

# Circuits and Transforms

## EE3900: Linear Systems and Signal Processing

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#### 1. DEFINITIONS

1.1 The unit step function is defined as

$$u(t) = \begin{cases} 1 & t > 0 \\ \frac{1}{2} & t = 0 \\ 0 & t < 0 \end{cases} \quad (1.1)$$

1.2 The Laplace transform of  $g(t)$  is defined as

$$G(s) = \int_{-\infty}^{\infty} g(t)e^{-st} dt \quad (1.2)$$

#### 2. LAPLACE TRANSFORM

2.1 In the circuit, the switch S is connected to position P for a long time so that the charge on the capacitor becomes  $q_1 \mu\text{C}$ . Then S is switched to position Q. After a long time, the charge on the capacitor is  $q_2 \mu\text{C}$

2.2 Draw the circuit using latex-tikz

#### **Solution:**

The following figure Fig. 2.2 is drawn using latex-tikz for the defined circuit.

2.3 Find  $q_1$ .

#### **Solution:**

After a long time when a steady state is

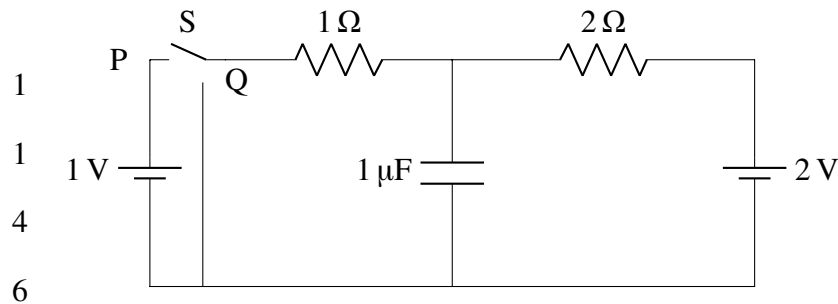


Fig. 2.2. Circuit diagram of the circuit in question

achieved, a capacitor behaves like an open circuit, that is, current passing through it is zero.

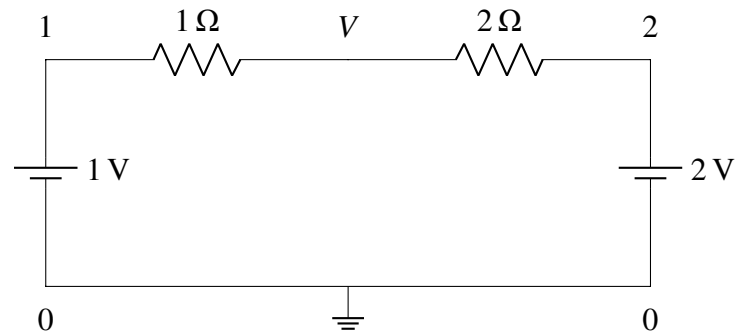


Fig. 2.3. Circuit diagram at steady state before flipping the switch

By Kirchoff's Law we can get,

$$\frac{V-1}{1} - \frac{V-2}{2} = 0 \quad (2.1)$$

$$\Rightarrow V = \frac{4}{3} \text{ V} \quad (2.2)$$

$$\Rightarrow q_1 = CV = \frac{4}{3} \mu\text{C} \quad (2.3)$$

2.4 Show that the Laplace Transform of  $u(t)$  is  $\frac{1}{s}$  and find the ROC.

**Solution:**

The Laplace Transform of  $u(t)$  is given by,

$$\mathcal{L}\{u(t)\} = \int_{-\infty}^{\infty} u(t)e^{-st} dt \quad (2.4)$$

$$= \int_0^{\infty} e^{-st} dt \quad (2.5)$$

$$= \lim_{R \rightarrow \infty} \frac{1 - e^{-sR}}{s} \quad (2.6)$$

This limit is finite only if  $\Re(s) > 0$ , which is going to be its ROC.

Therefore,

$$u(t) \xleftrightarrow{\mathcal{L}} \frac{1}{s} \quad \Re(s) > 0 \quad (2.7)$$

2.5 Show that,

$$e^{-at}u(t) \xleftrightarrow{\mathcal{L}} \frac{1}{s+a} \quad a > 0 \quad (2.8)$$

and find ROC.

**Solution:**

The Laplace Transform of  $e^{-at}u(t)$  for  $a > 0$  is given by,

$$\mathcal{L}\{u(t)\} = \int_{-\infty}^{\infty} e^{-at}u(t)e^{-st} dt \quad (2.9)$$

$$= \int_0^{\infty} e^{-(s+a)t} dt \quad (2.10)$$

$$= \lim_{R \rightarrow \infty} \frac{1 - e^{-(s+a)R}}{s+a} \quad (2.11)$$

This limit is finite only if  $\Re(s+a) > 0$ , which is going to be its ROC

Therefore

$$e^{-at}u(t) \xleftrightarrow{\mathcal{L}} \frac{1}{s+a} \quad \Re(s) > -a \quad (2.12)$$

since  $a$  is real.

2.6 Now consider the following resistive circuit transformed from Fig. 2.2 where

$$u(t) \xleftrightarrow{\mathcal{L}} V_1(s) \quad (2.13)$$

$$2u(t) \xleftrightarrow{\mathcal{L}} V_2(s) \quad (2.14)$$

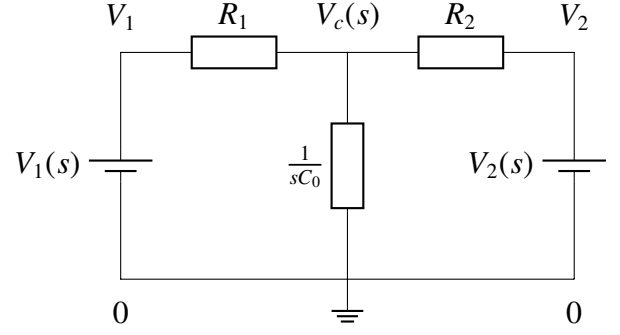


Fig. 2.6. Circuit diagram in  $s$ -domain before flipping the switch

Find the voltage across the capacitor  $V_c(s)$

**Solution:**

$$V_1(s) = \frac{1}{s} \quad \Re(s) > 0 \quad (2.15)$$

$$V_2(s) = \frac{2}{s} \quad \Re(s) > 0 \quad (2.16)$$

$$(2.17)$$

By Kirchoff's Junction Law, we get,

$$\frac{V_c - V_1}{R_1} + \frac{V_c - V_2}{R_2} + \frac{V_c - 0}{\frac{1}{sC_0}} = 0 \quad (2.18)$$

$$V_c \left( \frac{1}{R_1} + \frac{1}{R_2} + sC_0 \right) = \frac{V_1}{R_1} + \frac{V_2}{R_2} \quad (2.19)$$

$$V_c(s) = \frac{\frac{1}{sR_1} + \frac{2}{sR_2}}{\frac{1}{R_1} + \frac{1}{R_2} + sC_0} \quad (2.20)$$

$$V_c(s) = \frac{\frac{1}{R_1C_0} + \frac{2}{R_2C_0}}{s \left( s + \frac{1}{R_1C_0} + \frac{1}{R_2C_0} \right)} \quad (2.21)$$

2.7 Find  $v_c(t)$ . Plot the graph using Python.

**Solution:**

Upon performing the partial fraction decomposition upon the above obtained result, we get,

$$V_c(s) = \frac{\frac{1}{R_1C_0} + \frac{2}{R_2C_0}}{\frac{1}{R_1C_0} + \frac{1}{R_2C_0}} \left( \frac{1}{s} - \frac{1}{s} + \frac{1}{R_1C_0} + \frac{1}{R_2C_0} \right), \quad \Re(s) > 0 \quad (2.22)$$

On taking the inverse Laplace Transform we get,

$$v_c(t) = \frac{2R_1 + R_2}{R_1 + R_2} \left( u(t) - e^{-\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\frac{1}{C_0}} u(t) \right) \quad (2.23)$$

$$= \frac{2R_1 + R_2}{R_1 + R_2} \left( 1 - e^{-\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\frac{1}{C_0}} \right) u(t) \quad (2.24)$$

Substitute the values  $R_1 = 1 \Omega$ ,  $R_2 = 2 \Omega$  and  $C_0 = 1 \mu\text{F}$

$$v_c(t) = \frac{4}{3} \left( 1 - e^{-\frac{3}{2} \times 10^6 t} \right) \quad (2.25)$$

The code for plotting the graph can be obtained by using the following commands

```
$ wget https://raw.githubusercontent.com/HARI-donk-EY/sig_pros/main/circuit/codes/2_7.py
```

Run the code using.

```
$ python3 2_7.py
```

We get the Fig. 2.7.

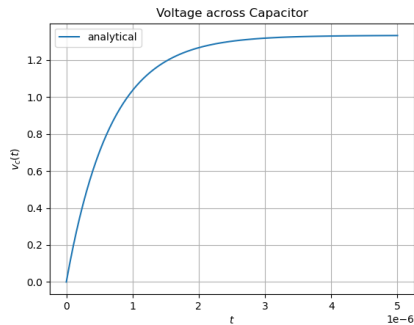


Fig. 2.7. Plot of  $v_c(t)$  before flipping the switch

2.8 Verify the results using ngspice.

**Solution:**

The code for plotting the graph can be obtained by using the following commands

```
$ wget https://raw.githubusercontent.com/HARI-donk-EY/sig_pros/main/circuit/codes/2_8.py
$ wget https://raw.githubusercontent.com/HARI-donk-EY/sig_pros/main/circuit/codes/2_8.cir
```

Run the code using.

```
$ ngspice 2_8.cir
$ python3 2_8.py
```

We get the Fig. 2.8.

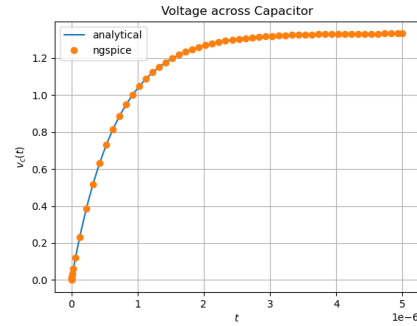


Fig. 2.8. Plot of  $v_c(t)$  before flipping the switch, comparing it along side data obtained from ngspice

2.9 Obtain Fig. 2.6 using equivalent differential equation.

**Solution:**

Using Kirchoff's Junction Law,

$$\frac{v_c(t) - v_1(t)}{R_1} + \frac{v_c(t) - v_2(t)}{R_2} + \frac{dq}{dt} = 0 \quad (2.26)$$

where  $q(t)$  is the charge on the capacitor

On taking the Laplace transform on both sides of this equation

$$\frac{V_c(s) - V_1(s)}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + (sQ(s) - q(0^-)) = 0 \quad (2.27)$$

But  $q(0^-) = 0$  and

$$q(t) = C_0 v_c(t) \quad (2.28)$$

$$\Rightarrow Q(s) = C_0 V_c(s) \quad (2.29)$$

Thus

$$\frac{V_c(s) - V_1(s)}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + sC_0 V_c(s) = 0 \quad (2.30)$$

$$\Rightarrow \frac{V_c(s) - V_1(s)}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + \frac{V_c(s) - 0}{\frac{1}{sC_0}} = 0 \quad (2.31)$$

which is the same equation as the one we obtained from Fig. 2.6

### 3. INITIAL CONDITIONS

3.1 Find  $q_2$  in Fig. 2.2

**Solution:**

After a long time, when steady state is achieved, a capacitor behaves like an open circuit, i.e., current passing through it is zero

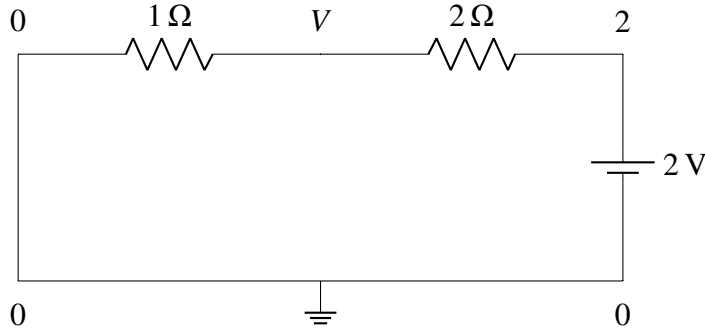


Fig. 3.1. Circuit diagram at steady state after flipping the switch

By Kirchoff's junction law, we get

$$\frac{V-0}{1} + \frac{V-2}{2} = 0 \quad (3.1)$$

$$\Rightarrow V = \frac{2}{3} \text{ V} \quad (3.2)$$

$$\Rightarrow q_2 = CV = \frac{2}{3} \mu\text{C} \quad (3.3)$$

3.2 Draw the equivalent  $s$ -domain resistive circuit when S is switched to position Q. Use variables  $R_1, R_2, C_0$  for the passive elements. Use latex-tikz

**Solution:**

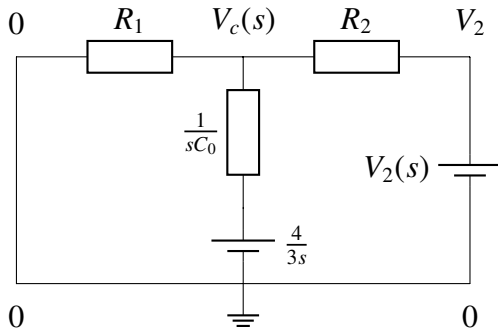


Fig. 3.2. Circuit diagram in  $s$ -domain after flipping the switch

The battery  $\frac{4}{3s}$  corresponds to the initial potential difference of  $\frac{4}{3}$  V across the capacitor

just before switching it to Q

3.3 Find  $V_c(s)$

**Solution:**

By Kirchoff's junction law, we get

$$\frac{V_c - 0}{R_1} + \frac{V_c - V_2}{R_2} + \frac{V_c - \frac{4}{3s}}{\frac{1}{sC_0}} = 0 \quad (3.4)$$

$$\Rightarrow V_c \left( \frac{1}{R_1} + \frac{1}{R_2} + sC_0 \right) = \frac{V_2}{R_2} + \frac{4}{3} C_0 \quad (3.5)$$

$$\Rightarrow V_c(s) = \frac{\frac{2}{sR_2} + \frac{4}{3} C_0}{\frac{1}{R_1} + \frac{1}{R_2} + sC_0} \quad (3.6)$$

$$= \frac{\frac{2}{R_2 C_0} + \frac{4}{3} s}{s \left( s + \frac{1}{R_1 C_0} + \frac{1}{R_2 C_0} \right)} \quad (3.7)$$

3.4 Find  $v_c(t)$ . Plot using Python

**Solution:** On performing partial fraction decomposition

$$V_c(s) = \frac{4}{3} \left( \frac{1}{s + \frac{1}{R_1 C_0} + \frac{1}{R_2 C_0}} \right) + \frac{\frac{2}{R_2 C_0}}{\frac{1}{R_1 C_0} + \frac{1}{R_2 C_0}} \left( \frac{1}{s} - \frac{1}{s + \frac{1}{R_1 C_0} + \frac{1}{R_2 C_0}} \right) \quad (3.8)$$

for  $\Re(s) > 0$

On taking the inverse Laplace transform, we get

$$v_c(t) = \frac{4}{3} e^{-\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \frac{t}{C_0}} u(t) + \frac{2R_1}{R_1 + R_2} \left( u(t) - e^{-\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \frac{t}{C_0}} u(t) \right) \quad (3.9)$$

Substitute the values  $R_1 = 1 \Omega, R_2 = 2 \Omega, C_0 = 1 \mu\text{F}$

$$v_c(t) = \frac{4}{3} e^{-\frac{3}{2} \times 10^6 t} u(t) + \frac{2}{3} \left( 1 - e^{-\frac{3}{2} \times 10^6 t} \right) u(t) \quad (3.10)$$

$$= \frac{2}{3} \left( 1 + e^{-\frac{3}{2} \times 10^6 t} \right) u(t) \text{ V} \quad (3.11)$$

The code for plotting the graph can be obtained by using the following commands

```
$ wget https://raw.githubusercontent.com/HARI-donk-EY/sig_pros/main/circuit/codes/3_4.py
```

Run the code using.

```
$ python3 3_4.py
```

We get the Fig. 3.4.

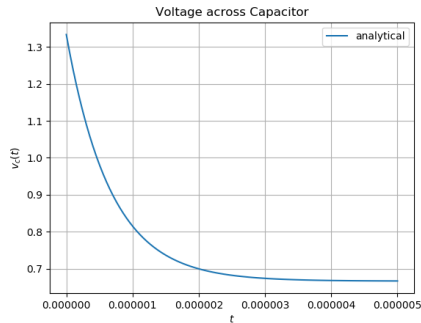


Fig. 3.4. Plot of  $v_c(t)$  after flipping the switch

3.5 Verify the results using ngspice.

#### Solution:

The code for plotting the graph can be obtained by using the following commands

```
$ wget https://raw.githubusercontent.com/HARI-donk-EY/sig_pros/main/circuit/codes/3_5.py
$ wget https://raw.githubusercontent.com/HARI-donk-EY/sig_pros/main/circuit/codes/3_5.cir
```

Run the code using.

```
$ ngspice 3_5.cir
$ python3 3_5.py
```

We get the Fig. 3.5.

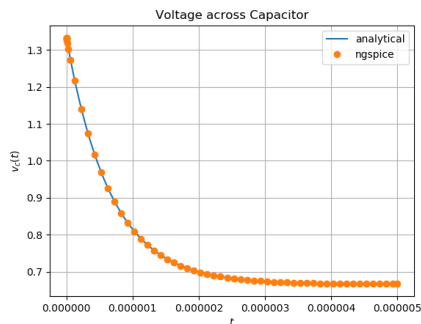


Fig. 3.5. Plot of  $v_c(t)$  after flipping the switch, comparing it along side data obtained from ngspice

3.6 Find  $v_c(0^-)$ ,  $v_c(0^+)$  and  $v_c(\infty)$

#### Solution:

At  $t = 0^-$ , the switch still hasn't been switched to Q and the circuit is in steady state

$$v_c(0^-) = \frac{4}{3} \text{ V} \quad (3.12)$$

For  $t \geq 0$ , we can use the above formula

$$v_c(0^+) = \lim_{t \rightarrow 0^+} v_c(t) = \frac{4}{3} \text{ V} \quad (3.13)$$

$$v_c(\infty) = \lim_{t \rightarrow \infty} v_c(t) = \frac{2}{3} \text{ V} \quad (3.14)$$

3.7 Obtain Fig. 3.2 using the equivalent differential equation

#### Solution:

Using Kirchoff's junction law

$$\frac{v_c(t) - 0}{R_1} + \frac{v_c(t) - v_2(t)}{R_2} + \frac{dq}{dt} = 0 \quad (3.15)$$

where  $q(t)$  is the charge on the capacitor

On taking the Laplace transform on both sides of this equation

$$\frac{V_c(s) - 0}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + (sQ(s) - q(0^-)) = 0 \quad (3.16)$$

But  $q(0^-) = \frac{4}{3}C_0$  and

$$q(t) = C_0 v_c(t) \quad (3.17)$$

$$\Rightarrow Q(s) = C_0 V_c(s) \quad (3.18)$$

Thus

$$\frac{V_c(s) - 0}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + \left( sC_0 V_c(s) - \frac{4}{3}C_0 \right) = 0 \quad (3.19)$$

$$\Rightarrow \frac{V_c(s) - 0}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + \frac{V_c(s) - \frac{4}{3s}}{\frac{1}{sC_0}} = 0 \quad (3.20)$$

which is the same equation as the one we obtained from Fig. 3.2

#### 4. BILINEAR TRANSFORM

4.1 In Fig. 2.2, consider the case when  $S$  is switched to  $Q$  right in the beginning. Formulate the differential equation

**Solution:**

The differential equation is the same as before

$$\frac{v_c(t) - 0}{R_1} + \frac{v_c(t) - v_2(t)}{R_2} + \frac{dq}{dt} = 0 \quad (4.1)$$

$$\text{i.e., } \frac{v_c(t)}{R_1} + \frac{v_c(t) - v_2(t)}{R_2} + C_0 \frac{dv_c}{dt} = 0 \quad (4.2)$$

but with a different initial condition

$$q(0^-) = q(0) = 0 \quad (4.3)$$

4.2 Find  $H(s)$  considering the output voltage at the capacitor

**Solution:**

On taking the Laplace transform on both sides of this equation

$$\frac{V_c(s)}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + sQ(s) - 0 = 0 \quad (4.4)$$

$$\Rightarrow V_c(s) \left( \frac{1}{R_1} + \frac{1}{R_2} \right) + sC_0 V_c(s) = \frac{V_2(s)}{R_2} \quad (4.5)$$

$$\Rightarrow \frac{V_c(s)}{V_2(s)} = \frac{\frac{1}{R_2}}{\frac{1}{R_1} + \frac{1}{R_2} + sC_0} \quad (4.6)$$

The transfer function is thus

$$H(s) = \frac{\frac{1}{R_2 C_0}}{s + \frac{1}{R_1 C_0} + \frac{1}{R_2 C_0}} \quad (4.7)$$

On substituting the values, we get

$$H(s) = \frac{5 \times 10^5}{s + 1.5 \times 10^6} \quad (4.8)$$

4.3 Plot  $H(s)$ . What kind of filter is it?

**Solution:**

Download the following Python code that plots Fig. 4.3

```
$ wget https://raw.githubusercontent.com/HARI-donk-EY/sig_pros/main/circuit/codes/4_3.py
```

Run the codes by executing

```
$ python3 4_3.py
```

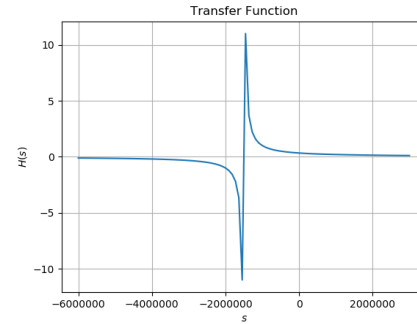


Fig. 4.3. Plot of  $H(s)$

Consider the frequency-domain transfer function by putting  $s = j\omega$

$$H(j\omega) = \frac{5 \times 10^5}{j\omega + 1.5 \times 10^6} \quad (4.9)$$

$$\Rightarrow |H(j\omega)| = \frac{5 \times 10^5}{\sqrt{\omega^2 + 2.25 \times 10^{12}}} \quad (4.10)$$

As  $\omega$  increases,  $|H(j\omega)|$  decreases.

In other words, the amplitude of high-frequency signals gets diminished and they get filtered out.

Therefore, this is a low-pass filter.

4.4 Using trapezoidal rule for integration, formulate the difference equation by considering

$$y(n) = y(t)|_{t=n} \quad (4.11)$$

**Solution:**

$$\frac{v_c(t)}{R_1} + \frac{v_c(t) - v_2(t)}{R_2} + C_0 \frac{dv_c}{dt} = 0 \quad (4.12)$$

$$\Rightarrow C_0 \frac{dv_c}{dt} = \frac{2u(t) - v_c(t)}{R_2} - \frac{v_c(t)}{R_1} \quad (4.13)$$

$$\Rightarrow v_c(t)|_{t=n}^{n+1} = \int_n^{n+1} \left( \frac{2u(t) - v_c(t)}{R_2 C_0} - \frac{v_c(t)}{R_1 C_0} \right) dt \quad (4.14)$$

By the trapezoidal rule of integration

$$\int_a^b f(t) dt \approx \frac{b-a}{2} (f(a) + f(b)) \quad (4.15)$$

Consider  $y(t) = v_c(t)$

$$y(n+1) - y(n) = \frac{1}{R_2 C_0} (u(n) + u(n+1)) - \frac{1}{2} (y(n+1) + y(n)) \left( \frac{1}{R_1 C_0} + \frac{1}{R_2 C_0} \right) \quad (4.16)$$

Thus, the difference equation is

$$\begin{aligned} y(n+1) & \left( 1 + \frac{1}{2R_1 C_0} + \frac{1}{2R_2 C_0} \right) \\ & = y(n) \left( 1 - \frac{1}{2R_1 C_0} - \frac{1}{2R_2 C_0} \right) \\ & \quad + \frac{1}{R_2 C_0} (u(n) + u(n+1)) \end{aligned} \quad (4.17)$$

4.5 Find  $H(z)$

**Solution:**

Let  $\mathcal{Z}\{y(n)\} = Y(z)$

On taking the Z-transform on both sides of the difference equation

$$\begin{aligned} zY(z) & \left( 1 + \frac{1}{2R_1 C_0} + \frac{1}{2R_2 C_0} \right) \\ & = Y(z) \left( 1 - \frac{1}{2R_1 C_0} - \frac{1}{2R_2 C_0} \right) \\ & \quad + \frac{1}{R_2 C_0} \left( \frac{1}{1-z^{-1}} + \frac{z}{1-z^{-1}} \right) \end{aligned} \quad (4.18)$$

$$\begin{aligned} Y(z) & \left( z + \frac{z}{2R_1 C_0} + \frac{z}{2R_2 C_0} - 1 + \frac{1}{2R_1 C_0} + \frac{1}{2R_2 C_0} \right) \\ & = \frac{1}{R_2 C_0} \frac{1+z}{1-z^{-1}} \end{aligned} \quad (4.19)$$

Also

$$v_2(t) = 2 \quad \forall t \geq 0 \quad (4.20)$$

$$\Rightarrow x(n) = 2u(n) \quad (4.21)$$

$$\Rightarrow X(z) = \frac{2}{1-z^{-1}} \quad |z| > 1 \quad (4.22)$$

Thus, the transfer function in  $z$ -domain is

$$H(z) = \frac{Y(z)}{X(z)} \quad (4.23)$$

$$= \frac{\frac{1+z}{2R_2 C_0}}{z + \frac{z}{2R_1 C_0} + \frac{z}{2R_2 C_0} - 1 + \frac{1}{2R_1 C_0} + \frac{1}{2R_2 C_0}} \quad (4.24)$$

$$= \frac{\frac{1+z^{-1}}{2R_2 C_0}}{1 + \frac{1}{2R_1 C_0} + \frac{1}{2R_2 C_0} - z^{-1} + \frac{z^{-1}}{2R_1 C_0} + \frac{z^{-1}}{2R_2 C_0}} \quad (4.25)$$

On substituting the values

$$H(z) = \frac{2.5 \times 10^5 (1+z^{-1})}{7.5 \times 10^5 + 1 + (7.5 \times 10^5 - 1)z^{-1}} \quad (4.26)$$

with the ROC being

$$|z| > \max \left( 1, \left| \frac{7.5 \times 10^5 - 1}{7.5 \times 10^5 + 1} \right| \right) \quad (4.27)$$

$$\Rightarrow |z| > 1 \quad (4.28)$$

4.6 How can you obtain  $H(z)$  from  $H(s)$ ?

**Solution:**

The Z-transform can be obtained from the Laplace transform by the substitution

$$s = \frac{2}{T} \frac{1-z^{-1}}{1+z^{-1}} \quad (4.29)$$

where  $T$  is the step size of the trapezoidal rule (1 in our case)

This is known as the bilinear transform

Thus

$$H(z) = \frac{\frac{1}{R_2 C_0}}{2 \frac{1-z^{-1}}{1+z^{-1}} + \frac{1}{R_1 C_0} + \frac{1}{R_2 C_0}} \quad (4.30)$$

$$= \frac{\frac{1+z^{-1}}{2R_2 C_0}}{1 - z^{-1} + \left( \frac{1}{2R_1 C_0} + \frac{1}{2R_2 C_0} \right) (1 + z^{-1})} \quad (4.31)$$

$$= \frac{\frac{1+z^{-1}}{2R_2 C_0}}{1 + \frac{1}{2R_1 C_0} + \frac{1}{2R_2 C_0} - z^{-1} + \frac{z^{-1}}{2R_1 C_0} + \frac{z^{-1}}{2R_2 C_0}} \quad (4.32)$$

$$= \frac{2.5 \times 10^5 (1+z^{-1})}{7.5 \times 10^5 + 1 + (7.5 \times 10^5 - 1)z^{-1}} \quad (4.33)$$

which is the same as what we obtained earlier

In order to find  $h(n)$  we represent  $H(z)$  as

$$H(z) = \frac{c(1+z^{-1})}{a+bz^{-1}} \quad (4.34)$$

$$= \frac{c}{b} + \frac{c(1-\frac{a}{b})}{a+bz^{-1}} \quad (4.35)$$

Taking the the inverse  $z$  transform

$$h(n) = \frac{c}{b} \delta(n) + \frac{c}{a} \left( 1 - \frac{a}{b} \right) \left( \frac{a}{b} \right)^n u(n) \quad (4.36)$$

4.7 Find  $v(n)$ . Verify using ngspice and the differential equation.

**Solution:**

We have,

$$H(z) = \frac{\frac{1}{R_2 C_0}}{\frac{2}{T} \frac{1-z^{-1}}{1+z^{-1}} + \frac{1}{R_1 C_0} + \frac{1}{R_2 C_0}} \quad (4.37)$$

$$= \frac{\frac{1}{R_2 C_0}}{\frac{2}{T} \frac{1-z^{-1}}{1+z^{-1}} + \frac{R_1 + R_2}{R_1 R_2 C_0}} \quad (4.38)$$

$$= \frac{\frac{1}{R_2 C_0}}{\frac{2}{T} \frac{1-z^{-1}}{1+z^{-1}} + \frac{1}{\tau}} \quad (4.39)$$

$$(4.40)$$

Here  $\tau := C_0 \frac{R_1 R_2}{R_1 + R_2}$

$$H(z) = \frac{T\tau(1+z^{-1})}{C_0 R_2 ((2\tau + T) - (2\tau - T)z^{-1})} \quad (4.41)$$

Then,

$$Y(z) = H(z)X(z) \quad (4.42)$$

$$= \frac{2T\tau(1+z^{-1})}{C_0 R_2 (1-z^{-1})((2\tau + T) - (2\tau - T)z^{-1})} \quad (4.43)$$

$$= \frac{T(z+1)}{z(2\tau + T)} \frac{1}{(1-z^{-1})\left(1 - \left(\frac{2\tau - T}{2\tau + T}\right)z^{-1}\right)} \quad (4.44)$$

$$= \frac{\tau(z+1)}{C_0 R_2} \sum_{k=-\infty}^{\infty} (1-p^k) u(k) z^{-k} \quad (4.45)$$

where  $p := \frac{2\tau - T}{2\tau + T}$ . Thus,

$$v(n) = \frac{2\tau}{C_0 R_2} \left[ u(n)(1-p^n) + u(n+1)(1-p^{n+1}) \right] \quad (4.46)$$

We take  $T = 10^{-7}$  as the sampling interval. The code for verifying the result can be obtained from

```
$ wget https://raw.githubusercontent.com/HARI-donk-EY/sig_pros/main/circuit/codes/4_7.cir
$ wget https://raw.githubusercontent.com/HARI-donk-EY/sig_pros/main/circuit/codes/4_7.py
```

Run the codes by using the commands,

```
$ ngspice 4_7.cir
$ python3 4_7.py
```

The Fig. 4.7 is obtained.

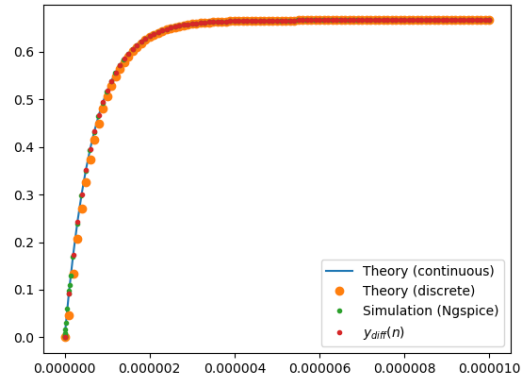


Fig. 4.7. Representation of output across  $C_0$