Analysis - Impedance Spectroscopy

May 5, 2019

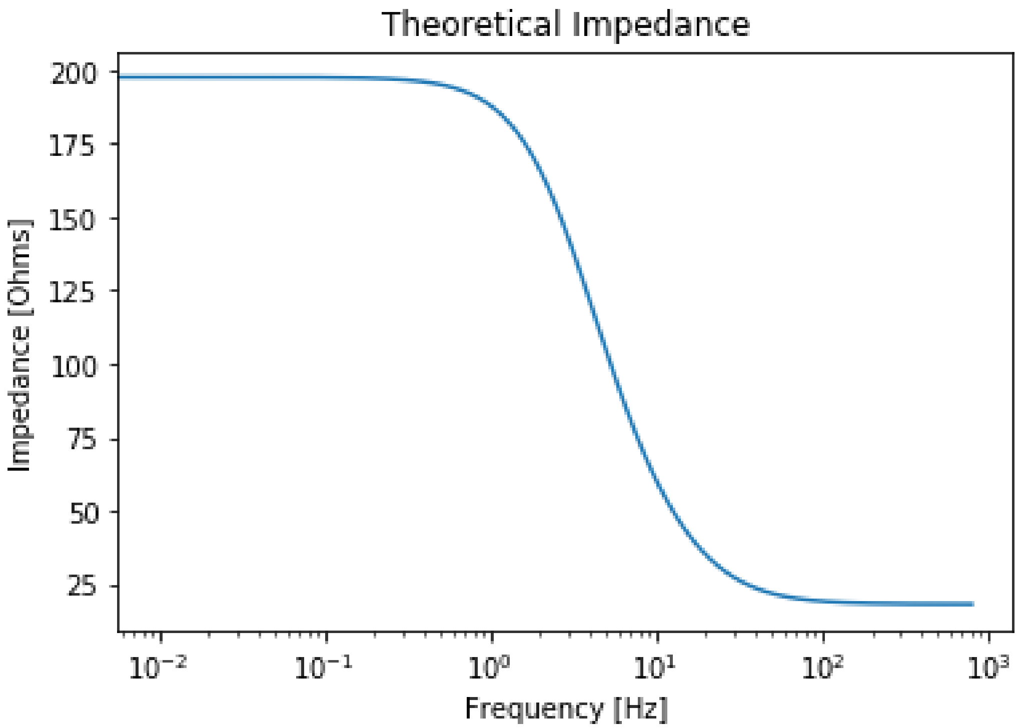
```
In [1]: #import stuff!
        import numpy as np
        from scipy.stats import chisquare
        from scipy.optimize import curve_fit
        import matplotlib.pyplot as plt
```

Theory

```
In [6]: #Setting up Constants
        j = (-1)**(1/2)
        R0 = 10020 #Voltage-Setting Resistor [Ohms]
        R1 = 197.7 #Parallel Resistor [Ohms]
        R2 = 20.0 #Series Resistor [Ohms]
        C = 0.000238 #Capacitor [Farads]
        V0_in = 0.707 #Voltage In [V]

        #creating shorthands
        R = R2/(R1+R2) #Based on equivalent resistance (unitless)
        I0 = V0_in/R0 #I calculated from VAC [A]
        wc = 1/((R1+R2)*C) #shorthand frequency constant [rad/s]

        #Creating Arrays
        f0 = [i/100 for i in range(80000)] #Creating a range of (linear) frequencies [Hz]

        w0 = []
        for i in f0:
            w0.append(2*np.pi*i)

In [7]: #Running Loops for Functions


        #Impedance Function.
        #Commented out because it is expressed always in terms of Real or Imaginary parts.

        #Z = []
        #for i in w:
        #    Z.append(R1*(1+i**2*R2(R1+R2)-j*i*C*R1)/(1+i*2*C**2*(R1+R2)**2))
```

```
#Real(Z)
ReZ = []
for i in w0:
    ReZ.append(R1*(1+i**2*C**2*R2*(R1+R2))/(1+i**2*C**2*(R1+R2)**2))

#Imaginary(Z)
ImZ = []
for i in w0:
    ImZ.append(-R1*i*C*R1/(1+i**2*C**2*(R1+R2)**2))

#Phase
Ph = []
i = 0
while i < len(ImZ):
    Ph.append(np.arctan(ImZ[i]/ReZ[i]))
    i += 1

#|Z|
i = 0
MagZ = []
while i < len(ImZ):
    MagZ.append((ReZ[i]**2+ImZ[i]**2)**(1/2))
    i += 1

#Voltage
V0 = []
for i in MagZ:
    V0.append(I0*i)
```

In [8]:
```
#Impedance Theory

plt.plot(f0,MagZ)
#plt.axis([0,100,0,200])
plt.xlabel('Frequency [Hz]')
plt.ylabel('Impedance [Ohms]')
plt.title('Theoretical Impedance')
plt.xscale('log')
plt.show()
```



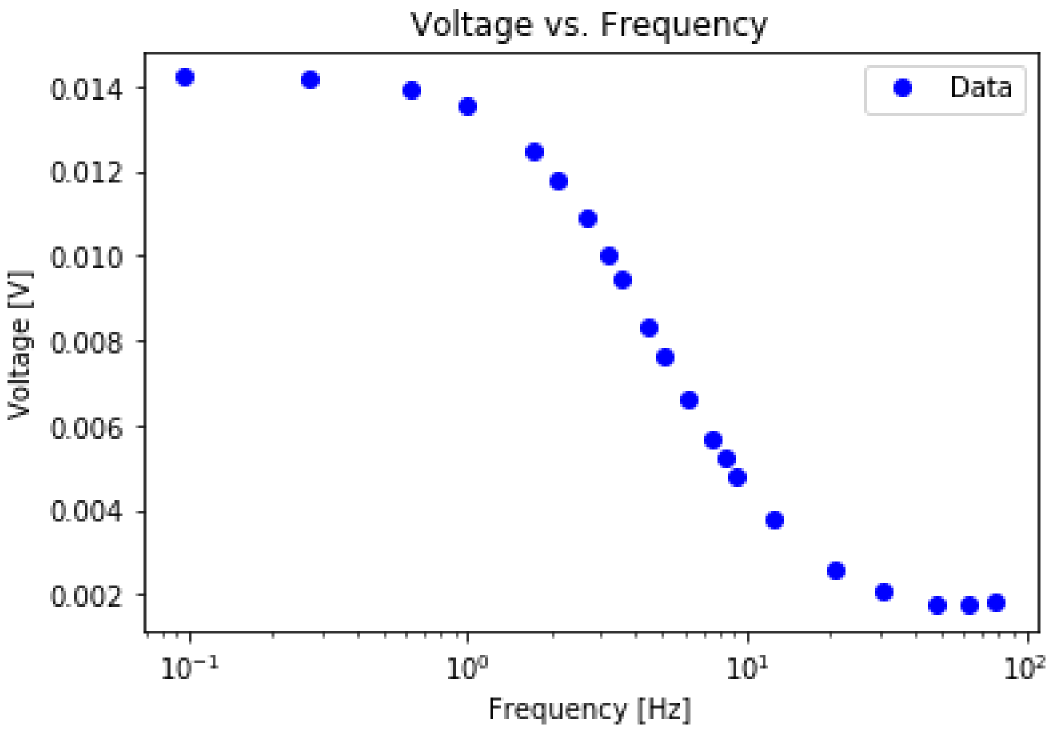
Data

```
In [9]: #Set up data. Keep data all in the same order! Also, make sure units are converted to

        #frequency - kHz, must be converted
        f_kHz = [96, 268, 630, 995, 1720, 2114, 2665, 3193, 3570, 4460, 5047, 6195, 7531, 8357
        #V_Orms - mV, must be converted
        V_mV = [14.22, 14.16, 13.95, 13.56, 12.47, 11.81, 10.88, 10.05, 9.48, 8.32, 7.65, 6.60
        #phase - Degrees, must be converted
        P_deg = [-1.3,-3.8,-9.9,-15.1,-24.3,-28.7,-33.8,-37.8,-40.2,-44.3,-46.3,-48.5,-49.8,-4

        P = [] #Phase in radians
        for n in P_deg:
            P.append(2*np.pi*n/360)

        V = [] #Voltage in Volts
        for n in V_mV:
            V.append(n*10**-3)

        P_inv = [] #negative of phase
        for n in P:
            P_inv.append(-n)

        f = []
```

```
for n in f_kHz:
    f.append(n/1000)
```

Curve Fitting

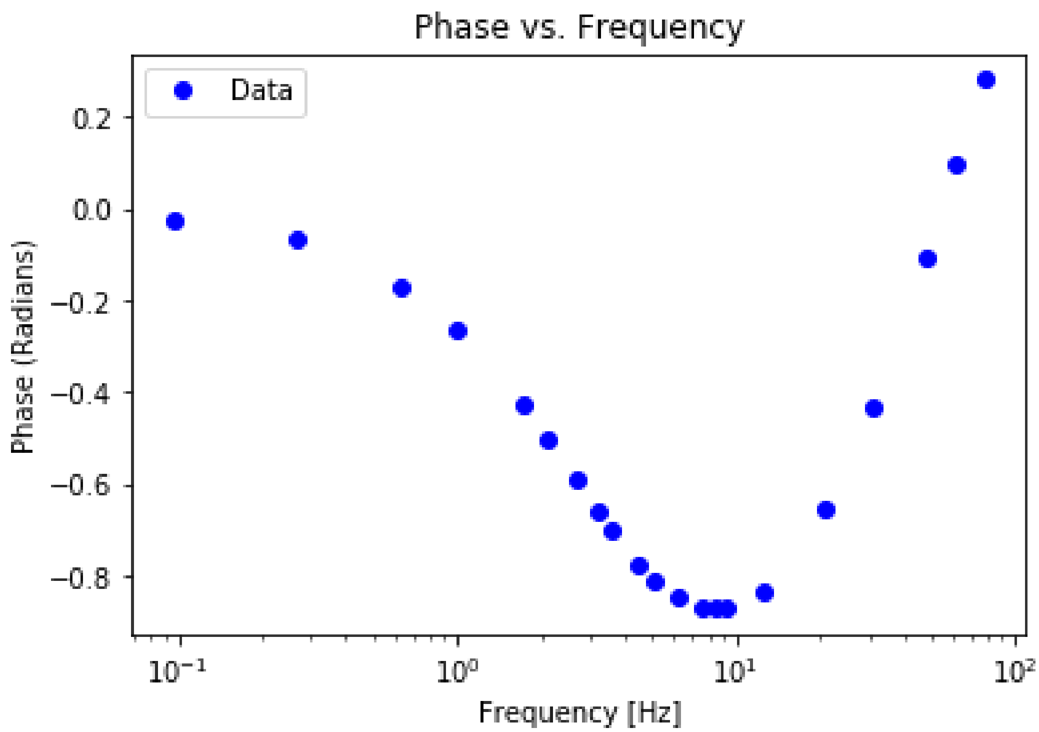
```
In [11]: ### Create Curve Fit

         def func(f,R0f,R1f,R2f,Cf):
             return (V0_in/R0f)*R1f*(((1+(2*np.pi*f)**2*Cf**2*R2f*(R1f+R2f))**2+(2*np.pi*f*Cf)

         popt, pcov = curve_fit(func,f,V)
         print(popt)

         ### Plotting - Voltage vs Frequency

         #x = freq
         #y = [func(i,popt[0],popt[1],popt[2],popt[3]) for i in freq]

         fig, sp = plt.subplots()

         plt.title('Voltage vs. Frequency')
         sp.plot(f,V,'bo',label='Data')
         #sp.plot(f0,V0,'--',label='Theory') #uncomment to view theory
         #sp.plot(w0,V0,'r--',label='Theory (Angular)') #uncomment to check angular vs linear
         #sp.plot(f,func(f,*parameter),'-',label='Fit') #uncomment when curve fit is fixed.
         legend = sp.legend(loc='upper right')
         plt.xlabel('Frequency [Hz]')
         plt.ylabel('Voltage [V]')
         plt.xscale('log')


         plt.show()

[-139.64558599   -1.7474466   -12.29023508 -180.88587252]
```




```
In [12]: #Create Curve Fit

         def func(f,R0f,R1f,R2f,Cf):
             return np.arctan(-2*np.pi*f*Cf/(1+(2*np.pi*f)**2*Cf**2*(R1f+R2f)**2))
         popt, pcov = curve_fit(func,f,P)
         parameter, covariance_matrix = curve_fit(func,f,P)

         #Plotting - Phase vs Frequency

         fig, sp = plt.subplots()

         plt.title('Phase vs. Frequency')
         sp.plot(f,P,'bo',label='Data')
         #sp.plot(f0,Ph,'--',label='Theory') #uncomment to view theory
         #sp.plot(w0,Ph,'r--',label='Theory (Angular)') #uncomment to check for angular vs lin
         #sp.plot(f,func(f,*parameter),'-',label='Fit') #uncomment when curve fit is working
         legend = sp.legend(loc='upper left')
         plt.xlabel('Frequency [Hz]')
         plt.ylabel('Phase (Radians)')
         plt.xscale('log')

         plt.show()
```

```
K:\Anaconda\lib\site-packages\scipy\optimize\minpack.py:794: OptimizeWarning: Covariance of the
```

```
category=OptimizeWarning)
```

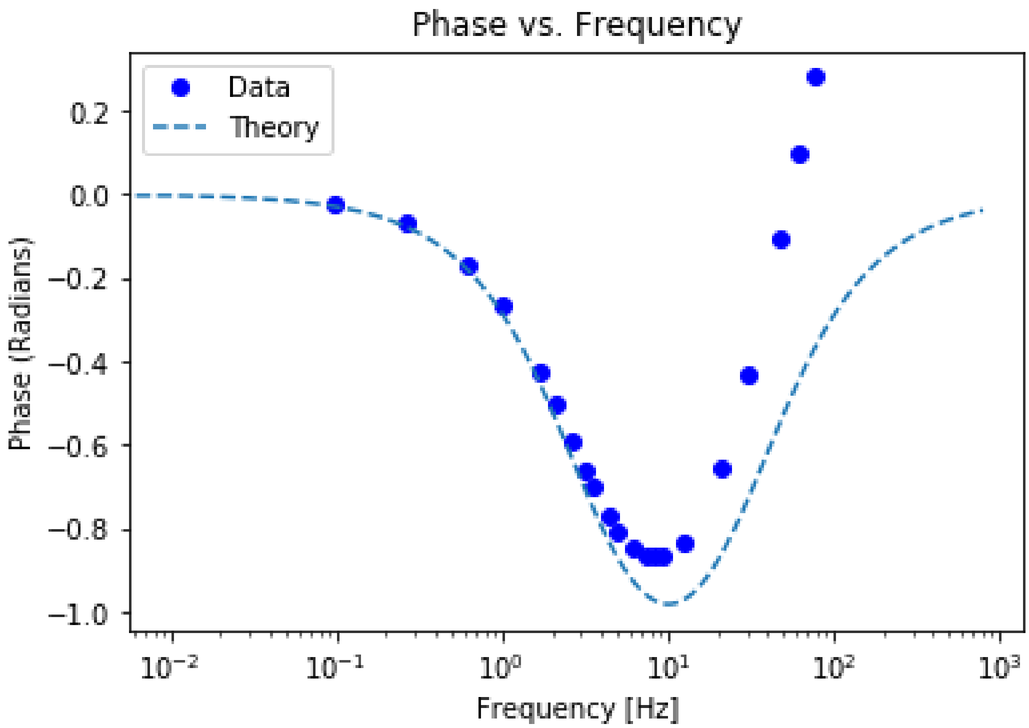


Theory vs. Data

In [13]:
```
#Running Loops for Expected values - we will need these for chi squared.
#These are based on theory, not on curve fitting.

#Real(Z)
ReZ_exp = []
for n in f:
    ReZ_exp.append(R1*(1+(2*np.pi*n)**2*C**2*R2*(R1+R2))/(1+(2*np.pi*n)**2*C**2*(R1+R2

#Imaginary(Z)
ImZ_exp = []
for n in f:
    ImZ_exp.append(-R1*(2*np.pi*n)*C*R1/(1+(2*np.pi*n)**2*C**2*(R1+R2)**2))

#Phase
P_exp = []
i = 0
while i < len(ImZ_exp):
    P_exp.append(np.arctan(ImZ_exp[i]/ReZ_exp[i]))
    i += 1
```

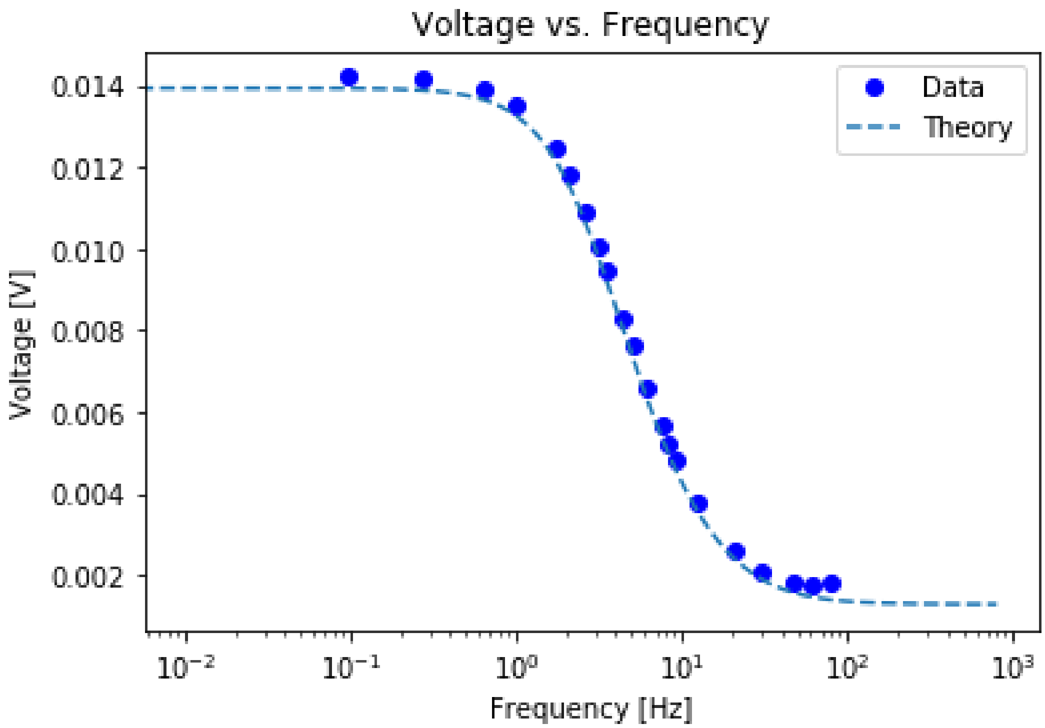
```
    #|Z|
    i = 0
    MagZ_exp = []
    while i < len(ImZ_exp):
        MagZ_exp.append((ReZ_exp[i]**2+ImZ_exp[i]**2)**(1/2))
        i += 1

    #Voltage
    V_exp = []
    for n in MagZ_exp:
        V_exp.append(I0*n)
```

```
In [14]: #Plotting - Phase vs Frequency

    fig, sp = plt.subplots()

    plt.title('Phase vs. Frequency')
    sp.plot(f,P,'bo',label='Data')
    sp.plot(f0,Ph,'--',label='Theory')
    #sp.plot(f,P_exp) #checking that expected value calculations are correct.
    legend = sp.legend(loc='upper left')
    plt.xlabel('Frequency [Hz]')
    plt.ylabel('Phase (Radians)')
    plt.xscale('log')

    plt.show()

    chisquare(P,P_exp)
```



Out[14]: Power_divergenceResult(statistic=-2.419738578497731, pvalue=1.0)

In [15]:
```
#plotting - Voltage vs Frequency

fig, sp = plt.subplots()

plt.title('Voltage vs. Frequency')
sp.plot(f,V,'bo',label='Data')
sp.plot(f0,V0,'--',label='Theory')
#sp.plot(f,V_exp) #checking that expected value calculations are correct
legend = sp.legend(loc='upper right')
plt.xlabel('Frequency [Hz]')
plt.ylabel('Voltage [V]')
plt.xscale('log')

plt.show()

chisquare(V,V_exp)
```



Out[15]: Power_divergenceResult(statistic=0.00042573181659759905, pvalue=1.0)

In [ ]: