Voltage-to-Current Converter with Grounded Load

Another version of the voltage-to-current converter is shown in Figure 1. In this circuit, one terminal of the load is grounded, and load current is controlled by an input voltage. The analysis of the circuit is accomplished by first determining the voltage V_1 at the noninverting input terminal and then establishing the relationship between V_1 and the load current.

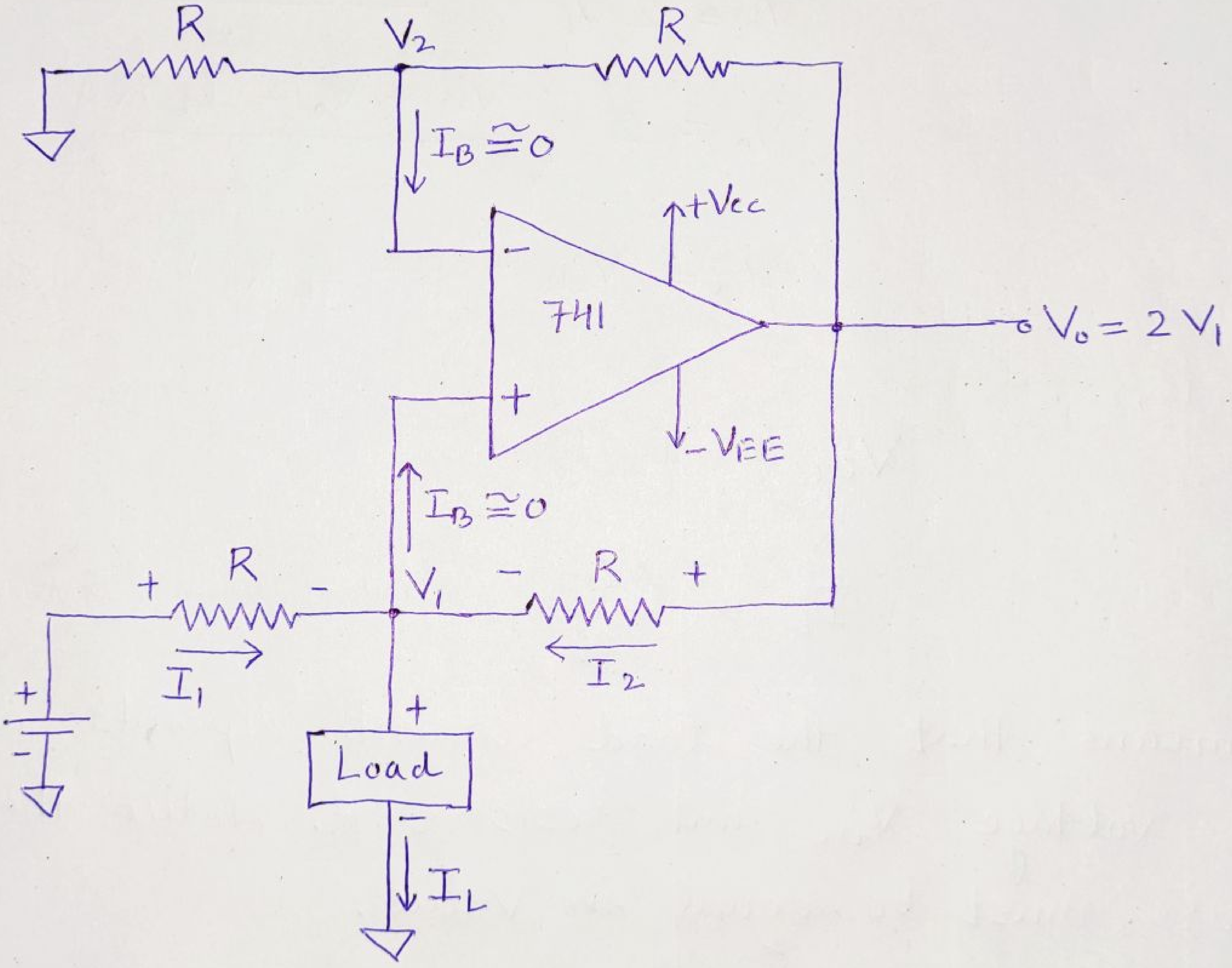


Figure 1. Voltage-to-current converter with grounded load.

Writing Kirchhoff's current equation at node V_1,

$$I_1 + I_2 = I_L$$

$$\frac{V_{in} - V_1}{R} + \frac{V_o - V_1}{R} = I_L$$

$$V_{in} + V_o - 2V_1 = I_L R$$

There fore,

$$V_1 = \frac{V_{in} + V_o - I_L R}{2} \quad \text{—— (1)}$$

Since the op-amp is connected in the noninverting mode, the gain of the circuit in Figure 1 is

$$1 + \frac{R}{R} = 2$$

Then the output voltage is

$$V_o = 2V_1 \quad \text{—— (2)}$$

$$V_o = 2\left(\frac{V_{in} + V_o - I_L R}{2}\right)$$

$$V_o = V_{in} + V_o - I_L R$$

That is,

$$V_{in} = I_L R$$

or,

$$I_L = \frac{V_{in}}{R} \quad \text{—— (3)}$$

This means that the load current depends on the input voltage V_{in} and resistor R. Notice that all resistors must be equal in value.

Q1. In the circuit of Figure 1, $V_{in} = 5\text{ V}$, $R = 10\text{ K}\Omega$ and $V_1 = 1\text{ V}$. Find (a) the load current and (b) the output voltage V_o. Assume that the op-amp is initially nulled.

Solution: (a) Using equation (3),

$$I_L = \frac{V_{in}}{R} = \frac{5}{10\text{ K}\Omega} = 0.50\text{ mA}$$

(b). Since $V_{in} = I_L R$, From equation (1),

$$V_o = 2V_1 = 2\ V.$$

The Integrator

A circuit in which the output voltage waveform is the integral of the input voltage waveform is the integrator or the integration amplifier. Such a circuit is obtained by using a basic inverting amplifier configuration if the feedback resistor R_F is replaced by a capacitor C_F [see Figure 2].

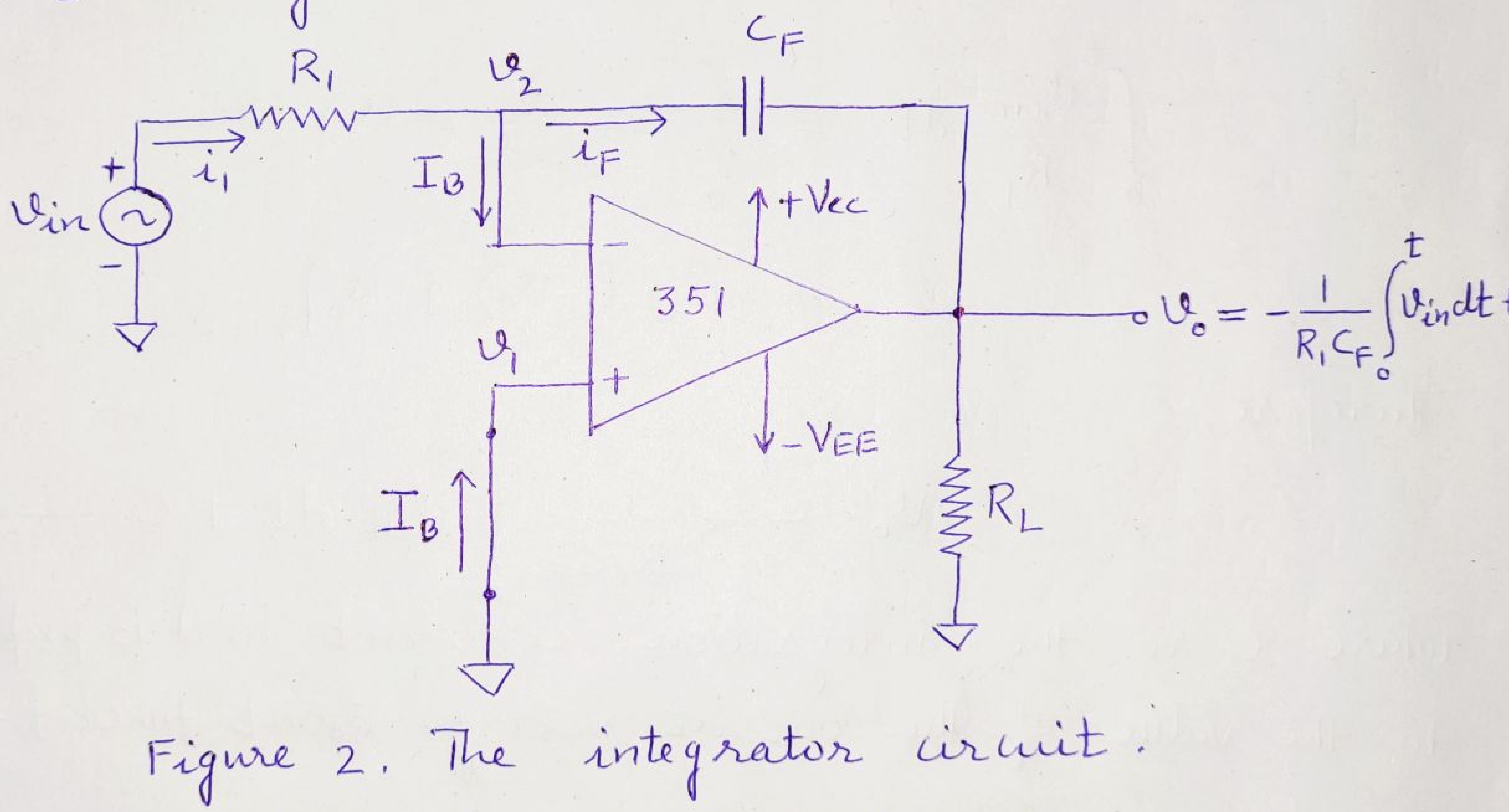


Figure 2. The integrator circuit.

The expression for the output voltage v_o can be obtained by writing Kirchhoff's current equation at node v_2:

$$i_1 = I_B + i_F$$

Since I_B is negligibly small,

$$i_1 \cong i_F$$

Recall that the relationship between current through and voltage across the capacitor is,

$$i_c = C \frac{dv_c}{dt}$$

Therefore,

$$\frac{v_{in} - v_2}{R_1} = C_F \left(\frac{d}{dt}\right)(v_2 - v_o)$$

However, $v_1 = v_2 \cong 0$ because A is very large. Therefore,

$$\frac{v_{in}}{R_1} = C_F \frac{d}{dt}(-v_o)$$

The output voltage can be obtained by integrating both sides with respect to time:

$$\int_0^t \frac{v_{in}}{R_1} dt = \int_0^t C_F \frac{d}{dt}(-v_o)\, dt$$

$$= C_F(-v_o) + v_o\big|_{t=0}$$

Therefore,

$$v_o = -\frac{1}{R_1 C_F}\int_0^t v_{in}\, dt + C \quad \text{--- (4)}$$

where C is the integration constant and is proportional to the value of the output voltage v_o at time $t = 0$ seconds.

Equation (4) indicates that the output voltage is directly proportional to the negative integral of the input voltage and inversely proportional to the time constant $R_1 C_F$. For example, if the input is a sine wave, the output will be a cosine wave; or if the input is a square wave, the output will be a tri-angular wave as shown in Figure 3. Note that these wave forms are drawn with the assumption that $R_1 C_F = 1$ second and $V_{OOT} = 0$ V, that is, $C = 0$.

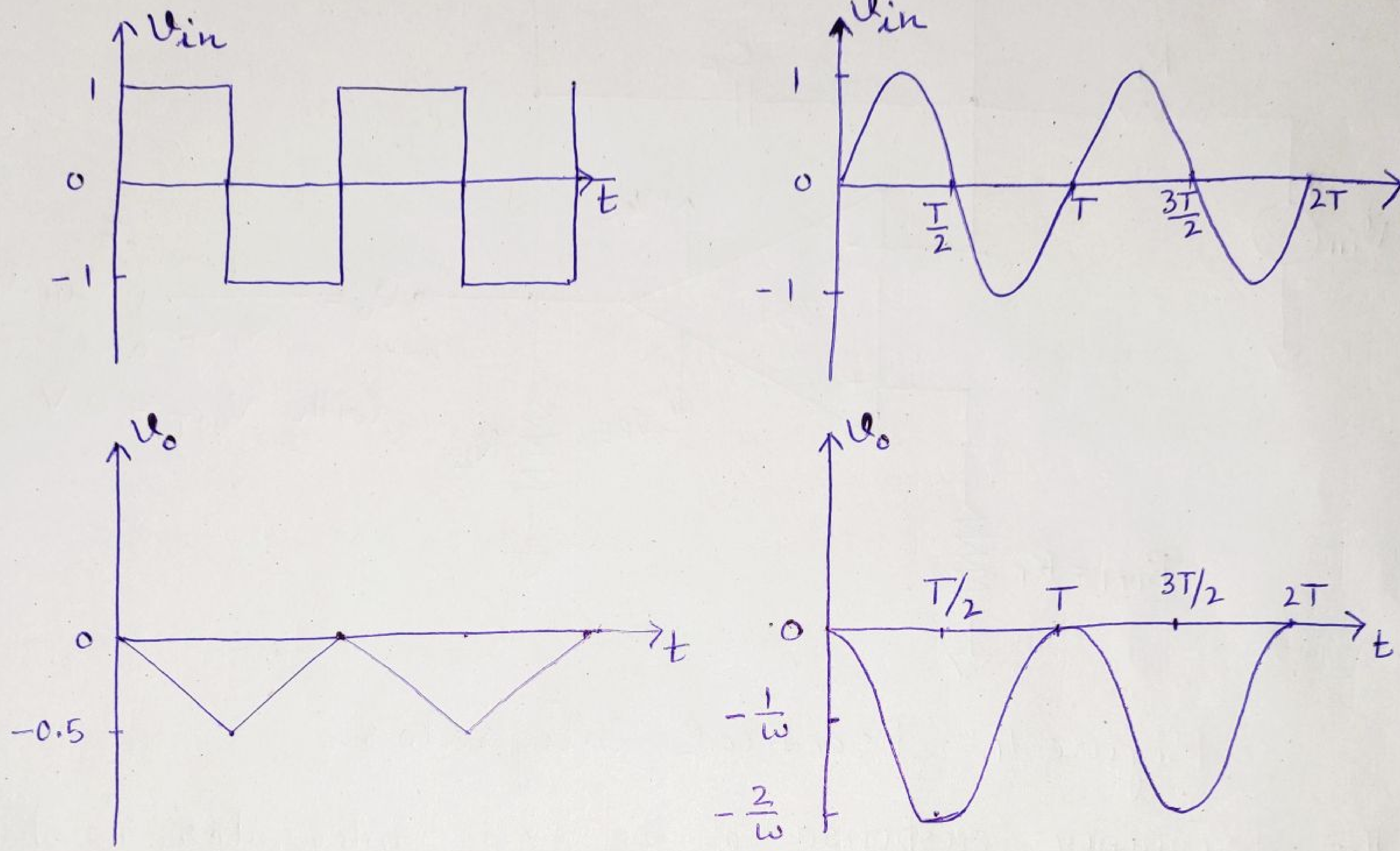


Figure 3. Input and output (ideal) waveforms for integrator ($R_1 C_F = 1$ second and $V_{OOT} = 0$ V assumed).

When $v_{in} = 0$, the integrator of Figure 2 works as an open-loop amplifier. This is because the capacitor C_F acts as an open circuit ($X_{CF} = \infty$) to the input offset voltage V_{io}. In other words, the input offset voltage V_{io} and the part of the input current charging capacitor C_F produce the error voltage at the output of the integrator. Therefore, in the practical integrator shown in Figure 4, to reduce the error voltage at the output, a resistor R_F is connected across the feedback capacitor C_F. Thus R_F limits the low-frequency gain and hence minimizes the variations in the output voltage.

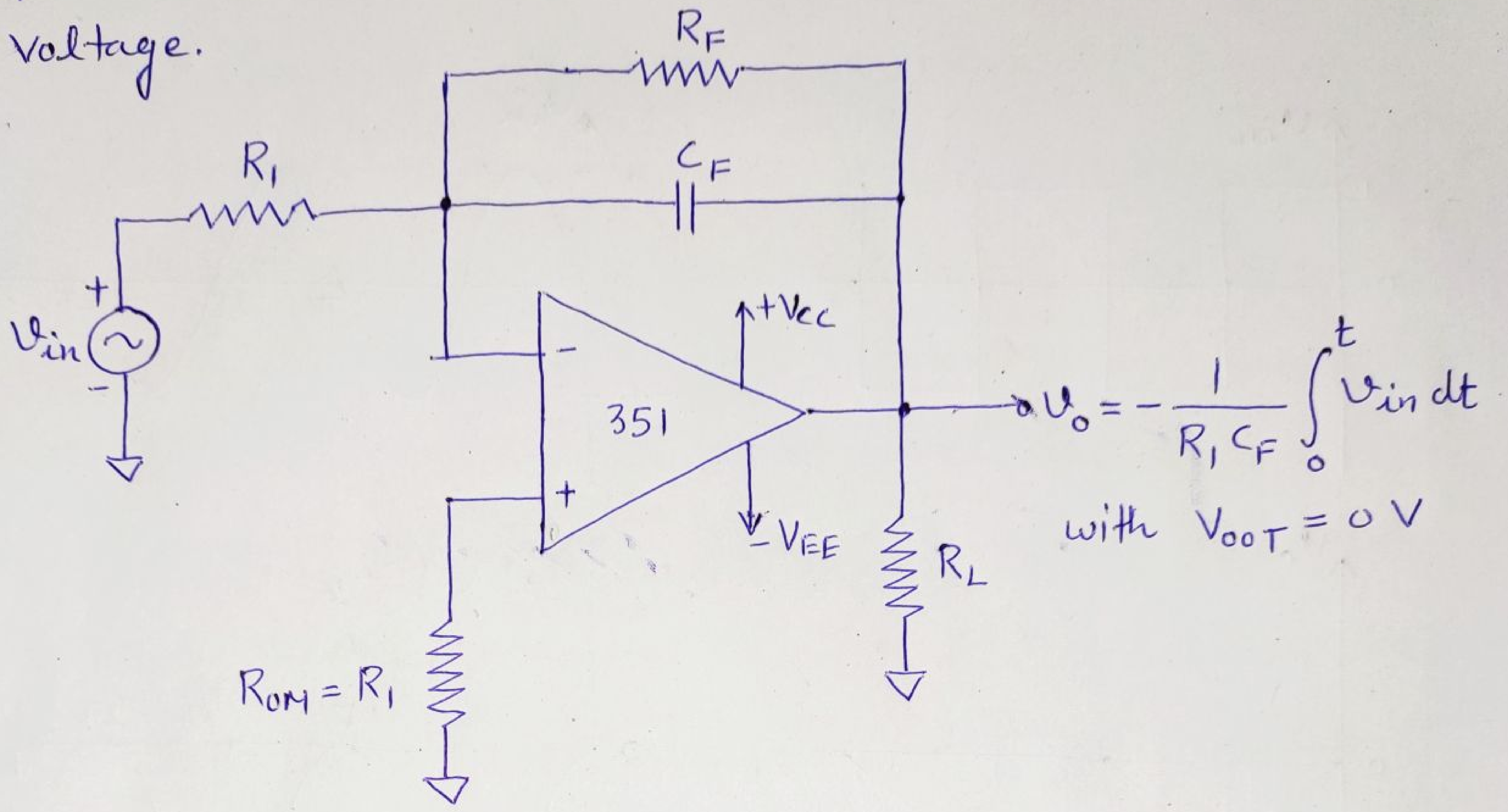


Figure 4. Practical integrator.

The frequency response of the basic integrator is shown in Figure 5. In this figure, f_b is the frequency at which the gain is 0 dB and is given by

$$f_b = \frac{1}{2\pi R_1 C_F} \qquad (5)$$

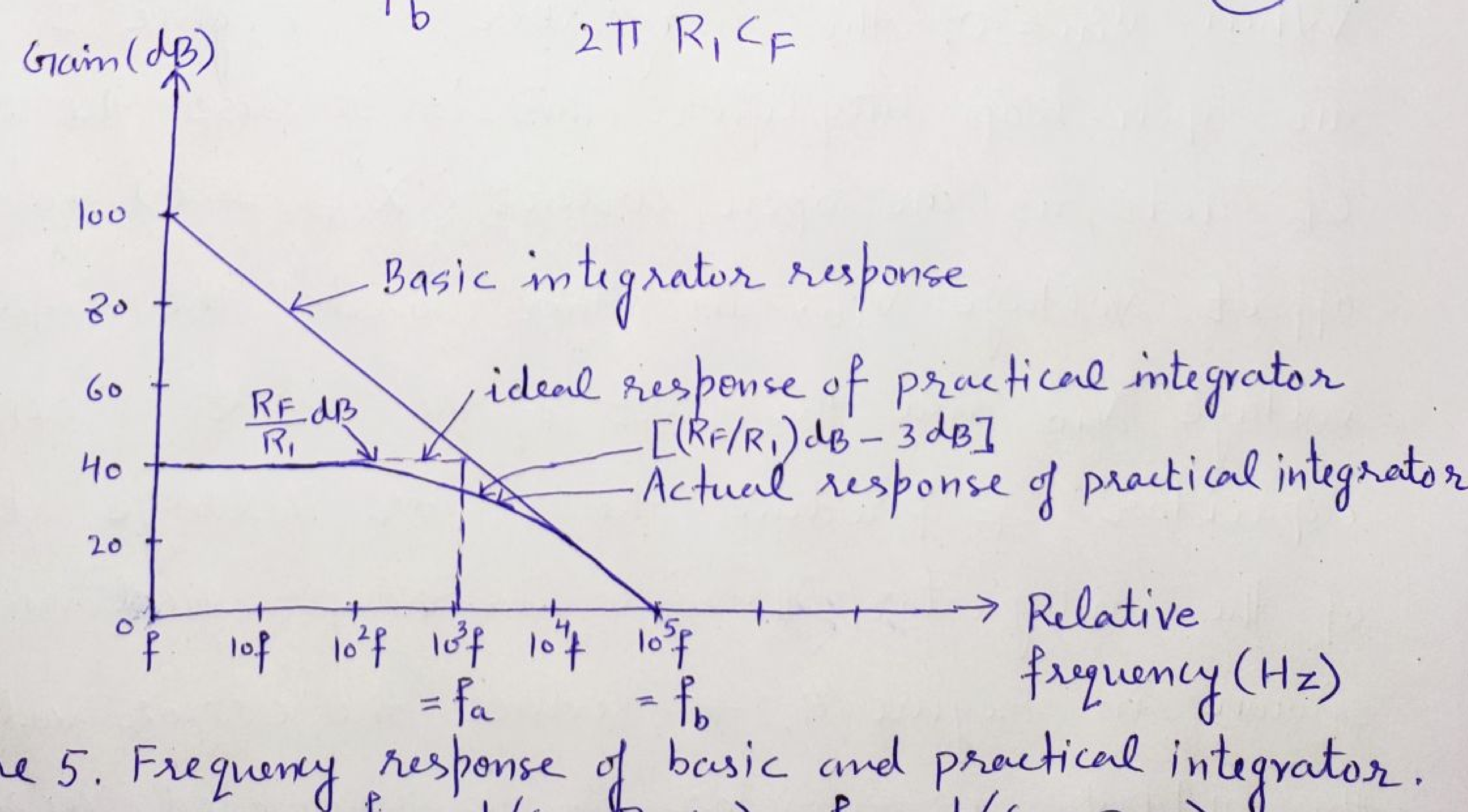


Figure 5. Frequency response of basic and practical integrator.
$f_a = 1/(2\pi R_F C_F)$, $f_b = 1/(2\pi R_1 C_F)$

Both the stability and the low-frequency roll-off problems can be corrected by the addition of a resistor R_F as shown in Practical Integrator of Figure 4. The frequency response of the practical integrator is shown in Figure 5 by a dashed line. In this figure, f is some relative operating frequency, and for frequencies f to f_a, the gain R_F/R_1 is constant. However, after f_a, the gain decreases at a rate of 20 dB/decade. In other words, between f_a and f_b, the circuit of Figure 4 acts as an integrator. The gain-limiting frequency f_a is given by,

$$f_a = \frac{1}{2\pi R_F C_F} \qquad (6)$$

Generally, the value of f_a and in turn $R_1 C_F$ and $R_F C_F$ values should be selected such that $f_a < f_b$. For exemple, if $f_a = f_b/10$, then $R_F = 10 R_1$. In fact, the input signal will be integrated properly if the time period T of the signal is larger than or equal to $R_F C_F$. That is,

$$T \geqslant R_F C_F$$

where

$$R_F C_F = \frac{1}{2\pi f_a}$$

The integrator is most commonly used in analog computers and analog-to-digital (ADC) circuits.

Q: 2. In the circuit of Figure 2, $R_1 C_F = 1$ second (8)
and the input is a step (dc) voltage as shown in Figure 6. Determine the output voltage and sketch it. Assume that the op-amp is initially nulled.

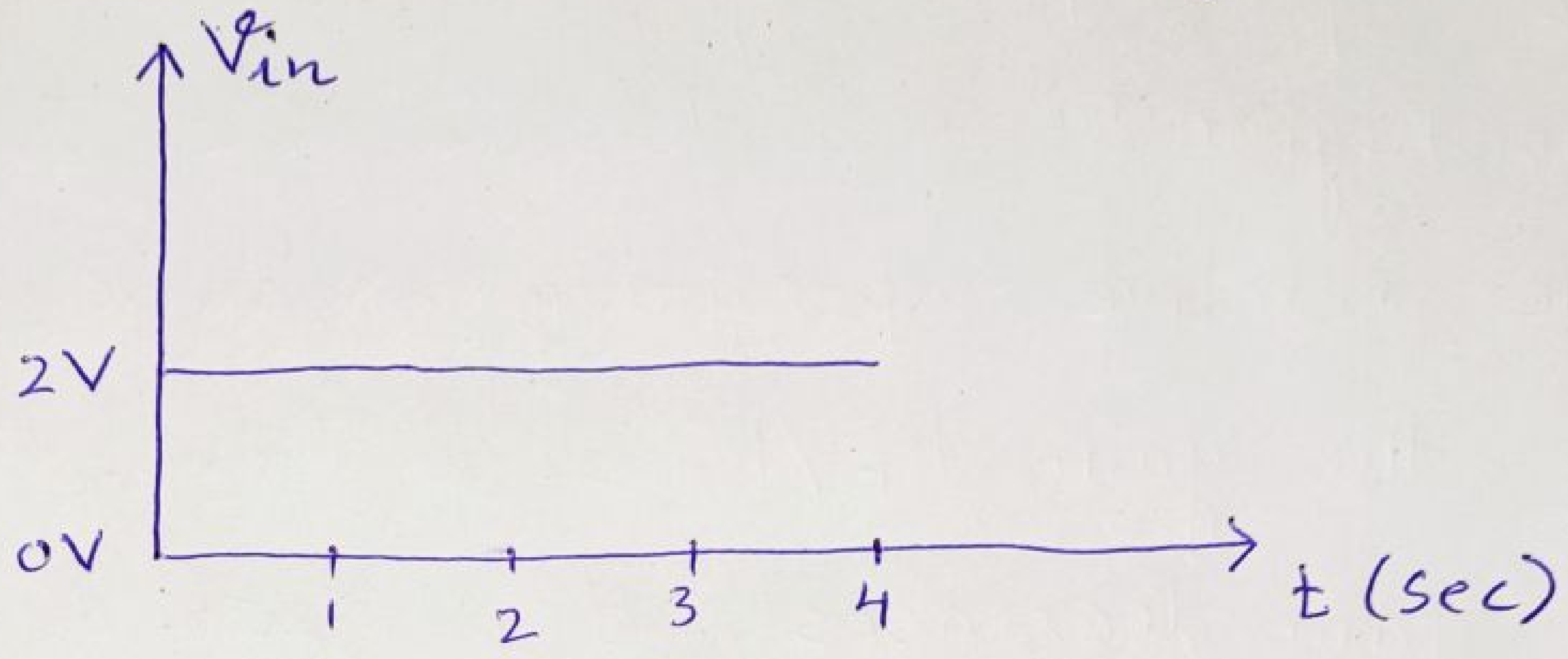


Figure 6: →

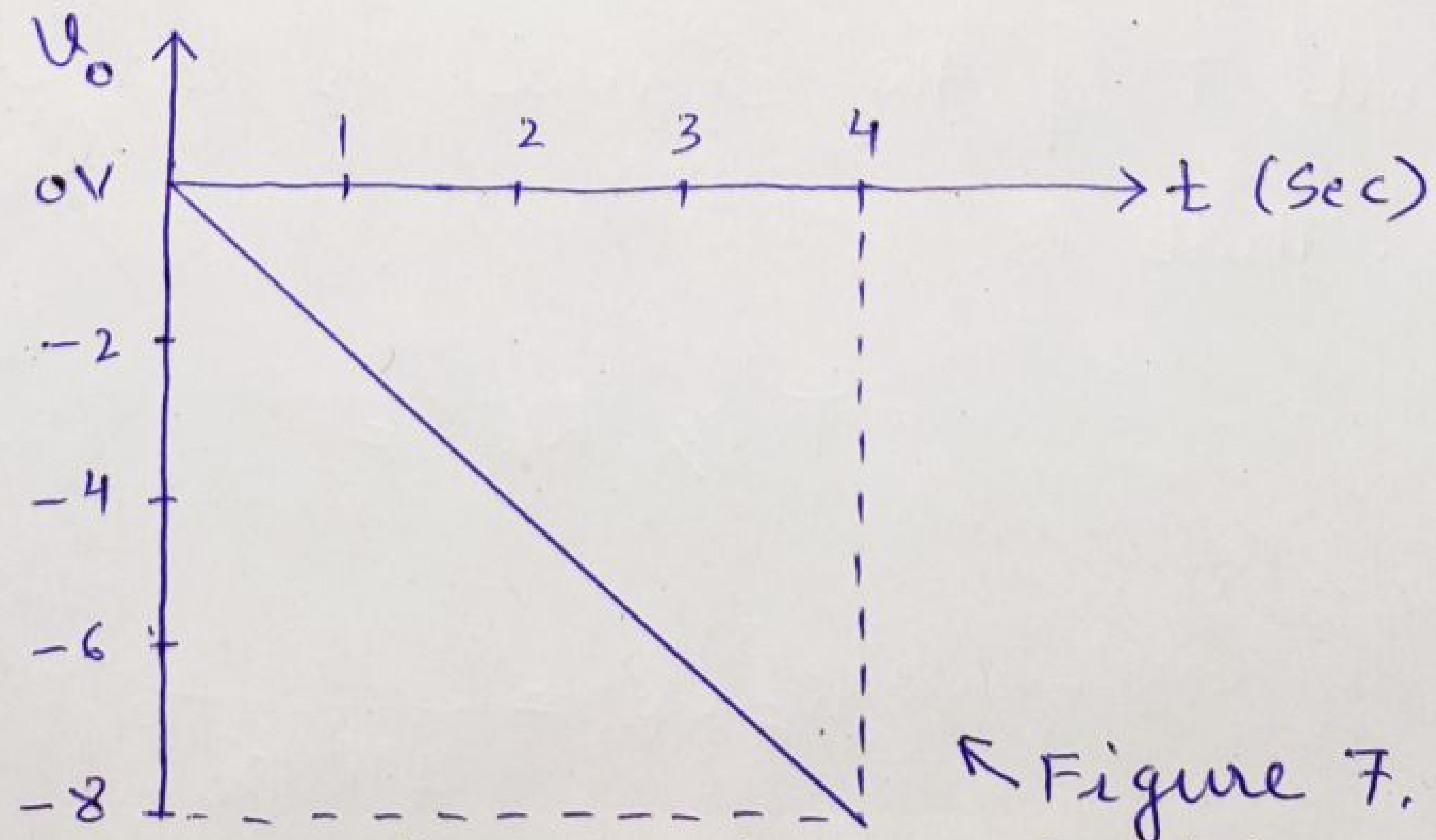
Solution: The input function is constant beginning at $t=0$ seconds. That is $v_{in} = 2\text{ V}$ for $0 \le t \le 4$. Therefore, using equation (4)

$$v_o = -\frac{1}{R_1 C_F} \int_0^{t=4} v_{in}\, dt + C$$

$$\therefore \quad v_o = -\int_0^4 2\, dt$$

$$= -\left[\int_0^1 2\, dt + \int_1^2 2\, dt + \int_2^3 2\, dt + \int_3^4 2\, dt \right]$$

$$v_o = -(2+2+2+2) = -8\text{ V}$$



↖ Figure 7.

The output voltage waveform is drawn in Figure 7. The waveform is called a ramp function. The slope of the ramp is -2V/s. Thus, with a constant voltage applied, the integrator gives a ramp at the output.