Calculation No: NSTXU-CALC-131 **Revision No: 0**

Title: Simulation of Inner PF Coil Surge Testing

Purpose of Calculation:

- Benchmark a surge test simulation model based on prototype testing
- Create versions of the model for PF1A, PF1B, and PF1C production coils
- Assess turn-to-turn fault detection sensitivity of the surge testing method for different types of faults that could, hypothetically, occur in the production coils

Codes and versions:

- PSCAD 4.5.4 circuit simulation software
- ANSYS Electromagnetics Suite v.19.0 - Maxwell 2D
- MS Excel for Mac v.16.17

References:

See section 3 of attached report.

Assumptions:

See section 4 of attached report.

Calculation

See section 5 of attached report.

Conclusion:

With an EAR detection threshold of 2%, faults that bridge across single turns can be detected < 1 ohm on PF1A, < 10 ohm on PF1B/PF1C, and faults that bridge across layers < 1000 ohms on all coils.

For PF1A the oscillation frequency will be ~ 2.75kHz and an EAR integration period of 2mS is recommended to capture 5 ~ 6 surge oscillation cycles. For PF1B and PF1C the oscillation frequency will be ~ 5kHz and an EAR integration period of 1mS is recommended.

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I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

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National Spherical Torus eXperiment Upgrade

NSTX-U

Simulation of Inner PF Coil Surge Testing

NSTXU-CALC-131-11-00

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Approved By – Responsible Engineer
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NSTX-U CALCULATION
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NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	11/05/18	Initial Release	

1 Purpose of Calculation

Turn-to-Turn acceptance testing of the NSTX-U Inner PF Coils has been a major emphasis of the NSTX-U recovery activity. The desire to facilitate this testing was the main driver for changing the mechanical support scheme to a “mandrel-less” design.

Various schemes for turn-to-turn testing were investigated [1], leading to the selection of a surge testing method based on capacitor discharge. A surge tester developed for CERN with characteristics appropriate for use on NSTX-U Inner PF Coils was procured [2]. An external filter circuit was constructed to limit the rise time to a safe level, as predicted by detailed modeling of the coil winding [3], to avoid internal voltage oscillations. A simplified model of the coil along with the actual surge tester internal circuitry was used [4,5] to design the external filter circuit. The surge tester was exercised on the Inner PF Coil prototype coil [6], which resembles the production PF1A coil.

The purpose of the work reported herein is to:

- Benchmark a surge test simulation model based on prototype testing
- Create versions of the model for PF1A, PF1B, and PF1C production coils
- Assess turn-to-turn fault detection sensitivity of the surge testing method for different types of faults that could, hypothetically, occur in the production coils

Notes:

1. This calculation is not a design input per se, but instead a study that provides input to the creation of test procedures and interpretation of test results.
2. Ideally, the surge response waveforms predicted by the simulation described herein could be used as a baseline for comparison with the production coils, but the simulation results are probably not accurate enough to serve this purpose, due to the complicated high frequency response of the coils.

2 Codes and Versions

- PSCAD 4.5.4 circuit simulation software
- ANSYS Electromagnetics Suite v.19.0 - Maxwell 2D
- MS Excel for Mac v.16.17

3 References

[1] NSTX-U Inner PF Coil Turn-to-Turn Testing Peer Review, https://drive.google.com/drive/folders/1fZtHviIApiZK2PfBAGeqIIKi-PyMiXLT

[2] Users Manual, Elytt Epowersys CDG 7000 Winding Insulation Tester, https://drive.google.com/file/d/1_cFjjY6HQwS6KGb7ofjF5IlUNroqUkq1/view?usp=sharing

[3] Detailed Modeling of Surge Testing on NSTX-U PF1A Coil, MAG-171018-AG-01, https://drive.google.com/file/d/1VCkRGLnR2pak84OUKRgj7T_2JjsZ6sJH/view?usp=sharing

[4] PF1A Surge Test Modelling and Benchtop Test Results, MAG-180315-NG-02, https://drive.google.com/file/d/1yaIq1vqyQOoZlbgUZC8oVyD7ht9vl2gv/view?usp=sharing

[5] Choosing a Snubber for PF Coil Testing, MAG-180425-NG-02 https://drive.google.com/file/d/1NfBpBQyVvhTHrwRqoB6d4zATiLhyXqmV/view?usp=sharing

[6] Inner PF Coil Prototype Coil Evaluation Report, NSTX-U-REC-040-00, https://drive.google.com/file/d/16-72tfhNXpJgXjZeJ7qhRSbNgWFzkuU4/view?usp=sharing

[7] Pulse Currents and EM Forces During Power Testing of Inner PF Coils, NSTXU-CALC-131-09-01, https://nstx-upgrade.pppl.gov/Engineering/Calculations/1_Torus_Systems/1_3_Magnets/Poloidal_Field_Magnets-WBS131/CALC-131-09-00/NSTXU-CALC-131-09-01.pdf

[8] Mutual Resistance in Spicelink, J. Bracken, ANSOFT Corp. http://www.oldfriend.url.tw/article/SI/mutualresistance.pdf

[9] Current State of Surge Testing of Induction Machines, J. Wilson, Iris Rotating Machine Conference, 2003 https://drive.google.com/file/d/1qTNDGVLglA1dMkJ8FcU8hu-5SwkWvPj5/view?usp=sharing

4 Assumptions

A simplified model is used for the coil under test, ignoring interwinding capacitances. This is justified based on previous findings in [3,4] and confirmed by benchmarking model with actual measurements on prototype coils. This simplification is exploited both in the ANSYS/Maxwell model that computes the impedance of the coil as a function of frequency, as well as the PSCAD circuit simulation model.

For circuit simulation, as shown in Figure 1, the coil is subdivided into normal (N) and shorted (S) turns that are bridged by a fault with resistance R_F. The normal and shorted turns are mutually coupled. The R and L values of the shorted turns are represented by R_S and L_S. The normal turns, typically in series in the main current path before and after the shorted turns, depending on which turns are bridged by the fault, are represented by equivalent lumped R and L values R_N and L_N as shown.

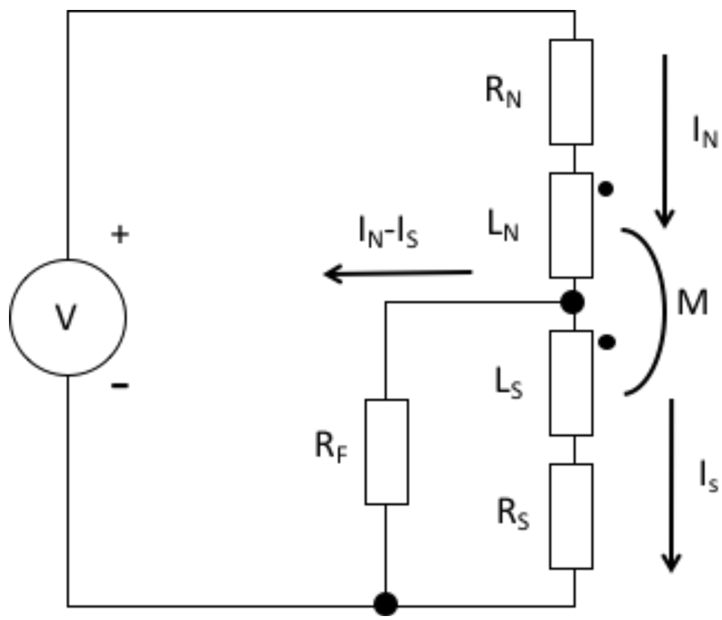

Figure 1 – Simplified model of coil with subset of turns bridged by a fault

5 Calculations

5.1 Coil impedance matrices

ANSYS/Maxwell was used by W. Que to model the PF1A, PF1B and PF1C production coil impedances as a function of frequency under near-DC conditions (1Hz) and at higher frequencies chosen to match the frequency of oscillation with the surge tester internal capacitance of 2uF. The ANSYS/Maxwell model includes both skin effect and proximity effect.

The prototype coil, which differs slightly in geometry compared to the production PF1A coil, was not modeled in ANSYS/Maxwell. But comparison between the Z vs. f measurements made on the prototype coil using the Hioki meter provides some level of benchmarking of the Maxwell calculations as described in Table 1. Here the ratio of Maxwell calculations to Hioki measurements is calculated after scaling for the calculated DC values of resistance R and inductance L. Considering the geometric differences, and the skin and proximity geometric effects not captured in the scaling based on DC values, this comparison is supportive of the Maxwell results.

Table 1 – Comparison of calculated and measured parameters

	Prototype					PF1A			
	Calc (DC)	Meas (DC)	10Hz - Hioki	1kHz - Hioki	2.75kHz - Hioki	Calc (DC)	1Hz - Maxwell	1kHz - Maxwell	2.75kHz - Maxwell
R (mohm)	5.83	5.70	9.45	275.00	479.00	7.52	7.38	299.09	520.61
L (mH)	1.97	-	1.80	1.59	1.57	2.13	1.95	1.75	1.73

	Ratio PF1A-Maxwell/Proto-Hioki (scaled)			
	Calc (DC)	1-10Hz	1kHz	2.75kHz
R Ratio	1.29	0.61	0.84	0.84
L Ratio	1.08	1.00	1.02	1.01

As a second means of verification, R and L values calculated by Maxwell at 1Hz (near-DC) provide an approximate basis for comparison with prior calculations using simpler formulas applicable to DC conditions [7].

Table 2 – Comparison of Maxwell 1Hz values with simple DC calculations

	R_Maxwell (mOhm)	R_DC (mOhm)	L_Maxwell (mH)	L_DC (mH)
PF1A	7.38	7.52	1.95	2.13
PF1B	5.20	5.23	0.47	0.48
PF1C	3.25	3.26	0.48	0.48

Impedance scans for PF1A, PF1B and PF1C production coils are given in Table 3, Table 4, Table 5, Figure 2, Figure 3, and Figure 4.

Table 3 - PF1A AC Impedance Scan

f (Hz)	L (mH)	R (mOhm)	Z (Ohm)
1	1.95	7	0.014
2	1.95	7	0.026
5	1.95	8	0.062
10	1.95	8	0.123
20	1.94	11	0.245
50	1.92	28	0.604
60	1.91	35	0.721
100	1.88	65	1.180
200	1.82	121	2.288
500	1.77	207	5.556
1000	1.75	299	10.974
2000	1.73	438	21.754
5000	1.72	720	53.933
10000	1.71	1031	107.360

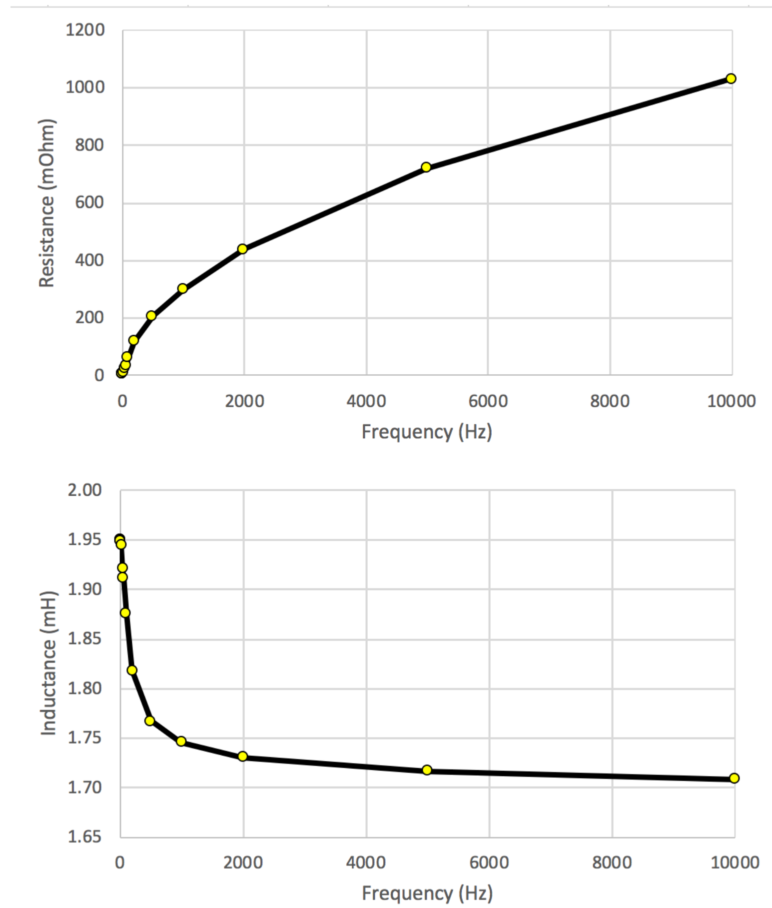

Figure 2 – PF1A AC Impedance Scan Resistance and Inductance

Table 4 - PF1B AC Impedance Scan

f (Hz)	L (uH)	R (mOhm)	Z (Ohm)
1	469	5	3
2	469	5	6
5	469	5	15
10	468	5	29
20	468	6	59
50	467	7	147
100	463	11	291
200	457	20	574
500	448	38	1407
1000	444	56	2789
2000	441	84	5541
5000	438	140	13766
10000	437	204	27439

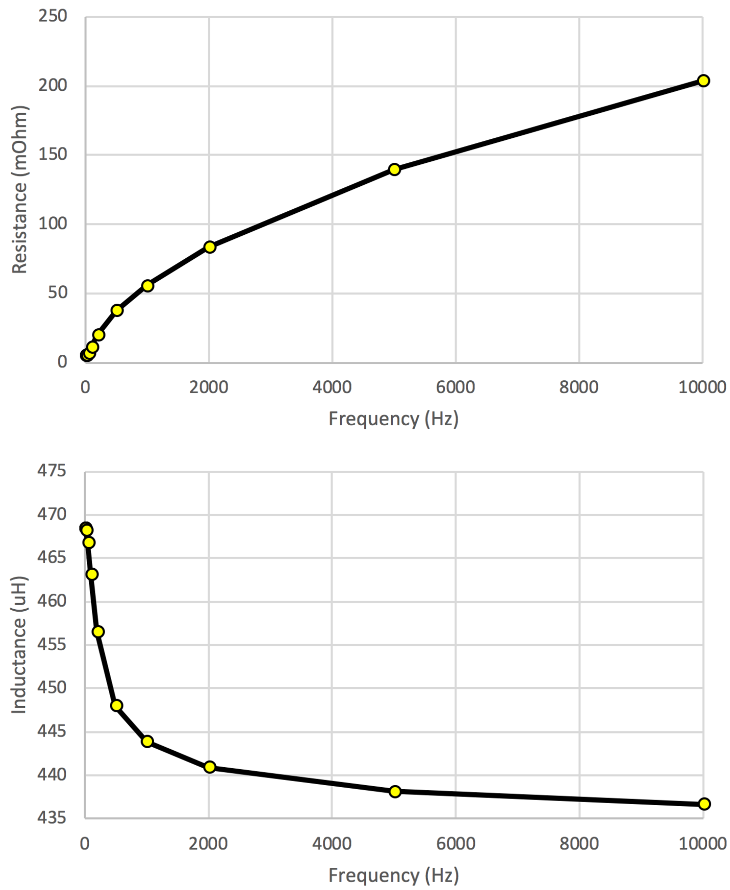

Figure 3 - PF1B AC Impedance Scan Resistance and Inductance

Table 5 - PF1C AC Impedance Scan

f (Hz)	L (uH)	R (mOhm)	Z (Ohm)
1	480.3	3.25	3
2	480.3	3.25	6
5	480.2	3.29	15
10	480.0	3.42	30
20	479.1	3.90	60
50	474.7	6.44	149
60	473.1	7.42	178
100	468.0	11.20	294
200	460.6	18.55	579
500	453.8	31.29	1426
1000	450.6	45.88	2831
2000	448.3	67.07	5633
5000	446.2	109.50	14017
10000	445.1	158.19	27967

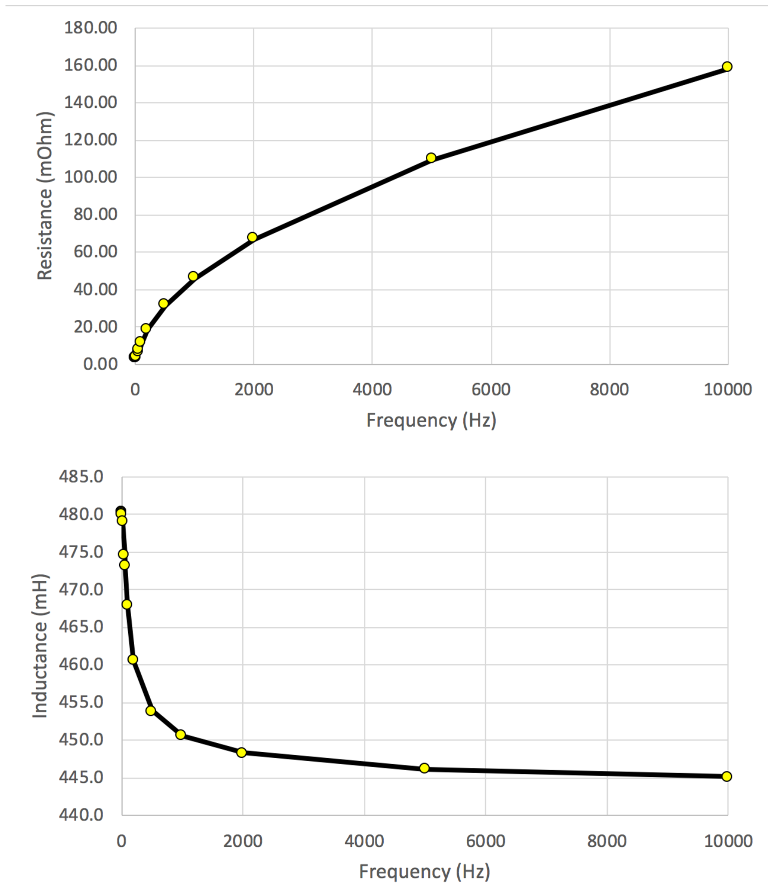

Figure 4 - PF1C AC Impedance Scan Resistance and Inductance

For the fault calculations described herein, relevant R and L values for different fault cases are computed from the raw data from Maxwell in XL spreadsheets ZPF1A_181105.xlsx, ZPF1B_181105.xlsx, and ZPF1C_181105.xlsx.

5.2 Coil simulation models

Fault cases and corresponding coil model parameters are given in Figure 5, Figure 6, Figure 7 and Table 6.

Note that the Maxwell representation of the coil that includes proximity effect includes both mutual inductance and mutual resistance [8] terms. Since mutual resistance is an unusual situation and is not modeled in PSCAD, the mutual resistances were added into the resistance for each turn along with its self-resistance. This provides a solution that is completely accurate when the current flow in the normal and shorted coils is exactly equal but the accuracy diminishes as the current shunted by the fault increased. However, the effect is small and the error is considered negligible and not significant.

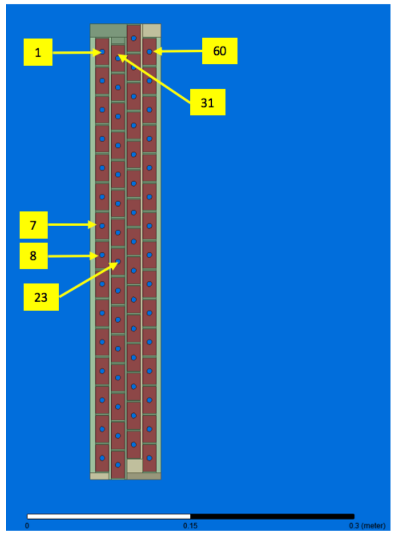

Figure 5 – PF1A coil and fault cases (7-8, 8-23, 1-31)

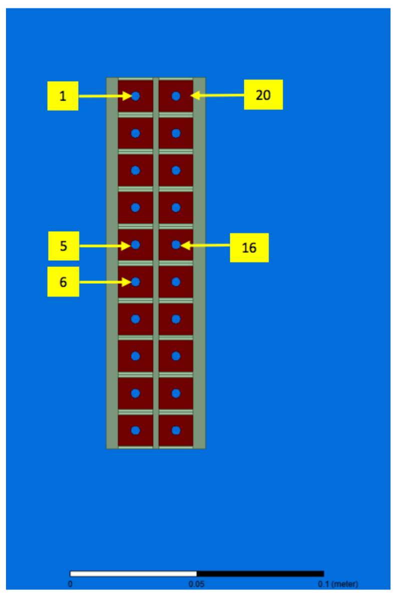

Figure 6 - PF1B coil and fault cases (5-6, 5-16)

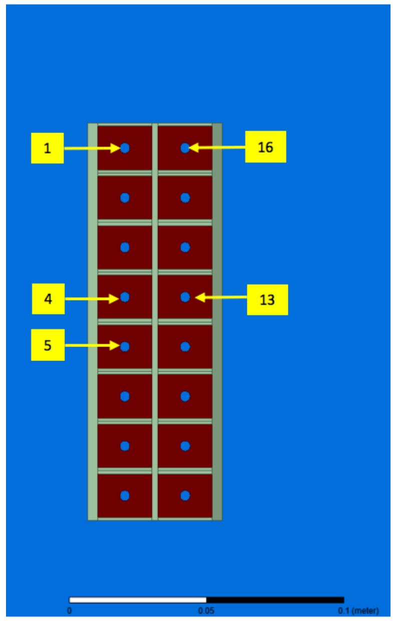

Figure 7 – PF1C coil and fault cases (4-5, 5-13)

Table 6 – R and L values for various fault cases

Coil	PF1A			PF1B		PF1C	
Frequency (kHz)	2.75						
Fault between turns-->	7-8	8-23	1-31	5-6	5-16	4-5	5-13
n	60	60	60	20	20	16	16
n_n	59	45	30	1	11	1	8
R_n (ohm)	5.10E-01	4.30E-01	3.21E-01	1.28E-01	8.10E-02	9.89E-02	5.47E-02
L_n (H)	1.67E-03	9.54E-04	4.50E-04	3.95E-04	1.01E-04	3.92E-04	1.21E-04
n_s	1	15	30	19	9	15	8
R_s (ohm)	1.09E-02	9.06E-02	2.00E-01	1.13E-02	5.85E-02	1.06E-02	5.48E-02
L_s (H)	7.66E-07	1.37E-04	4.29E-04	1.46E-06	1.47E-04	2.09E-06	1.21E-04
M_n-s (H)	2.86E-05	3.17E-04	4.23E-04	2.11E-05	9.51E-05	2.63E-05	1.03E-04
k	0.80	0.88	0.96	0.88	0.78	0.92	0.85
R_total (ohm)	5.21E-01	5.21E-01	5.21E-01	1.39E-01	1.39E-01	1.09E-01	1.09E-01
L_total (H)	1.73E-03	1.73E-03	1.73E-03	4.38E-04	4.38E-04	4.46E-04	4.46E-04

5.3 Simulation model including surge tester

PSCAD is used to simulate the surge tester and coil, including the Error Area Ratio (EAR) calculation [9] used as a metric for waveform comparison. A screenshot of the PSCAD canvas is given in Figure 8 with a zoom of the circuit in Figure 9. The model of the surge tester is the same as developed in [4,5] but with the surge tester series resistance adjusted to calibrate the model to match a baseline response from prototype testing.

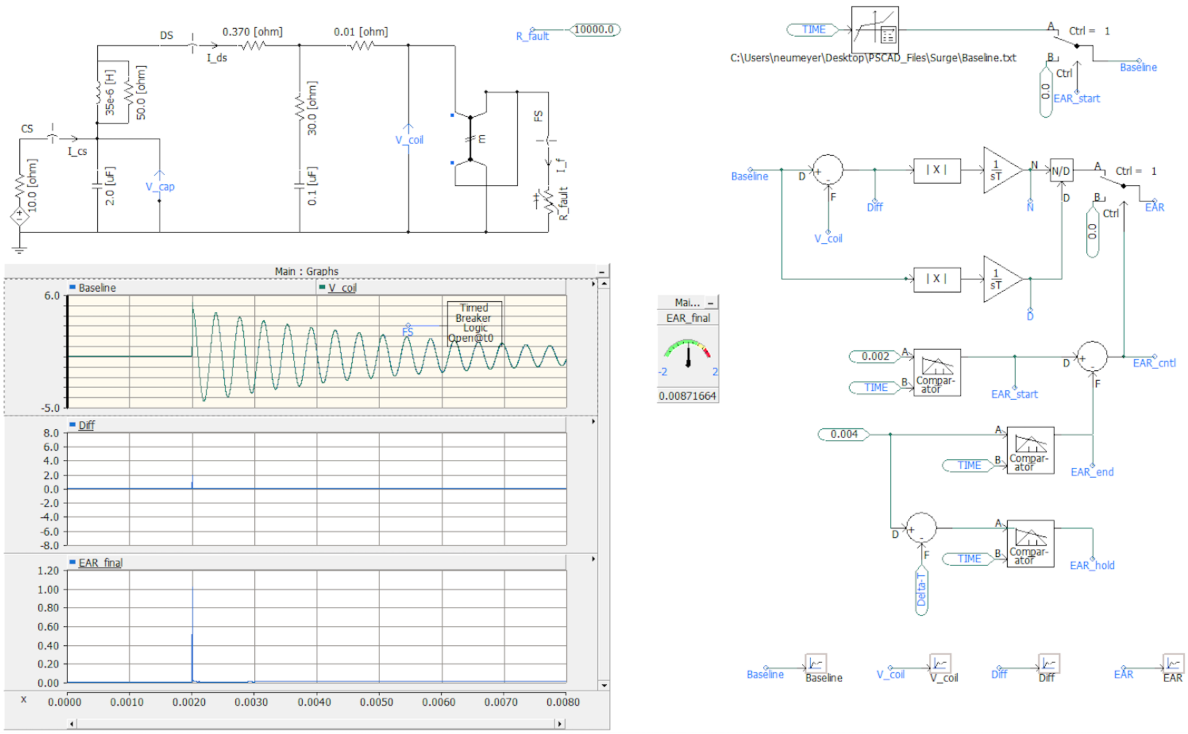

Figure 8 – PSCAD canvas

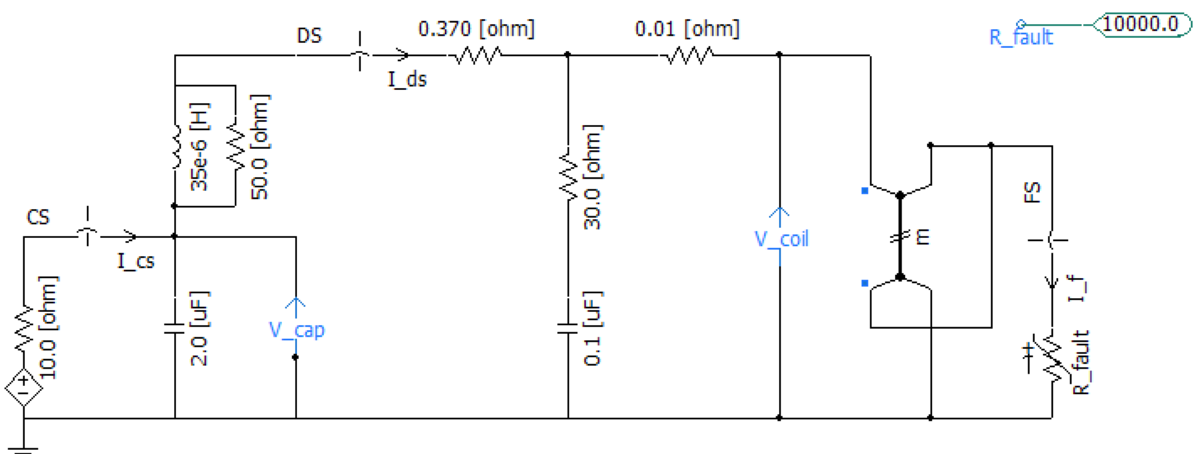

Figure 9 – Surge circuit simulation model

The basis of the EAR calculation is described in Figure 10.

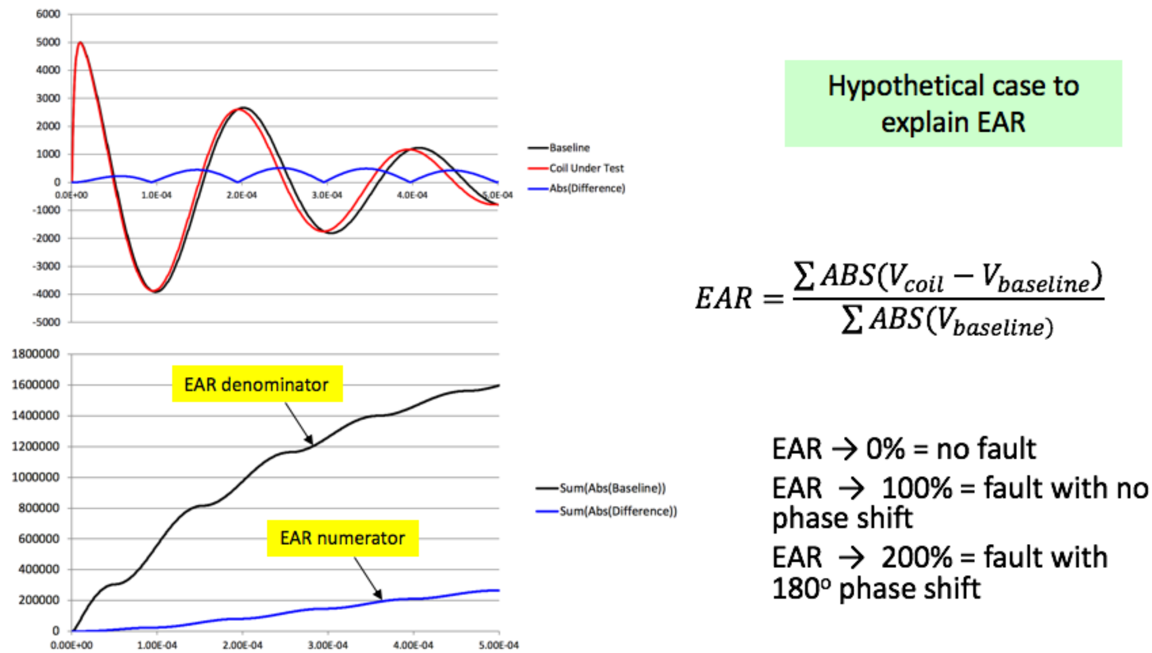

Figure 10 – Error Area Ratio (EAR)

In order to calibrate the model, the output data file from the surge tester obtained during the first 5kV test on the Everson-Tesla prototype coil was provided as an input to PSCAD in a “Baseline.txt” file. Then the simulation model was set up with the parameters of the prototype coil and run repeatedly with adjustments to the series resistance of the surge tester so as to minimize the EAR. Results are shown in Figure 11 and Figure 12.

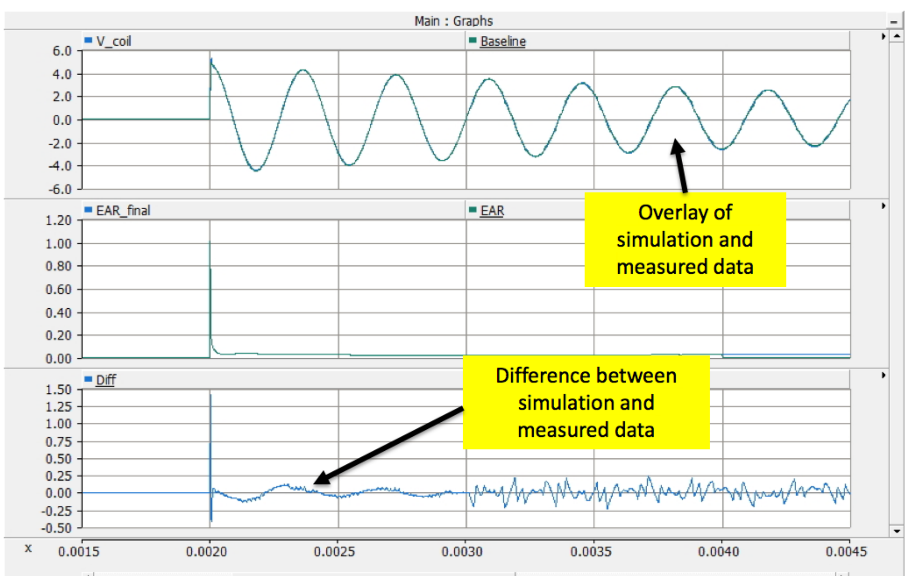

Figure 11 – Calibration result

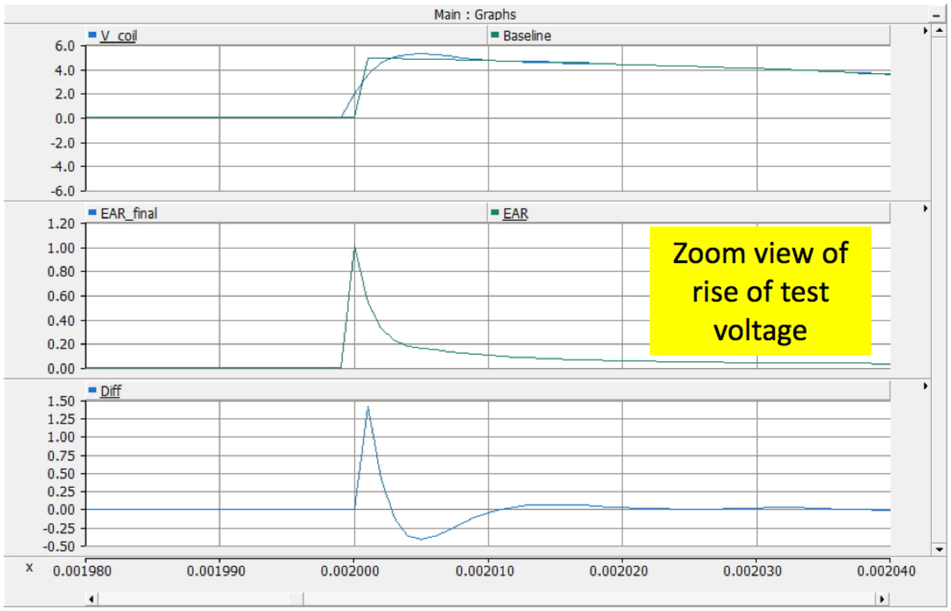

Figure 12 – Zoom view of calibration waveforms

The calibration resulted in a value of EAR of 2.4% based on a 2 mS integration period. Values of R and L that were chosen to minimize calibration error, as compared to the Hioki measurement at the resonant frequency are given in

Table 7 – Model calibration parameters

	Model calibration	Hioki
R (mOhm)	0.4789	0.4789
L (mH)	1.5583	1.5729

Note that the resistive component was adjusted using the source resistance model element with a final value chosen at 0.370 ohm.

Precision was limited by finite sampling (both surge tester data and PSCAD simulation), the need to interpolate between surge tester samples, and synchronization between measured data and simulation. For simulation cases comparing a no-fault condition to a fault condition, these problems will not limit the EAR precision since the surge tester data is not involved.

However, in practice, it has been observed that the lack of synchronization of the surge tester capacitor discharge with the data sampling creates an uncertainty resulting in ~ 1.5% EAR error [8]. On this basis, a 2% EAR threshold setting is recommended in practice.

Lastly, it is noted that the simulated voltage rise time is ~ 5 uS, a bit faster than the 10 uS that was targeted [3]. However, since the 10 uS was conservatively chosen, this is not a significant cause of concern.

5.4 Fault Simulations

Typical surge response waveforms for PF1A are given in Figure 13 and Figure 14. Note that the oscillation frequency of PF1A is ~ 2.75kHz while that of PF1B and PF1C is ~ 5kHz. For EAR calculations it is desirable to cover 5 ~ 6 cycles of oscillation, so the EAR interval for PF1A was chosen at 2 mS, and for PF1B/PF1C, 1 mS.

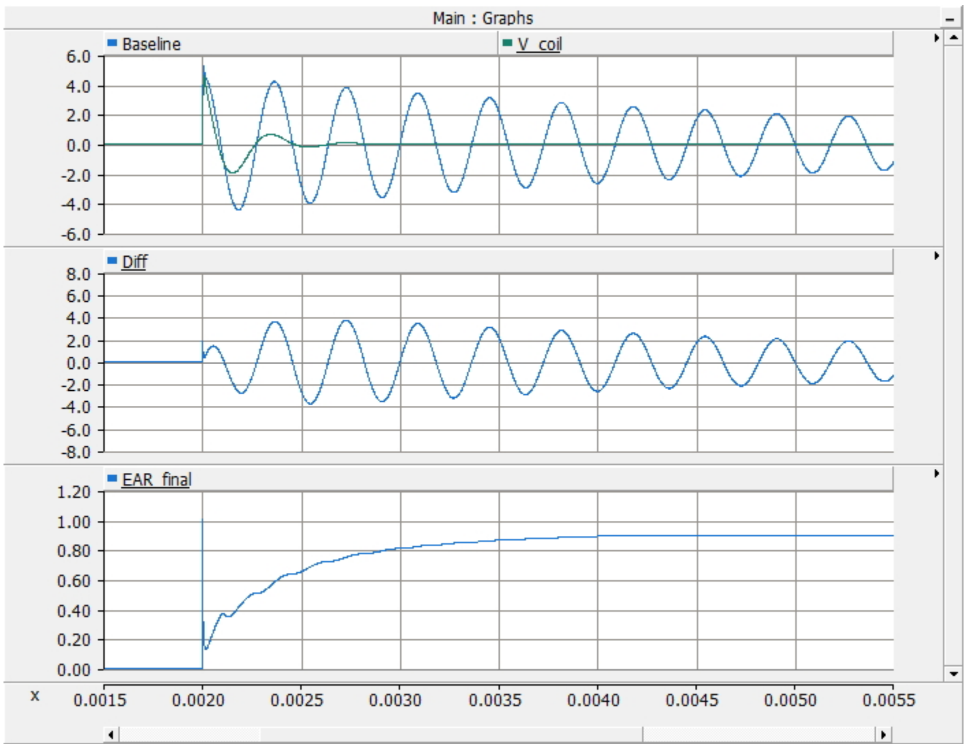

Figure 13 – PF1A layer-layer (turns 1-31) fault @ 100 ohms @ t = 0 after surge application

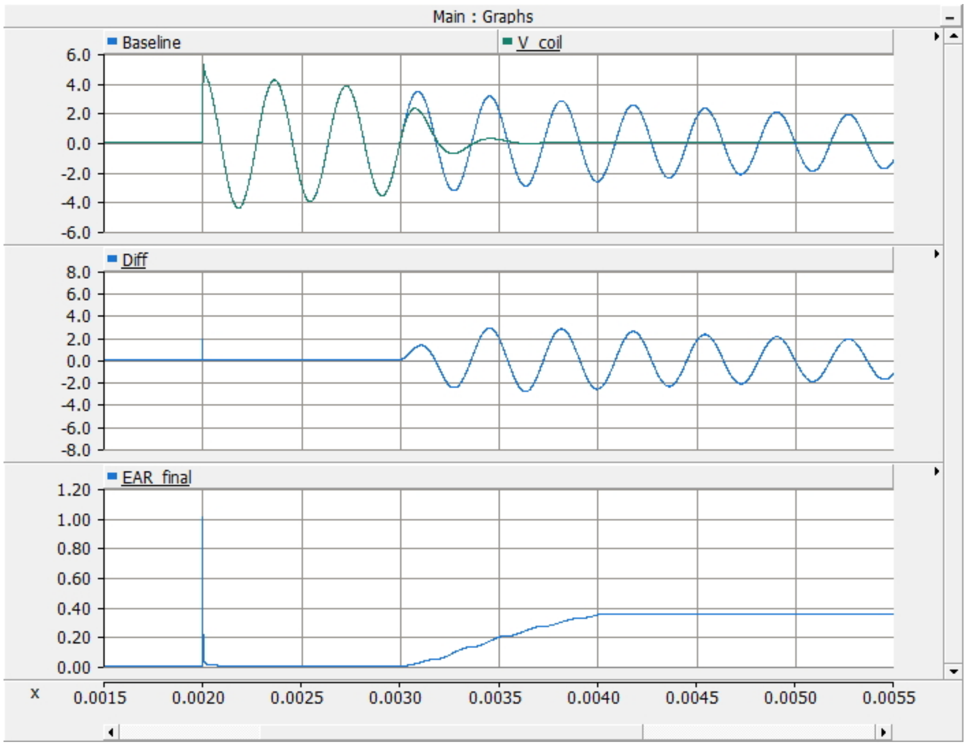

Figure 14 - PF1A layer-layer (turns 1-31) fault @ 100 ohms @ t = 1 mS after surge application

Fault detection sensitivity is summarized in Table 8 and depicted in Figure 15, Figure 16, and Figure 17.

Table 8 – Detection sensitivity (EAR%) vs. Fault resistance (ohm)

PF1A (EAR over 2mS)	**0.001**	**0.01**	**0.1**	**1**	**10**	**100**	**1000**	**10000**
One Turn	90.4	82.3	39.1	6.0	< 2	< 2	< 2	< 2
Midlayer-Midlayer	103.1	103.6	101.6	96.8	65.9	11.5	< 2	< 2
Layer-Layer	99.4	99.4	99.3	99.0	89.3	37.1	5.0	< 2
PF1B (EAR over 1mS)	**0.001**	**0.01**	**0.1**	**1**	**10**	**100**	**1000**	**10000**
One Turn	98.7	96.2	76.6	21.0	2.5	< 2	< 2	< 2
Midlayer-Midlayer	101.6	101.5	101.0	98.7	81.1	23.7	2.8	< 2
PF1C (EAR over 1mS)	**0.001**	**0.01**	**0.1**	**1**	**10**	**100**	**1000**	**10000**
One Turn	99.5	97.9	84.5	29.7	3.8	< 2	< 2	< 2
Midlayer-Midlayer	101.6	101.5	101	98.2	77.6	20.2	2.4	< 2

Note: green = detectible, yellow = not detectible, assuming 2% EAR threshold setting

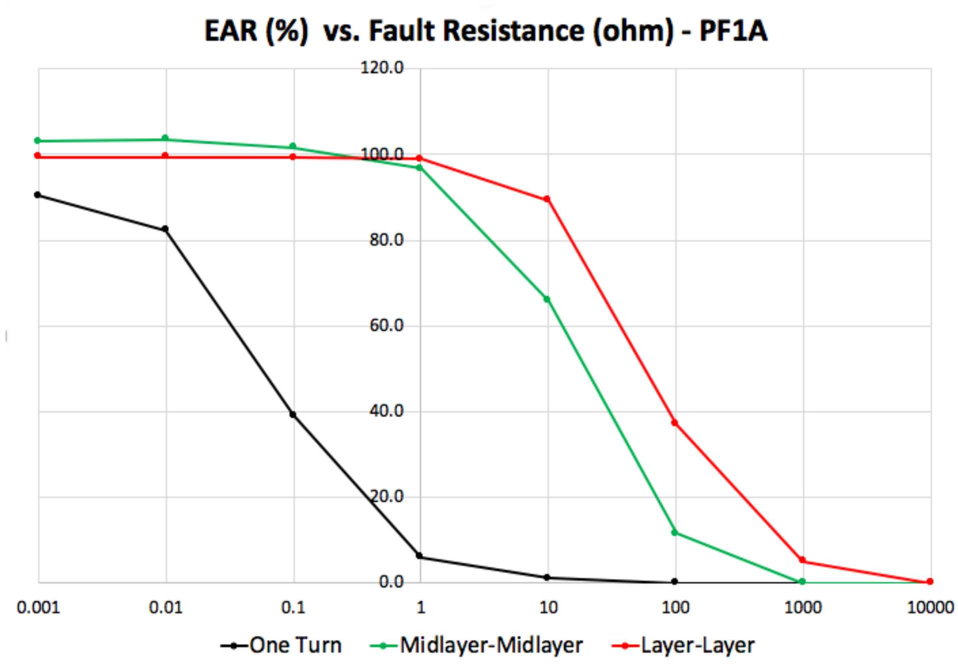

Figure 15 – PF1A fault detection sensitivity

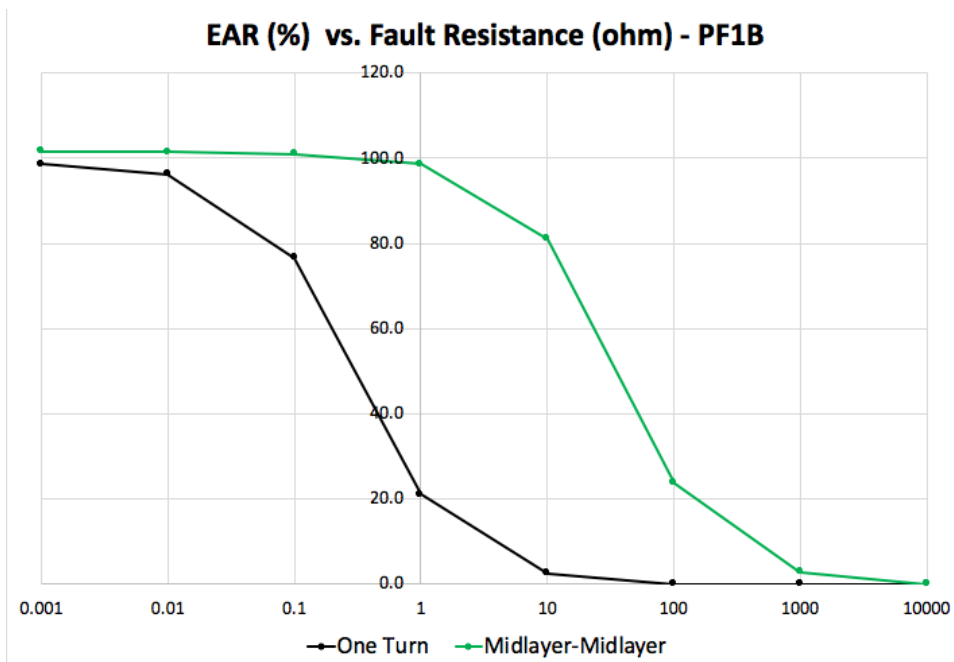

Figure 16 – PF1B fault detection sensitivity

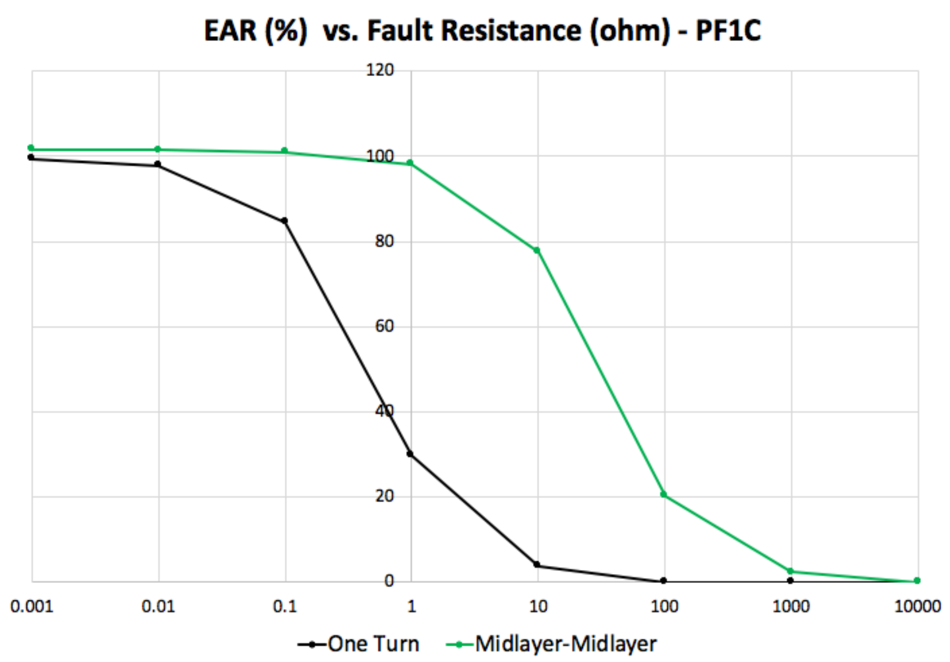

Figure 17 – PF1C fault detection sensitivity

6 Conclusions

With an EAR detection threshold of 2%, faults that bridge across single turns can be detected < 1 ohm on PF1A, < 10 ohm on PF1B/PF1C, and faults that bridge across layers < 1000 ohms on all coils.

For PF1A the oscillation frequency will be ~ 2.75kHz and an EAR integration period of 2mS is recommended to capture 5 ~ 6 surge oscillation cycles. For PF1B and PF1C the oscillation frequency will be ~ 5kHz and an EAR integration period of 1mS is recommended.