data_process

March 14, 2021

[1]:
```python
import pandas as pd
import matplotlib.pyplot as plt
import plotnine as pn
import numpy as np
from scipy.optimize import minimize
```

[56]:
```python
%matplotlib inline
```

1 Voltage Transfer Characteristics

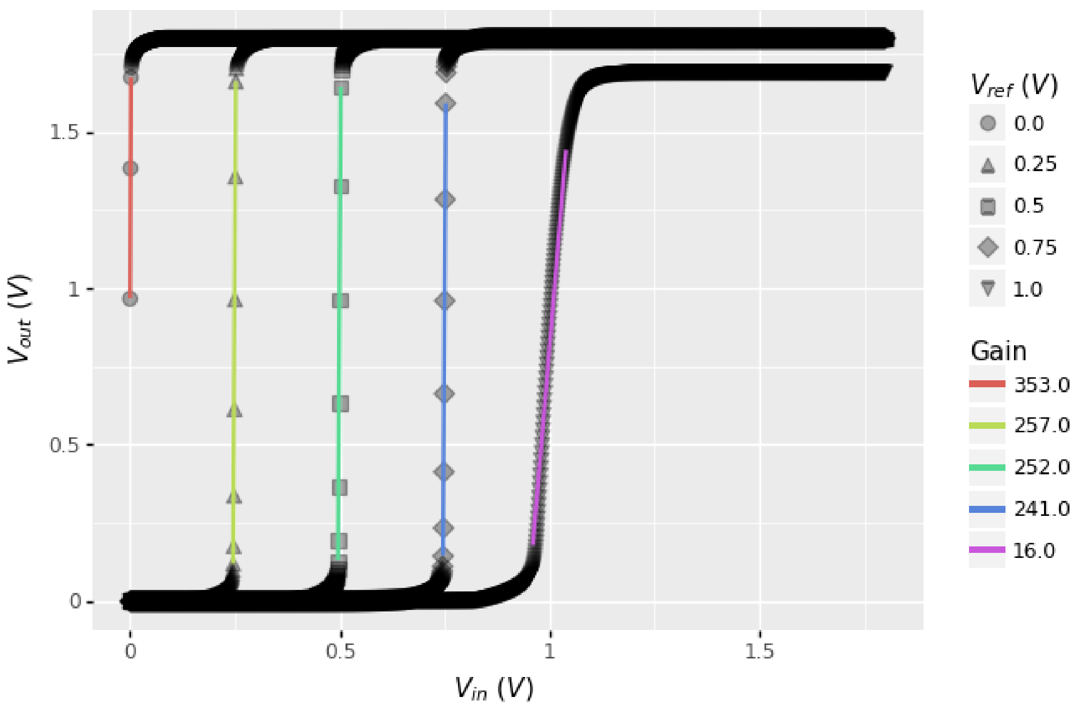
[3]:
```python
df_a = pd.read_csv("./schem/data/vtc_noninv.csv")
```

[4]:
```python
df_a = df_a.rename(columns={
    "v(V1)":"Vin",
    "v(V2)":"Vref",
    "v(Vout)":"Vout",
    "v(X1.net8)":"csrc"
                    })
df_a["Vref"] = df_a["Vref"].astype("str")
```

[5]:
```python
def gain(v, i, j):
    df_tmp = df_a[df_a.Vref==v].reset_index(drop=True).iloc[i:j].
 ↪reset_index(drop=True)
    m = int((df_tmp.iloc[-1].Vout - df_tmp.iloc[0].Vout)/(df_tmp.iloc[-1].Vin -␣
 ↪df_tmp.iloc[0].Vin))
    b = df_tmp.iloc[-1].Vout - m*df_tmp.iloc[-1].Vin
    df_plt = pd.DataFrame({
        "Vin": df_tmp.Vin,
        "Vout": m*df_tmp.Vin+b,
        "Vref": df_tmp.Vref,
        "m": m*np.ones(len(df_tmp.Vin))
    })
    df_plt["m"] = df_plt["m"].astype("str")
    return m, b, df_plt
```

[45]:
```python
_, _, df0_plt = gain("0.0", 0, 3)
_, _, df025_plt = gain("0.25", 246, 253)
```

```python
_, _, df05_plt = gain("0.5", 496, 503)
_, _, df075_plt = gain("0.75", 746, 753)
_, _, df1_plt = gain("1.0", 960, 1040)
(
    pn.ggplot(df_a, pn.aes(x="Vin",y="Vout", shape="Vref"))
    + pn.geom_point(size=3, alpha=0.33)
#     + pn.geom_line(pn.aes(x="Vin",y="Vin"), color="b")
#     + pn.geom_line(pn.aes(x="Vin",y="Vref"), color="salmon")
    + pn.geom_line(df0_plt, pn.aes(color="m"), size=1)
    + pn.geom_line(df025_plt, pn.aes(color="m"), size=1)
    + pn.geom_line(df05_plt, pn.aes(color="m"), size=1)
    + pn.geom_line(df075_plt, pn.aes(color="m"), size=1)
    + pn.geom_line(df1_plt, pn.aes(color="m"), size=1)
    + pn.labs(
        x="$V_{in}\ (V)$",
        y="$V_{out}\ (V)$",
        shape="$V_{ref}\ (V)$",
        color="Gain"
      )
)
```



[45]: <ggplot: (8757275397458)>

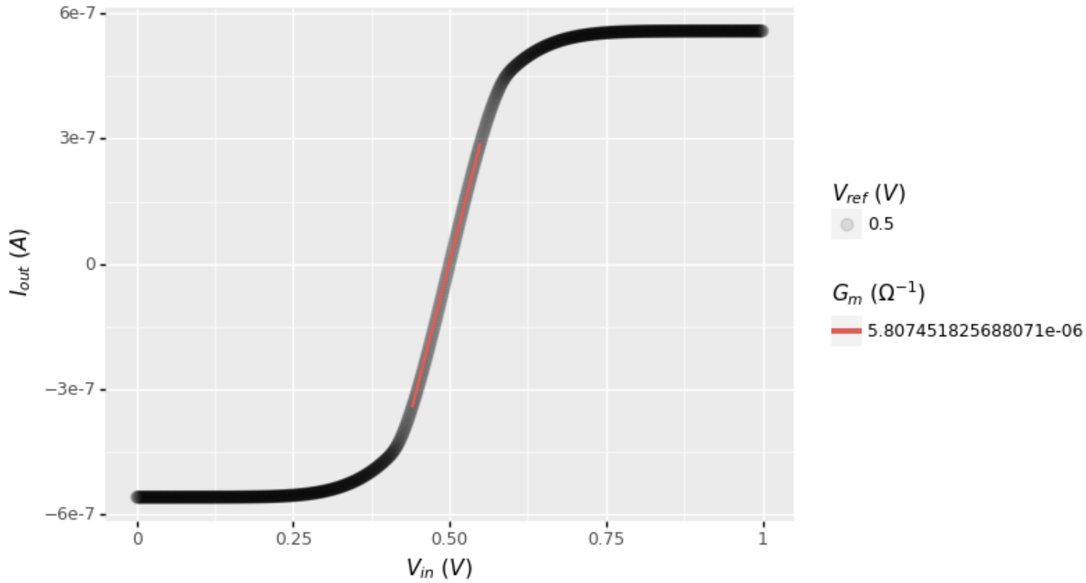
The DC gain of this circuit is roughly in between 350 and 240.

2 Voltage-to-Current Transfer Characteristics

[7]:
```
df_b = pd.read_csv("./schem/data/v2itc_noninv.csv")
df_b = df_b.rename(columns={
    "v(V1)":"Vin",
    "v(V2)":"Vref",
    "v(Vout)":"Vout",
    "I(V3)":"Iout"
                    })
df_b["Vref"] = df_b["Vref"].astype("str")
```

[8]:
```
def igain(i, j):
    df_tmp = df_b.iloc[i:j].reset_index(drop=True)
    m = ((df_tmp.iloc[-1].Iout - df_tmp.iloc[0].Iout)/(df_tmp.iloc[-1].Vin -␣
 ↪df_tmp.iloc[0].Vin))
    b = df_tmp.iloc[-1].Iout - m*df_tmp.iloc[-1].Vin
    df_plt = pd.DataFrame({
        "Vin": df_tmp.Vin,
        "Iout": m*df_tmp.Vin+b,
        "Vref": df_tmp.Vref,
        "m": m*np.ones(len(df_tmp.Vin))
    })
    df_plt["m"] = df_plt["m"].astype("str")
    return m, b, df_plt
```

[117]:
```
m, _, dfb_gain = igain(440, 550)
(
    pn.ggplot(df_b, pn.aes(x="Vin",y="Iout", shape="Vref"))
    + pn.geom_point(size=3, alpha=0.1)
    + pn.geom_line(dfb_gain, pn.aes(color="m"), size=1)
    + pn.labs(
        x="$V_{in}\ (V)$",
        y="$I_{out}\ (A)$",
        shape="$V_{ref}\ (V)$",
        color="$G_m\ (\Omega^{-1})$\n"
      )
)
```



[117]: <ggplot: (8757275261299)>

The incremental transconductance gain of the circuit, G_m, is roughly $5.81 \times 10^{-6}\Omega^{-1}$. The limiting value of the current is roughly $\pm 5.58 \times 10^{-7}\ A$.

3 Loopgain

[54]:
```
df_c = pd.read_csv("./schem/data/loopgain_noninv.csv")
```

[46]:
```
df_c.iloc[0]
```

[46]:
```
frequency     1.000000
Tmag         48.655403
Tphase       -0.032994
Name: 0, dtype: float64
```

[47]:
```
10**(4.8/2)
```

[47]: 251.18864315095797

[48]:
```
df_csort= df_c
df_csort["Tmag"]=abs(df_csort["Tmag"])
df_csort.sort_values("Tmag")
```

[48]:

	frequency	Tmag	Tphase
113	4.466836e+05	0.444998	-92.524984
114	5.011872e+05	0.556461	-92.884368

```
112  3.981072e+05   1.446151  -92.199061
115  5.623413e+05   1.558305  -93.281962
111  3.548134e+05   2.447059  -91.902285
..            …          …          …
206  1.995262e+10  74.680655 -359.519020
208  2.511886e+10  74.681201 -359.695304
207  2.238721e+10  74.681222 -359.610403
239  8.912509e+11  74.684153 -393.643956
240  1.000000e+12  75.123178 -397.332897

[241 rows x 3 columns]
```

[51]:
```
m_x = (-0.556461 - 0.444998)/(5.011872e5-4.466836e5)
b_x = -0.556461-m_x*5.011872e5
freq_x = -b_x/m_x
freq_x
```

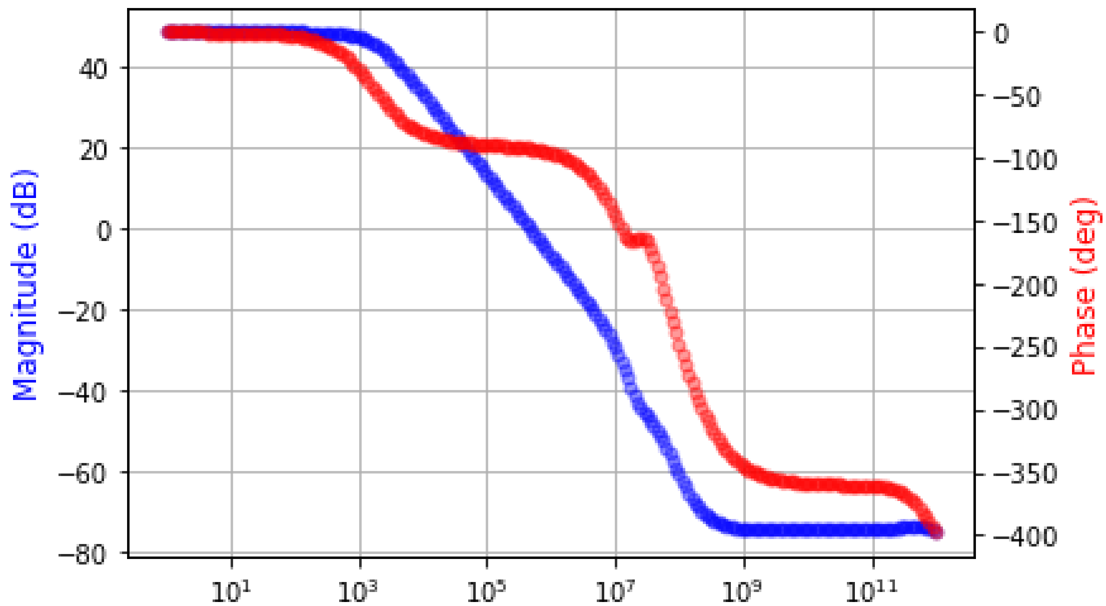
[51]:
```
470902.25797082053
```

[57]:
```
fig, ax = plt.subplots()

c1 = "b"
ax.semilogx(df_c.frequency, df_c.Tmag, "o", color=c1, alpha=0.4, markersize=5)
ax.set_ylabel("Magnitude (dB)", size=12, color=c1)
ax.grid()

ax2 = ax.twinx()
c2 = "r"
ax2.semilogx(df_c.frequency, df_c.Tphase, "o", color=c2, alpha=0.4,␣
 ↪markersize=5)
ax2.set_ylabel("Phase (deg)", size=12, color=c2)
```

[57]:
```
Text(0, 0.5, 'Phase (deg)')
```



At low frequencies, the loopgain of the folded cascode differential amplifier is 48dB, which translate to

$$Gain = 10^{4.8/2} \approx 251$$

It is very similar to most of the DC gains that we extracted in the first part of the simulation. The unity-gain crossover frequency is roughly $4.7092 \times 10^5\ Hz$.

Theoretically, the time constant of the circuit is given by

$$\tau = \frac{C}{G_m} = \frac{2 \times 10^{-12} F}{5.81 \times 10^{-6} \Omega^{-1}}$$

and the cutoff frequency is given by

$$f_c = \frac{1}{2\pi\tau} = 4.62345 \times 10^5\ Hz$$

which closely resembles what we have extracted from the simulation data.

[120]:
```
1/(2*np.pi*(2e-12/5.81e-6))
```

[120]: 462345.109681956

4 Unity-Gain Follower Frequency Response

[58]:
```
df_d = pd.read_csv("./schem/data/ac_noninv.csv")
```

[96]:
```
def freq_cutoff(df, i, j):
    df_tmp = df.iloc[int(i):int(j)].reset_index(drop=True)
```

```
    df_tmp["frequency"] = np.log10(df_tmp["frequency"])
    m = (df_tmp.iloc[-1].tmag - df_tmp.iloc[0].tmag)/(df_tmp.iloc[-1].frequency␣
↪- df_tmp.iloc[0].frequency)
    b = df_tmp.iloc[-1].tmag - m*df_tmp.iloc[-1].frequency
    df_plt = pd.DataFrame({
        "frequency": df_tmp.frequency,
        "tmag": m*df_tmp.frequency+b,
        "m": m*np.ones(len(df_tmp.frequency))
    })
    df_plt["m"] = df_plt["m"].astype("str")
    return m, b, df_plt
```

[97]:
```
m, b, df_freqroll = freq_cutoff(df_d, 120, 130)
```

[104]:
```
10**(-b/m)
```

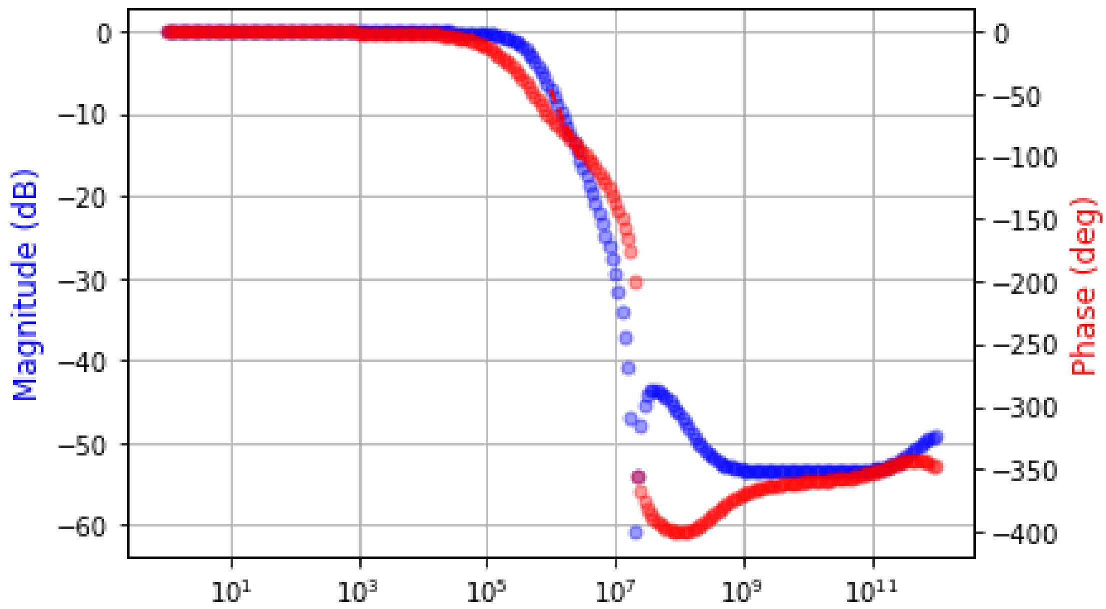
[104]: 416959.66847466904

[109]:
```
fig, ax = plt.subplots()

c1 = "b"
ax.semilogx(df_d.frequency, df_d.tmag, "o", color=c1, alpha=0.4, markersize=5)
ax.semilogx(10**df_freqroll.frequency, df_freqroll.tmag, "r--")
ax.set_ylabel("Magnitude (dB)", size=12, color=c1)
ax.grid()

ax2 = ax.twinx()
c2 = "r"
ax2.semilogx(df_d.frequency, df_d.tphase, "o", color=c2, alpha=0.4,␣
↪markersize=5)
ax2.set_ylabel("Phase (deg)", size=12, color=c2)
```

[109]: Text(0, 0.5, 'Phase (deg)')



From fitting a straight line near the initial rolloff, I believe the corner frequency in the circuit's frequency response is roughly 4.16960×10^5 Hz, which makes it veyr similar to the crossover frequency in the loopgain simulation.

5 Small Signal

[33]:
```
df_e = pd.read_csv("./schem/data/trans_ssig.csv").rename(columns={
    "v(V1)":"Vin",
    "v(Vout)":"Vout"})
```

[30]:
```
def exp_plot_r(X):
    return 0.01*(1 - np.exp(-df_e.time.values/X[0]))

def exp_plot_f(X):
    return 0.01*np.exp(-df_e.time.values/X[0])

def find_tau_r(df):
    df_tmp = df
    res = [j - i for i, j in zip(df_tmp.Vout[: -1], df_tmp.Vout[1 :])]
    df_tmp["d"] = np.array([0.0]+res)
    df_tmp["Vout"] = df_tmp["Vout"]-df_tmp.iloc[0].Vout
    df_tmp = df_tmp[df_tmp.d>0].reset_index(drop=True)
    t_off = df_tmp.iloc[0].time
    df_tmp["time"] = df_tmp["time"]-t_off

    df_res = df_tmp[df_tmp.Vout>0.01*(1-np.exp(-1))].reset_index(drop=True)
```

```
    return t_off, df_res.iloc[0].time#t_off, res_fit

def find_tau_f(df):
    df_tmp = df
    res = [j - i for i, j in zip(df_tmp.Vout[: -1], df_tmp.Vout[1 :])]
    df_tmp["d"] = np.array([0.0]+res)
    df_tmp["Vout"] = df_tmp["Vout"]-df_tmp.iloc[0].Vout
    df_tmp = df_tmp[df_tmp.time>2e-6].reset_index(drop=True)
    df_tmp = df_tmp[df_tmp.d<0].reset_index(drop=True)
    t_off = df_tmp.iloc[0].time
    df_tmp["time"] = df_tmp["time"]-t_off

    df_res = df_tmp[df_tmp.Vout<0.01*(np.exp(-1))].reset_index(drop=True)

    return t_off, df_res.iloc[0].time
```

[31]:
```
t_off_r, tau_r = find_tau_r(df_e)
t_off_f, tau_f = find_tau_f(df_e)
```

[35]:
```
fig, ax = plt.subplots()

c1 = "b"
ax.plot(df_e.time, df_e.Vin, "-", color=c1, alpha=1, markersize=5,␣
 ↪label="$V_{in}$")
ax.plot(df_e.time, df_e.Vout, ".", color="r", alpha=1, markersize=5,␣
 ↪label="$V_{out}$")
ax.plot(df_e.time+t_off_r, exp_plot_r([tau_r])+0.5014, "--", color="g",␣
 ↪alpha=1, markersize=5, label="Rise $t$:%.4E"%tau_r)
ax.plot(df_e.time+t_off_f, exp_plot_f([tau_f])+0.5014, ":", color="g", alpha=1,␣
 ↪markersize=5, label="Fall $t$:%.4E"%tau_f)
ax.set_ylabel("Voltage (V)", size=12, color=c1)
ax.set_xlabel("Time (s)", size=12)
ax.set_title("Small Signal Analysis")
ax.grid()
ax.legend()
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

[35]:
```
<matplotlib.legend.Legend at 0x7f6f66188be0>
```

[113]:
```
1/(2*np.pi*tau_r), 1/(2*np.pi*tau_f)
```

[113]:
```
(473901.09305590566, 478747.87357687176)
```

The input step needs to be small enough that the output current of the folded-cascode differential amplifier is not near its limiting value. (Referencing the figure in the voltage-to-current transfer characteristics.) The chosen step of 0.01V is small enough that it does not go near the limiting current value.

The response is not exactly symmetrical. The rise time constant is longer by something on the order of 10^{-9} second.

The natural frequency after being converted from their corresponding time constants with the following equation, is 4.74×10^5 Hz for the rise and 4.79×10^5 Hz for the fall. They closely resemble the cutoff frequency in the frequency sweep and the crossover frequency in the loopgain simulation.

$$f_c = \frac{1}{2\pi\tau}$$

6 Large Signal

[18]:
```
df_f = pd.read_csv("./schem/data/trans_lsig.csv").rename(columns={
    "v(V1)":"Vin",
    "v(Vout)":"Vout"})
```

[19]:
```
def slew(df, i, j):
    df_tmp = df.iloc[int(i):int(j)].reset_index(drop=True)
    m = (df_tmp.iloc[-1].Vout - df_tmp.iloc[0].Vout)/(df_tmp.iloc[-1].time -␣
 ↪df_tmp.iloc[0].time)
    b = df_tmp.iloc[-1].Vout - m*df_tmp.iloc[-1].time
    df_plt = pd.DataFrame({
        "time": df_tmp.time,
        "Vout": m*df_tmp.time+b,
        "m": m*np.ones(len(df_tmp.Vin))
    })
    df_plt["m"] = df_plt["m"].astype("str")
    return m, b, df_plt
```

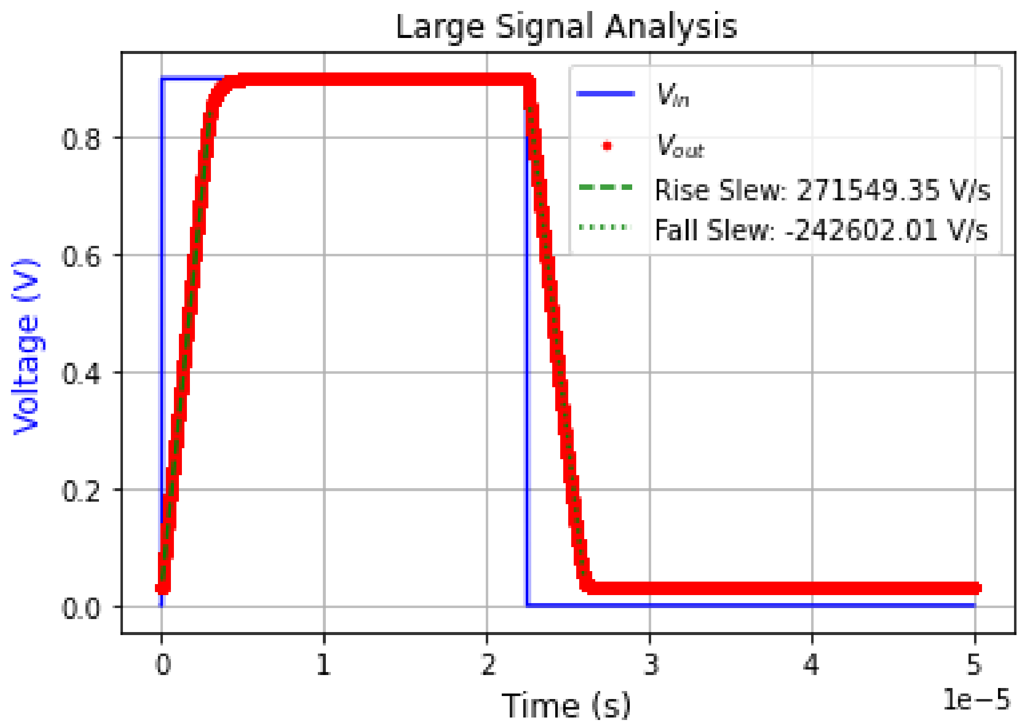
[20]:
```
m_r,_,slew_r = slew(df_f, 500, 30000)
m_f,_,slew_f = slew(df_f, 22.7e4, 26e4)
```

[114]:
```
fig, ax = plt.subplots()

c1 = "b"
ax.plot(df_f.time, df_f.Vin, "-", color=c1, alpha=1, markersize=5,␣
 ↪label="$V_{in}$")
ax.plot(df_f.time, df_f.Vout, ".", color="r", alpha=1, markersize=5,␣
 ↪label="$V_{out}$")
ax.plot(slew_r.time, slew_r.Vout, "--", color="g", alpha=1, markersize=5,␣
 ↪label="Rise Slew: %.2f V/s"%m_r)
ax.plot(slew_f.time, slew_f.Vout, ":", color="g", alpha=1, markersize=5,␣
 ↪label="Fall Slew: %.2f V/s"%m_f)
ax.set_ylabel("Voltage (V)", size=12, color=c1)
```

```python
ax.set_xlabel("Time (s)", size=12)
ax.set_title("Large Signal Analysis")
ax.grid()
ax.legend()
```

[114]: <matplotlib.legend.Legend at 0x7f6f6479f4c0>



The response of the circuit to the large-amplitude steps is not exactly symmetrical. The rise slew rate is slightly larger in magnitude than the fall slew rate.

The slew rate calculated from the below equation is $2.79 \times 10^5\ V/s$.

$$\frac{I_{limit}}{C_{load}} \approx \frac{5.58 \times 10^{-7}\ A}{2 \times 10^{-12}\ F} = 279000\ V/s$$

which is very close to the value that we have extracted from the large signal analysis of the response.

[40]:
```python
5.58e-7/2e-12
```

[40]: 279000.0

[ ]: