Week 4 LT Spice

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1. Introduction

In this week two major application areas of op-amps were studied namely, op-amps as an integrator and op-amps as an differentiator.[1]

Prerequisites:

- Inverting Amplifier working and its gain equation
- Capacitor Basics

2. Op-amp as an integrator

An integrator circuit using op-amp simply integrates the input voltage waveform. It has a similar configuration like the inverting amplifier with feedback, except the R_F is replaced by C_F.

2.1 Basic Integrator Circuit

The circuit below [1] shows the basic integrator circuit[2].

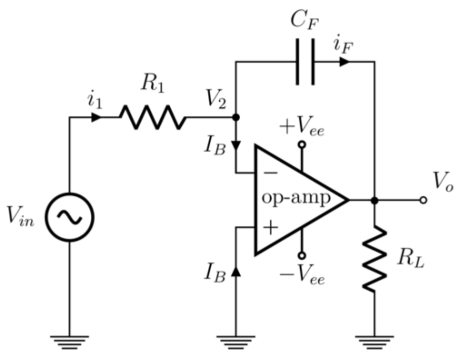


Figure 1: Basic Integrator Circuit

In fig [1] , we know that

$$i_1 = i_F + I_B$$

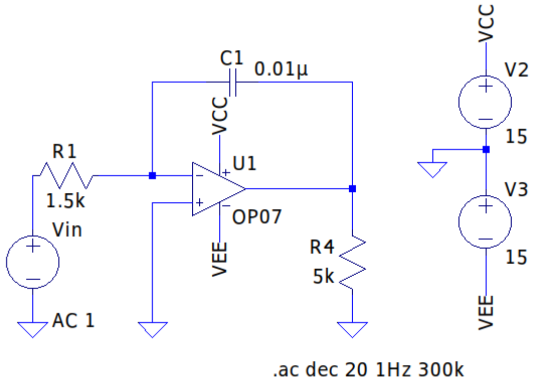
Since, $I_B \approx 0$, so $i_1 = i_F$ and $i_F = i_c =$ current through the capacitor $= C\frac{dv_c}{dt}$
Using this information and solving the circuit by Kirchhoff's law, we get

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

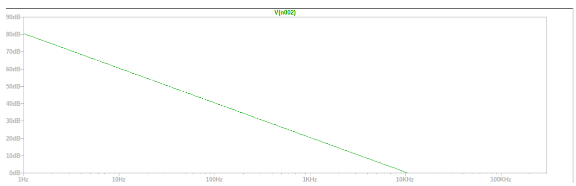
where C is the integration constant and is proportional to the value of the output voltage v_o at time t = 0 seconds. Here the output voltage V_o is directly proportional to the negative value of the input signal and inversely proportional to the time constant,R_1C_F.

Now, this circuit is intentionally called basic as it has a few limitations which needs to addressed when used for practical purposes.

We know any capacitor has a reactance value which is analogous to resistance in a resistor whose value is $X_c = \frac{1}{2\pi fC}$, i.e for smaller value of f we have a very high capacitive reactance(X_c)



((i)) Circuit Diagram



((ii)) Waveform

Figure 2: Basic integrator and its frequency response

and similarly for larger values of f we get very small X_c. Taking reference of the gain equation for an inverting amplifier circuit, for fig [1] we have $A_{\prime} = -\frac{X_c}{R_1} = -\frac{1}{2\pi R_1 Cf}$. The fig [2] shows the circuit diagram of a basic integrator and its frequency response.

Thus we can clearly see that the gain of the circuit will be very very high for the larger value of X_c which will result in an unstable operating range of the circuit and can only stabilize(reduced gain) after a particular value of frequency. The frequency response of this circuit shown in is a clear evidence. Also the huge gain will amplify the error signals in the output of the integrator at low frequency and thus will disturb the entire measurement system.
Such problems of stability and low frequency roll off problems can be corrected by a practical amplifier.

2.2 Practical Integrator Circuit

The practical integrator circuit is as shown below. To address the issue of instability at the low frequency ranges of the basic integrator circuit, a modified circuit (practical circuit) is designed where a resistor R_F is connected in parallel to the feedback capacitor.
In this case, as we know at low frequency the reactance is very high for the capacitor which in turn affects the gain of the circuit .So to counter that affect we connect a resistor in parallel to the capacitor, so that the equivalent resistance is comparable to R_F when f is low and X_c is high and comparable to X_c when f is high and X_c is low.[3]

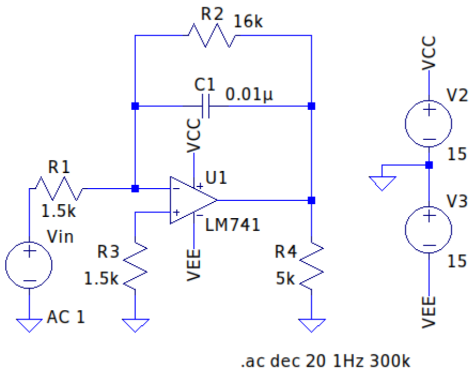
The fig [3] shows the circuit diagram of a practical integrator and its frequency response.In the frequency response f_a is called the gain limiting frequency which is given by $f_a = \frac{1}{2\pi R_F C_F}$. From frequency 0 to f_a gain $\frac{R_F}{R_1}$ is constant and after f_a gain decreases at the rate of 20dB/decade. f_b is the frequency at which gain is 0 dB which is given by $f_b = \frac{1}{2\pi R_1 C_F}$ In other words, this circuit behaves as an integrator from f_a to f_b. Generally, the value of f_a and in turn $R_1 C_F$ and $R_F C_F$ should be selected such that $f_a < f_b$.

2.3 Integrator Circuit Example Waveform

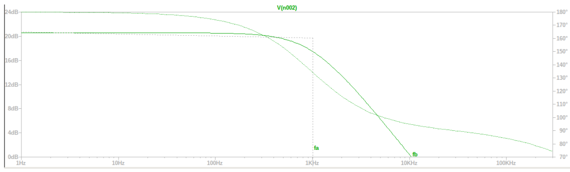
- Input waveform is a sine wave. Figure[4]
- Input waveform is a Square Wave. Figure[5]
- Input is a triangular wave. Figure [6]

3. Op-amp as an differentiator

An integrator circuit using op-amp simply differentiator the input voltage waveform. It has a similar configuration like the inverting amplifier with feedback, except the R_1 is replaced by C_1.

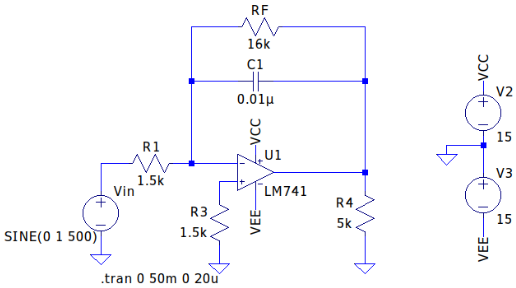


((i)) Circuit Diagram

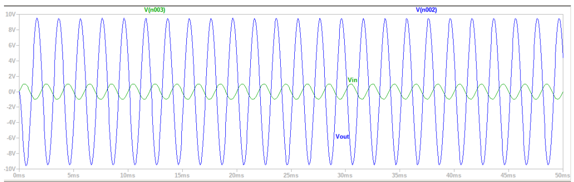


((ii)) Waveform

Figure 3: Practical amplifier and its frequency response

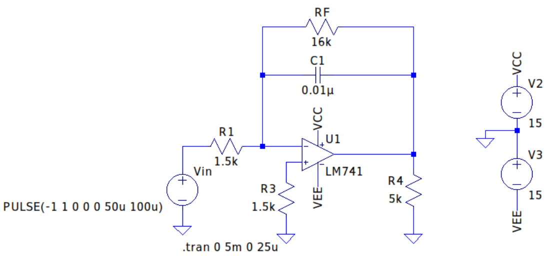


((i)) Circuit Diagram

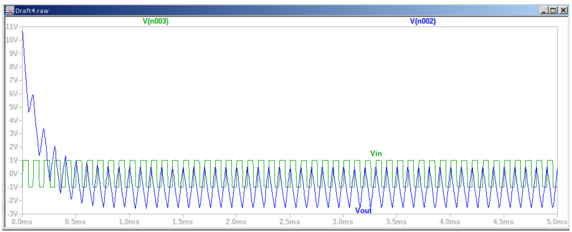


((ii)) Waveform

Figure 4: Integrator circuit: Input - sine wave and Output - cosine wave

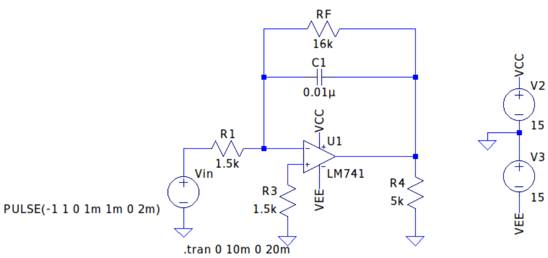


((i)) Circuit Diagram

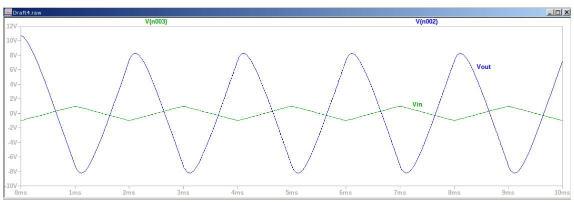


((ii)) Waveform

Figure 5: Integrator circuit: Input - Square wave and Output - Triangular wave



((i)) Circuit Diagram



((ii)) Waveform

Figure 6: Integrator circuit: Input - Triangle wave and Output - Sine wave

3.1 Basic Differentiator Circuit

The circuit below [7] shows the basic integrator circuit[4].

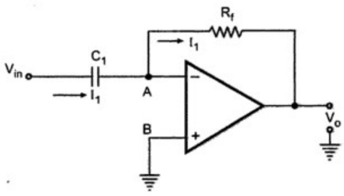


Figure 7: Basic Differentiator Circuit

The assumptions here will be the same as in the integrator configuration. Thus, solving the circuit by Kirchhoff's law, we get

$$V_o = -R_F C_1 \frac{dv_{in}}{dt}$$

where the output v_o is equal to $R_F C_1$ times the negative instantaneous rate of change of the input voltage with time.

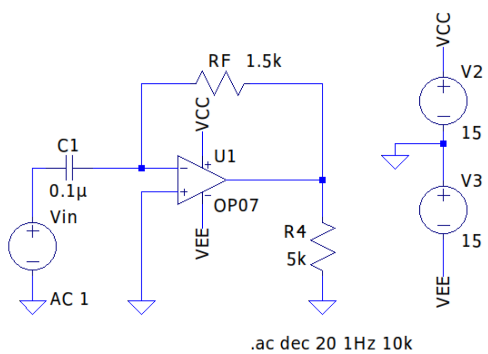
Similar to the integrator basic circuit, this basic differentiator circuit also has a few limitations which needs to addressed when used for practical purposes.

We know any capacitor has a reactance value which is analogous to resistance in a resistor whose value is $X_c = \frac{1}{2\pi f C}$, i.e for smaller value of f we have a very high capacitive reactance(X_c) and similarly for larger values of f we get very small X_c. Taking reference of the gain equation for an inverting amplifier circuit, for fig [**??**] we have $A\prime = -\frac{R_F}{C_1} = -2\pi R_F C f$. The fig [**??**] shows the circuit diagram of a basic integrator and its frequency response.

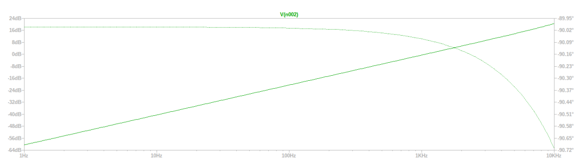
Thus we can clearly see that the gain of the circuit will be very very high for the smaller value of X_c which will result in an unstable operating range of the circuit and can only stabilize(reduced gain) before a particular value of frequency. The frequency response of this circuit shown in is a clear evidence. Also the huge gain will amplify the error signals in the output of the integrator at high frequency and thus will disturb the entire measurement system.
Such problems of stability in high frequency conditions can be corrected by a practical amplifier.

3.2 Practical Differentiator Circuit

The practical differentiator circuit is as shown in fig[9(i)]. To address the issue of instability at the high frequency ranges of the basic differentiator circuit, a modified circuit (practical circuit) is designed where a resistor C_F is connected in parallel to the feedback resistor, R_F and a resistor R_1 is connected in series with the capacitor C_1.
In this case, as we know at high frequency the reactance is low for the capacitor which in turn affects the gain of the circuit . So to counter that affect we connect a resistorR_1 in series to the

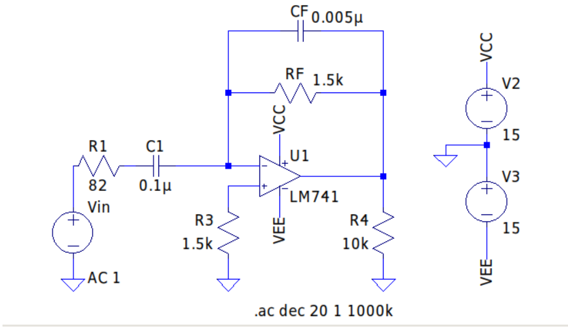


((i)) Circuit Diagram

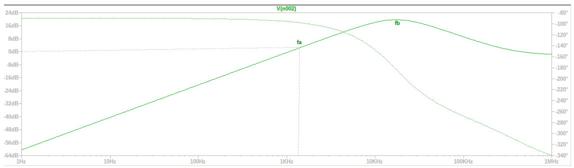


((ii)) Waveform

Figure 8: Basic Differentiator and its frequency response

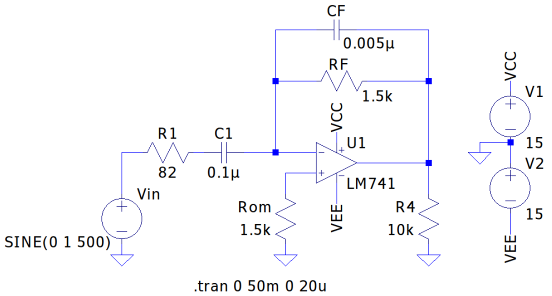


((i)) Circuit Diagram

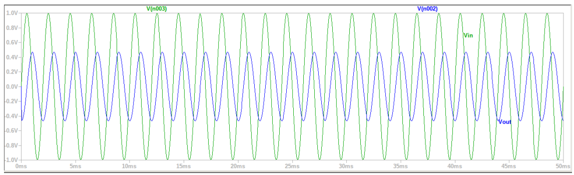


((ii)) Waveform

Figure 9: Practical differentiator and its frequency response



((i)) Circuit Diagram



((ii)) Waveform

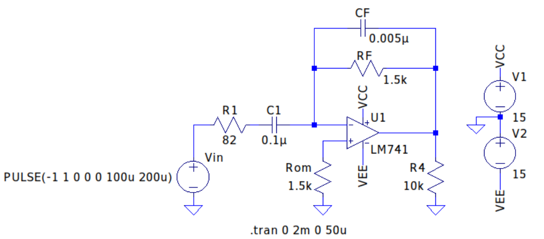
Figure 10: Differntiator circuit: Input - sine wave and Output - cosine wave

input capacitor, C_1, so that the equivalent resistance is comparable to X_c when f is low and X_c is high and comparable to R_1 when f is high and X_c is low. Similarly for the feedback loop, the equivalent resistance with be R_F when f is low and C_F when f is high. [3]

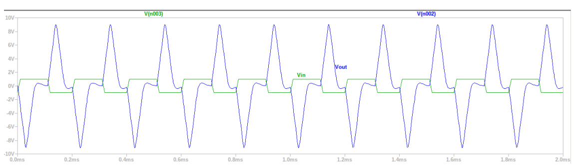
The fig [9] shows the circuit diagram of a practical differentiator and its frequency response.In the frequency response f_a is the gain at 0 dB which is given by $f_a = \frac{1}{2\pi R_F C_1}$. From frequency 0 to f_b gain increases at the rate of 20dB/decade and after f_b the gain decreases.f_b is called the gain limiting frequency which is given by which is given by $f_b = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi R_F C_F}$ In other words, this circuit behaves as an integrator from 0 to f_A and as a differentiator from f_a to f_b. Generally, the value of f_a and in turn $R_1 C_F$ and $R_F C_F$ should be selected such that $f_a < f_b < f_c$, where f_c is the unity gain bandwidth.

3.3 Differentiator Circuit Example Waveform

- Input waveform is a sine wave. Figure[10]
- Input waveform is a Square Wave. Figure[11]
- Input is a triangular wave. Figure [12]

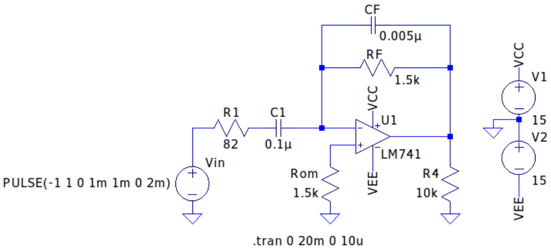


((i)) Circuit Diagram

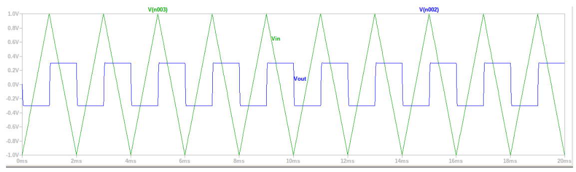


((ii)) Waveform

Figure 11: Differentiator circuit: Input - Square wave and Output - Spikes



((i)) Circuit Diagram



((ii)) Waveform

Figure 12: Differentiator circuit: Input - Triangle wave and Output - Square wave

References

[1] Ramakant A. Gayakwad. *Op-Amps and Linear Integrated Circuits*. PHI Learning Pvt. Ltd., New Delhi-110001, fourth edition, 2010.

[2] Wikipedia. Op amp integrator. https://www.wikiwand.com/en/Op_amp_integrator.

[3] Eduphile. Operational Amplifier Playlist. https://www.youtube.com/channel/UC-WnK7if_o95z_b6tHDrcdQ.

[4] Ashok Saini. Ideal Differentiator by using op-amp- circuit analysis and applications. https://eeebooks4u.com/2021/06/10/ideal-differentiator-by-using-op-amp/.