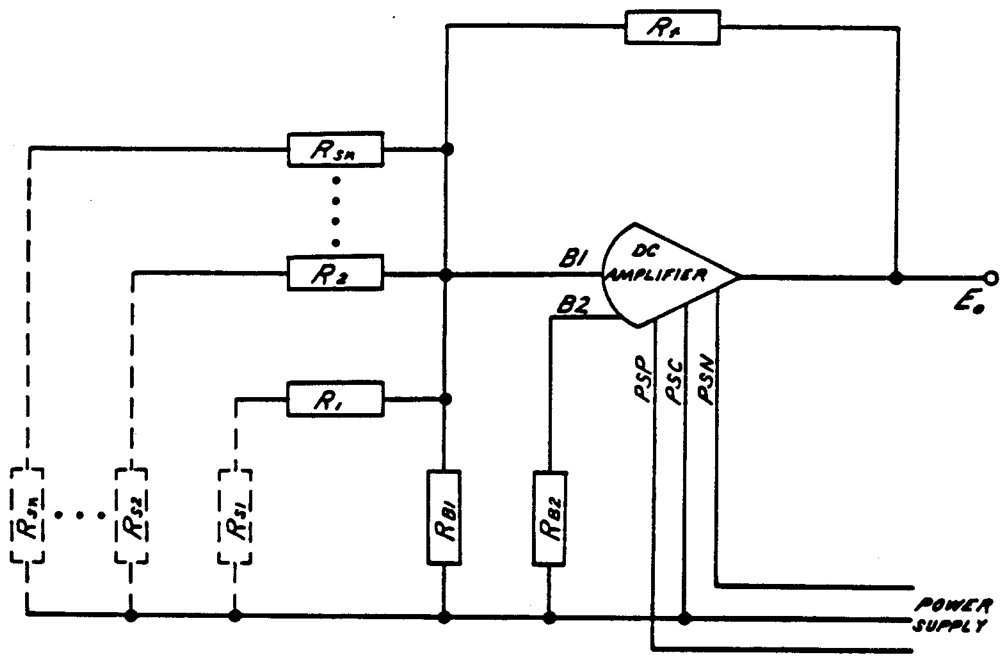


FIGURE 7 - NON-STABILIZED AMPLIFIER

C. Output Voltage Limiters

A schematic diagram of the output limiter circuit is given in Figure 8.

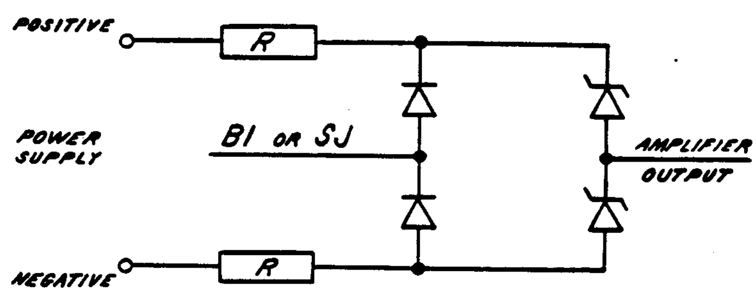


FIGURE 8 - AMPLIFIER LIMITER CIRCUIT

The limiters operate through the use of biased feedback diodes between the amplifier output and the summing junction (B1) of the operational amplifier. This bias voltage is established by the zener diodes. When the output voltage exceeds this zener voltage, the feedback diodes become conductive reducing the forward gain of the amplifier drastically. Any further increase in the input voltage will not increase the amplifier output voltage.

However, saturation of the amplifier can occur even when output limiters are used. Large input signals can overdrive the limiters and demand more feedback current than the amplifier is capable of supplying.

III. CHECKING OPERATIONAL AMPLIFIERS

A. General

1. For maximum stability and minimum drift due to temperature changes, the 24 volt power supply for the TOA modules should be left on at all times. When mills are shut down, the power supply selector should be left in the AUX position.

2. If all power is turned off during an extended shut down, the auxiliary power should be turned on again for at least one hour before making any tests or adjustments on the TOA modules.

3. If the 24 volt power supply is turned off for short periods to make test connections or minor repairs, turn the supply on at least five minutes before proceeding with tests.

4. When making test connections to a TOA module, it is advisable to turn off the 24 volt power supply to avoid possible shorts and blown fuses. This can be done locally by using the toggle switch on the power supply module.

5. Any TOA input terminal can be shorted to PSC after removing the input lead. However, care should be exercised to avoid shorting the output terminal.

6. When reinstalling a module into the cabinet, always check the schematic diagram for lead connections to avoid errors. Note that two leads connected to the same terminal may not have the same wire number, as the general practice on signal circuits is to number the wires in sequence from the original source.

7. During and after testing, check all leads for possible frayed wires or broken strands. Where terminated, check all shields for solid connection to PSC.

8. If shields are not terminated, do not allow the shield to come in contact with another shield or PSC. In general, single conductor shielded signal leads have their shields connected to PSC only at the input to modules (receiving end). Always refer to the schematic diagram for confirmation.

9. Be sure to replace the screen cover on the module before reinstalling it in the cabinet. These covers are omitted from Voltage Sensors and Isolating Amplifier modules.

B. Recommended Test Equipment

1. To facilitate grounding the inputs, make up a special octopus jumper consisting of three or four spade terminal leads connected to a single clip lead. This will provide more positive connection of all input leads to PSC and avoid the clutter of using several clip jumpers.

2. Have available several 1 1/4 inch lengths of 3/8 inch ID thin plastic tubing, such as heat shrinkable tubing. Place these over the spade terminal of all leads removed to avoid shorting or grounding.

3. For miscellaneous test connections, make up several clip jumpers eight to ten inches long using small spring clips such as MUELLER NO 30 or NO 34.

4. For test connections where clip jumpers are not practical, make up several jumpers four to six inches long using spade lugs to fit the TOA module terminal block.

5. Make up a test voltage source having a fine control from 0 to 12 or 24 volts. This may be accomplished by using a HELIPOT and a lantern battery for the power supply. Provide a reversing switch and an ON-OFF switch. The output leads should be single conductor shielded fitted with miniature spring clips or spade lugs.

6. For reading input and output voltages, two meters having zero center scales of 1, 10 and 30 nominal volts should be available. One meter may be incorporated in the test voltage source.

7. An ohmmeter should be available.

8. Hand tools should include a medium sized screwdriver and a pair of long nosed pliers.

C. Nulling The Amplifier

1. Turn off the 24 volt power supply.

2. Remove leads from ALL input terminals, insulate the removed leads, and connect all input terminals on the TOA to PSC.

3. Connect a 1-0-1 voltmeter between the output terminal and PSC.

4. Turn on the 24 volt power supply and wait about five minutes for warm-up.

5. Check the schematic diagram to determine if the module has an internal relay contact in its input or output circuit. If so, jumper the external contact circuit, generally terminal 11 to the relay coil terminal, to actuate the relay so that the module is in its normal operating condition.

6. Read the output voltage and record the polarity and magnitude if it is not zero, for future reference. For integrators, see item 8 below.

7. If the output is not zero, adjust potentiometer 1P to give a zero output within plus or minus 1/10 volt. Move the potentiometer screw back and forth a few times about the null point to clean the wiper. Wait a few minutes to determine that the null set will not drift. If the drift is more than one or two tenths of a volt, allow a longer warm-up period. If the module appears unstable, check for poor connections, both external and internal, or replace the TOA board or 1P or both.

8. Integrator modules, capacitor feedback without parallel resistor, cannot be nulled for permanent zero output, but will always tend to drift in one polarity or the other. The ideal setting for potentiometer 1P is when the tendency to drift is at a minimum when the module is in the ON condition. If the module has a relay in the feedback circuit, the drift should be adjusted to a minimum when this contact is first opened. Each time 1P is changed, the output should be driven to zero by closing this relay contact or MOMENTARILY shorting the feedback capacitor, or shorting the output to PSC. If any input has an internal relay contact, this contact must be in the normal RUN state when the null setting is checked.

D. Checking The Gain Of The Amplifier

NOTE: The voltmeter method of checking gain can be used effectively only on SUMMER or TIME DELAY type amplifiers. For INTEGRATOR or PROPORTIONAL PLUS INTEGRATOR types, a BRUSH recorder should be used to measure the output volts per second.

1. Turn off the 24 volt power supply.

2. Remove the leads from ALL input terminals, insulate the removed leads, and connect all but one of the TOA input terminals to PSC.

3. Connect a 10-0-10 voltmeter between the output terminal and PSC.

4. Connect a low voltage test source to the open input to be tested.

5. Check the schematic diagram to determine if the module is turned on or off by an internal relay. If so, jumper the external contact circuit, generally terminal 11 to the relay coil terminal, to actuate the relay.

6. Observe that the output voltage is zero. If not, adjust the null set per instructions in paragraph C - NULLING THE AMPLIFIER.

7. Apply a test signal to the input until the output is exactly five volts. On TIME DELAY amplifiers, allow time for the output voltage to reach steady state value.

8. Accurately read and record the input voltage. The amplifier gain equals the output volts divided by the input volts for any one input circuit. This gain value can be verified by dividing the feedback resistance by the input resistance.

$$G = \frac{E_o}{E_i} \qquad = \qquad G = \frac{R_f}{R_i}$$

If the module has a gain adjusting potentiometer in the circuit, the above ratio of resistances must be divided by a factor K, where K is the ratio of the resistance between the gain potentiometer slider and PSC to the total resistance between the output terminal and PSC. If the module does not have an output limiter, its output can be raised to 10 volts for a type P101 or 20 volts for a type P201.

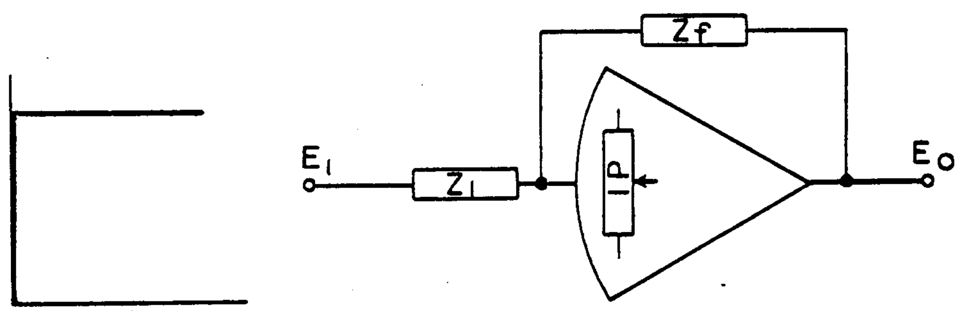
E. Checking The Output Limiter

1. Proceed in the same manner as described in D - Checking The Gain Of The Amplifier, except omit steps 2 and 6. This test applies to ALL types of amplifiers having limiter circuits.

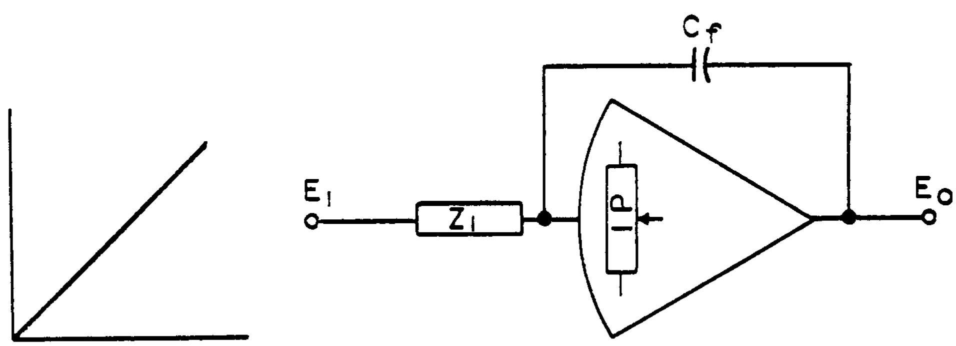
2. Apply a test signal to any TOA input terminal until the output reaches a maximum steady state value. This value is the limiter voltage. Check that the limiter voltage is approximately the same with a reversed input of the same amplitude. Tolerance on 9.1 volt zener diodes is plus or minus 0.5 volt.

F. Operational Amplifier Functions

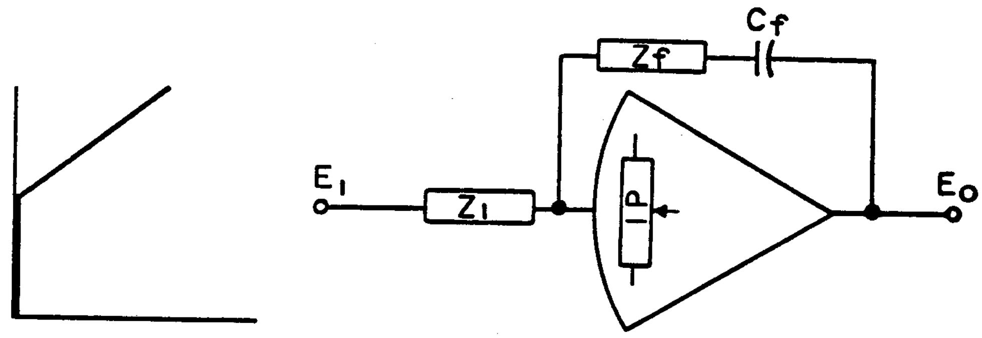
1. Responses to a step input.



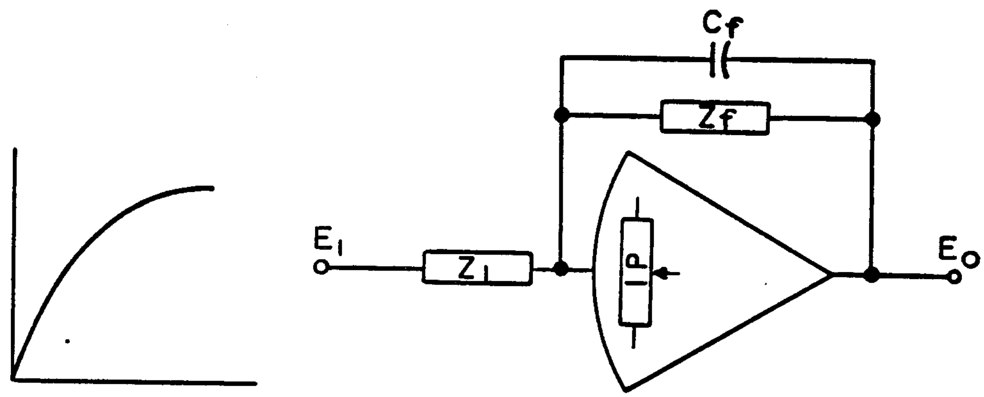
PROPORTIONAL CONFIGURATION



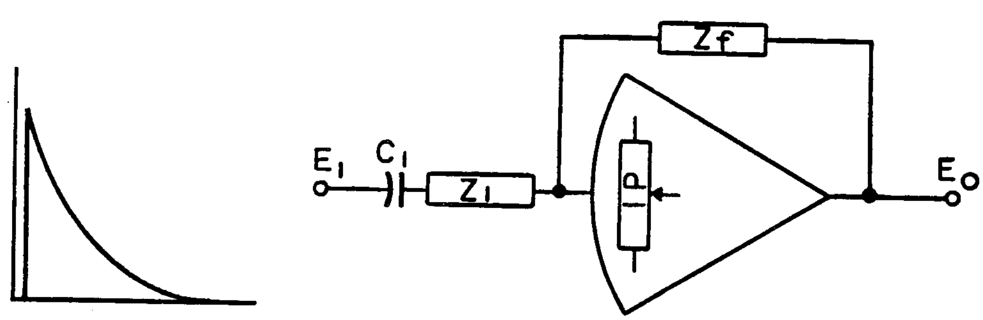
INTEGRAL CONFIGURATION



PROPORTIONAL PLUS INTEGRAL CONFIGURATION



DELAY CONFIGURATION



DIFFERENTIAL CONFIGURATION