Measurement Circuits and Modeling Techniques for Titanium Capacitors

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July 2015

Acknowledgements

- Dr. Merat
- Dr. Welsch
- Steven Ehret
- Thesis Committe
- Case Western Reserve University
- ARPA-E (contract DE–AR000016)

Outline

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Background

- 2011 ARPA-E grant to Dr. Welsch.
- Titanium capacitors to replace tantalum.
- Availability, cost, energy and power density.

Purpose

- Design instrumentation for Ti capacitors.
- Characterize capacitor parameters.

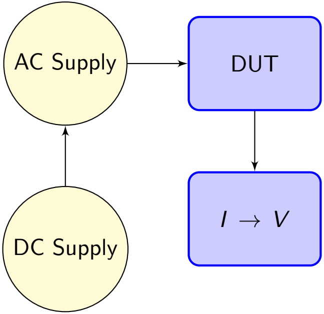
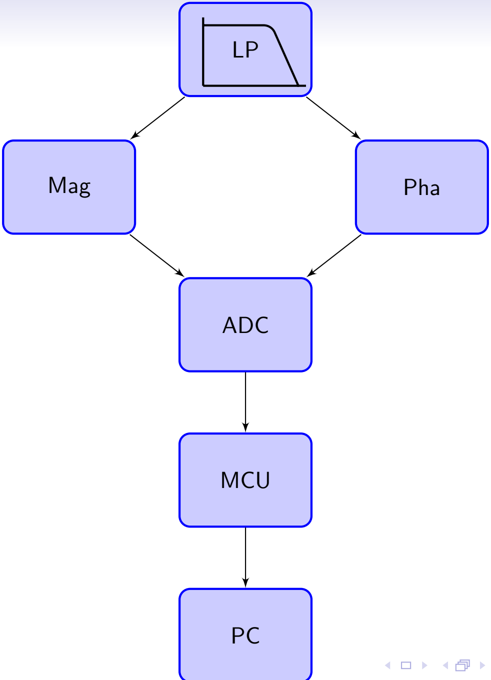
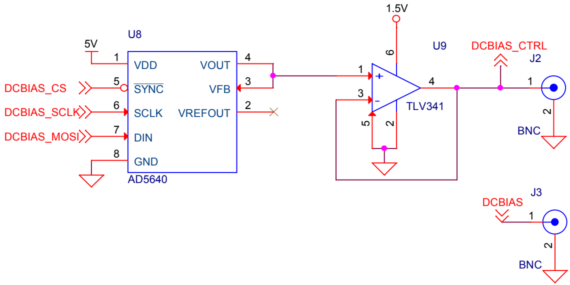
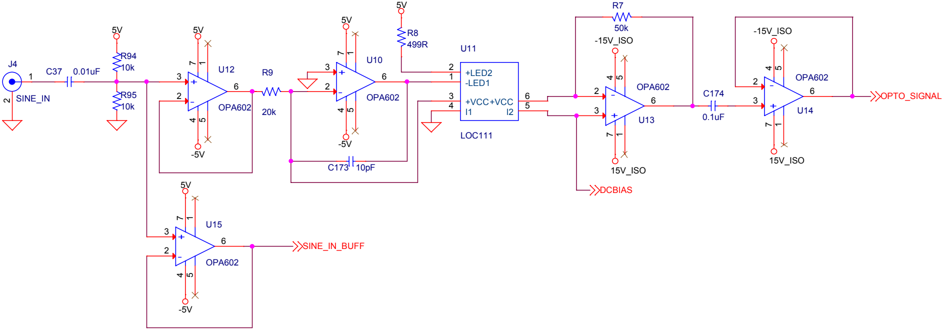


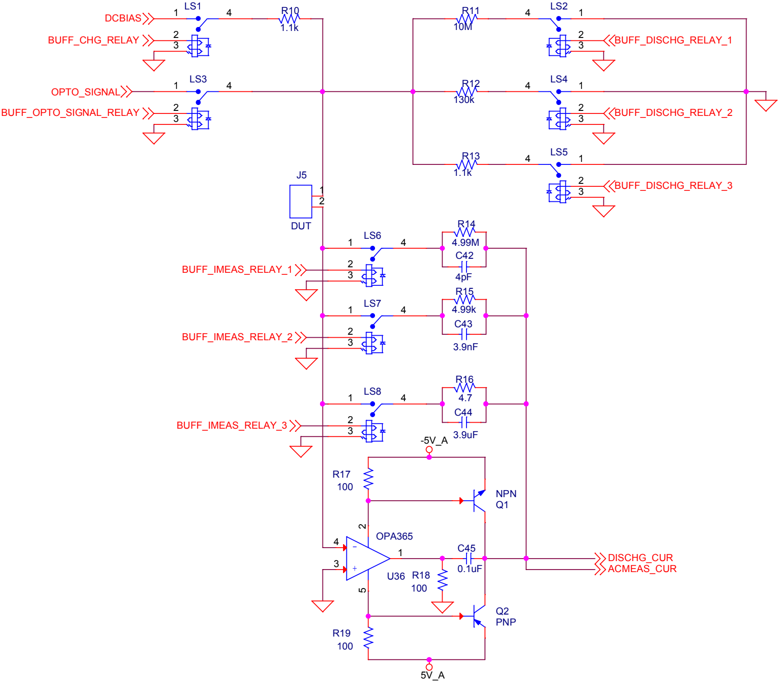
Figure: Circuit Flow Chart


LP
Mag
Pha
ADC
MCU
PC

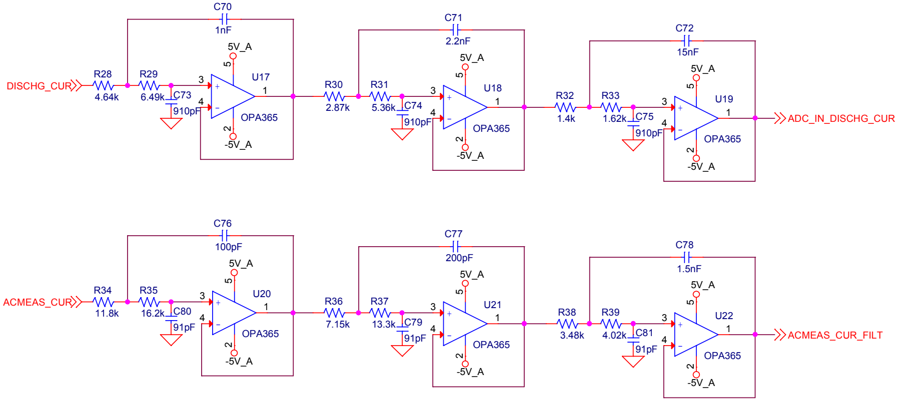


U8
5V
VDD
VOUT
SYNC
VFB
SCLK
VREFOUT
DIN
GND
AD5640
DCBIAS_CS
DCBIAS_SCLK
DCBIAS_MOSI
1.5V
U9
TLV341
DCBIAS_CTRL
J2
BNC
J3
DCBIAS
BNC

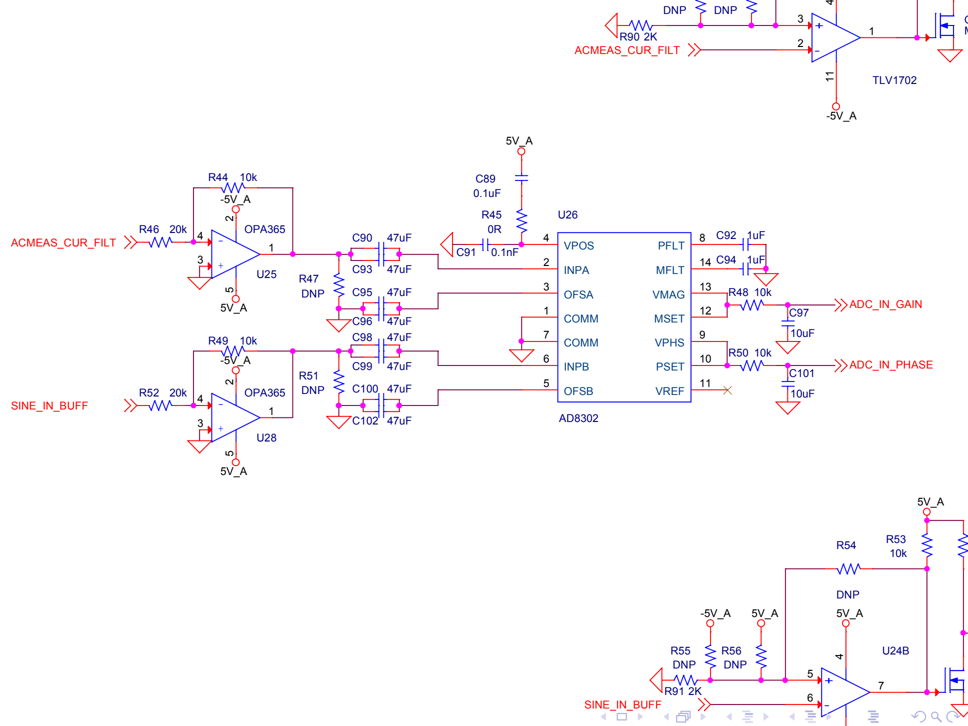

J4
SINE_IN
C37
0.01uF
5V
R94
10k
R95
10k
U12
OPA602
-5V
R9
20k
U10
OPA602
C173
10pF
R8
499R
U11
+LED2
-LED1
+VCC+VCC
I1
I2
LOC111
R7
50k
-15V_ISO
15V_ISO
OPA602
U13
DCBIAS
C174
0.1uF
U14
OPTO_SIGNAL
U15
SINE_IN_BUFF

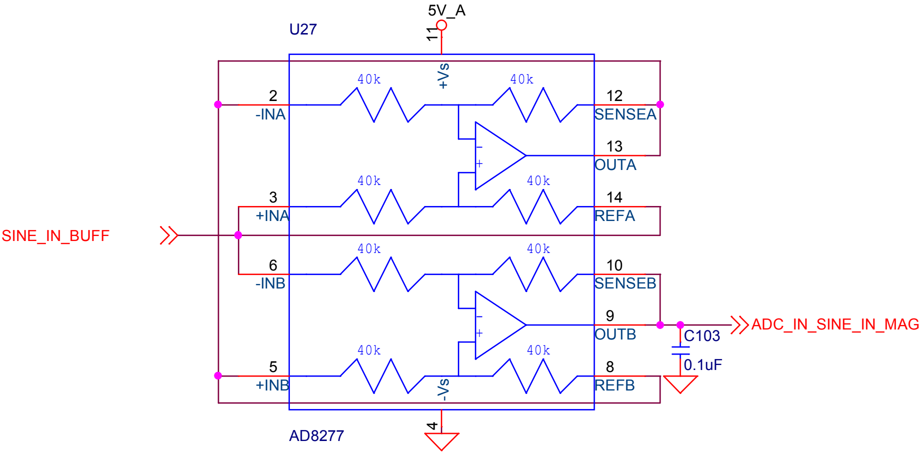


DCBIAS
BUFF_CHG_RELAY
OPTO_SIGNAL
BUFF_OPTO_SIGNAL_RELAY
LS1
LS2
LS3
LS4
LS5
LS6
LS7
LS8
R10
1.1k
R11
10M
R12
130k
R13
1.1k
BUFF_DISCHG_RELAY_1
BUFF_DISCHG_RELAY_2
BUFF_DISCHG_RELAY_3
J5
DUT
R14
4.99M
C42
4pF
R15
4.99k
C43
3.9nF
R16
4.7
C44
3.9uF
BUFF_IMEAS_RELAY_1
BUFF_IMEAS_RELAY_2
BUFF_IMEAS_RELAY_3
-5V_A
R17
100
NPN
Q1
OPA365
U36
C45
0.1uF
R18
100
DISCHG_CUR
ACMEAS_CUR
Q2
PNP
R19
100
5V_A

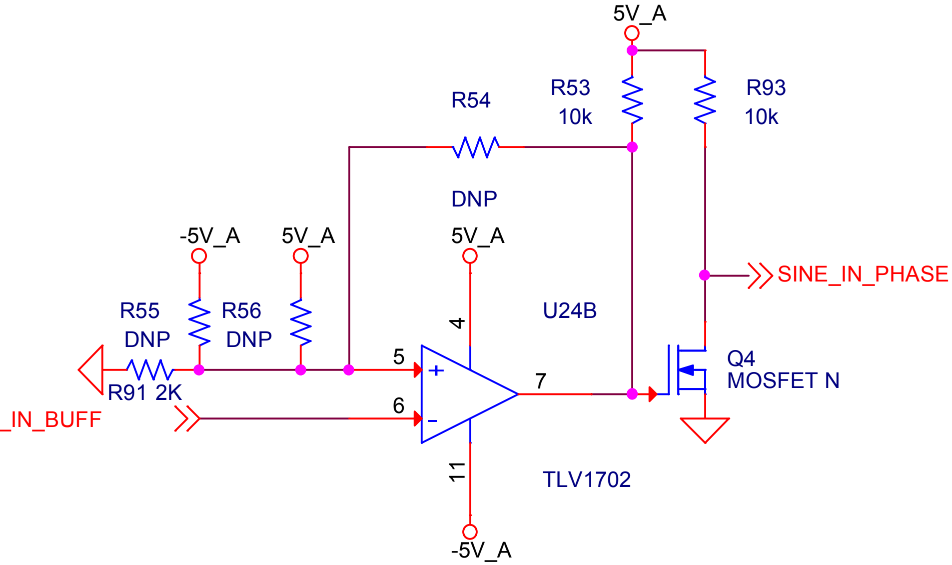


C70
1nF
DISCHG_CUR
R28
4.64k
R29
6.49k
C73
910pF
5V_A
U17
OPA365
-5V_A
R30
2.87k
R31
5.36k
C74
910pF
C71
2.2nF
U18
OPA365
R32
1.4k
R33
1.62k
C75
910pF
C72
15nF
U19
OPA365
ADC_IN_DISCHG_CUR
C76
100pF
ACMEAS_CUR
R34
11.8k
R35
16.2k
C80
91pF
U20
OPA365
R36
7.15k
R37
13.3k
C79
91pF
C77
200pF
U21
OPA365
R38
3.48k
R39
4.02k
C81
91pF
C78
1.5nF
U22
OPA365
ACMEAS_CUR_FILT


DNP
DNP
R90 2K
ACMEAS_CUR_FILT
TLV1702
-5V_A
5V_A
C89
0.1uF
R45
0R
U26
R44 10k
-5V_A
OPA365
R46 20k
ACMEAS_CUR_FILT
U25
5V_A
C90 47uF
C93 47uF
R47
DNP
C95 47uF
C96 47uF
C91 0.1nF
VPOS
INPA
OFSA
COMM
COMM
INPB
OFSB
PFLT
MFLT
VMAG
MSET
VPHS
PSET
VREF
AD8302
C92 1uF
C94 1uF
R48 10k
ADC_IN_GAIN
C97
10uF
R50 10k
ADC_IN_PHASE
C101
10uF
R49 10k
-5V_A
OPA365
R52 20k
SINE_IN_BUFF
U28
5V_A
C98 47uF
C99 47uF
R51
DNP
C100 47uF
C102 47uF
5V_A
R54
R53
10k
DNP
-5V_A
5V_A
5V_A
R55
DNP
R56
DNP
U24B
R91 2K
SINE_IN_BUFF


5V_A
U27
11
+Vs
40k
40k
2
-INA
12
SENSEA
13
OUTA
40k
40k
3
+INA
14
REFA
SINE_IN_BUFF
40k
40k
6
-INB
10
SENSEB
9
OUTB
ADC_IN_SINE_IN_MAG
C103
0.1uF
40k
40k
5
+INB
8
REFB
-Vs
4
AD8277

MAGNITUDE


5V_A
R53
10k
R93
10k
R54
DNP
-5V_A
5V_A
5V_A
SINE_IN_PHASE
R55
DNP
R56
DNP
U24B
4
5
Q4
MOSFET N
R91 2K
7
_IN_BUFF
6
11
TLV1702
-5V_A

PHASE

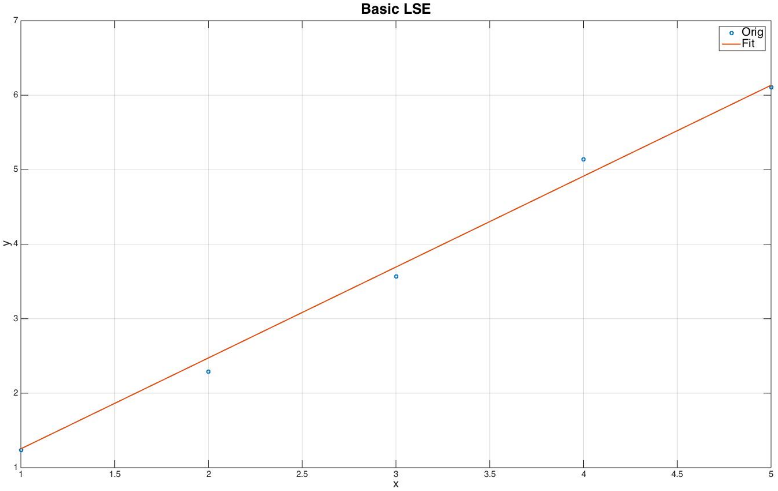


Figure: Basic LSE

Basic Regression

$$y = a_0 + a_1 x \tag{1}$$

$$E^2 = \sum_{i=1}^{n} (y_i - y)^2 \tag{2}$$

$$E^2 = \sum_{i=1}^{n} (y_i - (a_0 + a_1 x_i))^2 \tag{3}$$

$$\frac{\partial E^2}{\partial a_0} = 0 = \sum_{i=1}^{n} (-2y_i + 2a_0 + 2a_1 x_i) \tag{4}$$

$$\frac{\partial E^2}{\partial a_1} = 0 = \sum_{i=1}^{n} (-2y_i x_i + 2a_0 x_i + 2a_1 x_i^2) \tag{5}$$

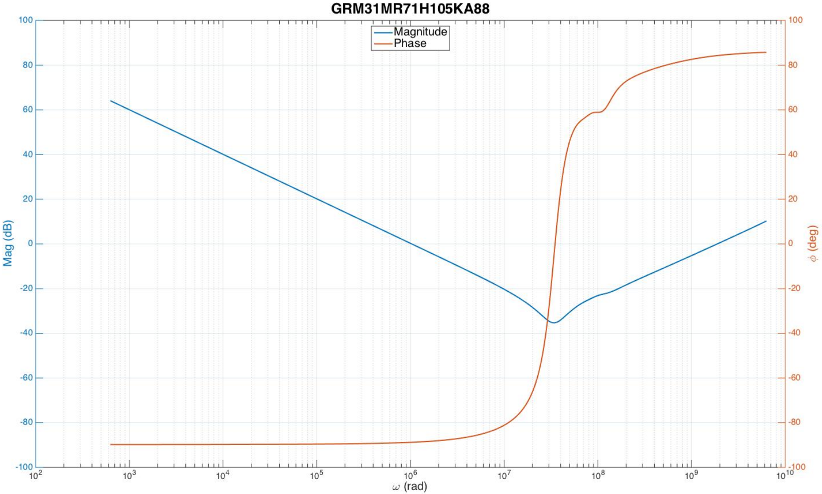


Figure: GRM31MR71H105KA88 Capacitor Data [3]

$$G(s) = \frac{A_0 + A_1 s + A_2 s^2 + ... + A_n s^n}{B_0 + B_1 s + B_2 s^2 + ... + B_m s^m} \text{ [1][}Eq.\text{ 3]} \tag{6}$$

$$\lambda_h = \sum_{k=0}^{m} \omega_k^h \text{ [1][}Eq.\text{ 15]} \tag{7}$$

$$S_h = \sum_{k=0}^{m} \omega_k^h R_k \text{ [1][}Eq.\text{ 16]} \tag{8}$$

$$T_h = \sum_{k=0}^{m} \omega_k^h I_k \text{ [1][}Eq.\text{ 17]} \tag{9}$$

$$U_h = \sum_{k=0}^{m} \omega_k^h (R_k^2 + I_k^2) \text{ [1][}Eq.\text{ 18]} \tag{10}$$

$$M = \begin{bmatrix} \lambda_0 & 0 & -\lambda_2 & 0 & \cdots & T_1 & S_2 & -T_3 & -S_4 & \cdots \\ 0 & \lambda_2 & 0 & -\lambda_4 & \cdots & -S_2 & T_3 & S_4 & -T_5 & \cdots \\ \lambda_2 & 0 & -\lambda_4 & 0 & \cdots & T_3 & S_4 & -T_5 & -S_6 & \cdots \\ 0 & \lambda_4 & 0 & -\lambda_6 & \cdots & -S_4 & T_5 & S_6 & -T_7 & \cdots \\ \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots & \vdots & \\ T_1 & -S_2 & -T_3 & S_4 & \cdots & U_2 & 0 & -U_4 & 0 & \cdots \\ S_2 & T_3 & -S_4 & -T_5 & \cdots & 0 & U_4 & 0 & -U_6 & \cdots \\ T_3 & -S_4 & -T_5 & S_6 & \cdots & U_4 & 0 & -U_6 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} [1][Eq. 21a] \tag{11}$$

$$N = \begin{bmatrix} A_0 \\ A_1 \\ A_2 \\ A_3 \\ \vdots \\ B_1 \\ B_2 \\ B_3 \\ \vdots \end{bmatrix} \; [1][Eq.\ 21b] \quad (12) \qquad C = \begin{bmatrix} S_0 \\ T_1 \\ S_2 \\ T_3 \\ \vdots \\ 0 \\ U_2 \\ 0 \\ \vdots \end{bmatrix} \; [1][Eq.\ 21c] \quad (13)$$

$$MN = C \; [1][Eq.\ 20] \qquad (14)$$

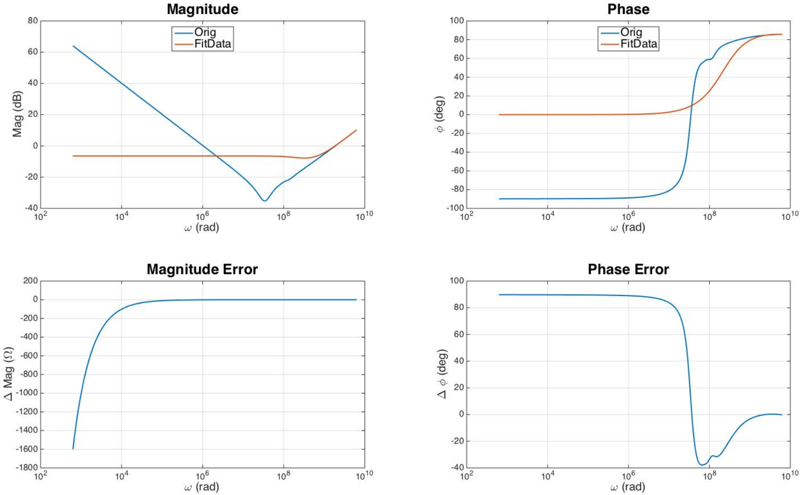


Figure: Levy's Technique

$$W_{kL} = \frac{1}{|Q(jw_k)_{L-1}|^2} \text{ [2]} \tag{15}$$

$$E = \sum_{k=1}^{n} |\epsilon_k^{'}|^2 W_{kL} \text{ [2][}Eq.\text{ 7]} \tag{16}$$

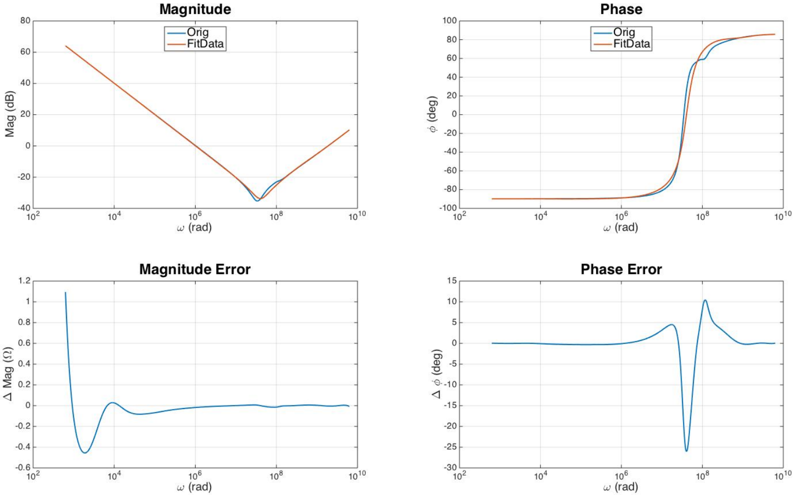


Figure: LSE + Iteration

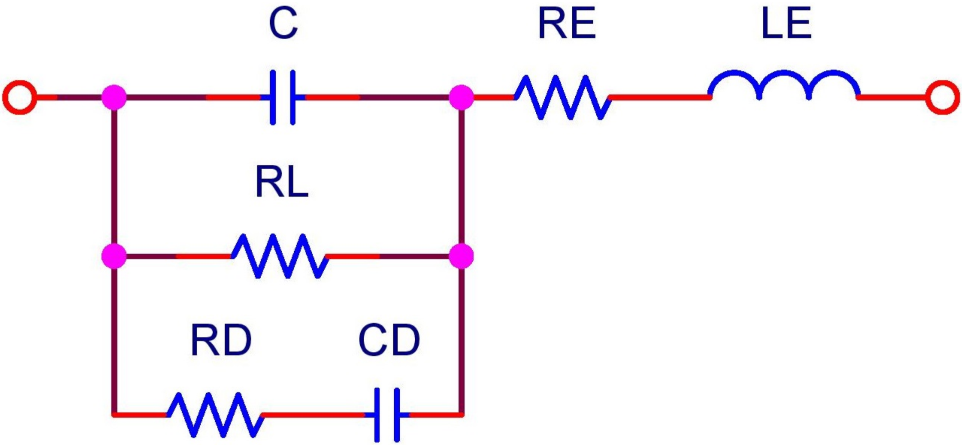


Figure: 6 Term Model

$$\bar{Z}(s) = \frac{(R_E + R_L) + (L_E + C_D R_D R_E + C_D R_D R_L + C R_E R_L + C_D R_E R_L)s}{1 + (C_D R_D + C R_L + C_D R_L)s + C C_D R_D R_L s^2} + \frac{(C_D L_E R_D + C L_E R_L + C_D L_E R_L + C C_D R_D R_E R_L)s^2 + C C_D L_E R_D R_L s^3}{1 + (C_D R_D + C R_L + C_D R_L)s + C C_D R_D R_L s^2} \tag{17}$$

$$\bar{Z}(s) = \frac{a_0 + a_1 s + a_2 s^2 + a_3 s^3}{b_0 + b_1 s + b_2 s^2} \tag{18}$$

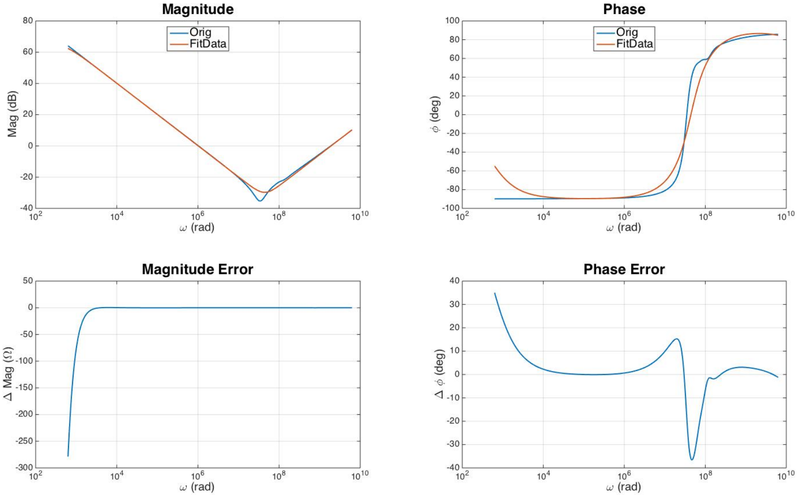


Figure: 6 Term Model: Bad Initilization

$$
\begin{aligned}
a_0 &= 5.9991E^{+03} \\
a_1 &= 1.7934E^{-04} \\
a_2 &= 3.3158E^{-12} \\
a_3 &= 6.8295E^{-22} \\
b_0 &= 1.0000 \\
b_1 &= 5.9057E^{-03} \\
b_2 &= 1.4067E^{-12}
\end{aligned}
\tag{19}
$$

$$
\begin{aligned}
C &= -8.2563E^{-10} \\
R_E &= 3.1886E^{-01} \\
L_E &= 4.8551E^{-10} \\
R_L &= 4.8551E^{-10} \\
C_D &= 9.8536E^{-07} \\
R_D &= -2.8824E^{-01}
\end{aligned}
\tag{20}
$$

$$
\begin{aligned}
a_0 &= 1 \\
a_1 &= 1 \\
a_2 &= 1 \\
a_3 &= 1 \\
b_0 &= 1 \\
b_1 &= 0 \\
b_2 &= 0
\end{aligned}
\tag{21}
$$

$$
\begin{aligned}
C &= INF \\
R_E &= INF \\
L_E &= INF \\
R_L &= IND \\
C_D &= IND \\
R_D &= IND
\end{aligned}
\tag{22}
$$

$$
\begin{aligned}
a_0 &= 2 \\
a_1 &= 5 \\
a_2 &= 4 \\
a_3 &= 1 \\
b_0 &= 1 \\
b_1 &= 3 \\
b_2 &= 1
\end{aligned} \tag{23}
$$

$$
\begin{aligned}
C &= 1 \\
R_E &= 1 \\
L_E &= 1 \\
R_L &= 1 \\
C_D &= 1 \\
R_D &= 1
\end{aligned} \tag{24}
$$

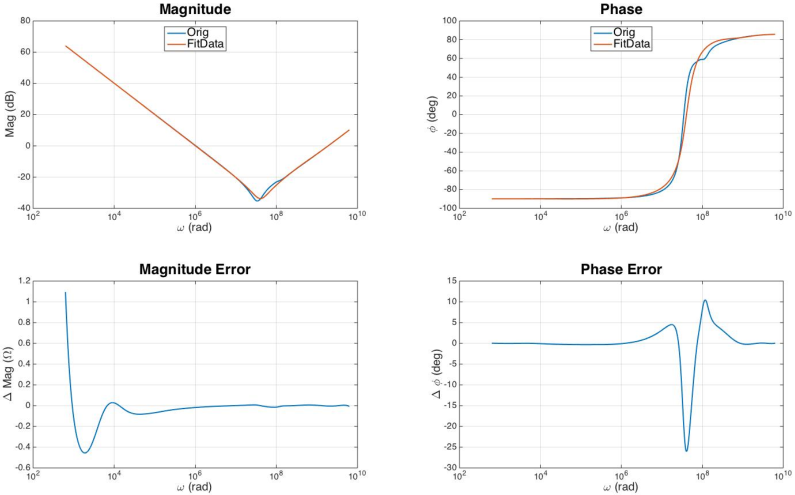


Figure: 6 Term Model: Good Initilization

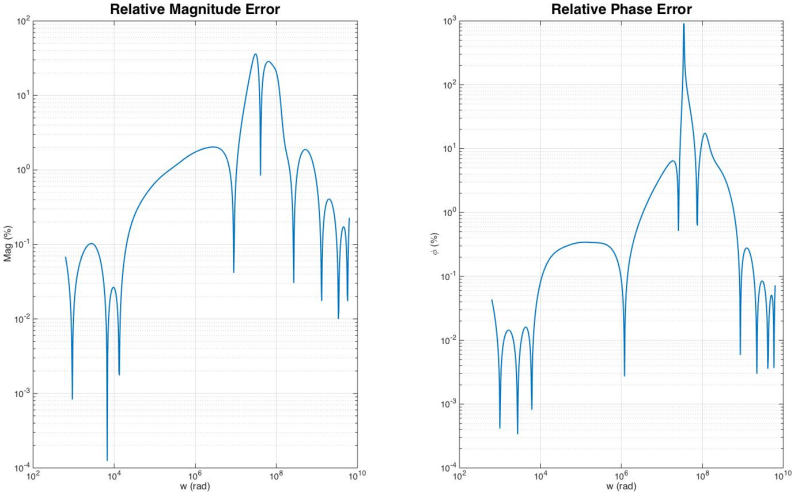


Figure: 6 Term Model: Relative Error

Conclusion

Circuit Capabilities:

- Discharge Curve
- Impedance

Measurement Range:

- DC bias range 0$\rightarrow$500V.
- Frequency Range of 100Hz$\rightarrow$40kHz.

Regression Accuracy:

- Accurrate outside of resonance.
- 2Ω and 2°.
- $<$ 5%.

Future Work

- Build the circuit and validate against the stated capabilities and accuracy.
- Increase the available frequency range for the measurement circuitry.
- Add additional fail-safe protection to the circuit.
- Update the regression technique for better accuracy.
- Evaluate the accuracy of the six term model.

- E. C. Levy.
  Complex-curve fitting.
  Automatic Control, IRE Transactions on, AC-4(1):37–44, 1959.

- C. K. Sanathanan and J. Koerner.
  Transfer function synthesis as a ratio of two complex polynomials.
  Automatic Control, IEEE Transactions on, 8(1):56–58, Jan 1963.

- Sim surfing.
  `http://ds.murata.co.jp/software/simsurfing/en-us/index.html?intcid5=com_xxx_xxx_cmn_nv_xxx`.

Questions?