EEE 3571 Electronic Engineering I

Lecture 9: Operational Amplifiers- Non-Inverting Ckts

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References

Our main reference text books in this course are

[1] Neil S., Electronics: A Systems Approach, 4th edition, 2009, Pearson Education Limited, ISBN 978-0-273-71918-2.

[2] Boylestad R. L., Nashelsky L., Electronic Devices and Circuit Theory, 11th Ed, 2013, Prentice-Hall, ISBN 978-0-13-262226-4.

[3] Smith R. J., Dorf R. C., Circuits Devices and Systems, 5th Ed., 2004, John Wiley, ISBN ISBN 9971-51-172-X.

However, feel free to use pretty much any additional text which you might find relevant to our course.

9.3 Noninverting Circuit Applications

- In a noninverting circuit, shown in Fig. 1, the input signal is applied to the noniverting + terminal, and a fraction of the output signal is fed back to the inverting – terminal.
- Here R_1 and R_F constitute a voltage divider across the output voltage. For an ideal op amp with $v_i = 0$,

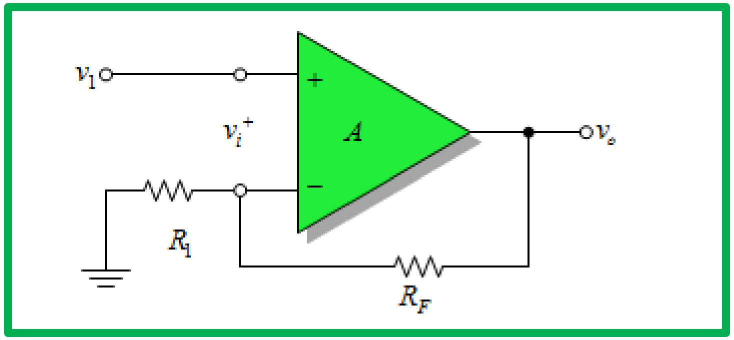

Fig. 1: The noniverting amplifier circuit.

$$v_1 - \frac{R_1}{R_1 + R_F} v_o = v_i = 0 \qquad [1]$$

Thus,

$$A_F = \frac{v_o}{v_i} = \frac{R_1 + R_F}{R_1} \qquad [2]$$

- This basic noninverting amplifier has two distinctive features.

- First, output signals are in phase with those at the input. Second, the input resistance is very high, approaching infinity in practical terms, and the output resistance is very low.

Noninverting Circuit Applications

- This implies that noninverting amplifiers do not "load" their sources and, in turn, they are not affected by their loads.

Voltage Follower

- A useful special case of the noninverting circuit is shown in Fig. 2. Here $R_F = 0$ and $R_1 = \infty$ (open circuit). From Eq. [3], the circuit gain is now

$$A_F = \frac{v_o}{v_i} \cong \frac{R_1 + R_F}{R_1} = 1 \quad [3]$$

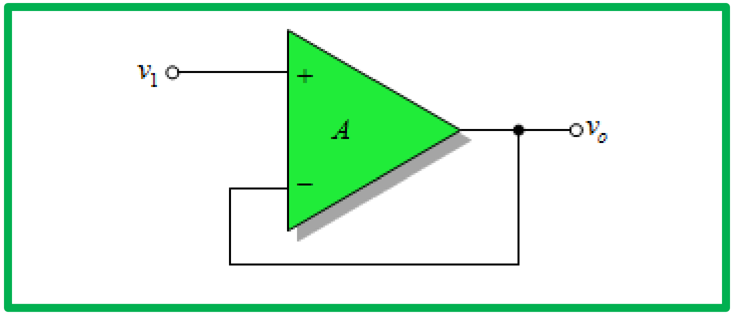

Fig. 2: The voltage-follower circuit.

- The output voltage is just equal to the input voltage and this is the voltage follower.

- It is known as a voltage follower because the potential at the v_o terminal "follows" the potential at the v_1 terminal.

[Example 1] Noninverting Circuit Applications

- In the circuit of Fig. 3a, $R_s = 1\ \mathrm{k\Omega}$ and $R_L = 10\ \mathrm{k\Omega}$. For the op amp, $A = 10^5$, $R_i = 100\ \mathrm{k\Omega}$, and $R_o = 100\ \Omega$. For $v_o = 10$ V, calculate v_s and v_o/v_s and estimate the input resistance of the circuit.

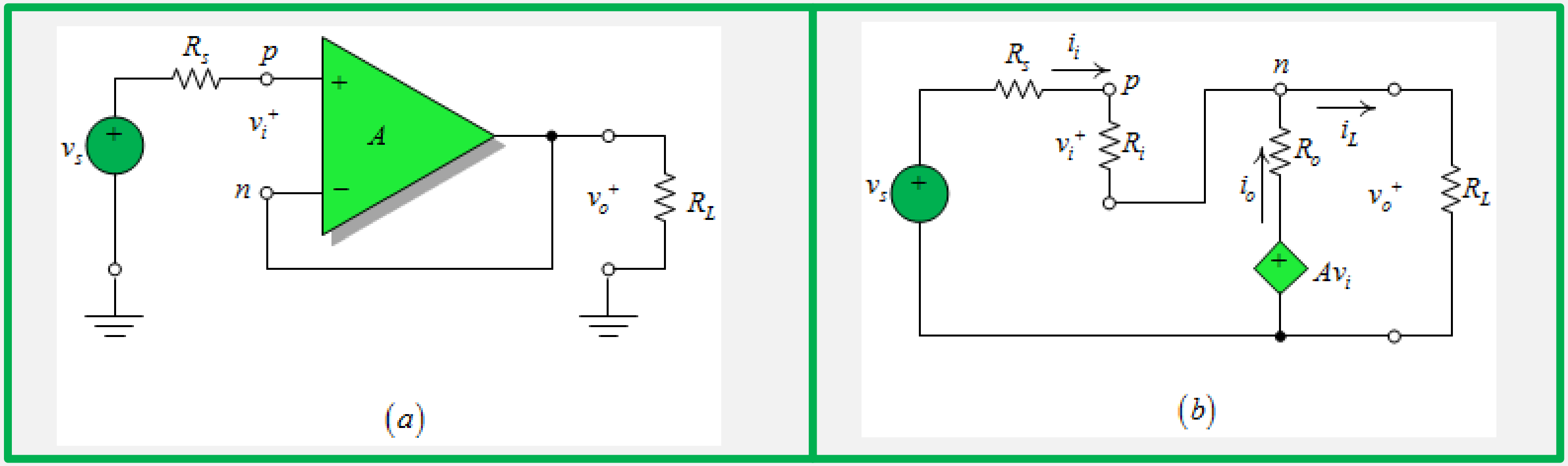

Fig. 3: Voltage-follower application.

[Solution]

- We first redraw the circuit as shown in Fig. 3b, where R_i is in series with the input v_s and R_o in series with Av_i .

[Example 1] Noninverting Circuit Applications Cont'd

- For $v_o = 10\ \text{V}$, it follows that,

$$i_L = \frac{v_o}{R_L} = \frac{10}{10^4} = 10^{-3}\ \text{A}$$

- Expecting i_i to be very small, $i_o \cong i_L$ and we write

$$Av_i = v_o + i_o R_o \cong v_o + i_L R_o = 10 + 10^{-3} \times 10^2 = 10.1\ \text{V}$$

$$\therefore v_i = (Av_i)/A = 10.1 \times 10^{-5}\ \text{V}$$

- Here, $i_i = v_i/R_i = v_i/10^5 = 1.01 \times 10^{-9}\ \text{A}$, thus assumption regarding i_i is justified. It follows that,

$$v_s = v_o + i_i(R_s + R_i) = 10 + 1.01 \times 10^{-9}(10.1 \times 10^{-5})$$

$$= 10.0001\ \text{V}$$

$$A_F = v_o/v_s = 10/10.0001 = 0.99999$$

[Example 1] Noninverting Circuit Applications Cont'd

- Clearly, the circuit in question is a voltage follower with unity gain. With feedback, the input resistance is

$$R_{iF} \cong \frac{v_s}{i_i} \cong \frac{10}{1.01 \times 10^{-9}} \cong 10^{10}\ \Omega$$

a very high value.

Unity-Gain Buffer

- Example 1 demonstrates that the gain of a voltage follower is almost exactly 1. Its usefulness lies in its ability to isolate a high-resistance source from a low-resistance load. To achieve this, the isolating network ought to have a very high input resistance and a very low output resistance.
- In general, such a network is known as a buffer. We cannot use the ideal op amp model to derive the general input and output characteristics of such a unity-gain buffer since they depend on the non-ideal properties of the op amp.

Noninverting Circuit Applications

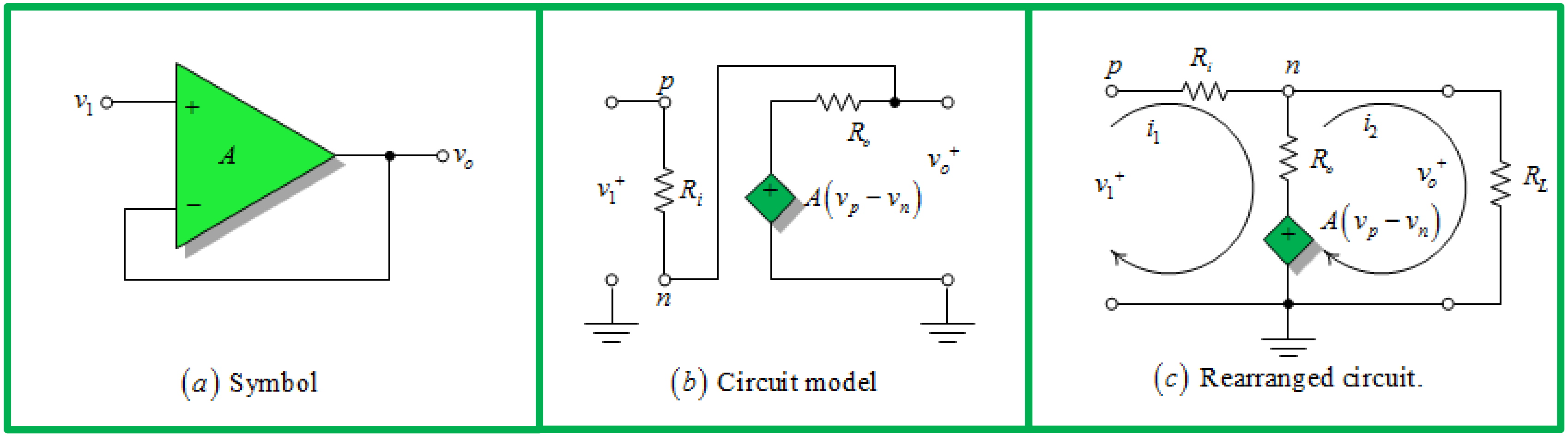

Fig. 4: Analysis of the unity-gain buffer circuit.

- Instead, we use the model shown in Fig. 4*b* that includes the finite values of R_i and R_o for the op amp, and we proceed without the simplifying assumption made in the previous example.
- **Input resistance**. Loop equations from the rearranged circuit, are,

$$v_1 - R_i i_1 - R_o(i_1 - i_2) - Av_1 + Av_o = 0 \quad [4]$$

$$v_1 - R_i i_1 - R_L i_2 = 0 \quad [5]$$

Noninverting Circuit Applications

- By inspection, $v_o = R_L i_2$ and, from Eq. [5], $i_2 = \left(v_1 - R_i i_1\right)/R_L$. Substituting these values in Eq. [4] yields

$$v_1 - R_i i_1 - R_o i_1 + R_0 \frac{v_1 - R_i i_1}{R_L} - A v_1 + A R_L \frac{v_1 - R_i i_1}{R_L} = 0 \qquad [6]$$

- Solving, the input resistance with feedback is

$$R_{iF} = \frac{v_1}{i_1} = \frac{R_i + R_o + \left(R_o / R_L\right) R_i + A R_i}{1 + R_o / R_L}$$

$$= \frac{R_L R_i + R_L R_o + R_o R_i + A R_L R_i}{R_L + R_o} \qquad [7]$$

- For the practical case of *A* very large and $R_L >> R_o$, this becomes

$$R_{iF} = \frac{R_L R_i \left(1 + A\right)}{R_L} + \frac{R_o \left(R_L + R_i\right)}{R_L} \cong A R_i \qquad [8]$$

Noninverting Circuit Applications

- A buffer using an op amp with $R_i = 100\ \text{k}\Omega$ and $A = 10^5$ would present an input resistance of about $10{,}000\ \text{M}\Omega$.
- **Output Resistance**. Working with Fig. 4c, the output resistance can be obtained as $v_{\text{OC}}/i_{\text{SC}}$. For $i_2 = 0$.

$$v_{\text{OC}} = v_1 - R_i i_1 = v_1 - R_i \frac{v_1 - Av_1 + Av_{\text{OC}}}{R_i + R_o} \quad [9]$$

- Solving, gives

$$v_{\text{OC}} = v_1 \frac{R_i + R_o + (A-1)R_i}{R_i + R_o + AR_i} = v_1 \frac{R_o + AR_i}{R_o + (1+A)R_i} \quad [10]$$

- For the output shorted, $v_o = 0$ and

$$i_{\text{SC}} = \frac{v_1}{R_i} + \frac{Av_1}{R_o} = v_1 \frac{R_o + AR_i}{R_o R_i} \quad [11]$$

Noninverting Circuit Applications

- For the practical case of A very large and $R_i >> R_o$, these yield

$$R_{oF} = \frac{v_{OC}}{i_{SC}} = \frac{R_o R_i}{R_o + (1+A) R_i} \cong \frac{R_o}{A} \quad [12]$$

- A buffer using an op-amp with $R_o = 100\,\Omega$ and $A = 10^5$ will present an output resistance of about $0.001\,\Omega$.

[Example 2] Noninverting Circuit Applications

- Let $R_L = R_o$ in the ckt of Fig. 4c. Find R_{iF} and compare that to R_{iF} in Eq. [8].

[Solution]

- Starting from Eq. [7], we have $R_{iF} = \frac{v_1}{i_1} = \frac{R_L R_i + R_L R_o + R_o R_i + A R_L R_i}{R_L + R_o}$

- Since $R_L = R_o$, we have

$$R_{iF} = \frac{R_o R_i + R_o R_o + R_o R_i + A R_o R_i}{2R_o} = \frac{R_o R_i (A+2) + R_o R_o}{2R_o}$$

[Example 2] Noninverting Circuit Applications Cont'd

- Which simplifies to, $R_{iF} = \left(\frac{A}{2}+1\right)R_i + \frac{R_o}{2} \cong \frac{A}{2}R_i, \quad \text{for } A >> 1$

[Example 3] Noninverting Circuit Applications

- An instrumentation transducer is characterized by a voltage $V_T = 5\text{ V}$ in series with a resistance $R_T = 2000\,\Omega$. It operates an inductor characterized by an input resistance of $100\,\Omega$. Predict the voltage and power delivered to the inductor with and without the use of a buffer.

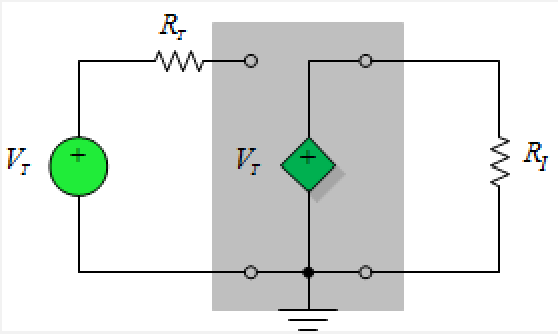

Fig. 5: Buffer application.

[Solution]

- Disregarding the buffer in Fig. 5, the voltage across the inductor would be

$$V_I = V_T \frac{R_I}{R_T + R_I} = 5\frac{100}{2100} = 0.238\text{ V}$$

[Example 3] Noninverting Circuit Applications Cont'd

and the power delivered would be

$$P_I = V_I^2 / R_I = (0.238)^2 / 100 = 0.566\,\text{mW}$$

- With a unity-gain buffer, the output voltage follows the input. Sine $R_i \to \infty$, no input current flows and, since $R_o \to 0$, there is no output voltage drop. Therefore, the model of the voltage follower is as shown in Fig. 5. Now,

$V_I = V_T = 5\,\text{V}$ and the power is

$$P_I = V_I^2 / R_I = 5^2 / 100 = 250\,\text{mW}$$

- The power gain achieved by inserting the buffer is

$$\frac{P_2}{P_1} = \frac{250}{0.566} = 442$$

Noninverting Circuit Applications

Voltage Regulator

- The simple Zener diode voltage regulator is meant to alleviate the effects of supply voltage fluctuation V_1 and load current variation I_L on the load voltage V_L .
- By using a high-gain amplifier and negative feedback, we can obtain much better regulation.
- In a practical power supply, a transformer provides an ac voltage at the proper level, a diode rectifier provides unidirectional current, and a capacitor filter develops an unregulated dc voltage. Thus, a regulator is added to alleviate voltage fluctuations.
- In Fig. 6a, transistor *T* acts as a variable voltage dropping element, in series, with the load resistance R_L so that $V_{CE} = V_1 - V_L$.
- The op-amp such as 741 is used as a sensitive control of the pass element *T*. The Zener diode provides a constant reference voltage $V_Z = \upsilon_p$.

Noninverting Circuit Applications

- The variable voltage divider R_1-R_2 takes a fraction $H = R_1/(R_1 + R_2)$ of the load voltage V_L and feeds it back to the inverting terminal so that $v_n = V_f = HV_L$.

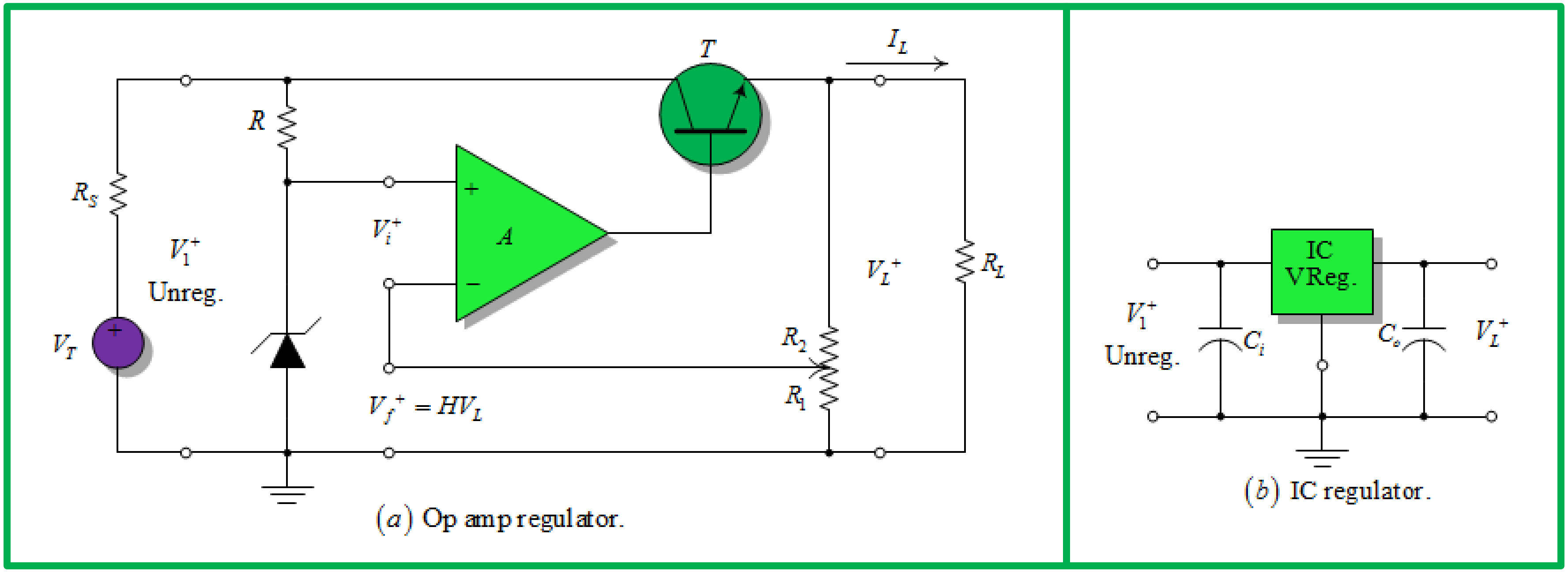

Fig. 6: Voltage regulators with feedback.

Noninverting Circuit Applications

- In effect, we compare V_f to the reference voltage V_Z ; any difference is amplified and used to control the base current to the transistor *T*.
- If for any reason the load voltage tends to drop, V_f decreases slightly, $V_i = \upsilon_p - \upsilon_n$ increases significantly, and the base current to *T* increases, increasing emitter current and stabilizing V_L .
- The pass transistor must be able to dissipate the power $P_D = V_{CE} I_L$; an adequate "heat sink" is required.
- The variation of V_{BE} and V_Z with temperature is a principal limitation on the voltage stability of the ckt in Fig. 6a. Furthermore, the ckt provides no high-current protection; as a short ckt may destroy *T*.
- To alleviate these difficulties, the sophisticated circuitry in IC form is used, see Fig. 6b. Capacitor C_i and C_o improve the operation by reducing the effect of transformer inductance at the input and minimizing the effect of sudden changes in load at the output.

End of Lecture 2

Thank you for your attention!