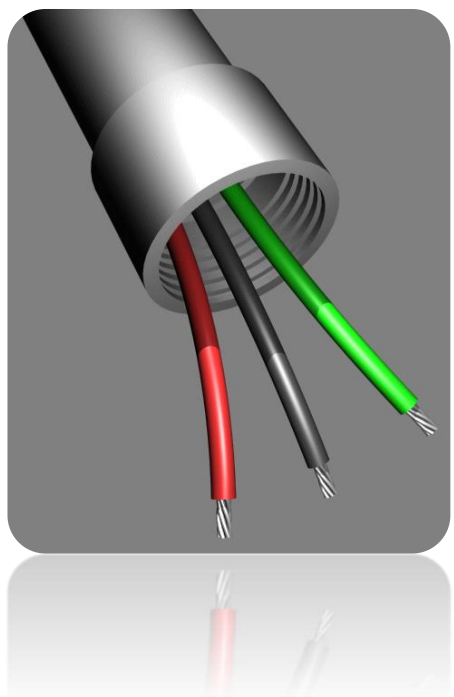
GEMI

Grounding & EMI Analysis Program
For Conduit-Enclosed Power Circuits



Single Circuit Analysis Module

User's Manual

Program Version: 3.03 – January 13, 2022

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1. GEMI Historical Review

The GEMI (**G**rounding and **E**lectro-**M**agnetic **I**nfluence) program facilitates the design of steel conduit enclosed power circuits. The first three releases of this program (1994-1998) were compatible with the IBM PC with the DOS operating system. In 1999, the first Windows version was released (see Table 1.1) followed by two other releases in 2002 and 2004. A major software update was undertaken in 2018, which resulted in release of version 3.00 in 2020, and the present version (GEMI 3.03) released in January 2022.

Table 1.1: GEMI Release History

Year Released	Version	OS
1994	SCA.1	DOS
1996	GEMI.1	
1998	GEMI 2.4	
1999	GEMI W 1.0	Windows
2002	GEMI W 2.0	
2004	GEMI W 2.2	
2020	GEMI W 3.0	
2022	**GEMI W 3.03**	

GEMI is based on a mathematical model known as ***Finite Element Analysis.*** This method takes into account the electromagnetic fields developing in and around conduit-enclosed circuits and evaluates the effectiveness of steel conduits in limiting EMI and providing a low impedance earth current return to fault currents.

The original GEMI model was developed in the late 1980s. The original model was validated by extensive laboratory and field tests performed in the early 1990's (See Figure 1.1).

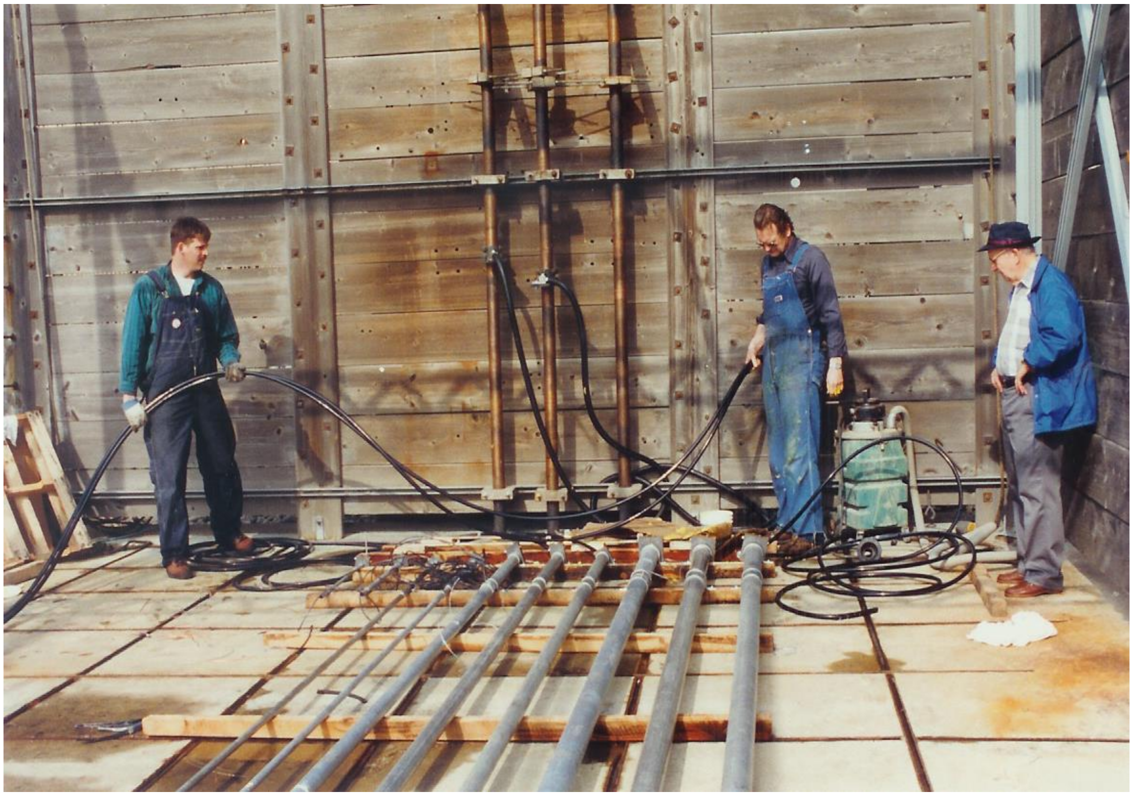


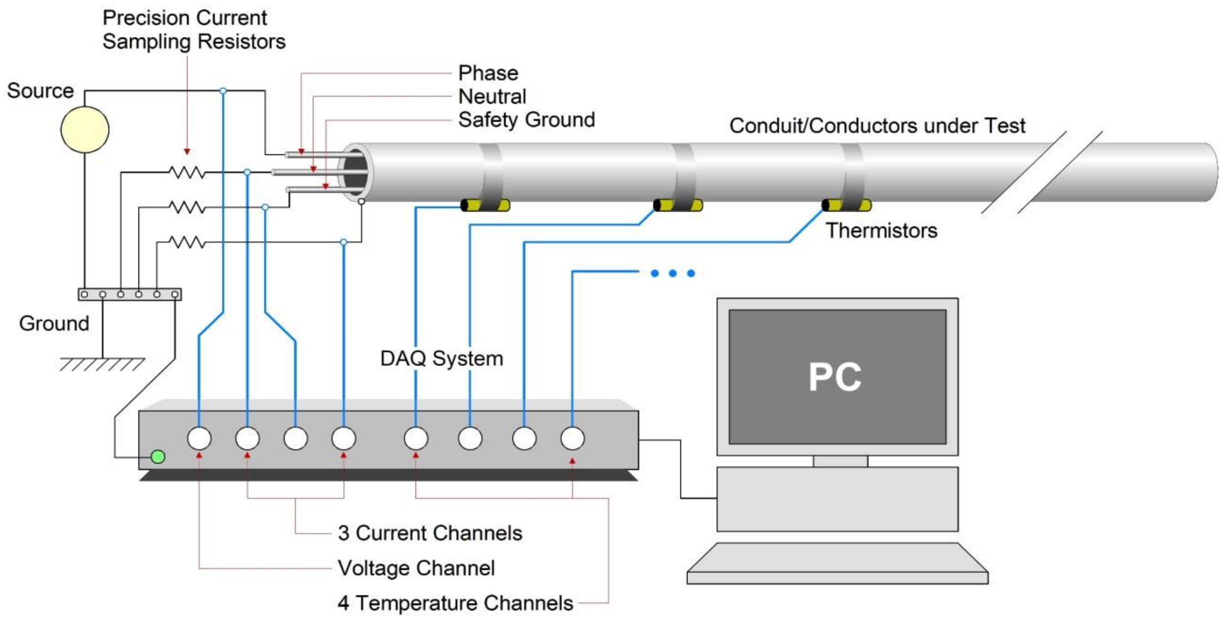
Figure 1.1: Field Tests for the Validation of the Original GEMI Model

During the period 2018-2020 a new version of the GEMI model was developed, providing several enhancements over the original model including:

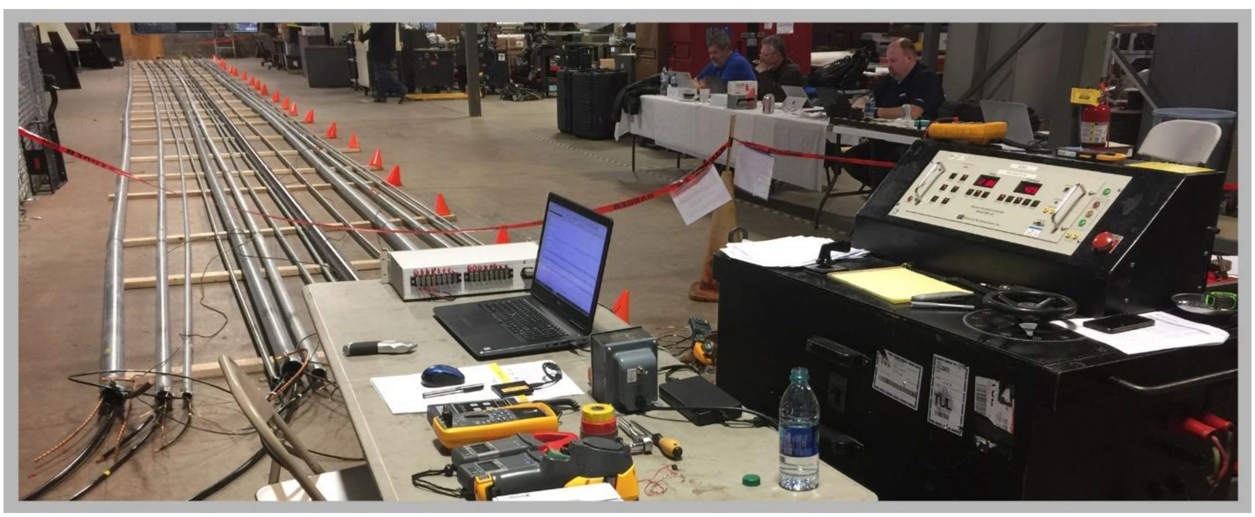
- Modeling of non-concentric arrangement effects
- Use of English or metric units.
- Automatic default settings based on NEC article 250.
- Conduit fill factor computation
- Detailed circuit cross-section view with EM field displays.
- Visualization of EM fields along any user selectable path.
- Increased accuracy and computational efficiency.

The new model was validated by conducting new field and laboratory testing (See Figures 1.2 and 1.3). The tests performed in December 2019 and additional tests in 2019. The detailed test report and verification can be obtained from STI. A summary of the results id given in Appendix D.

The new user interface developed for GEMI version 3.00 is described in the next section.



(a)

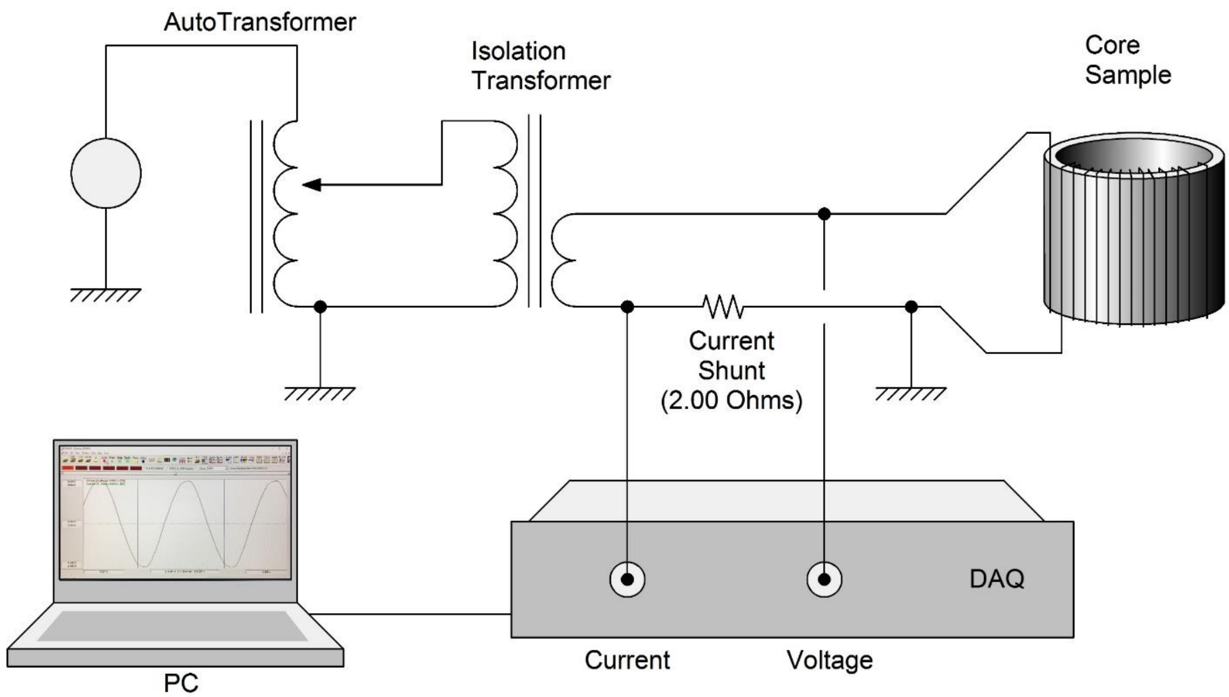


(b)

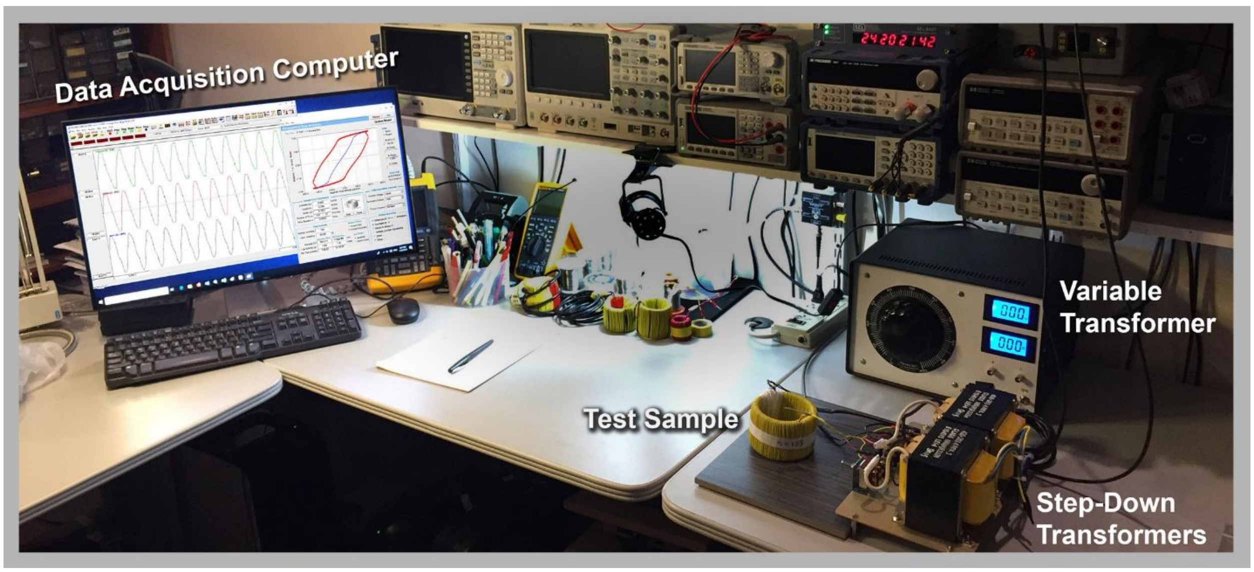
Figure 1.2: High Current Field Test Setup – December 2018

(a) Test Setup Block Diagram

(b) Test Setup View



(a)



(b)

Figure 1.3: Permeability Measurement Setup - 2019

(a) Test Setup Block Diagram

(b) Test Setup View

2. The GEMI User Interface

The GEMI main window is illustrated in Figure 2.1. It provides seven functions, which illustrate the performance of a single steel conduit enclosed power circuit:

1. Allowable Conduit Length
2. Allowable Length versus Arc Voltage
3. Impedance versus Current
4. Magnetic Field and Permeability
5. Conduit with Suppl. Ground Conductor
6. Allowable Circuit Length w/o Conduit
7. Fault Current at "Source Power"

The GEMI function is selected by clicking on the radio buttons located under the **Select Function** title (See Figure 2.1)

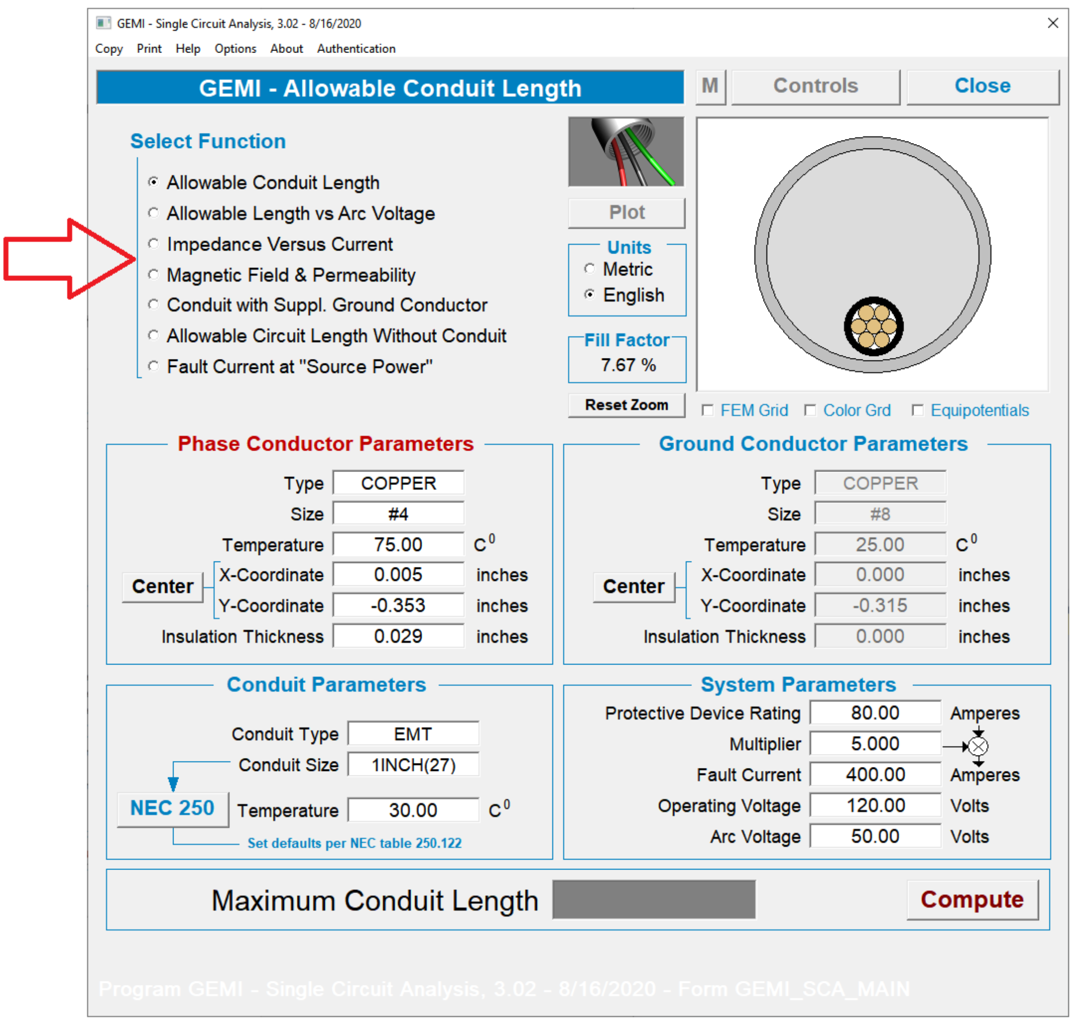


Figure 2.1: Function Selection Radio Buttons

The input data required for each function are entered in the blocks titled:

- Phase Conductor Parameters
- Ground Conductor Parameters
- Conduit Parameters, and
- System Parameters

The phase and ground conductor parameters include:

- Conductor type and size (selected from tables)
- Conductor x and y coordinates
- Temperature
- Insulation thickness

Coordinates, temperature and thickness are entered in English or metric units. Units are selected by radio buttons located under the "Units" title – See Figure 2.1). When the conductor coordinates or the insulation thickness is modified, the cross-section view drawing is automatically updated. The conductor positions can also be edited by moving the conductor images in the cross-section view using the mouse. ***Note that conductors must not be overlapping. Furthermore, all conductors must be located inside the conduit***.

The circuit section view can be zoomed and panned using the mouse wheel and the right mouse button respectively. Conductor selection is made using the left mouse button. A left button double click on a conductor opens the conductor selection library window. The **Reset Zoom** button re-centers the image to the default position.

The **Plot** button opens a field plot window, which displays the computed magnetic field along a user specified path (See Figure 2.2). The path is indicated by a red line (or circle) appearing on the circuit cross-section display. The path can be modified using the mouse.

A number of radio buttons located on the field plot window allow the selection of the plotted quantity, namely:

- Magnetic scalar potential (A)
- Magnetic flux density (B)
- Magnetic field intensity (H)
- Current density (J)
- Relative permeability (μ)

Additional radio buttons select the plot path shape (straight line or circular), the plotted field component direction (parallel or perpendicular to the path), plot-scaling mode (automatic or fixed), and the plot interpolation mode (linear or none).

The seven GEMI computational functions are described in Sections 3 through 9.

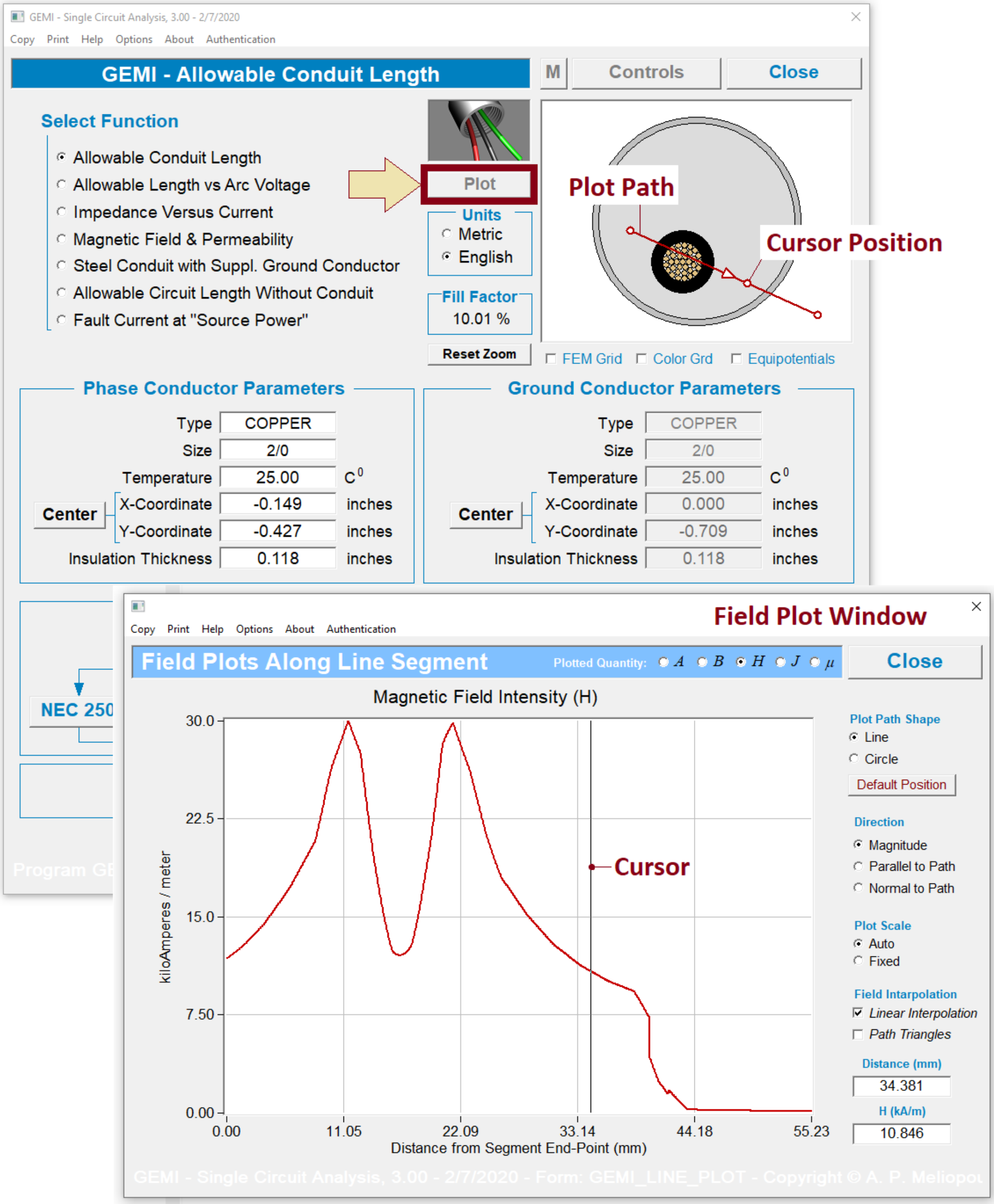


Figure 2.2: Field Plot Window Example

3. Allowable Conduit Length

The Allowable Conduit Length function computes the maximum length of a steel conduit enclosed circuit that will ensure fault current is higher than a specified level. The required input data for this function are:

- Phase Conductor Type, Size and Temperature
- Conduit Type, Size and Temperature
- Operating Voltage
- Arc Voltage
- Fault Current

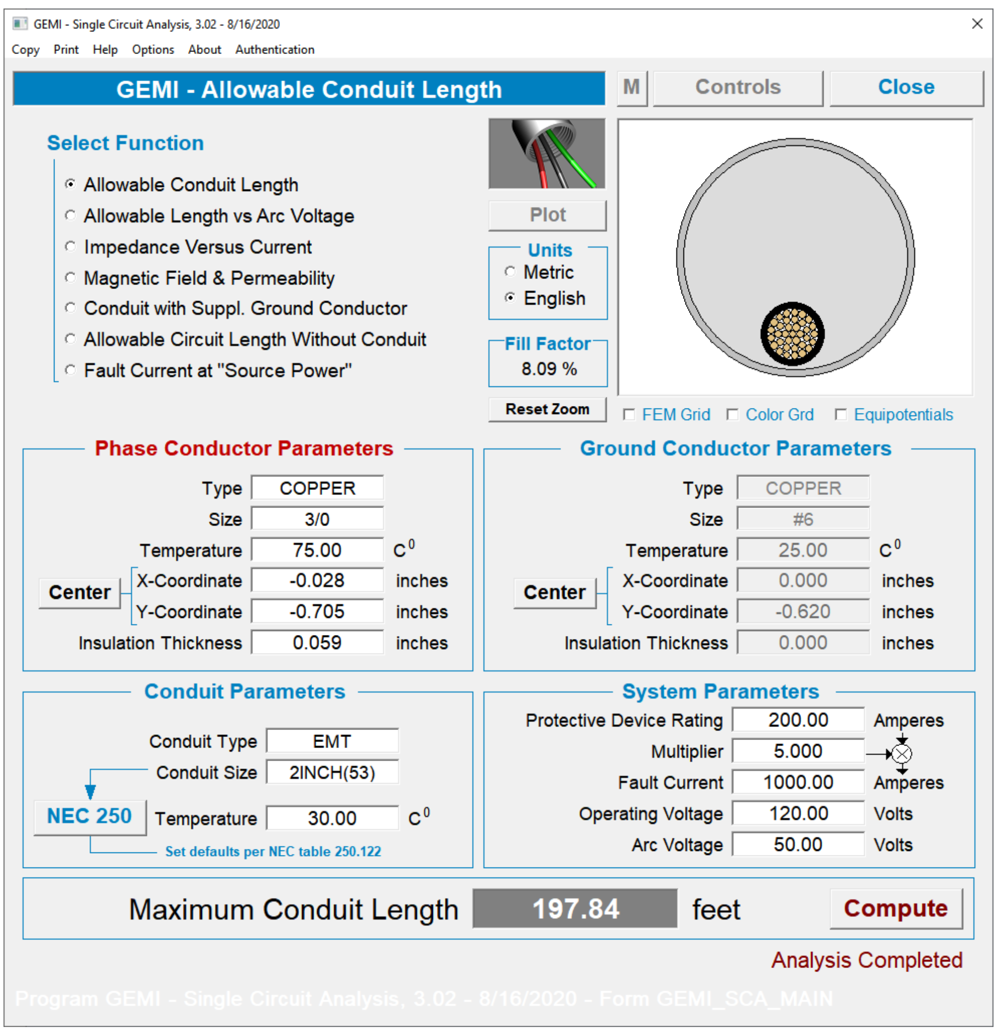


Figure 3.1: Allowable Conduit Length Function

4. Allowable Length versus Arc Voltage

The Allowable Length versus Arc Voltage function generates plots of the permissible circuit length as a function of arc voltage for three electric current levels

Input Data:

- Phase Conductor Type, Size and Temperature
- Conduit Type, Size and Temperature
- Operating Voltage
- Current Range of Interest

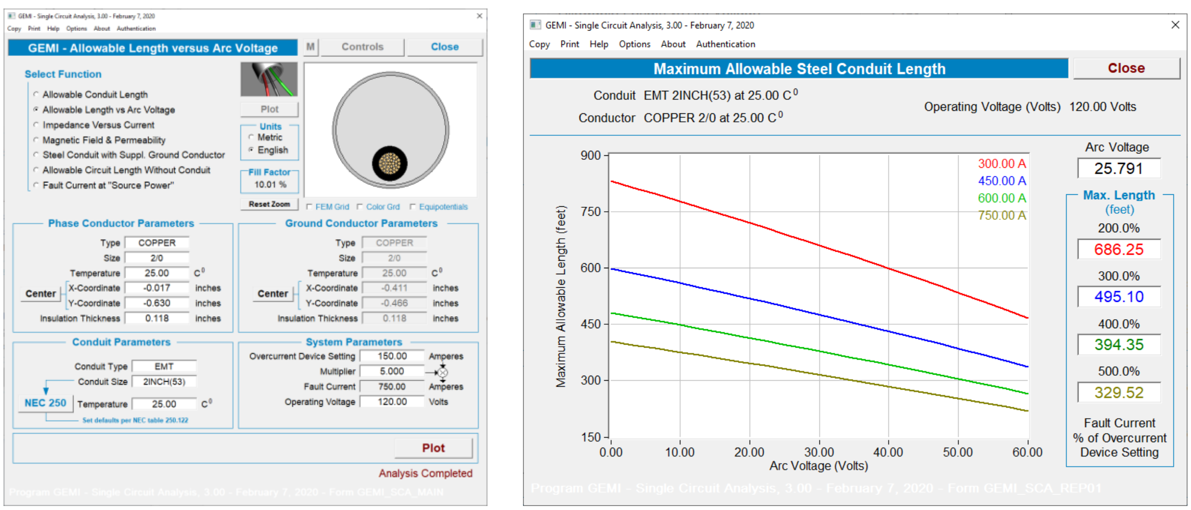


Figure 4.1: Allowable Length versus Arc Voltage Function

5. Impedance versus Current

The Impedance versus Current function generates tables of plots of the circuit impedance as a function of electric current.

Input Data:

- Phase Conductor Type, Size and Temperature
- Conduit Type, Size and Temperature
- Current Range of Interest

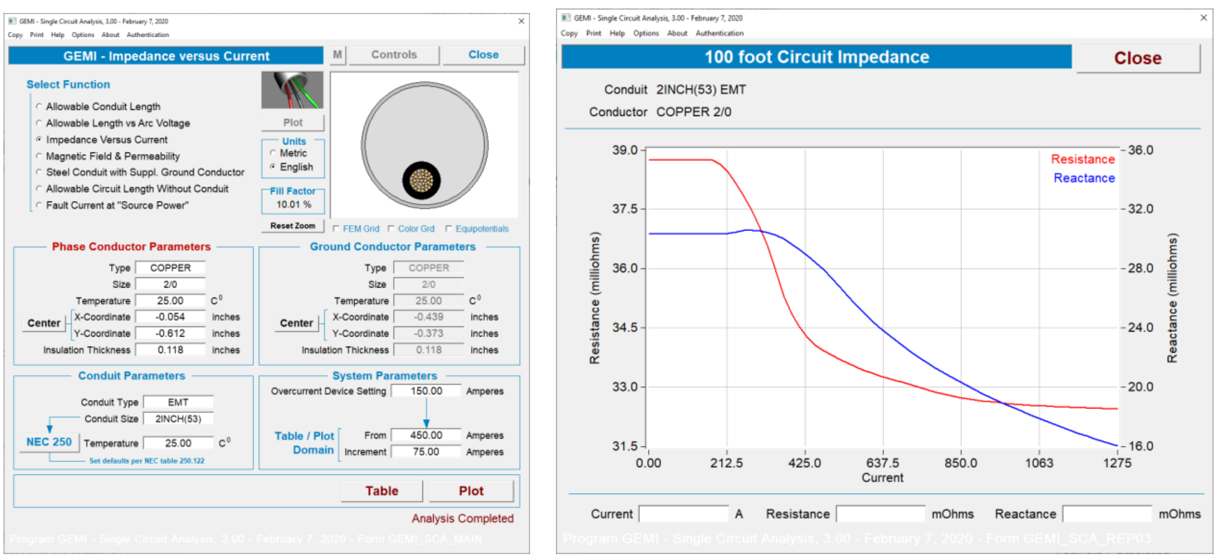


Figure 5.1: Impedance versus Current Function

6. Magnetic Field and Permeability

The Magnetic Field and Permeability function generates plots of the magnetic field intensity, magnetic flux density and relative permeability along a line starting at the phase conductor center and ending at the conduit external surface.

Input Data:

- Phase Conductor Type, Size and Temperature
- Conduit Type, Size and Temperature
- Electric Current

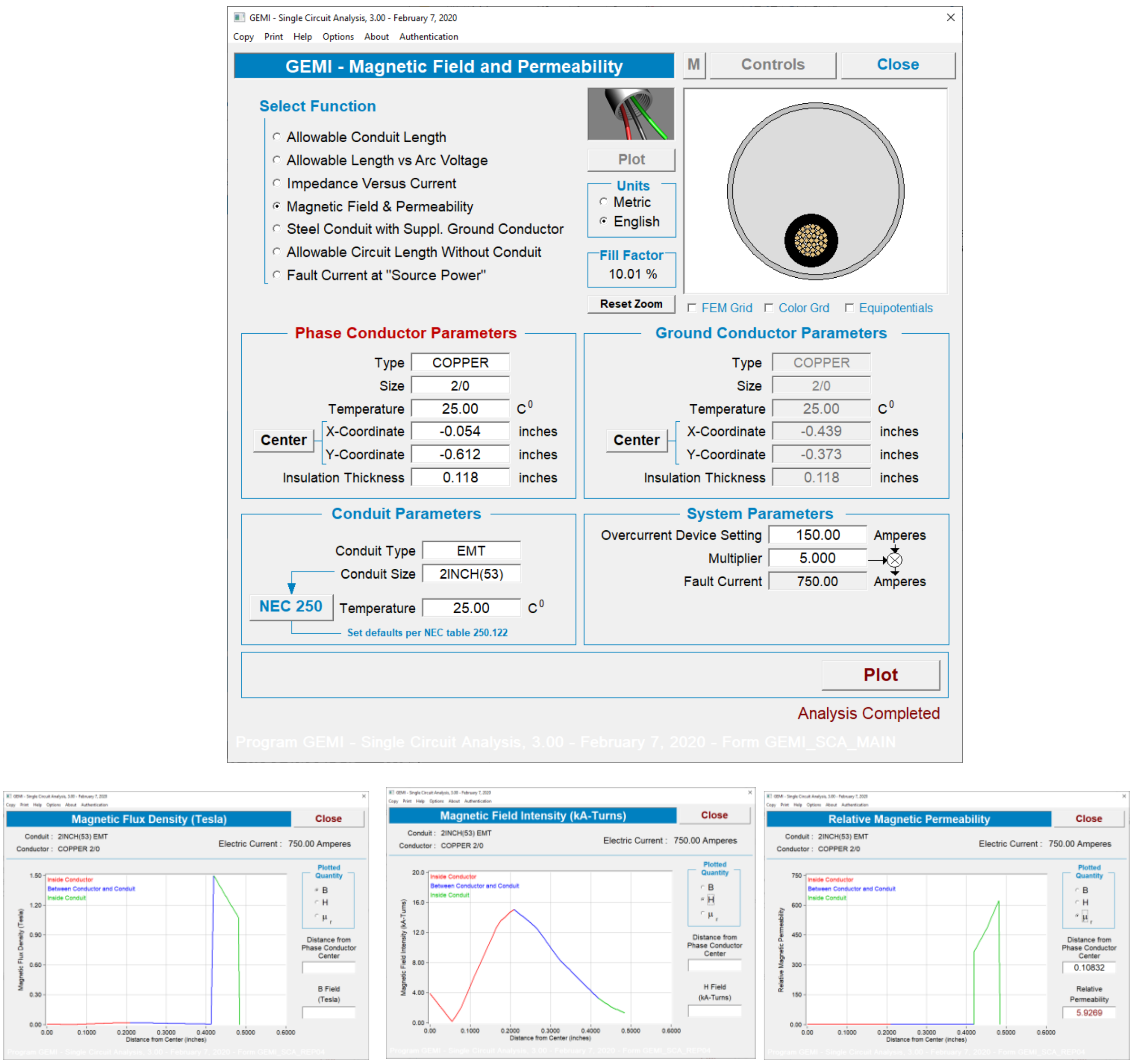


Figure 6.1: Magnetic Field and Permeability Function

7. Steel Conduit with Supplemental Ground Conductor

The Conduit with Supplemental Ground Conductor function computes the maximum length of a steel conduit enclosed circuit equipped with a supplemental ground conductor that will ensure fault current is higher than a specified level

Input Data:

- Phase Conductor Type, Size and Temperature
- Conduit Type, Size and Temperature
- Ground Conductor Type, Size and Temperature
- Operating Voltage
- Arc Voltage
- Fault Current

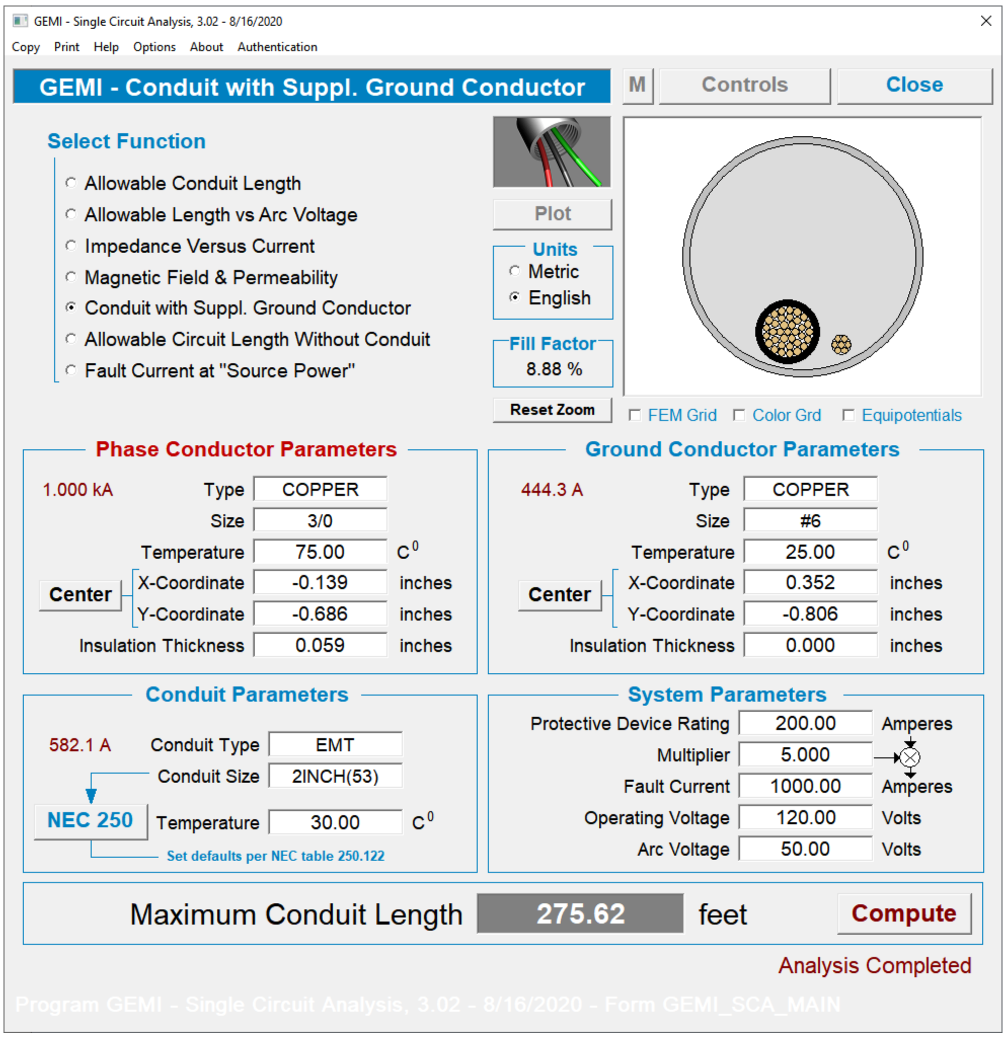


Figure 7.1: Steel Conduit with Supplemental Ground Conductor Function

8. Allowable Circuit Length without Conduit

The Allowable Circuit Length without Conduit function computes the maximum length of a circuit consisting of a phase and a ground conductor, which will ensure that the fault current is higher than a specified level.

Input Data:

Phase Conductor Type, Size and Temperature

- Ground Conductor Type, Size and Temperature
- Operating Voltage
- Arc Voltage
- Fault Current

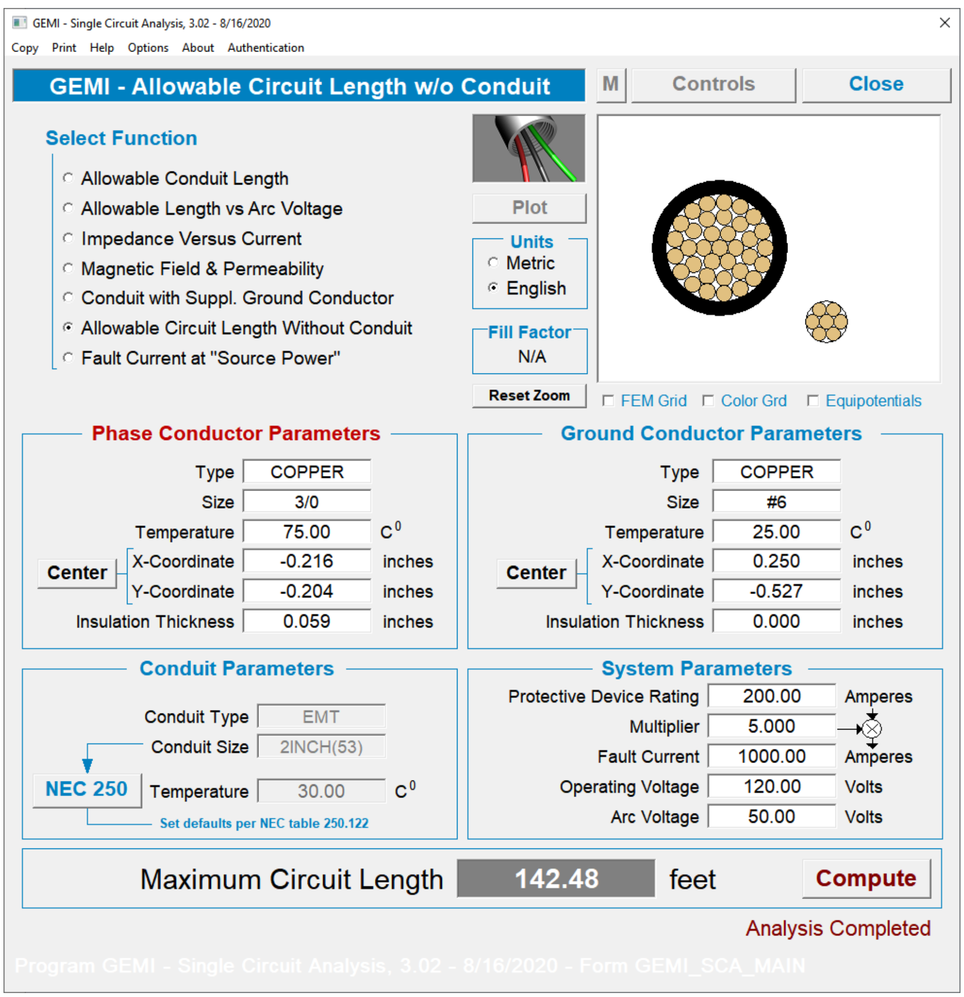


Figure 8.1: Allowable Circuit Length without Conduit Function

9. Fault Current at Source Power

The Fault Current at "Source Power" function computes the fault current of a steel conduit enclosed circuit of a user specified length, assuming the source has infinite capacity and there is a fault at the end of the circuit with user defined fault parameters (arc voltage).

Input Data:

- Phase Conductor Type, Size and Temperature
- Conduit Type, Size and Temperature
- Circuit Length
- Operating Voltage
- Arc Voltage

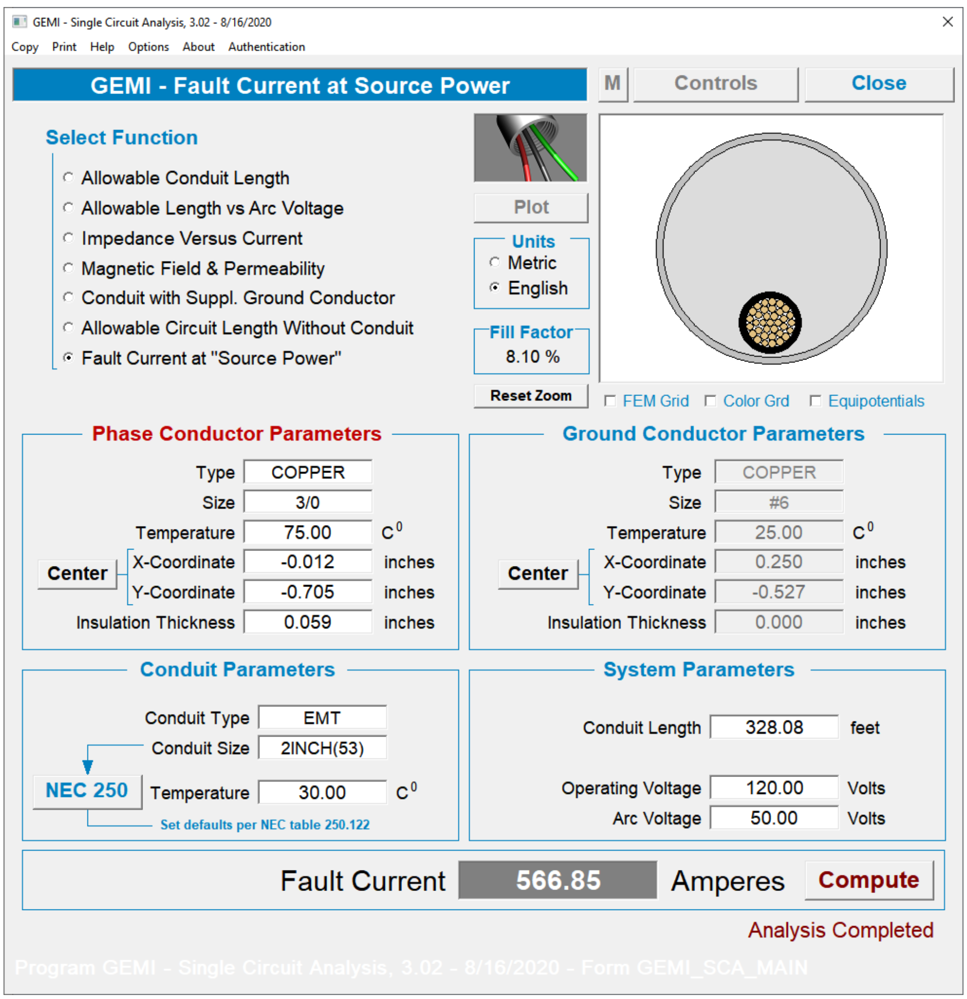


Figure 9.1: Fault Current at Source Power Function

Appendix A: Conductor Library

The GEMI program includes a comprehensive conductor library which provides electrical parameters for a large number of commercially available conductors. The conductor selection window (shown below) opens by double click on a conductor image shown in the GEMI main window or by clicking on the conductor type entry field located in the phase conductor and ground conductor control groups.

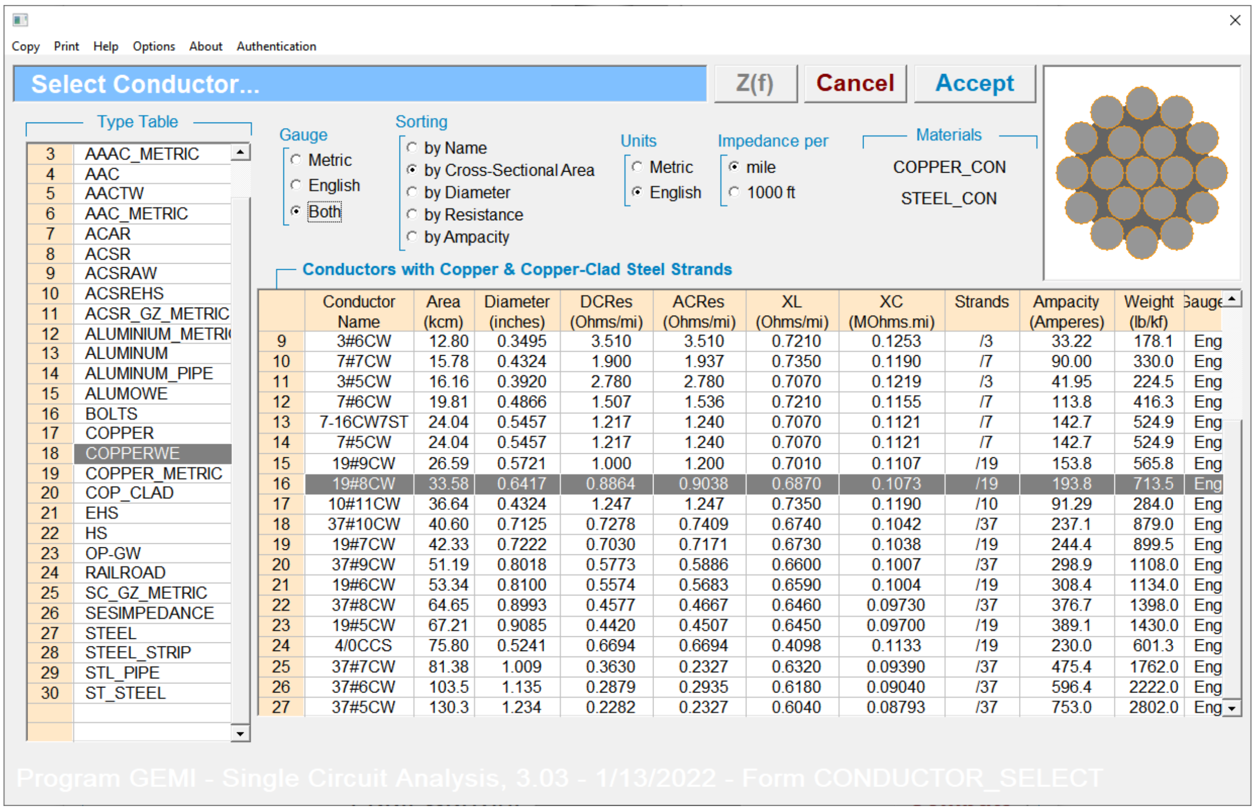


Figure 10.1: Conductor Selection Window

To select a conductor, first click on a “Conductor Type” listed in the conductor type column, then click on the desired conductor size listed on the table located to the right of the type table.

Note that the conductor size table can be sorted by name, cross-sectional area, diameter, resistance, and ampacity, using the radio buttons under the “Sorting” heading. Additional radio buttons (Units and Impedance headings) allow displaying the conductor parameters in metric or English units.

Appendix B: Steel Conduit Parameters

The conduit types and sizes included in the GEMI program library are listed in Tables B1 through B4. Furthermore, the steel permeability parameters for EMT, IMC, and GRC type steel conduits are listed. The measurement methodology used to obtain the permeability data is briefly described.

Table B1: EMT Steel Conduit Data

#	Size	Inner Diameter (inches)	Outer Diameter (inches)	Resistance (Ohms/mile)
1	1/2IN(16)	0.622	0.706	3.95360
2	3/4IN(21)	0.824	0.922	2.57750
3	1INCH(27)	1.049	1.163	1.74890
4	1-1/4IN(35)	1.380	1.510	1.17390
5	1-1/2IN(41)	1.610	1.740	1.01270
6	2INCH(53)	2.067	2.197	0.79560
7	2-1/2IN(63)	2.731	2.875	0.54630
8	3INCH(78)	3.356	3.500	0.44670
9	3-1/2IN(91)	3.834	4.000	0.33910
10	4INCH(103)	4.334	4.500	0.30070

Table B2: GRC Steel Conduit Data

#	Size	Inner Diameter (inches)	Outer Diameter (inches)	Resistance (Ohms/mile)
1	1/2IN(16)	0.632	0.840	1.69990
2	3/4IN(21)	0.836	1.050	1.28960
3	1INCH(27)	1.063	1.315	0.86850
4	1-1/4IN(35)	1.394	1.660	0.64070
5	1-1/2IN(41)	1.624	1.900	0.53510
6	2INCH(53)	2.083	2.375	0.39980
7	2-1/2IN(63)	2.489	2.875	0.25140
8	3INCH(78)	3.090	3.500	0.19260
9	3-1/2IN(91)	3.570	4.000	0.15990
10	4INCH(103)	4.050	4.500	0.13530
11	5INCH(129)	5.073	5.563	0.09990
12	6INCH(155)	6.093	6.625	0.07690

Table B3: IMC Steel Conduit Data

#	Size	Inner Diameter (inches)	Outer Diameter (inches)	Resistance (Ohms/mile)
1	1/2IN(16)	0.660	0.815	2.10190
2	3/4IN(21)	0.864	1.029	1.53850
3	1INCH(27)	1.105	1.290	1.08460
4	1-1/4IN(35)	1.448	1.637	0.81980
5	1-1/2IN(41)	1.683	1.882	0.67400
6	2INCH(53)	2.149	2.359	0.50750
7	2-1/2IN(63)	2.557	2.857	0.29590
8	3INCH(78)	3.176	3.476	0.24080
9	3-1/2IN(91)	3.671	3.971	0.20960
10	4INCH(103)	4.166	4.466	0.18560

Table B4: Stainless Steel Conduit Data

#	Size	Inner Diameter (inches)	Outer Diameter (inches)	Resistance (Ohms/mile)
1	3/8IN	0.493	0.675	14.46474
2	1/2IN	0.622	0.840	9.64763
3	3/4IN	0.824	1.050	7.26017
4	1IN	0.828	1.060	4.88985
5	1-1/4IN	1.380	1.660	3.61238
6	1-1/2IN	1.610	1.900	3.02078
7	2IN	2.067	2.375	2.24748
8	2-1/2IN	2.469	2.875	1.41720
9	3IN	3.090	3.500	1.08370
10	4IN	4.026	4.500	0.76085
11	5IN	5.073	5.563	0.59000
12	6IN	6.093	6.625	0.45400

Permeability Measurement

The permeability measurement for IMC, EMT and GRC materials was performed using samples of IMC, EMT and GRC conduits listed in Table B-5. Two windings were added on each sample, specifically, a primary winding distributed along the complete circumference, and a concentrated secondary winding. Figure B-1 illustrates the sample dimensions and the added windings. The primary winding was driven by a sinusoidal voltage source. The primary RMS winding current and the secondary RMS winding voltage were measured at various amplitudes, and the permeability parameters were derived from these measurements.

Table B-5: Conduit Sample Dimensions

#	Material	Size	Outside Diameter (d - inches)	Width (w - inches)	Height (h - inches)	Weight (g)	Turns Prim/Sec
1	EMT	2”	2.20”	0.068”	2.25”	123 g	84/20
2	IMC	2”	2.36”	0.111”	1.83”	174 g	88/20
3	GRC	2”	2.38”	0.145”	2.03”	255 g	90/20
4	Stainless Steel	1”	1.33”	0.138”	1.347”	110 g	44

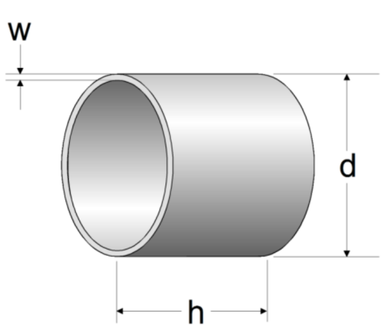


Figure B-1: Conduit Samples

The RMS V-I measurement data for IMC, EMT and GRC materials are listed in Tables R-3, R-4 nad R-5 respectively. Note that the Tables include:

- Primary winding current (column 2)
- Secondary winding voltage (column 3)
- Phase angle between voltage and current (column 4)
- Computed magnetic field intensity H (column 5)
- Computed magnetic flux density B (column 6)
- Computed relative permeability (column 7)

Note that the measurement of the V/I phase angle makes possible the separation of the hysteresis effect from the magnetic saturation effect. The magnetic field intensity H is computed from the measured RMS current using the formula:

$$H_{RMS} = \frac{N_1}{\pi(d-a)} I_{RMS} \sin(\theta)$$

where *a* and *d* are defined in the Figure below, N_1 is the number of primary turns and θ is the phase angle between voltage and current. *Note that the factor* ***sin(θ)*** *in the above equation removes the hysteresis effect from the permeability saturation model*.

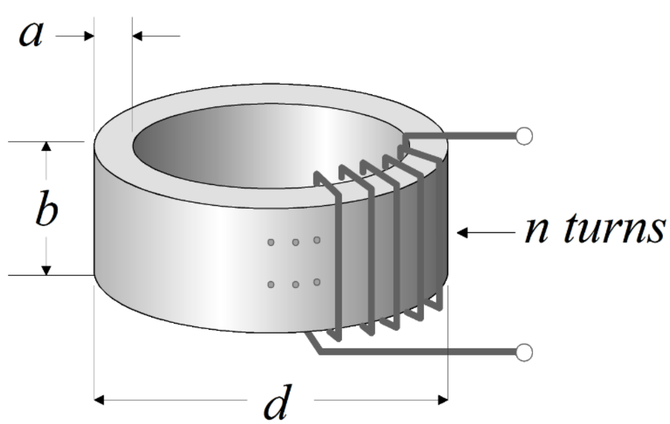


Figure B-2: Conduit Sample Geometric Data

The magnetic flux density B is computed from the measured RMS voltage using the formula:

$$B = \frac{V}{N_2 ab\omega}$$

where *a* and *d* are defined in the above Figure, N_2 is the number of secondary turns and ω is the excitation frequency.

Note also that:

$$v(t) = \frac{d}{dt}\lambda(t) = \frac{d}{dt}\frac{ab\mu_0\mu_{rel}N_1N_2 i(t)}{\pi(d-a)}$$

Assuming sinusoidal conditions, and converting to the frequency domain:

$$V = \frac{\omega ab\mu_0\mu_{rel}N_1N_2 I}{\pi(d-a)}$$

Or:

$$\mu_{rel} = \frac{\pi(d-a)\mathrm{V}}{\omega ab\mu_0 N_1 N_2 I}$$

The above formula can be used to compute the material permeability before saturation onset. Subsequently, multiple measurements were taken by increasing the excitation current to levels that ensured magnetic material saturation. The collected data were analyzed using a time domain model. The saturation curves were derived by minimizing the RMS error between measurement and model results. The saturation curves were expressed in terms of piece-wise linear/quadratic functions as illustrated in Figure A-3.

Figures A-4, through A-15 provide plots of the measurement data for IMC, EMT and GRC materials.

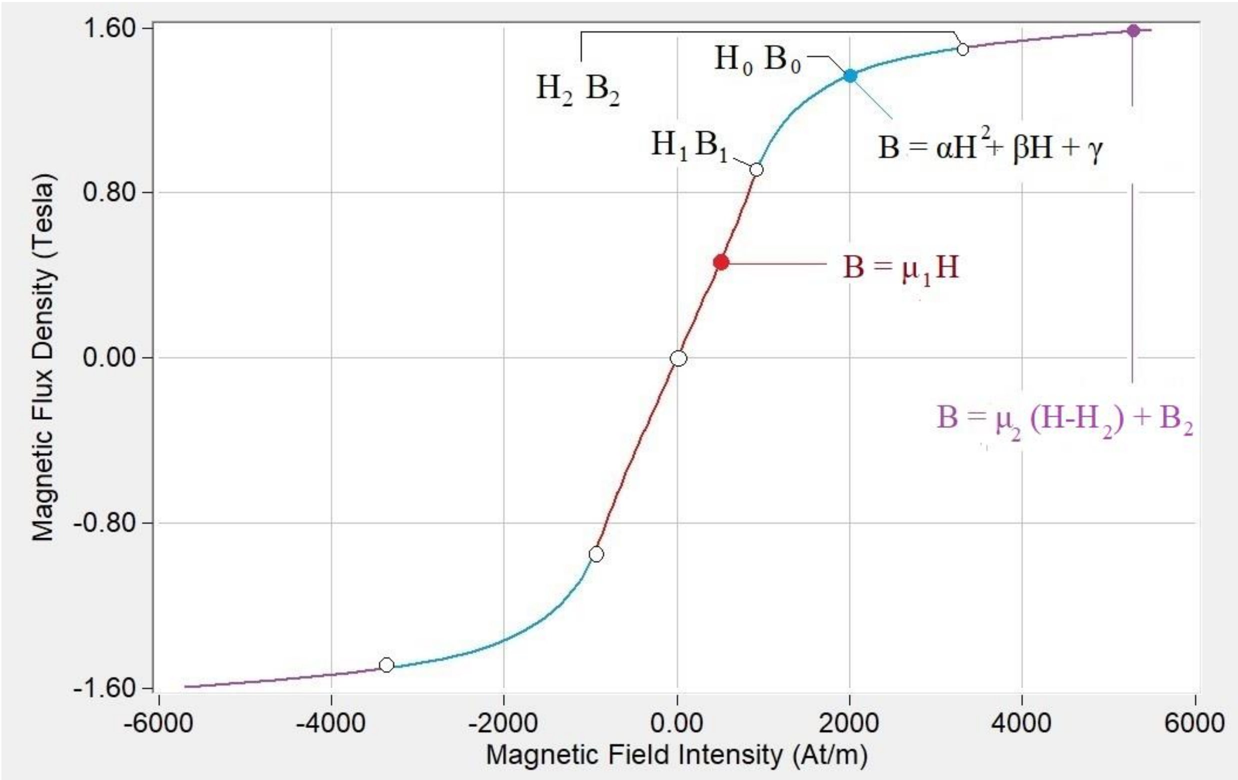


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Figure B-3: B versus H function definition

Table B-6: RMS Measurement Data for IMC Material

File #	**Current** (Arms)	**Voltage** (Vrms)	**Phase** (Degrees)	**H** At/m	**B** Tesla	**μ rel**
0	0.0000	0.0000	66.0000	0.00	0.00	N/A
1	0.2620	0.0358	49.6800	97.96	0.04	294.59
2	0.3660	0.0588	44.4000	125.58	0.06	376.96
3	0.5110	0.1020	38.1400	154.76	0.10	530.69
4	0.7520	0.1960	31.0200	190.04	0.20	830.44
5	0.8560	0.2300	30.1500	210.84	0.23	878.37
6	1.0610	0.2910	29.2000	253.84	0.29	923.08
7	1.2390	0.3370	28.9500	294.11	0.34	922.64
8	1.5570	0.4090	29.0500	370.76	0.41	888.26
9	1.7820	0.4540	29.2000	426.33	0.46	857.46
10	2.0810	0.5090	29.4400	501.59	0.52	817.09
11	2.2400	0.5370	29.4900	540.75	0.54	799.61
12	2.6300	0.6010	29.8400	641.75	0.61	754.08
13	2.8140	0.6300	29.9700	689.36	0.64	735.87
14	3.0920	0.6720	30.1500	761.58	0.68	710.49
15	3.5150	0.7340	30.4100	872.53	0.74	677.36
16	3.9600	0.7910	30.6700	990.58	0.80	642.97
17	4.4610	0.8540	31.0500	1128.36	0.86	609.42
18	4.9110	0.9110	31.6700	1264.43	0.92	580.13
18a	5.5380	1.0000	34.3700	1533.163	1.012	525.189
19	6.0180	1.0400	36.5000	1755.43	1.05	477.04
19a	6.5640	1.0920	39.4900	2047.07	1.10	429.53
20	7.0690	1.1190	41.5100	2297.49	1.13	392.18
21	8.2680	1.1790	46.2800	2930.34	1.19	323.97
22	9.1250	1.2160	48.8900	3371.56	1.23	290.41
23	10.2700	1.2600	51.0000	3913.97	1.27	259.21
24	12.0900	1.3060	52.9300	4730.63	1.32	222.29

Table B-7: RMS Measurement Data for EMT Material

File #	Current (Arms)	Voltage (Vrms)	Phase (Degrees)	H At/m	B Tesla	μ rel
0	0.136	0.014	66.40	58.61	0.02	211.74
0a	0.229	0.030	58.73	92.05	0.03	291.38
0b	0.292	0.045	54.15	111.30	0.05	355.74
0c	0.400	0.077	46.63	136.74	0.09	501.18
1	0.506	0.122	40.18	153.53	0.14	706.89
1a	0.748	0.220	34.50	199.24	0.25	982.26
2	1.012	0.329	32.45	255.35	0.37	1146.11
3	1.542	0.496	33.01	395.05	0.55	1116.88
4	2.029	0.619	35.83	558.55	0.69	985.83
5	2.527	0.716	40.97	779.16	0.80	817.45
6	3.040	0.779	46.19	1031.66	0.87	671.70
8	3.512	0.813	49.66	1258.85	0.91	574.50
9	4.082	0.849	52.57	1524.36	0.95	495.44
10	4.465	0.871	54.55	1710.48	0.97	452.97
11	4.950	0.895	56.47	1940.45	1.00	410.29
12	5.464	0.919	58.00	2179.08	1.03	375.16
13	5.953	0.938	59.23	2405.39	1.05	346.89
14	7.212	0.991	61.57	2982.52	1.11	295.57
15	8.251	1.032	63.04	3458.47	1.15	265.44
16	9.002	1.061	63.98	3804.23	1.19	248.10
17	10.260	1.106	65.30	4383.47	1.24	224.45

Table B-8: RMS Measurement Data for GRC Material

File #	Current (Arms)	Voltage (Vrms)	Phase (Degrees)	H At/m	B Tesla	μ rel
0	0.0000	0.0000	55.0000	0.00	0.00	
1	0.2640	0.0419	45.0900	94.35	0.03	246.96
2	0.3580	0.0626	41.5200	119.75	0.04	290.76
3	0.5100	0.1040	36.2600	152.22	0.07	380.04
4	0.7470	0.1860	30.1800	189.50	0.13	545.95
5	1.0270	0.2850	26.7200	233.02	0.20	680.30
6	1.2270	0.3490	25.7200	268.71	0.24	722.44
7	1.5050	0.4280	25.1400	322.65	0.30	737.86
8	1.7190	0.4820	25.0900	367.84	0.34	728.87
9	2.0590	0.5590	25.2600	443.38	0.39	701.28
10	2.5560	0.6570	25.7200	559.75	0.46	652.87
11	3.0320	0.7400	26.1500	674.32	0.52	610.41
12	3.4910	0.8140	26.5200	786.60	0.57	575.61
13	3.9850	0.8880	26.9000	909.83	0.62	542.89
14	4.6180	0.9760	27.3400	1070.28	0.68	507.24
15	5.0000	1.0260	27.5400	1166.63	0.72	489.19
16	5.9420	1.1410	27.9900	1407.26	0.80	450.99
17	7.1460	1.2730	28.5100	1721.23	0.89	411.38
18	8.1630	1.3700	30.0000	2059.65	0.96	369.99
19	10.260	1.575	33.38	2848.61	1.10	307.54
20	12.280	1.706	40.27	4005.59	1.19	236.90

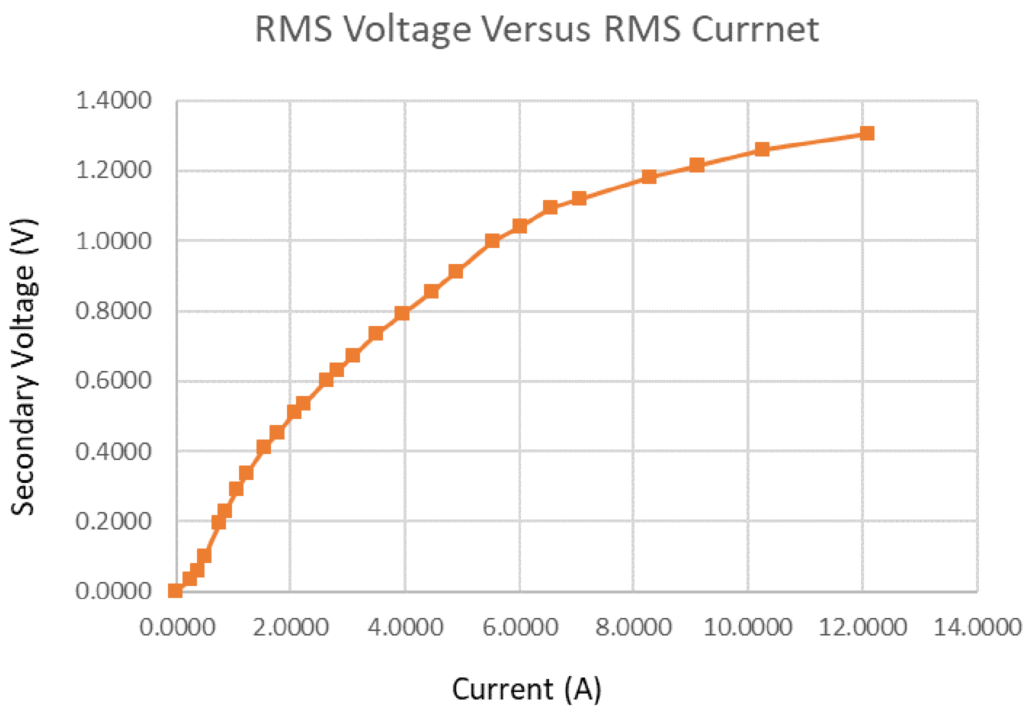

Figure B-4: RMS Voltage vs Current for IMC 2" Sample

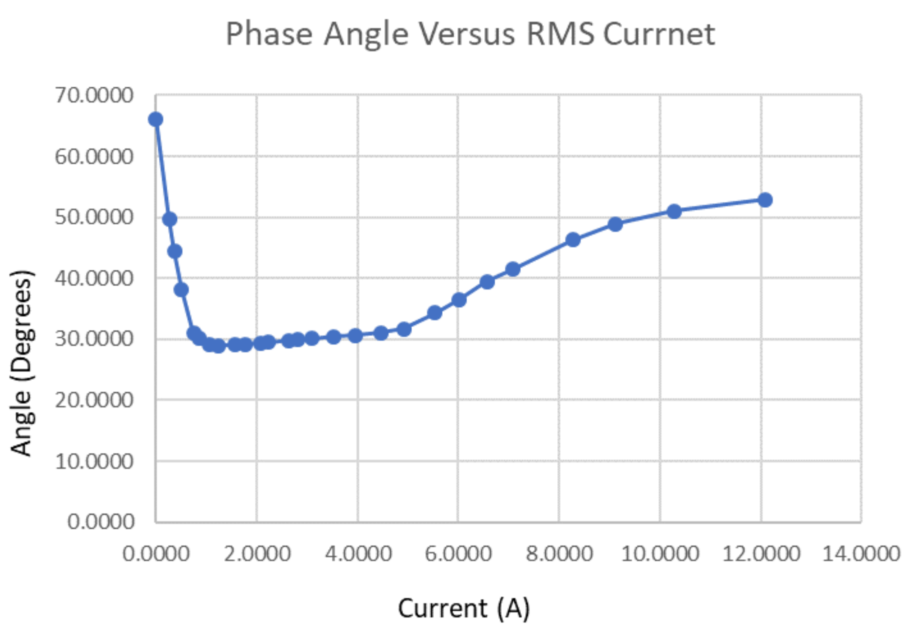

Figure B-5: V-I Phase Angle vs Current for IMC 2" Sample

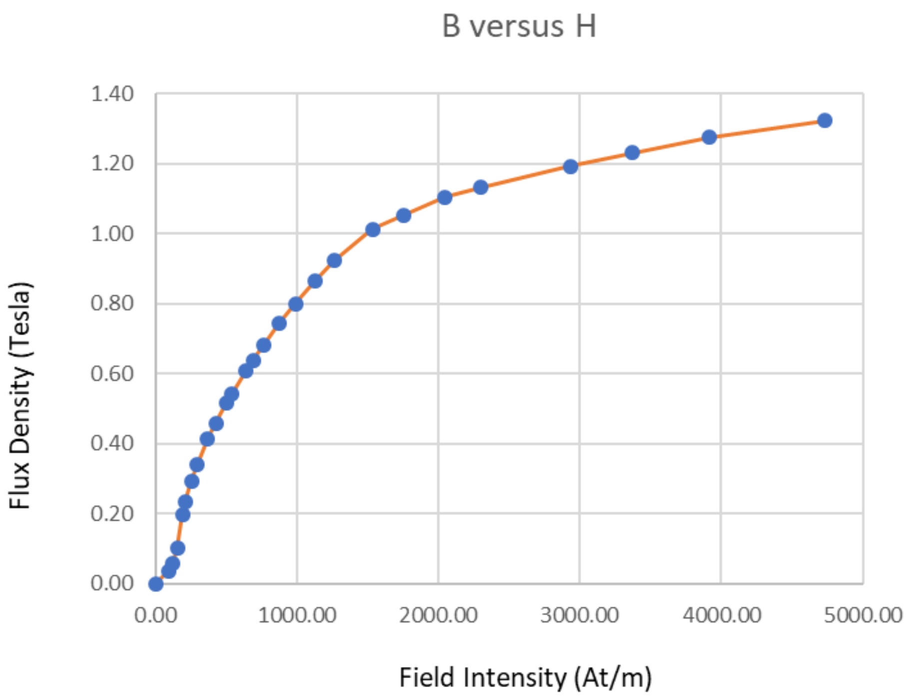

Figure B-6: B vs H for IMC 2" Sample

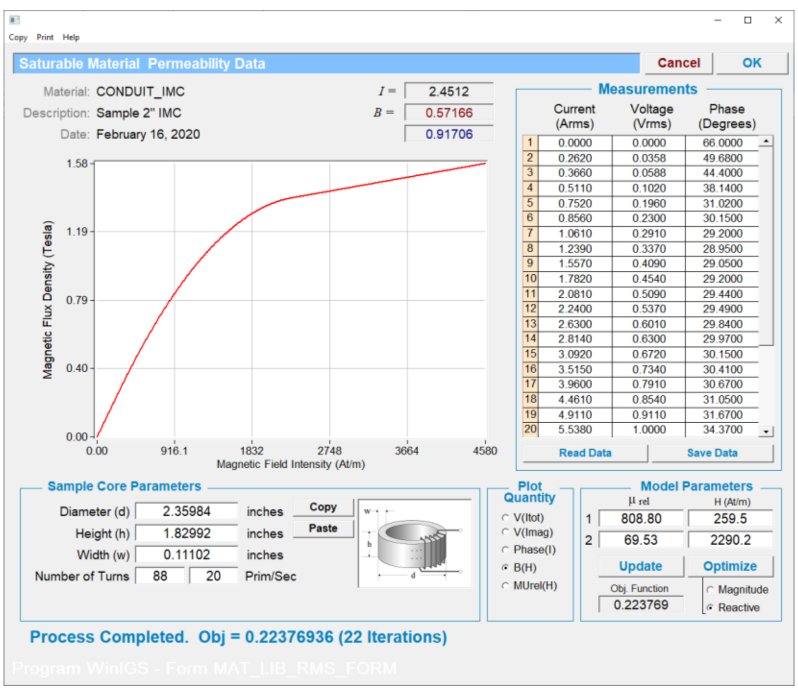

Figure B-7: PWLQ model of B vs H for IMC Material

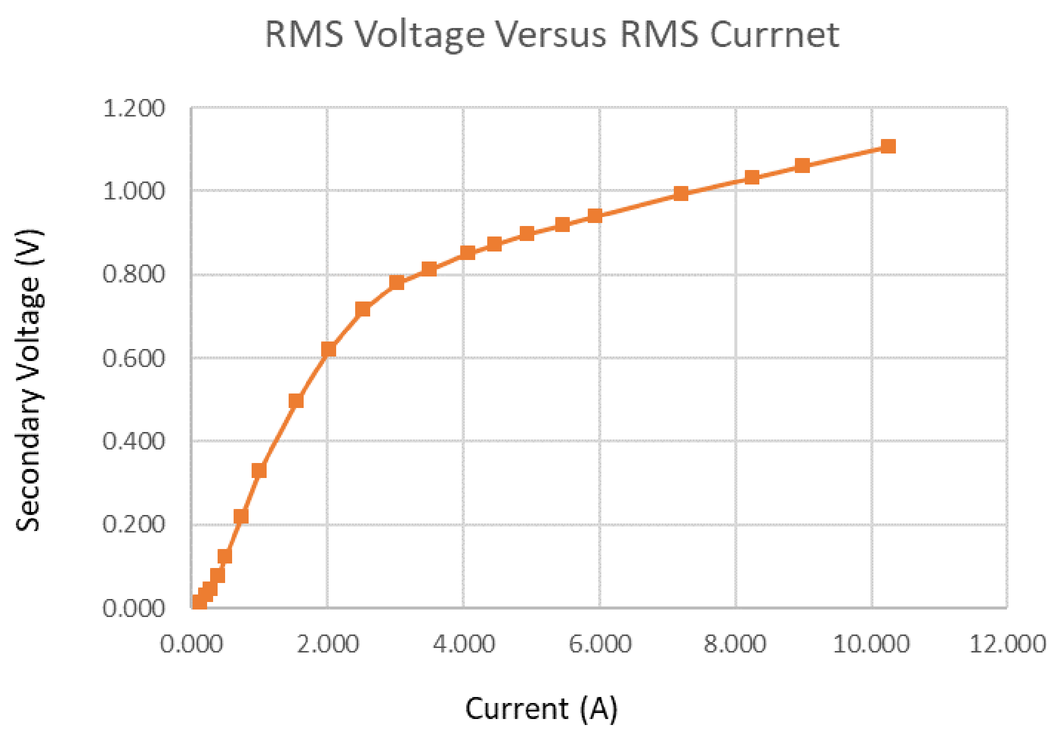

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Figure B-8: RMS Voltage vs Current for EMT 2” Sample

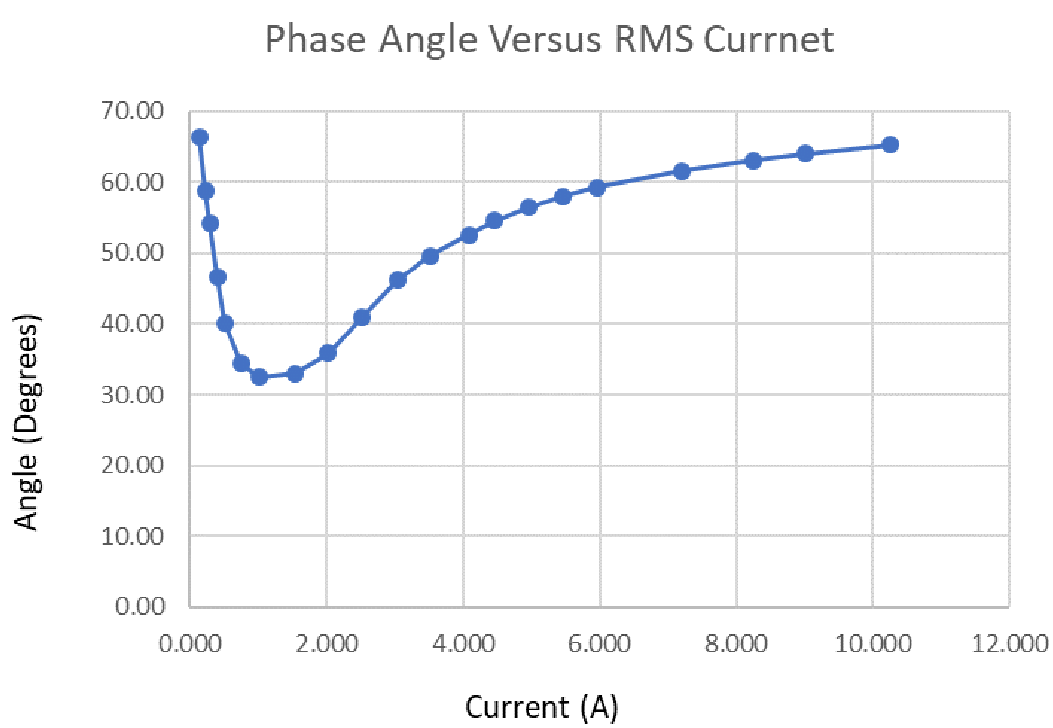


Figure B-9: V-I Phase Angle vs Current for EMT 2” Sample

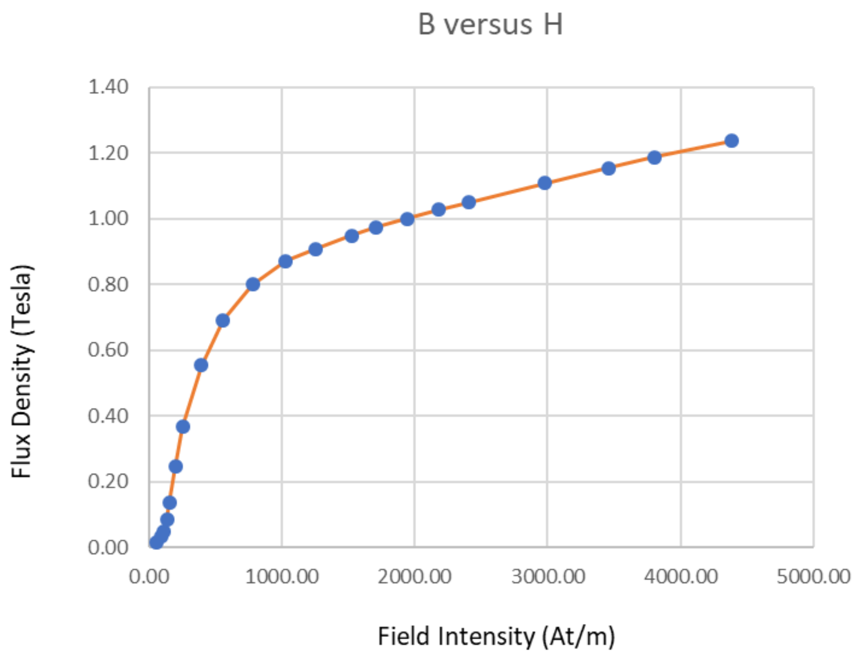


Figure B-10: B vs H for EMT 2" Sample

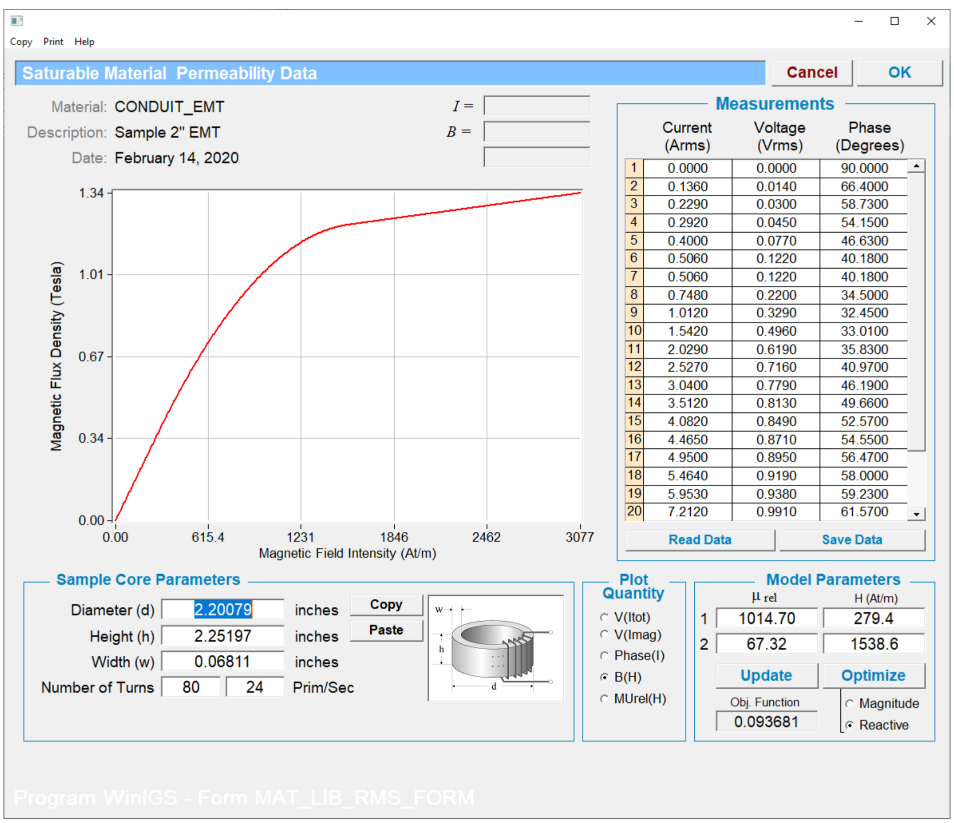


Figure B-11: PWLQ model of B vs H for EMT Material

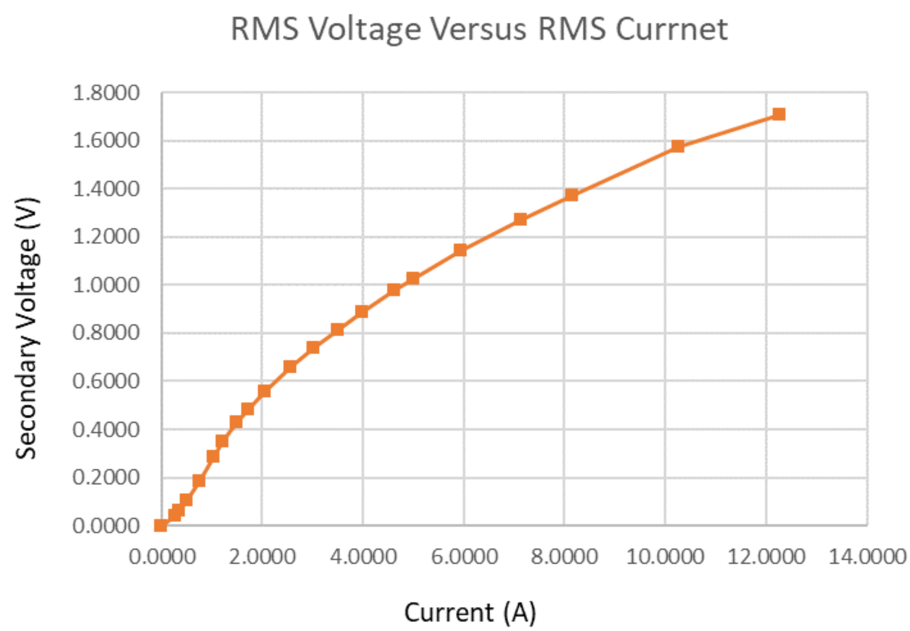


Figure B-12: RMS Voltage vs Current for GRC 2" Sample

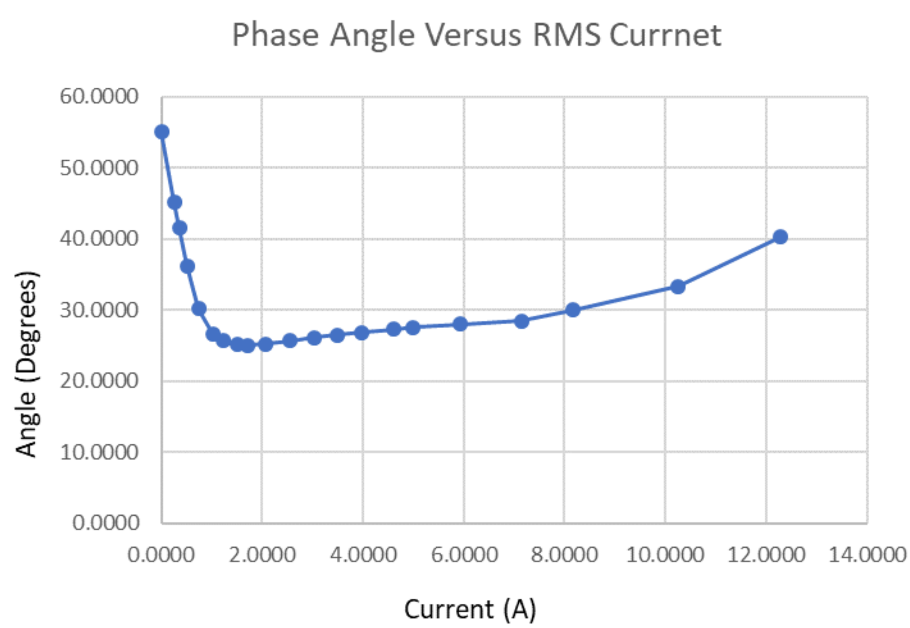


Figure B-13: V-I Phase Angle vs Current for GRC 2" Sample

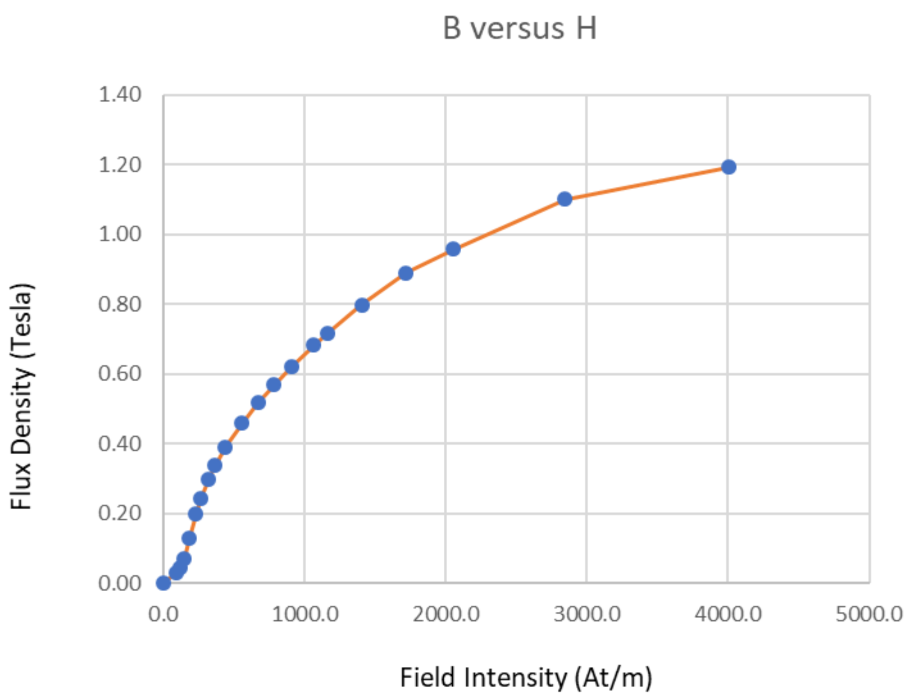


Figure B-14: B vs H for GRC 2" Sample

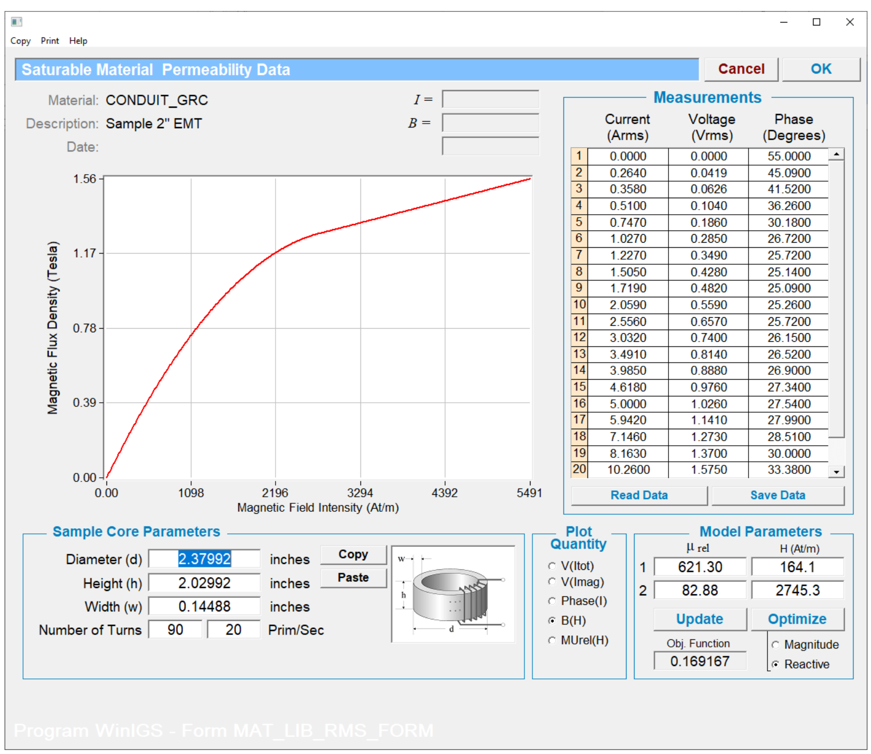


Figure B-15: PWLQ model of B vs H for GRC Material

Appendix C: Aluminum Conduit Data

The parameters of the aluminum conduit sizes included in the GEMI program library are listed in Table C1.

Table C1: Aluminum Conduit Data

#	Size	Inner Diameter (inches)	Outer Diameter (inches)	Resistance (Ohms/mile)
1	1/2INCH(16)	0.622	0.840	0.4010
2	3/4INCH(21)	0.824	1.050	0.3018
3	1INCH(27)	1.049	1.315	0.2033
4	1-1/4IN(35)	1.380	1.660	0.1502
5	1-1/2IN(41)	1.610	1.900	0.1256
6	2INCH(53)	2.067	2.375	0.0934
7	2-1/2IN(63)	2.469	2.875	0.0589
8	3INCH(78)	3.068	3.500	0.0450
9	3-1/2IN(91)	3.548	4.000	0.0375
10	4INCH(103)	4.026	4.500	0.0316
11	5INCH(128)	5.047	5.563	0.0233
12	6INCH(155)	6.065	6.625	0.0180

Appendix D: PVC Conduit Data

The parameters of the PVC conduit sizes included in the GEMI program library are listed in Table D1.

Table D1: PVC Conduit Data

#	Size	Inner Diameter (inches)	Outer Diameter (inches)
1	1/2INCH(16)	0.622	0.840
2	3/4INCH(21)	0.824	1.050
3	1INCH(27)	1.049	1.315
4	1-1/4IN(35)	1.380	1.660
5	1-1/2IN(41)	1.610	1.900
6	2INCH(53)	2.067	2.375
7	2-1/2IN(63)	2.469	2.875
8	3INCH(78)	3.068	3.500
9	3-1/2IN(91)	3.548	4.000
10	4INCH(103)	4.026	4.500
11	5INCH(128)	5.047	5.563
12	6INCH(155)	6.065	6.625

Appendix E: High Current Test Results

This Appendix summarizes the results of the high current conduit impedance measurements.

Table E-1: 3" EMT Conduit Tests – 500 kcm Phase & Neutral Conductor

#	Configuration	Current (A)	Voltage (V)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	345	3.159	9.159	52.2	20.17
2		1336	14.36	10.74	56.5	20.30
3		1981	25.71	12.98	60.37	20.58
4	P-N-C-G	1429	12.87	8.999	51.79	22.94
5		2300	25.27	10.99	55.59	24.19
6	P-C-G	1404	20.83	14.84	43.13	30.34
7		1763	26.24	14.89	43.36	30.74

Table E-2: 3" GRC Conduit Tests – 500 kcm Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	3.461	385.7	8.974	52.90	20.43
2		14.36	1413	10.16	56.54	20.43
3		25.81	2050	12.59	61.30	20.45
4	P-N-C-G	12.10	1420	8.515	56.91	20.58
5		25.26	2299	10.98	61.08	20.72
6	P-C-G	4.734	354.3	13.36	41.48	21.93
7		20.79	1395	14.89	45.49	22.08
8		26.33	1734	15.18	44.98	22.47
9	P-N-C (NG)	3.086	355.0	8.695	53.15	24.23
10		14.27	1428	9.985	56.10	24.33
11		25.39	2161	11.75	58.20	24.43
12	P-C (NG,FN)	12.89	350.3	**36.78**	29.43	24.99
13		27.65	1041.8	**26.55**	32.02	25.42
14		21.14	701.3	**30.15**	31.15	26.35

Table E-3: 3” IMC Conduit Tests – 500 kcm Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	3.308	368.1	8.987	55.17	20.96
2		14.93	1448	10.31	55.59	24.18
3		25.40	2029	12.51	60.48	24.26
4	P-N-C-G	11.39	1387	8.209	56.44	23.13
5		24.88	2302	10.81	61.07	23.47
6	P-C-G	4.629	361.2	12.81	46.70	20.97
7		20.60	1357	15.17	47.39	21.29
8		26.16	1720	15.20	47.08	21.77
9	P-N-C (NG)	2.955	357.6	8.266	51.57	25.04
10		13.54	1394	9.707	55.33	24.52
11		25.10	2160	11.62	58.02	24.66
12	P-C (NG,FN)	12.76	361.9	**35.25**	34.73	26.26
13		20.76	691.7	**30.01**	35.09	29.62
14		27.54	1053.9	**26.13**	35.93	27.79

Table E-4: 3" STAINLESS Conduit Tests – 500 kcm Phase & Neutral Conductor

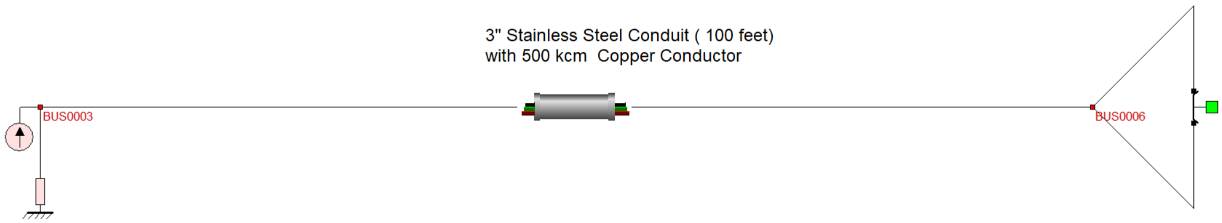
#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	2.668	351	7.599	49.02	21.29
2	P-N, C-G	11.68	1431	8.154	46.46	27.79
3	P-N, C-G	24.24	2489	9.738	52.29	28.05
4	P-N-C-G	9.793	1389	7.046	48.31	26.68
5	P-N-C-G	22.02	2574	8.552	53.68	27.00
6	P-C-G	4.028	344.9	11.68	35.07	21.31
7	P-C-G	17.34	1460	11.87	32.87	21.74
8	P-C-G	25.54	2009	12.71	29.43	24.56
9	P-N-C (NG)	2.513	339.4	7.406	43.67	29.09
10	P-N-C (NG)	10.90	1416	7.696	44.95	29.11
11	P-N-C (NG)	23.98	2597	9.233	50.12	29.26
12	P-C (NG,FN)	9.574	397	**24.12**	7.478	29.74
13	P-C (NG,FN)	27.43	1238	**22.15**	8.363	30.08

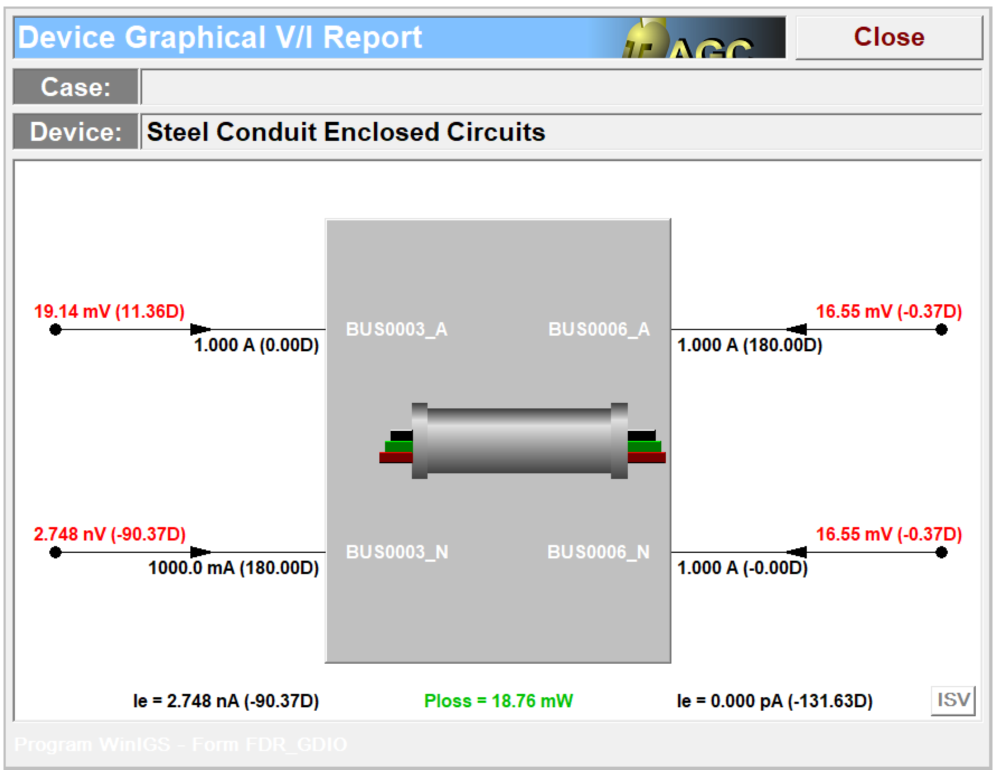
Comparison with Model

The WinIGS simulated conduit self-impedance for 100 ft conduit is 16.55 mΩ. Adding the estimated coupling impedance (at 0.56 mΩ per coupling x 9 couplings) yields:

$$Z_{model} = 16.55 + 9 \times 0.56\ m\Omega = \mathbf{21.59}\ m\Omega$$

The above is consistent with the measured value range of 22 – 24 mΩ.





WinIGS/GEMI Simulation Result

Table E-5: 2" EMT Conduit Tests – 3/0 Copper Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	3.223	201.5	16.00	30.5	20.85
2		14.52	793.6	18.30	39.56	20.91
3		26.71	1219.4	21.91	38.03	30.94
4	P-N-C-G	12.61	806.2	15.63	37.47	22.29
5		26.35	1423.0	18.52	42.30	27.86
6	P-C-G	6.571	205.6	31.96	23.72	22.95
7		23.42	789.6	29.67	27.68	25.90
8		27.52	968.4	28.42	26.92	25.44
9	P-N-C (NG)	3.231	207.1	15.61	28.72	41.13
10		14.27	1428.9	9.984	56.09	24.33
11		26.48	1374.7	19.27	38.27	32.92
12	P-C (NG,FN)	12.48	212.4	**58.76**	29.95	41.71
13		28.06	696.2	**40.29**	29.93	41.66
14		28.00	681.7	**41.08**	27.37	38.43

Table E-6: 2” GRC Conduit Tests – 3/0 Copper Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	3.288	204.9	16.05	31.26	20.33
2		14.00	800.8	17.48	36.94	20.35
3		26.65	1306.8	20.39	39.56	25.05
4	P-N-C-G	12.14	788.6	15.39	35.68	20.55
5		26.35	1477.4	17.84	42.61	24.39
6	P-C-G	6.643	201.3	33.01	20.13	21.12
7		23.98	766.1	31.30	24.09	21.48
8		27.64	893.0	30.95	24.05	23.33
9	P-N-C (NG)	3.157	205.0	15.40	30.93	31.69
10		13.78	798.6	17.26	36.03	31.54
11		26.55	1431.3	18.55	38.59	26.26
12	P-C (NG,FN)	12.47	214.8	**58.07**	26.07	32.02
13		28.11	674.0	**41.70**	27.59	30.41
14		28.25	690.1	**40.94**	24.77	27.12

Table E-7: 2" IMC Conduit Tests – 3/0 Copper Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	3.116	198.0	15.73	29.66	21.24
2		14.55	796.3	18.28	39.95	21.24
3		26.43	1273.3	20.76	39.95	27.79
4	P-N-C-G	12.23	795.9	15.37	36.43	21.64
5		26.11	1458.5	17.90	41.65	27.11
6	P-C-G	6.580	195.7	33.63	24.66	22.39
7		25.68	780.02	32.92	25.07	23.49
8		27.34	917.7	29.79	27.66	27.11
9	P-N-C (NG)	3.108	202.9	15.32	28.87	36.74
10		13.93	797.6	17.47	36.70	36.23
11		26.27	1358.3	19.34	37.15	29.07
12	P-C (NG,FN)	11.65	201.3	57.90	32.40	35.85
13		27.92	655.2	42.61	29.92	36.16
14		27.78	650.3	42.72	26.32	32.76

Table E-8: 1" EMT Conduit Tests – #4 Copper Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	2.291	42.74	53.62	9.839	21.16
2		9.420	172.4	54.63	9.958	21.13
3		24.87	374.8	66.35	9.879	21.52
4	P-N-C-G	7.630	155.2	49.16	10.16	29.78
5		27.12	466.4	58.15	9.479	33.84
6	P-C-G	18.32	229.4	79.87	12.73	46.21
7		28.49	337.6	84.39	12.85	47.91
8		28.37	390.07	72.60	13.40	37.68
9	P-N-C (NG)	3.846	82.83	46.45	11.95	22.84
10		11.50	233.2	49.34	11.74	22.92
11		23.79	453.2	52.51	12.92	23.37
12	P-C (NG,FN)	9.859	82.27	120.0	24.55	27.05
13		22.45	237.6	94.50	23.08	28.61
14		28.69	311.4	92.13	21.10	33.49

Table E-9: 1” GRC Conduit Tests – #4 Copper Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	4.626	83.89	55.14	9.426	20.25
2		13.35	235.3	56.74	10.32	20.27
3		27.91	411.5	67.83	10.84	30.76
4	P-N-C-G	10.74	237.7	45.19	11.02	20.62
5		24.50	453.7	54.01	11.77	27.19
6	P-C-G	5.737	83.81	68.45	12.03	21.69
7		16.32	237.0	68.88	12.52	21.75
8		28.08	385.8	72.78	13.51	23.18
9	P-N-C (NG)	4.608	87.26	52.81	10.44	35.53
10		13.09	240.1	54.53	10.62	35.07
11		26.72	464.1	57.58	12.60	34.18
12	P-C (NG,FN)	11.08	82.54	134.0	20.99	36.58
13		24.46	236.7	103.0	21.04	36.36
14		28.45	293.5	96.92	20.80	35.63

Table E-10: 1” IMC Conduit Tests – #4 Copper Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	4.785	86.51	55.31	9.665	20.82
2		13.40	233.9	57.29	10.37	21.07
3		27.69	416.6	66.47	11.07	34.19
4	P-N-C-G	10.30	232.1	44.37	11.38	21.73
5		24.48	473.4	51.72	12.50	31.31
6	P-C-G	4.962	80.67	61.51	14.53	22.40
7		16.40	234.9	69.82	13.16	22.66
8		28.33	357.8	79.16	12.94	26.32
9	P-N-C (NG)	3.823	78.39	48.78	11.54	35.51
10		12.65	239.3	52.88	11.59	34.94
11		26.79	485.7	55.15	13.38	35.80
12	P-C (NG,FN)	9.723	80.61	121.0	22.80	36.63
13		24.77	240.7	103.0	21.04	36.02
14		28.44	291.3	97.63	21.23	36.63

Table E-11: 1” Stainless Steel Conduit Tests – #4 Copper Phase & Neutral Conductor

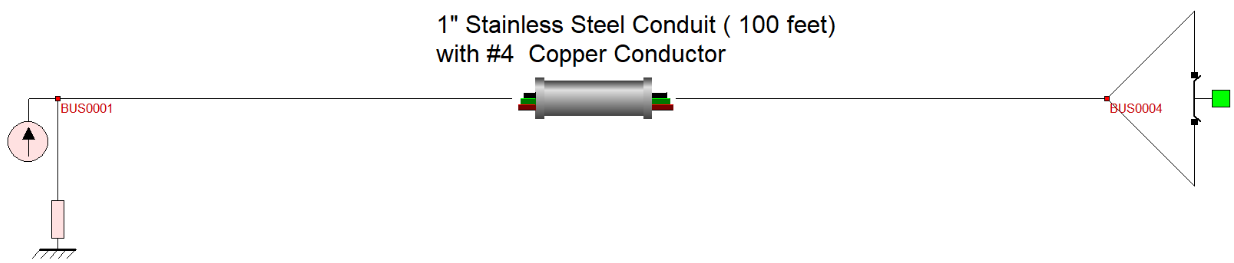
#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	4.549	82.47	55.16	7.543	21.31
2		13.45	237.6	56.61	7.670	21.32
3		28.06	428.9	65.42	7.627	27.07
4	P-N-C-G	11.00	239.9	45.87	7.354	21.77
5		23.87	473.4	50.43	7.561	25.17
6	P-C-G	6.367	84.03	75.77	5.090	22.13
7		16.88	234.0	75.12	4.860	22.33
8		28.23	385.3	73.26	4.683	23.65
9	P-N-C (NG)	4.711	85.59	55.04	6.499	32.48
10		12.79	233.9	54.69	6.432	32.14
11		26.62	465.7	57.16	6.867	29.82
12	P-C (NG,FN)	11.53	79.27	146.0	1.715	32.75
13		19.59	150.2	130.0	1.982	32.78
14		28.65	232.2	123.0	2.116	31.49

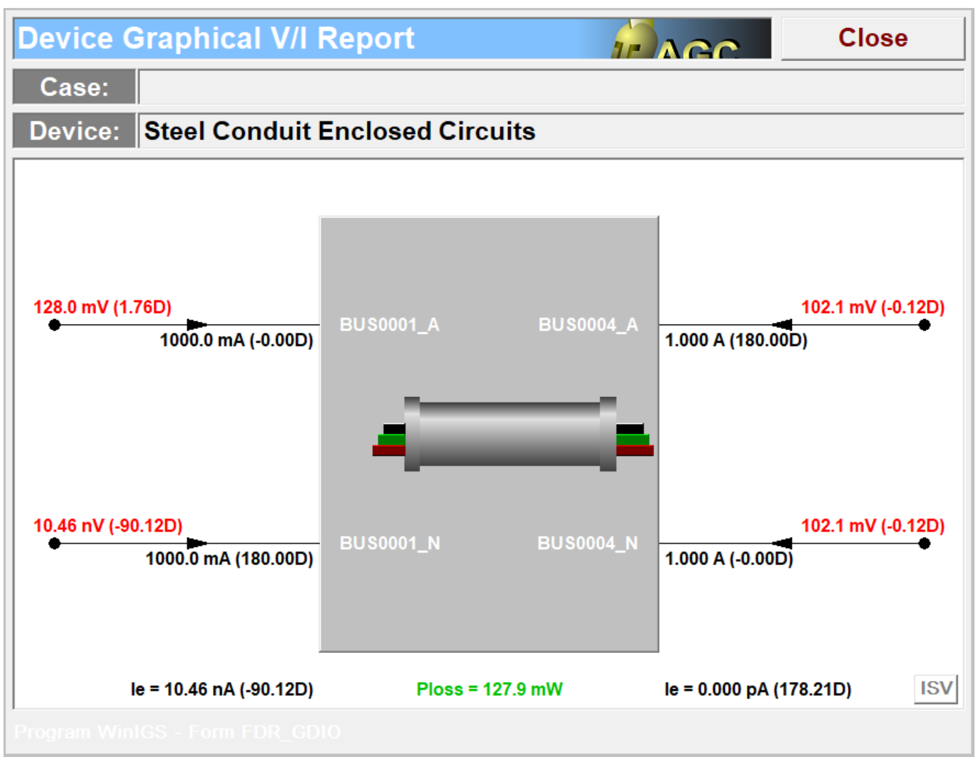
Comparison with Model

The WinIGS simulated conduit self-impedance for 100 ft. conduit is 16.55 mΩ. Adding the estimated coupling impedance (at 0.56 mΩ per coupling x 9 couplings) yields:

$$Z_{model} = 102.1 + 9 \times 1.26\ \text{m}\Omega = \mathbf{113.45}\ \text{m}\Omega$$

The above is near the measured value range of 123 – 146 mΩ.





WinIGS/GEMI Simulation Result

Table E-12: ¾" EMT Conduit Tests – #8 Copper Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	5.411	36.63	137.0	3.494	20.63
2		21.34	147.3	145.0	4.145	20.84
3		27.41	177.1	155.0	4.283	22.10
4	P-N-C-G	18.07	156.9	115.0	5.770	26.03
5		18.07	156.9	115.0	5.770	26.03
6	P-C-G	21.34	144.4	148.0	9.385	38.45
7		27.34	180.6	151.0	9.299	41.40
8	P-C-IG	19.67	142.9	138.0	7.299	29.91
9		27.00	194.1	139.0	7.560	35.08

Table E-13: ¾” GRC Conduit Tests – #8 Copper Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	5.831	43.05	135.0	3.906	19.87
2		21.99	151.9	145.0	4.467	19.91
3		28.13	183.2	154.0	4.553	20.23
4	P-N-C-G	17.21	159.9	108.0	5.736	22.69
5		26.33	243.1	108.0	6.251	23.79
6	P-C-G	5.976	44.68	134.0	8.352	24.85
7		21.38	162.2	132.0	8.639	25.10
8		28.19	212.0	133.0	8.819	25.63
9	P-N-C (NG)	5.014	43.52	115.0	7.168	25.99
10		18.86	156.8	120.0	6.982	25.84
11		27.90	220.2	127.0	7.449	26.12
12	P-C (NG,FN)	8.781	43.35	203.0	17.15	27.51
13		25.35	152.1	167.0	16.44	27.87
14		28.40	174.1	163.0	16.17	28.65

Table E-14: ¾" IMC Conduit Tests – #8 Copper Phase & Neutral Conductor

#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (⁰C)
1	P-N, C-G	5.656	41.22	137.0	3.752	20.66
2		22.28	152.7	146.0	4.433	20.87
3		28.06	187.8	149.0	4.848	21.39
4	P-N-C-G	16.57	153.1	108.0	5.981	24.11
5		27.79	249.9	111.0	6.548	25.40
6	P-C-G	5.296	42.44	125.0	10.56	26.86
7		21.66	163.9	132.0	9.463	27.03
8		28.17	208.5	135.0	9.386	27.38
9	P-N-C (NG)	4.654	42.85	109.0	8.635	27.16
10		18.78	158.9	118.0	7.797	26.92
11		24.94	203.7	122.0	7.919	26.91
12	P-C (NG,FN)	8.155	42.51	192.0	20.60	27.92
13		25.30	152.1	166.0	17.72	28.25
14		28.39	174.4	163.0	17.28	28.70

Table E-15: 3" Stainless-Steel Conduit Impedance Test Results

Test Configuration	(a)	(b)	(c)
Injected Current	165.4 A	218.6 A	142.7 A
Voltage Along Cable	0.295 V	0.592 V	0.207
Voltage Along Conduit	1.185 V	0.329 V	1.078
Total Circuit Voltage	1.443 V	–	–
Conduit Self-Impedance	7.159 mΩ	–	7.546 mΩ
Conductor Self-Impedance	1.764 mΩ	2.665 mΩ	–
Mutual-Impedance	–	1.457 mΩ	1.424 mΩ

Table E-16: 1" Stainless-Steel Conduit Impedance Test Results

Test Configuration	(a)	(b)	(c)
Injected Current	64.82 A	170.9 A	65.15 A
Voltage Along Cable	0.217 V	0.716 V	0.125 V
Voltage Along Conduit	1.459 V	0.320 V	1.475 V
Total Circuit Voltage	1.670 V	–	–
Conduit Self-Impedance	22.53 mΩ	–	22.64 mΩ
Conductor Self-Impedance	3.326 mΩ	4.180 mΩ	–
Mutual-Impedance	–	1.861 mΩ	1.860 mΩ