HW01

EE 538 Spring 2020
Analog Circuits for Sensor Systems
University of Washington Electrical & Computer Engineering

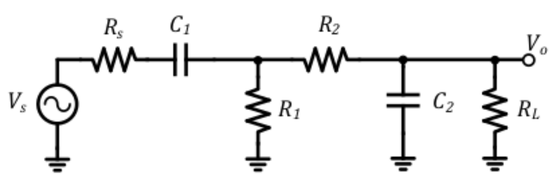
Due: April 11, 2020
Author: Kevin Egedy

In [1]:
```
# Imports
import os
import sys
import cmath
import math
import matplotlib.pyplot as plt
import matplotlib
import numpy as np
import pandas as pd
import ltspice
import sympy as sp
from scipy import signal
%matplotlib inline
from IPython.core.interactiveshell import InteractiveShell
InteractiveShell.ast_node_interactivity = "all"
```

In [2]:
```
def read_ltspice_tran(file_name):
    cols = []
    arrs = []
    with open(file_name, 'r',encoding='utf-8') as data:
        for i,line in enumerate(data):
            if i==0:
                cols = line.split()
                arrs = [[] for _ in cols]
                continue
            parts = line.split()
            for j,part in enumerate(parts):
                arrs[j].append(part)
    df = pd.DataFrame(arrs,dtype='float64')
    df = df.T
    df.columns = cols
    return df
```

In [3]:
```python
def RoundNonZeroDecimal(num, place, rnd='ceil'):
    # Requires numpy library
    # Examples:
    #   RoundNonZeroDecimal(0.0004512,1,'floor') -> 0.0045
    #   RoundNonZeroDecimal(0.0004512,1,'ceil') -> 0.0046
    #
    tmp = num # implement so that num can be array
    mag = 0

    if rnd=='ceil':
        while(abs(tmp)<1):
            tmp*=10
            mag+=1
        for i in range(place):
            tmp*=10
            mag+=1
        return int(np.ceil([tmp])[0])/(10**(mag))

    if rnd=='floor':
        while(abs(tmp)<1):
            tmp*=10
            mag+=1
        for i in range(place):
            tmp*=10
            mag+=1
        return int(np.floor([tmp])[0])/(10**(mag))

    else:
        raise ValueError('Invalid argument')
        return None
```

Problem 1: Circuit loading, filtering



Design the bandpass RC filter to achieve >20dB attenuation at 1MHz and less than 0.1dB attenuation from 1 Hz to 10 kHz.

a) First, ignoring loading effects, determine 3dB frequencies ($f_{3dB,HP}$ and $f_{3db,LP}$) that meet the specifications.
b) With R_s = 100Ω and R_L = 10MΩ, choose R_1, R_2, C_1, and C_2 to minimize loading effects.
c) Simulate the frequency response (V_o/V_s) in Ltspice and plot it together with the ideal response in MATLAB/Python.

Part A Let $R = 1000\Omega$ for initial calculations

LP & HP filters: $f_{3\text{dB}} = \frac{1}{2\pi RC}$

$$\text{Choose } f_{3\text{dB,HP}} \text{ to be 1 decade before 1Hz}$$

$$0.1\text{Hz} = \left.\frac{1}{2\pi R_1 C_1}\right|_{R_1=1000} \rightarrow C_1 \quad = 1.59\text{mA}$$

$$\text{Choose } f_{3\text{dB,LP}} \text{ to be 1 decade after 10KHz}$$

$$100\text{KHz} = \left.\frac{1}{2\pi R_2 C_2}\right|_{R_2=1000} \rightarrow C_2 \quad = 1.59\text{nA}$$

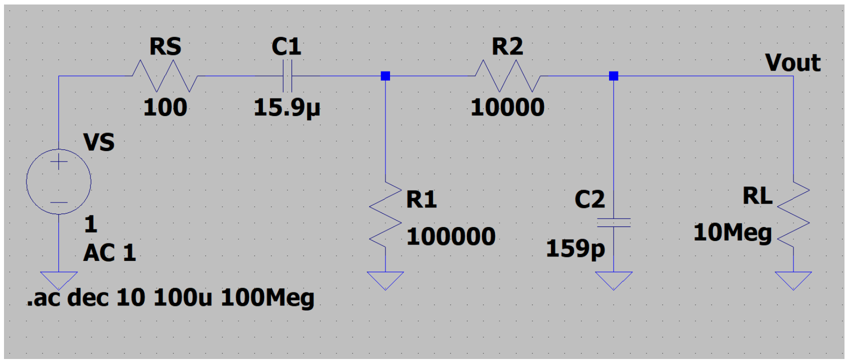
Part B

Notes: HP/LP worst loading effect is determined by R.

To minimize loading effects choose R_1, R_2 to be at least 10*x* larger than R_S and at least 10*x* smaller than R_L. LTspice was used to validate and tune these values.

$R_1 = 100K\Omega, C_1 = 15.9\mu\text{F}$
$R_2 = 10K\Omega, C_2 = 159p\text{F}$

Part C

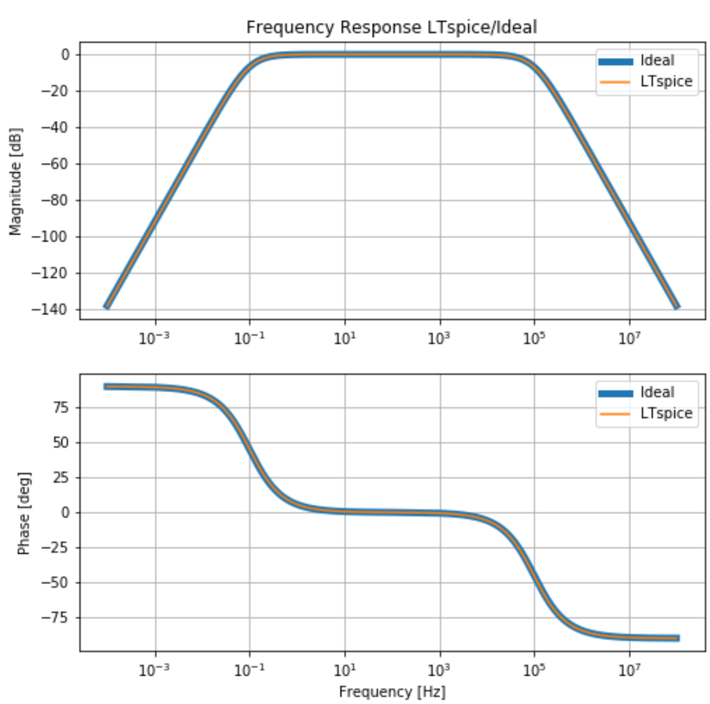



```
In [4]: def parallel(Z1,Z2):
            return 1/((1/Z1)+(1/Z2))

        def voltdiv(Z1,Z2):
            return Z2/(Z1+Z2)
```

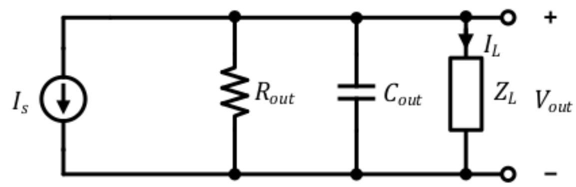
In [5]:

```
f1 = np.linspace(1e-4,1e2,100000)
f2 = np.linspace(1e2,1e8,100000)
f = np.concatenate((f1,f2))
w = 2*np.pi*f
RS = 100
R1 = 100e3
R2 = 10e3
RL = 10e6
C1 = 15.9e-6
C2 = 159e-12
tau1 = R1*C1
tau2 = R2*C2
#LP = 1/(1+1j*w*tau2)
#HP = (1j*w*tau1)/(1+1j*w*tau1)
ZC1 = 1/(1j*w*C1)
ZC2 = 1/(1j*w*C2)
H = voltdiv(RS+ZC1,R1)*voltdiv(R2,ZC2)

filepath = 'data/Q1.raw'
l = ltspice.Ltspice(filepath); l.parse()
V1 = l.getData('V(vout)')
freq = l.getFrequency()

fig, axs = plt.subplots(2,figsize=(8,8))
axs[0].set_title('Frequency Response LTspice/Ideal')
axs[0].semilogx(f, 20*np.log(abs(H)),linewidth=5,label='Ideal')
axs[0].semilogx(freq, 20*np.log(abs(V1)),label='LTspice')
axs[0].set_ylabel('Magnitude [dB]')
axs[0].grid()
axs[0].legend()

axs[1].semilogx(f, np.angle(H,deg=True),linewidth=5, label='Ideal')
axs[1].semilogx(freq,np.angle(V1,deg=True),label='LTspice')
axs[1].set_ylabel('Phase [deg]')
axs[1].set_xlabel('Frequency [Hz]')
axs[1].grid()
axs[1].legend()
plt.show();
```

```
/home/kegedy/anaconda3/lib/python3.7/site-packages/IPython/core/pylabtools.py:128: UserWarning:
Creating legend with loc="best" can be slow with large amounts of data.
  fig.canvas.print_figure(bytes_io, **kw)
```



Problem 2: Current sources, frequency response, loading



Use the circuit and variables (no values) for the following.

a) Sketch the frequency response (magnitude and phase) V_{out}/I_s for $Z_L \to \infty$.
b) Sketch the frequency response (magnitude and phase) V_{out}/I_s together with the unloaded response (part a) for the two conditions
   1. $Z_L = C_L$
   2. $Z_L = R_L$
c) Sketch the transient response of V_{out} for I_s as a current step from 0 to I_{max} ($Z_L \to \infty$).

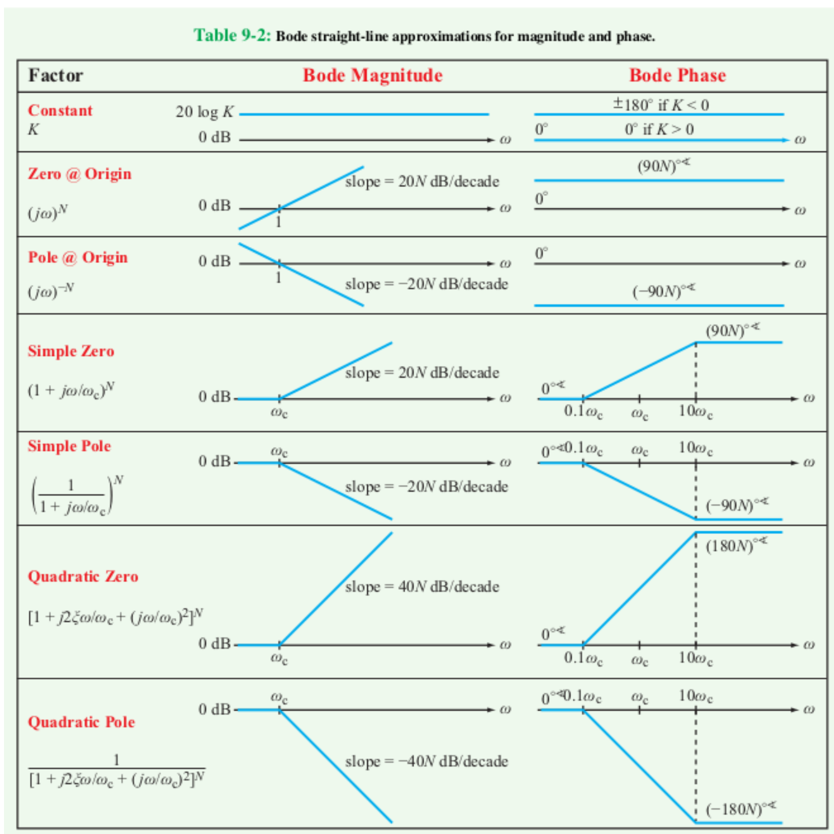


Table 9-2: Bode straight-line approximations for magnitude and phase.

Factor	Bode Magnitude	Bode Phase
Constant K	$20 \log K$; 0 dB; ω	$\pm 180°$ if $K < 0$; $0°$; $0°$ if $K > 0$; ω
Zero @ Origin $(j\omega)^N$	0 dB; 1; slope = $20N$ dB/decade; ω	$(90N)°$; $0°$; ω
Pole @ Origin $(j\omega)^{-N}$	0 dB; 1; slope = $-20N$ dB/decade; ω	$0°$; $(-90N)°$; ω
Simple Zero $(1 + j\omega/\omega_c)^N$	0 dB; ω_c; slope = $20N$ dB/decade; ω	$(90N)°$; $0°$; $0.1\omega_c$; ω_c; $10\omega_c$; ω
Simple Pole $\left(\frac{1}{1 + j\omega/\omega_c}\right)^N$	0 dB; ω_c; slope = $-20N$ dB/decade; ω	$0°$; $0.1\omega_c$; ω_c; $10\omega_c$; $(-90N)°$; ω
Quadratic Zero $[1 + j2\xi\omega/\omega_c + (j\omega/\omega_c)^2]^N$	0 dB; ω_c; slope = $40N$ dB/decade; ω	$(180N)°$; $0°$; $0.1\omega_c$; ω_c; $10\omega_c$; ω
Quadratic Pole $\frac{1}{[1 + j2\xi\omega/\omega_c + (j\omega/\omega_c)^2]^N}$	0 dB; ω_c; slope = $-40N$ dB/decade; ω	$0°$; $0.1\omega_c$; ω_c; $10\omega_c$; $(-180N)°$; ω

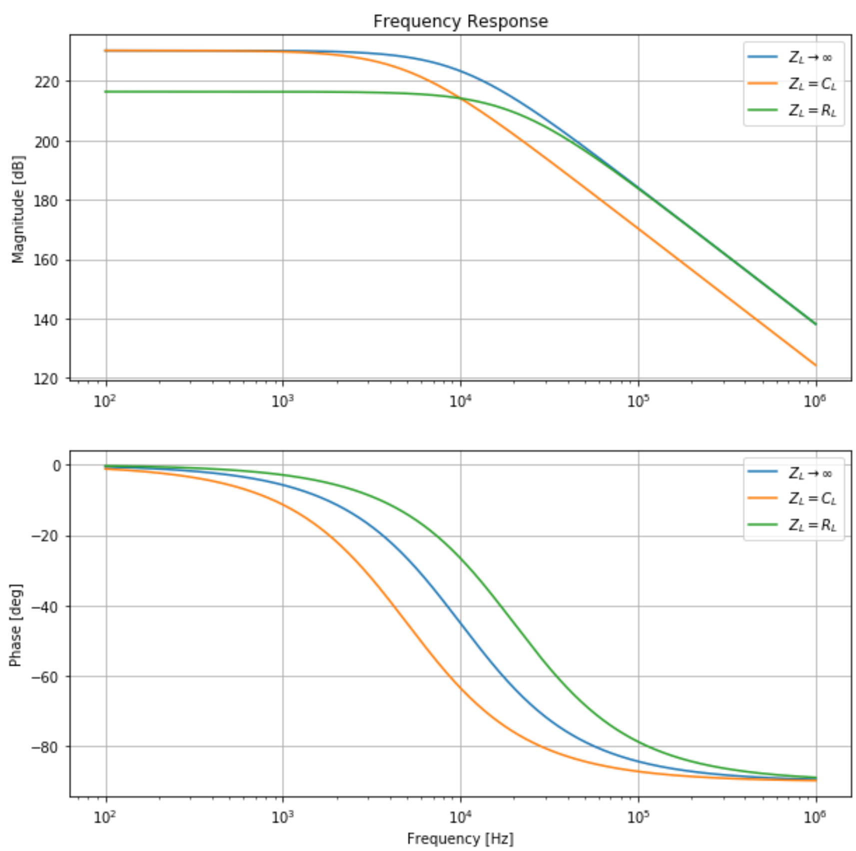
Reference: Circuit Analysis and Design by Fawwaz T. Ulaby, Michel M. Maharbiz, and Cynthia M. Fuse

Part A and B

Note:
- parallel capacitance add like resistors in series
- parallel resistance can be rearranged in any order

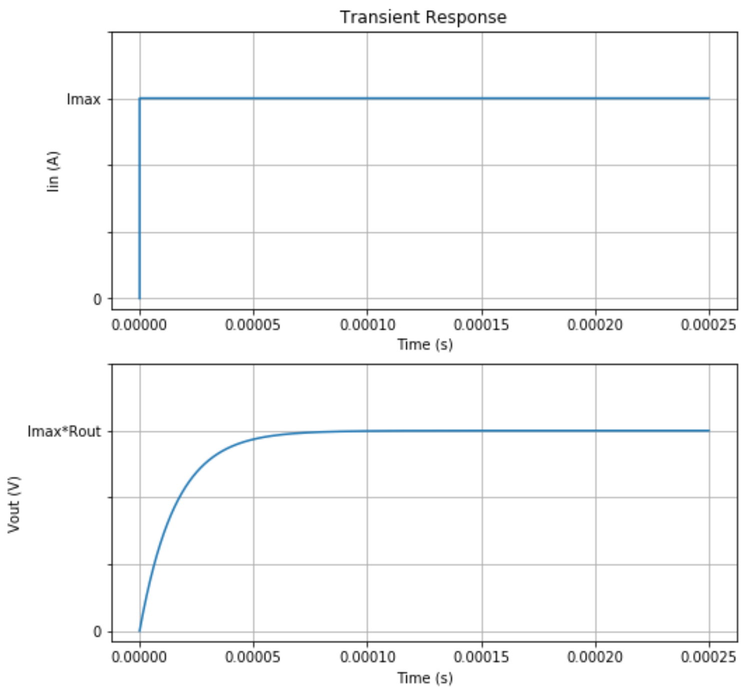
Transfer Function: $K\frac{a}{s+a}$ and $a = \frac{1}{RC}, K = R$

In [6]:
```
f = np.linspace(100,1e6,1000000)
w = 2*np.pi*f
H1 = 1/((1/R1)+1j*w*C2)
H2 = 1/((1/R1)+1j*w*2*C2)   # Z_L = C_L -> smaller cutoff
H3 = 1/((1/(R1/2)+1j*w*C2)) # Z_L = R_L -> larger cutoff and smaller lowpass magnitude; R_L = R_
out

fig, axs = plt.subplots(2,figsize=(10,10))
axs[0].set_title(r'Frequency Response')
axs[0].semilogx(f, 20*np.log(abs(H1)), label=r'$Z_L \rightarrow \infty$')
axs[0].semilogx(f, 20*np.log(abs(H2)), label=r'$Z_L = C_L$')
axs[0].semilogx(f, 20*np.log(abs(H3)), label=r'$Z_L = R_L$')
axs[0].set_ylabel('Magnitude [dB]')
axs[0].legend()
axs[0].grid()

axs[1].semilogx(f, np.angle(H1,deg=True), label=r'$Z_L \rightarrow \infty$')
axs[1].semilogx(f, np.angle(H2,deg=True), label=r'$Z_L = C_L$')
axs[1].semilogx(f, np.angle(H3,deg=True), label=r'$Z_L = R_L$')
axs[1].set_ylabel('Phase [deg]')
axs[1].set_xlabel('Frequency [Hz]')
axs[1].legend()
axs[1].grid()
plt.show();
```

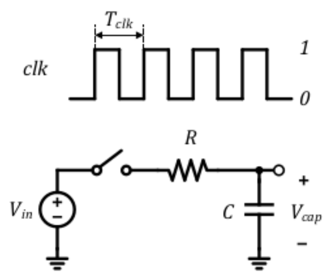


Part C

In [7]:
```
t = np.linspace(0,0.00025,100000)
step = 3*np.ones(len(t)-1)
x = [0]+step.tolist()
Tau = R1*C2
y = x*(1-np.exp(-t/Tau))
fig, axs = plt.subplots(2,figsize=(8,8))


axs[0].set_title('Transient Response')
axs[0].step(t,x)
axs[0].set_ylabel('Iin (A)')
axs[0].set_xlabel('Time (s)')
axs[0].set_yticks([0,1,2,3,4])
axs[0].set_yticklabels(['0','','','Imax',''])
axs[0].grid()

axs[1].plot(t,y)
axs[1].set_ylabel('Vout (V)')
axs[1].set_xlabel('Time (s)')
axs[1].set_yticks([0,1,2,3,4])
axs[1].set_yticklabels(['0','','','Imax*Rout',''])
axs[1].grid()
plt.show();
```



Problem 3: Sampling, settling, power dissipation



The clock waveform shown above is used to drive the switch open and closed ($clk = 1 \rightarrow$ switch closed, $clk = 0 \rightarrow$ switch open). T_{clk} is the clock period (50% duty cycle), where $T_{clk} = 1/f_{clk}$. V_{in} = 1V, $R = 100\ \Omega$, and C = 10 pF

a) What is the maximum clock frequency, f_{clk}, that allows 0.1% settling precision of V_{cap} each period?
b) Given this clock frequency, what is the average current delivered to the capacitor?
c) Verify your answers to a) and b) using Ltspice. To do this using a DC source fo V_{in}, you need to use an initial condition (0V) on V_{cap}. Include any relevant plots in your submission.
d) Perform an AC simulation on the circuit in Ltspice (switch closed). Relate the frequency response to the settling time and include any relevant plots.

Part A

Maximum clock frequency is defined by the smallest clock period that satisfies the precision settling time.

Given: 0.1% precision settling time $\rightarrow t_{\text{settle}} \geq -\ln(0.001) \approx 6.9\tau$

In low pass filter, $\tau = RC = (100)(10 \cdot 10^{-12}) = 10^{-9}s$, thus $t_{\text{settle}} = 6.9\tau = 6.9\text{ns}$

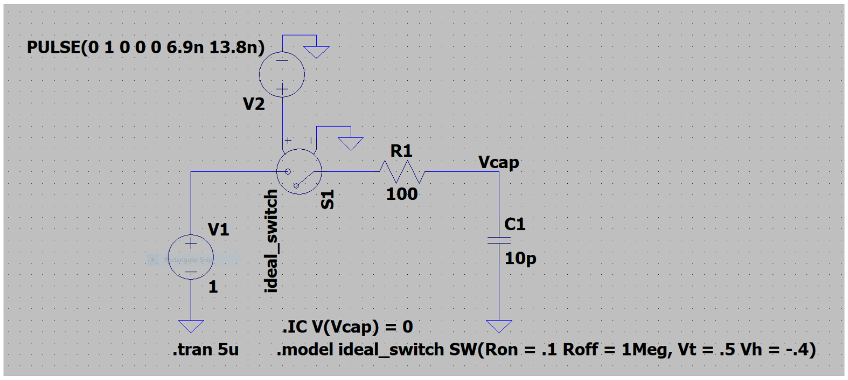
$$
\begin{aligned}
T_{\text{clk}}(50\%\text{ duty cycle}) &= \frac{1}{2f_{\text{clk}}} \\
t_{\text{settle}} &= \frac{1}{2f_{\text{clk}}} \\
f_{\text{clk}} &= \frac{1}{2 \cdot 6.9 \cdot 10^{-9}} \\
f_{\text{clk}} &= 7.246 \cdot 10^{7}
\end{aligned}
$$

The maximum clock frequency is $72.46\ \text{MHz}$.

Part B

The capacitor reactance $\frac{1}{jwC}$ becomes very small at high frequecies and the voltage across the capacitor approaches $V_{\text{in}} = 1$V. Since the capacitor is never discharged, the average current delivered to the capacitor is zero as t approaches infinity.

Part C

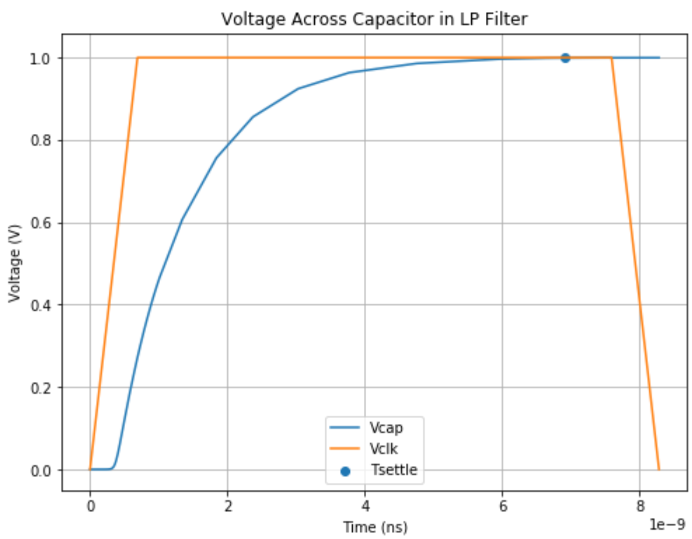


In [8]:
```
filepath = 'data/Q3.txt'
df = read_ltspice_tran(filepath)
df = df[df['time']<10e-9]
```

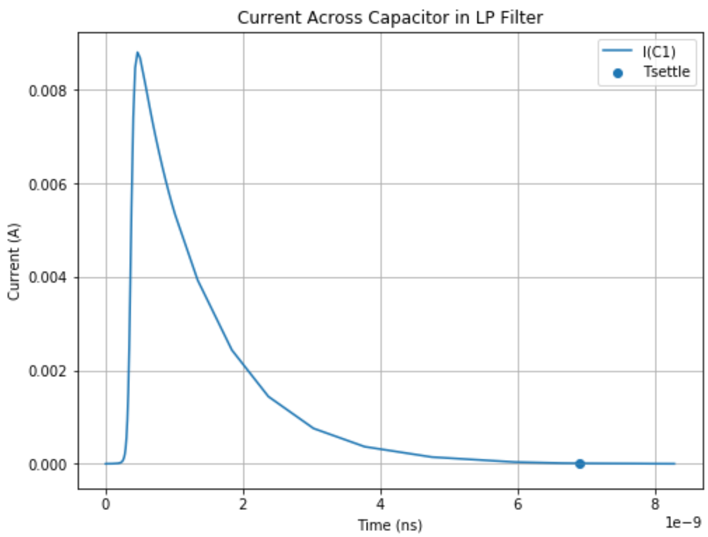
In [9]:
```
v = 1-np.exp(-6.9)
print(f'Vcap theoretical voltage is {round(v,6)}V at 6.9ns')

time = df['time'].to_numpy()
x0 = np.where(time<=7e-9)[0][-1]
v = df.iloc[x0]['V(vcap)']
i = df.iloc[x0]['I(C1)']
t = df.iloc[x0]['time']
print(f'Vcap simulated voltage is {v}V at {RoundNonZeroDecimal(t,4)}s')
```

```
Vcap theoretical voltage is 0.998992V at 6.9ns
Vcap simulated voltage is 0.9990016V at 6.9e-09s
```

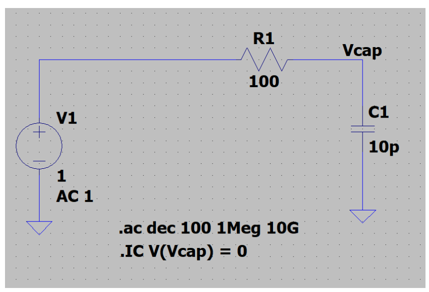
In [10]:
```
fig, ax = plt.subplots(1,figsize=(8,6))
ax.set_title('Voltage Across Capacitor in LP Filter')
ax.plot(df['time'], df['V(vcap)'],label='Vcap')
ax.plot(df['time'], df['V(n001)'],label='Vclk')
ax.scatter(t,v,label='Tsettle')
ax.set_ylabel('Voltage (V)')
ax.set_xlabel('Time (ns)')
ax.grid()
ax.legend()
plt.show();
```



In [11]:
```
fig, ax = plt.subplots(1,figsize=(8,6))
ax.set_title('Current Across Capacitor in LP Filter')
ax.plot(df['time'], df['I(C1)'],label='I(C1)')
ax.scatter(t,i,label='Tsettle')
ax.set_ylabel('Current (A)')
ax.set_xlabel('Time (ns)')
ax.grid()
ax.legend()
plt.show();
```

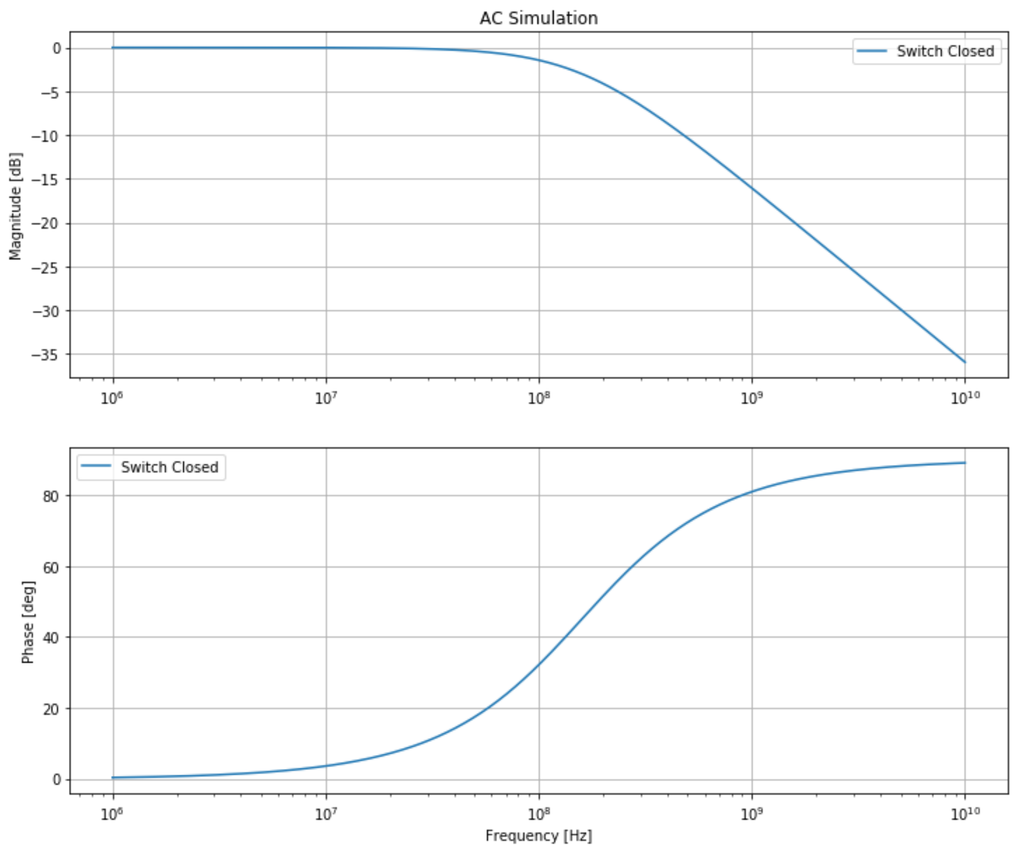


Part D



In [12]:
```
filepath = 'data/Q3_ACanalysis.txt'
df = read_ltspice_tran(filepath)
df['Vcap_Mag'] = df['V(vcap)'].apply(lambda x: x.split(',')[0])
df['Vcap_Mag'] = df['Vcap_Mag'].apply(lambda x: x[1:-2])
df['Vcap_Mag'] = df['Vcap_Mag'].astype('float64')
df['Vcap_Phase'] = df['V(vcap)'].apply(lambda x: x.split(',')[1])
df['Vcap_Phase'] = df['Vcap_Phase'].apply(lambda x: x[1:-2])
df['Vcap_Phase'] = df['Vcap_Phase'].astype('float64')
df['Freq.'] = df['Freq.'].astype('float64')
```

In [13]:
```
fig, axs = plt.subplots(2,figsize=(12,10))
f = df['Freq.']
mag = df['Vcap_Mag']
ang = df['Vcap_Phase']

axs[0].set_title('AC Simulation')
axs[0].semilogx(f, mag, label='Switch Closed')
axs[0].set_ylabel('Magnitude [dB]')
axs[0].grid()
axs[0].legend()
axs[1].semilogx(f, ang, label='Switch Closed')
axs[1].set_ylabel('Phase [deg]')
axs[1].set_xlabel('Frequency [Hz]')
axs[1].grid()
axs[1].legend()
plt.show();
```



The transfer function is a single pole characterized by $\omega_{\text{cutoff}} = \frac{1}{\tau} = \frac{1}{RC}$. Notice this is inversly proportional to $t_{\text{settle}} = 6.9\tau = 6.9\text{RC}$. If RC is small, then the ω_{cutoff} will occur at a greater frequency and t_{settle} will be shorter. Likewise, if RC is large, then the cutoff will occur at a smaller frequency and t_{settle} will be longer.

In [ ]: