

# Circuits and Transforms

## EE3900: Linear Systems and Signal Processing

### Indian Institute of Technology Hyderabad

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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

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

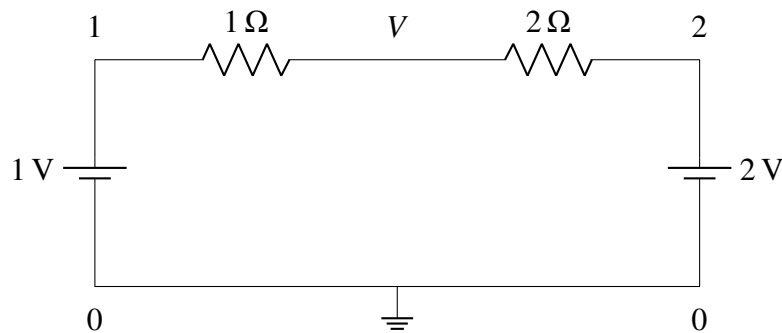


Fig. 2.3. Circuit diagram at steady state before flipping the switch

#### 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:**

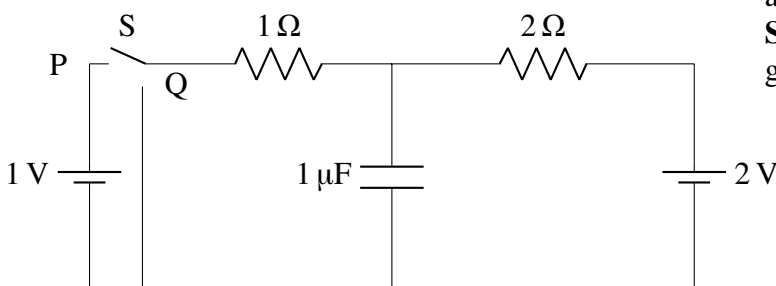


Fig. 2.2. Circuit diagram of the circuit in question

2.3. Find  $q_1$

**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

By Kirchoff's junction law, we 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 the 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

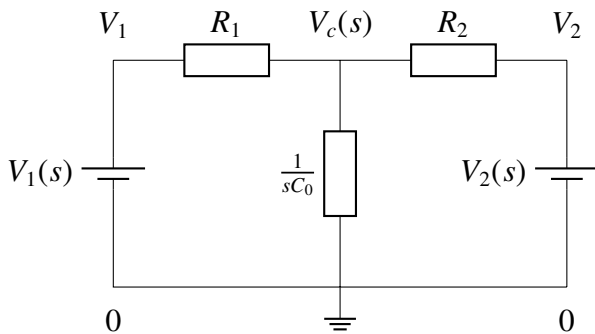


Fig. 2.6. Circuit diagram in  $s$ -domain before flipping the switch

where

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

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

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

**Solution:**

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

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

By Kirchoff's junction law, we get

$$\frac{V_c - V_1}{R_1} + \frac{V_c - V_2}{R_2} + \frac{V_c - 0}{\frac{1}{sC_0}} = 0 \quad (2.17)$$

$$\Rightarrow V_c \left( \frac{1}{R_1} + \frac{1}{R_2} + sC_0 \right) = \frac{V_1}{R_1} + \frac{V_2}{R_2} \quad (2.18)$$

$$\Rightarrow V_c(s) = \frac{\frac{1}{sR_1} + \frac{2}{sR_2}}{\frac{1}{R_1} + \frac{1}{R_2} + sC_0} \quad (2.19)$$

$$= \frac{\frac{1}{R_1C_0} + \frac{2}{R_2C_0}}{s \left( s + \frac{1}{R_1C_0} + \frac{1}{R_2C_0} \right)} \quad (2.20)$$

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

**Solution:** On performing partial fraction decomposition

$$V_c(s) = \frac{\frac{1}{R_1C_0} + \frac{2}{R_2C_0}}{\frac{1}{R_1C_0} + \frac{1}{R_2C_0}} \left( \frac{1}{s} - \frac{1}{s + \frac{1}{R_1C_0} + \frac{1}{R_2C_0}} \right), \Re(s) > 0 \quad (2.21)$$

On taking the inverse Laplace transform, we get

$$v_c(t) = \frac{2R_1 + R_2}{R_1 + R_2} \left( u(t) - e^{-\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\frac{t}{C_0}} u(t) \right) \quad (2.22)$$

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

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

$$v_c(t) = \frac{4}{3} \left( 1 - e^{-\frac{3}{2} \times 10^6 t} \right) u(t) \text{ V} \quad (2.24)$$

2.8. Verify your result using ngspice

**Solution:** Download the following codes for simulation and plotting Fig. 2.8 respectively

```
wget https://github.com/Dhatrreddyy/circuits/
blob/main/codes/2.8.cir
wget https://github.com/Dhatrreddyy/circuits/
blob/main/codes/2.7.py
```

Run the codes by executing

```
ngspice 2.8.cir
python3 2.7.py
```

2.9. Obtain Fig. 2.6 using the equivalent differential equation

**Solution:** Using Kirchoff's junction law

$$\frac{v_c(t) - v_1(t)}{R_1} + \frac{v_c(t) - v_2(t)}{R_2} + \frac{dq}{dt} = 0 \quad (2.25)$$

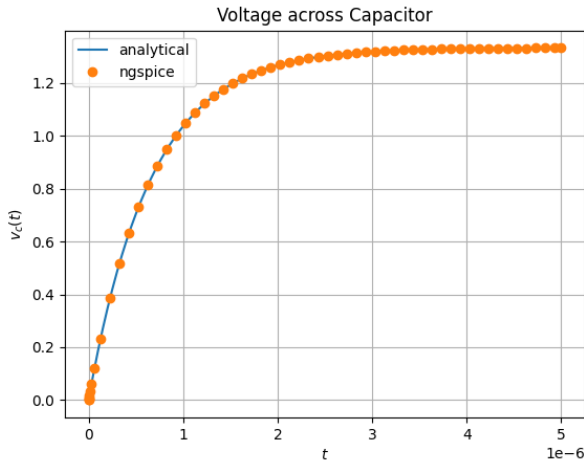


Fig. 2.8. Plot of  $v_c(t)$  before flipping the switch

where  $q(t)$  is the charge on the capacitor  
On taking the Laplace transform on both sides  
of this equation

$$\frac{V_c(s) - V_1(s)}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + (sQ(s) - q(0^-)) = 0 \quad (2.26)$$

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

$$q(t) = C_0 v_c(t) \quad (2.27)$$

$$\Rightarrow Q(s) = C_0 V_c(s) \quad (2.28)$$

Thus

$$\frac{V_c(s) - V_1(s)}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + sC_0 V_c(s) = 0 \quad (2.29)$$

$$\Rightarrow \frac{V_c(s) - V_1(s)}{R_1} + \frac{V_c(s) - V_2(s)}{R_2} + \frac{V_c(s) - 0}{\frac{1}{sC_0}} = 0 \quad (2.30)$$

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

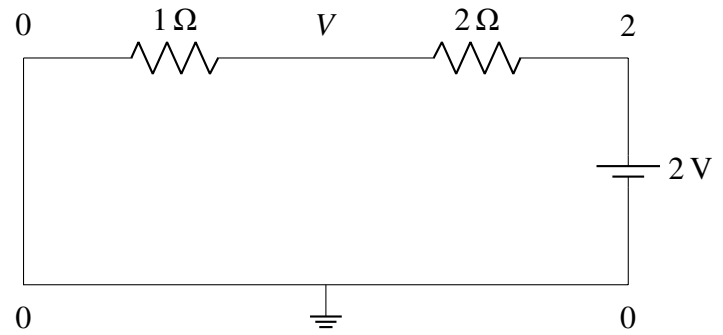


Fig. 3.1. Circuit diagram at steady state after flipping the switch

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:**

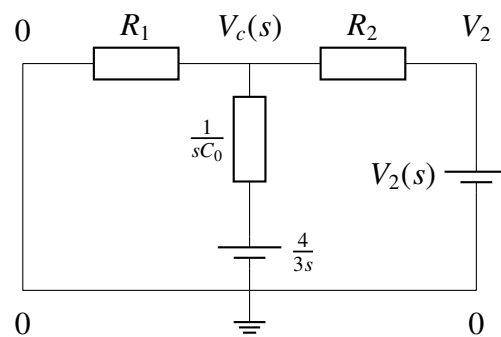


Fig. 3.2. Circuit diagram in  $s$ -domain after flipping the switch

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

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

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

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

$$= \frac{\frac{2}{R_2C_0} + \frac{4}{3}s}{s \left( s + \frac{1}{R_1C_0} + \frac{1}{R_2C_0} \right)} \quad (3.7)$$

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

**Solution:** On performing partial fraction decomposition

$$V_c(s) = \frac{4}{3} \left( \frac{1}{s + \frac{1}{R_1C_0} + \frac{1}{R_2C_0}} \right) + \frac{\frac{2}{R_2C_0}}{\frac{1}{R_1C_0} + \frac{1}{R_2C_0}} \left( \frac{1}{s} - \frac{1}{s + \frac{1}{R_1C_0} + \frac{1}{R_2C_0}} \right) \quad (3.8)$$

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

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

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

3.5. Verify your result using ngspice

**Solution:** Download the following codes for simulation and plotting Fig. 3.5 respectively

```
wget https://github.com/Dhatrreddyy/circuits/blob/main/codes/3.5.cir
wget https://github.com/Dhatrreddyy/circuits/blob/main/codes/3.4.py
```

Run the codes by executing

```
ngspice 3.5.cir
python3 3.4.py
```

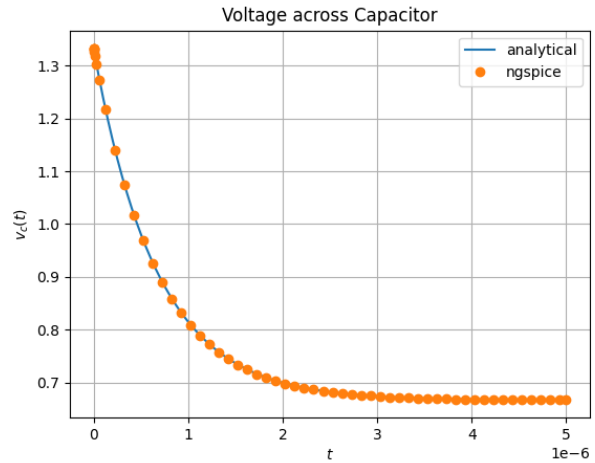


Fig. 3.5. Plot of  $v_c(t)$  after flipping the switch

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

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

(3.19)

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

(3.20)

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