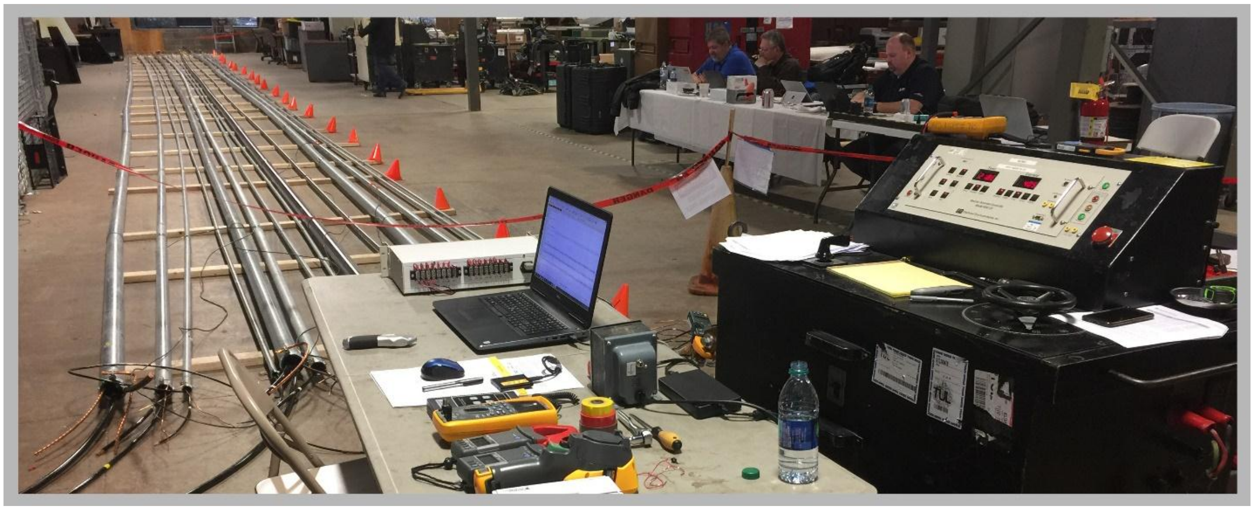
Technical Report

Steel Conduit Enclosed Power Circuit Testing



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Advanced Power Concepts

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1. Introduction

The test samples consist of 100 foot sections of steel conduit enclosed power circuits. Each 100 foot circuit consisted of one steel conduit, one phase conductor, one neutral conductor, one safety ground. All conductors were appropriately selected with respect to the conduit size. The set of circuits used are listed in Table A-1.

Table 1: List of Steel Conduit Enclosed Power Circuits

Circuit No.	Conduit	Phase Conductor	Neutral Conductor	Safety Ground	Test Current (Amperes)
1	EMT ¾	#8 Cu, Insu	#8 Cu, Insu	#10 Cu, bare	40/160/320
2	IMC ¾	#8 Cu, Insu	#8 Cu, Insu	#10 Cu, bare	40/160/320
3	GRC ¾	#8 Cu, Insu	#8 Cu, Insu	#10 Cu, bare	40/160/320
4	EMT 1-inch	#4 Cu, Insu	#4 Cu, Insu	#8 Cu, bare	80/240/480
5	IMC 1-inch	#4 Cu, Insu	#4 Cu, Insu	#8 Cu, bare	80/240/480
6	GRC 1-inch	#4 Cu, Insu	#4 Cu, Insu	#8 Cu, bare	80/240/480
7	Stainless Steel 1-inch	#4 Cu, Insu	#4 Cu, Insu	#8 Cu, bare	80/240/480
8	EMT 2-inch	3/0 Cu, Insu	3/0 Cu, Insu	#6 Cu, bare	200/800/1600
9	IMC 2-inch	3/0 Cu, Insu	3/0 Cu, Insu	#6 Cu, bare	200/800/1600
10	GRC 2-inch	3/0 Cu, Insu	3/0 Cu, Insu	#6 Cu, bare	200/800/1600
11	EMT 3-inch	500kcm, insu	500kcm, insu	#3 Cu, bare	350/1400/2800
12	IMC 3-inch	500kcm, insu	500kcm, insu	#3 Cu, bare	350/1400/2800
13	GRC 3-inch	500kcm, insu	500kcm, insu	#3 Cu, bare	350/1400/2800
14	Stainless Steel 3-inch	500kcm, insu	500kcm, insu	#3 Cu, bare	350/1400/2800

Each 100 foot circuit was supported by 2”x4” wood beams to avoid conduct with the concrete floor. Figure 1 illustrates the installation.

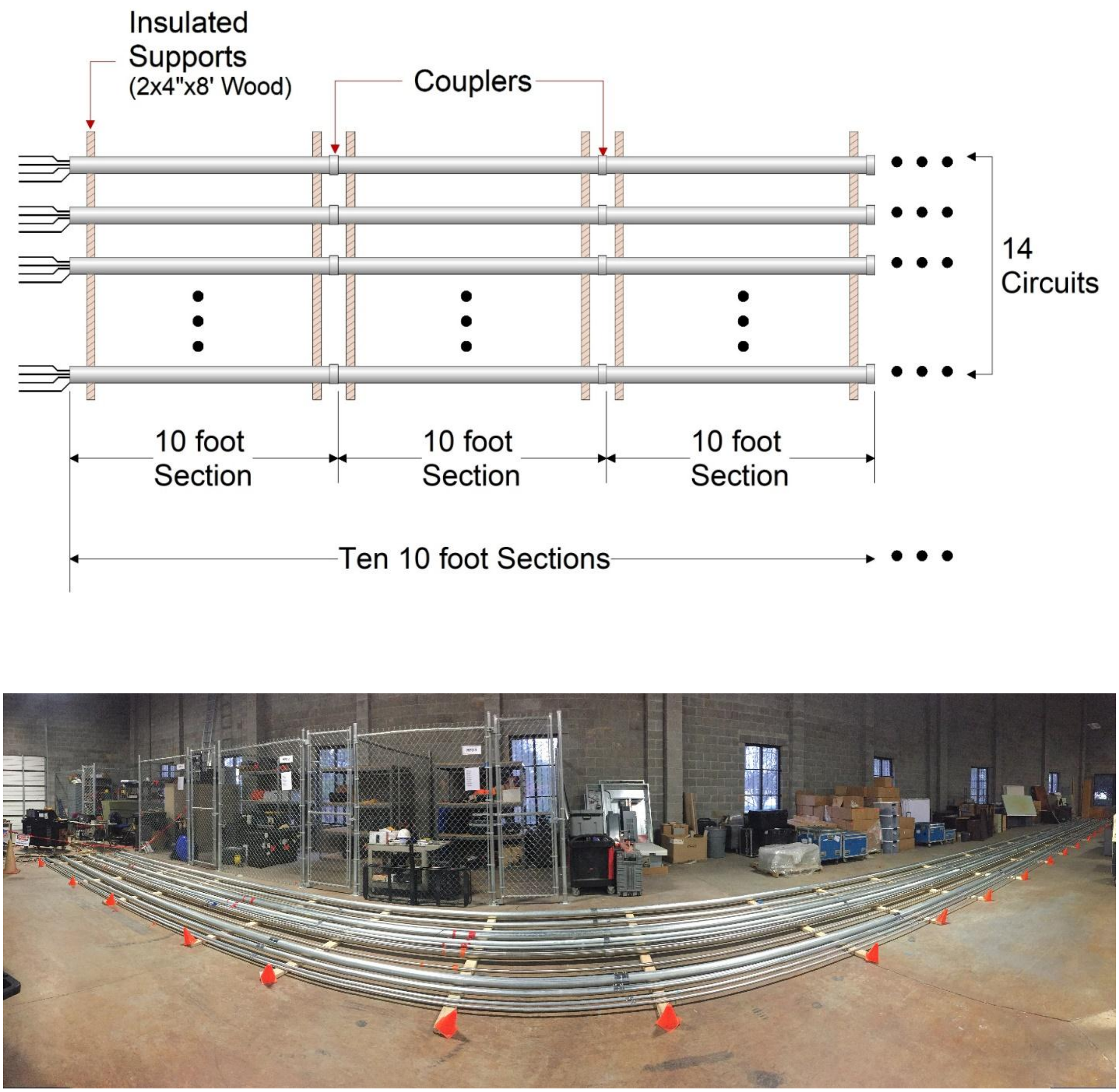


Figure 1: Installation of the Fourteen 100 ft Conduit Enclosed Circuits

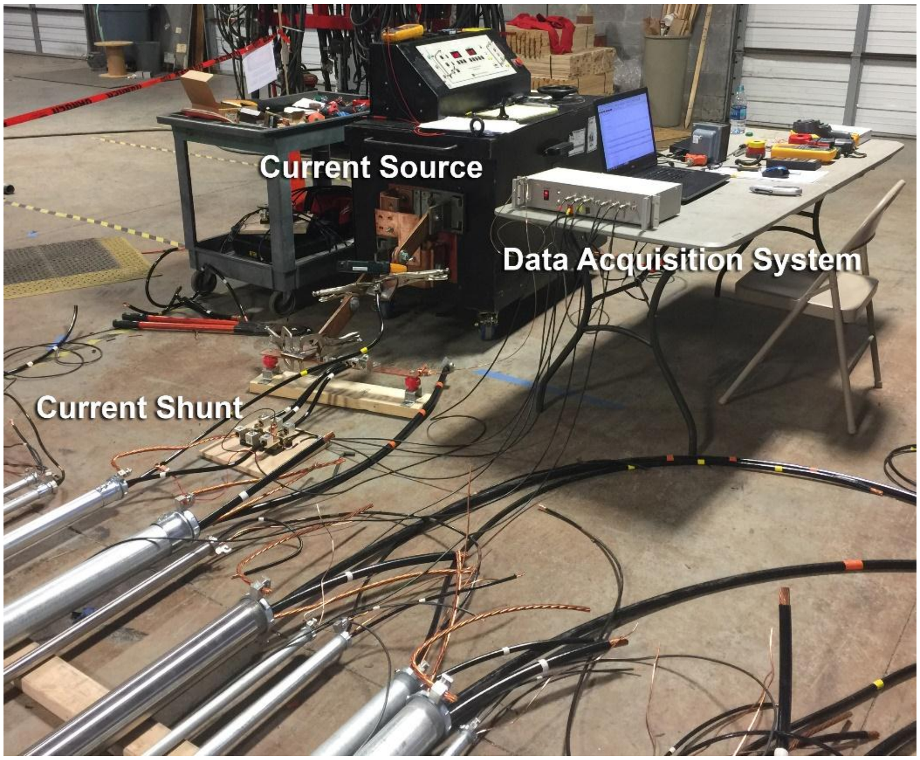


Figure 2: Test Setup

Figure 3: Current Source

Figure 4: Circuit Termination Ground Bar

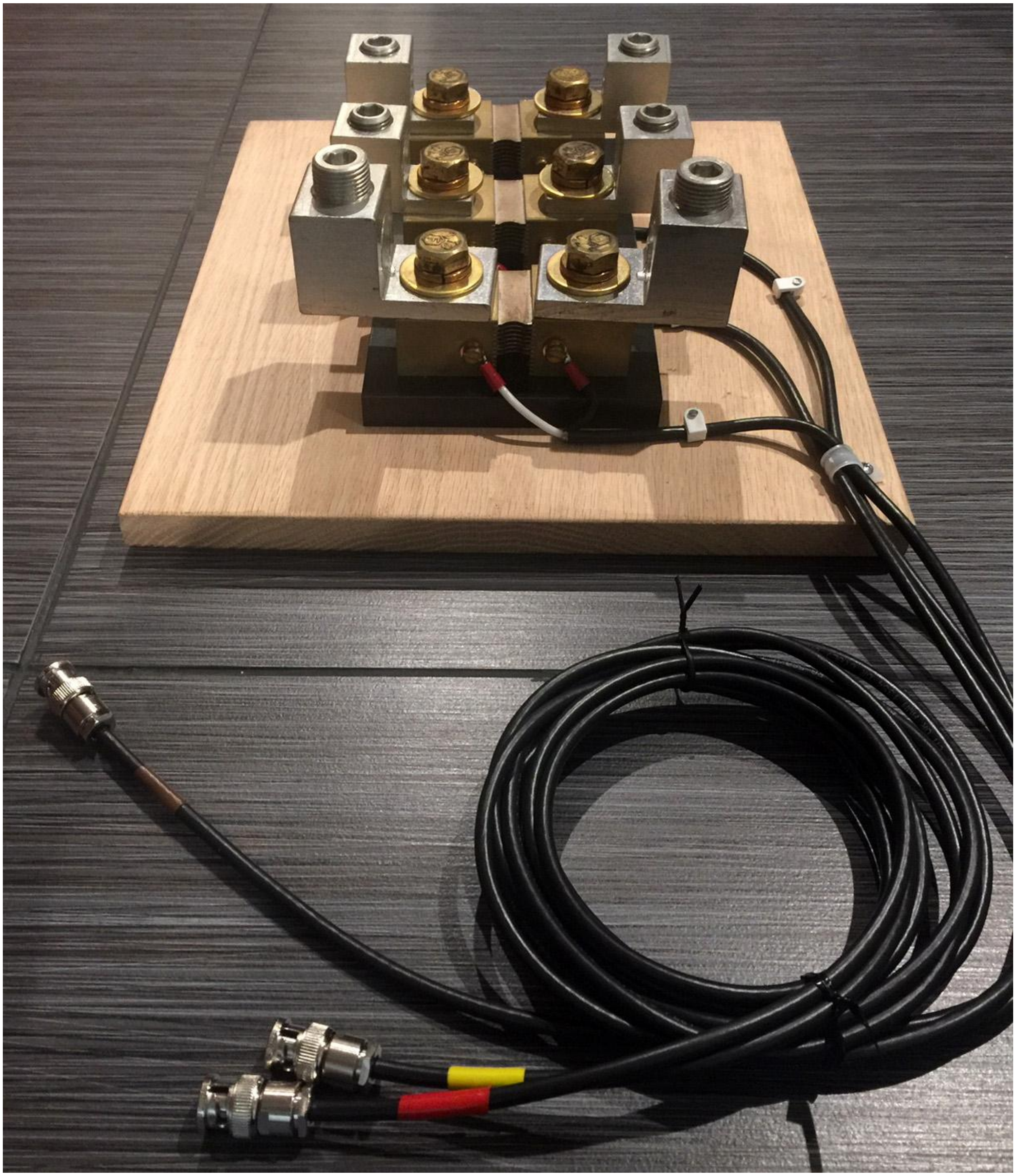


Figure 5: Current Shunt Arrangement (1500A, 50 mV)

Each 100-foot circuit was instrumented to measure: (a) the total voltage applied at the power circuit source side, (b) the electric currents through the conduit, neutral and safety ground, and (c) the conduit temperature at selected points along the conduit. Note that the phase conductor current does not need to be measured directly, since it can be computed as the sum of currents on the remaining conductors and conduit. Figure A-2 illustrates the instrumentation setup for each of the 14 circuits.

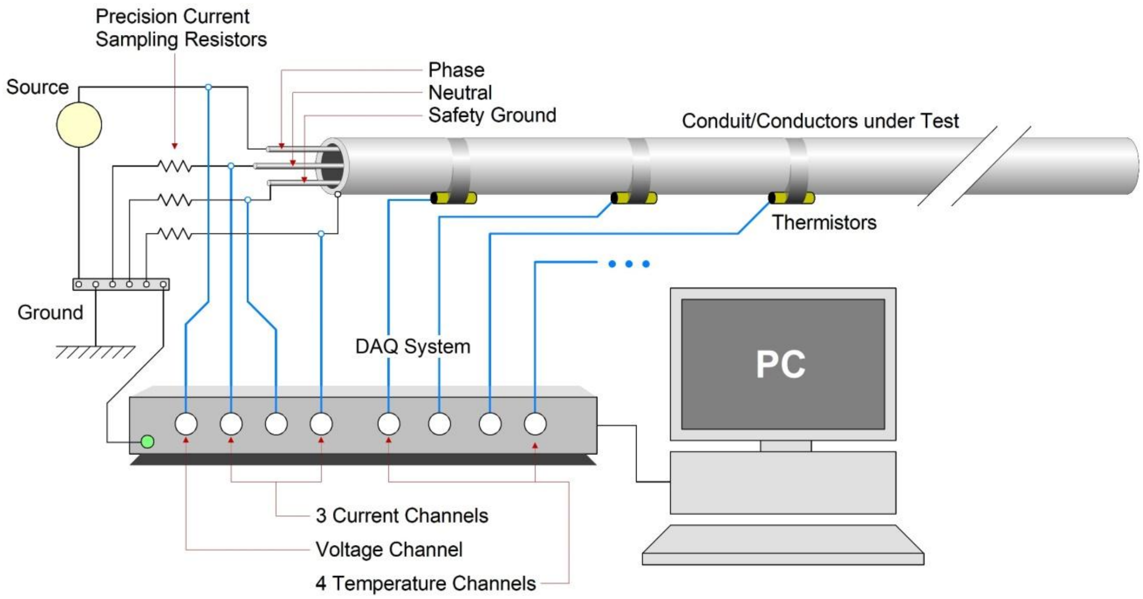


Figure 3: Test System

Precision Current Shunt Specifications

Current Rating	Voltage at Current Rating	Accuracy	Manufacturer Part Number
200 A	100 mV	0.25%	Crompton Instruments FH-200-100
500 A	100 mV	0.25%	Crompton Instruments FH-500-100
1500 A	50 mV	0.25%	Crompton Instruments FH-1500-50

2. Results Summary

Table 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 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 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 4: 3” STAINLESS Conduit Tests – 500 kcm Phase & Neutral Conductor

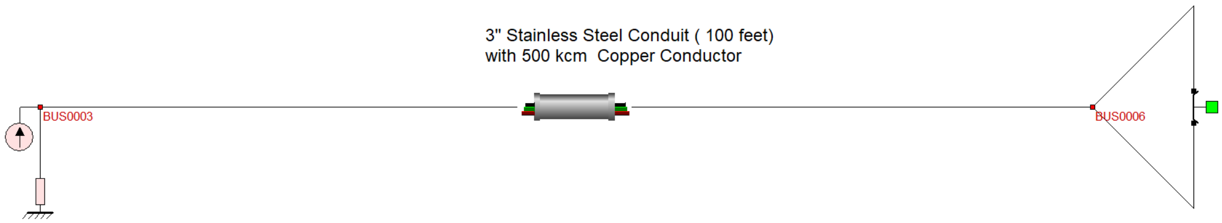
#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	2.668	351	7.599	49.02	21.29
2		11.68	1431	8.154	46.46	27.79
3		24.24	2489	9.738	52.29	28.05
4	P-N-C-G	9.793	1389	7.046	48.31	26.68
5		22.02	2574	8.552	53.68	27.00
6	P-C-G	4.028	344.9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

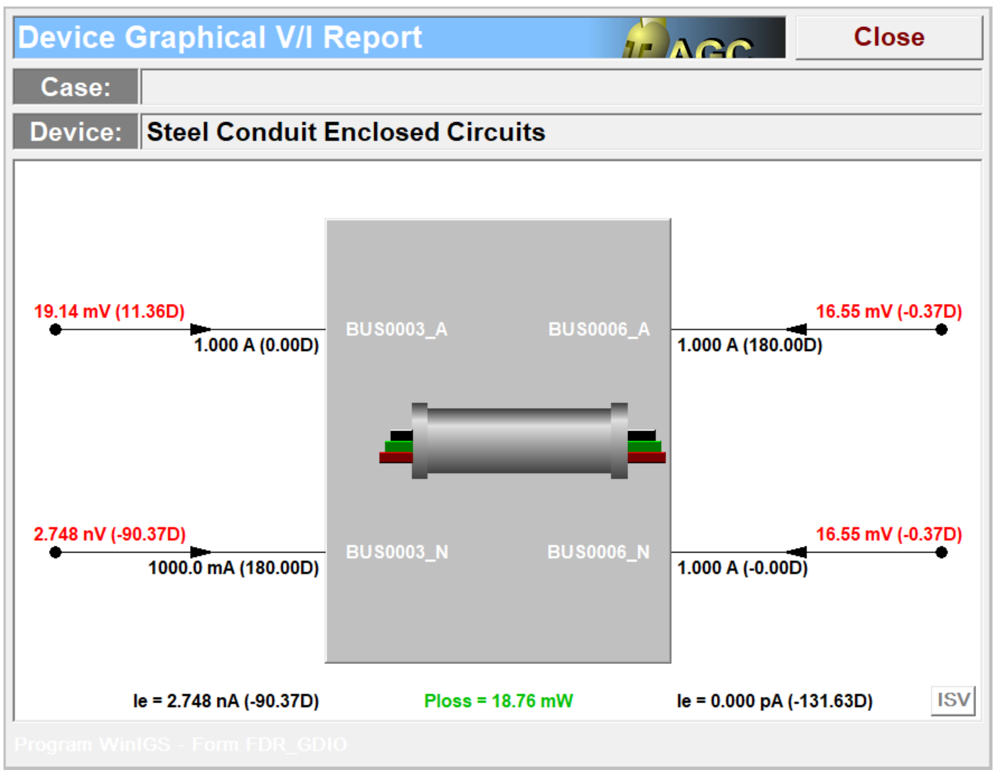
Comparison with Model

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:

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

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





WinIGS/GEMI Simulation Result

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

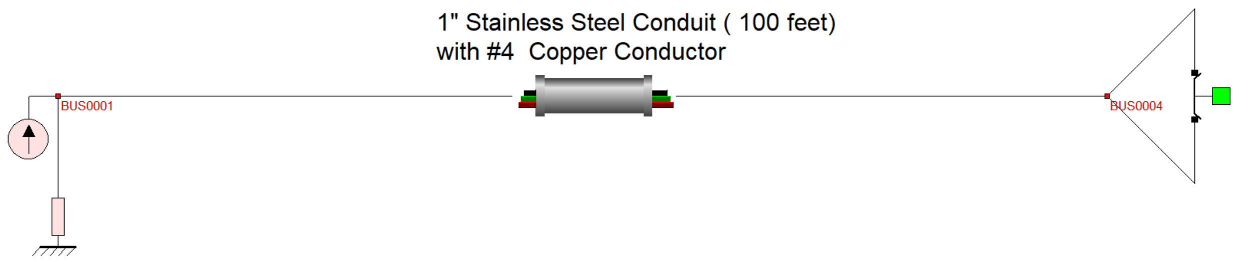
#	Configuration	Voltage (V)	Current (A)	Impedance Magnitude (mΩ)	Impedance Phase (Degrees)	Temperature (^{0}C)
1	P-N, C-G	4.549	82.47	55.16	7.543	21.31
2		13.45	237.6	56.61	7.670	21.32
3		28.06	428.9	65.42	7.627	27.07
4	P-N-C-G	11.00	239.9	45.87	7.354	21.77
5		23.87	473.4	50.43	7.561	25.17
6	P-C-G	6.367	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

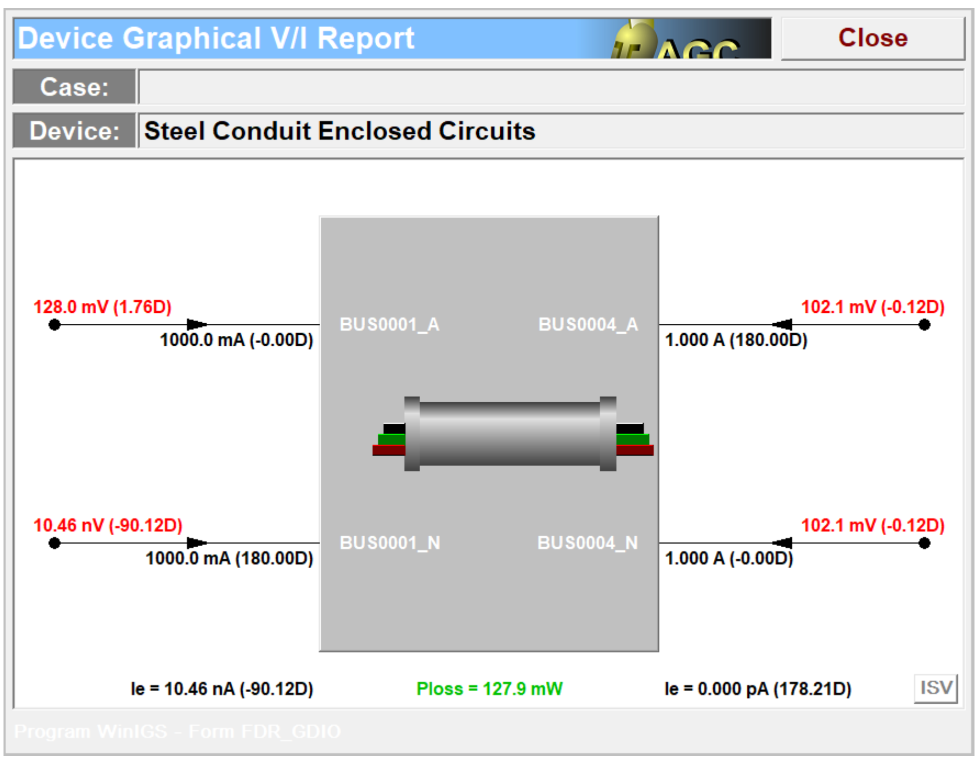
Comparison with Model

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:

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

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





WinIGS/GEMI Simulation Result

Table 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 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 14: ¾” IMC 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	5.656	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 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 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

Appendix A – 3” EMT Raw Data Plots

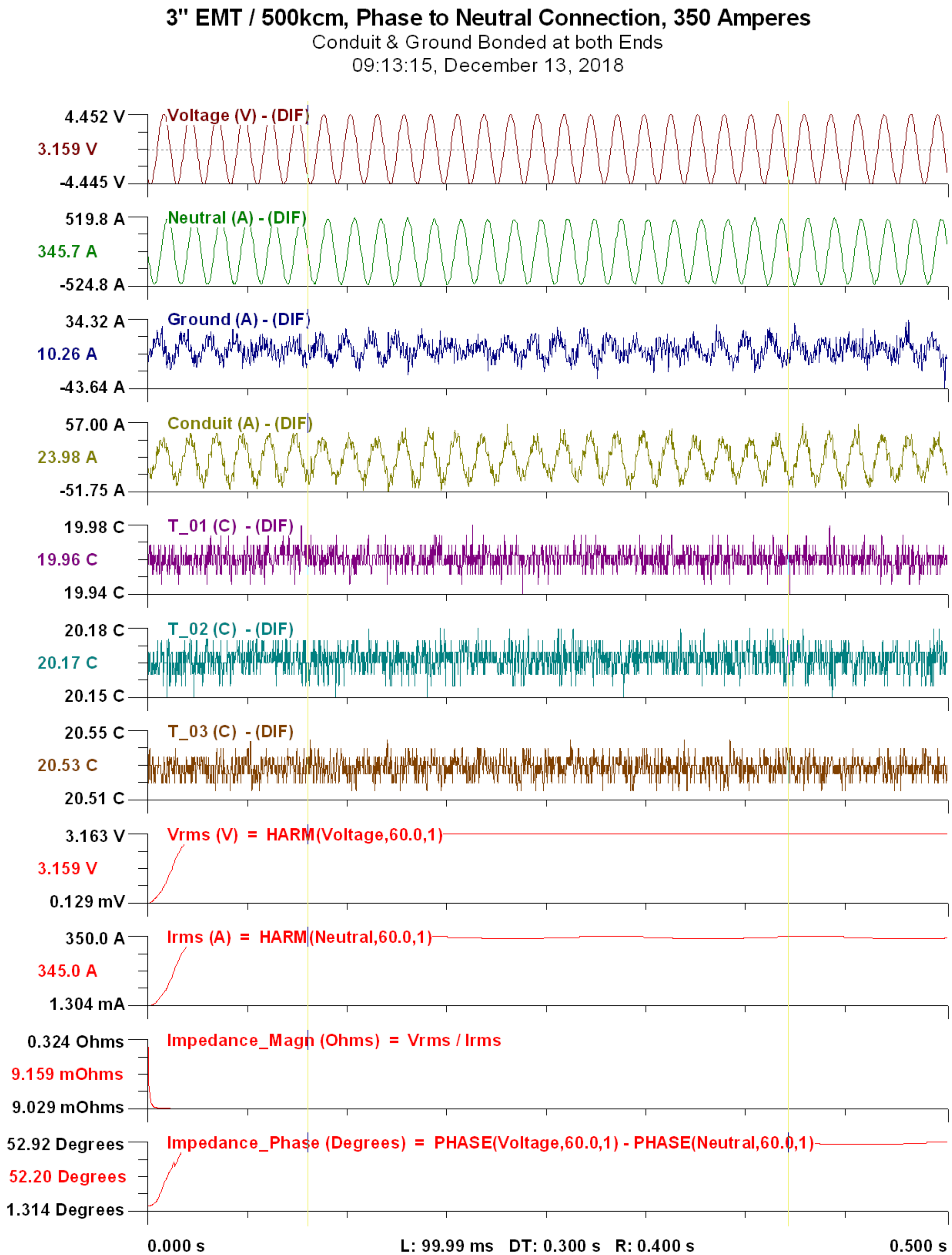


Figure A-1: Case Name EMT3_001

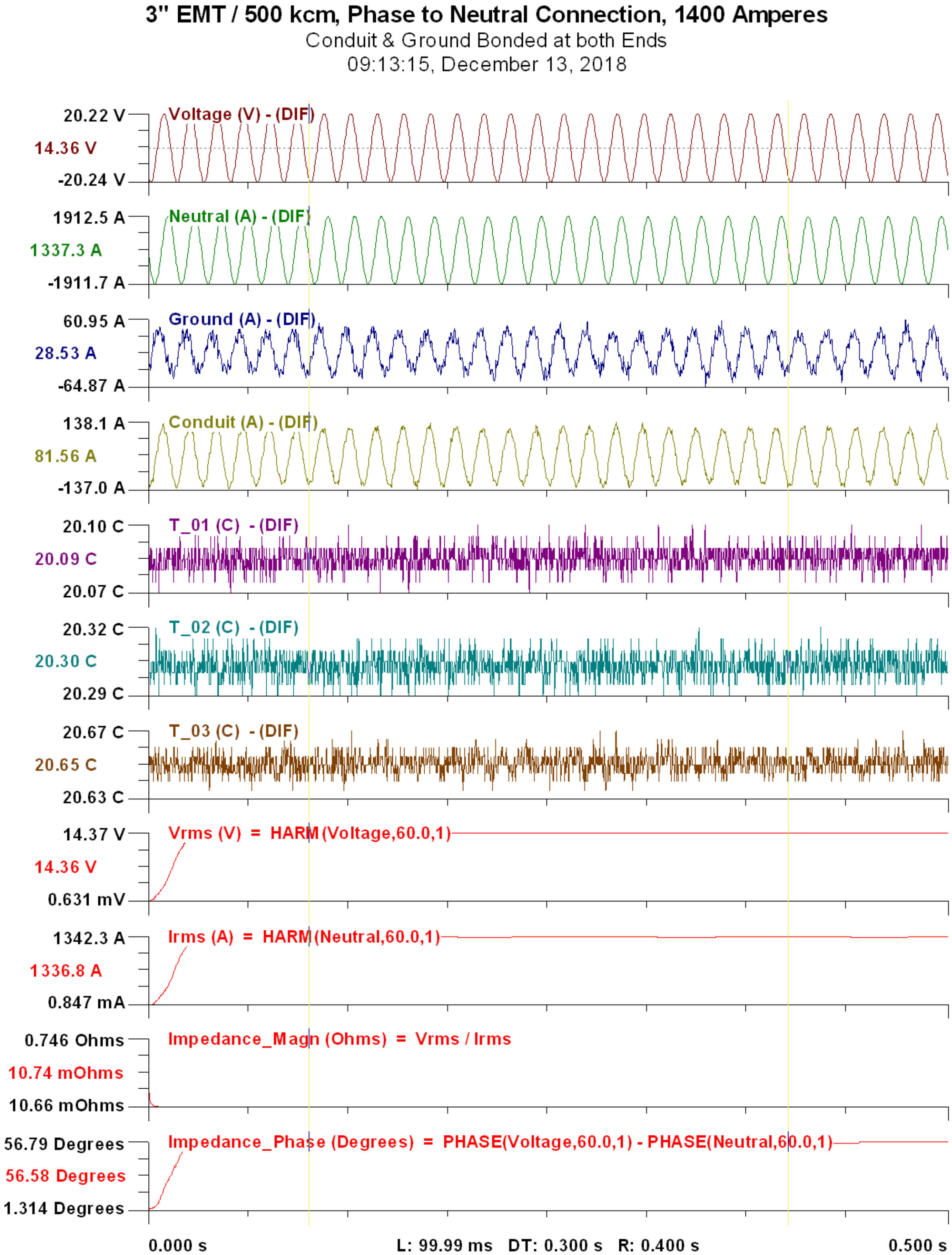


Figure A-2: Case Name EMT3_002

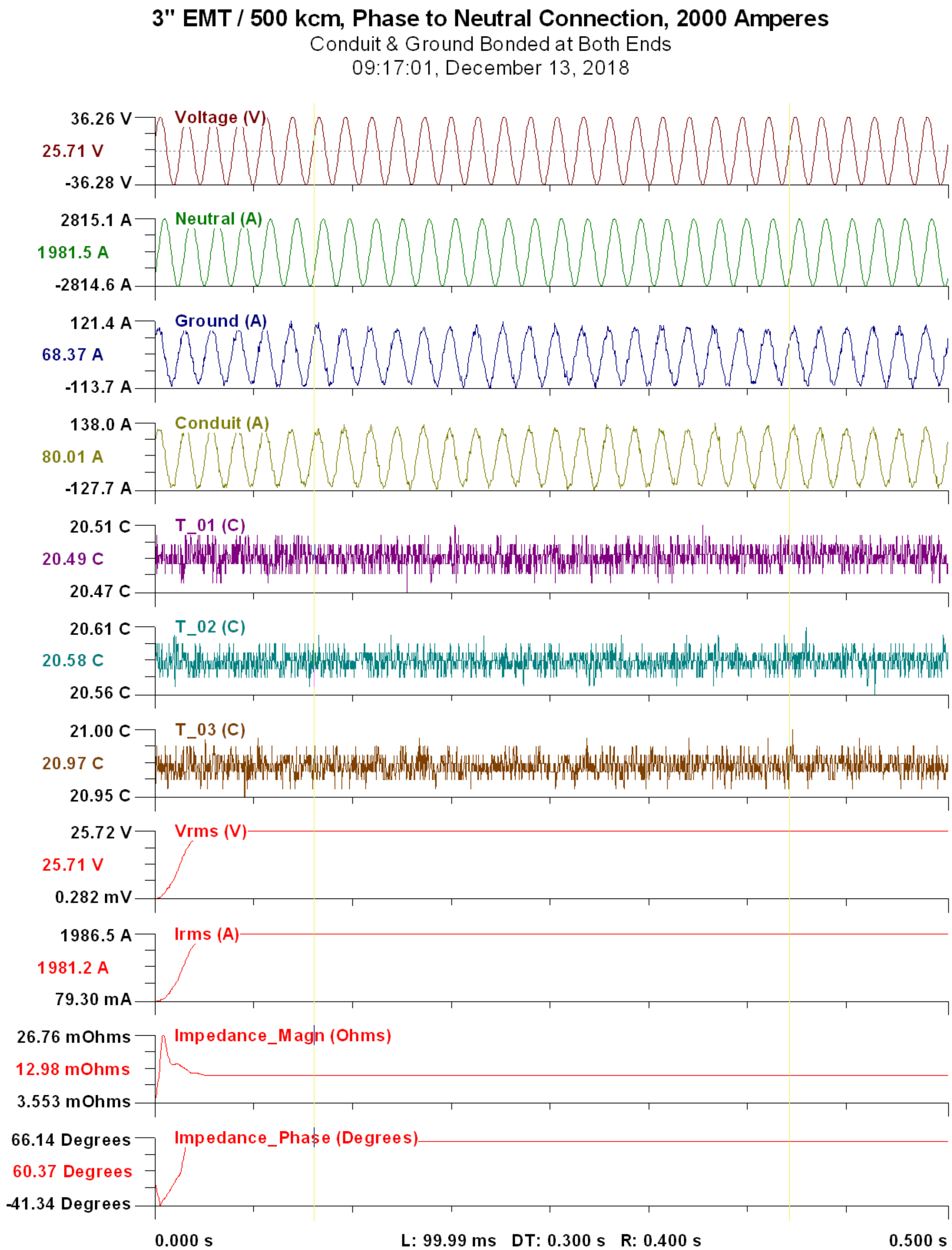


Figure A-3: Case Name EMT3_003

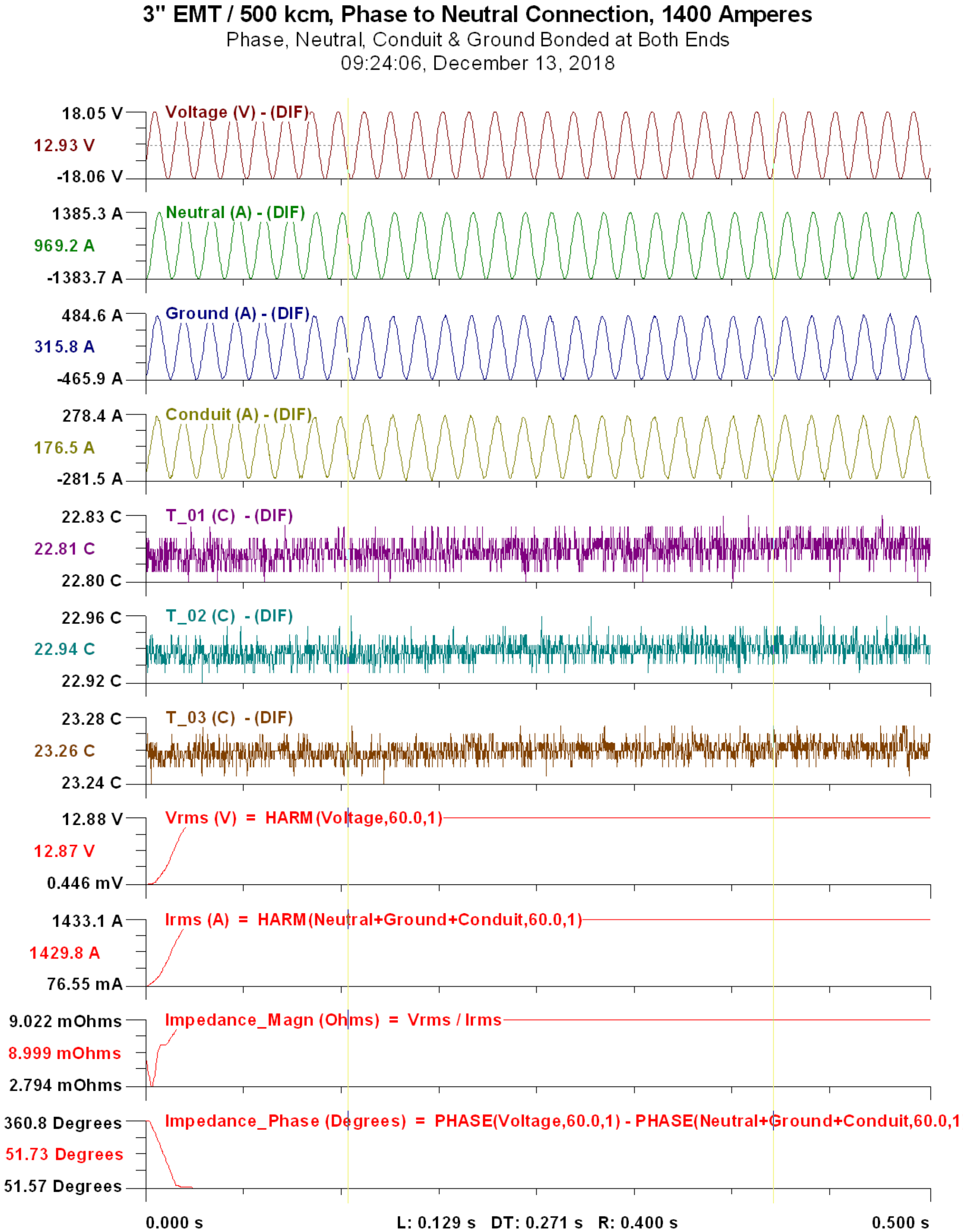


Figure A-4: Case Name EMT3_004

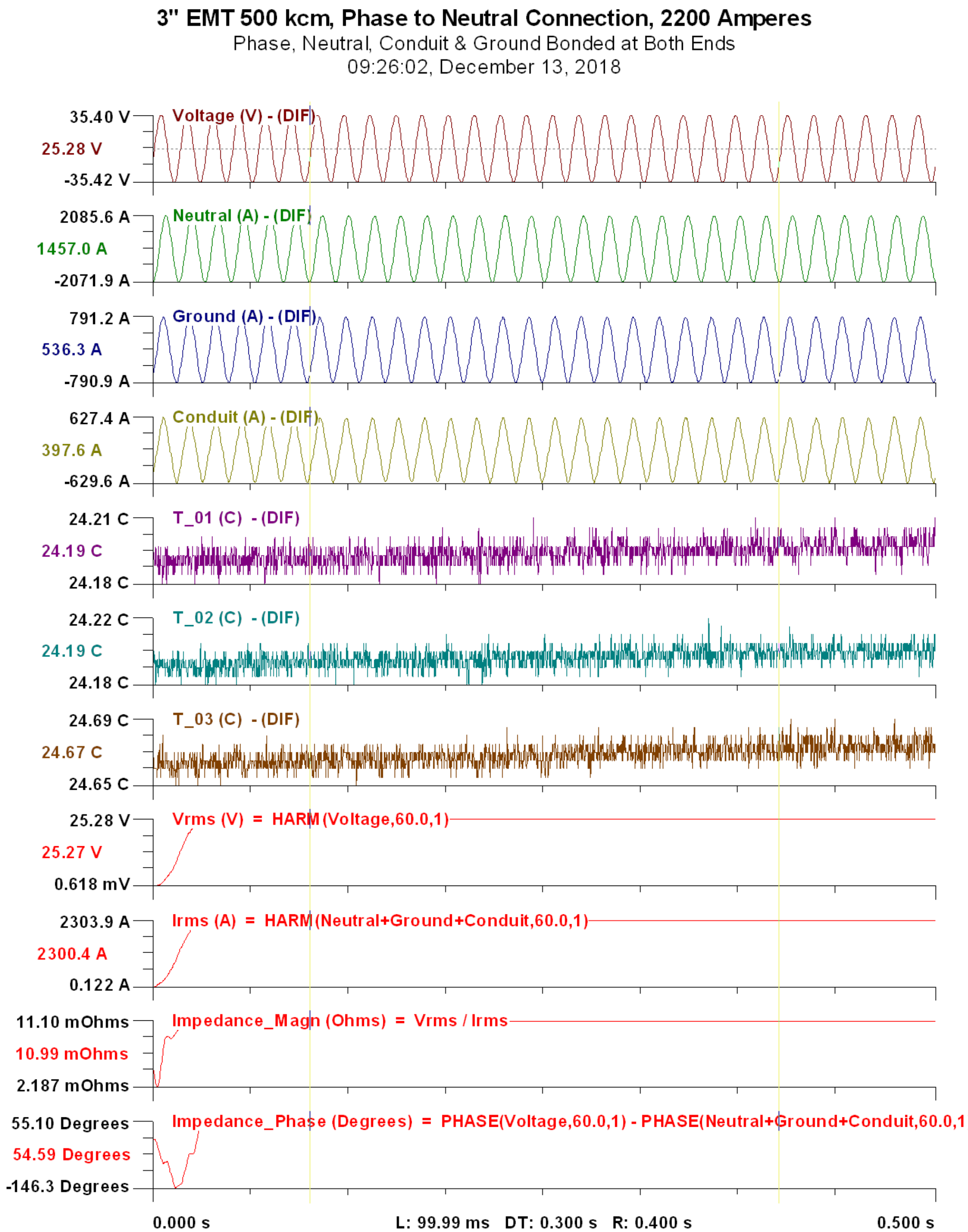


Figure A-5: Case Name EMT3_005

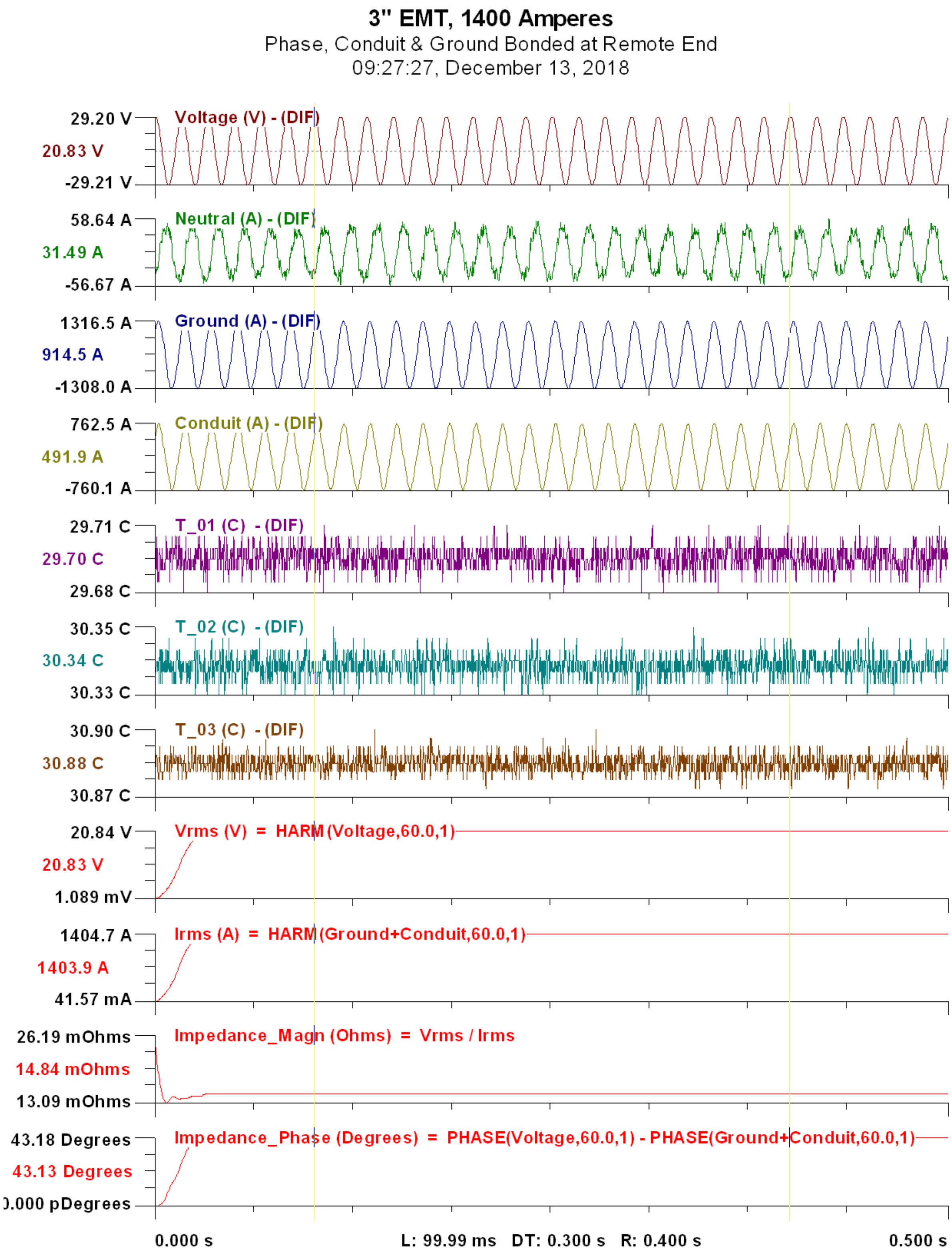


Figure A-6: Case Name/ EMT3_006

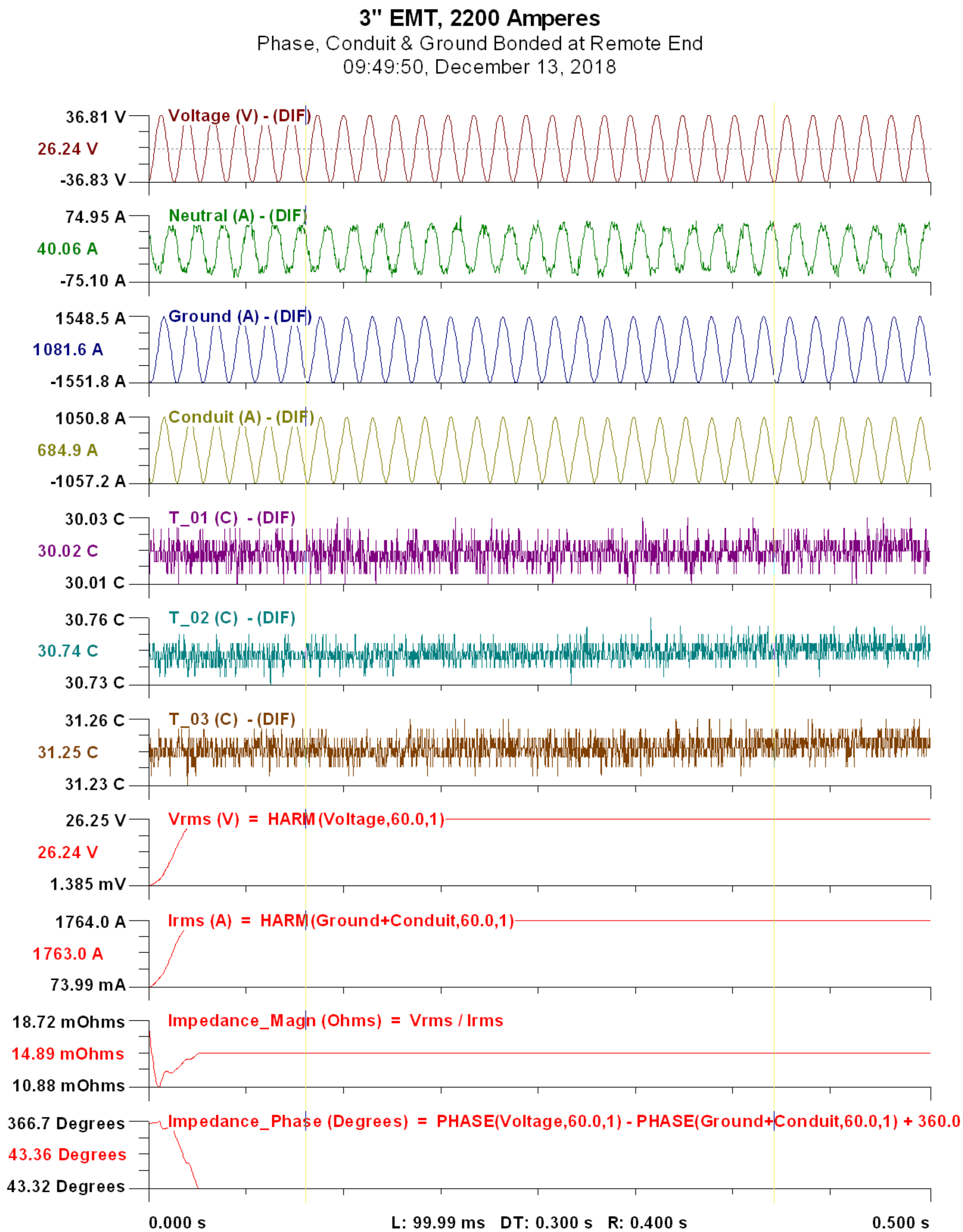


Figure A-7: Case Name EMT3_007

Appendix B – 3” GRC Raw Data Plots

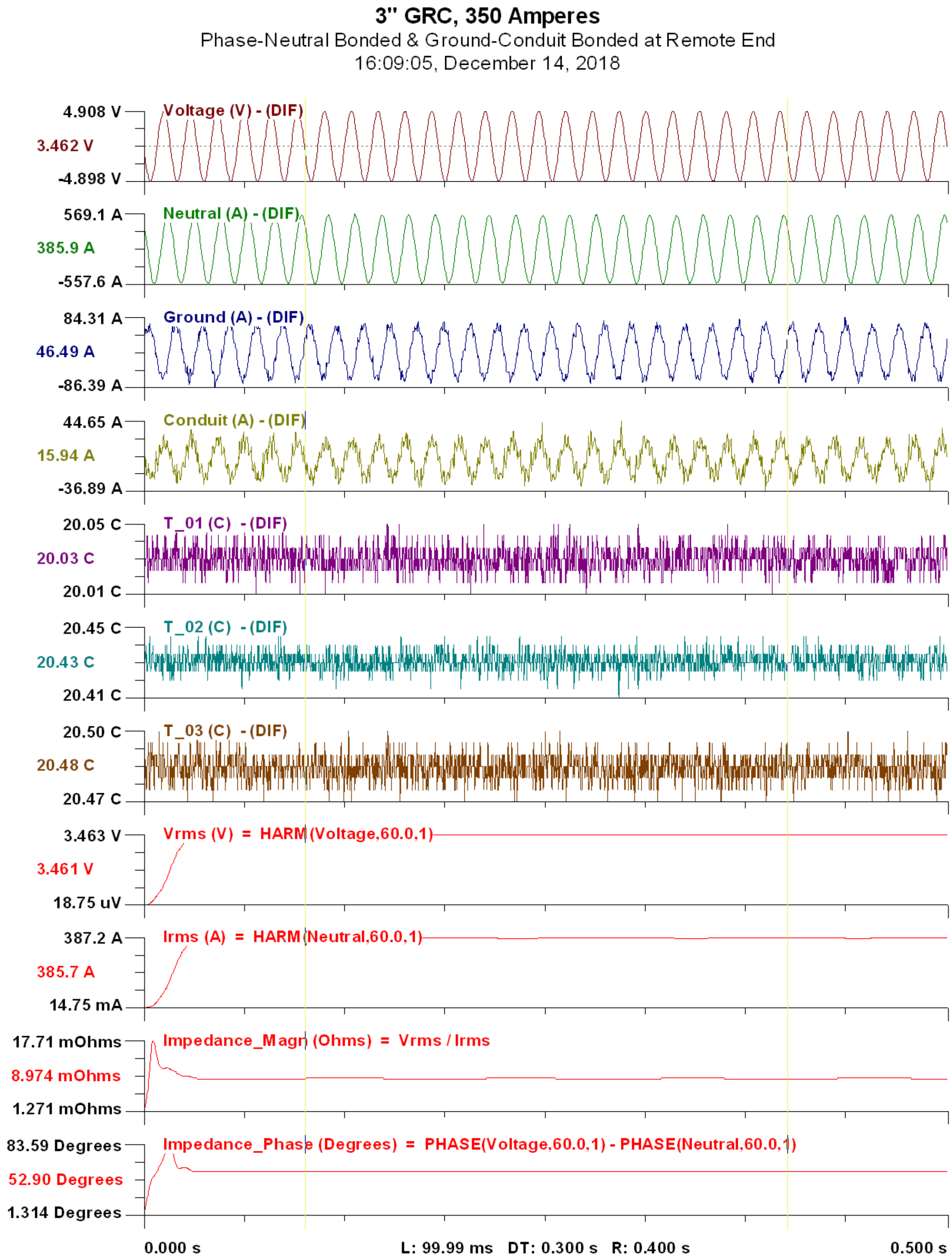


Figure B-1: Case Name GRC300_001

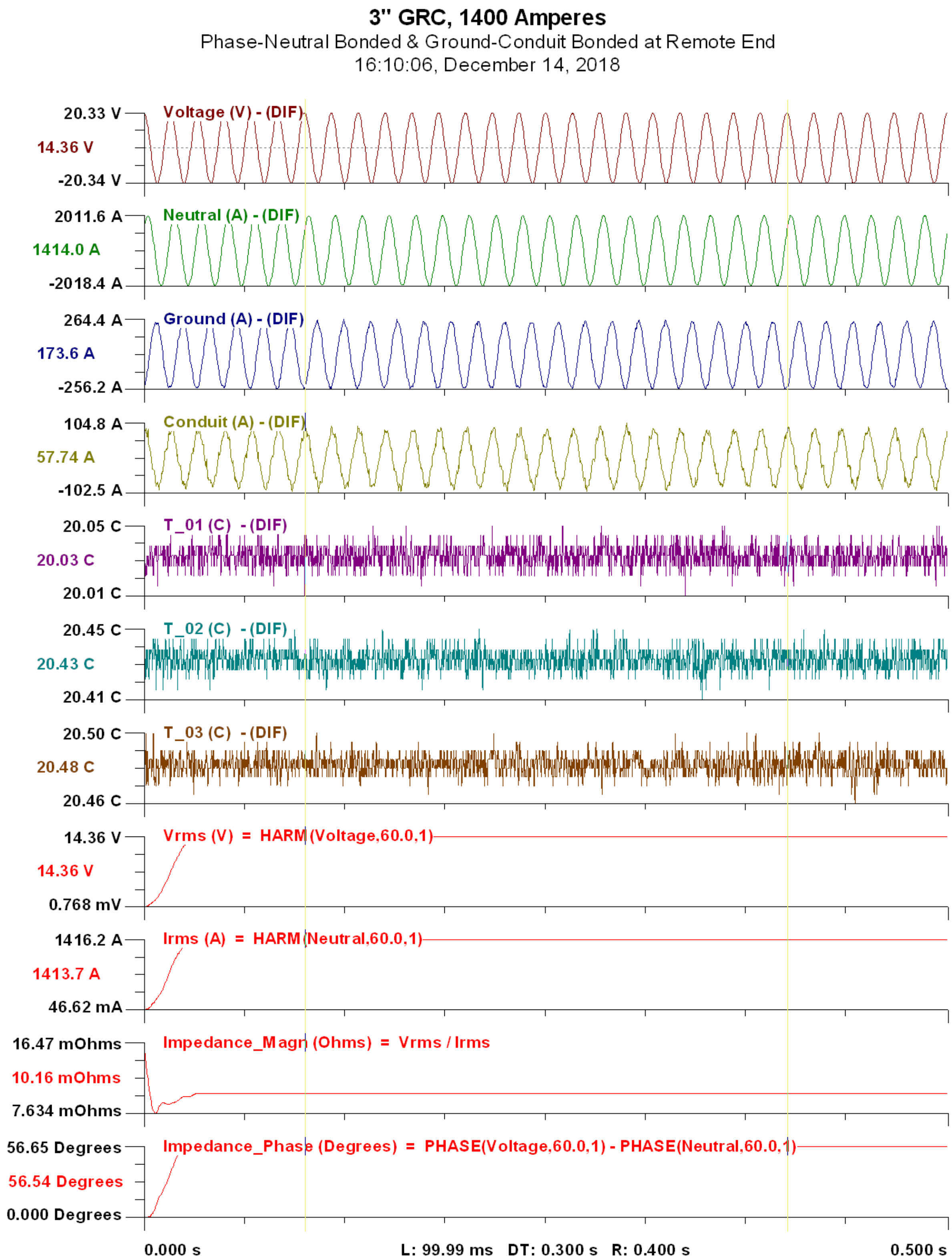


Figure B-2: Case Name GRC300_002

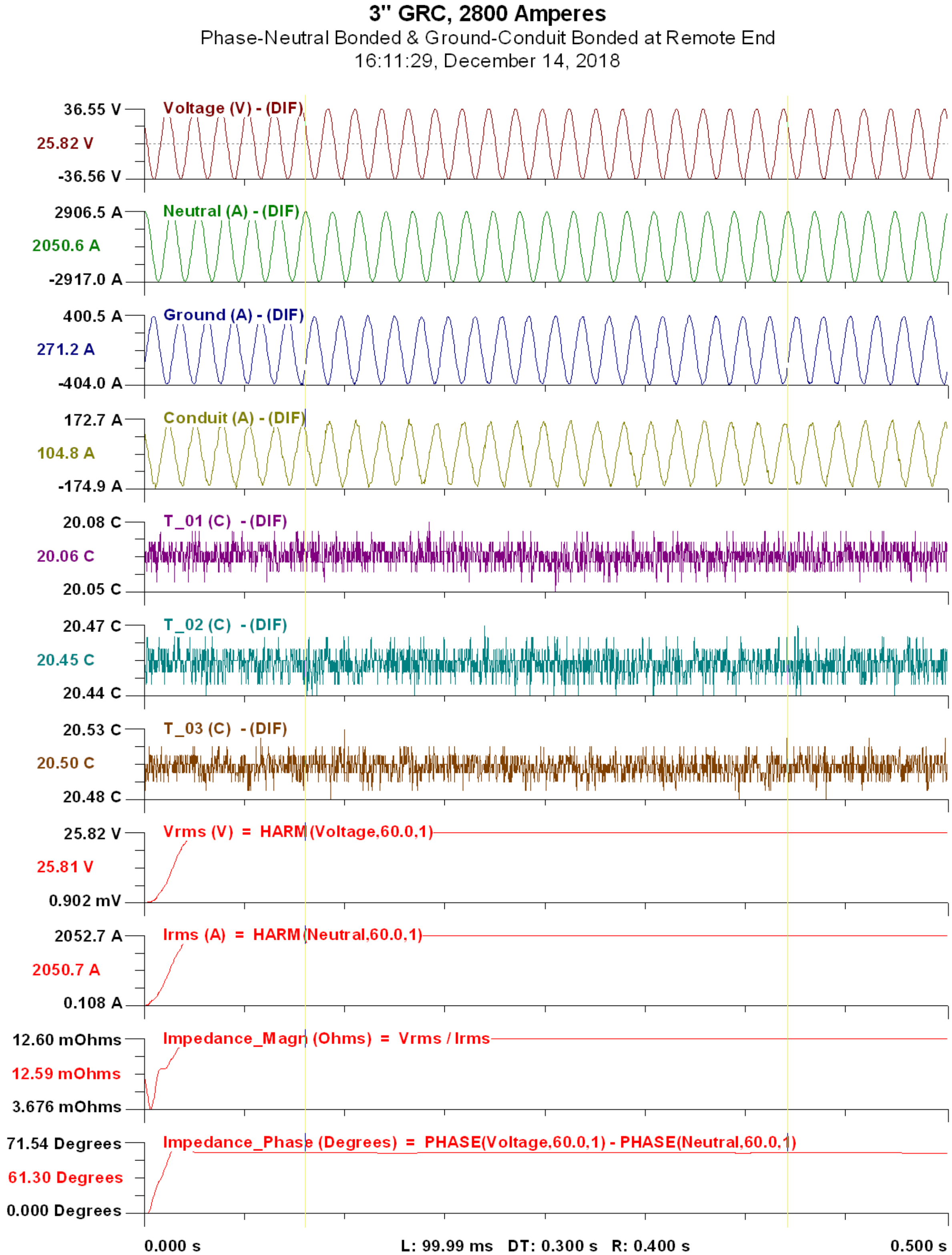


Figure B-3: Case Name GRC300_003

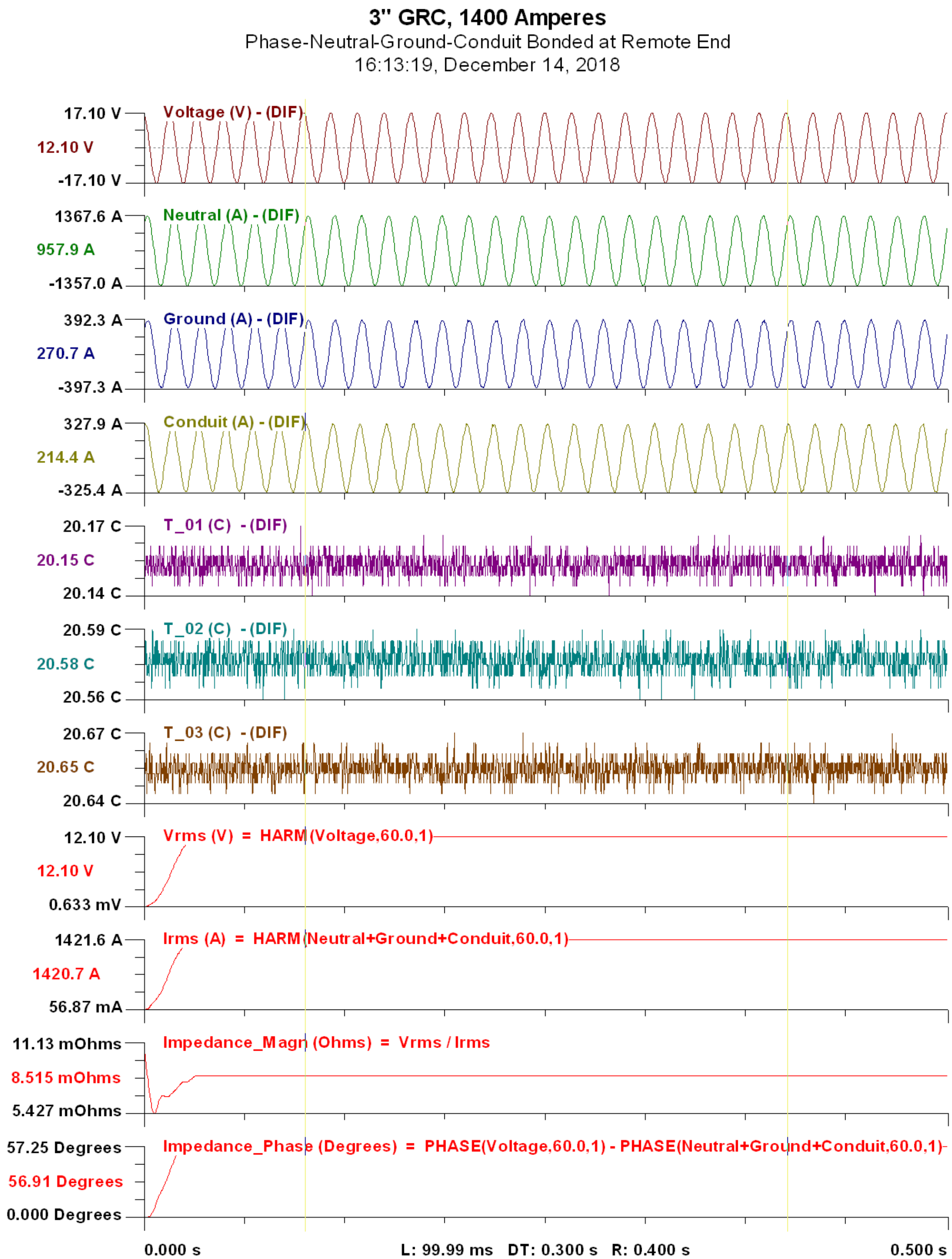


Figure B-4: Case Name GRC300_004

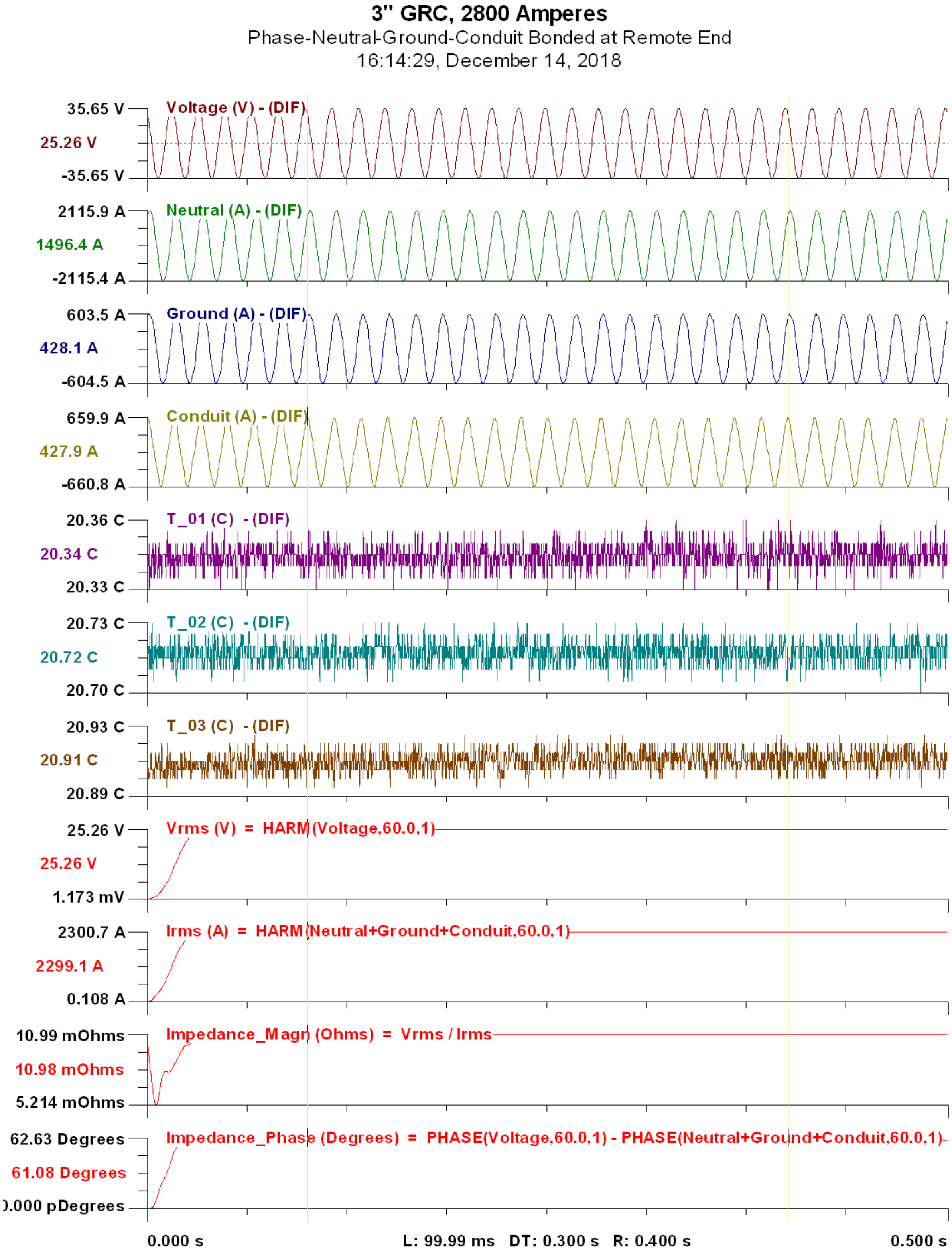


Figure B-5: Case Name GRC300_005

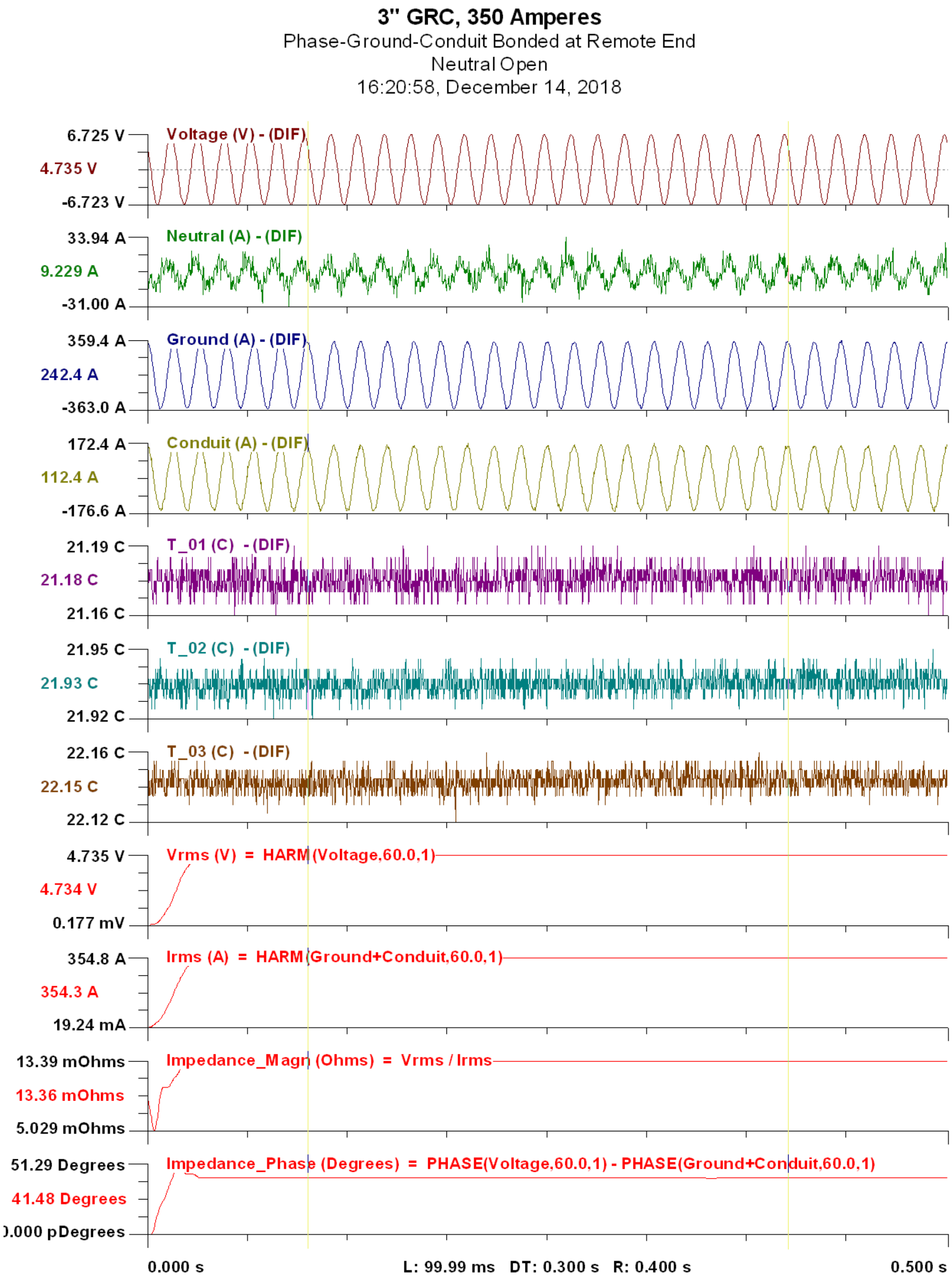


Figure B-6: Case Name GRC300_006

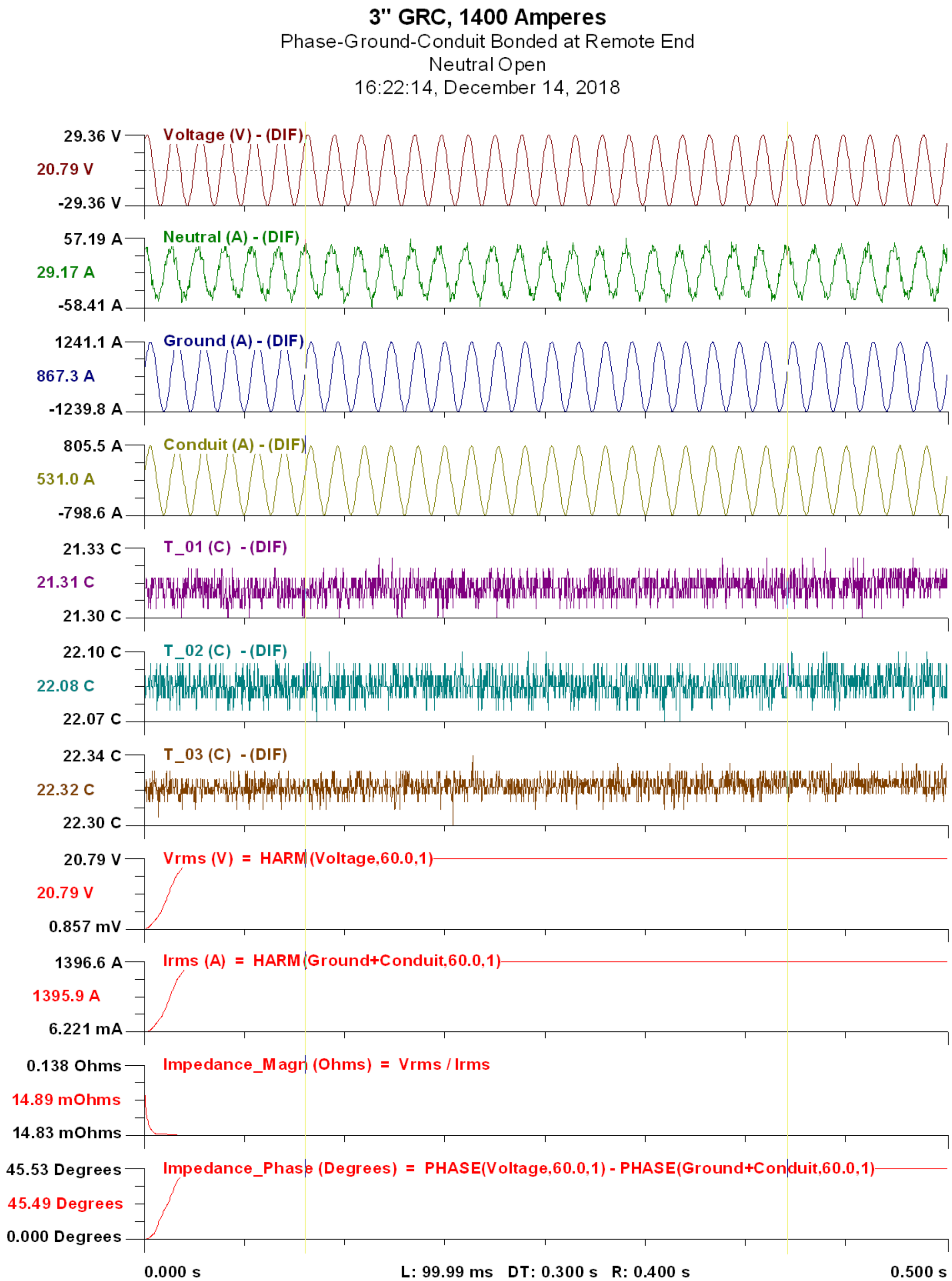


Figure B-7: Case Name GRC300_007

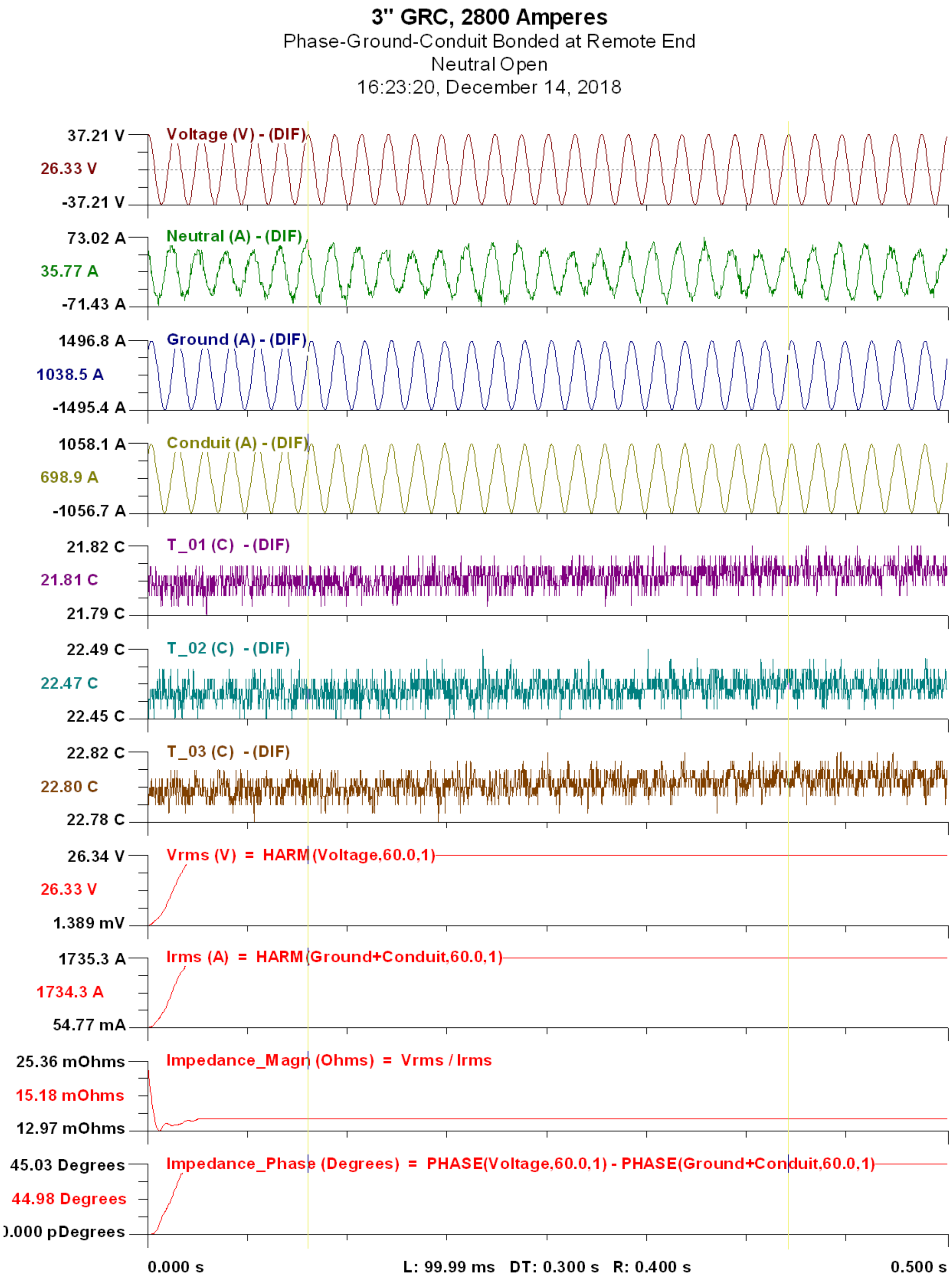


Figure B-8: Case Name GRC300_008

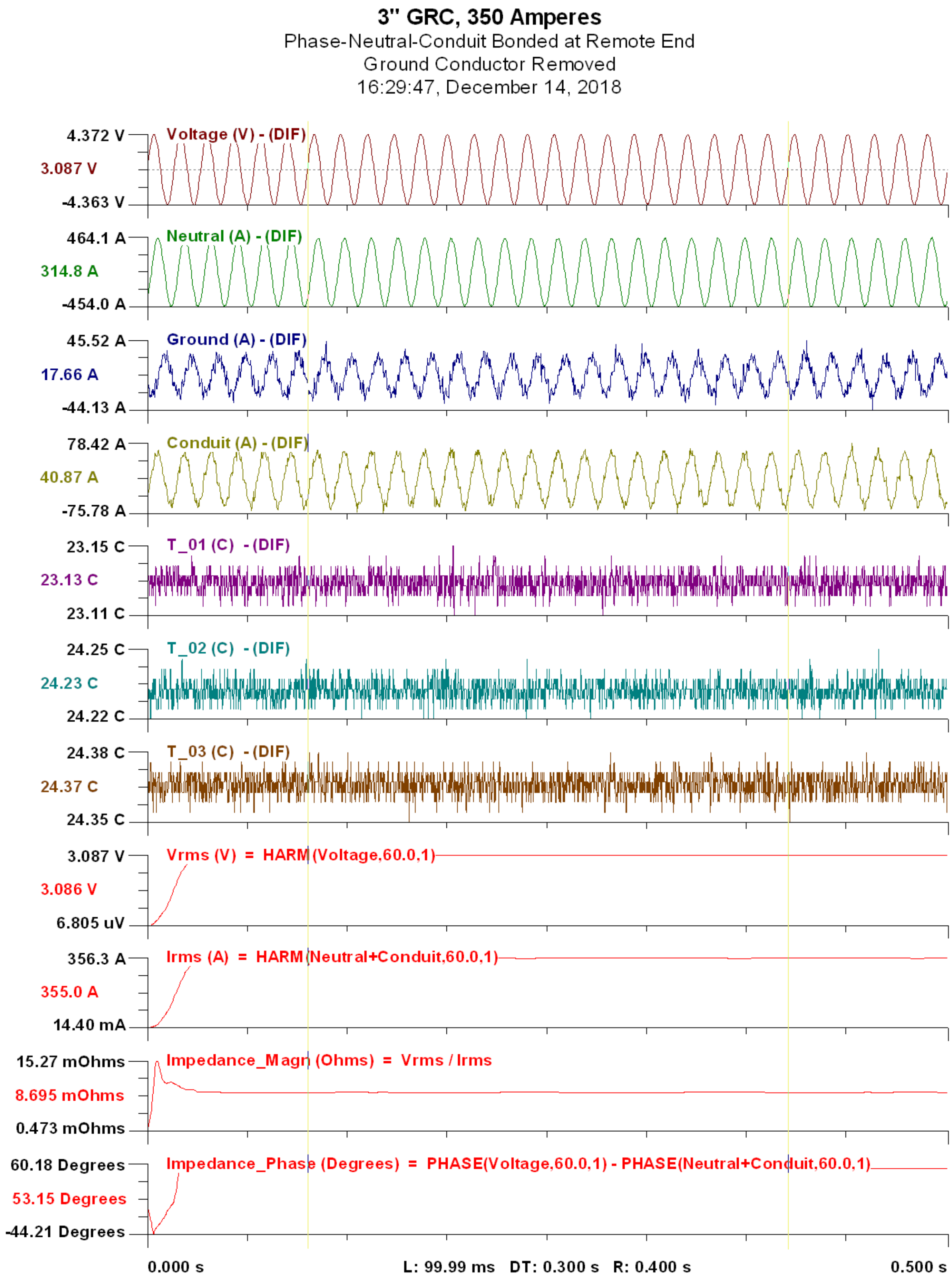


Figure B-9: Case Name GRC300_009

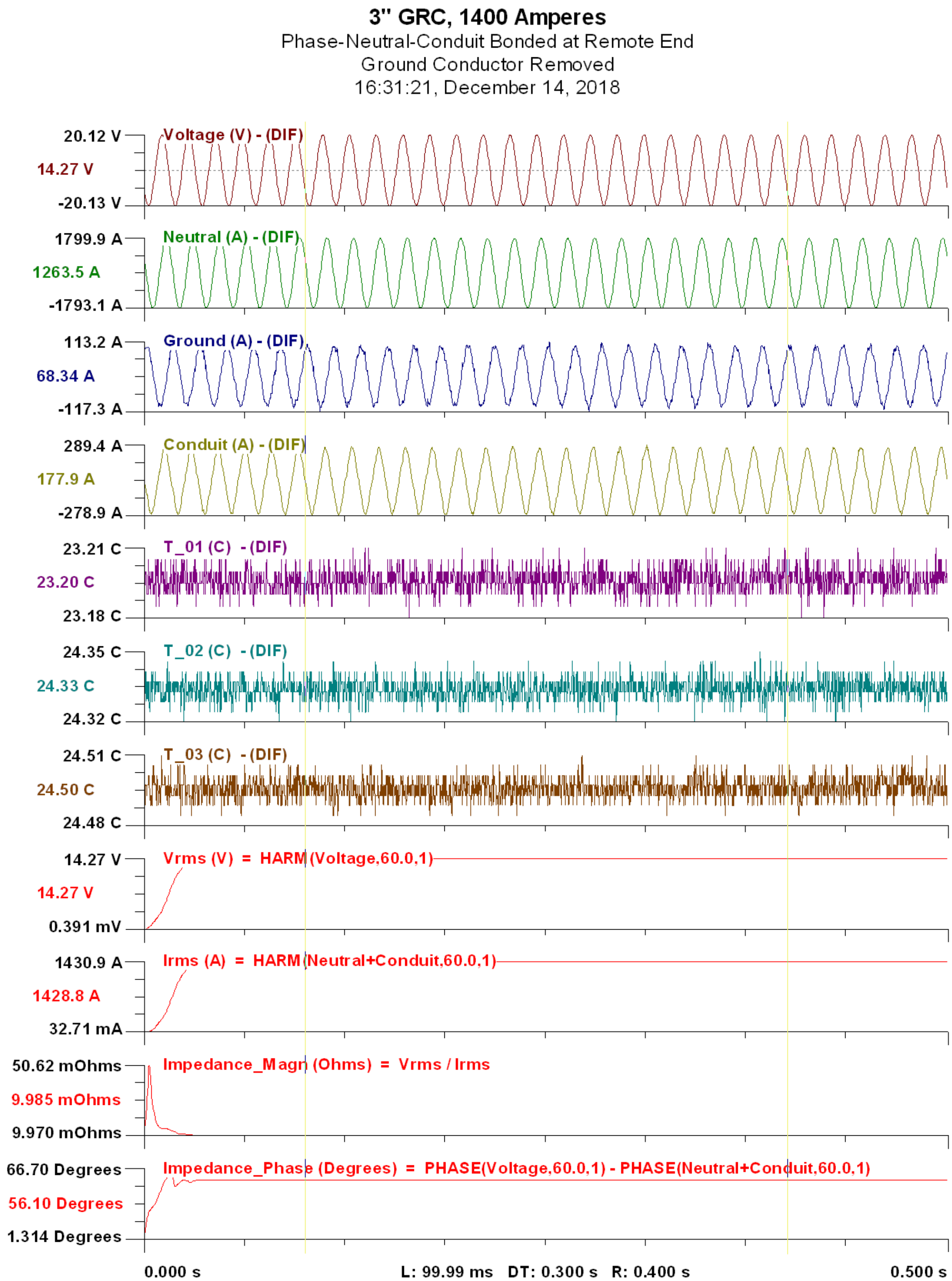


Figure B-10: Case Name GRC300_010

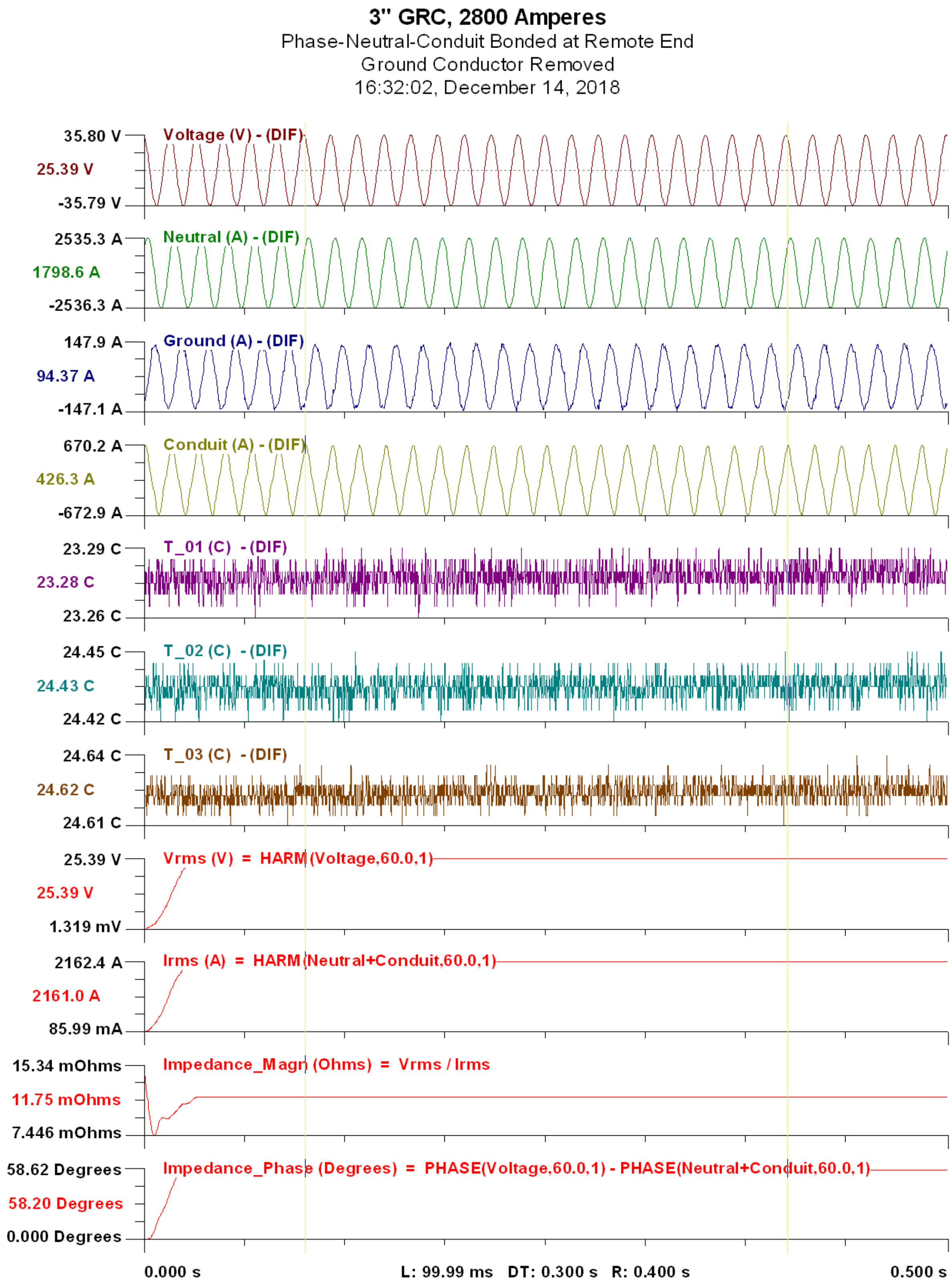


Figure B-11: Case Name GRC300_011

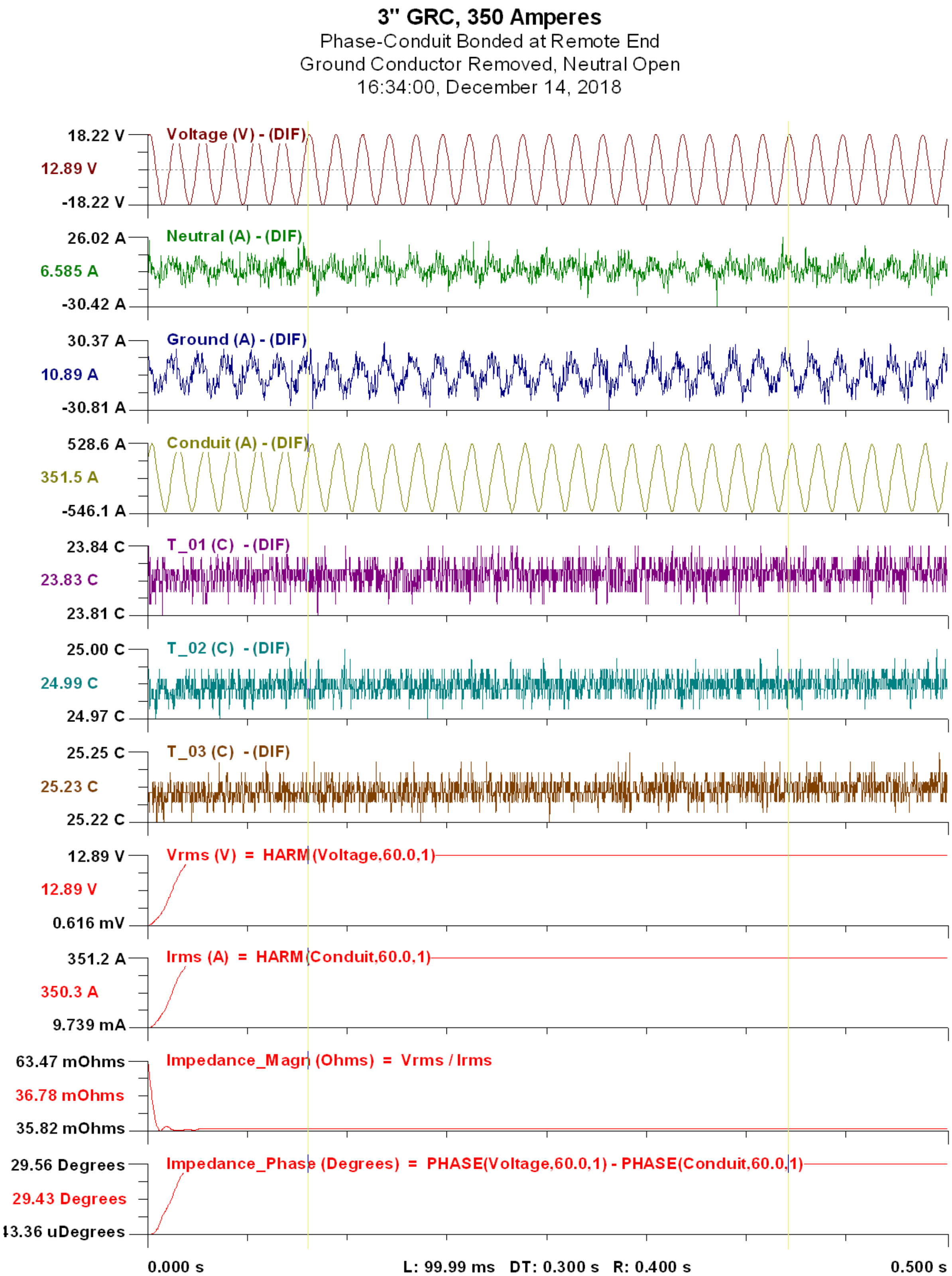


Figure B-12: Case Name GRC300_012

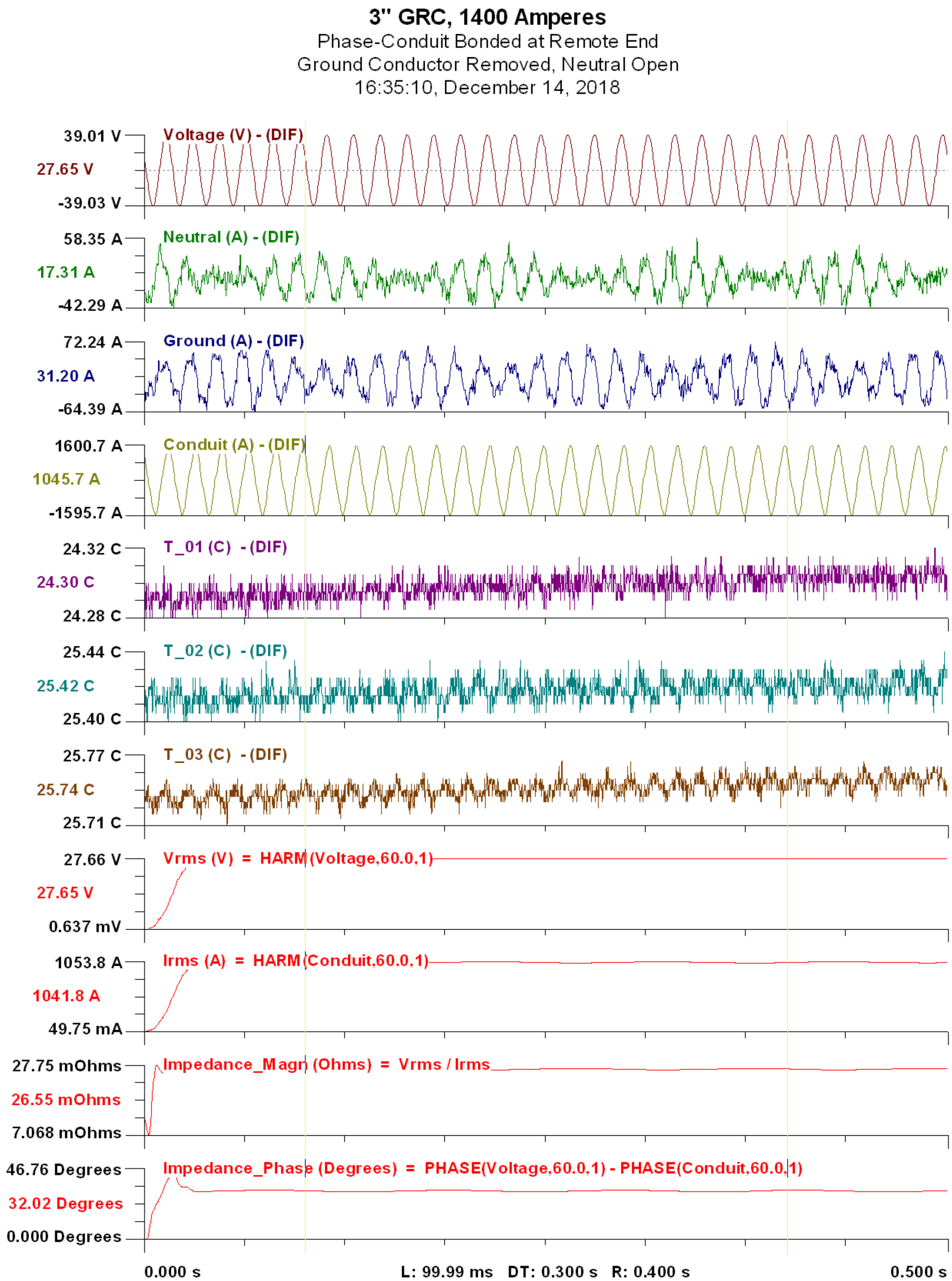


Figure B-13: Case Name GRC300_013

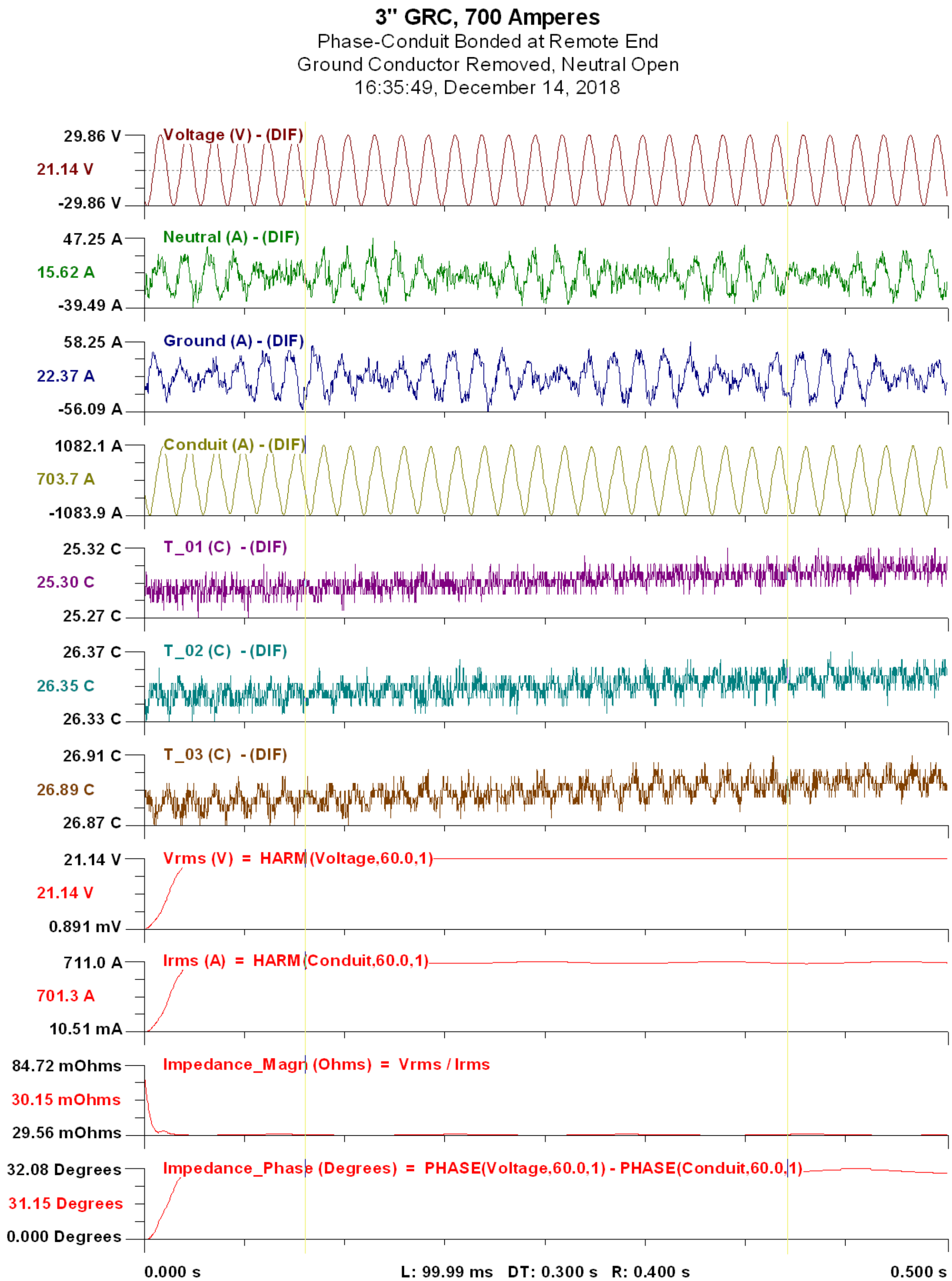


Figure B-14: Case Name GRC300_014

Appendix C – 3” IMC Raw Data Plots

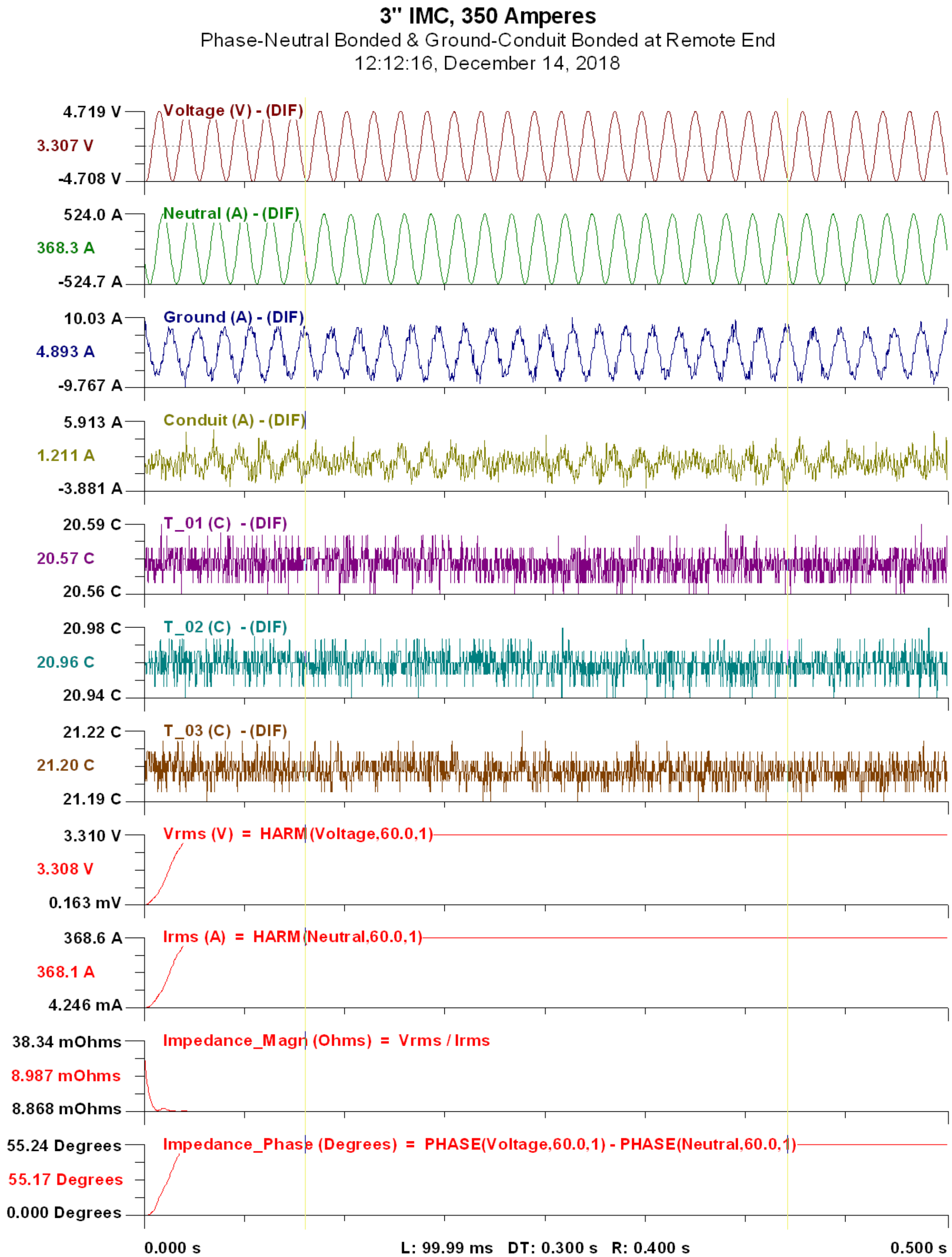


Figure C-1: Case Name IMC300_001

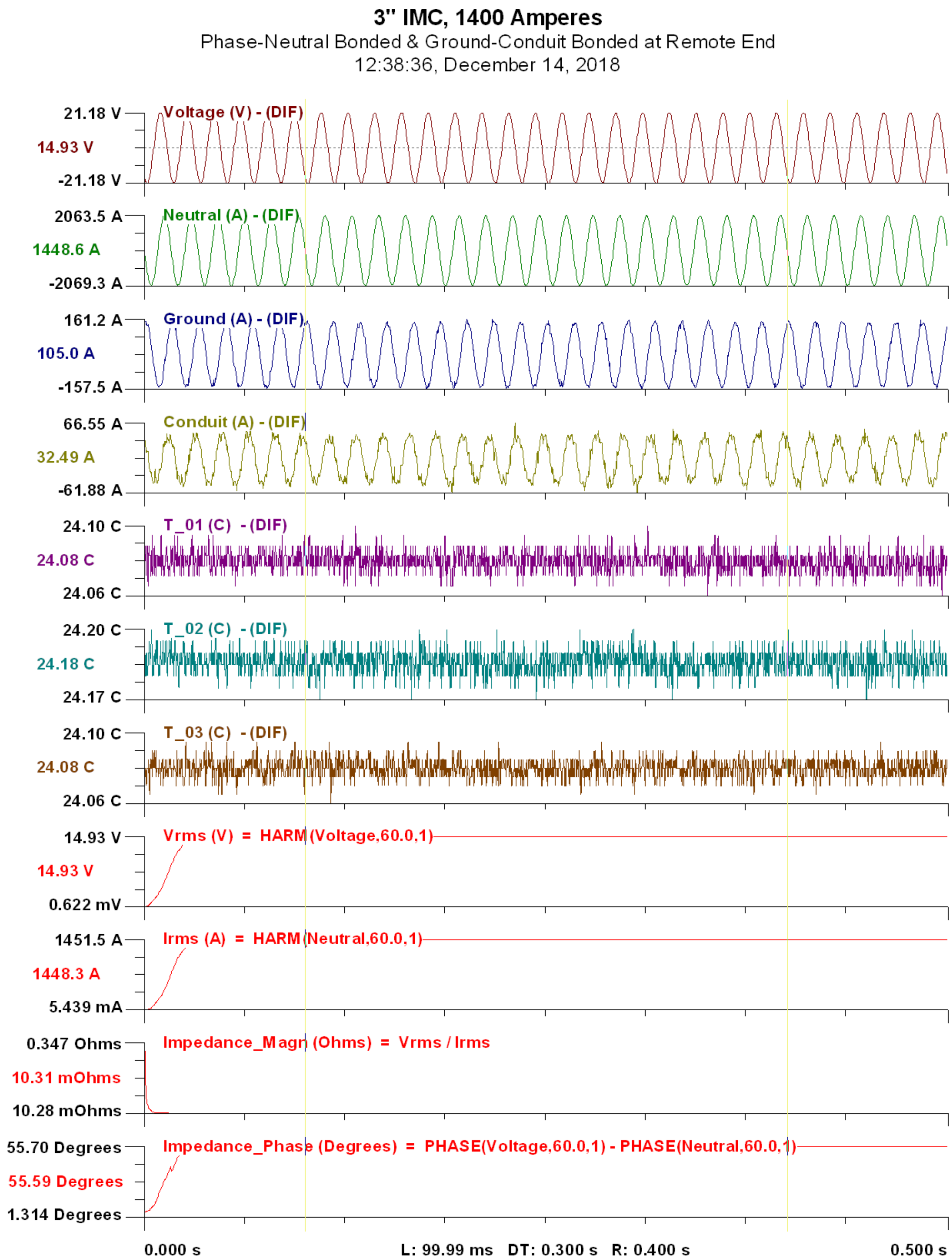


Figure C-2: Case Name IMC300_002

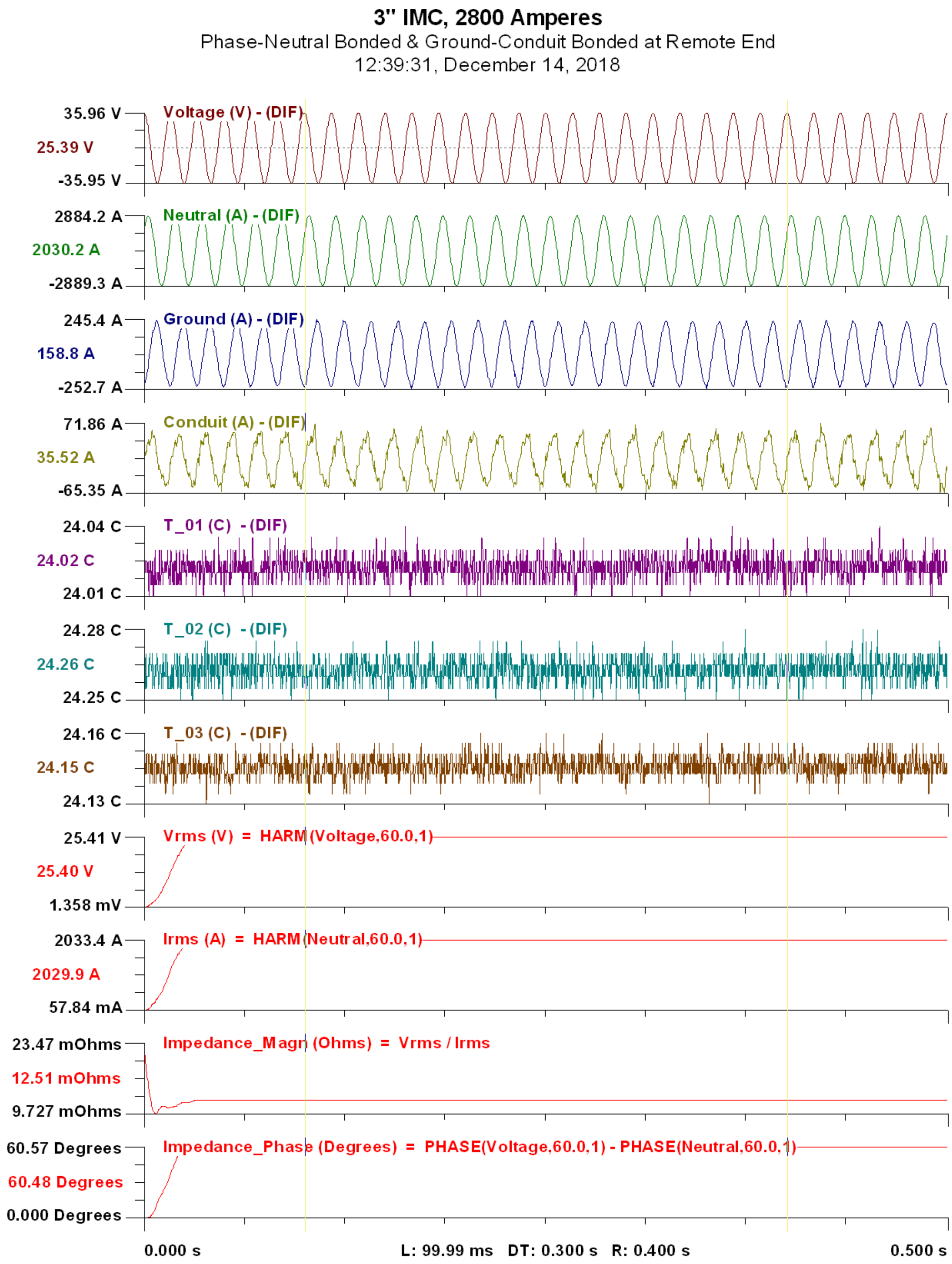


Figure C-3: Case Name IMC300_003

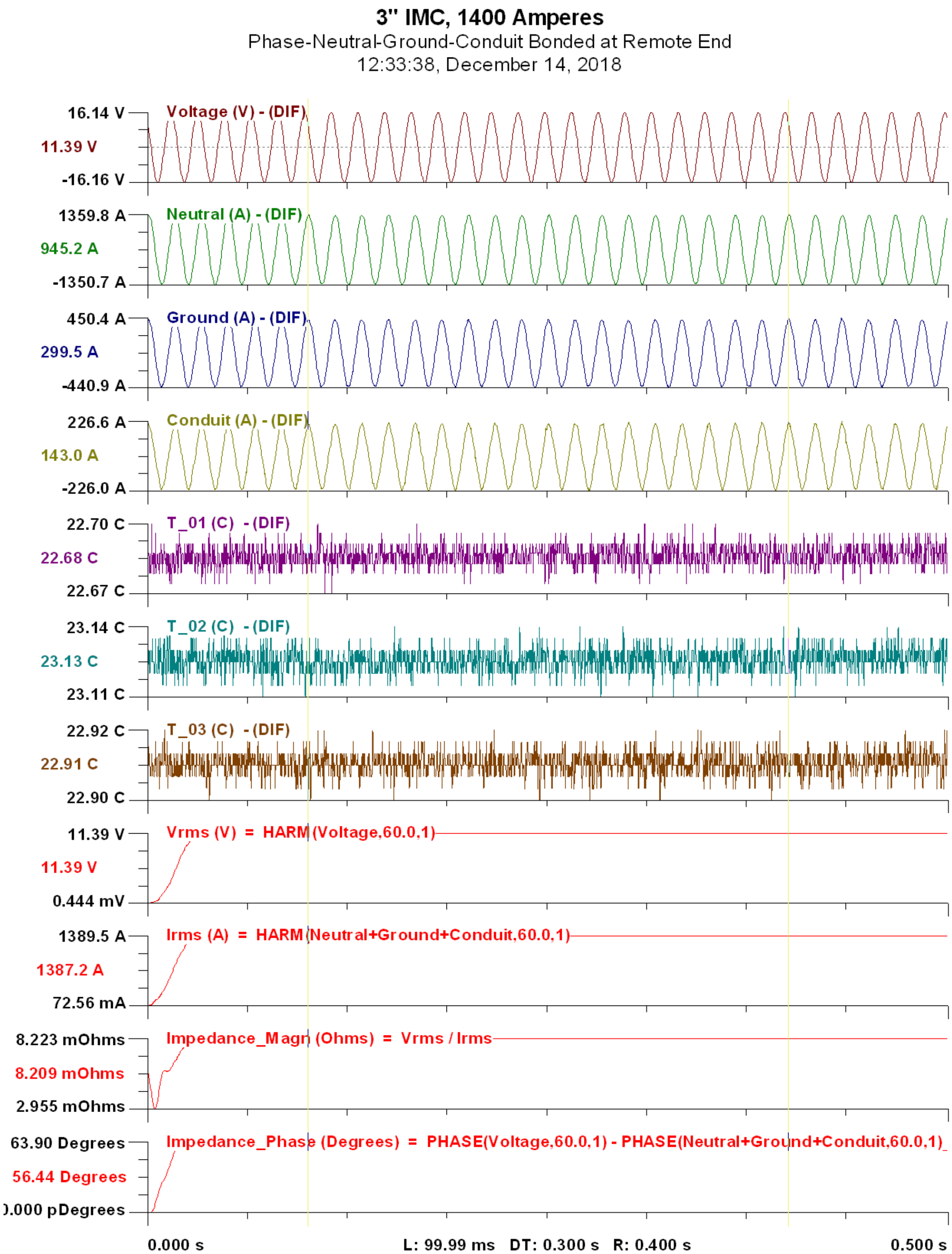


Figure C-4: Case Name IMC300_004

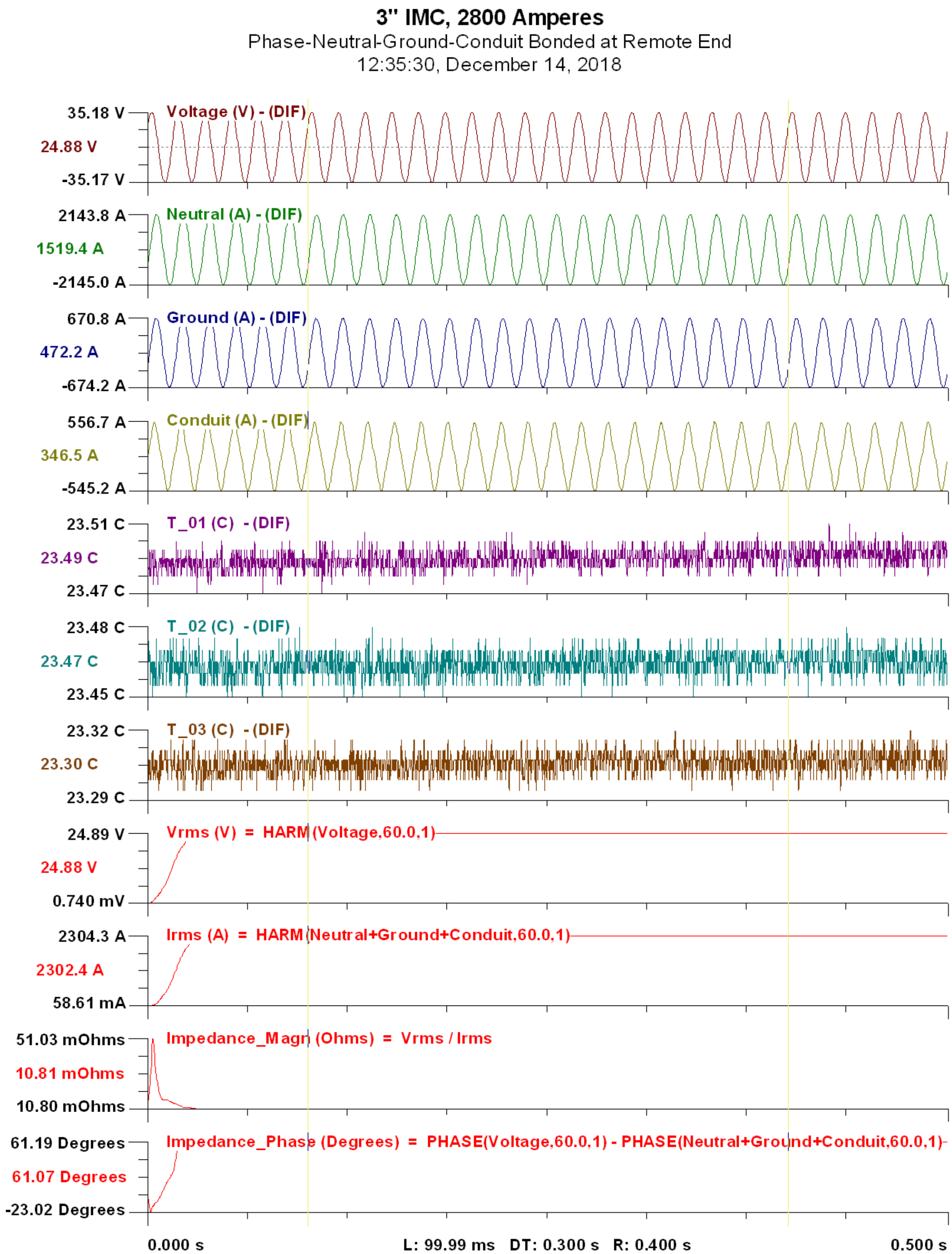


Figure C-5: Case Name IMC300_005

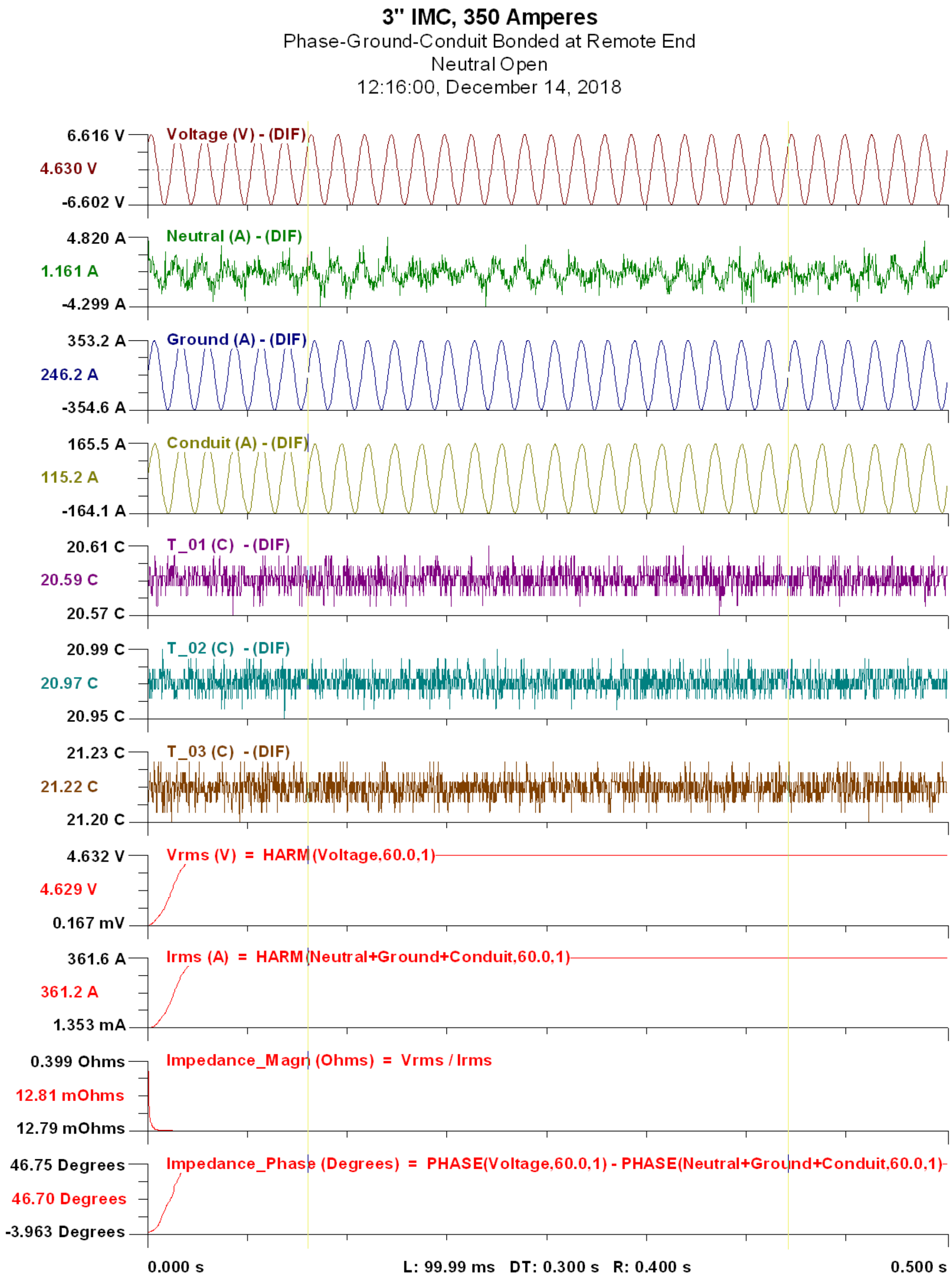


Figure C-6: Case Name IMC300_006

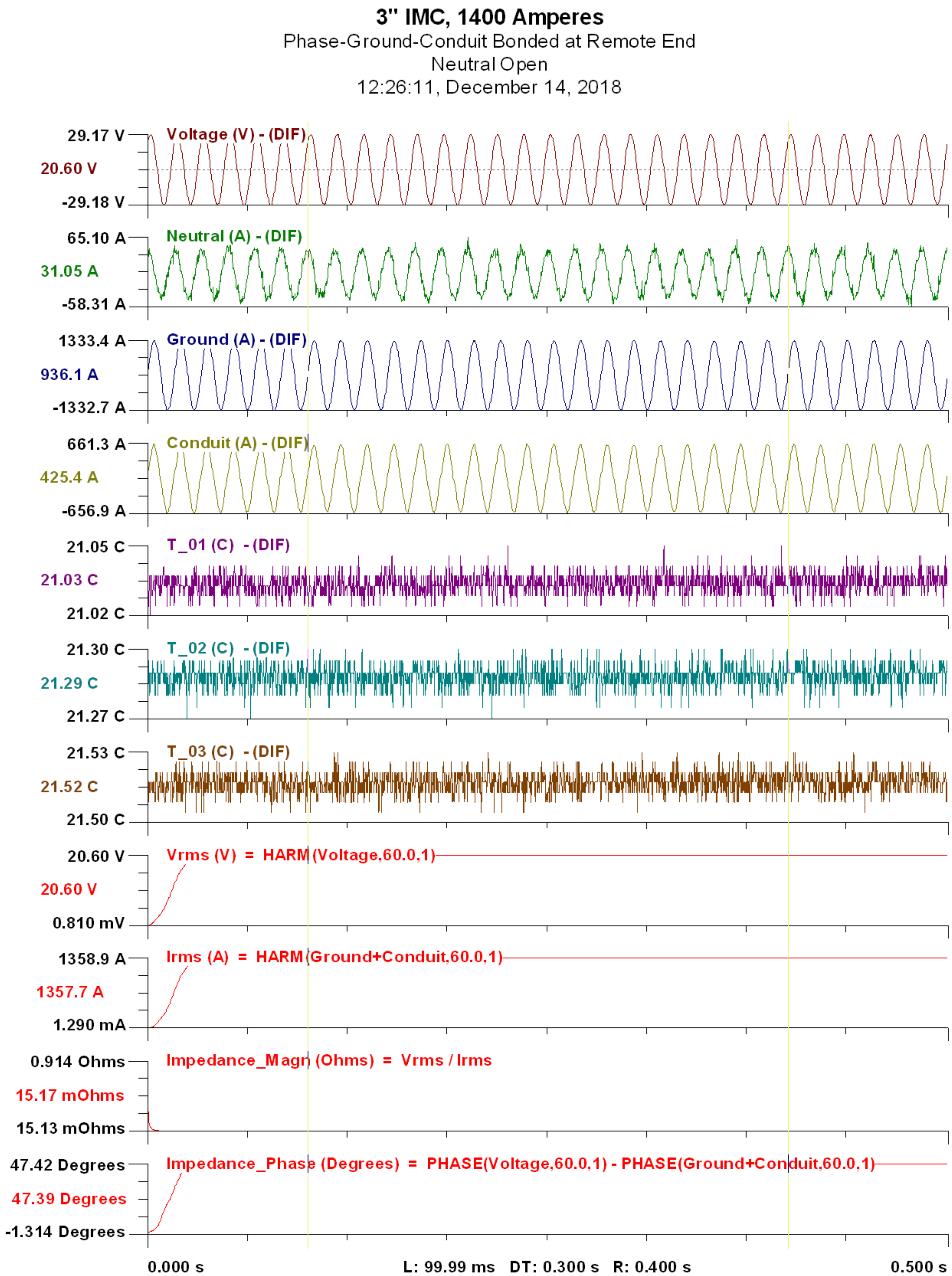


Figure C-7: Case Name IMC300_007

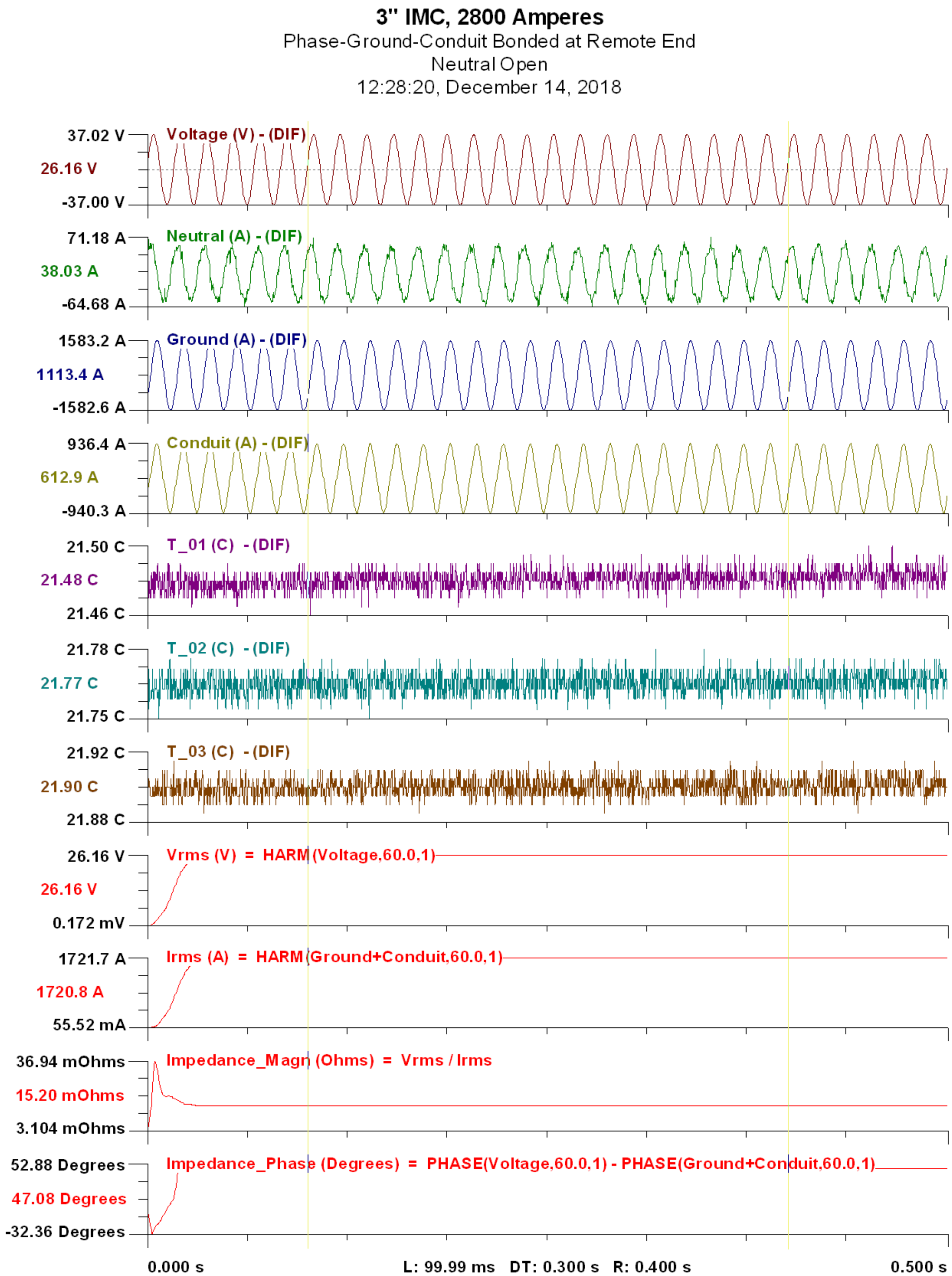


Figure C-8: Case Name IMC300_008

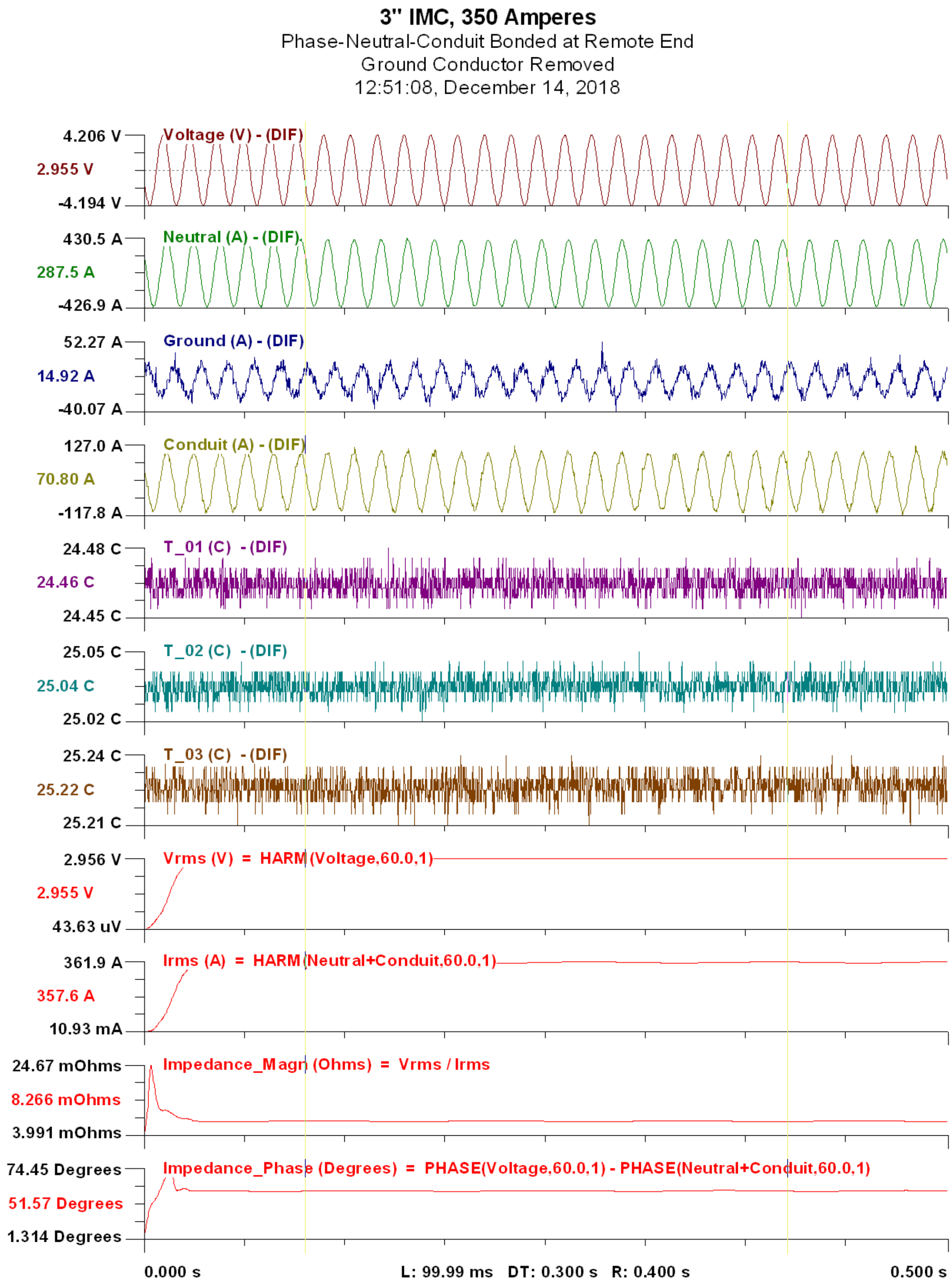


Figure C-9: Case Name IMC300_009

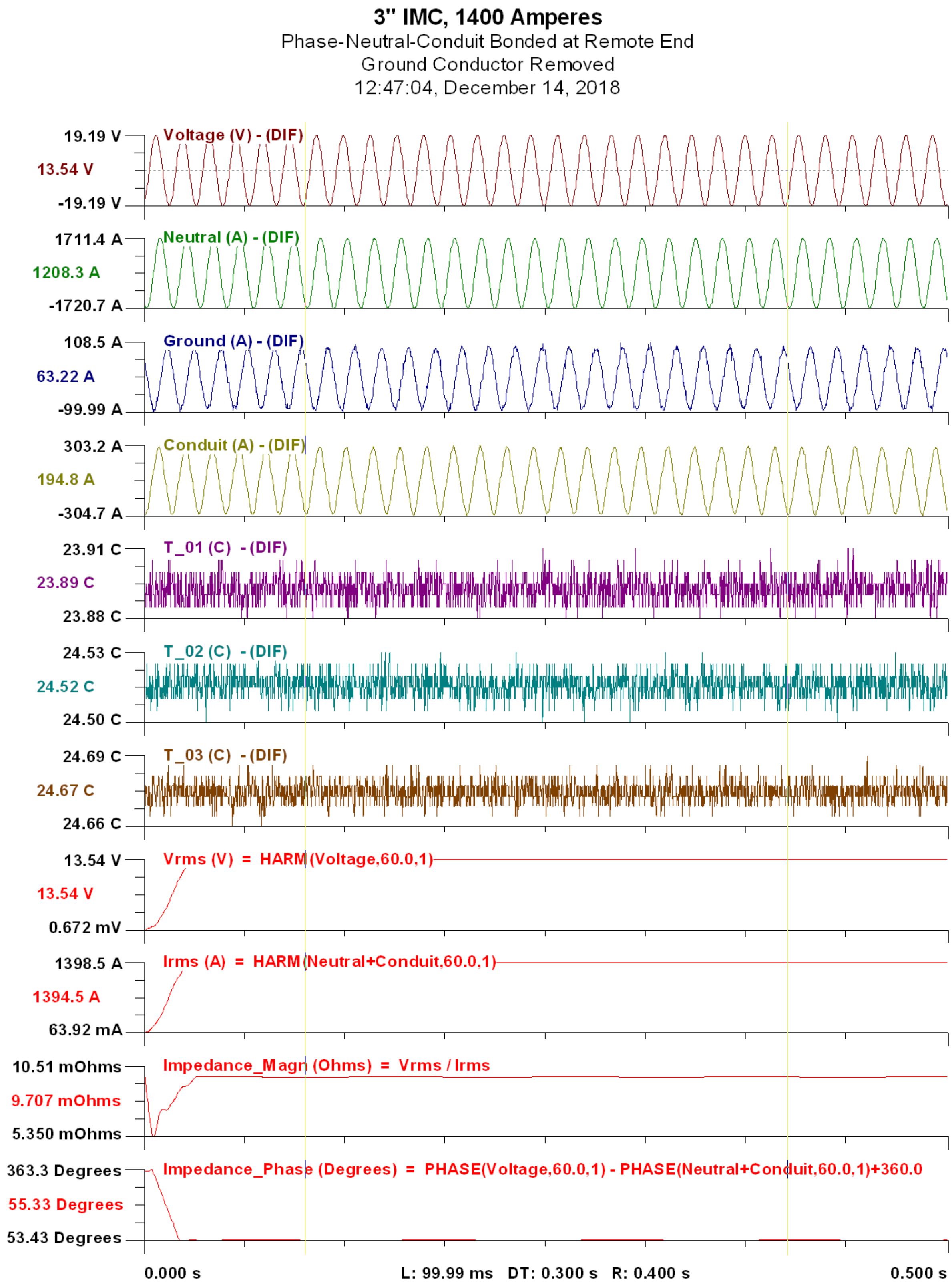


Figure C-10: Case Name IMC300_010

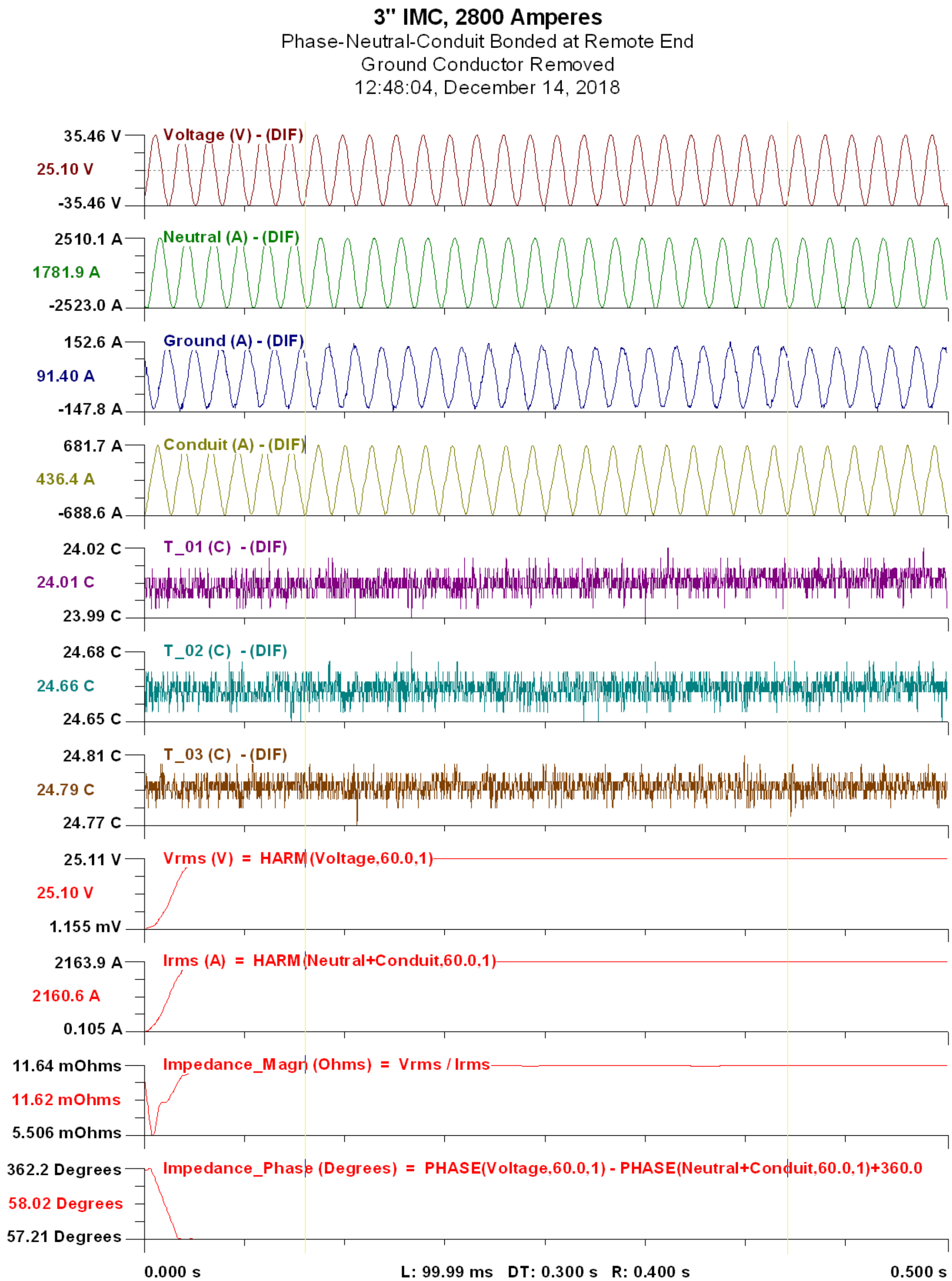


Figure C-11: Case Name IMC300_011

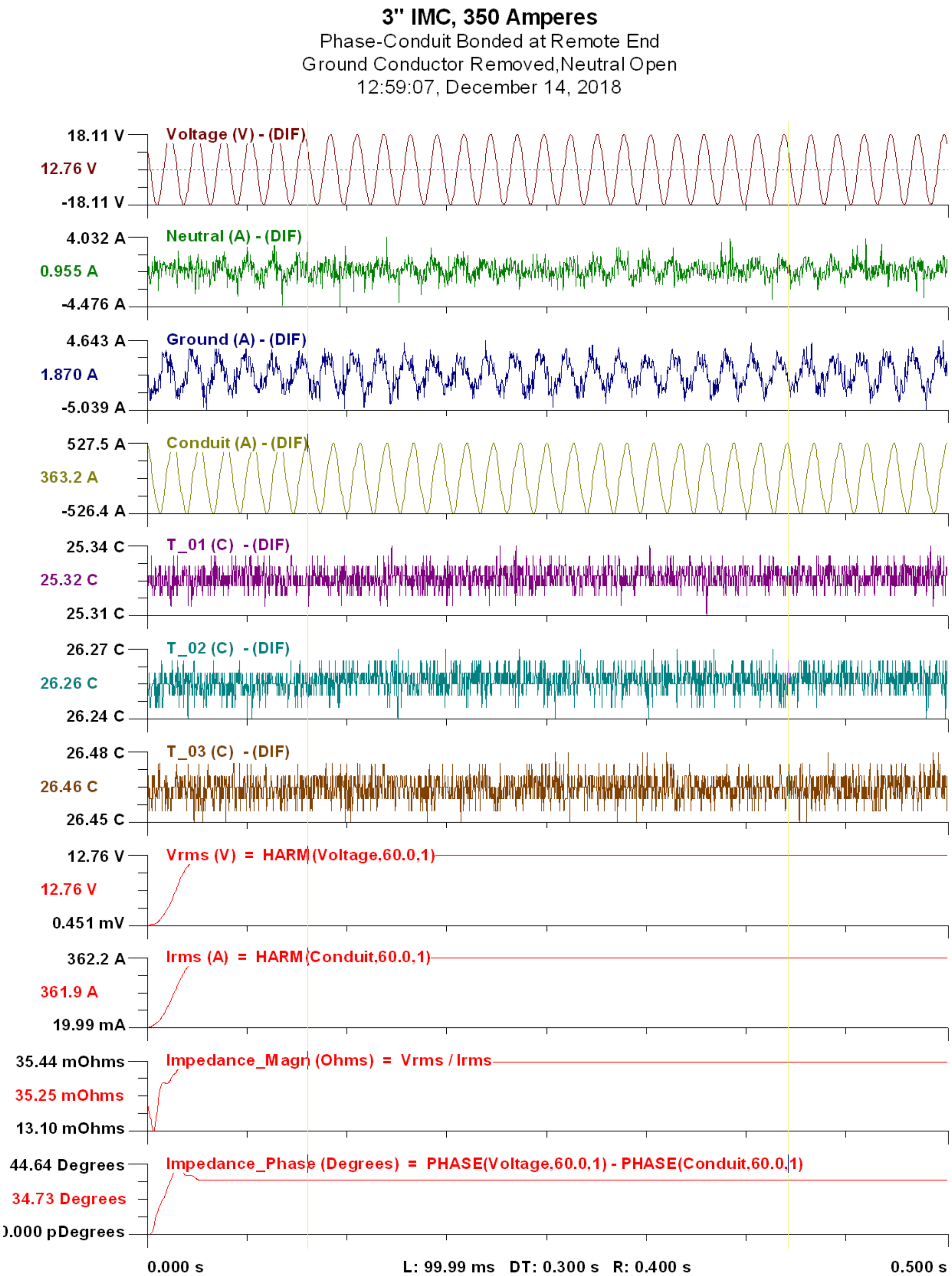


Figure C-12: Case Name IMC300_012

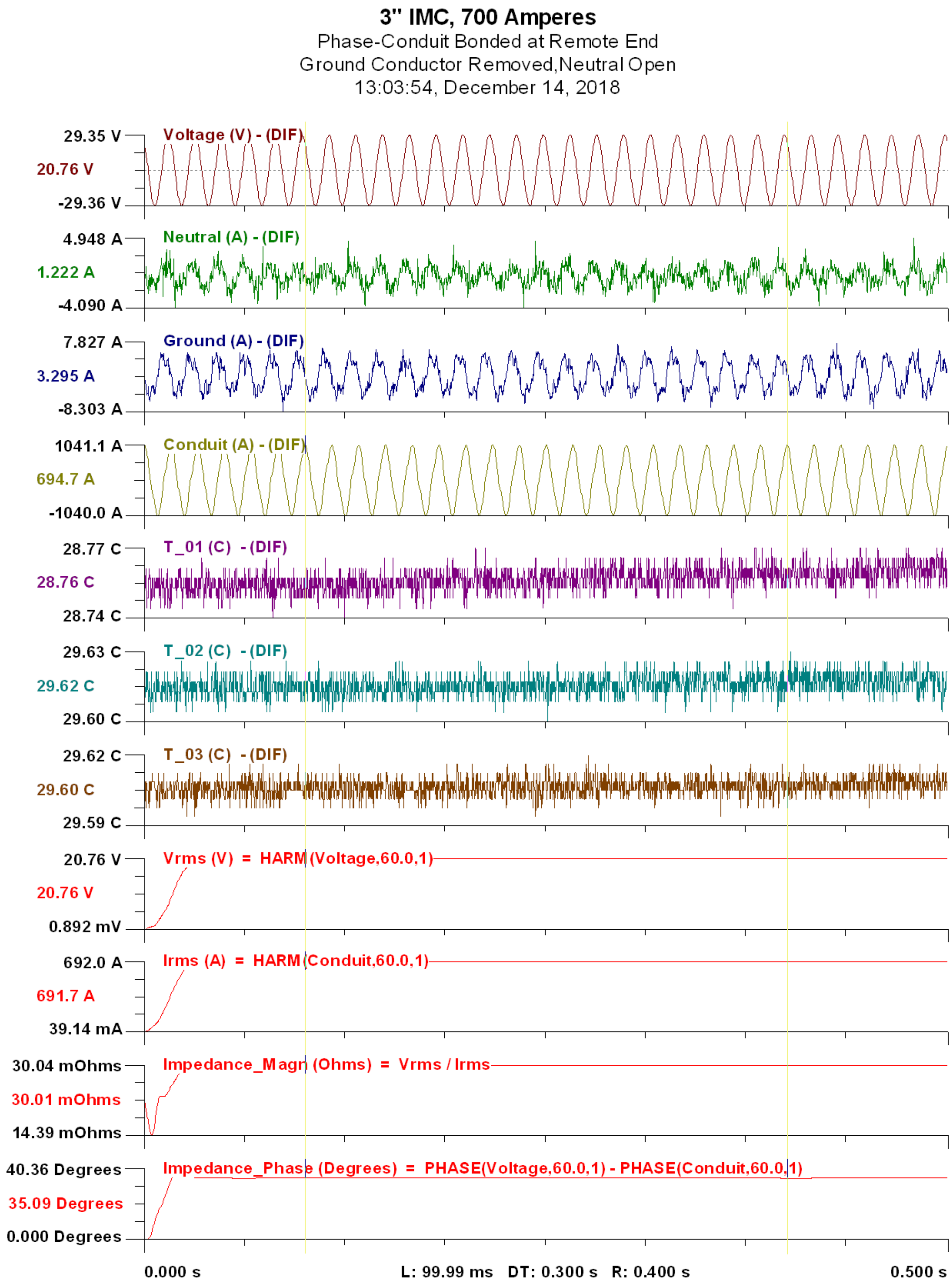


Figure C-13: Case Name IMC300_013

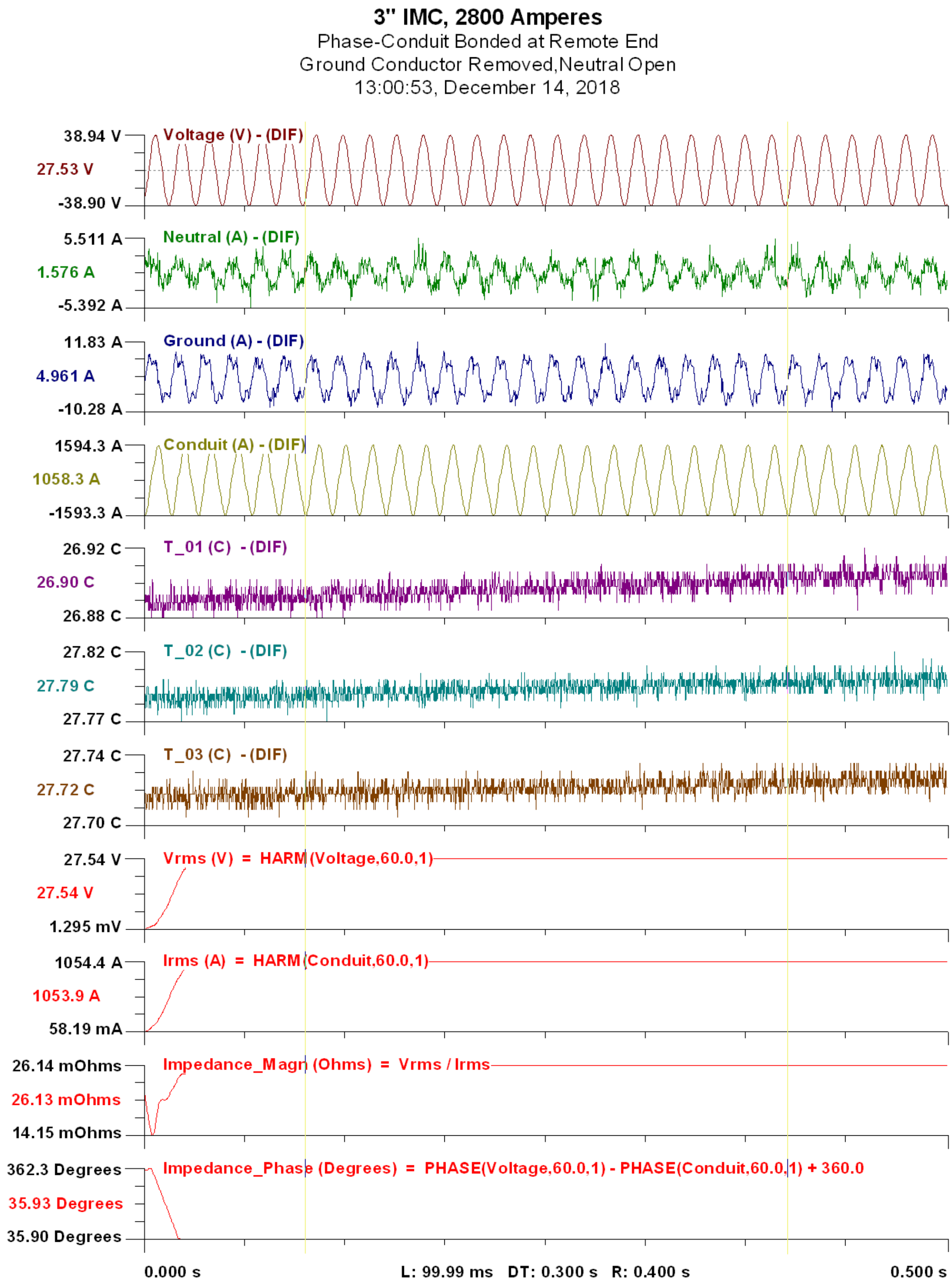


Figure C-14: Case Name IMC300_014

Appendix D – 3” Stainless Steel Raw Data Plots

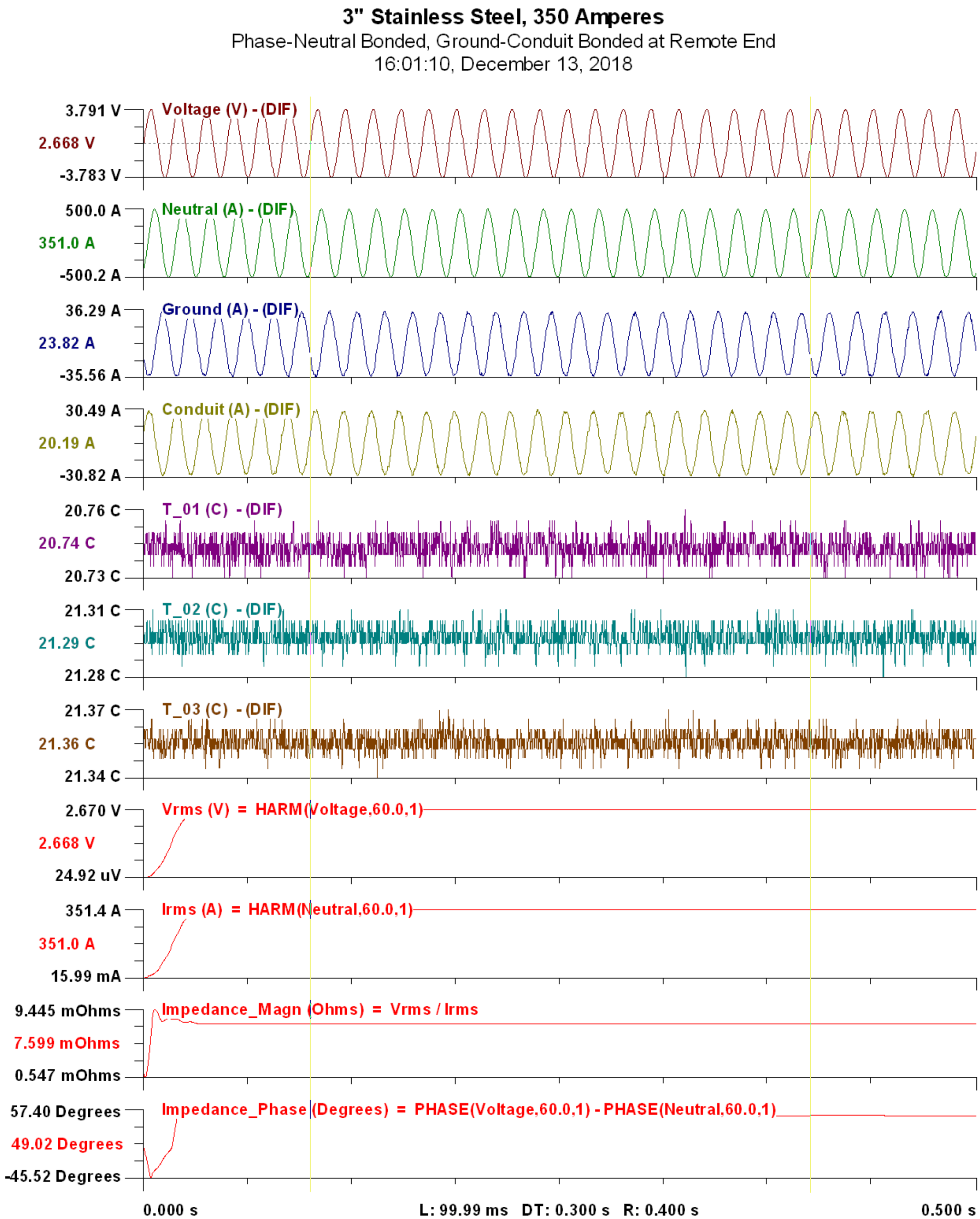


Figure D-1: Case Name STAINLESS300_001

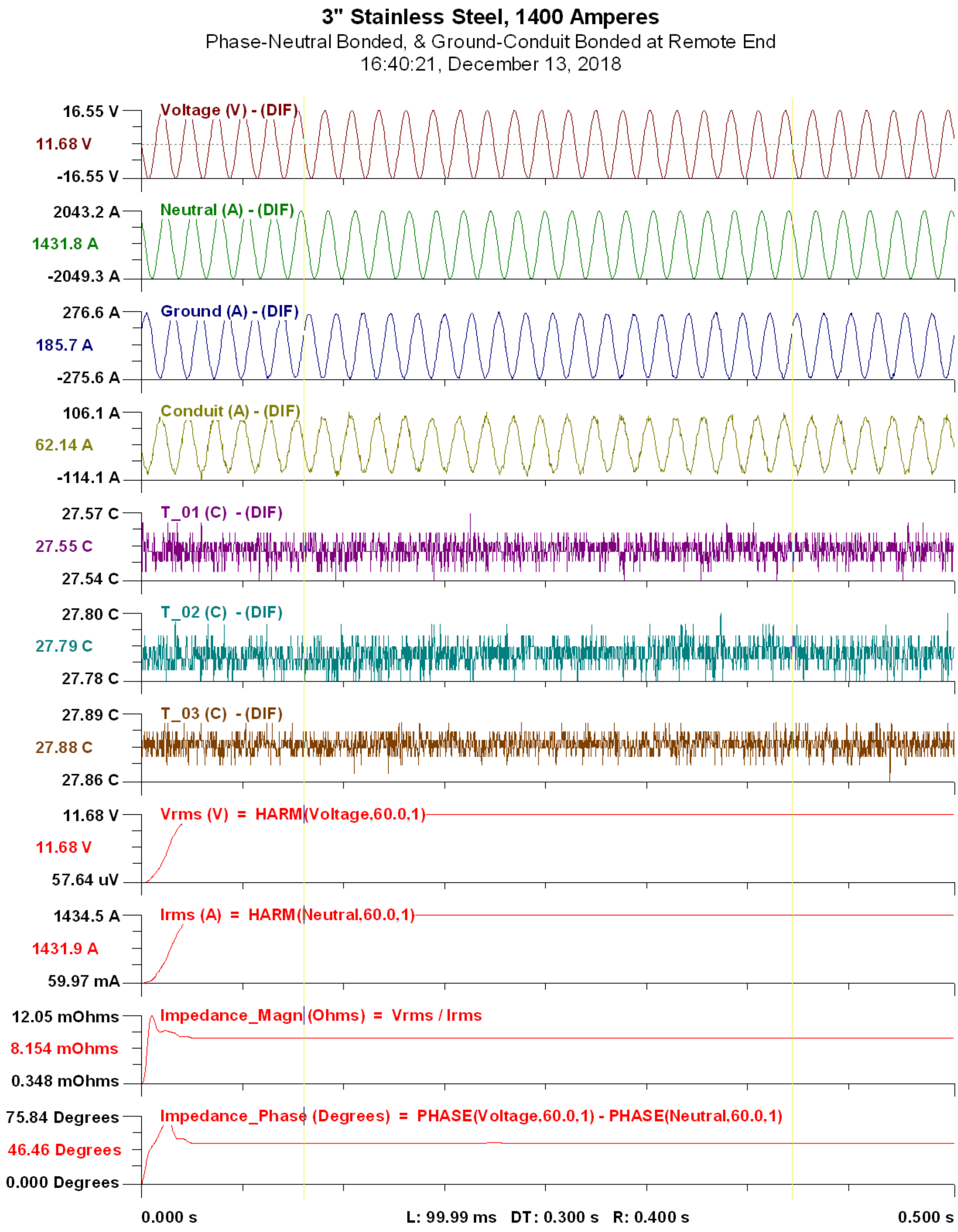


Figure D-1: Case Name STAINLESS300_002

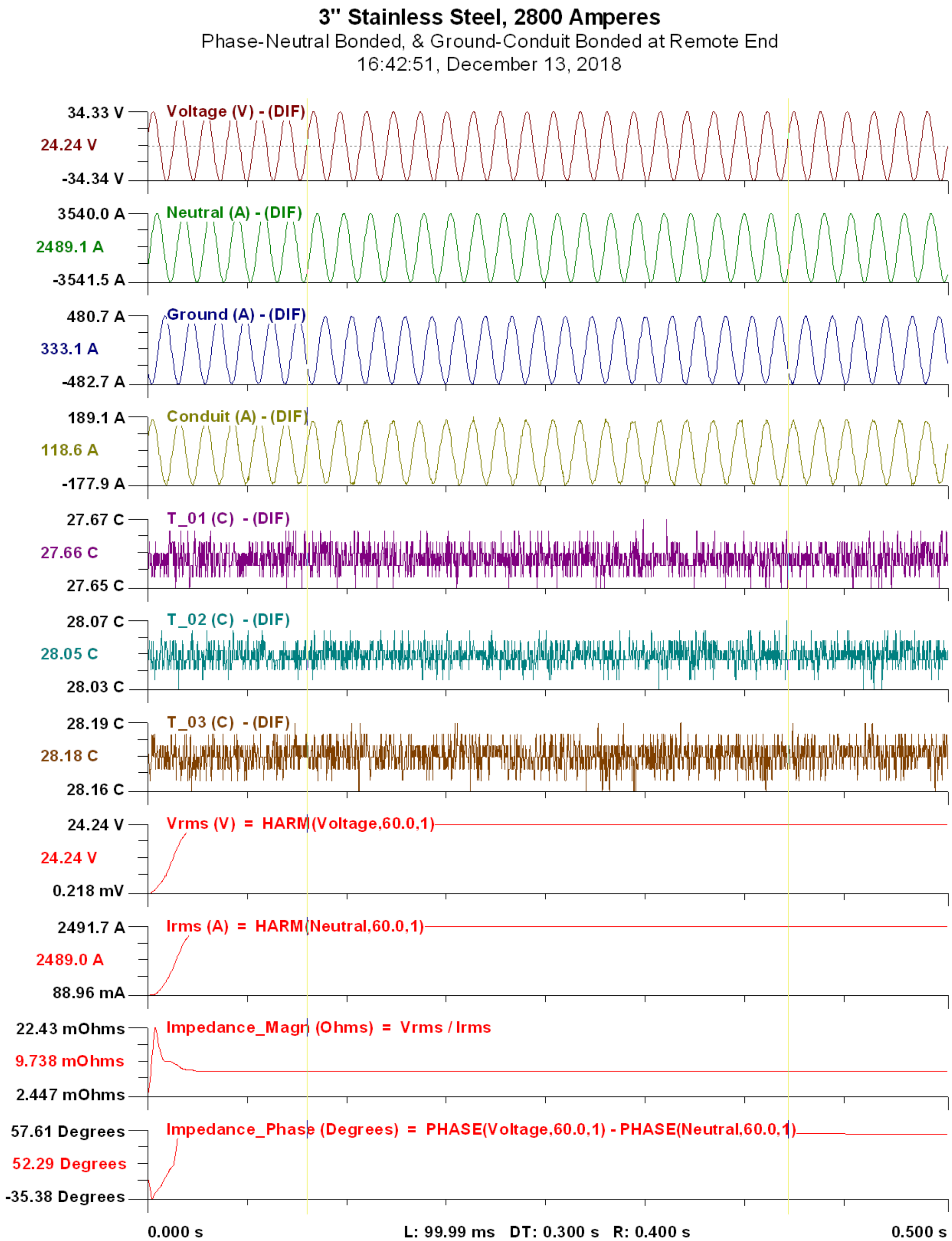


Figure D-1: Case Name STAINLESS300_003

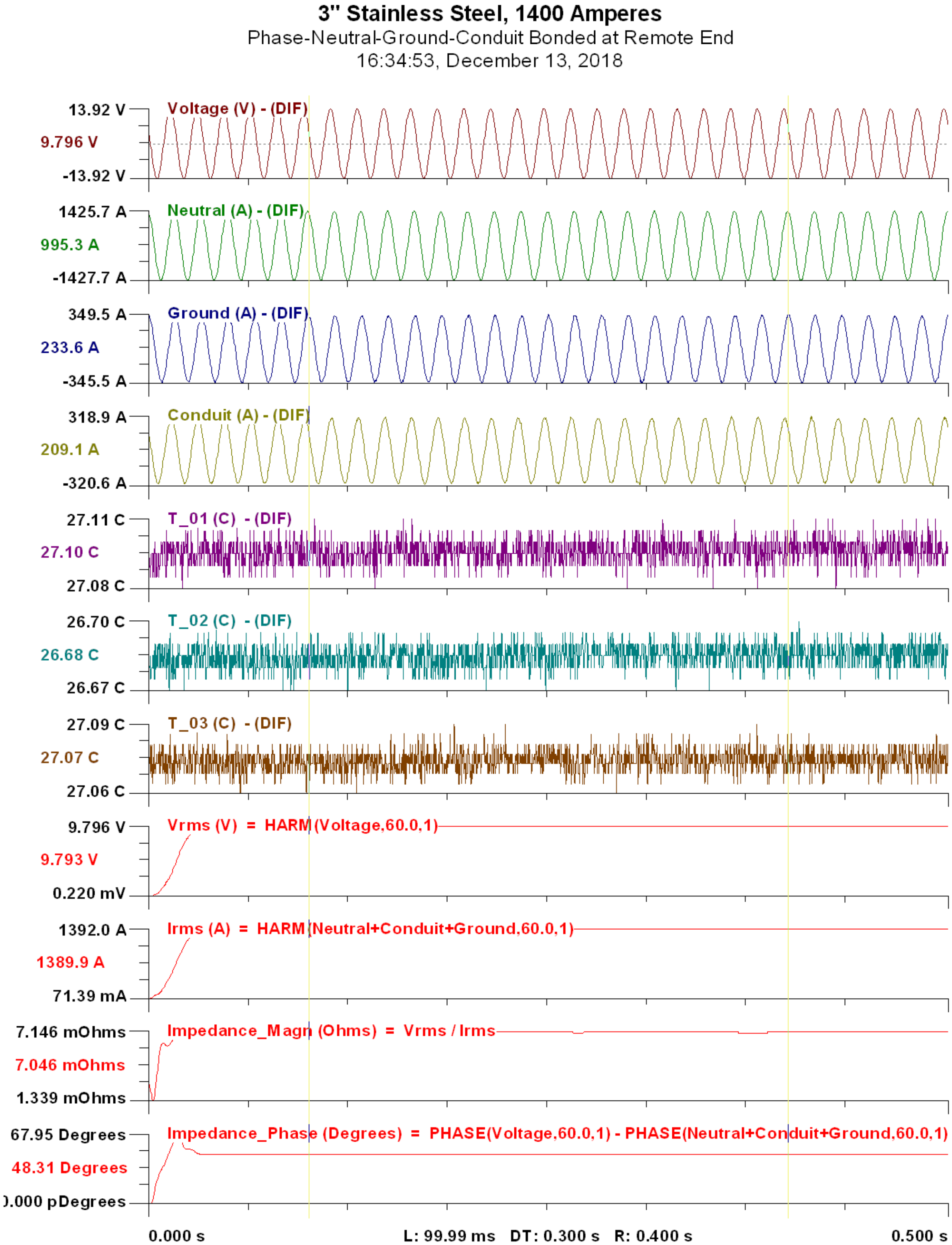


Figure D-1: Case Name STAINLESS300_004

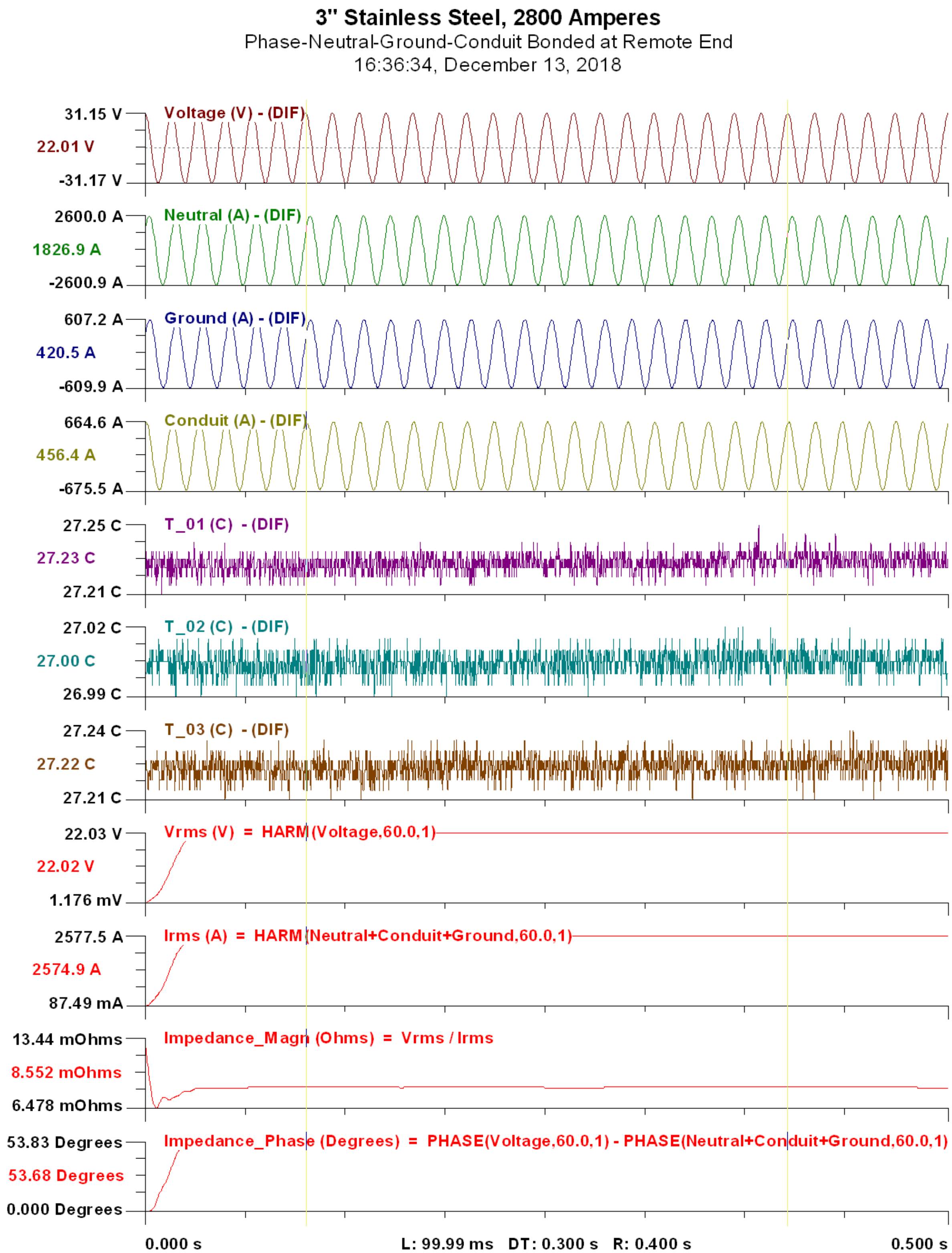


Figure D-1: Case Name STAINLESS300_005

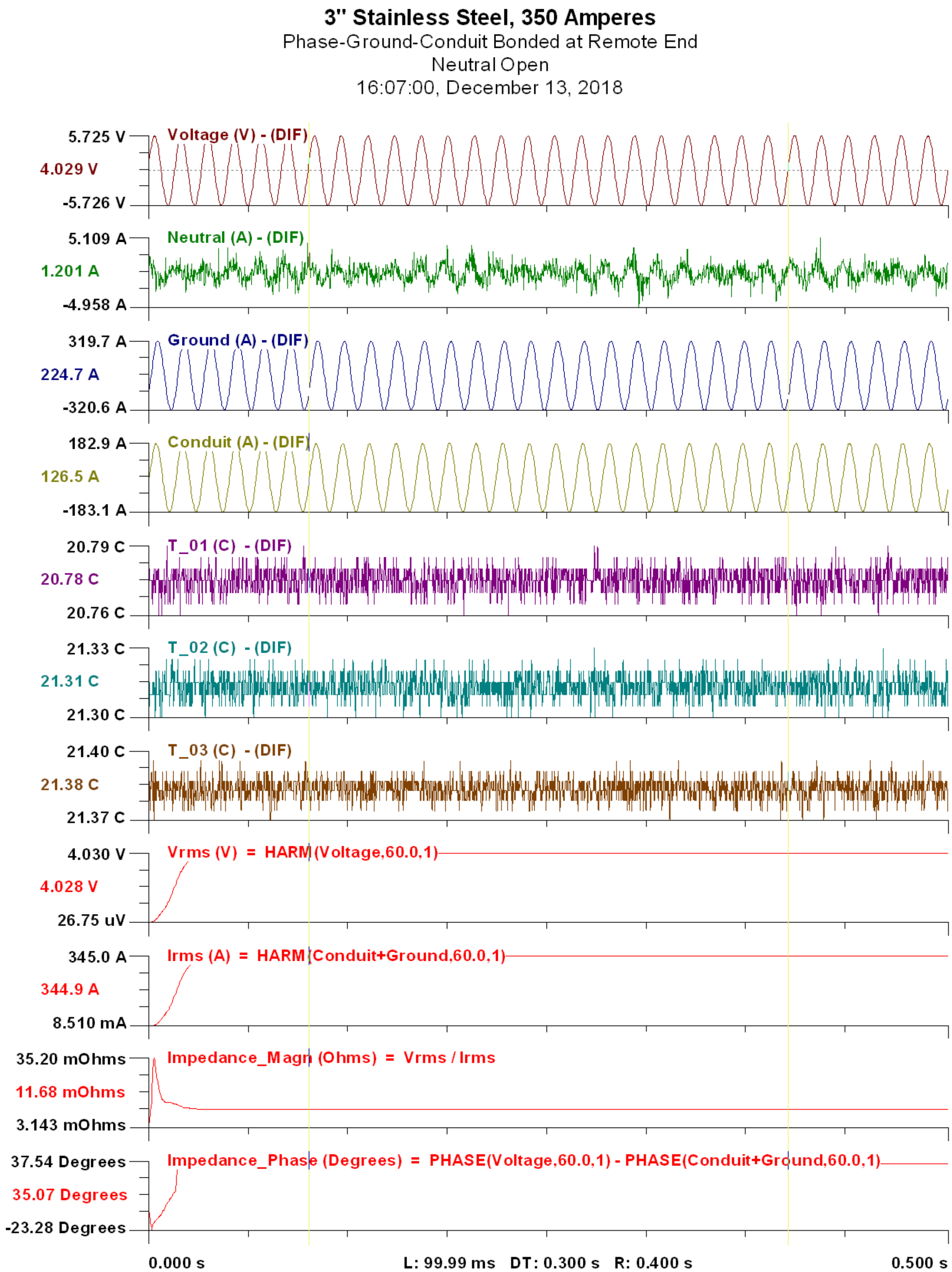


Figure D-1: Case Name STAINLESS300_006

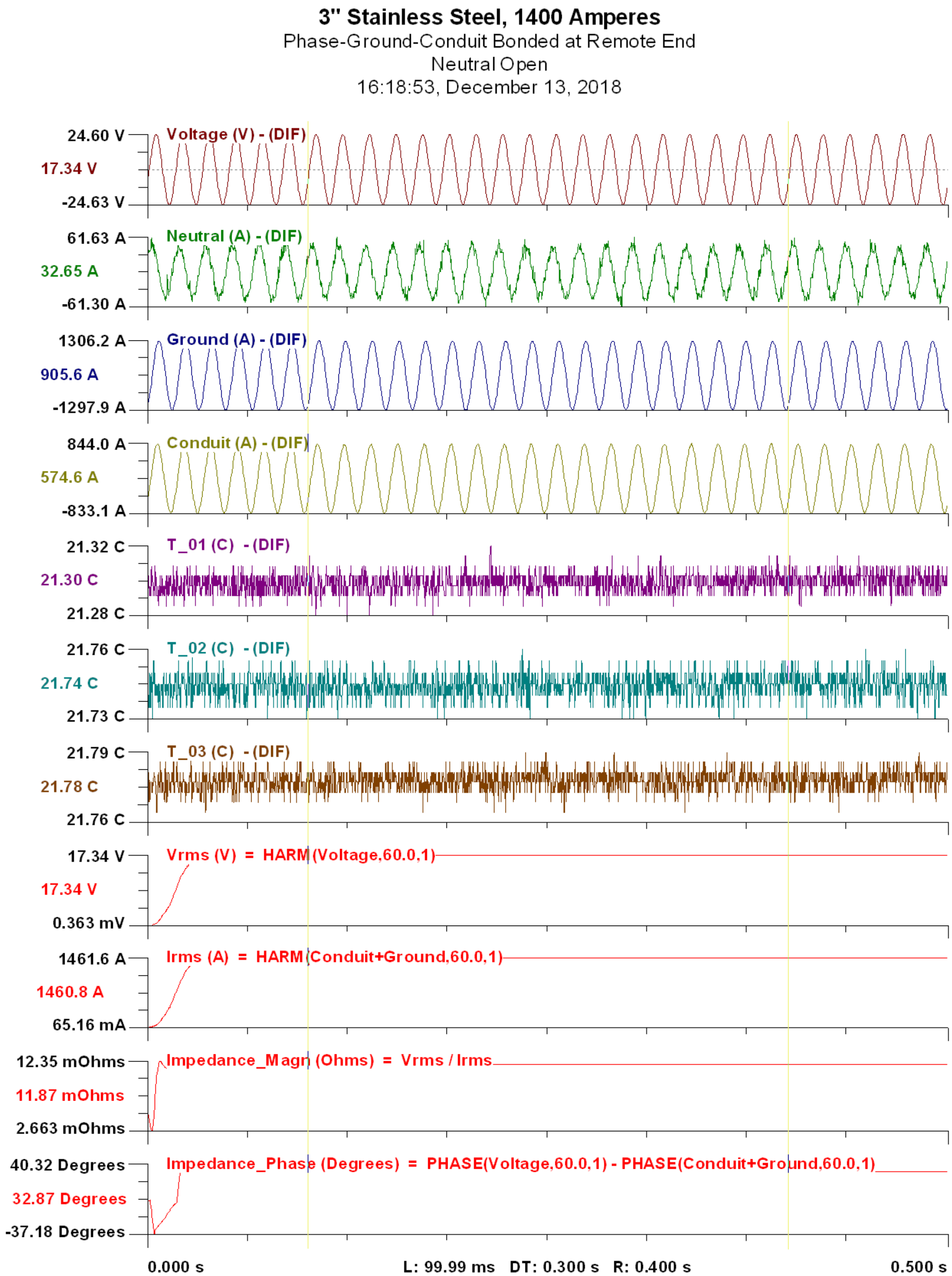


Figure D-1: Case Name STAINLESS300_007

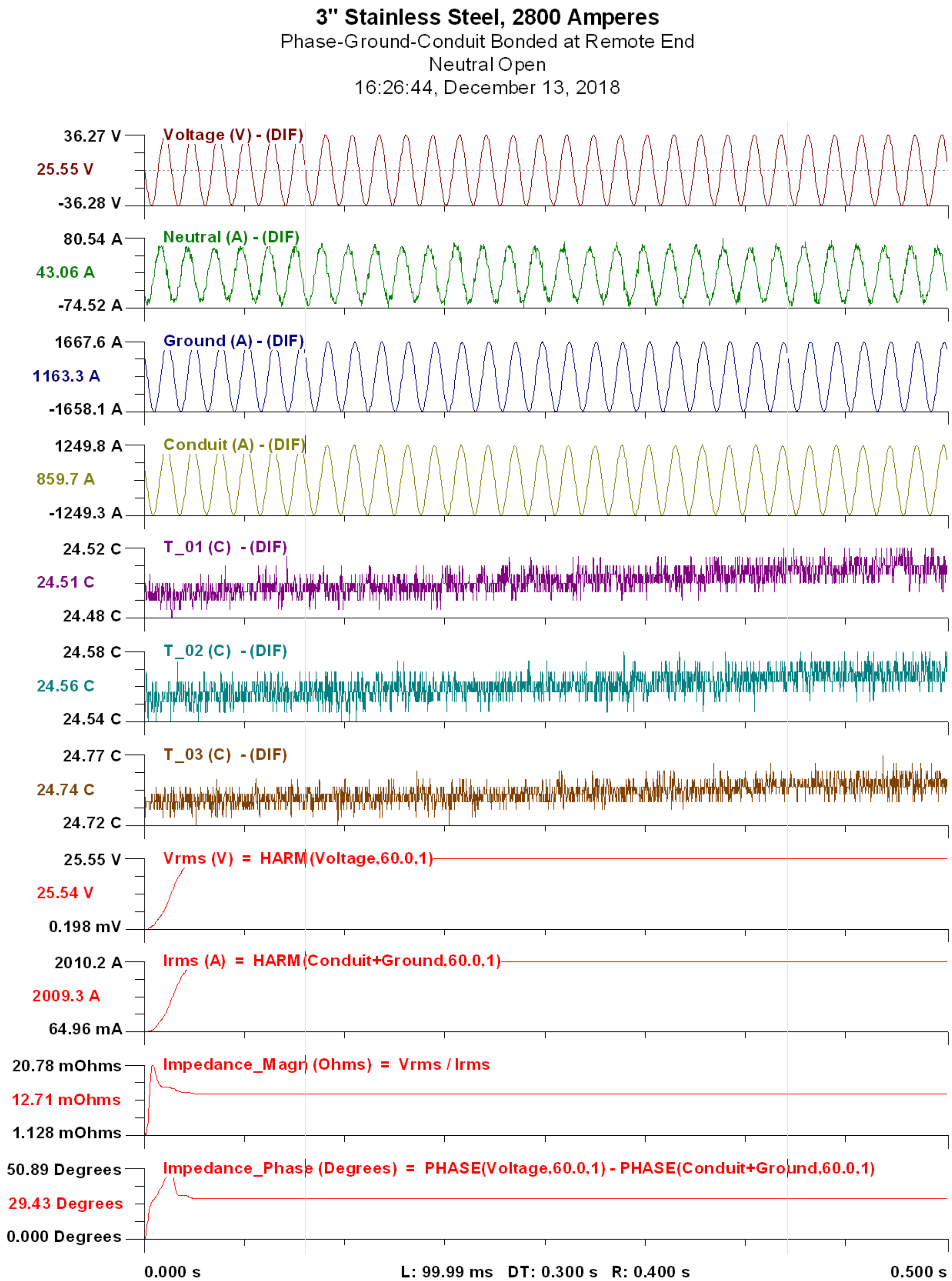


Figure D-1: Case Name STAINLESS300_008

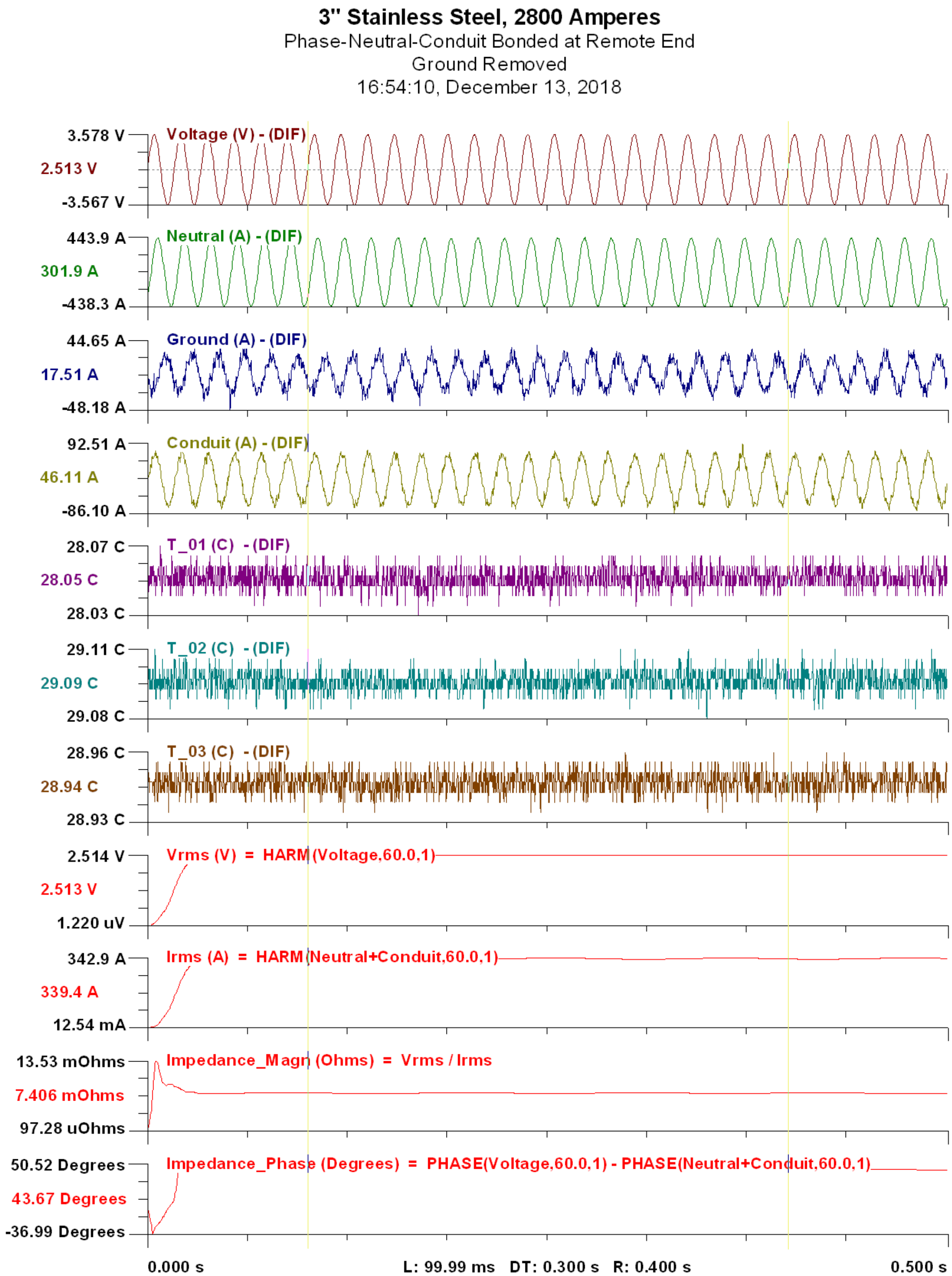


Figure D-1: Case Name STAINLESS300_009

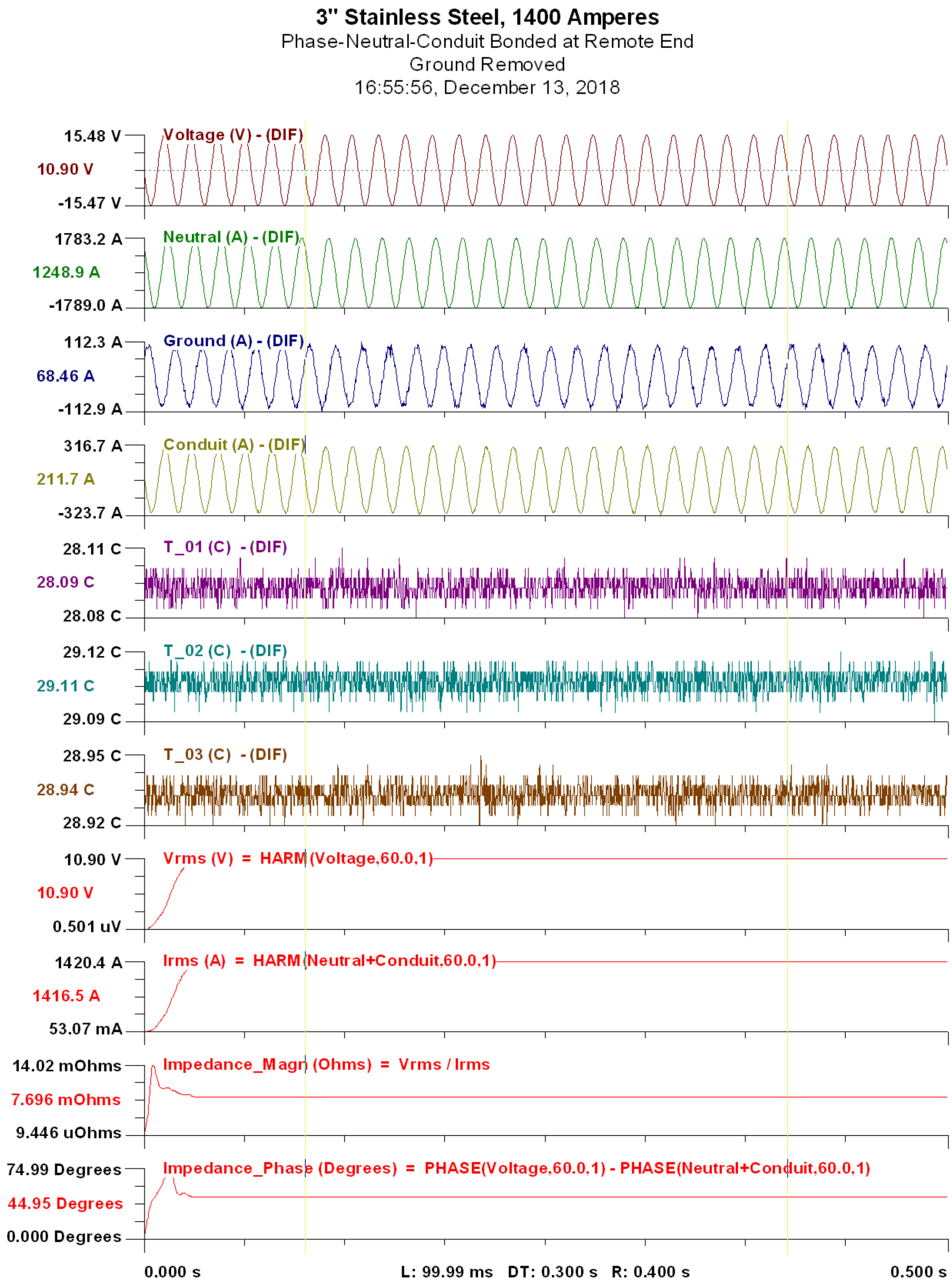


Figure D-1: Case Name STAINLESS300_010

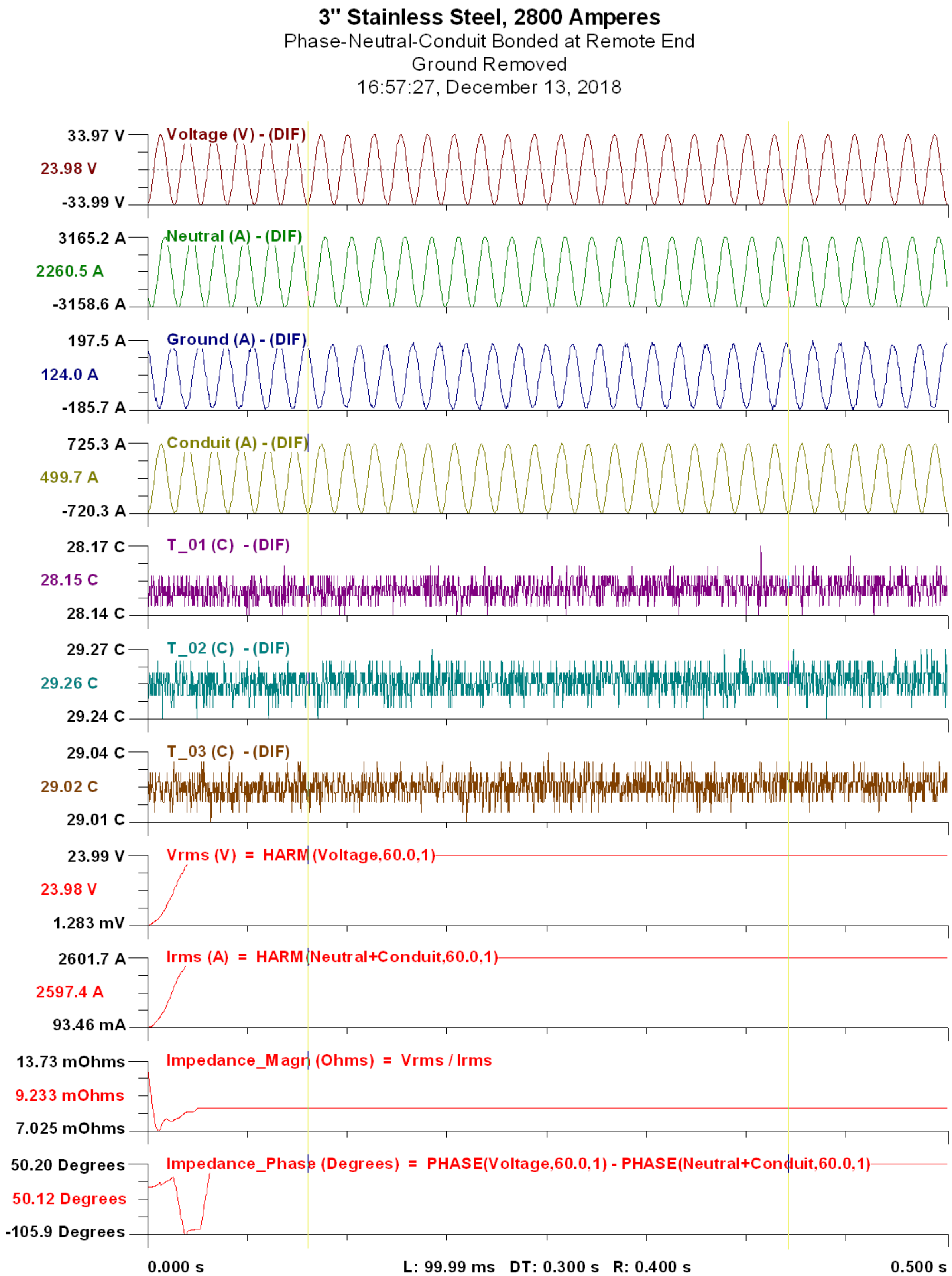


Figure D-1: Case Name STAINLESS300_011

Figure D-1: Case Name STAINLESS300_012

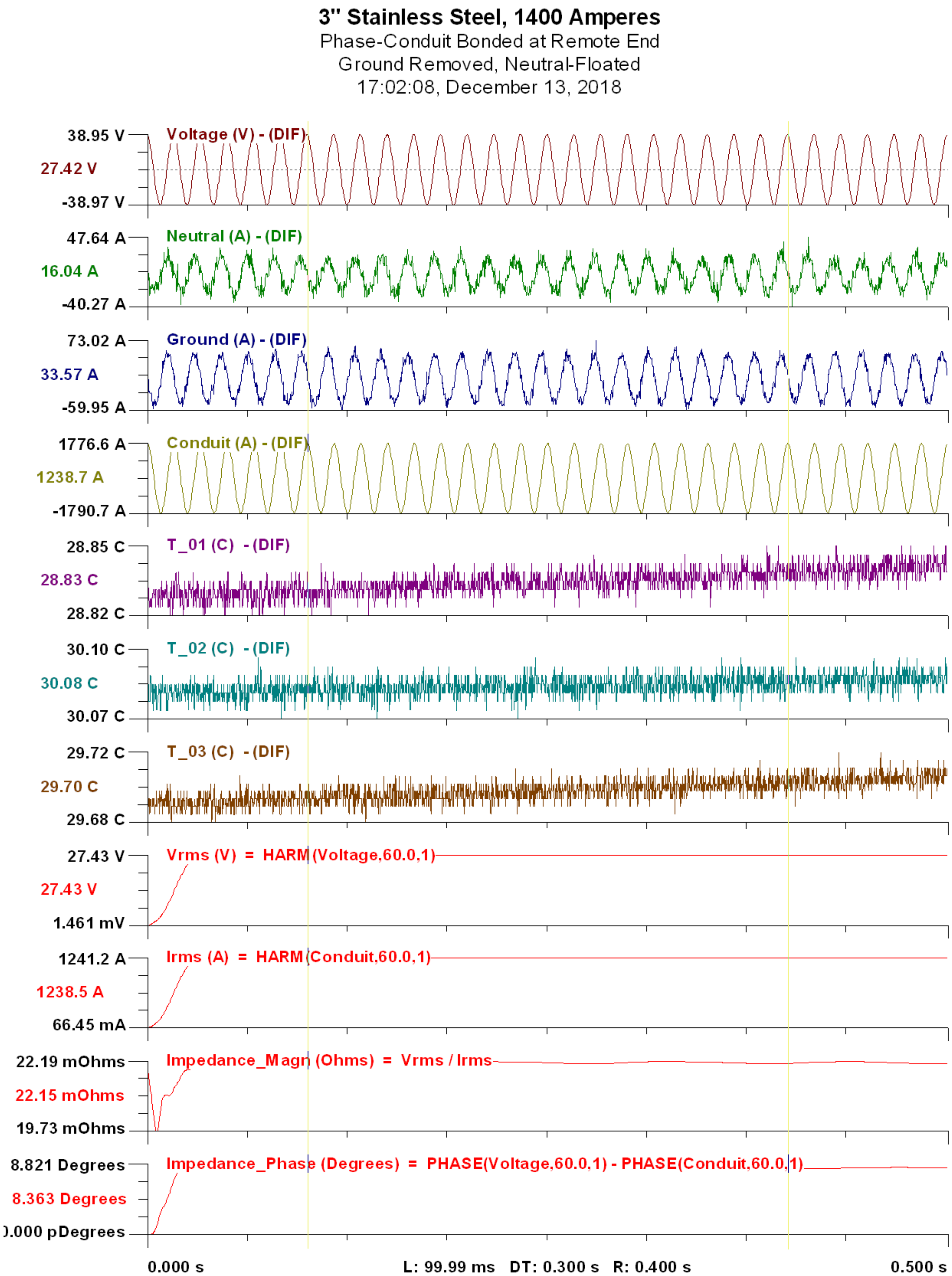


Figure D-1: Case Name STAINLESS300_013

Appendix E – 2” EMT Raw Data Plots

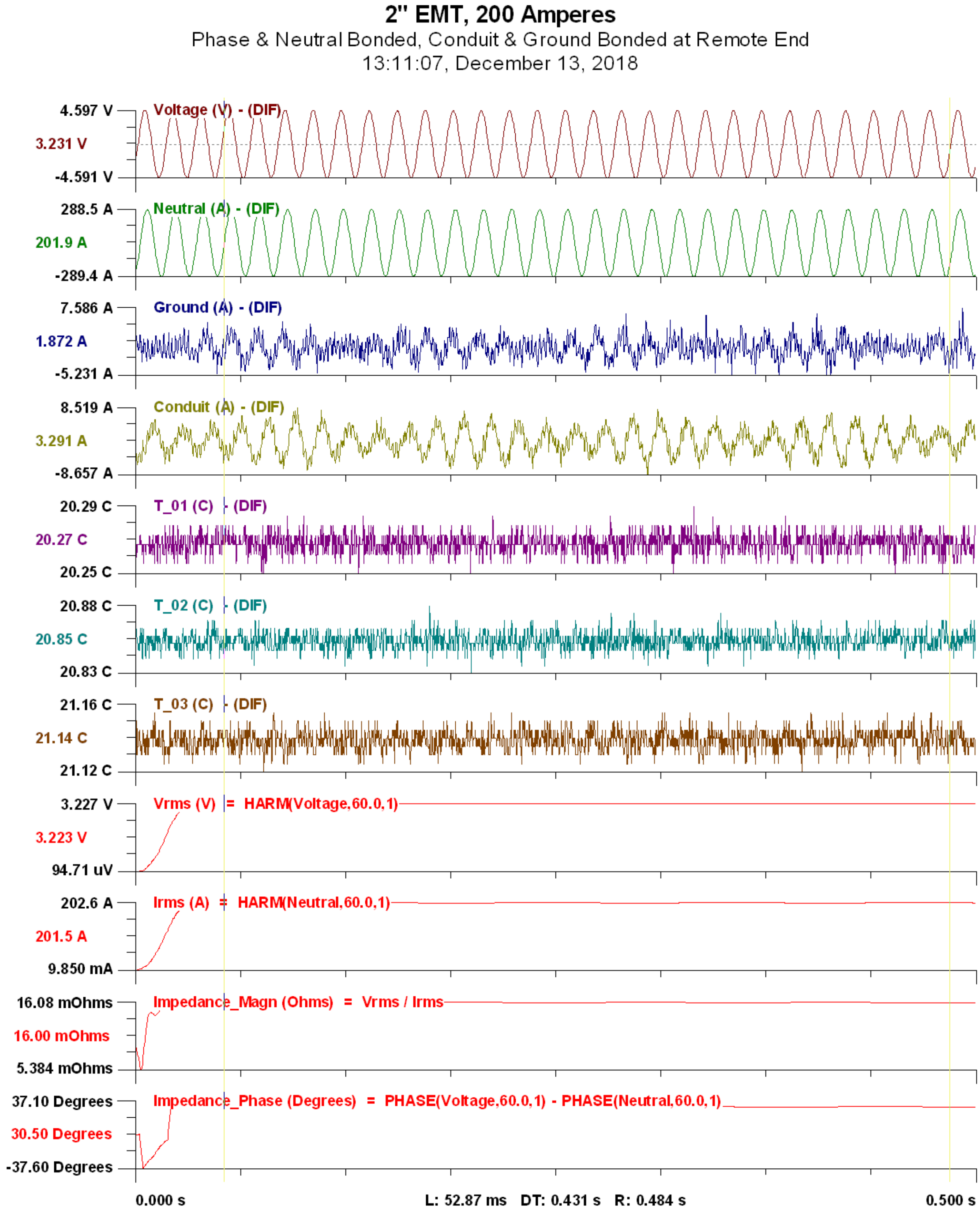


Figure E-1: Case Name EMT200_001

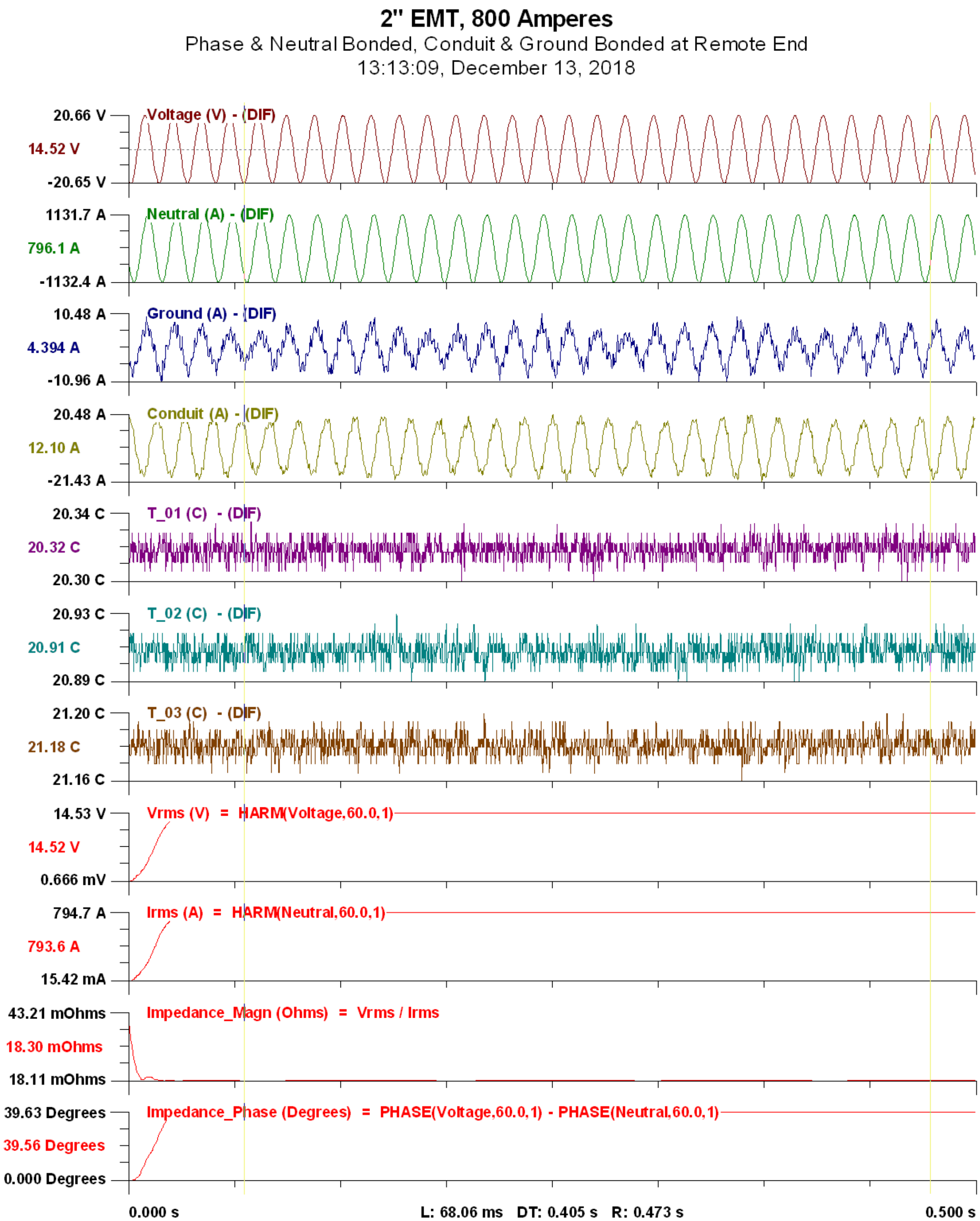


Figure E-2: Case Name EMT200_002

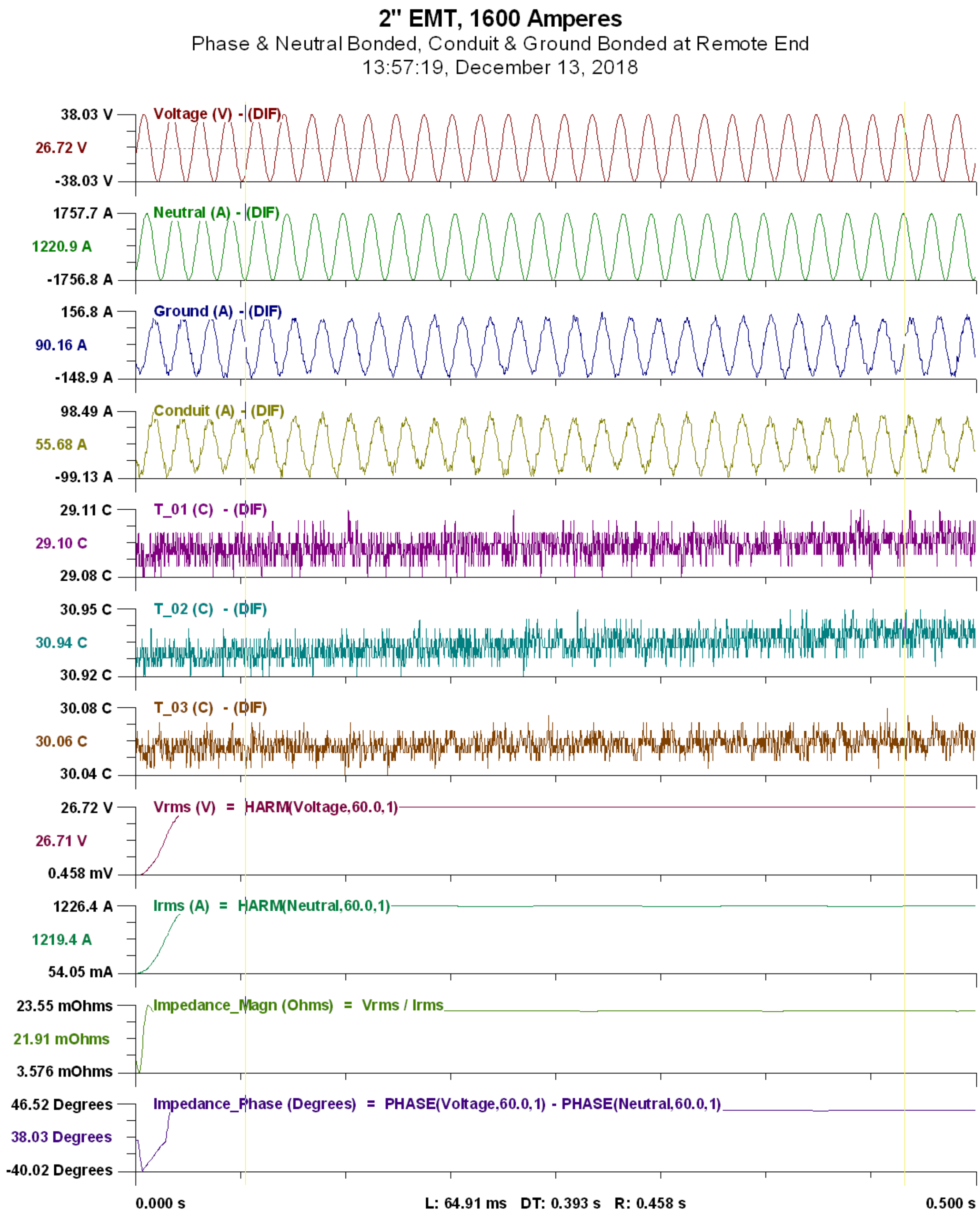


Figure E-3: Case Name EMT200_003

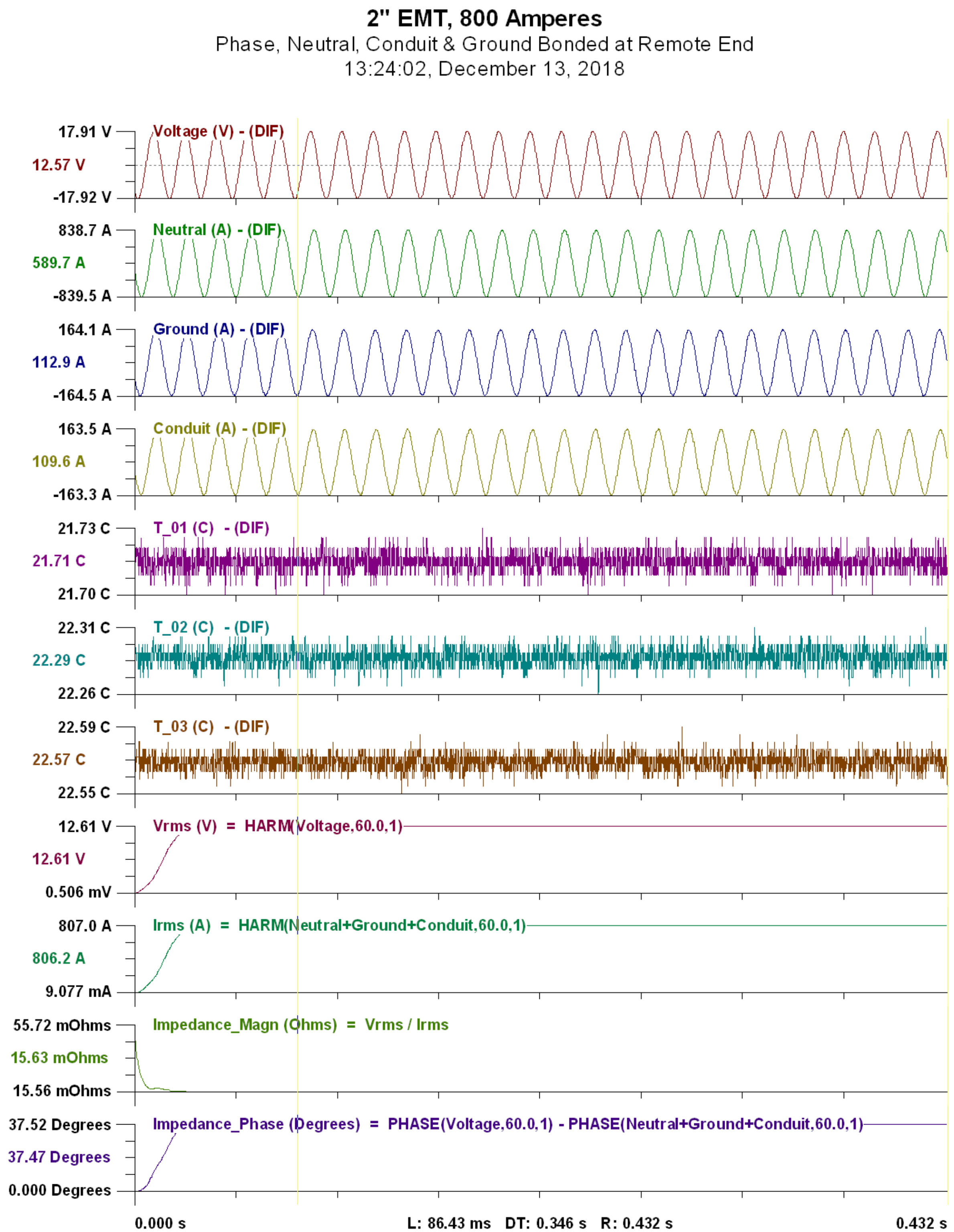


Figure E-4: Case Name EMT200_004

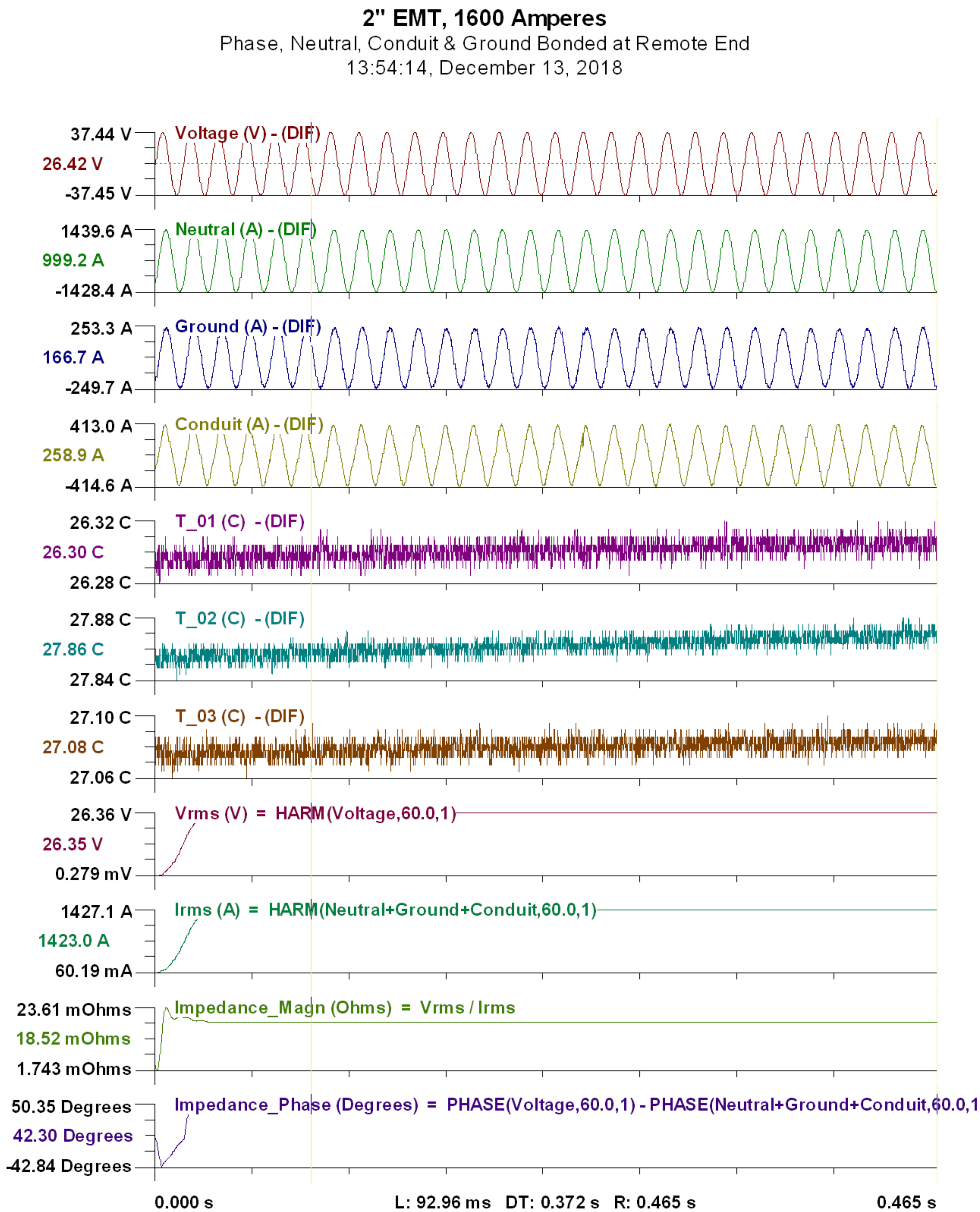


Figure E-5: Case Name EMT200_005

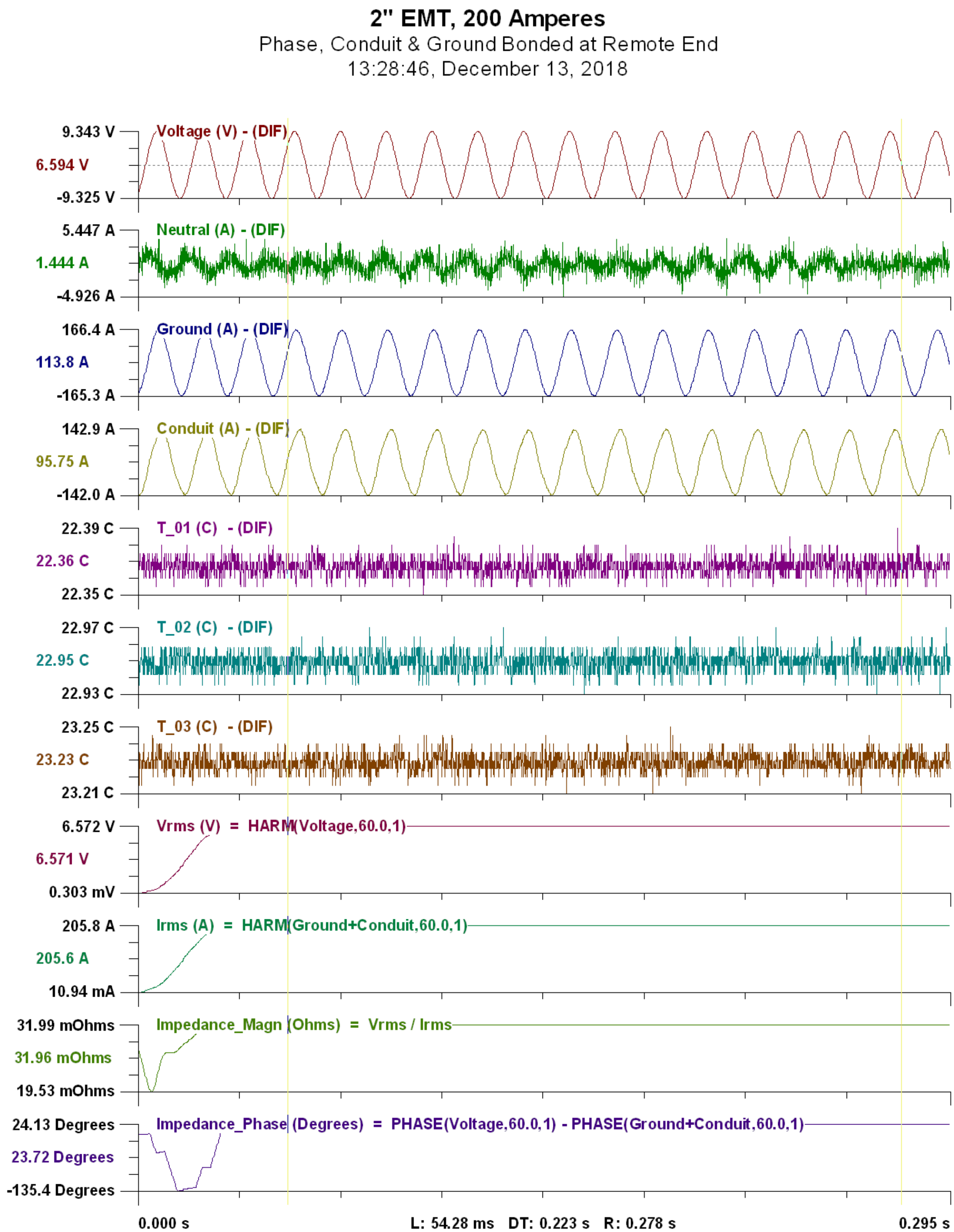


Figure E-6: Case Name EMT200_006

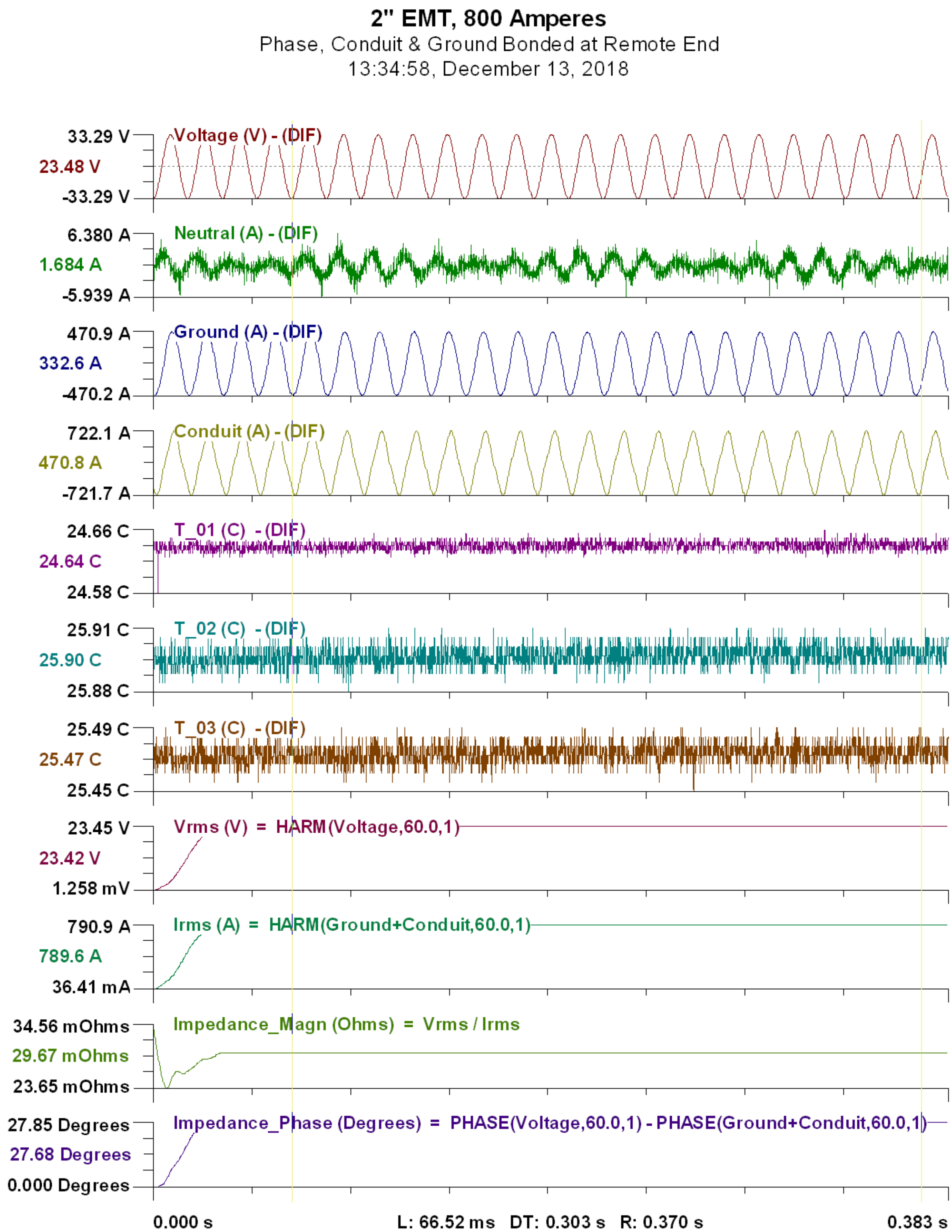


Figure E-7: Case Name EMT200_007

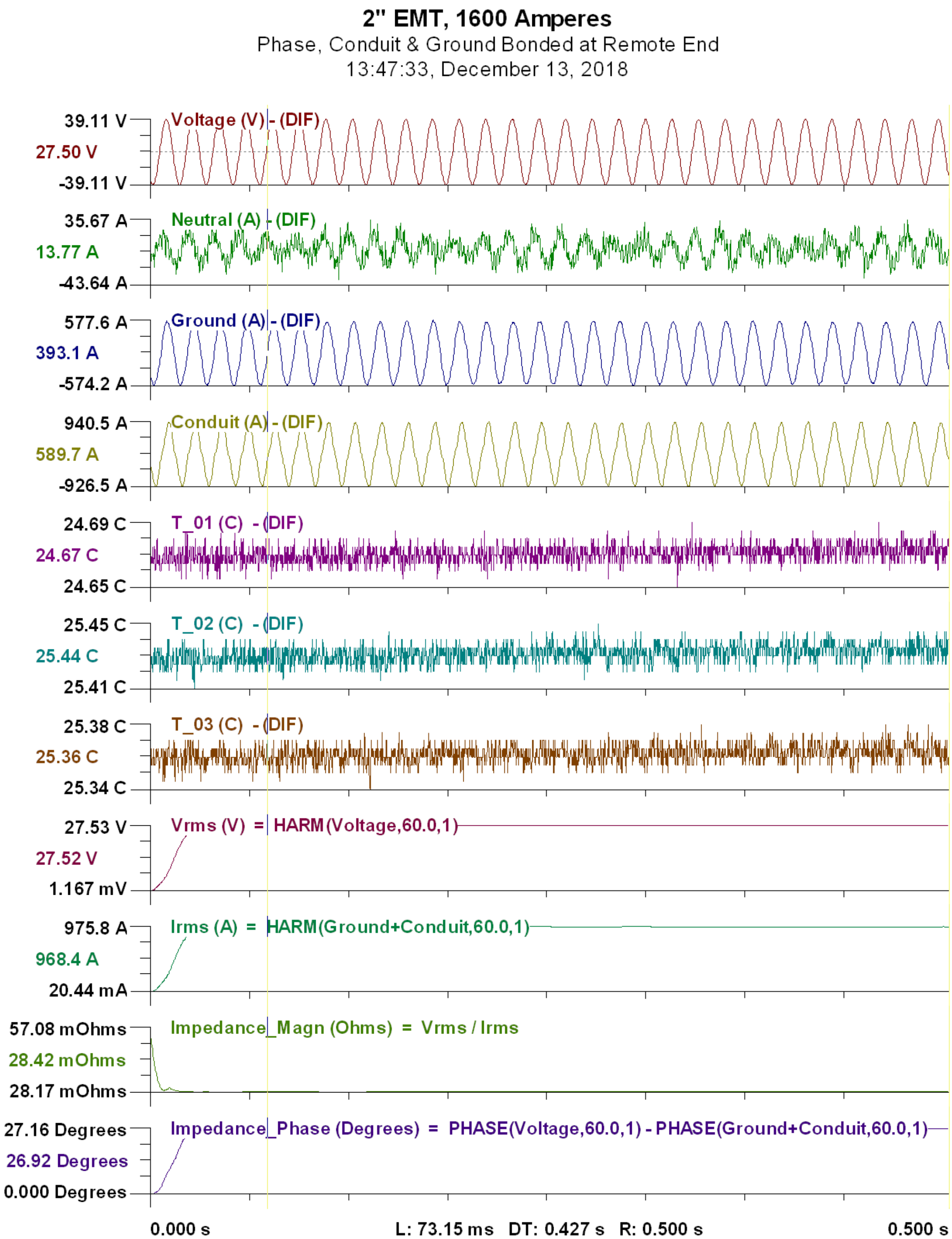


Figure E-8: Case Name EMT200_008

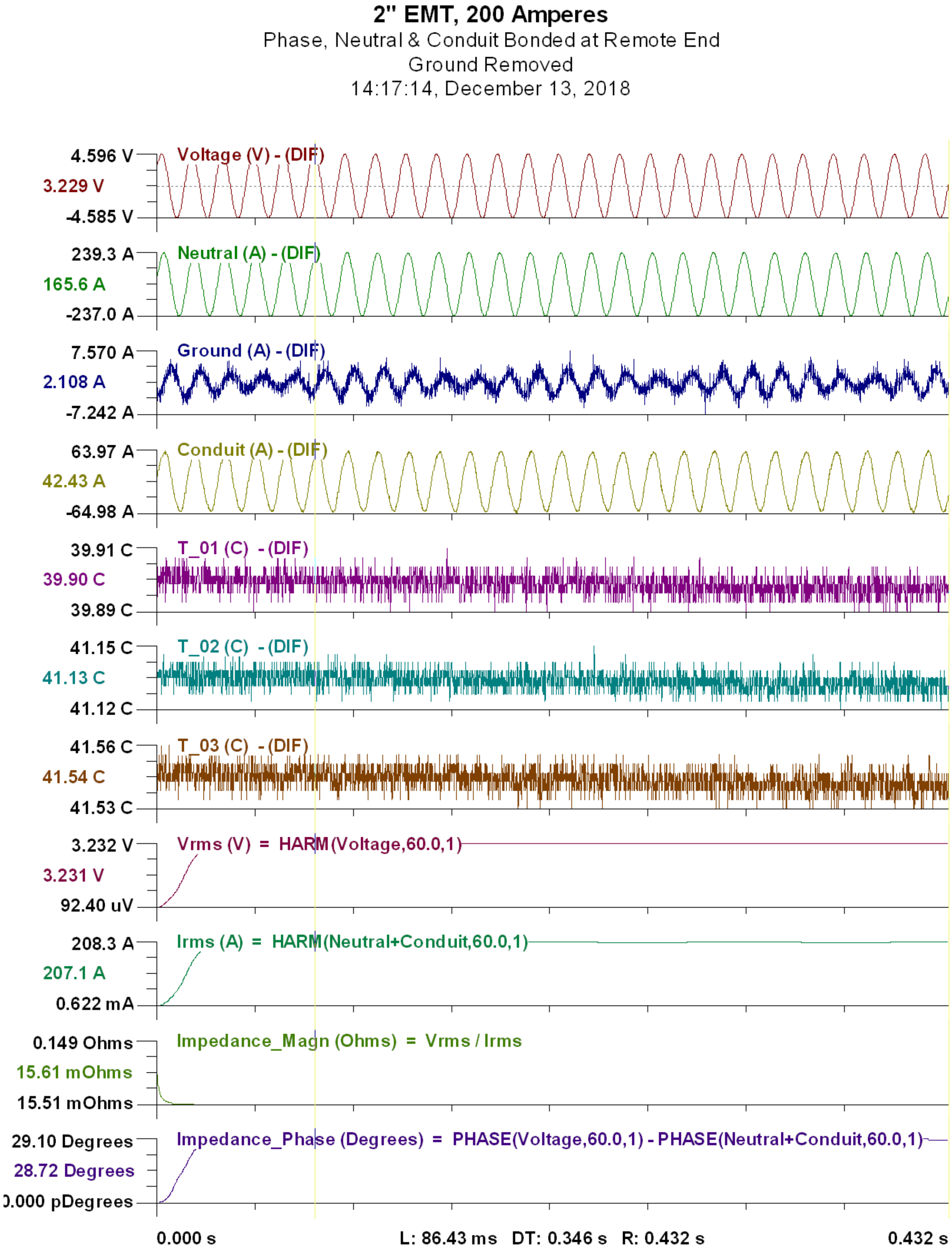


Figure E-9: Case Name EMT200_009

3" GRC, 1400 Amperes

Phase-Neutral-Conduit Bonded at Remote End

Ground Conductor Removed

16:31:21, December 14, 2018

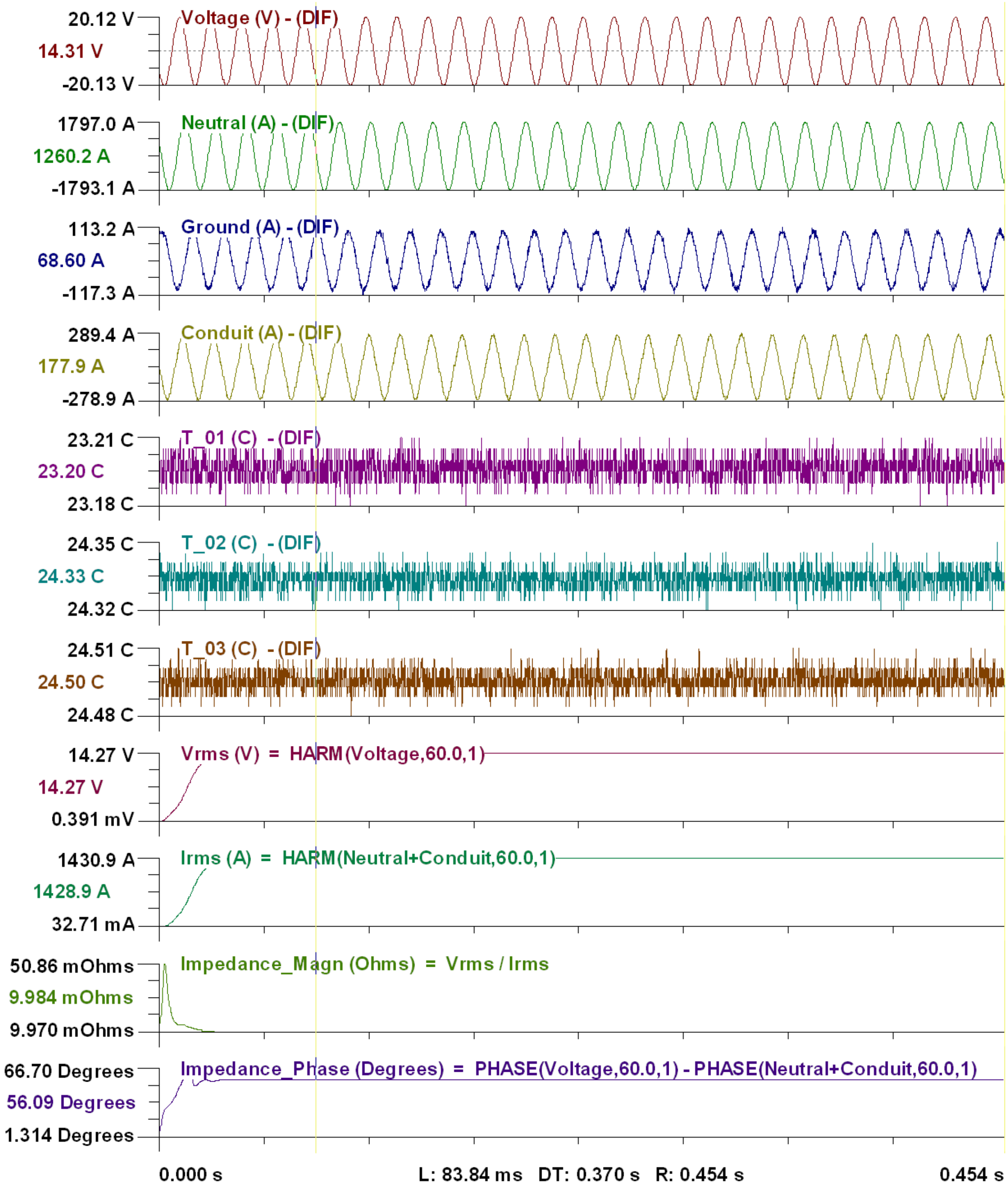


Figure E-10: Case Name EMT200_010

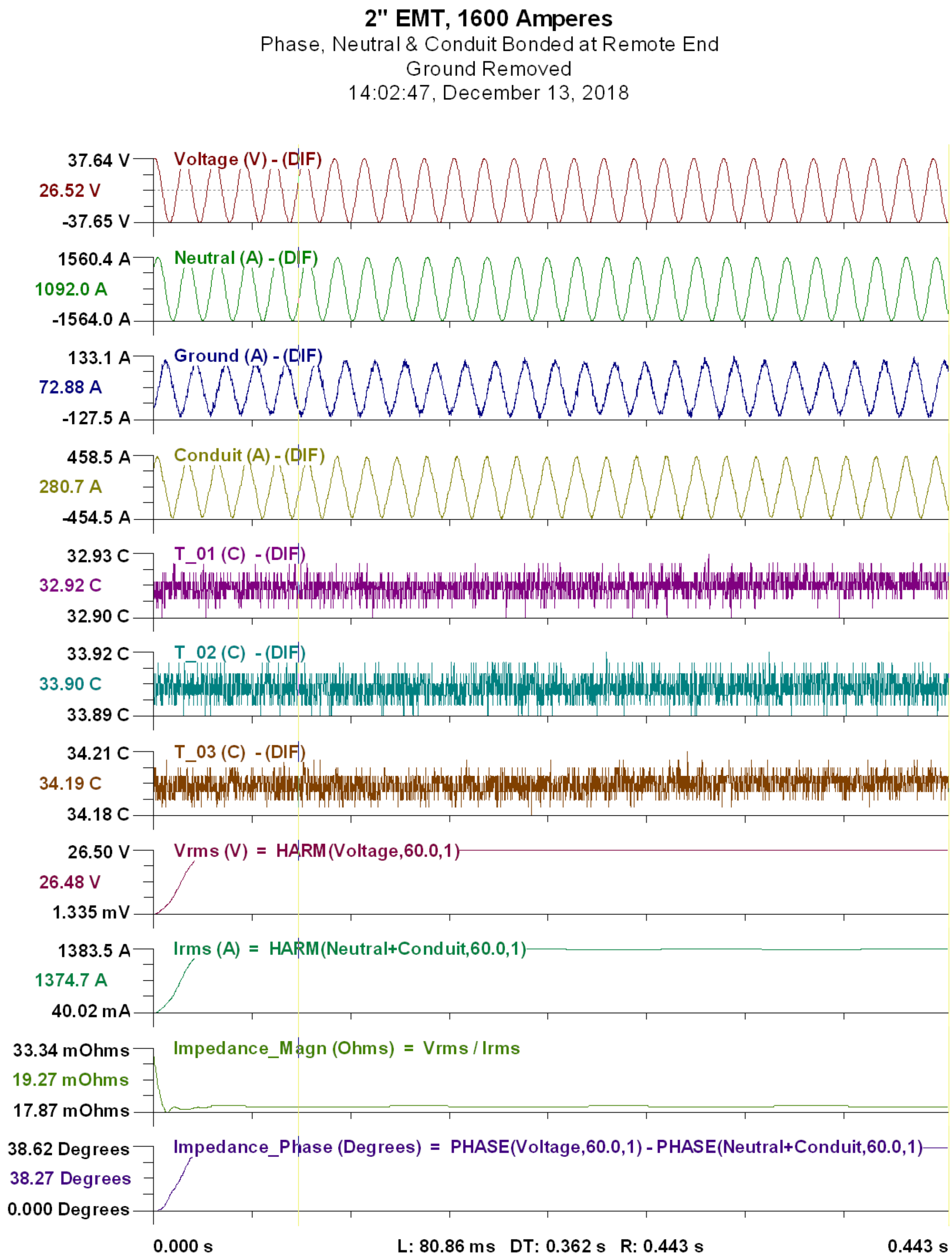


Figure E-11: Case Name EMT200_011

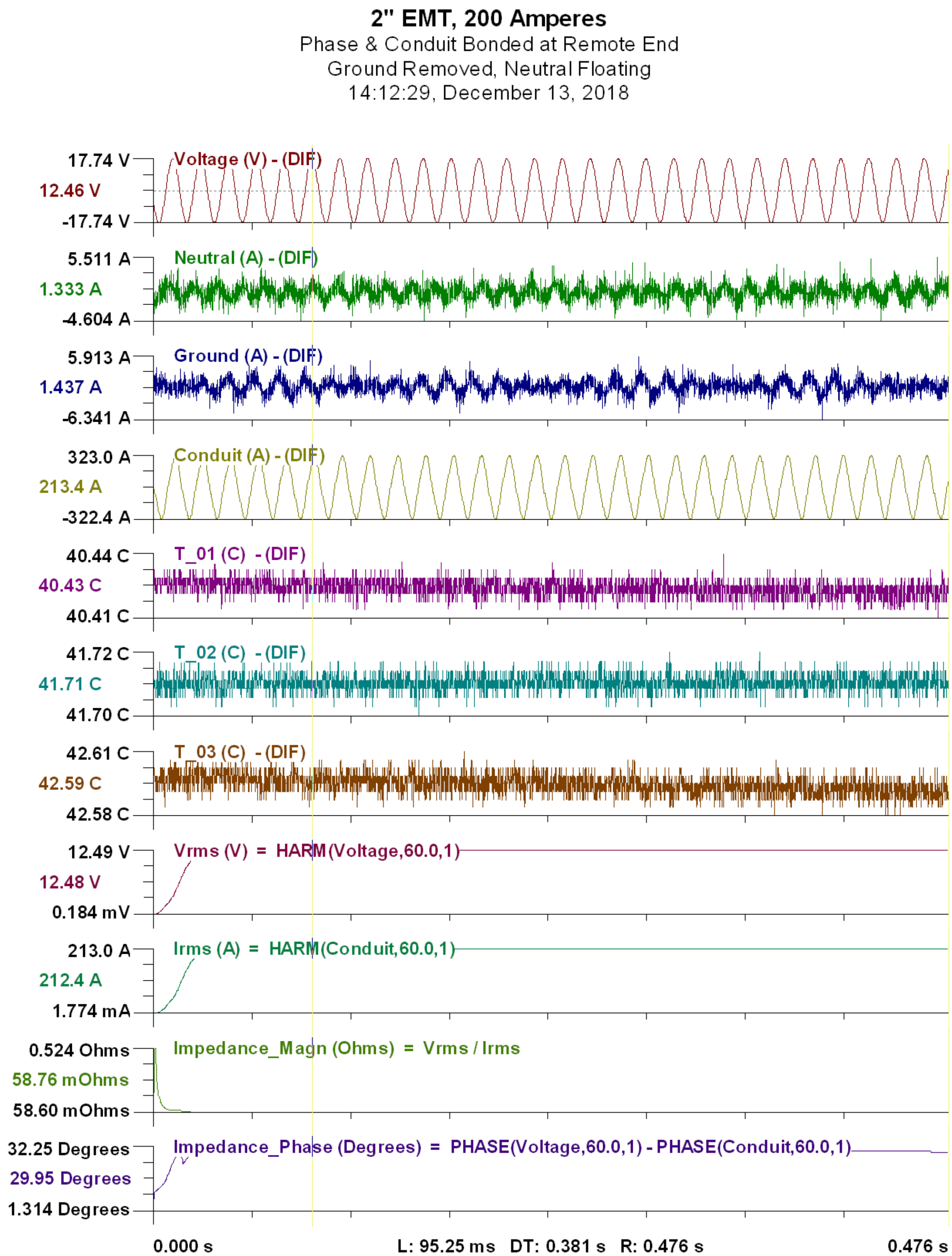


Figure E-12: Case Name EMT200_012

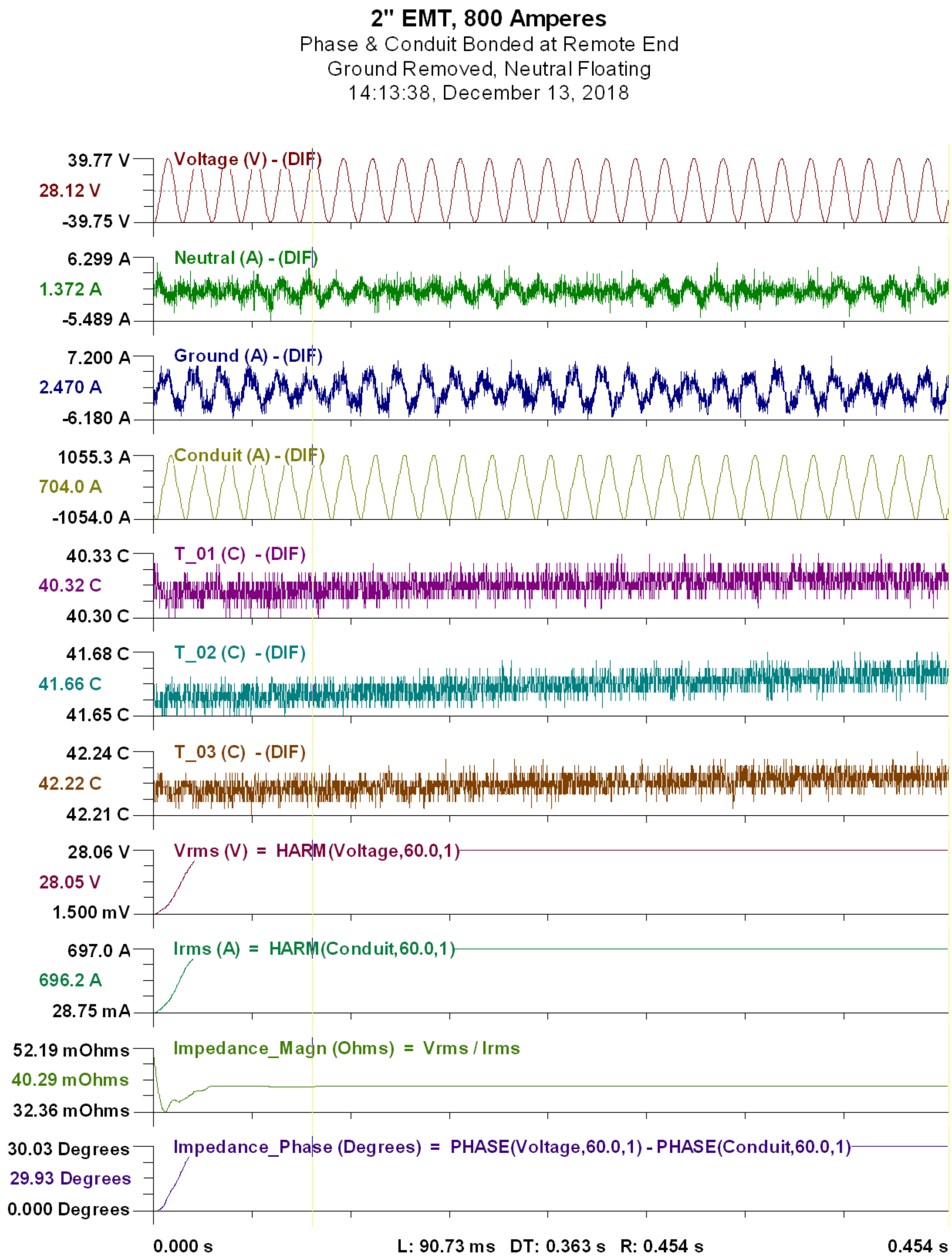


Figure E-13: Case Name EMT200_013

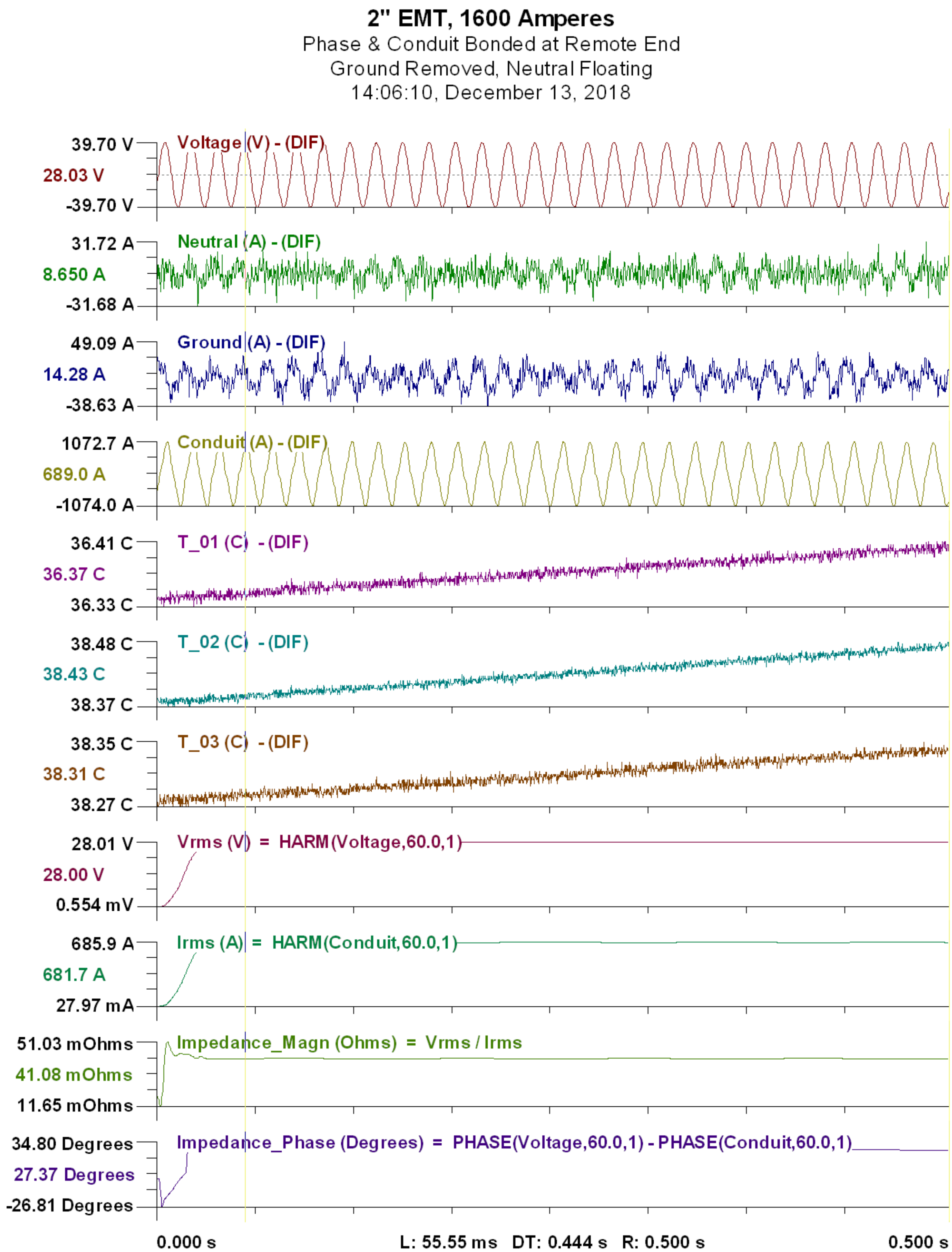


Figure E-14: Case Name EMT200_014

Appendix F – 2” GRC Raw Data Plots

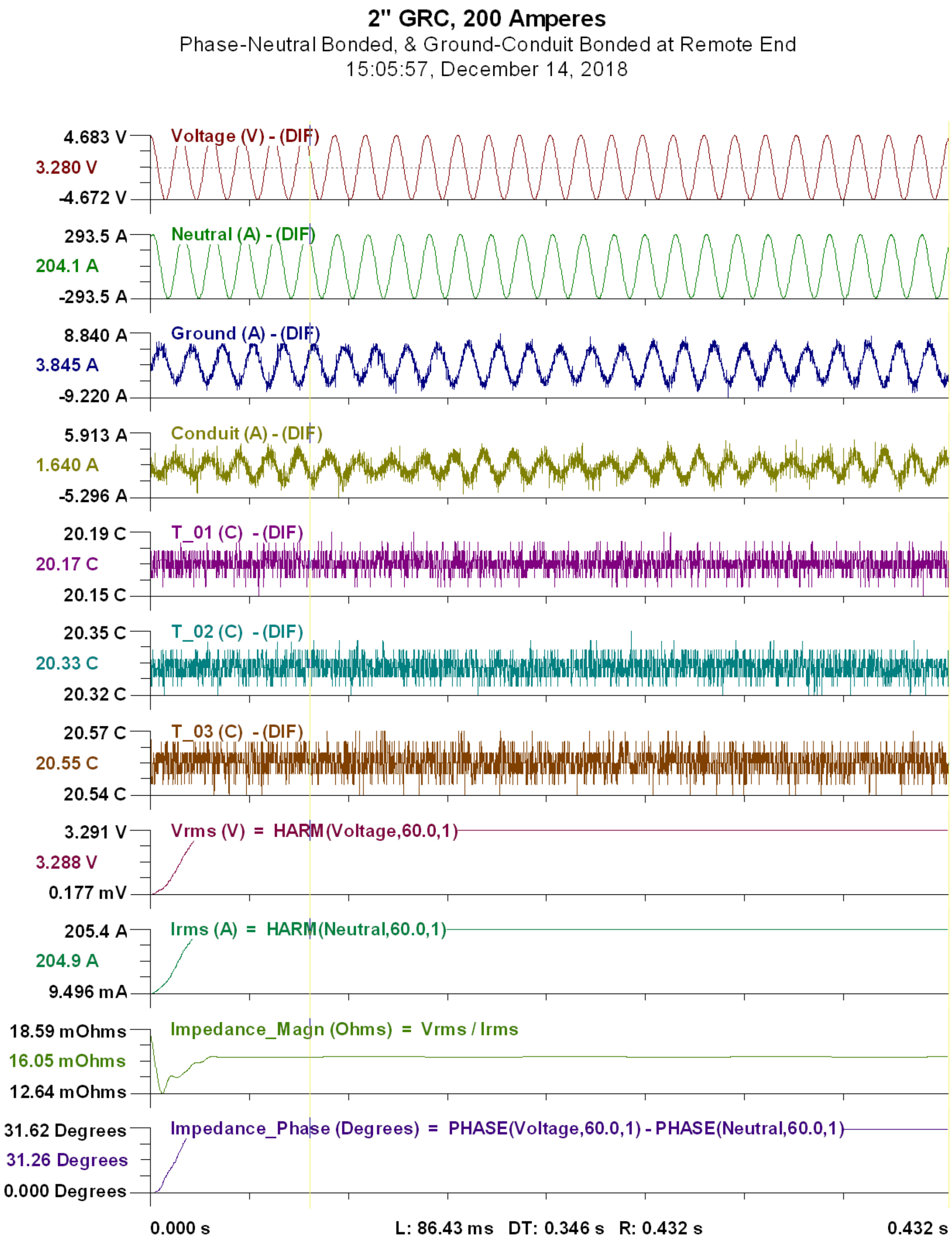


Figure F-1: Case Name GRC200_001

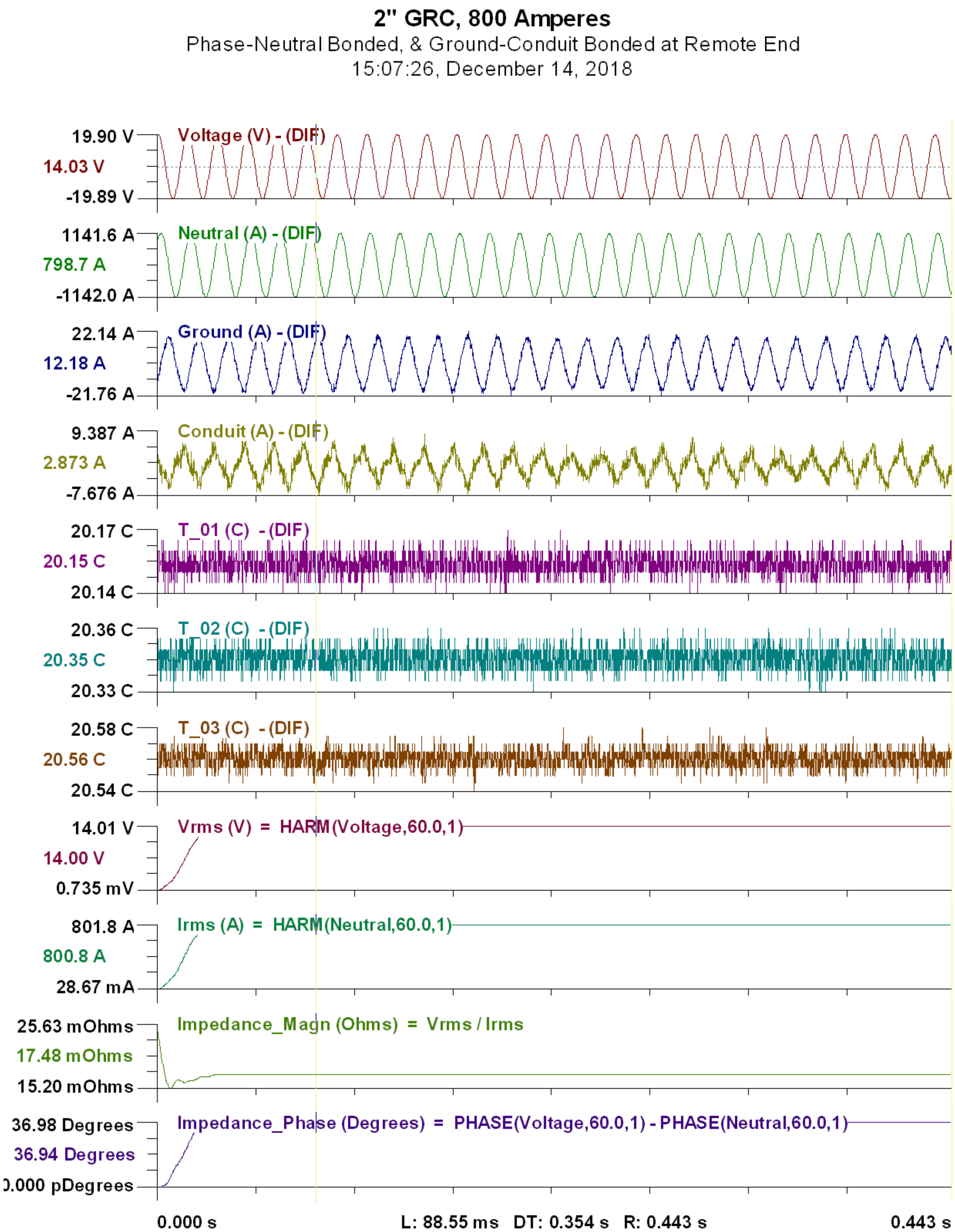


Figure F-2: Case Name GRC200_002

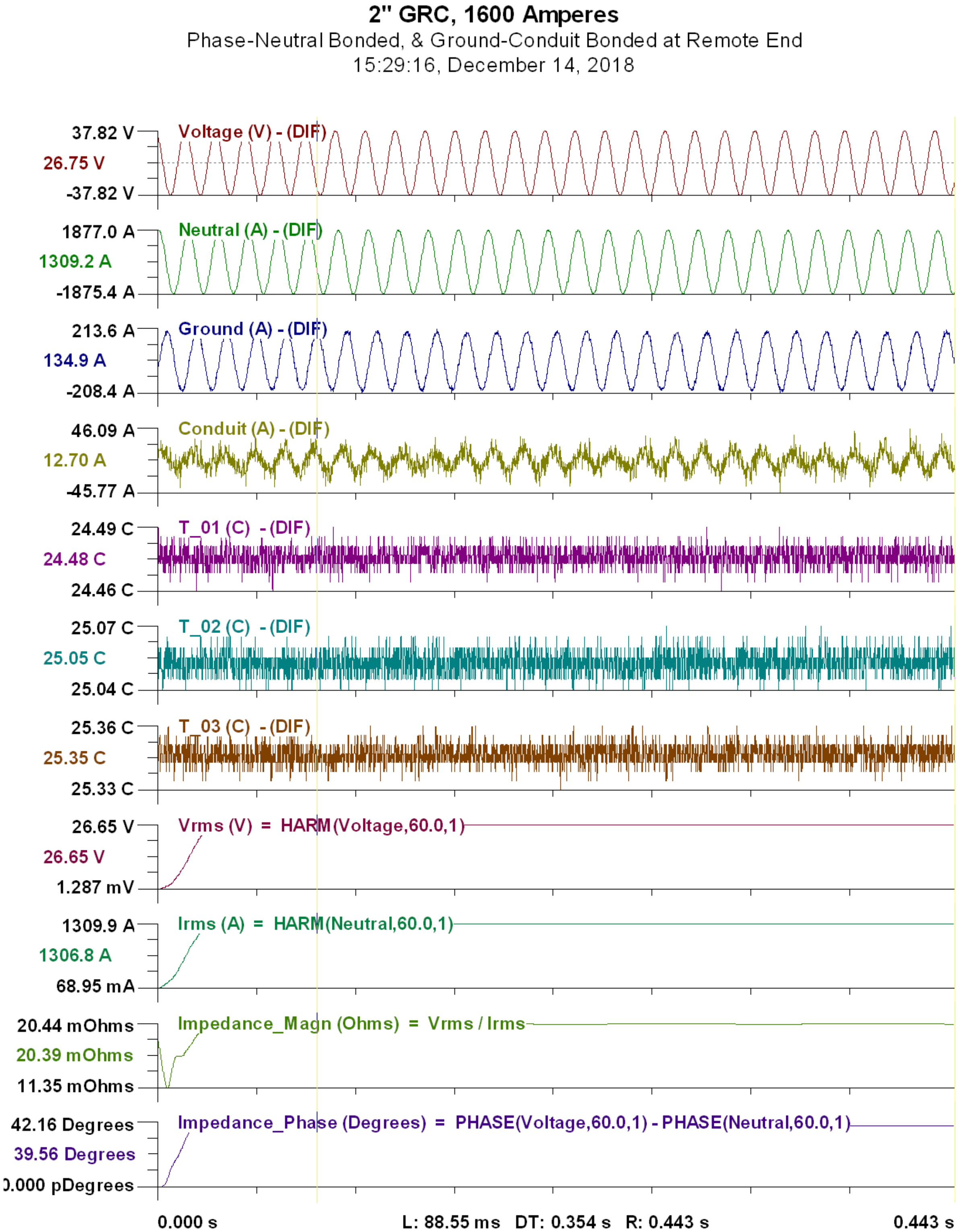


Figure F-3: Case Name GRC200_003

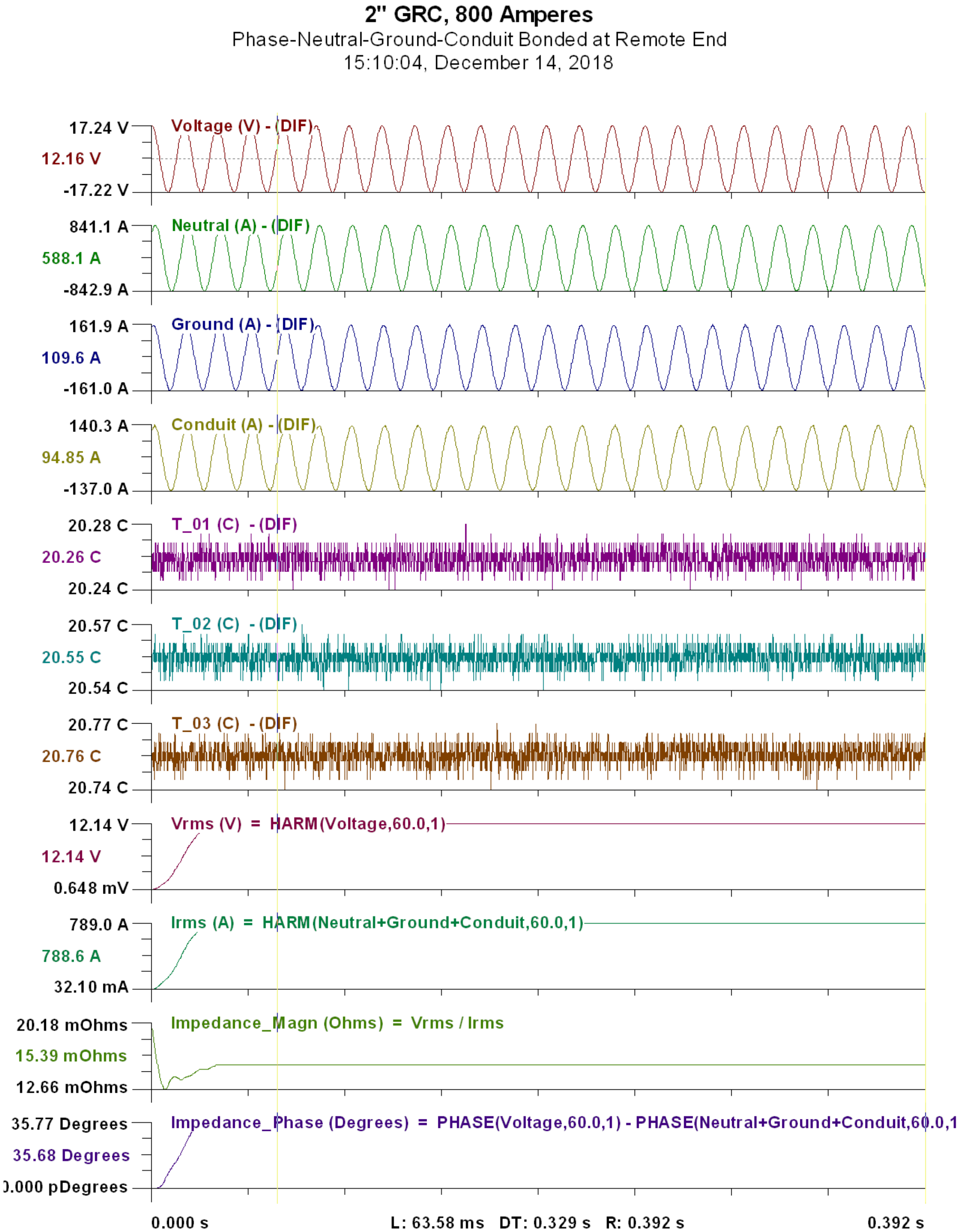


Figure F-4: Case Name GRC200_004

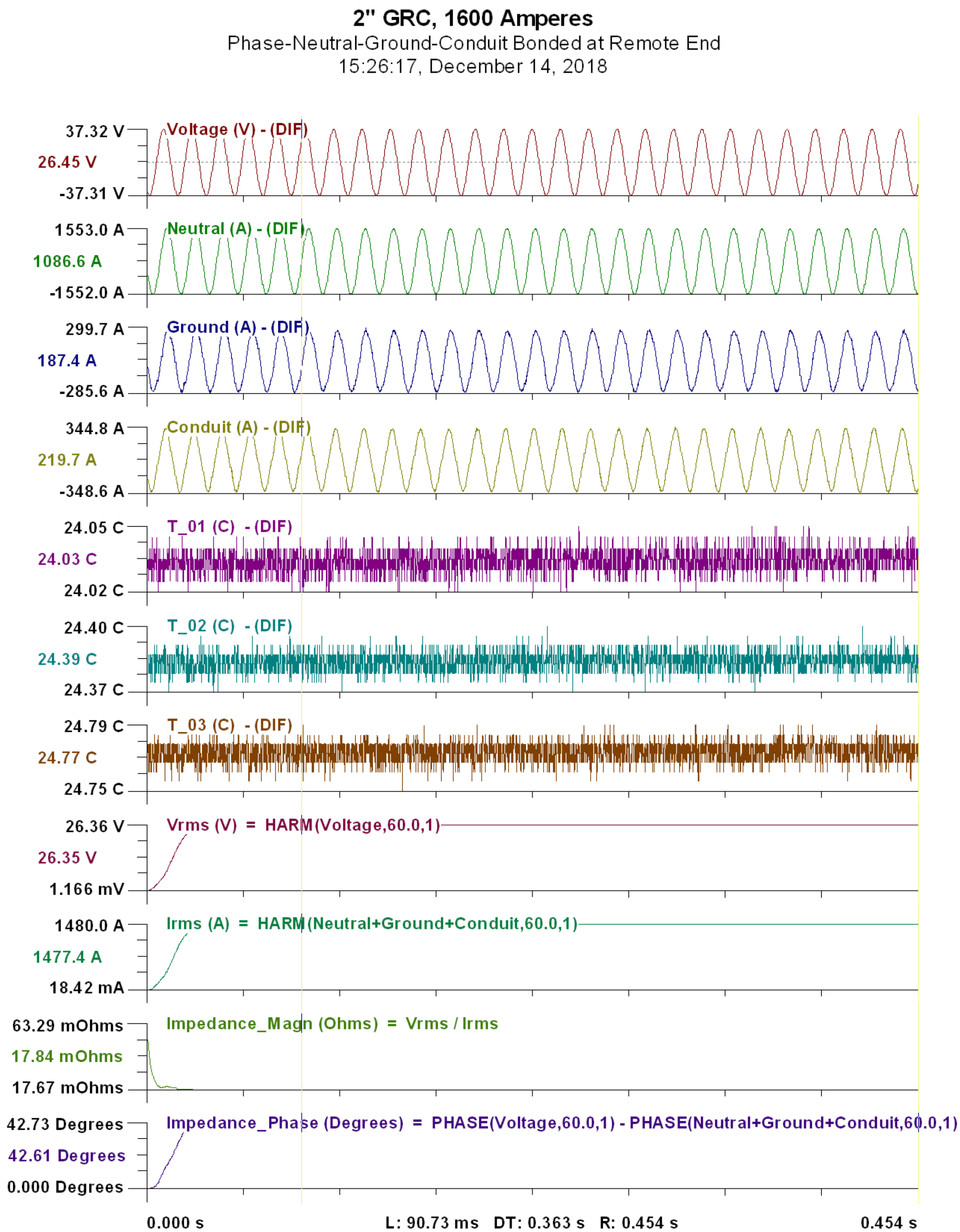


Figure F-5: Case Name GRC200_005

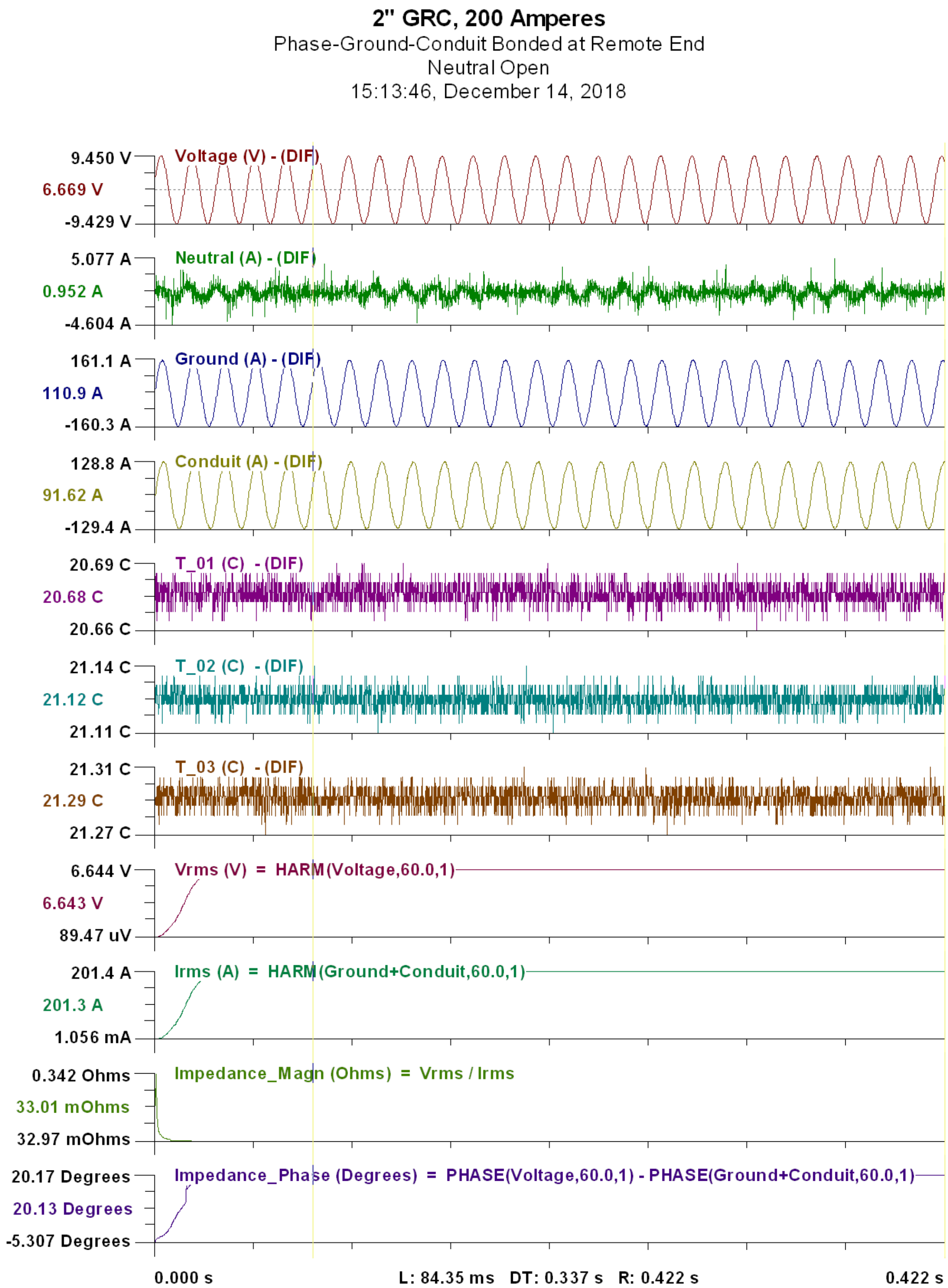


Figure F-6: Case Name GRC200_006

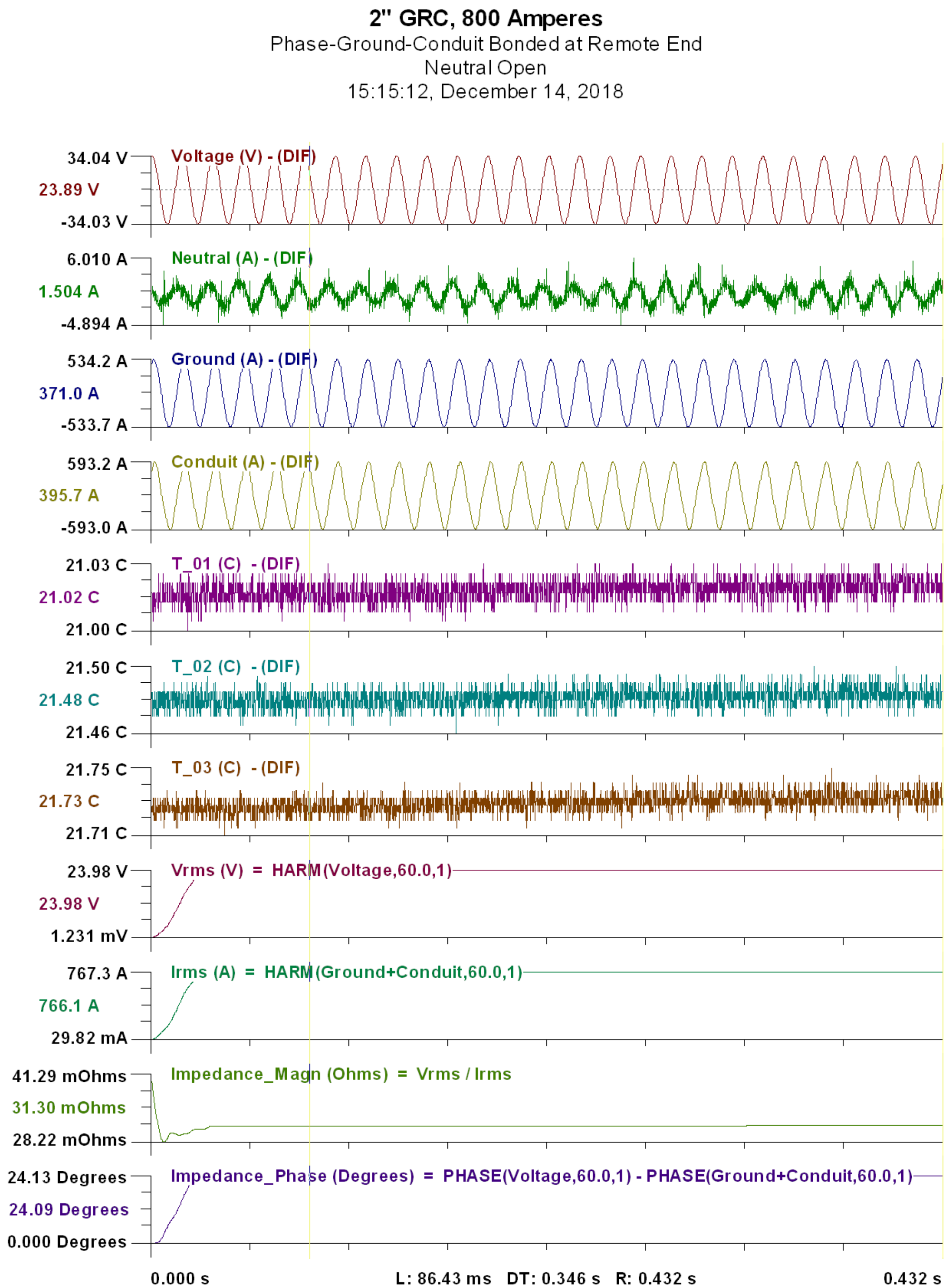


Figure F-7: Case Name GRC200_007

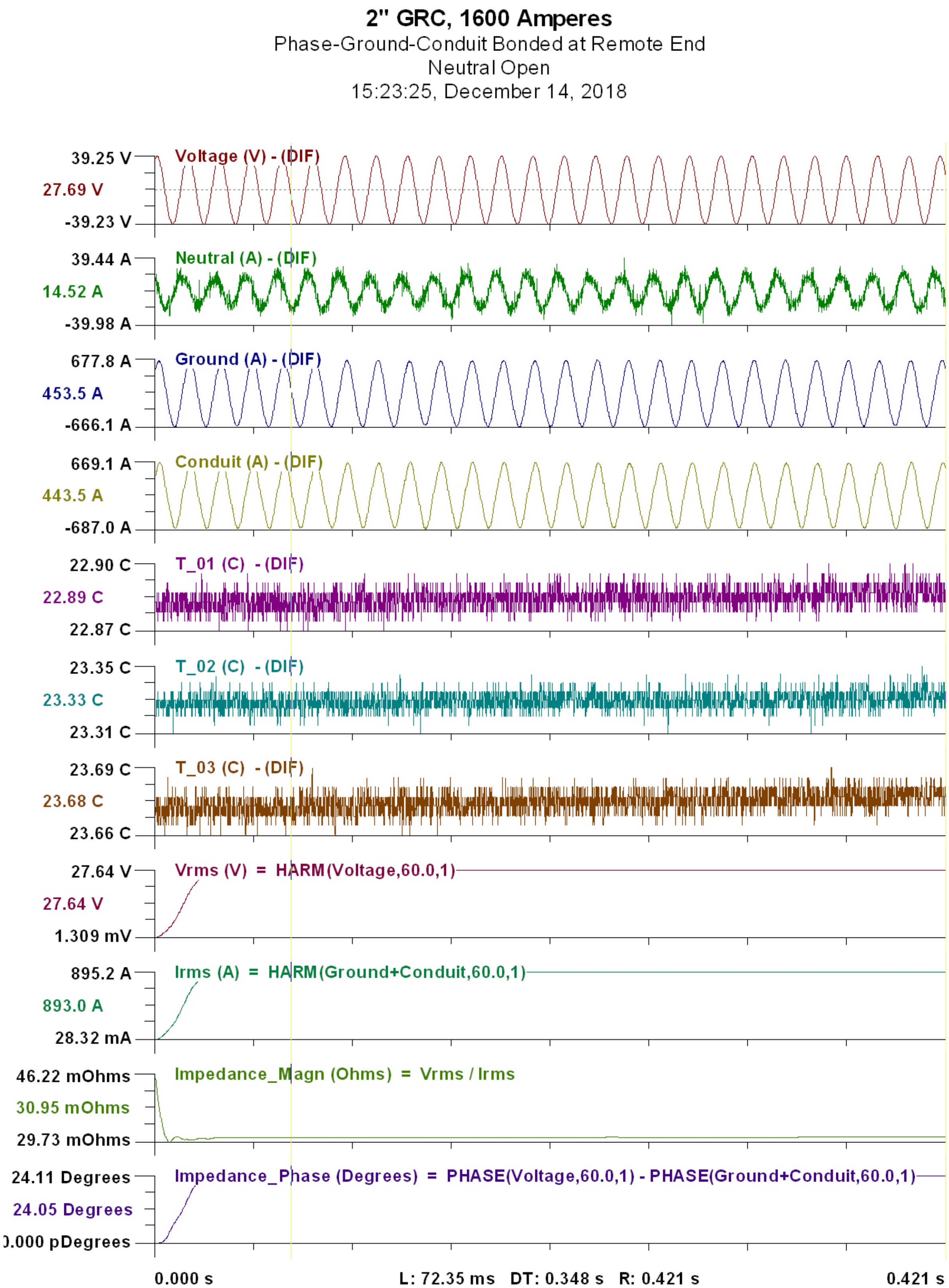


Figure F-8: Case Name GRC200_008

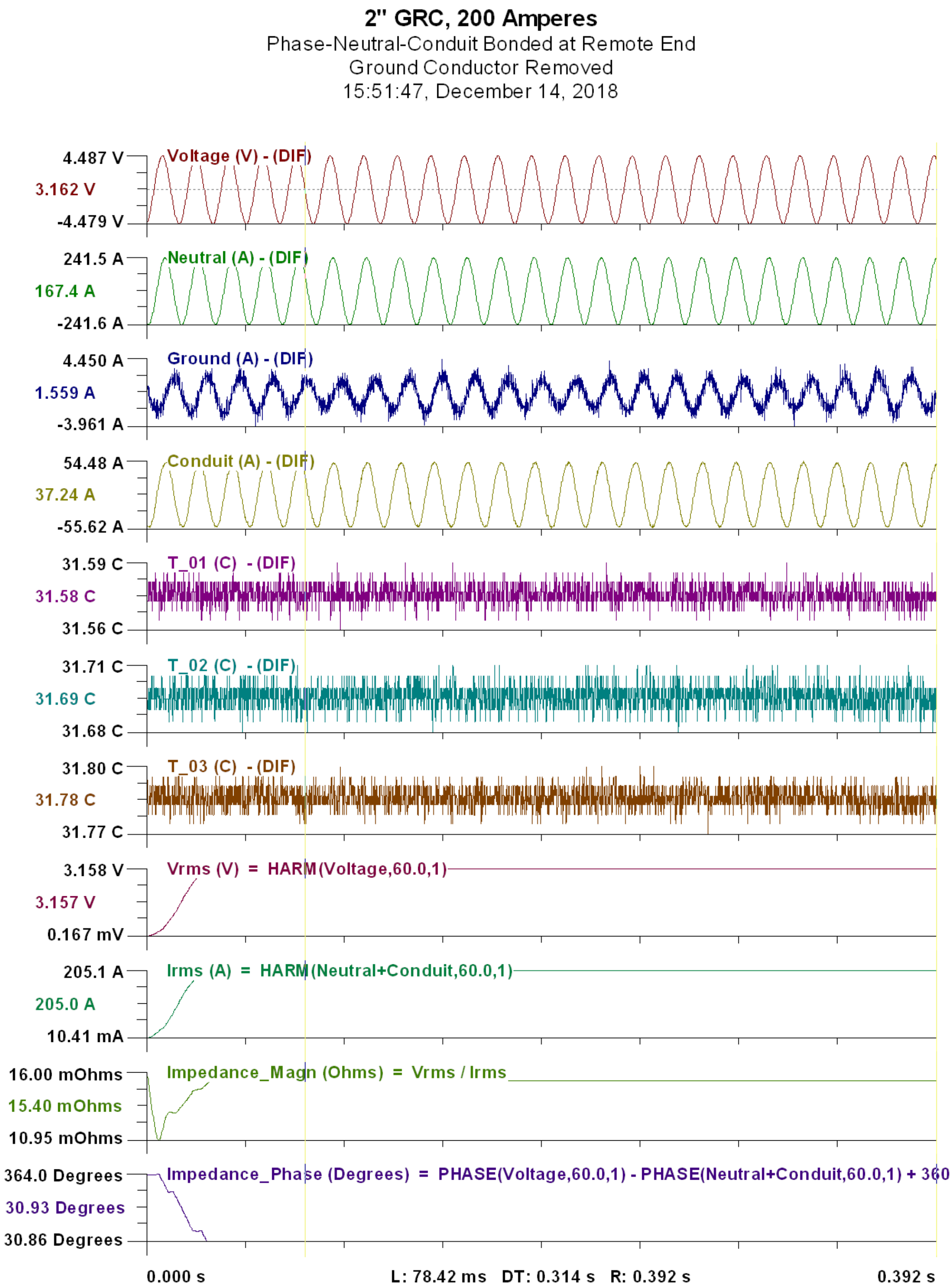


Figure F-9: Case Name GRC200_009

2" GRC, 800 Amperes
Phase-Neutral-Conduit Bonded at Remote End
Ground Conductor Removed
15:52:53, December 14, 2018

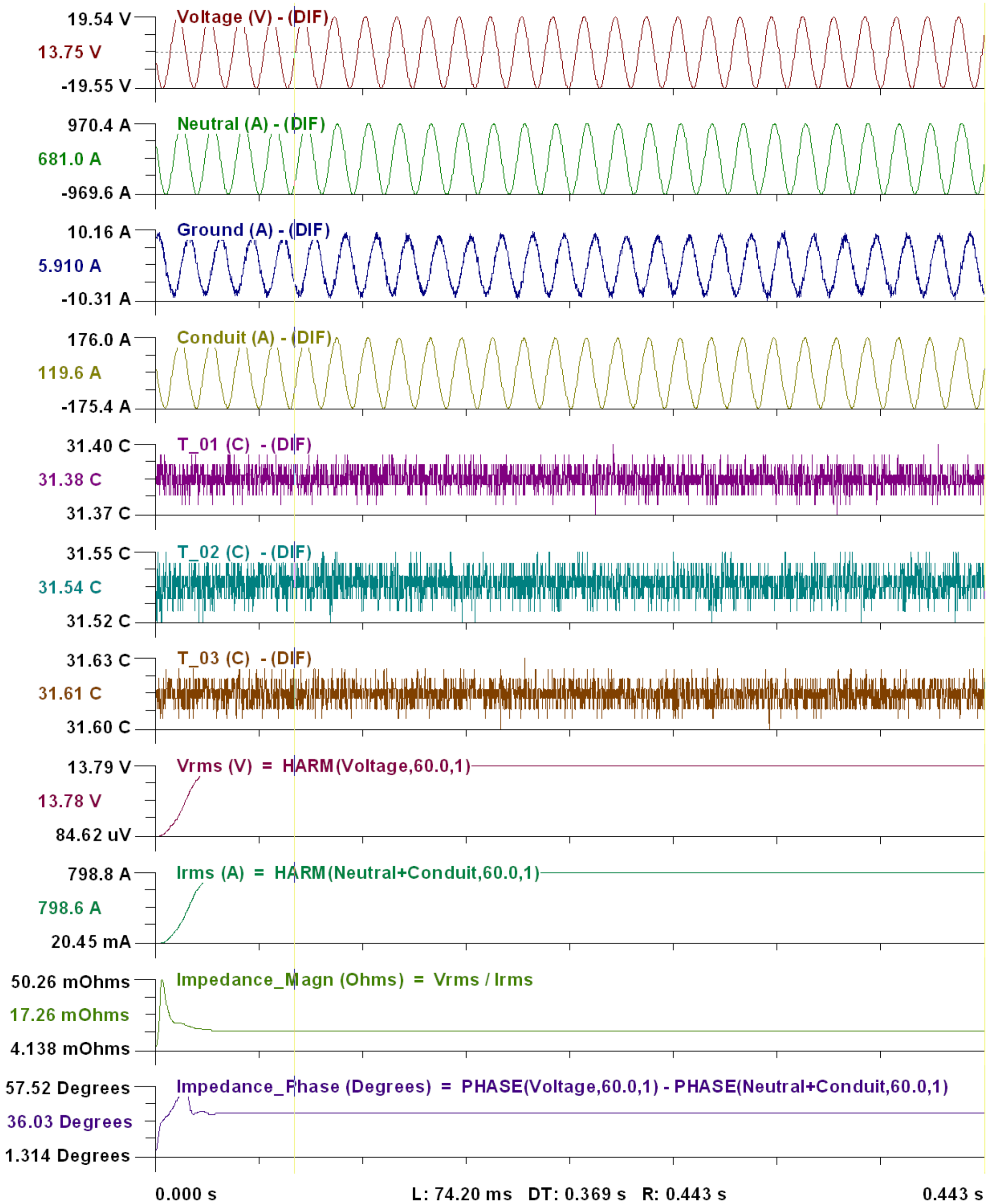


Figure F-10: Case Name GRC200_010

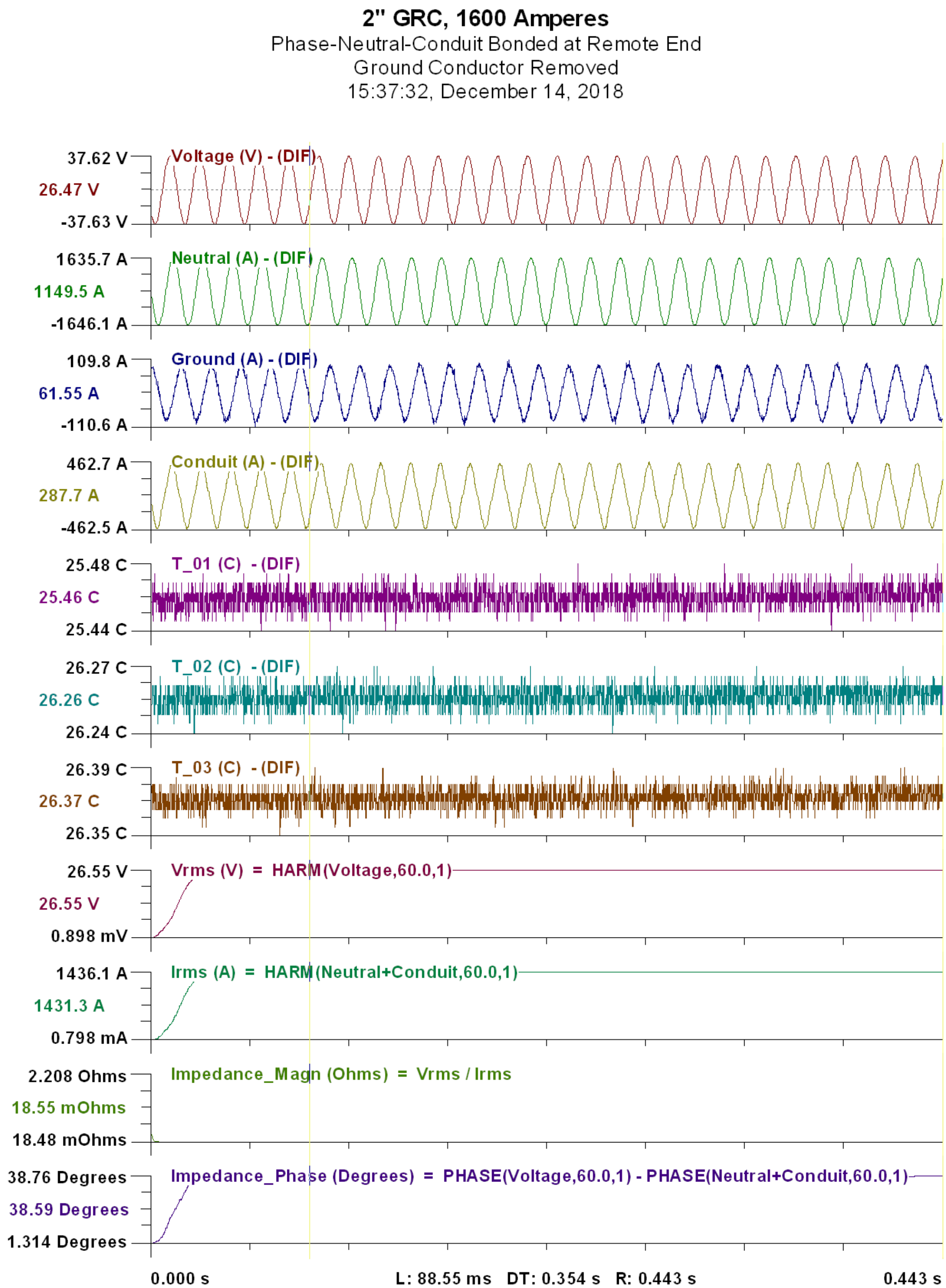


Figure F-11: Case Name GRC200_011

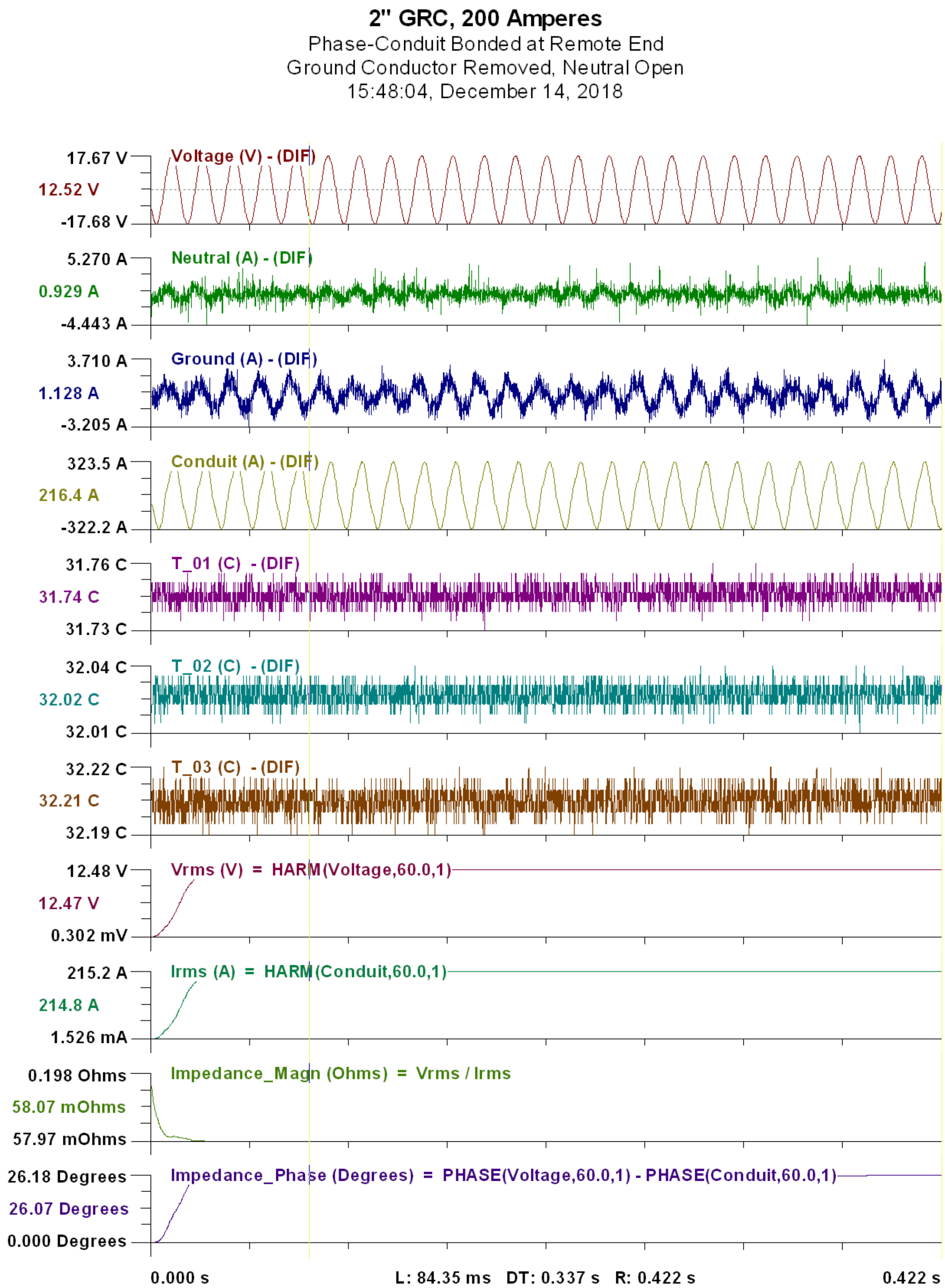


Figure F-12: Case Name GRC200_012

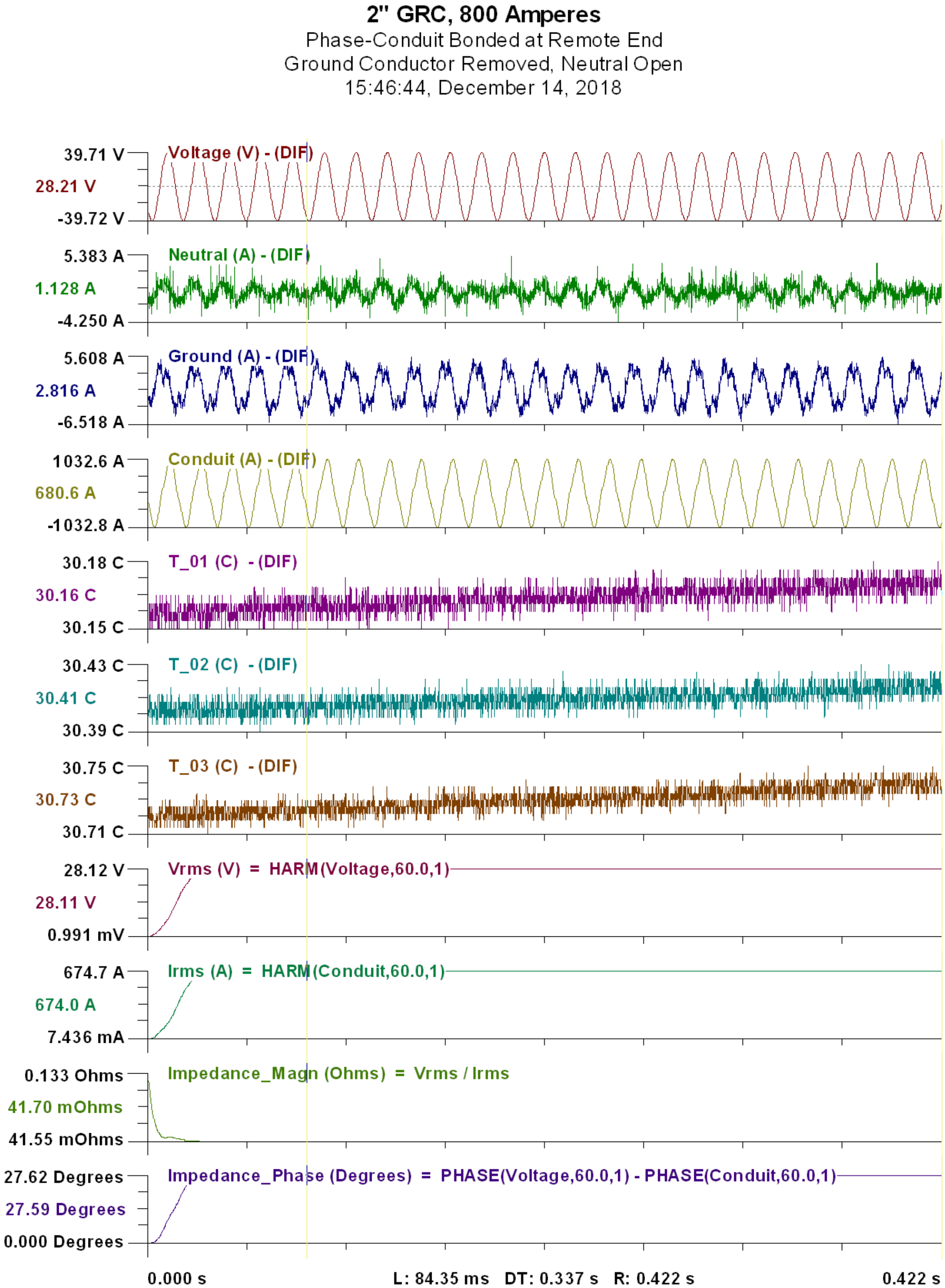


Figure F-13: Case Name GRC200_013

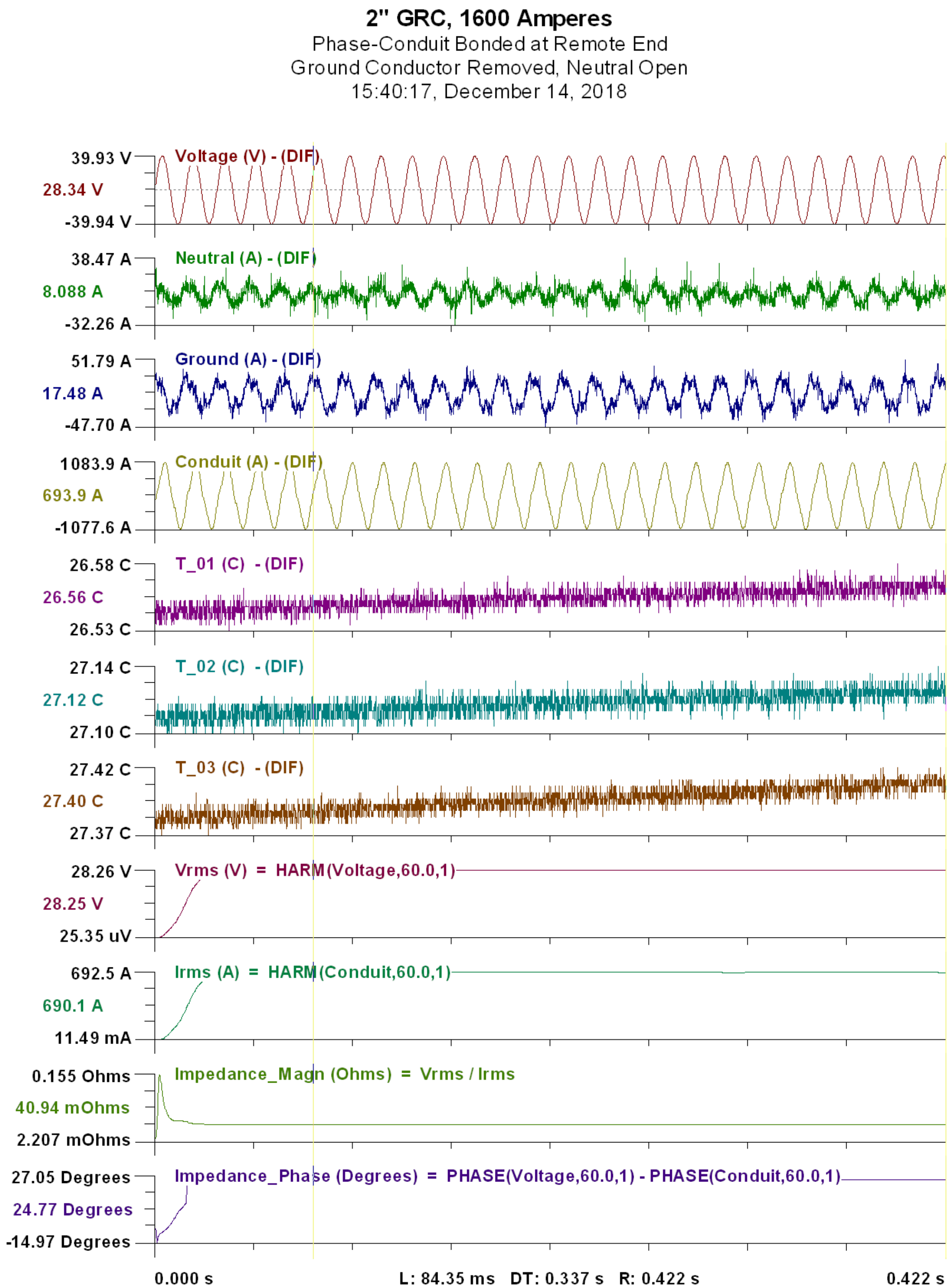


Figure F-14: Case Name GRC200_014

Appendix G – 2” IMC Raw Data Plots

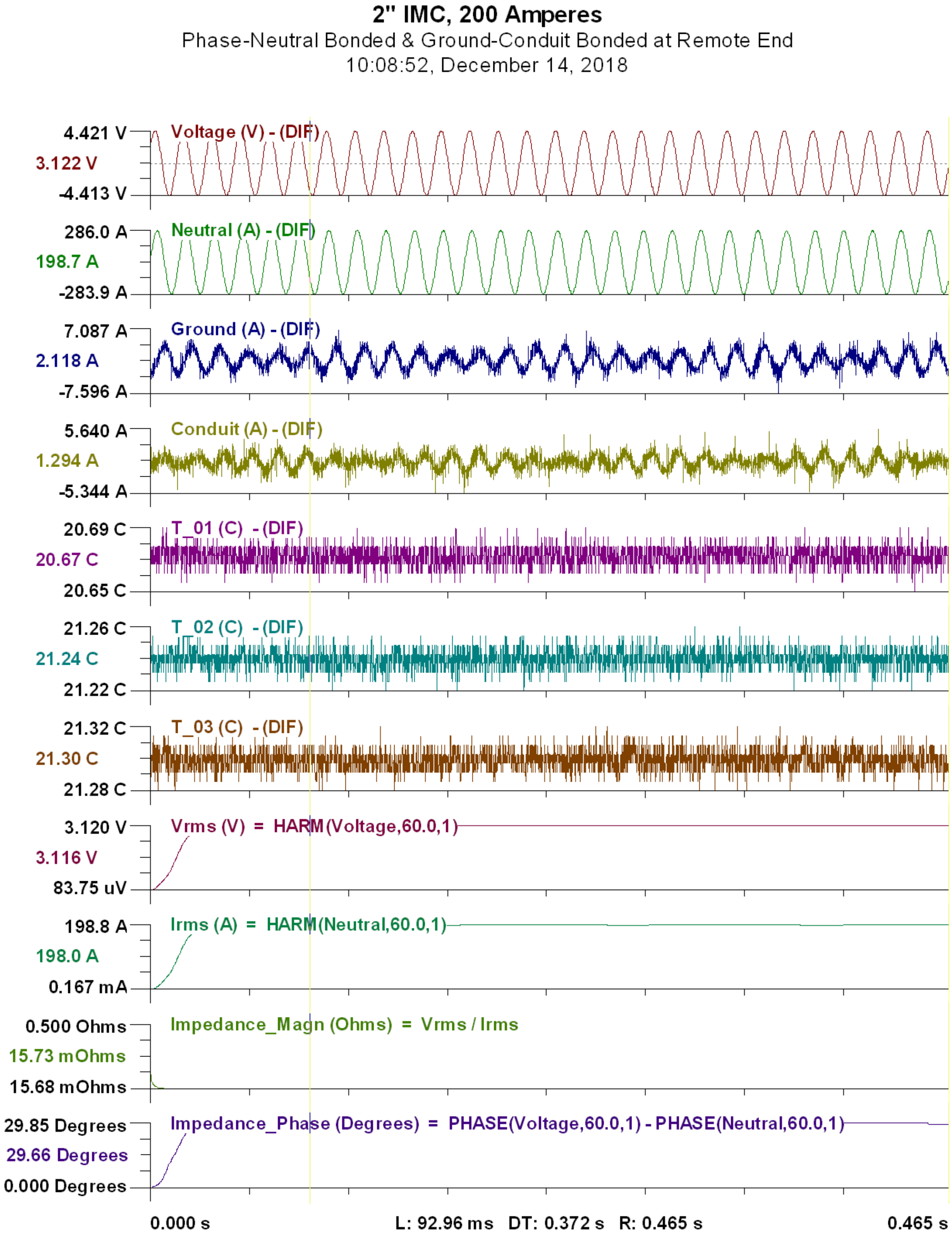


Figure G-1: Case Name IMC200_001

Figure G-2: Case Name IMC200_002

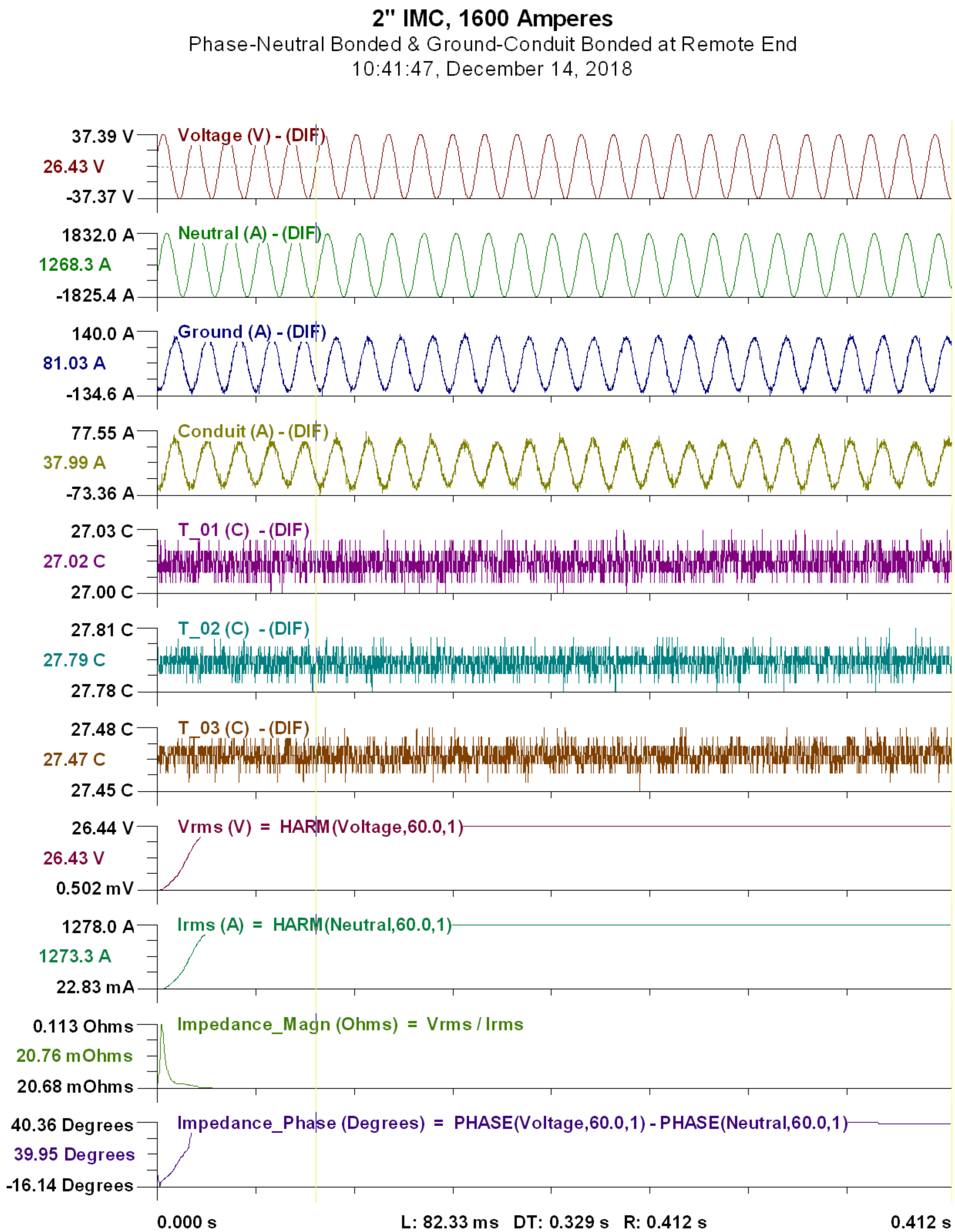


Figure G-3: Case Name IMC200_003

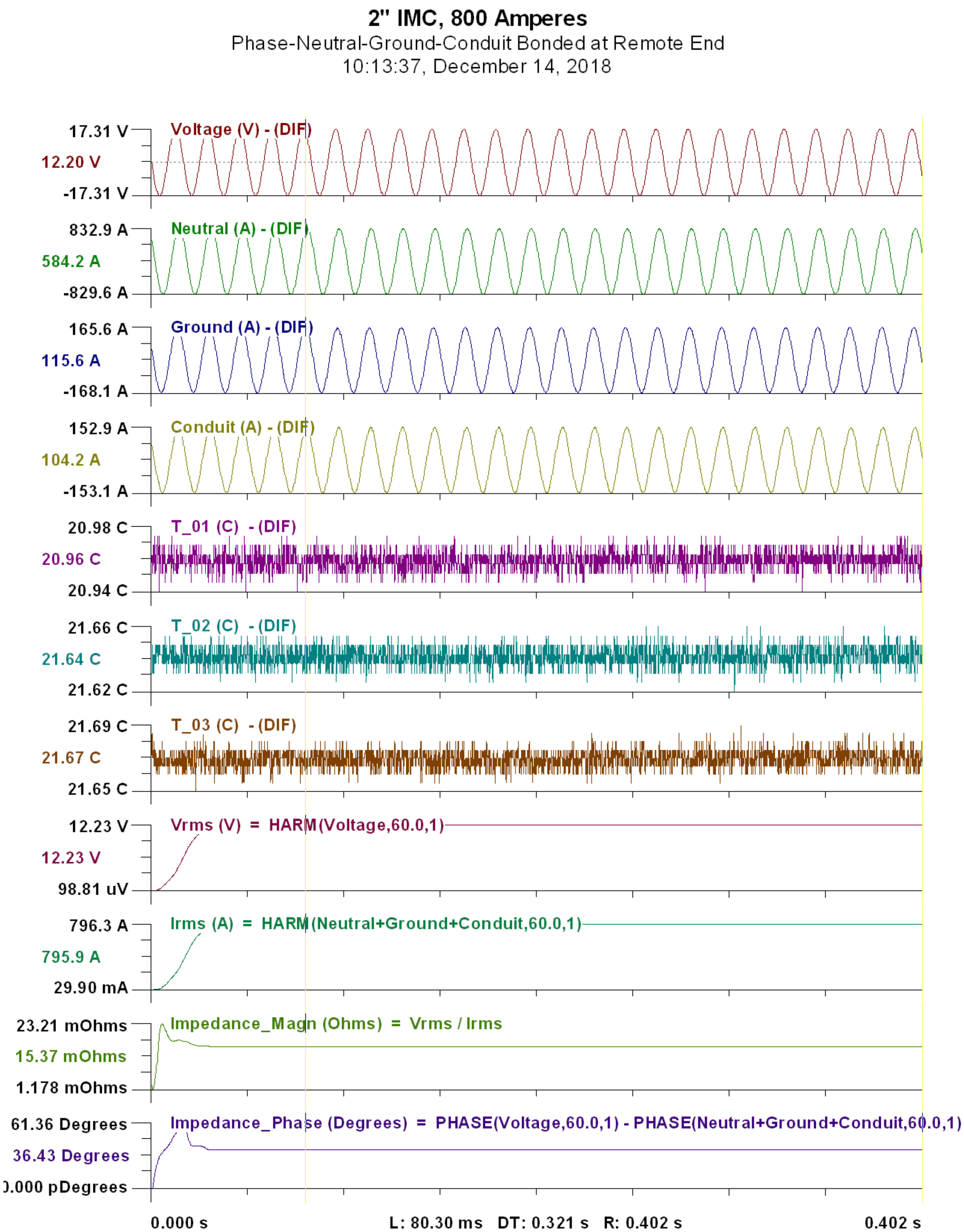


Figure G-4: Case Name IMC200_004

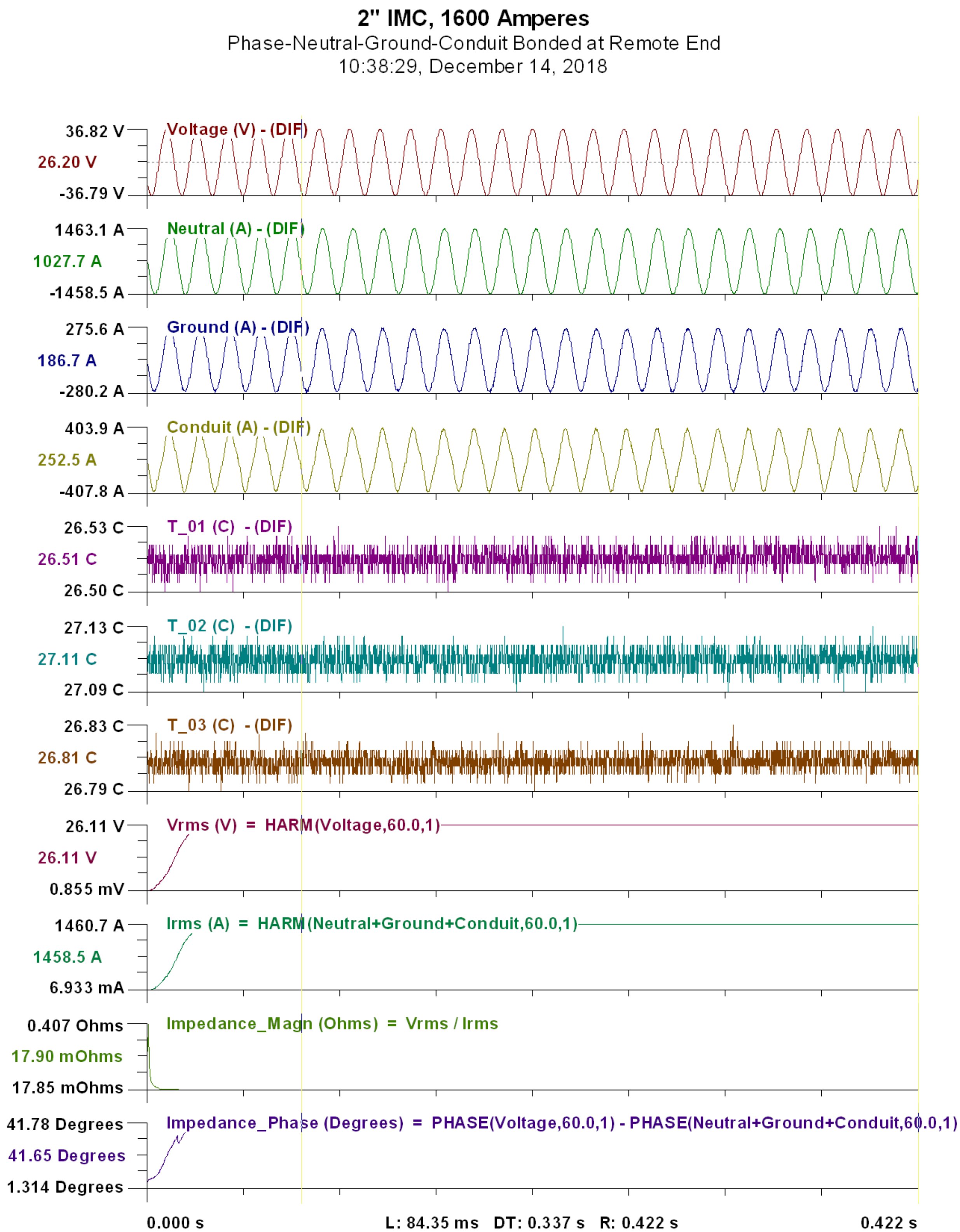


Figure G-5: Case Name IMC200_005

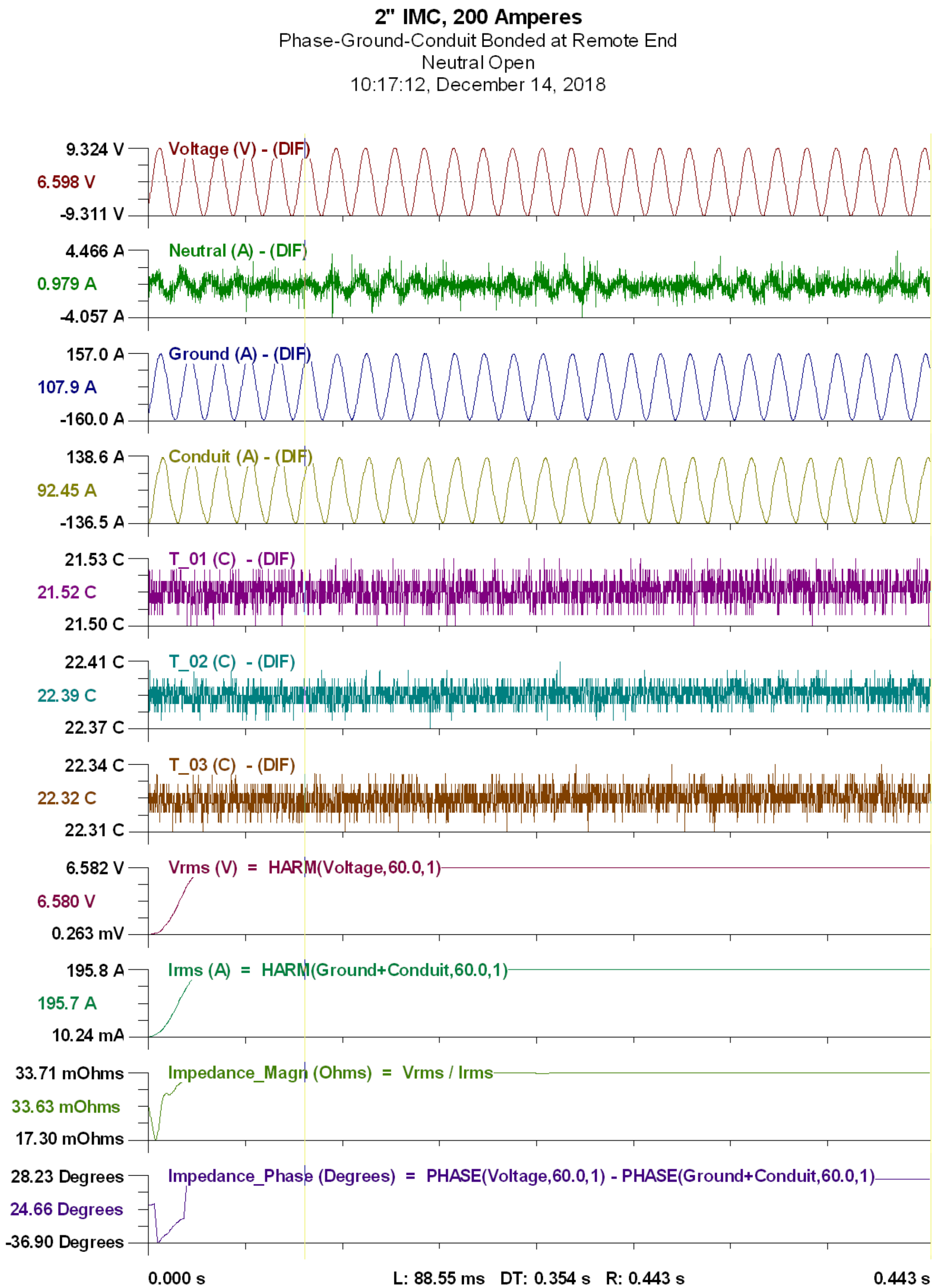


Figure G-6: Case Name IMC200_006

2" IMC, 800 Amperes

Phase-Ground-Conduit Bonded at Remote End

Neutral Open

10:18:54, December 14, 2018

Figure G-7: Case Name IMC200_007

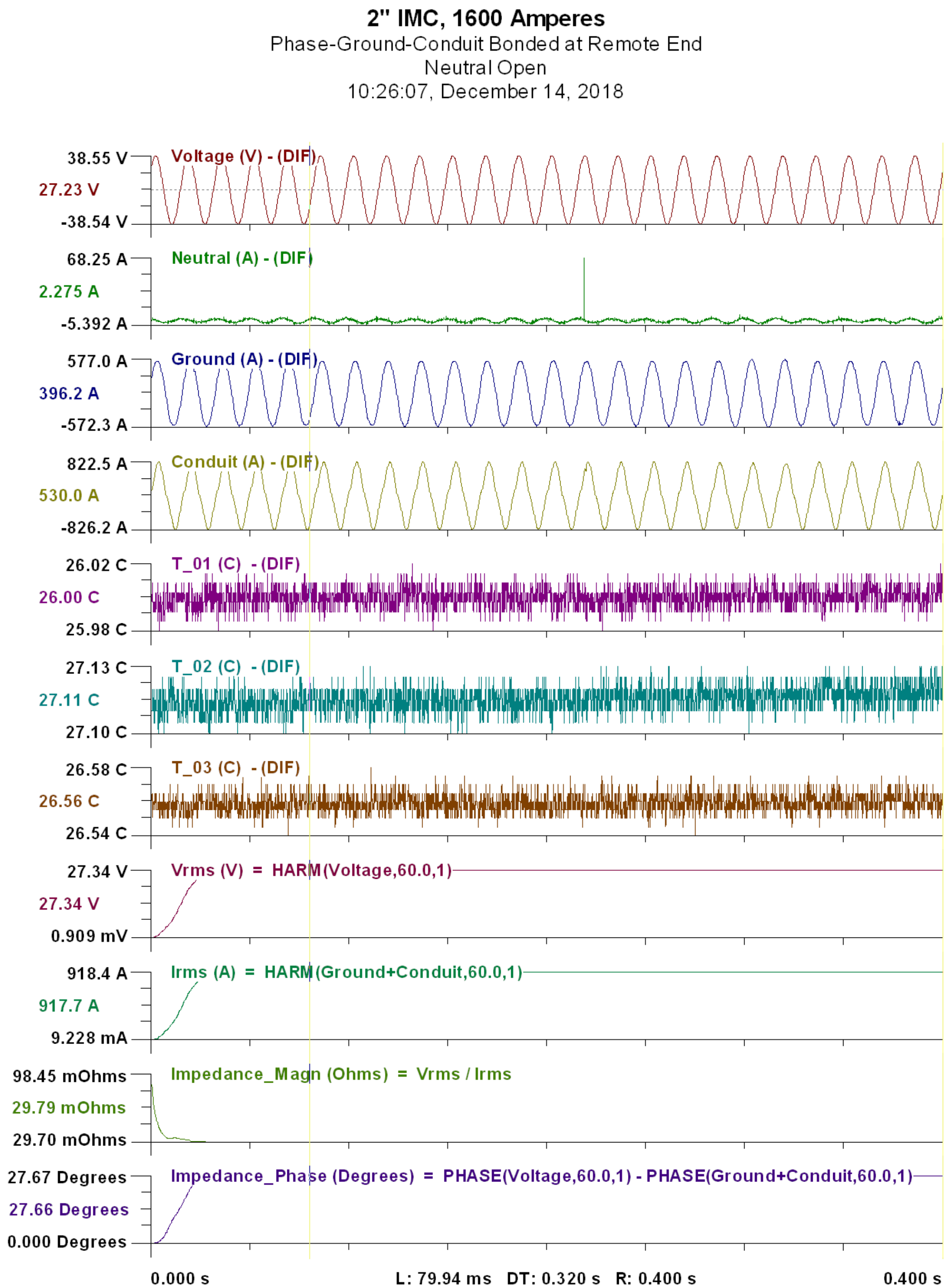


Figure G-8: Case Name IMC200_008

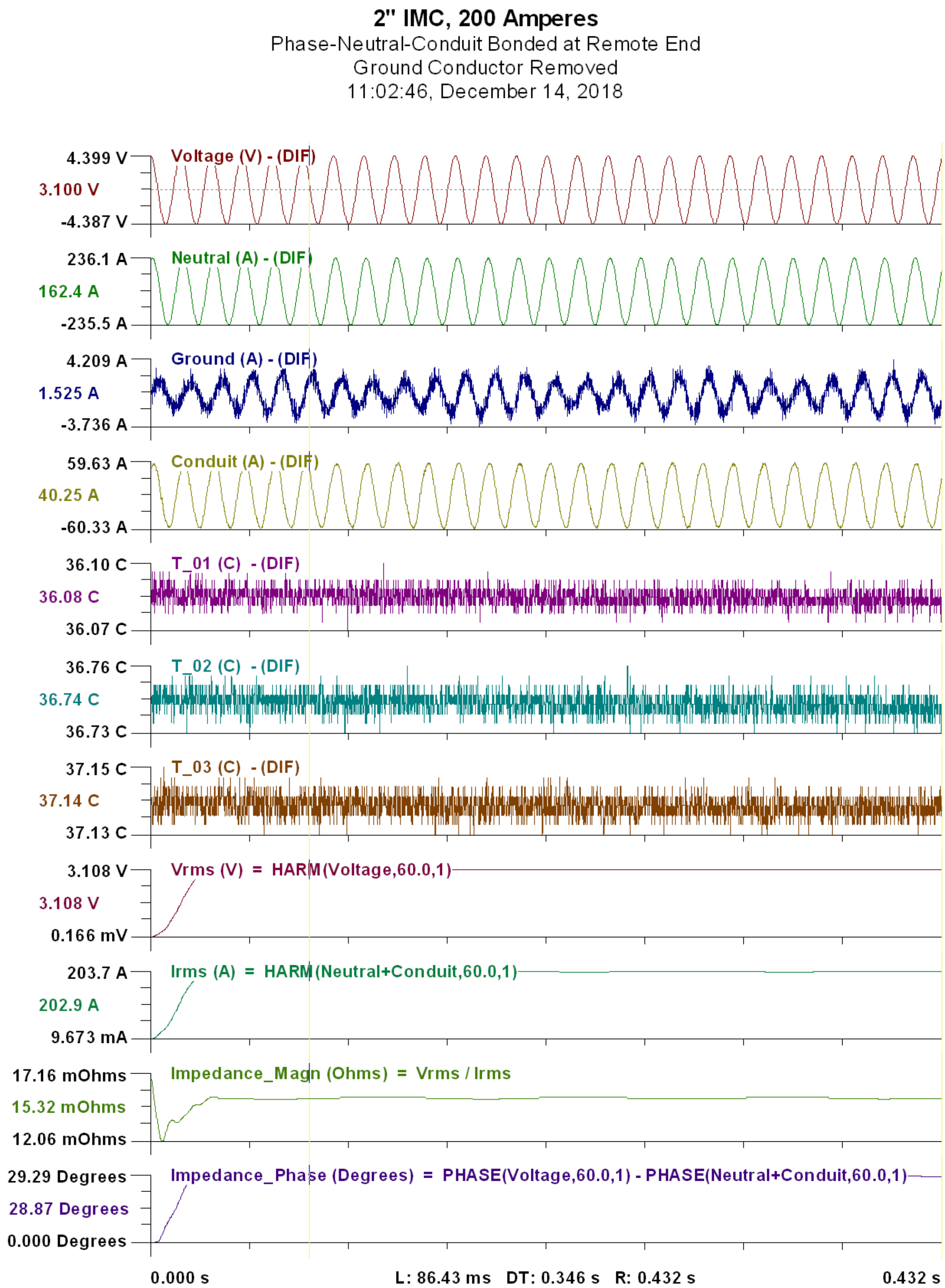


Figure G-9: Case Name IMC200_009

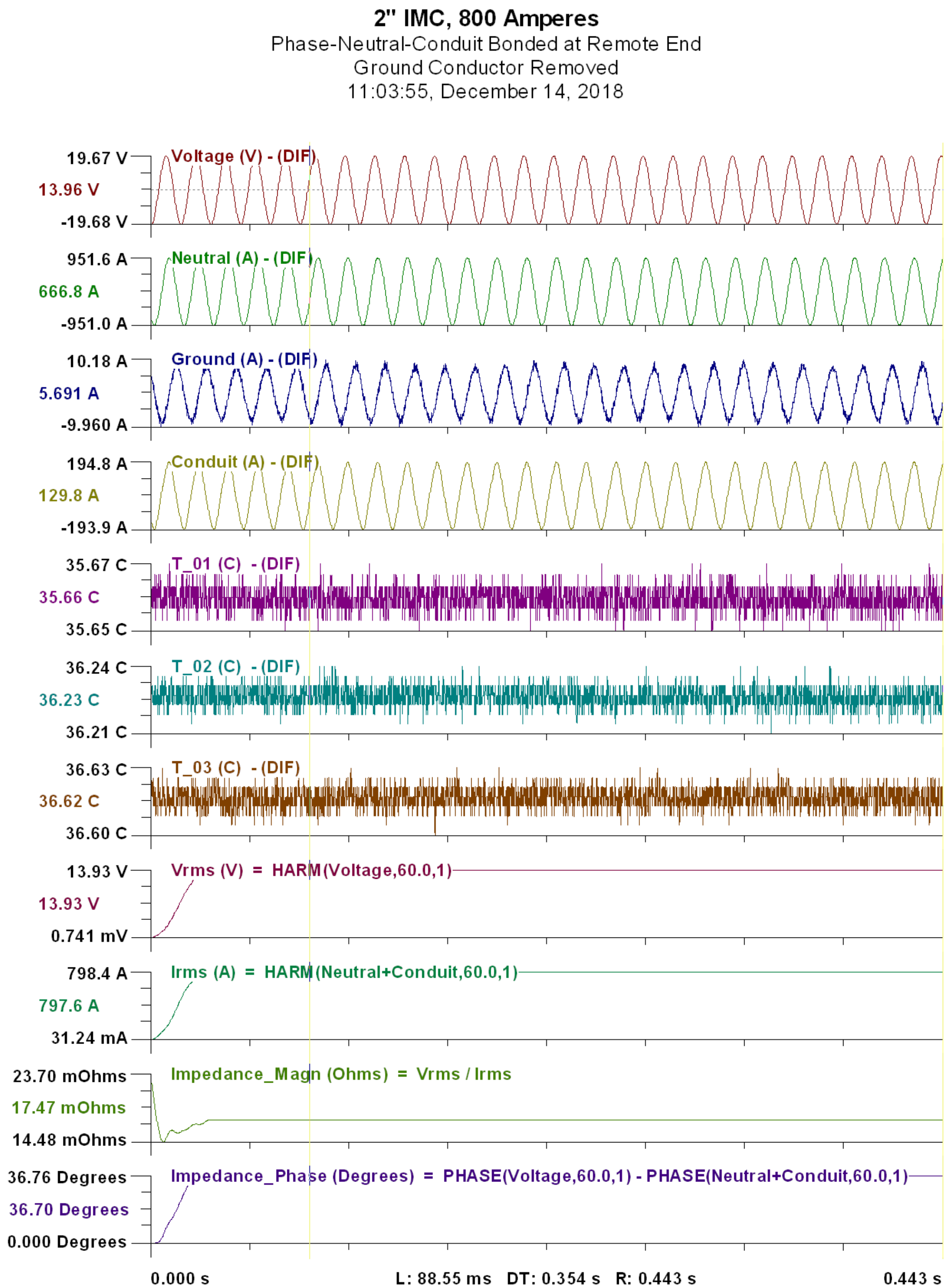


Figure G-10: Case Name IMC200_010

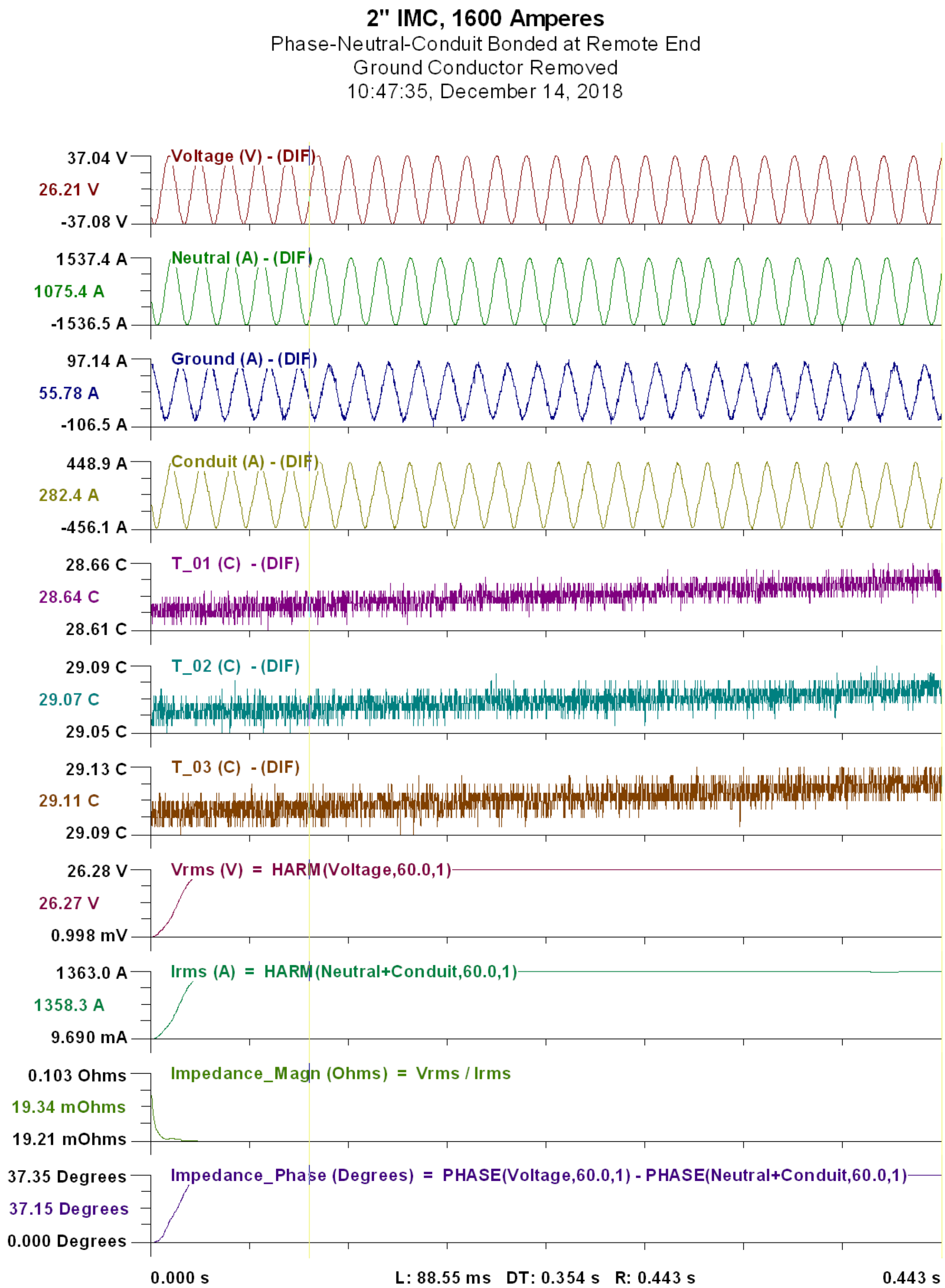


Figure G-11: Case Name IMC200_011

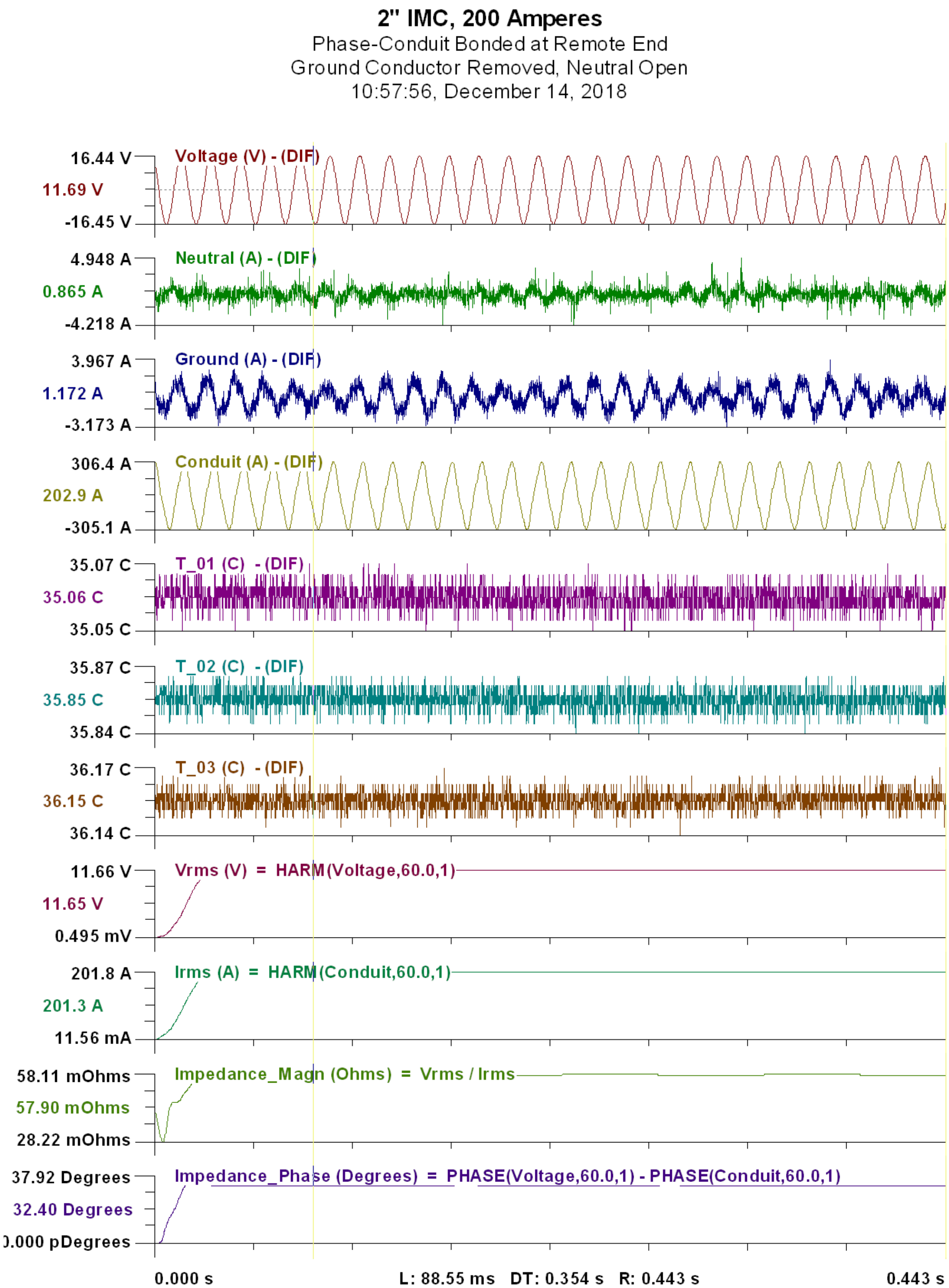


Figure G-12: Case Name IMC200_012

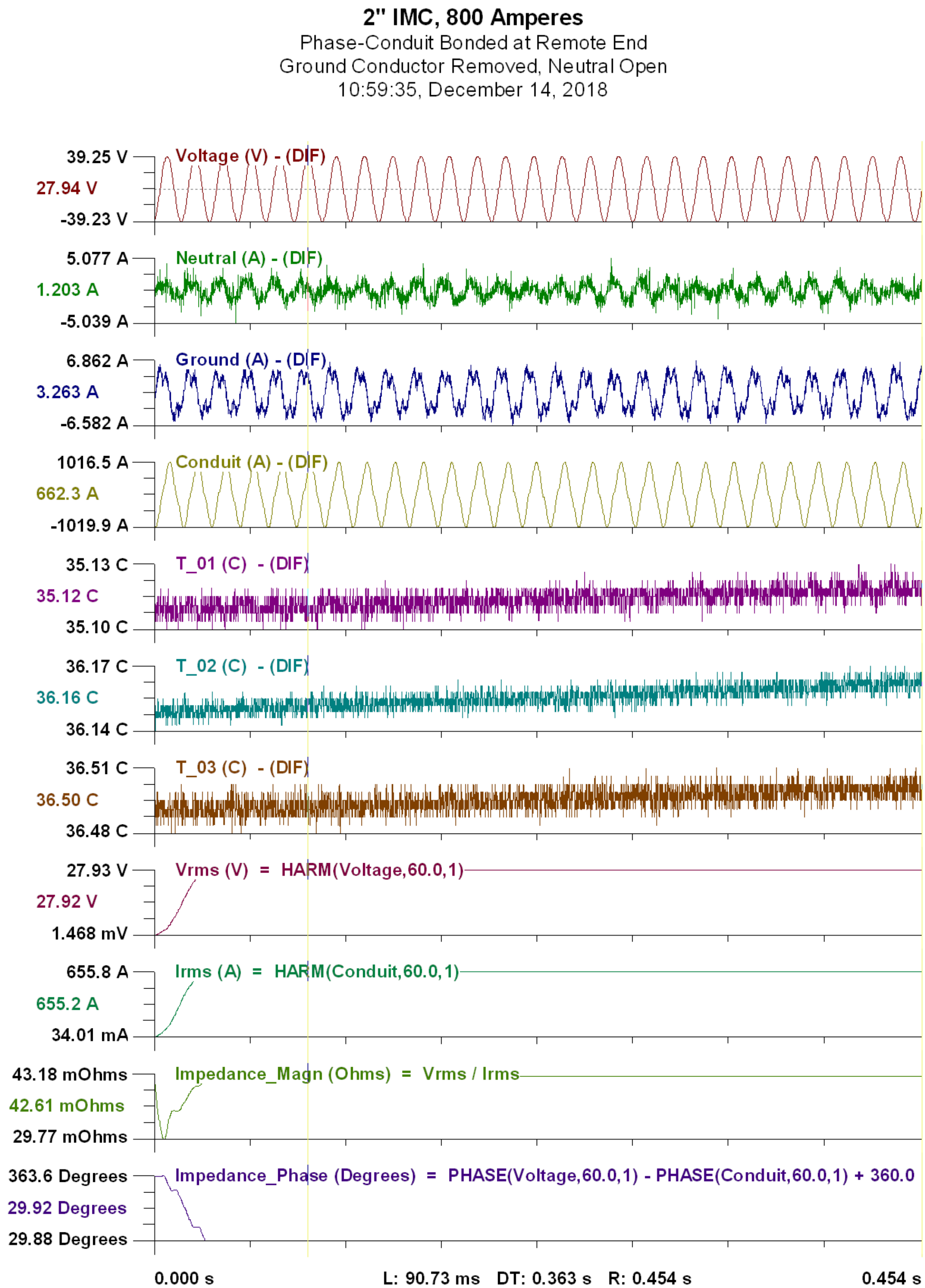


Figure G-13: Case Name IMC200_013

2" IMC, 1600 Amperes
Phase-Conduit Bonded at Remote End
Ground Conductor Removed, Neutral Open
10:50:44, December 14, 2018

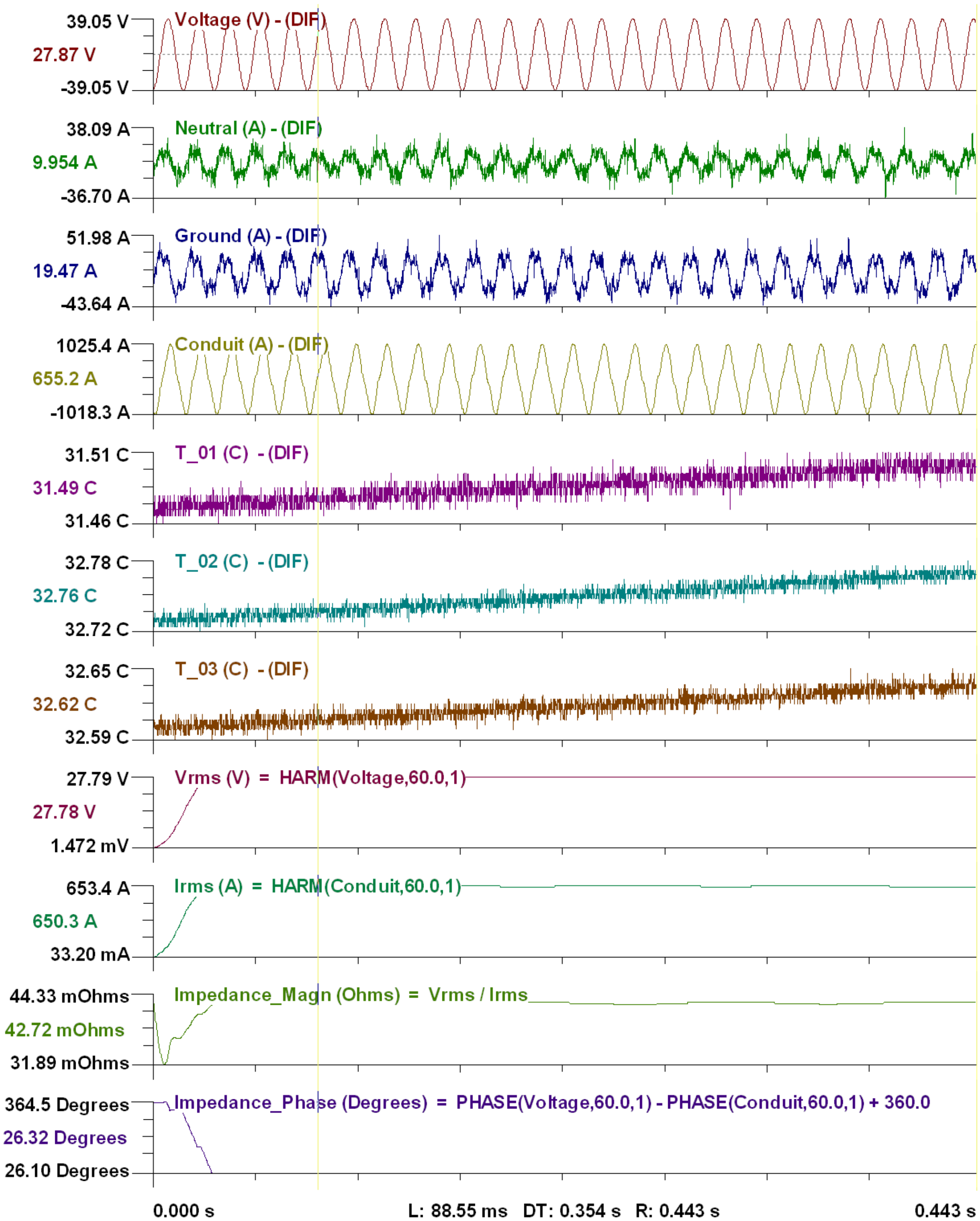


Figure G-14: Case Name IMC200_014

Appendix H – 1” EMT Raw Data Plots

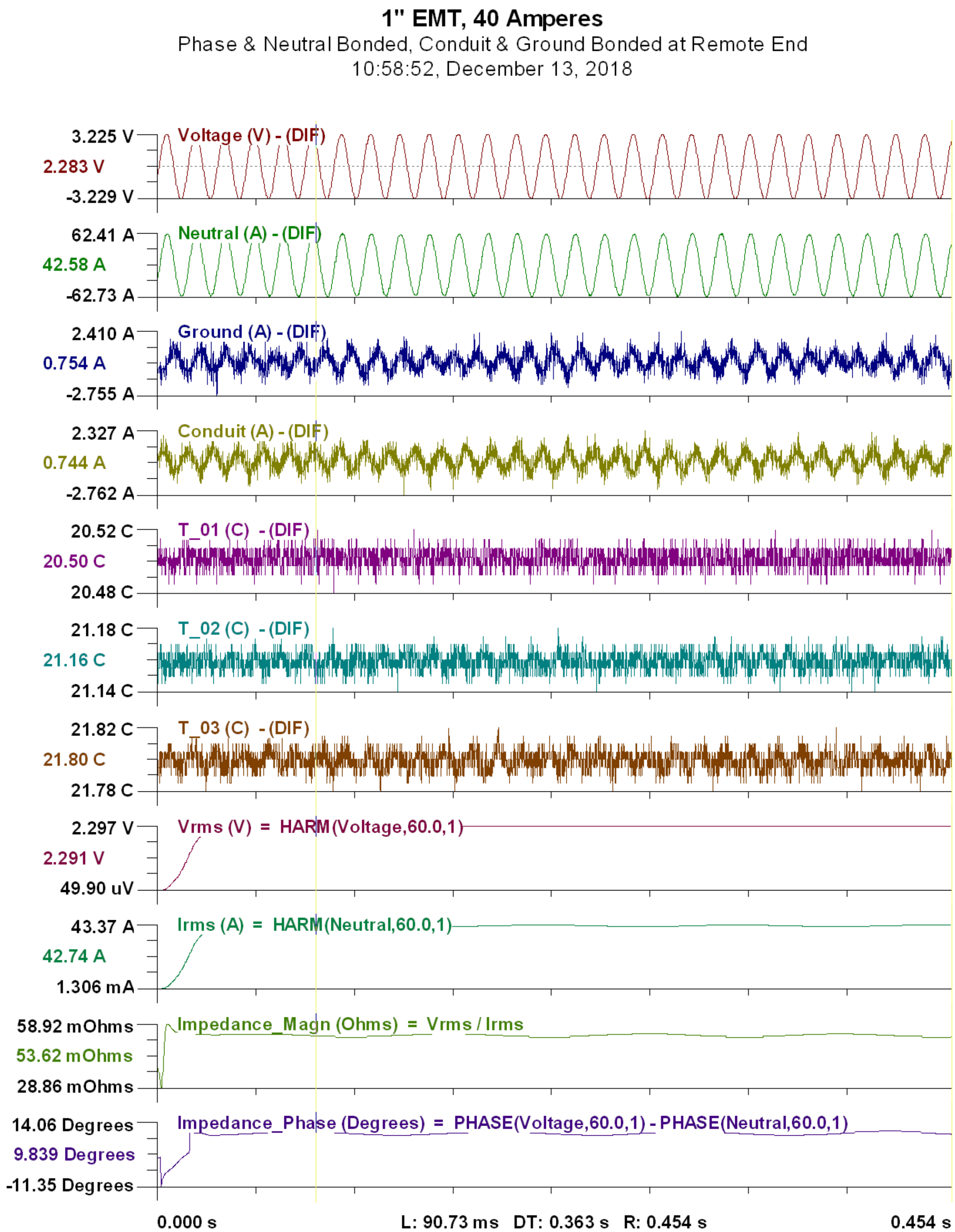


Figure H-1: Case Name EMT100_001

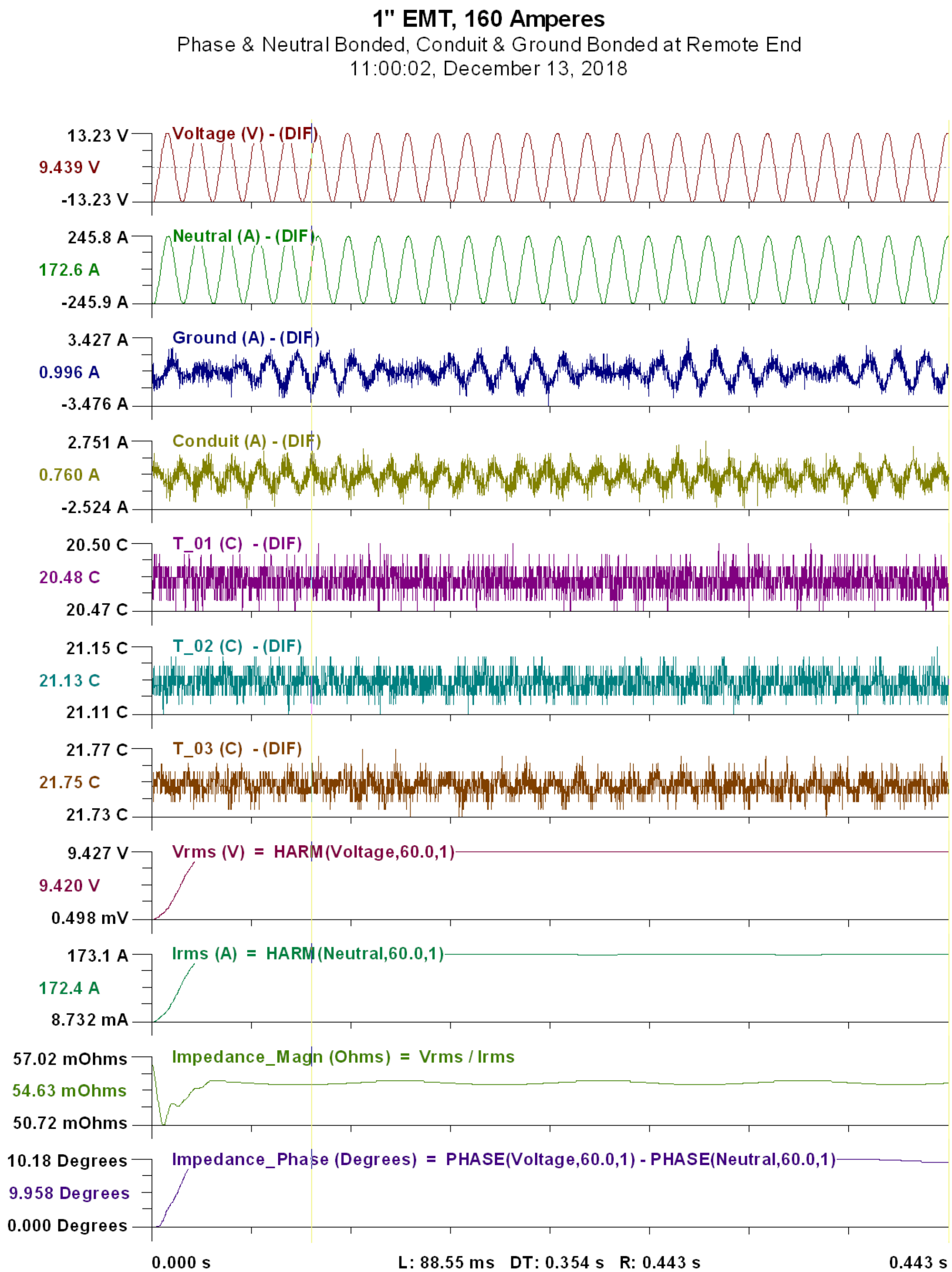


Figure H-2: Case Name EMT100_002

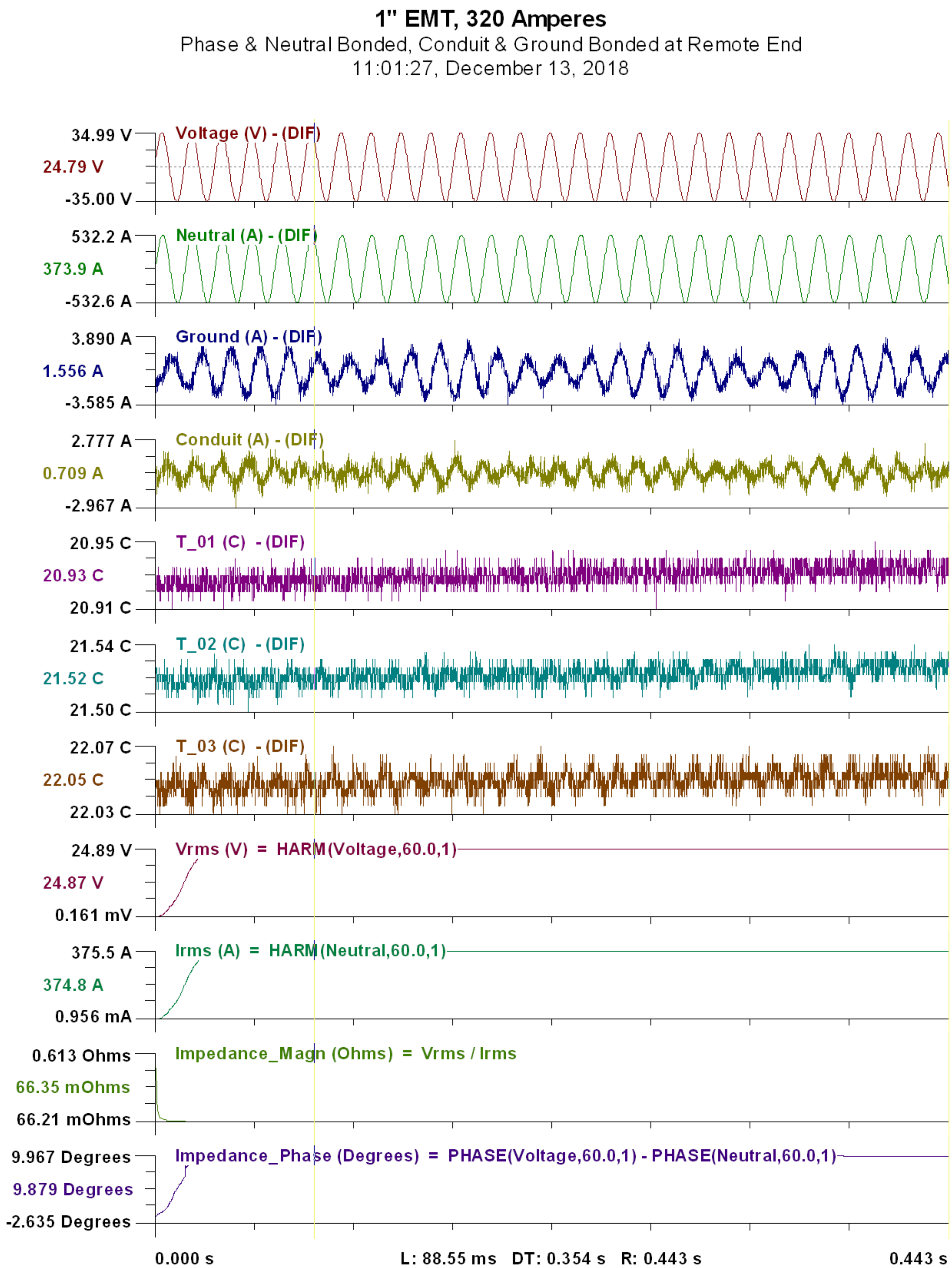


Figure H-3: Case Name EMT100_003

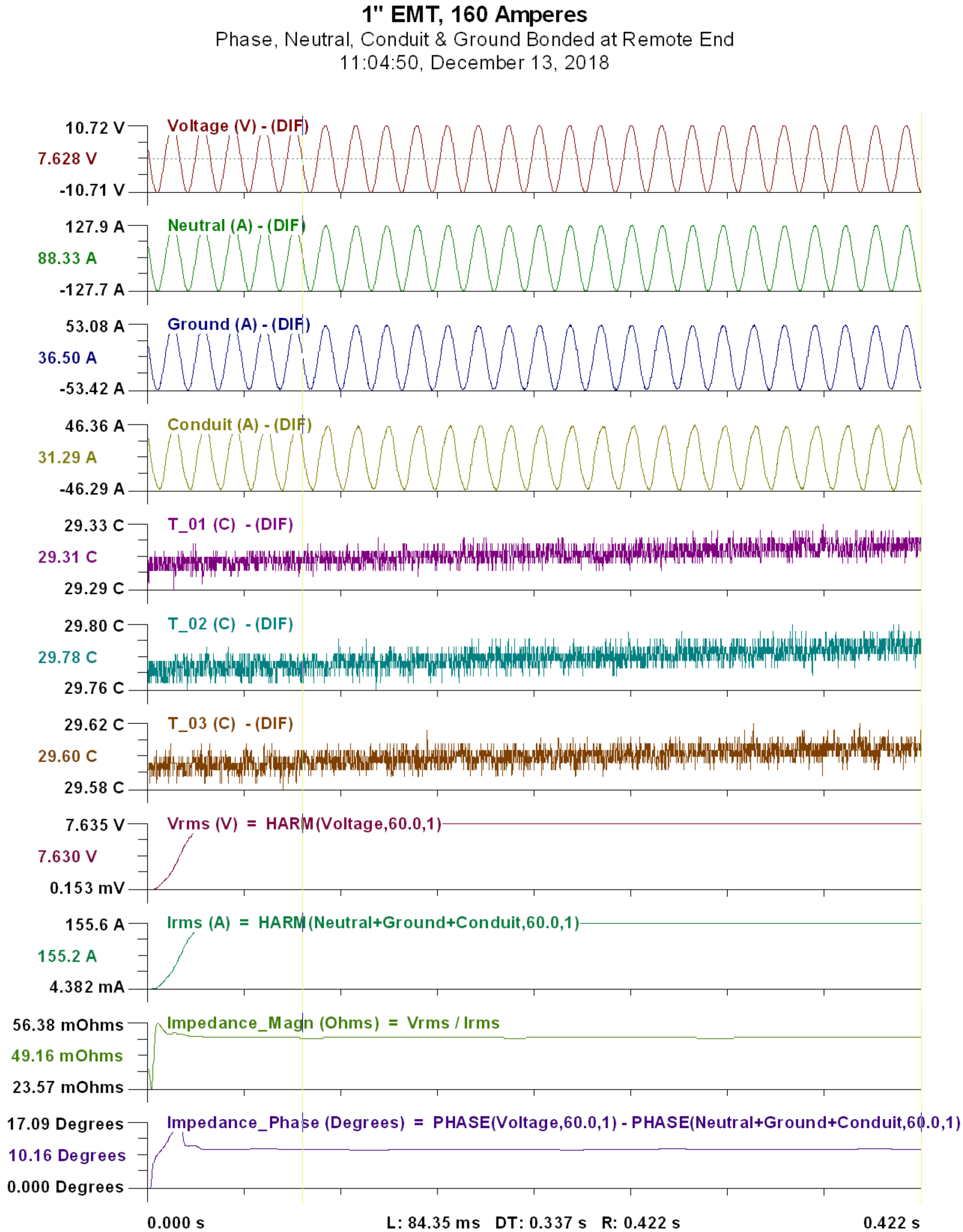


Figure H-4: Case Name EMT100_004

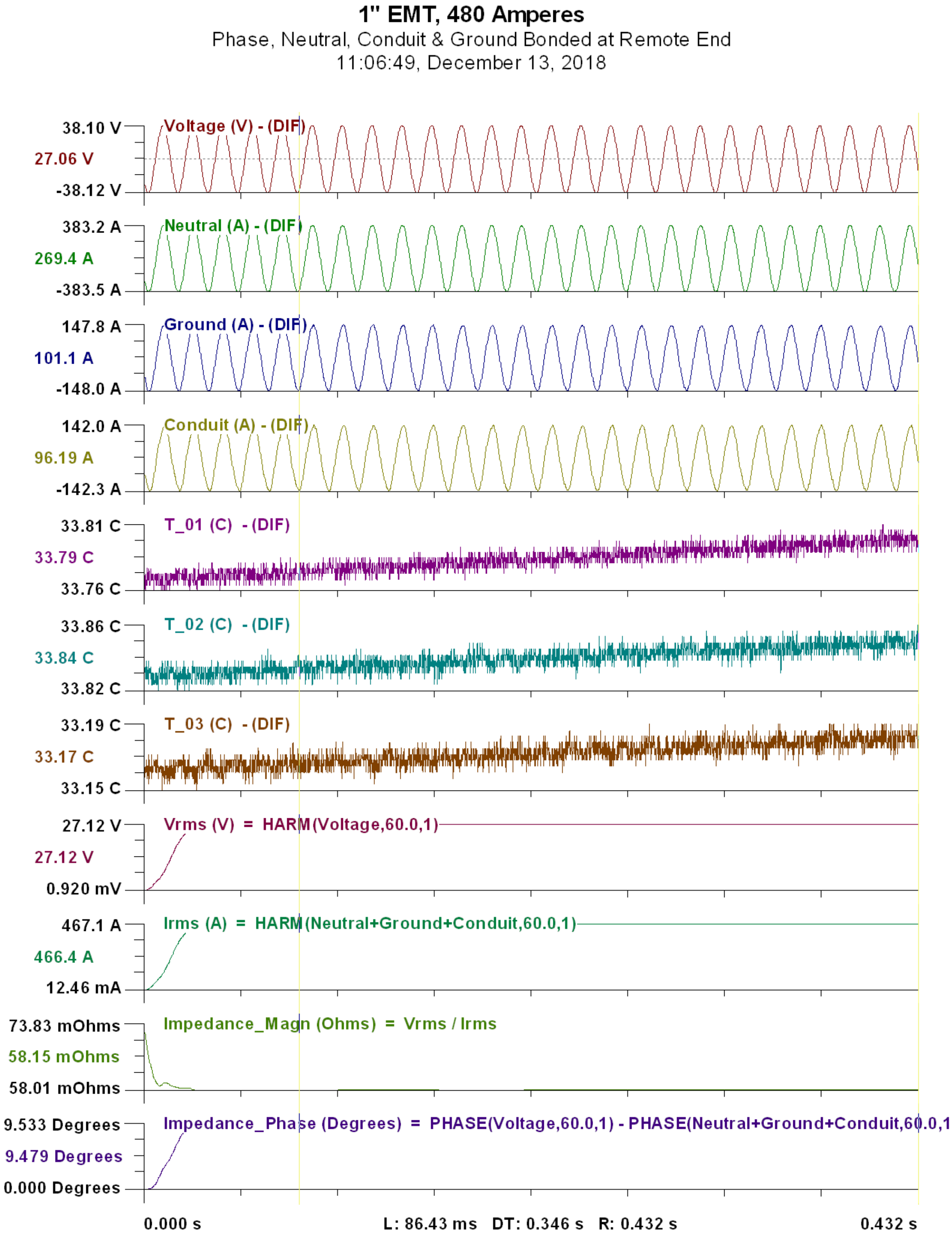


Figure H-5: Case Name EMT100_005

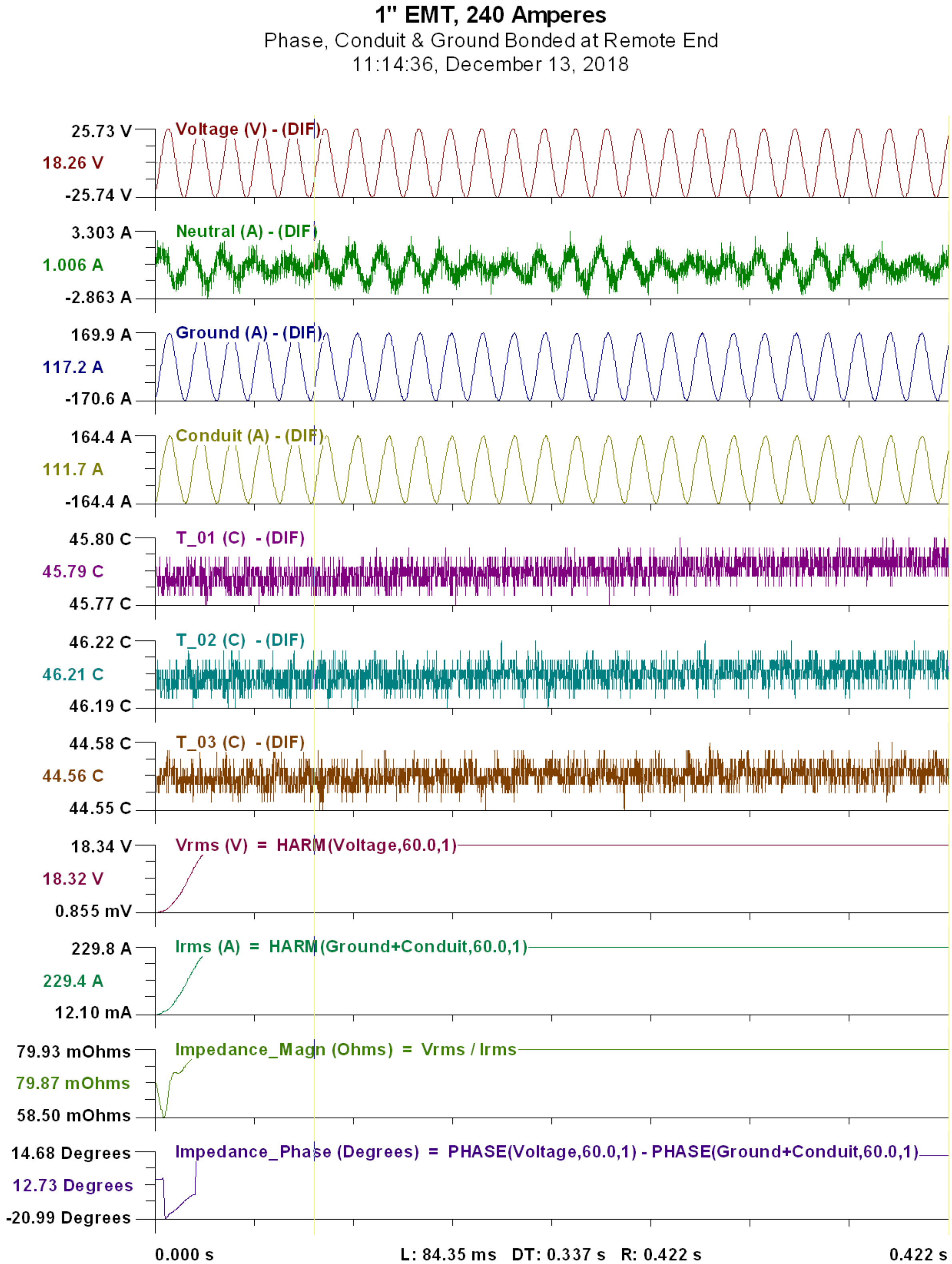


Figure H-6: Case Name EMT100_006

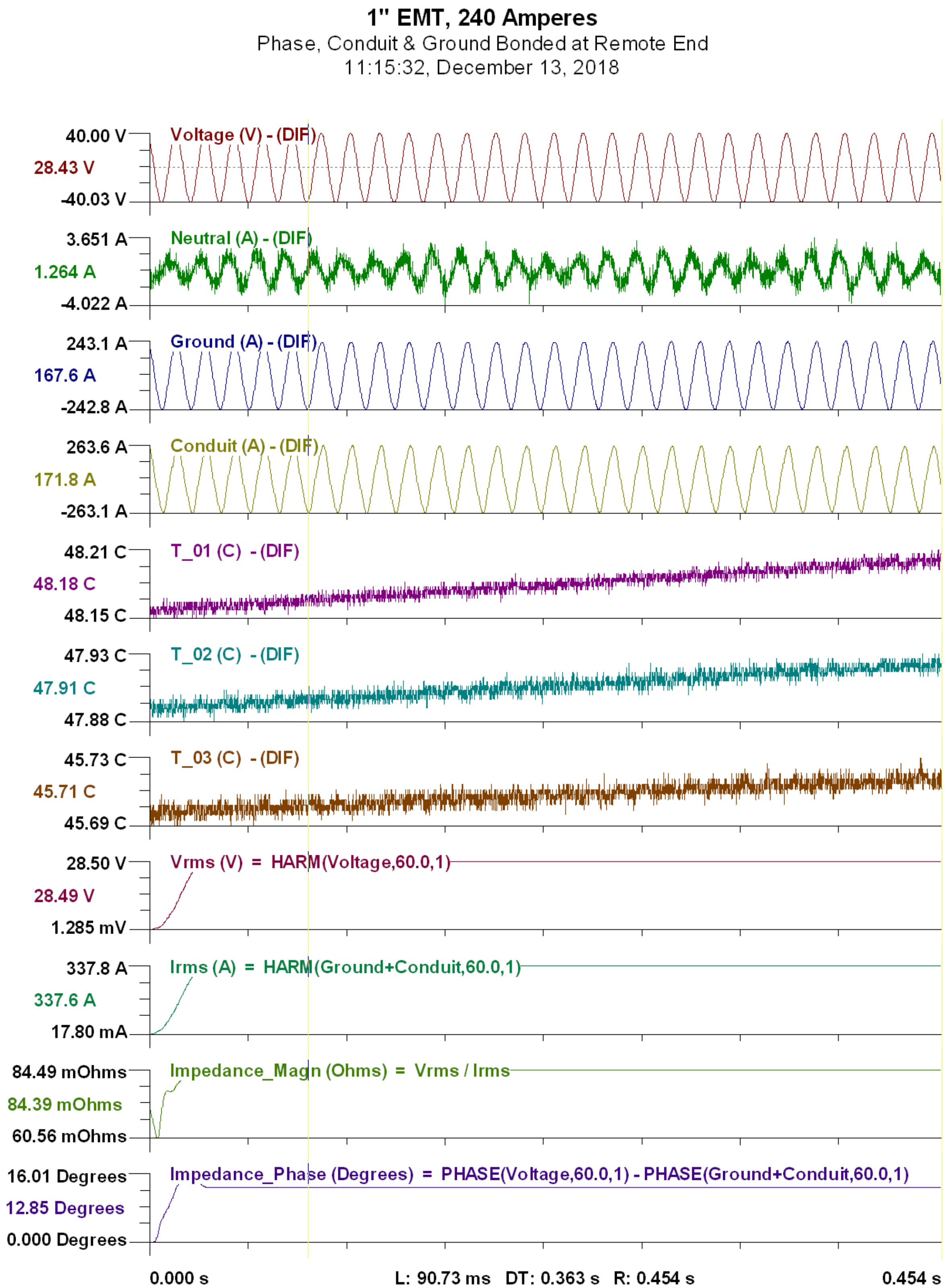


Figure H-7: Case Name EMT100_007

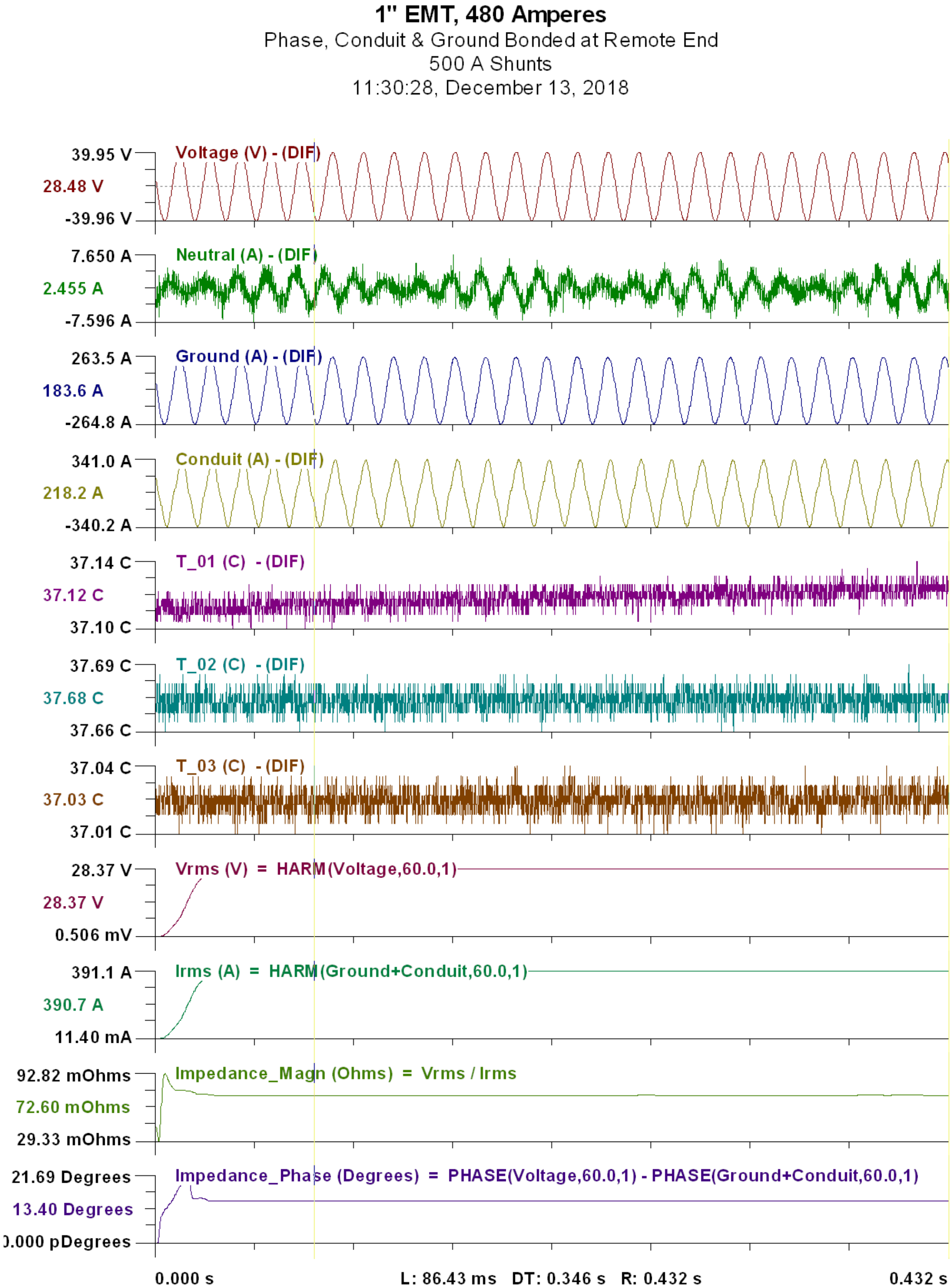


Figure H-8: Case Name EMT100_008

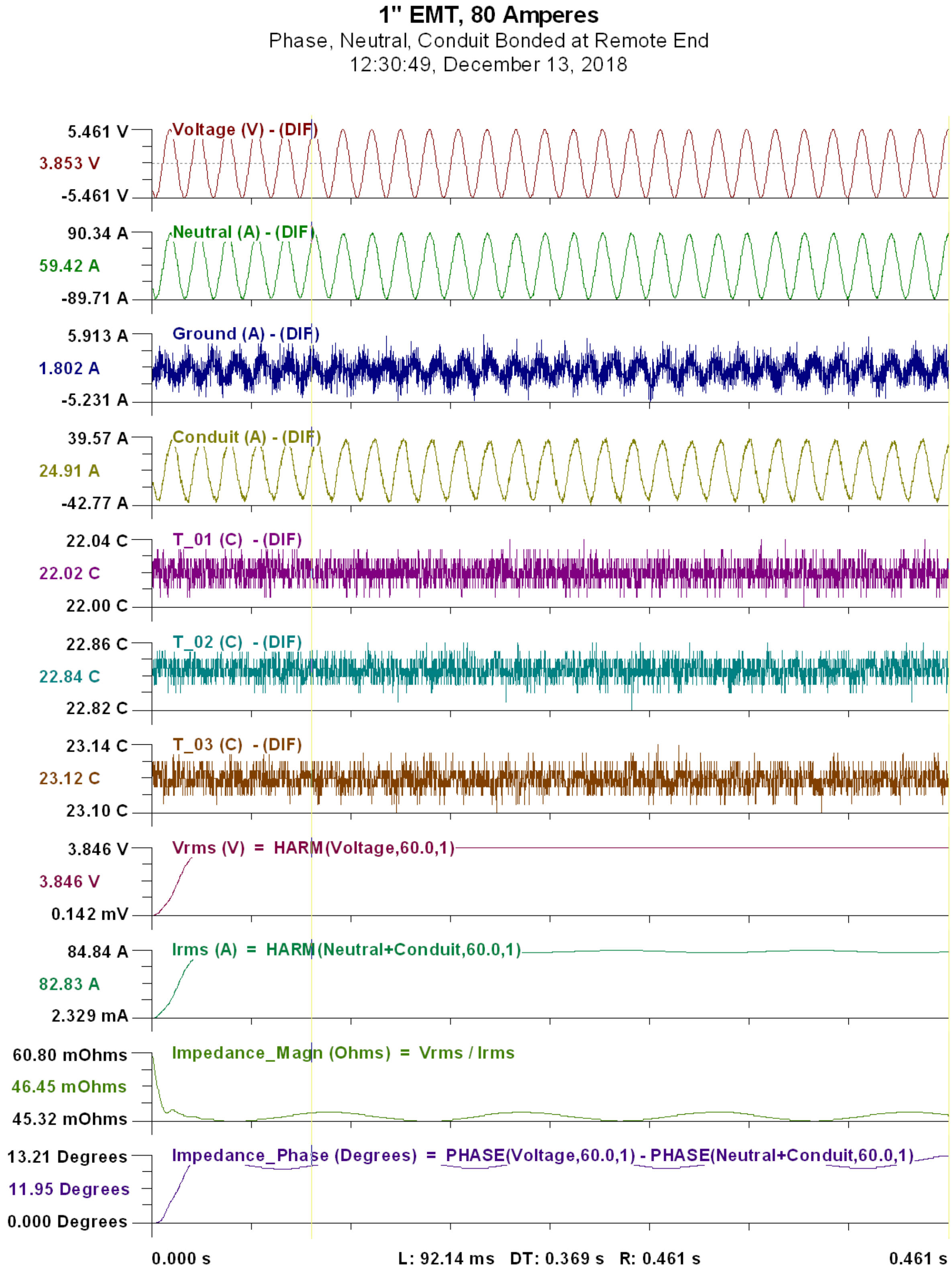


Figure H-9: Case Name EMT100_009

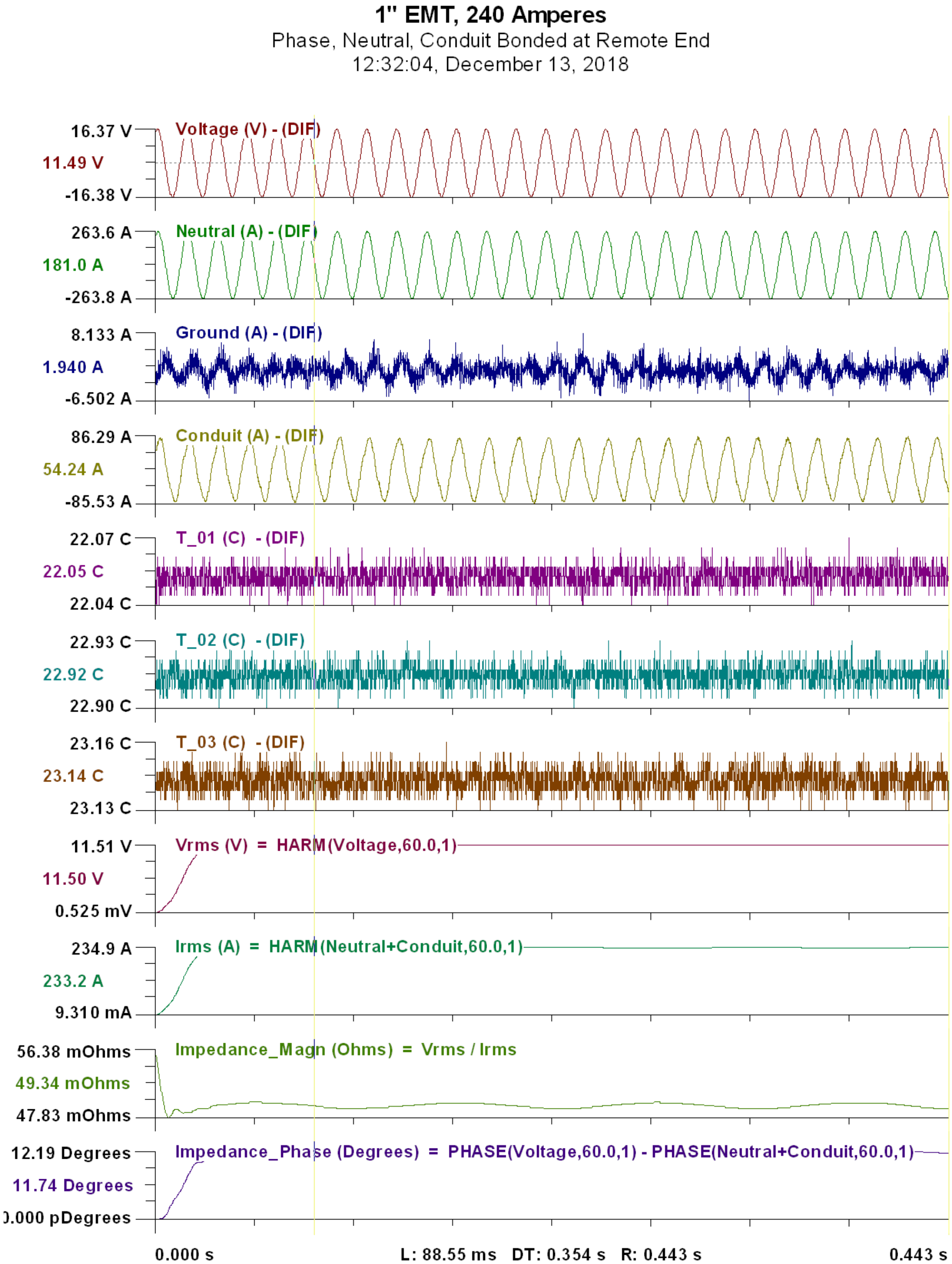


Figure H-10: Case Name EMT100_010

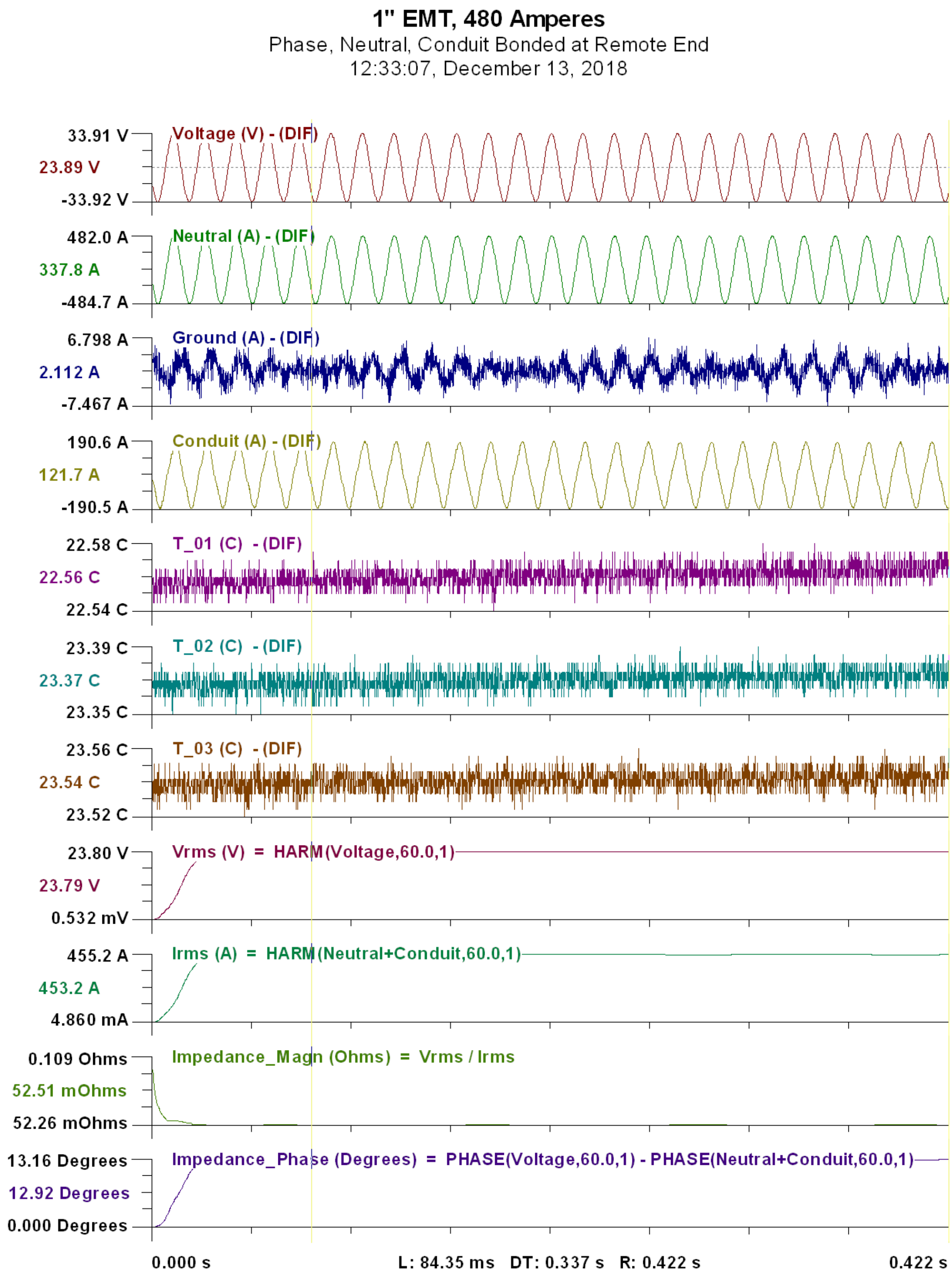


Figure H-11: Case Name EMT100_011

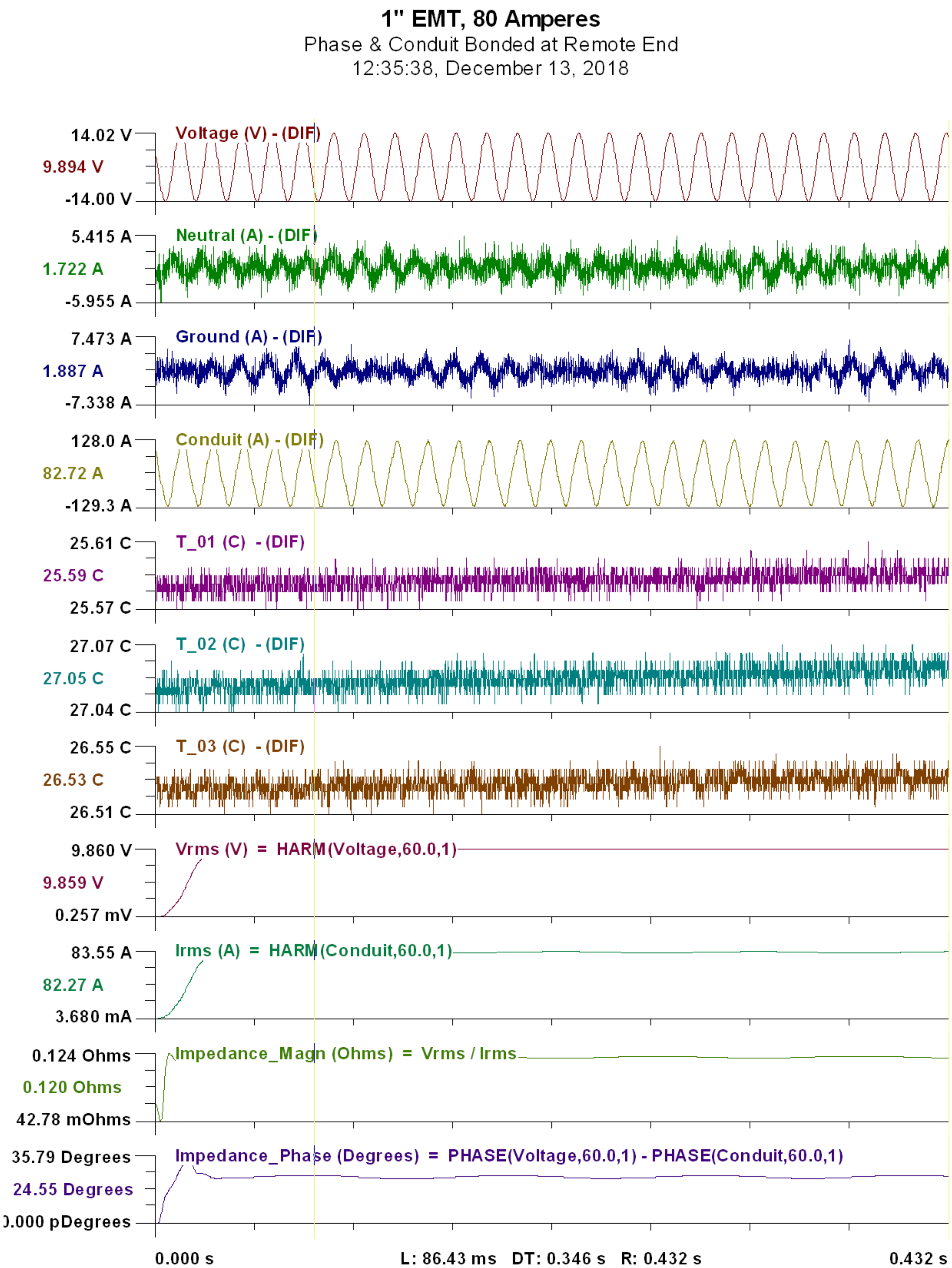


Figure H-12: Case Name EMT100_012

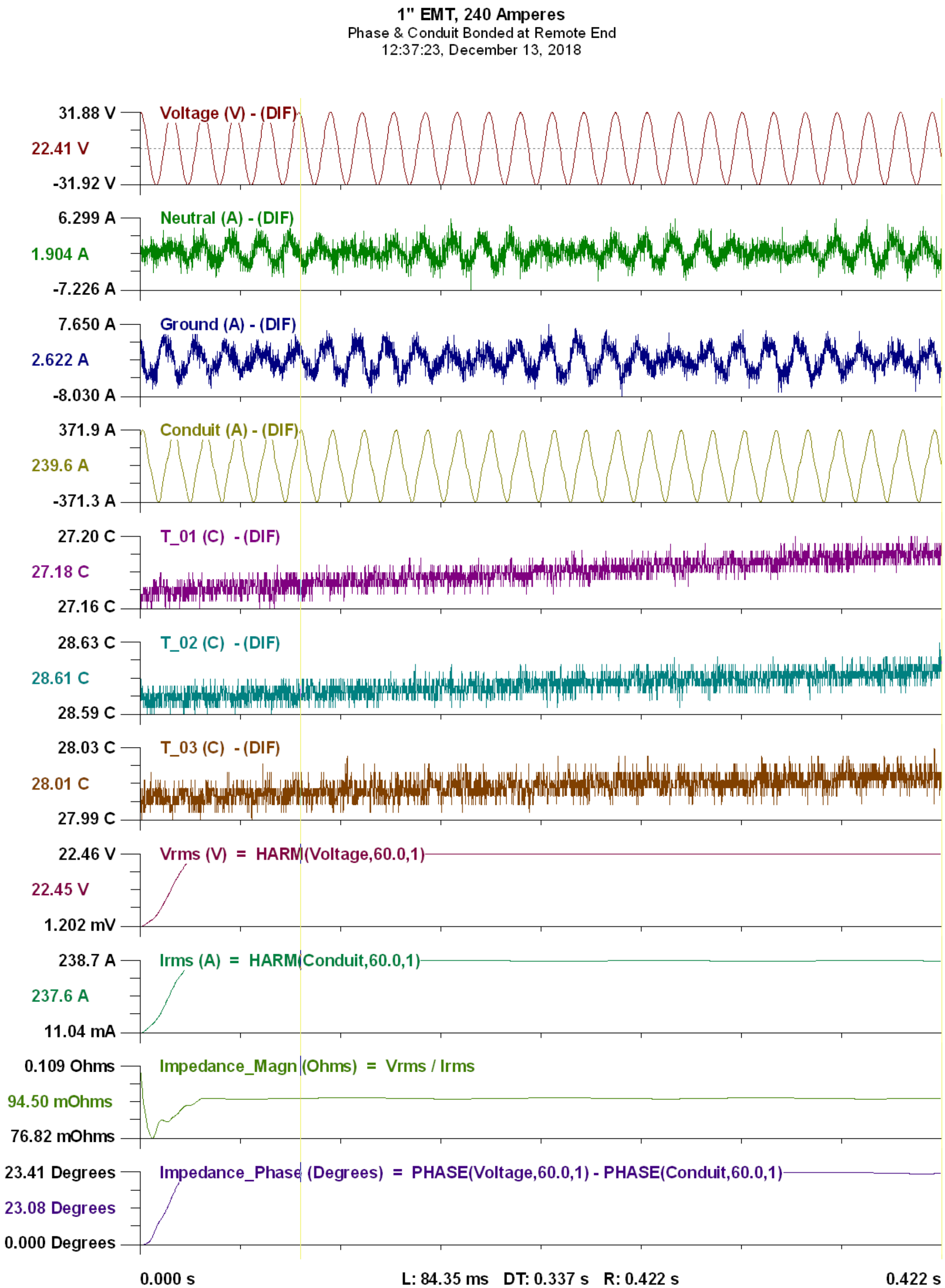


Figure H-13: Case Name EMT100_013

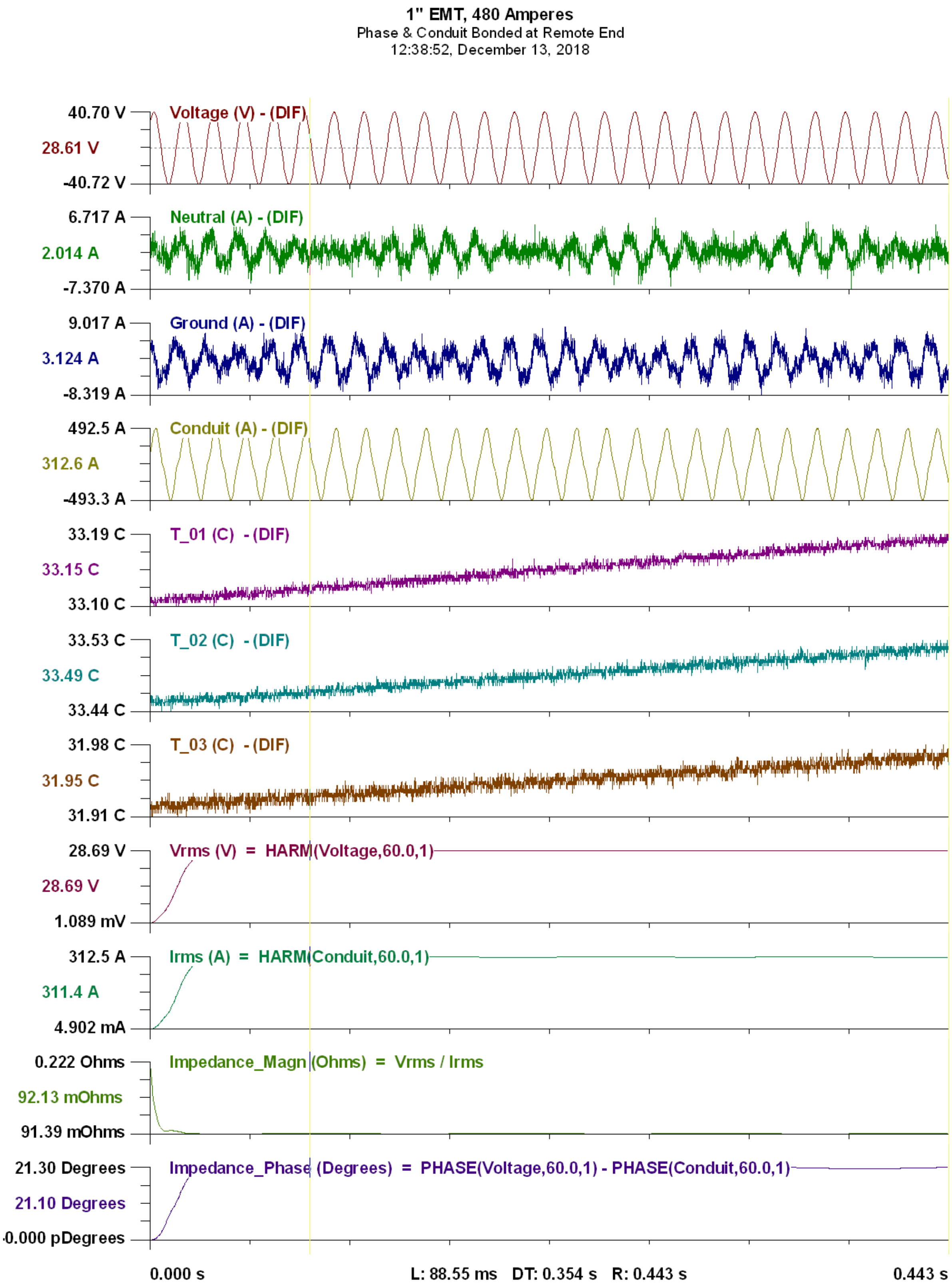


Figure H-14: Case Name EMT100_014

Appendix I – 1” GRC Raw Data Plots

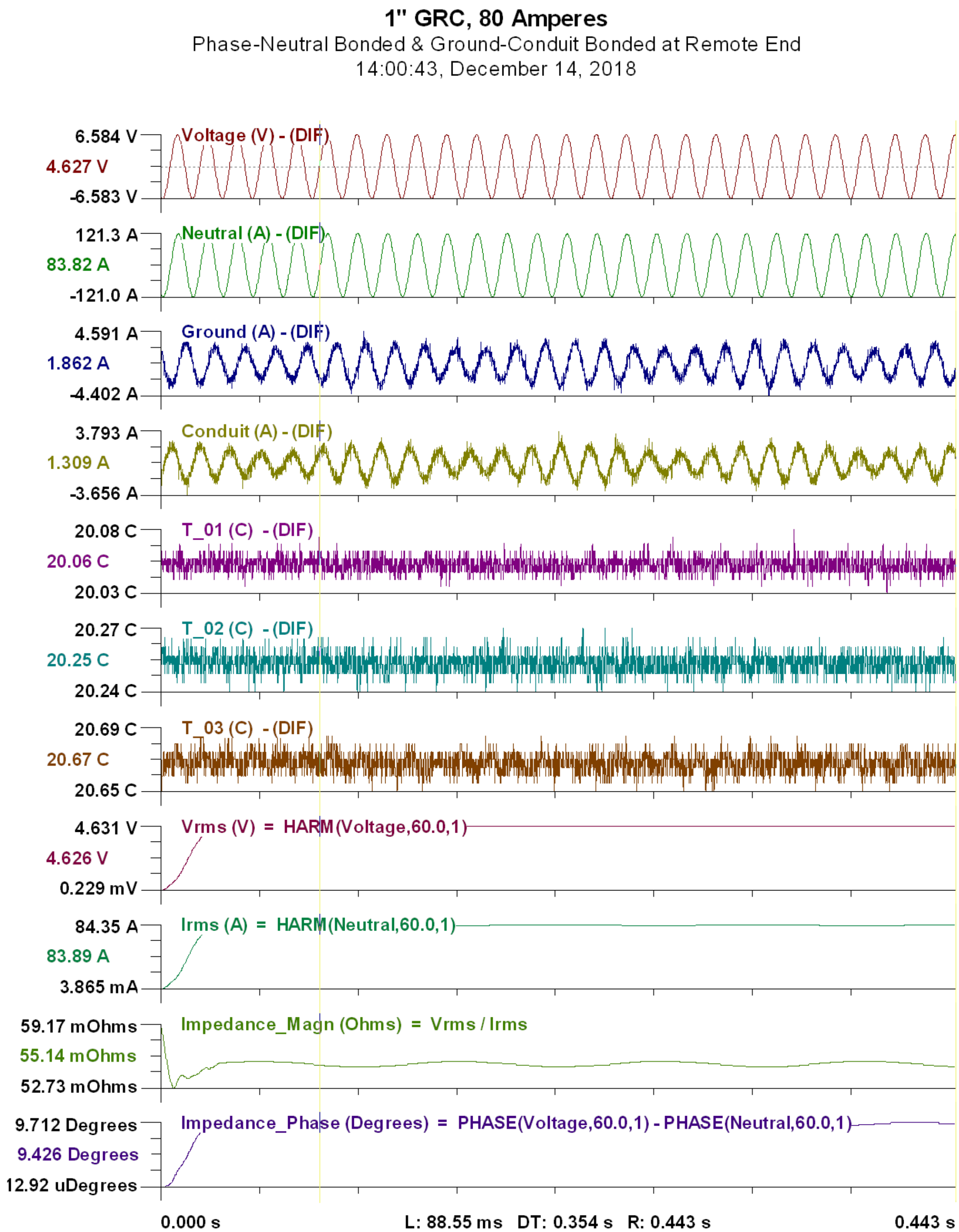


Figure I-1: Case Name GRC100_001

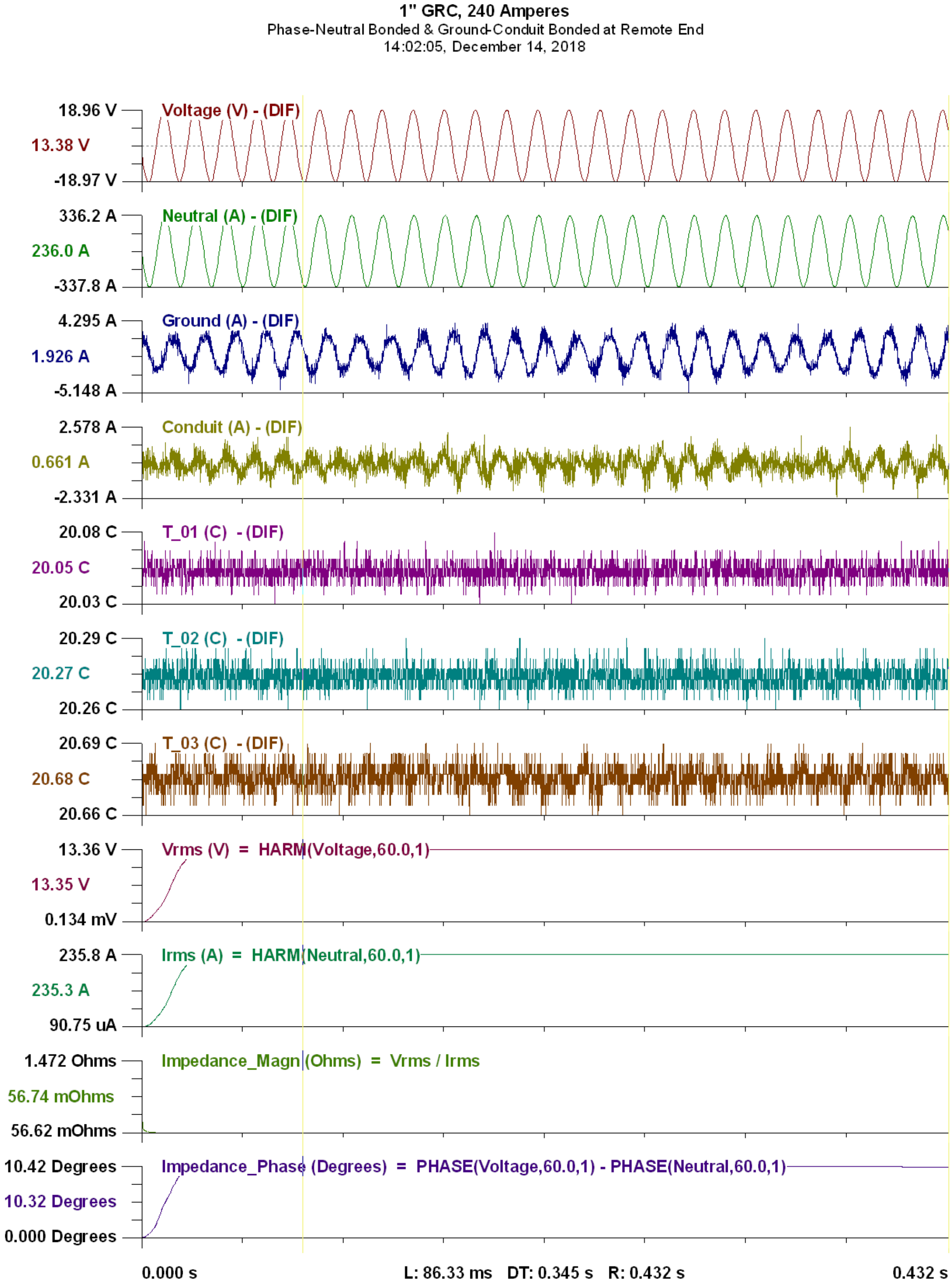


Figure I-2: Case Name GRC100_002

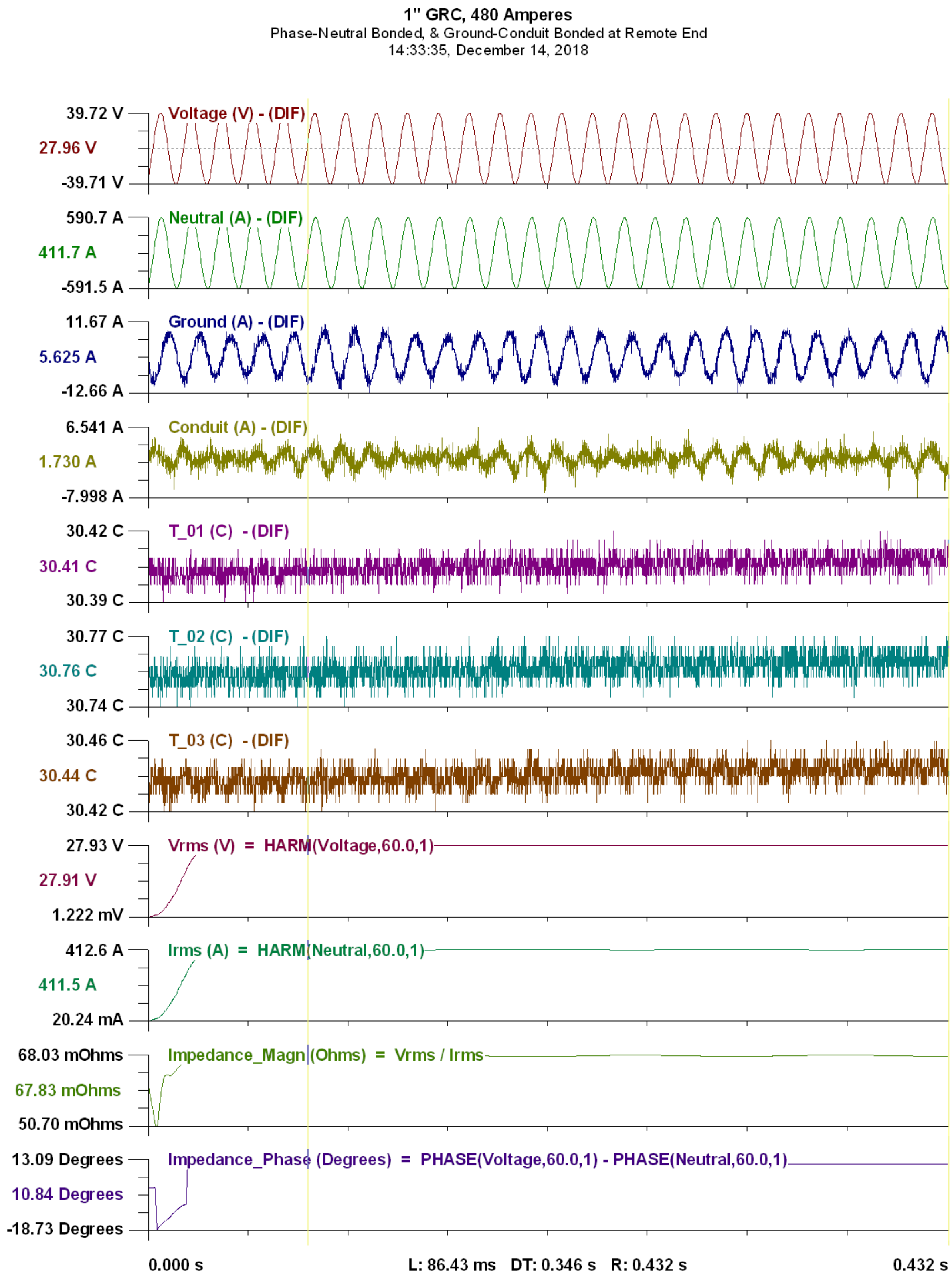


Figure I-3: Case Name GRC100_003

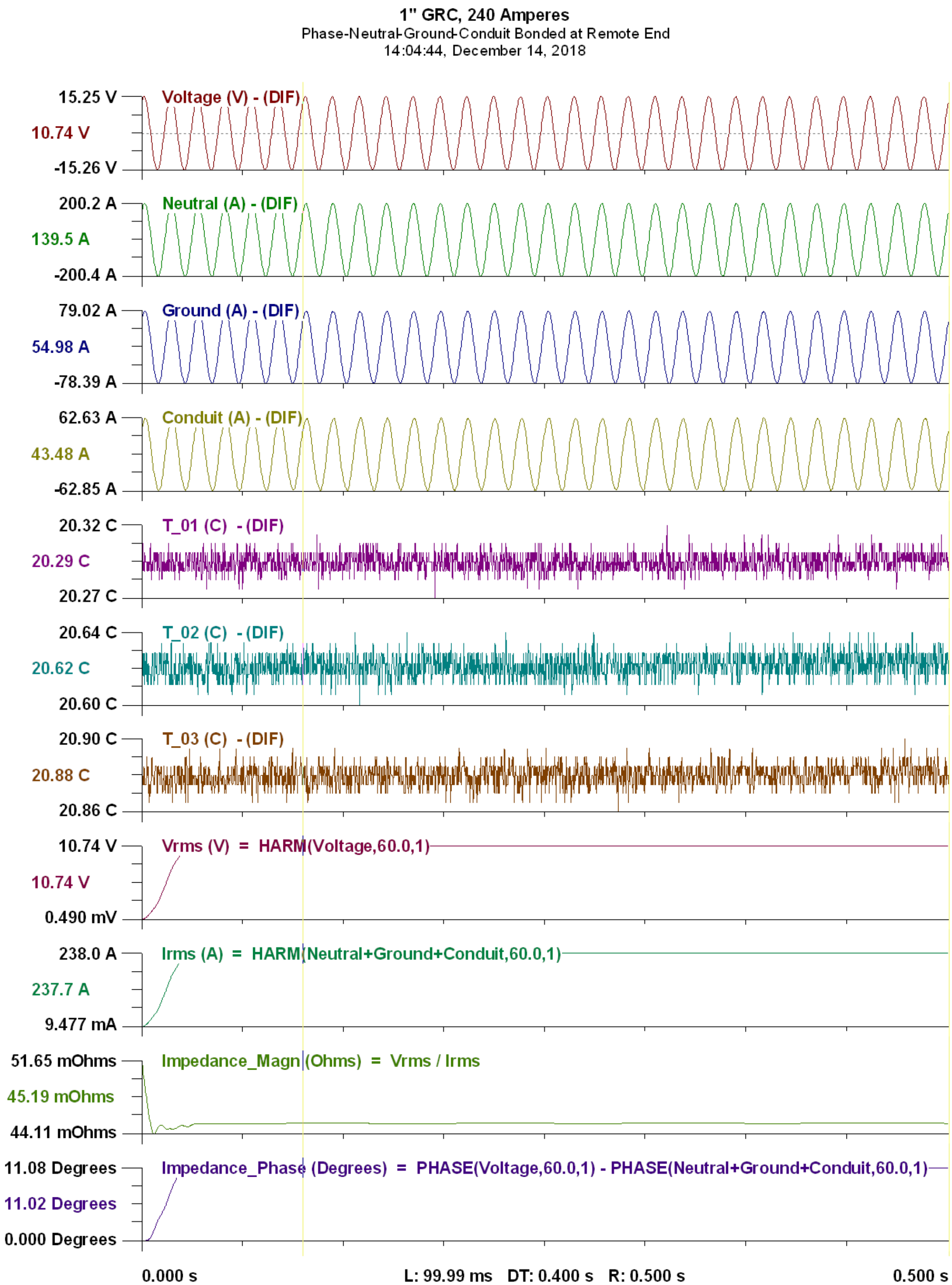


Figure I-4: Case Name GRC100_004

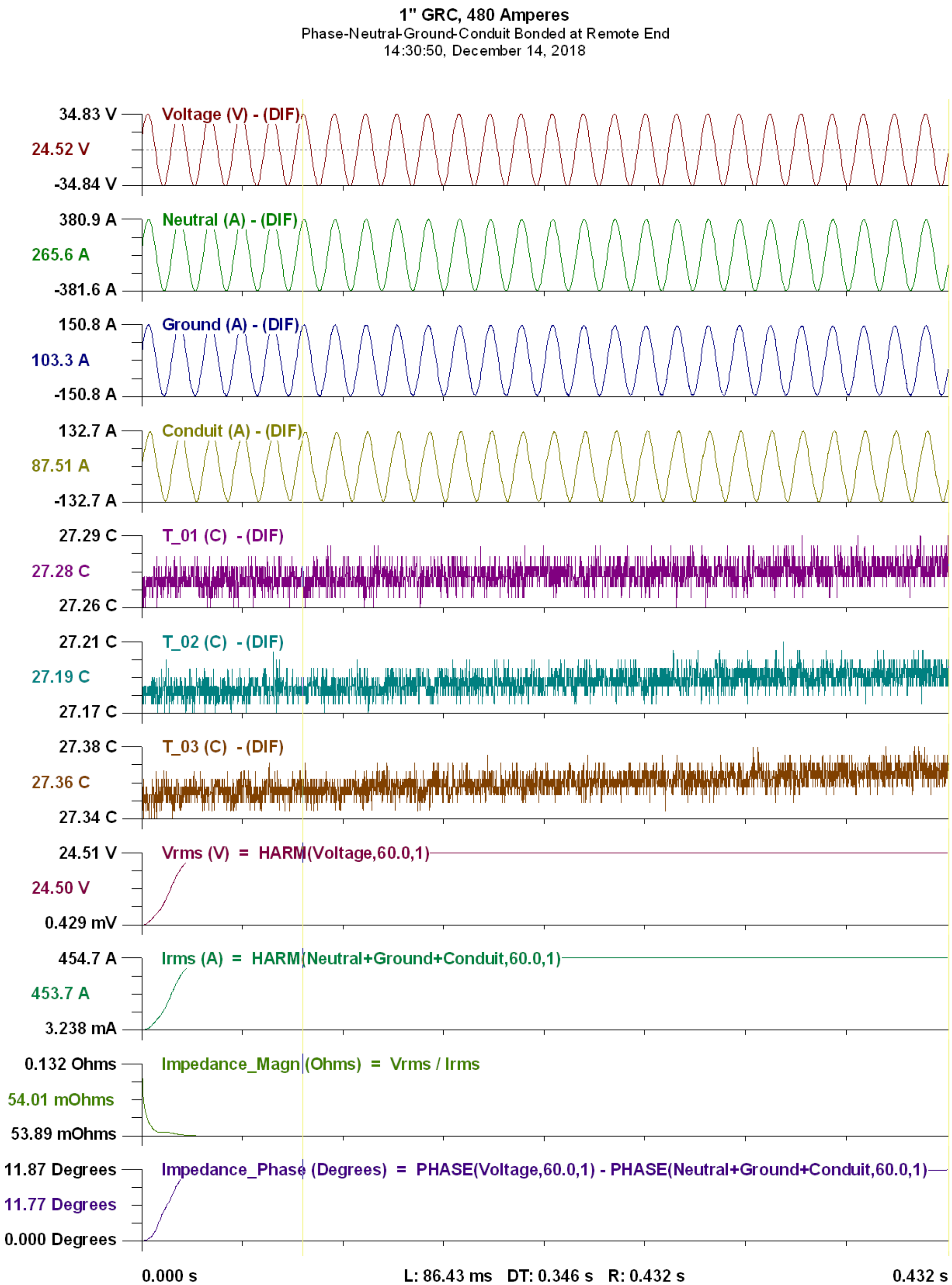


Figure I-5: Case Name GRC100_005

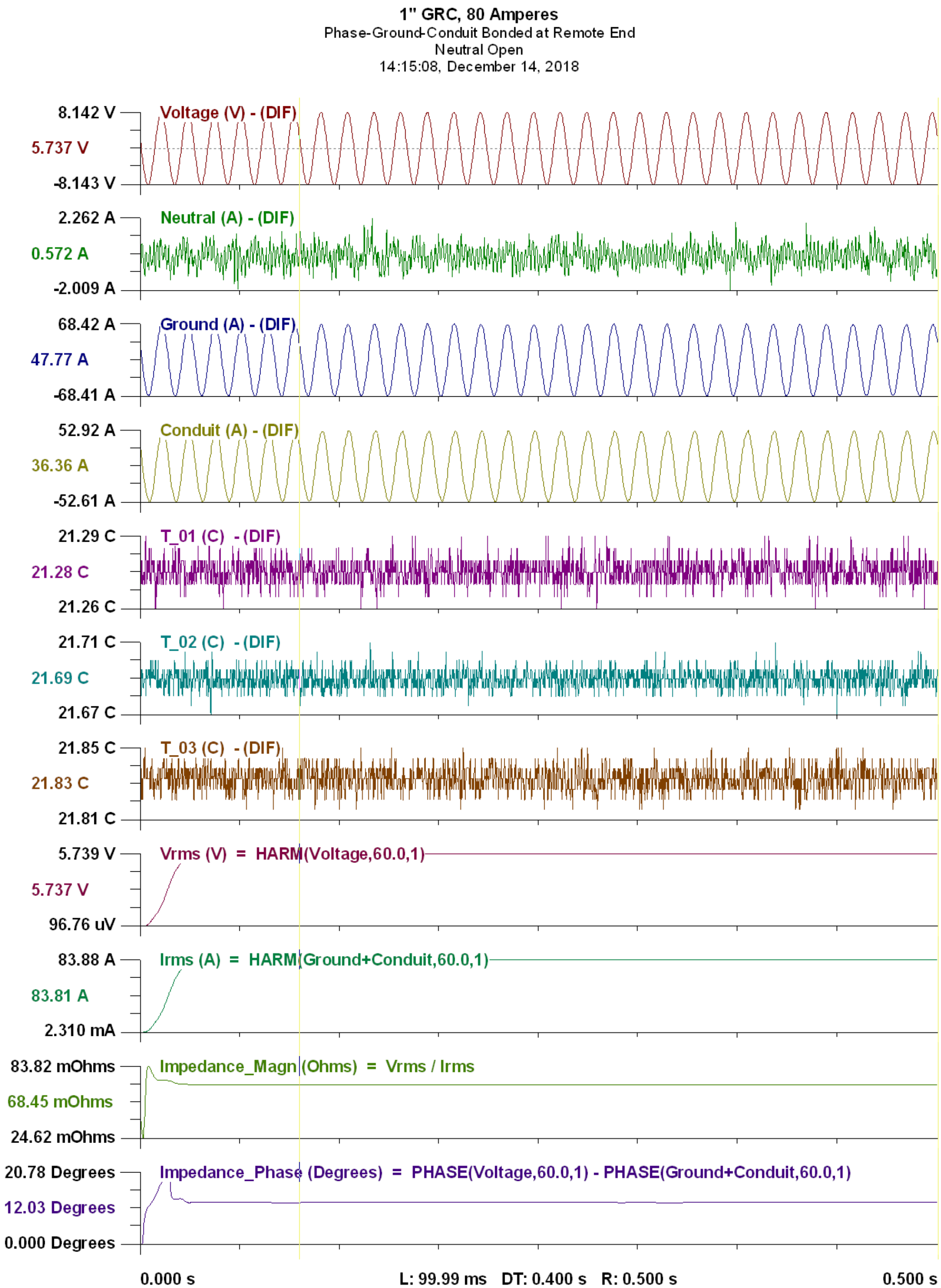


Figure I-6: Case Name GRC100_006

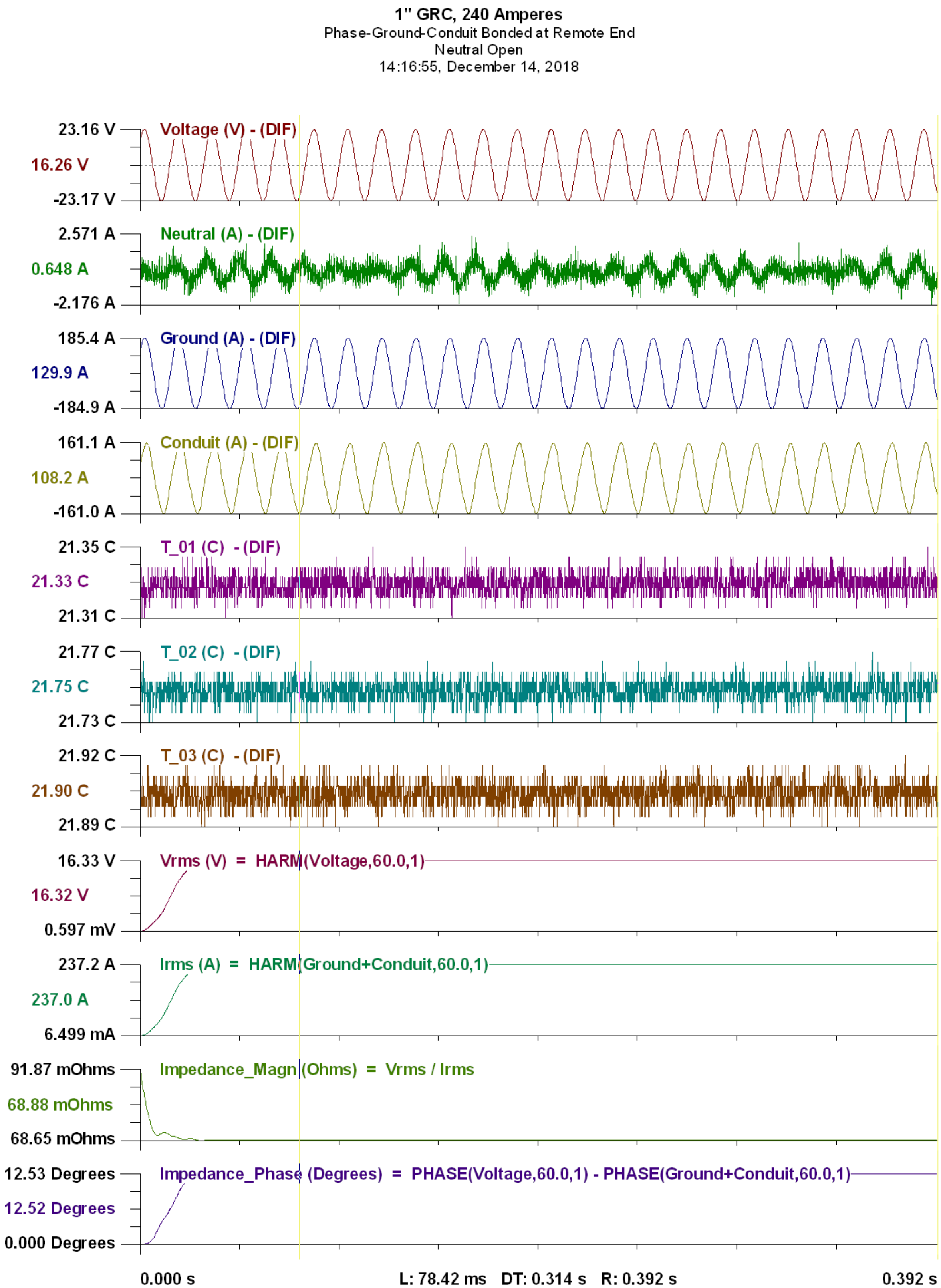


Figure I-7: Case Name GRC100_007

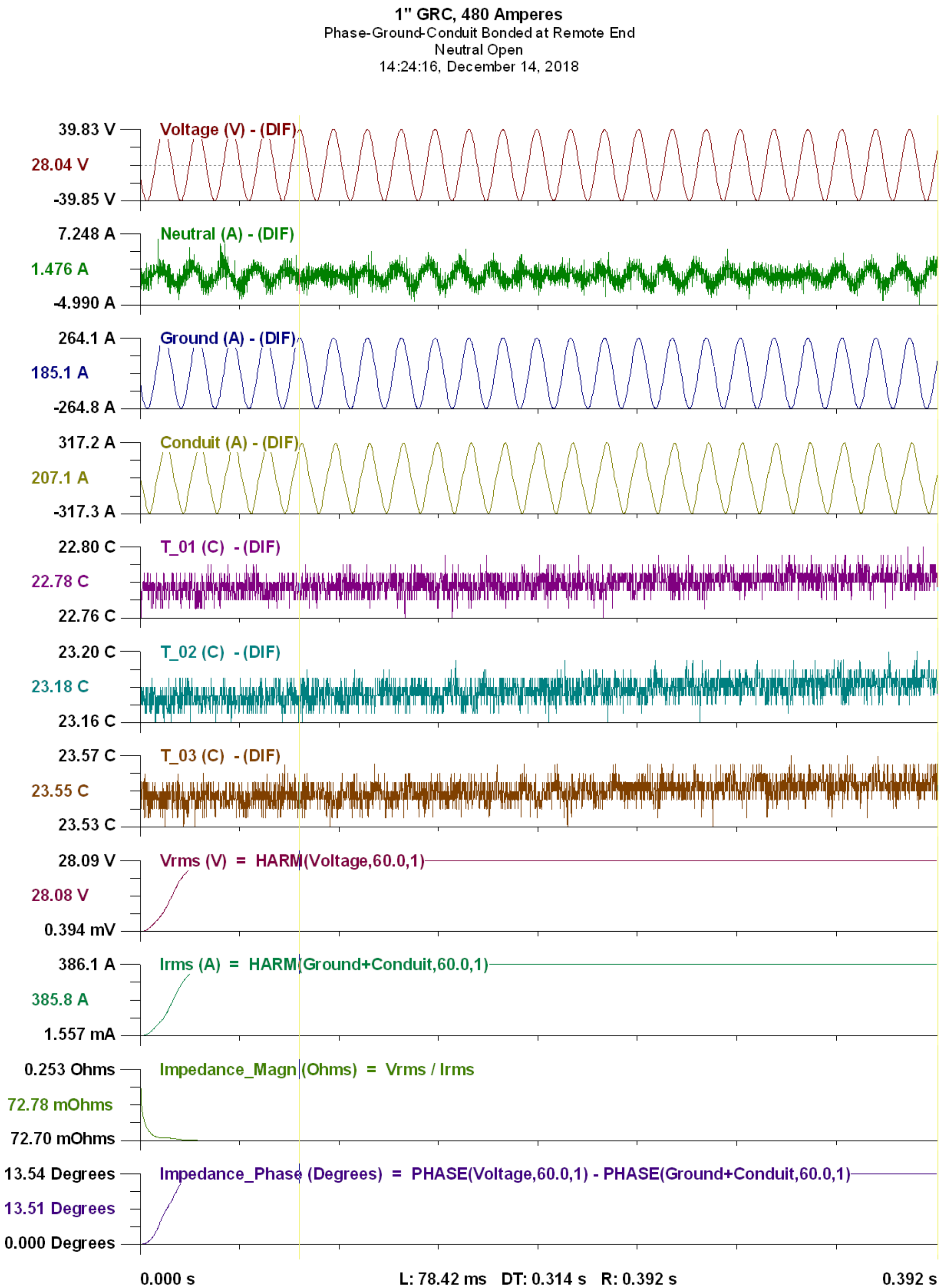


Figure I-8: Case Name GRC100_008

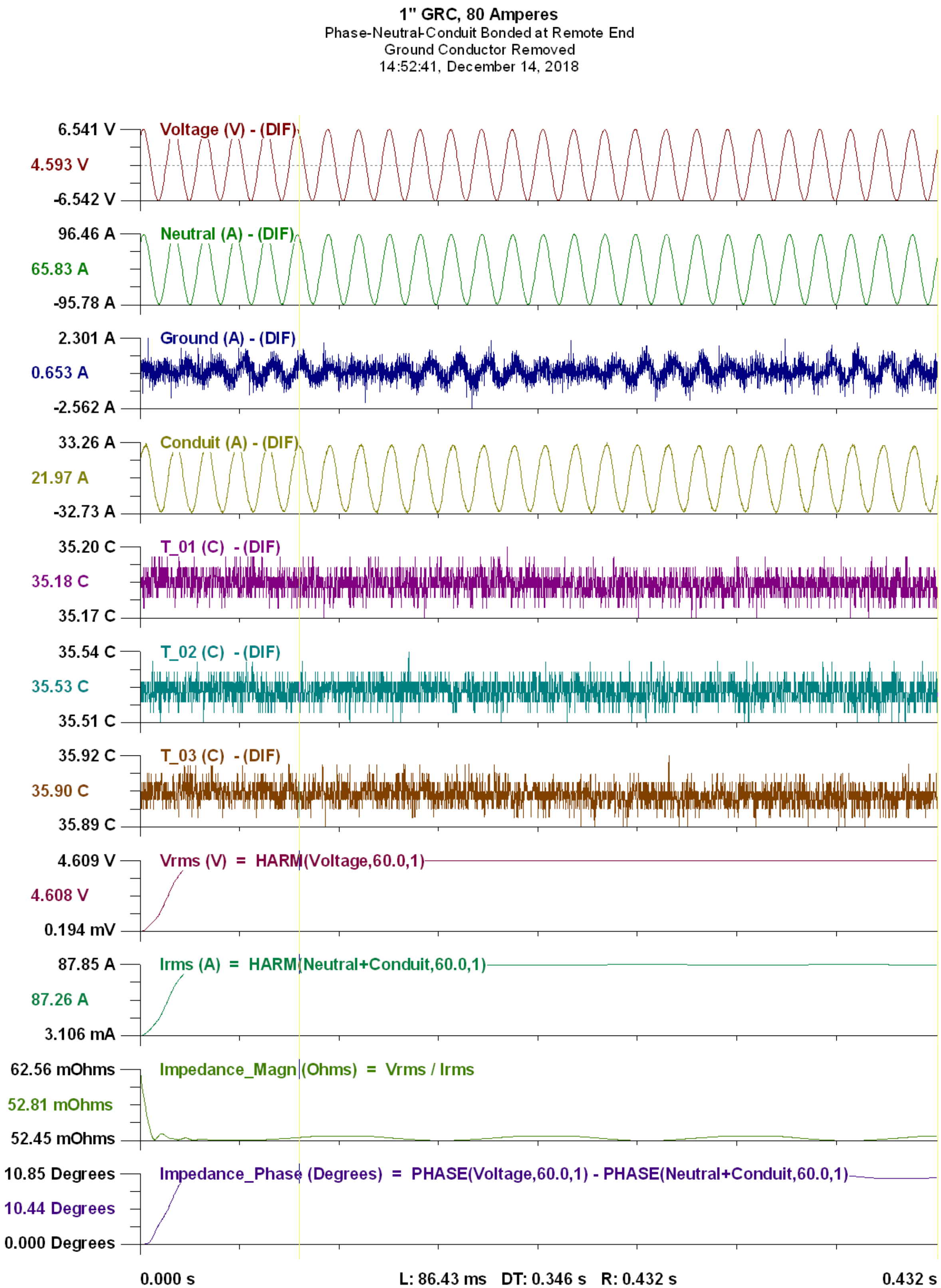


Figure I-9: Case Name GRC100_009

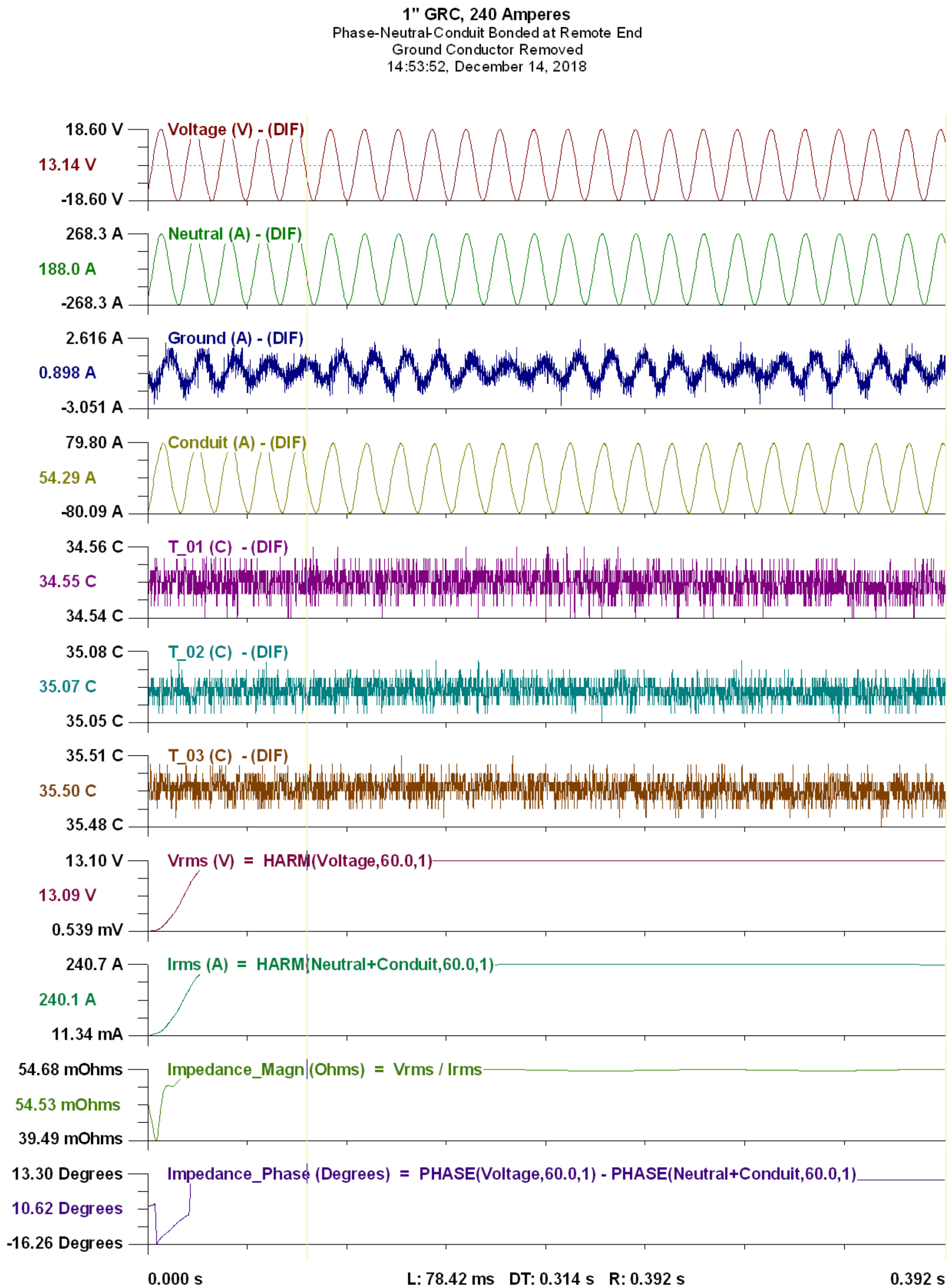


Figure I-10: Case Name GRC100_010

1" GRC, 480 Amperes
Phase-Neutral-Conduit Bonded at Remote End
Ground Conductor Removed
14:39:59, December 14, 2018

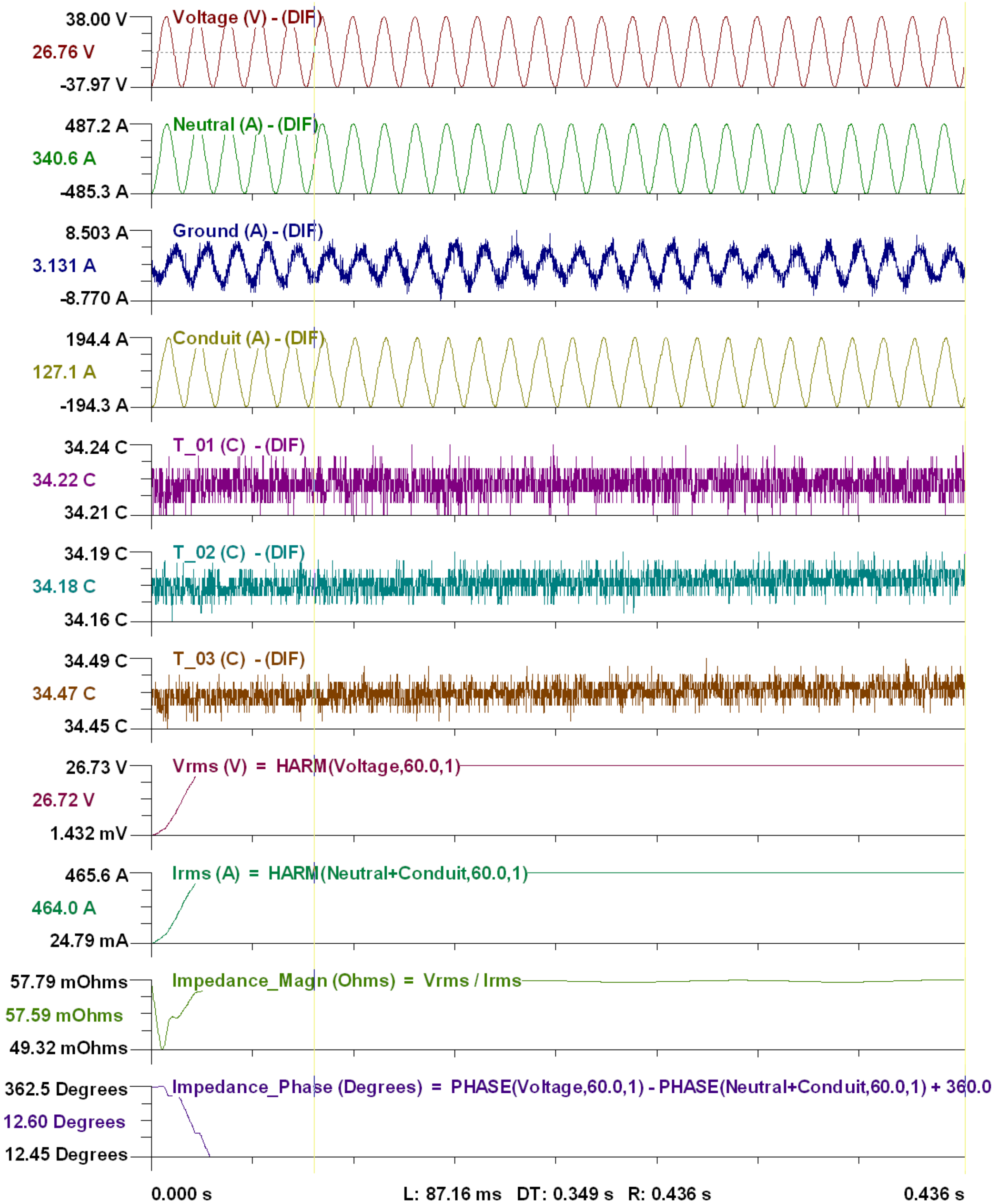


Figure I-11: Case Name GRC100_011

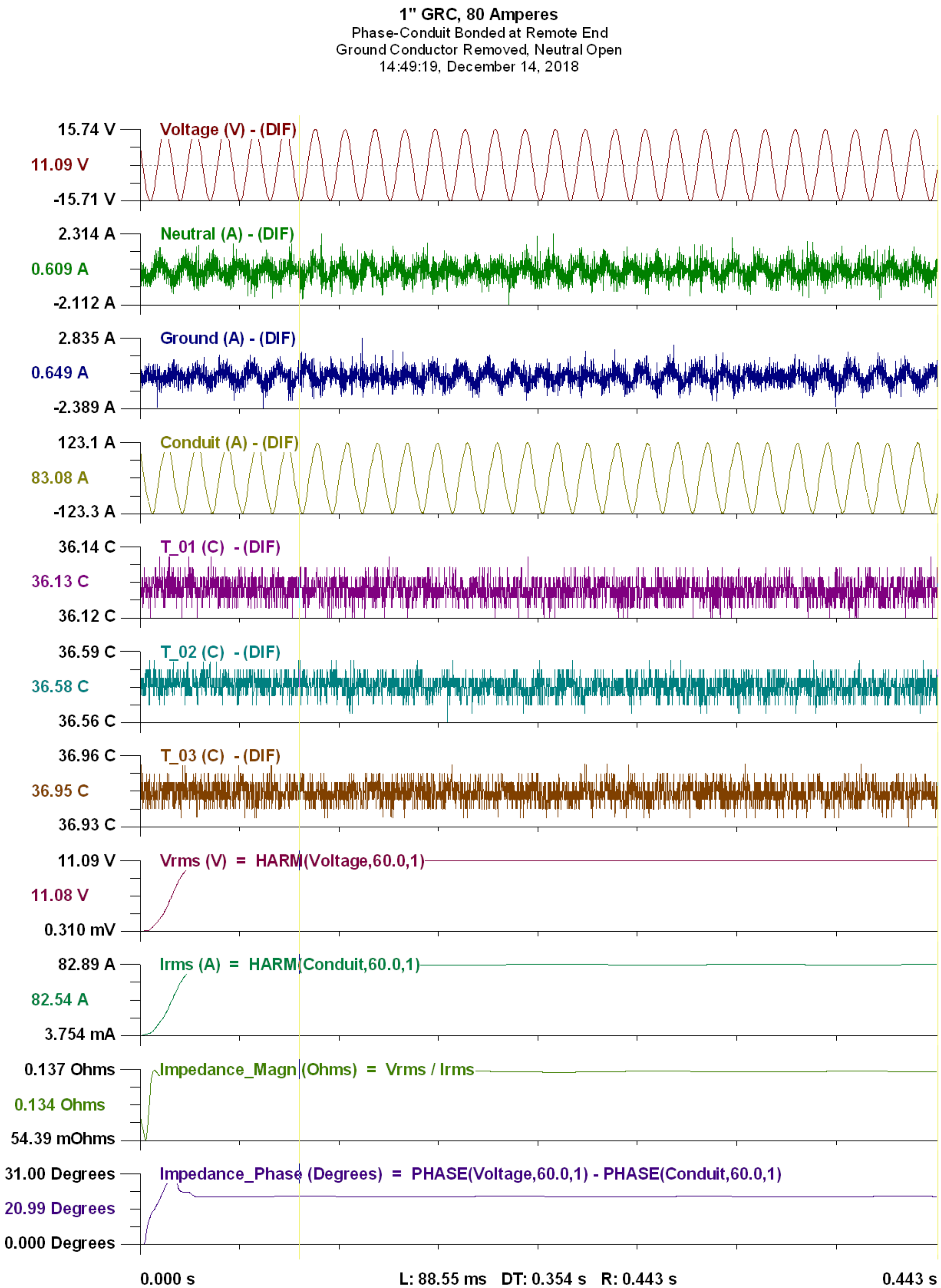


Figure I-12: Case Name GRC100_012

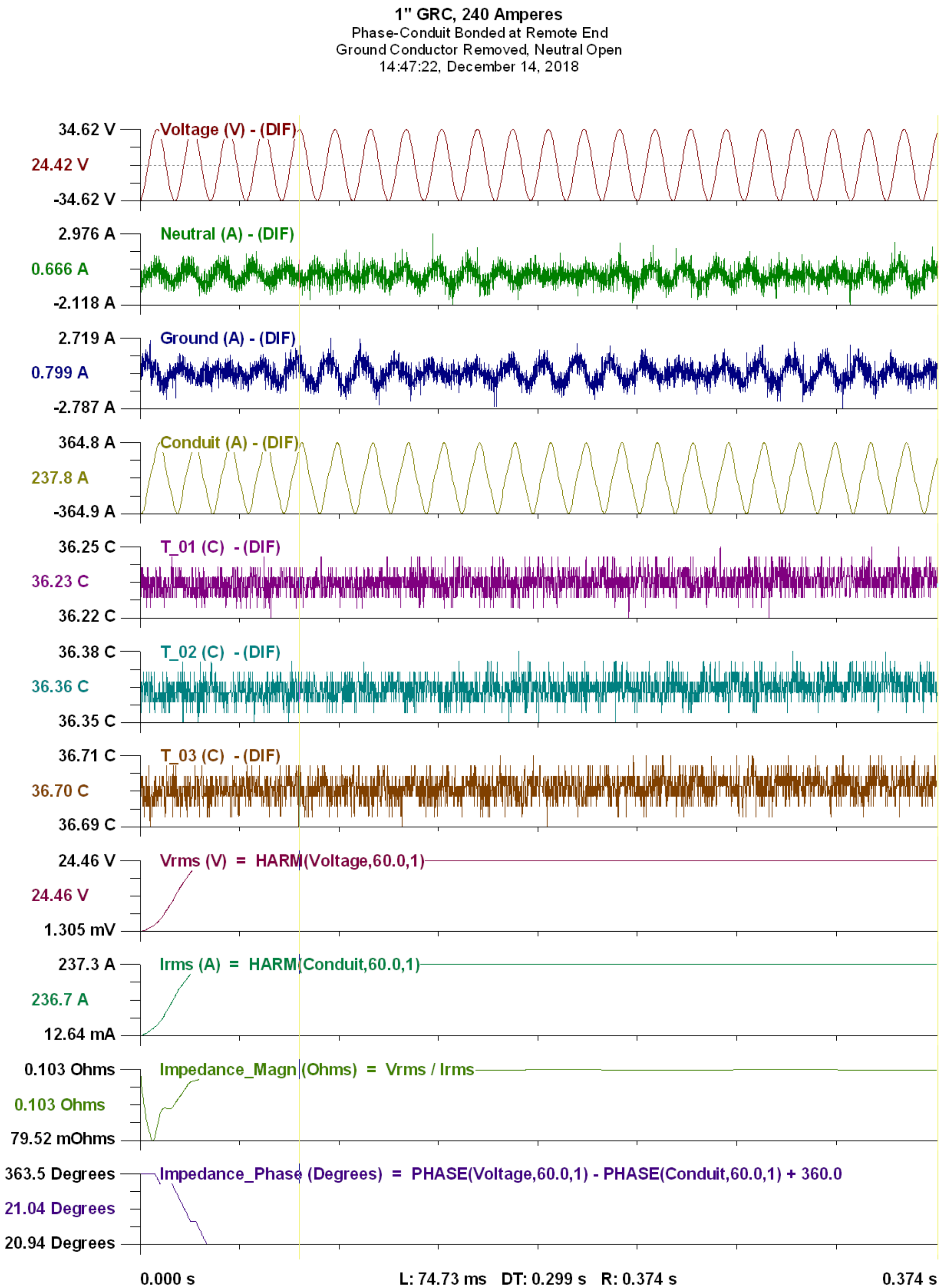


Figure I-13: Case Name GRC100_013

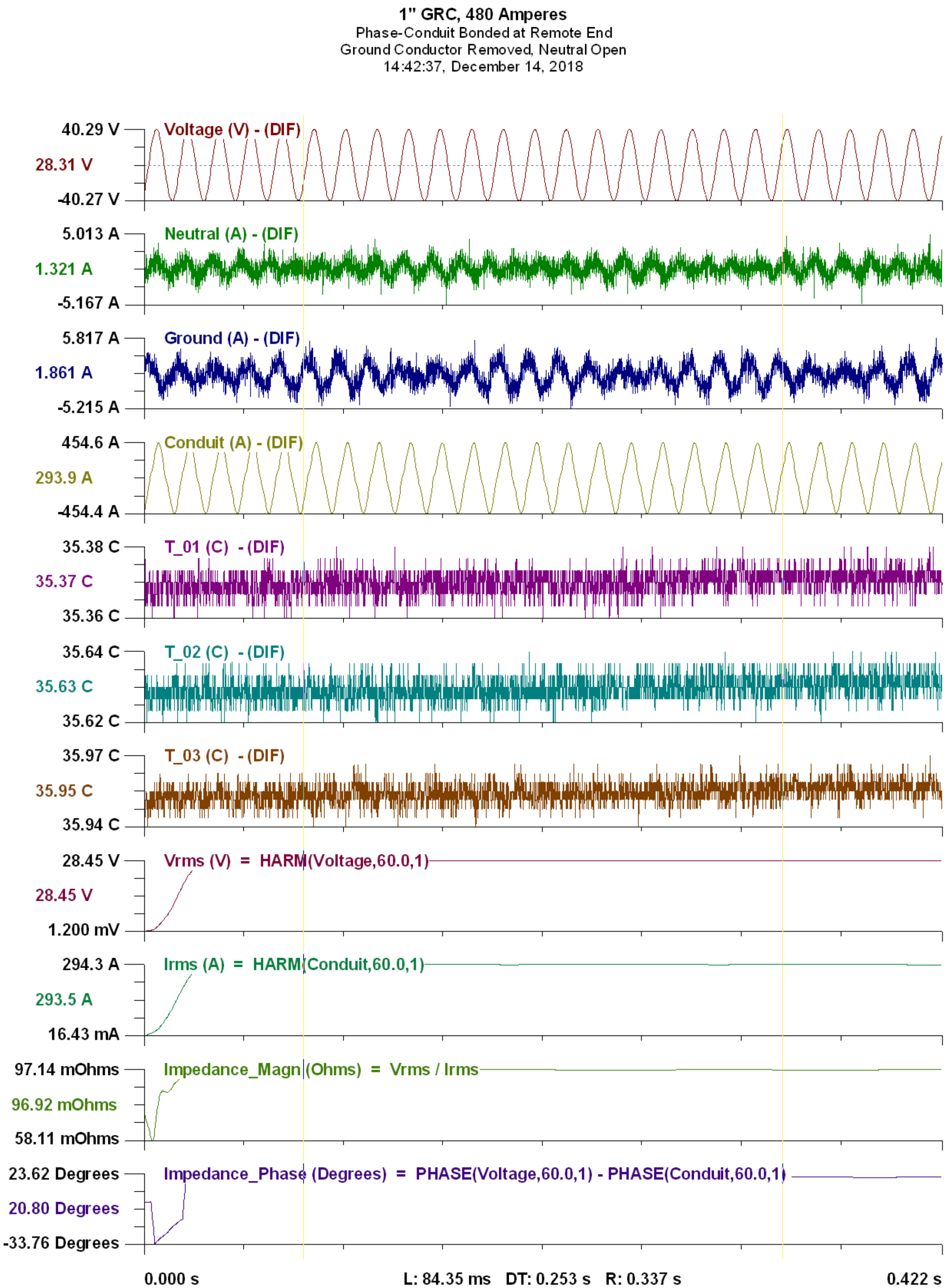


Figure I-14: Case Name GRC100_014

Appendix J – 1” IMC Raw Data Plots

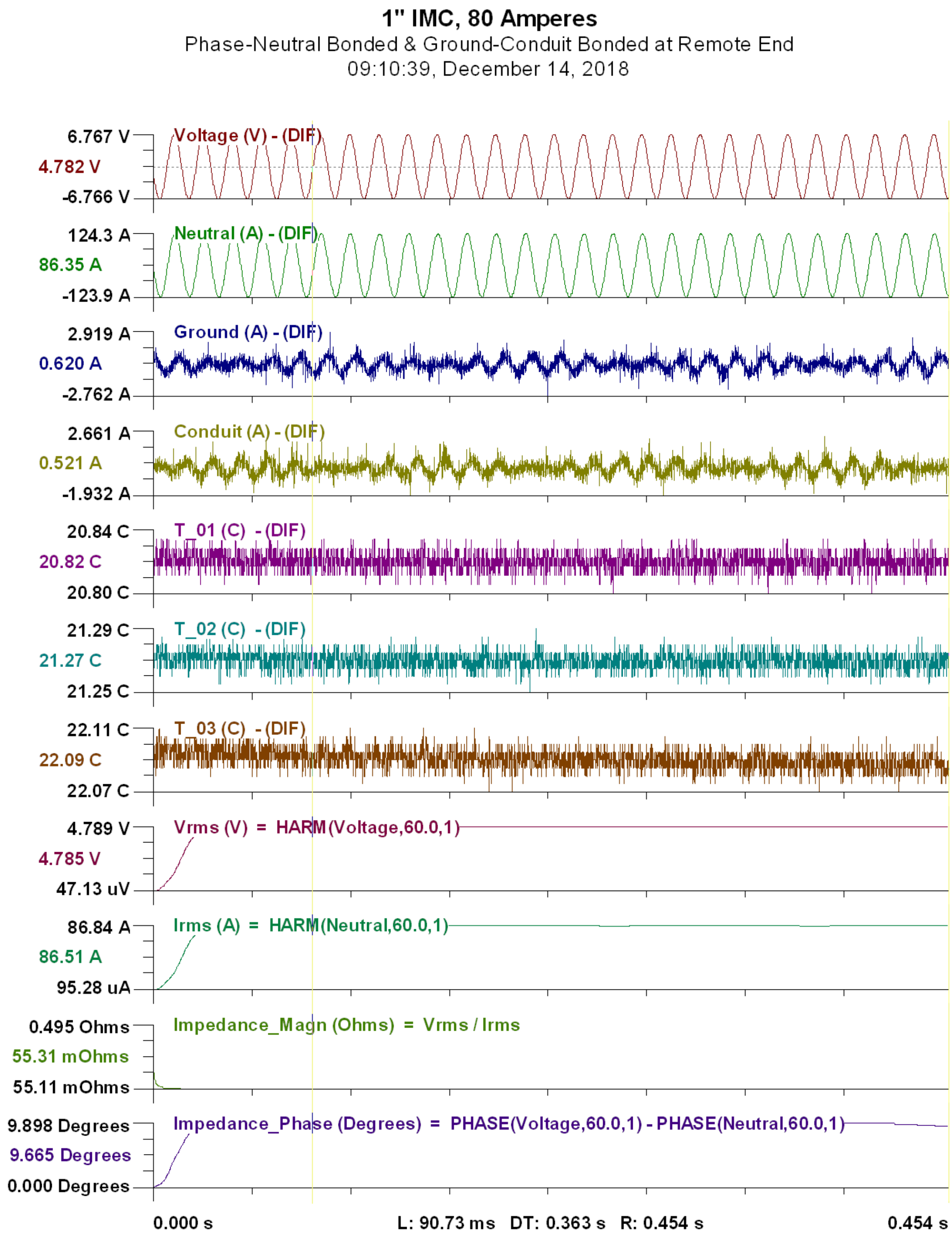


Figure J-1: Case Name IMC100_001

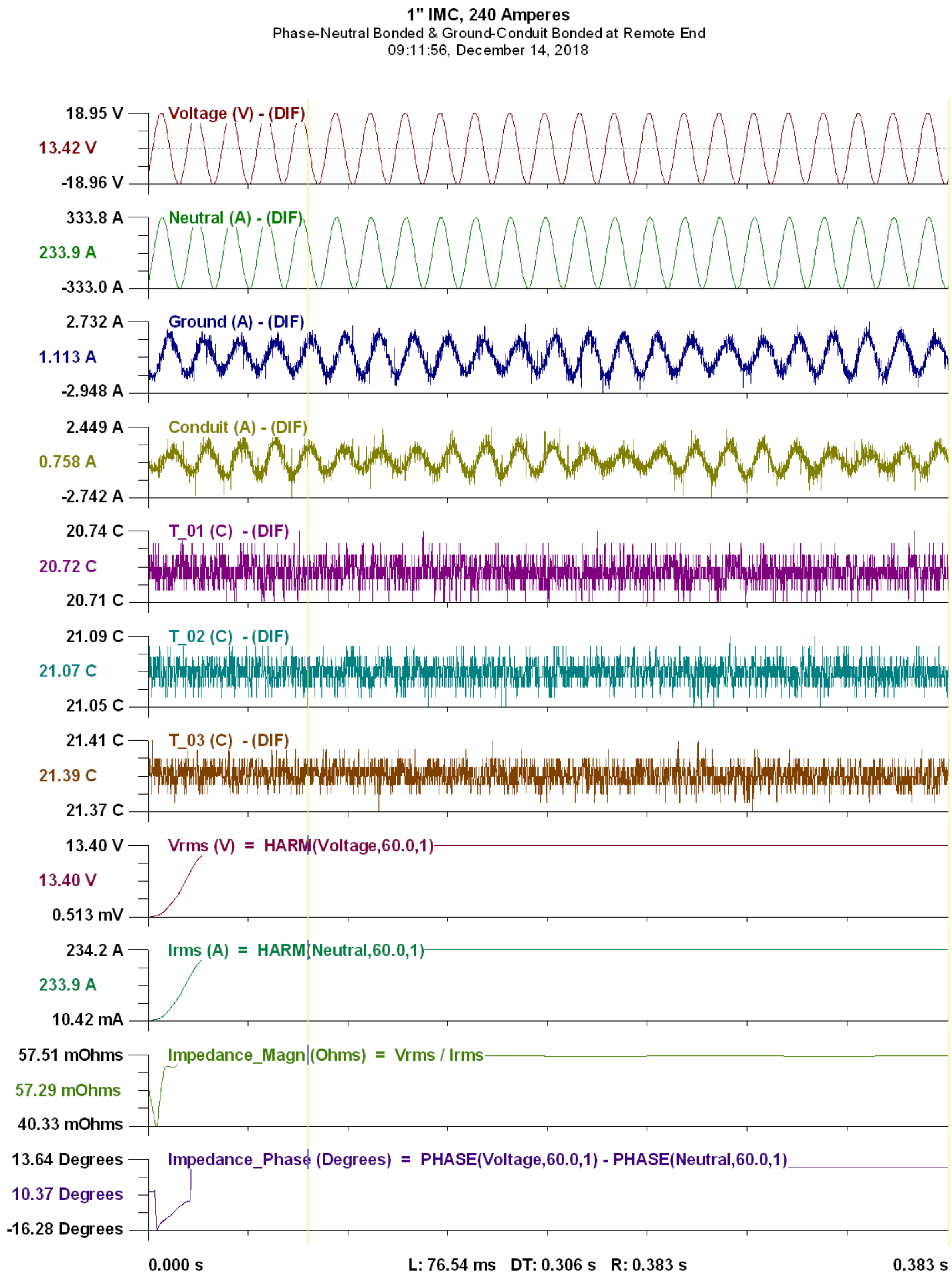


Figure J-2: Case Name IMC100_002

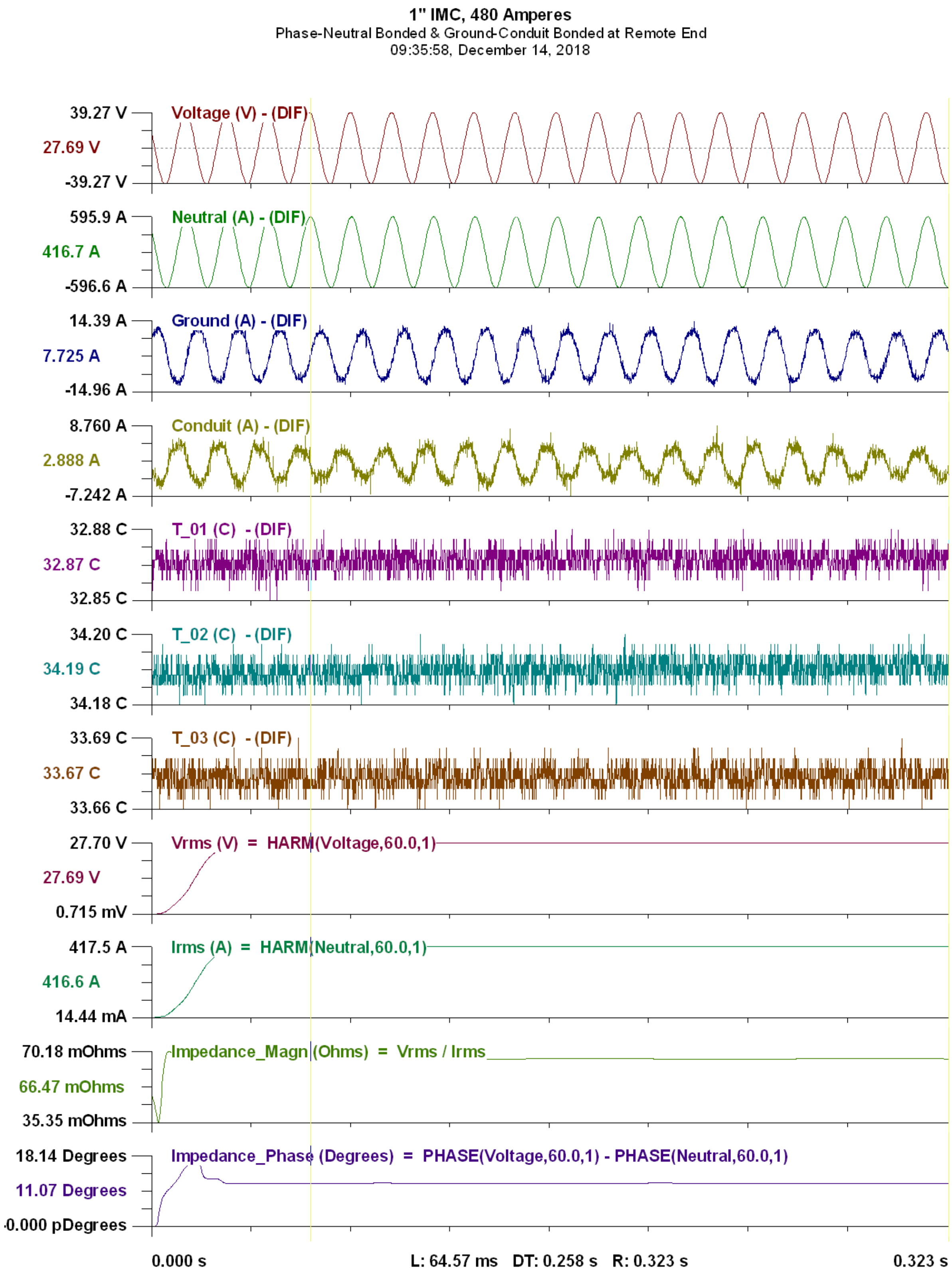


Figure J-1: Case Name IMC100_003

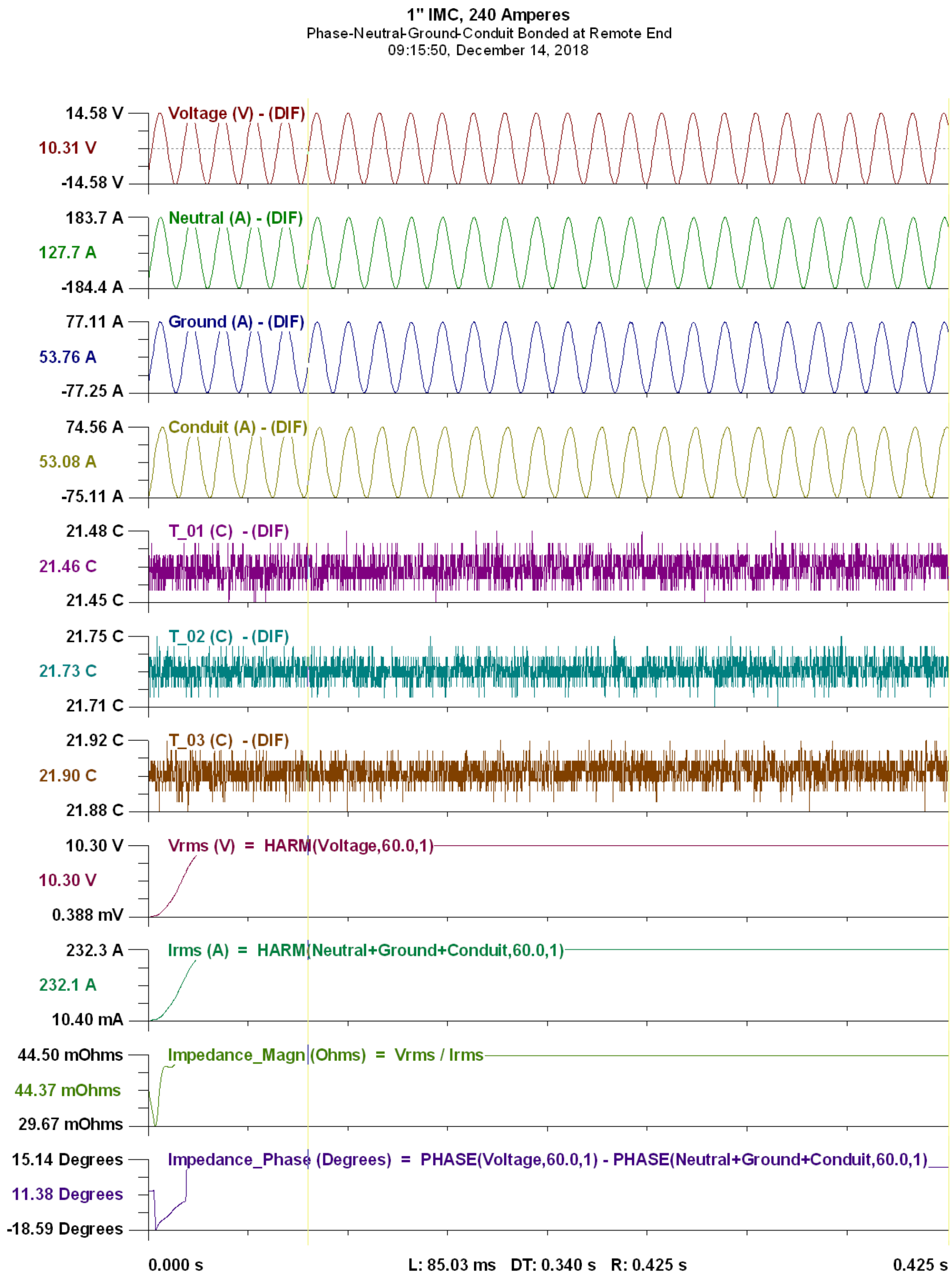


Figure J-1: Case Name IMC100_004

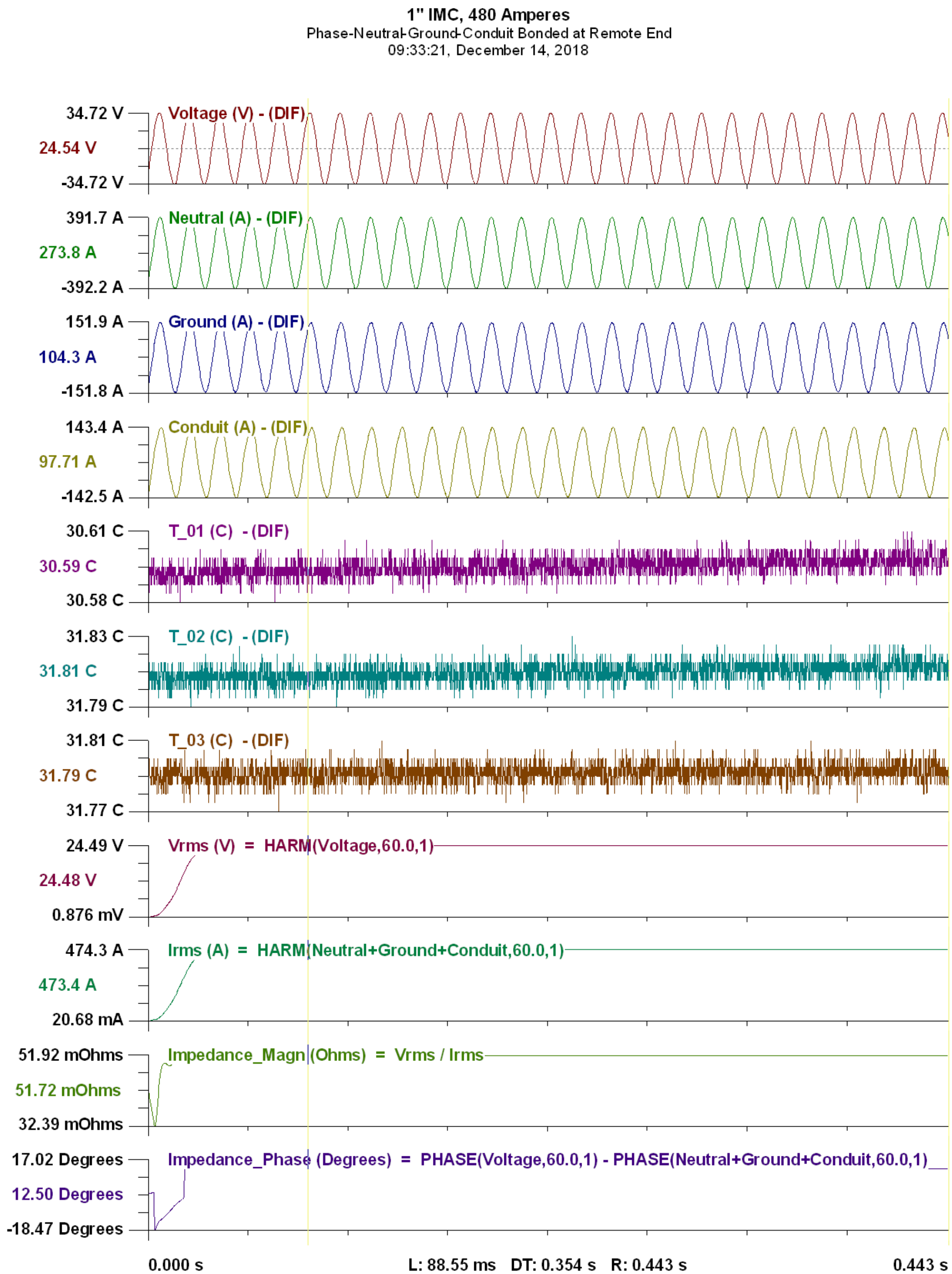


Figure J-1: Case Name IMC100_005

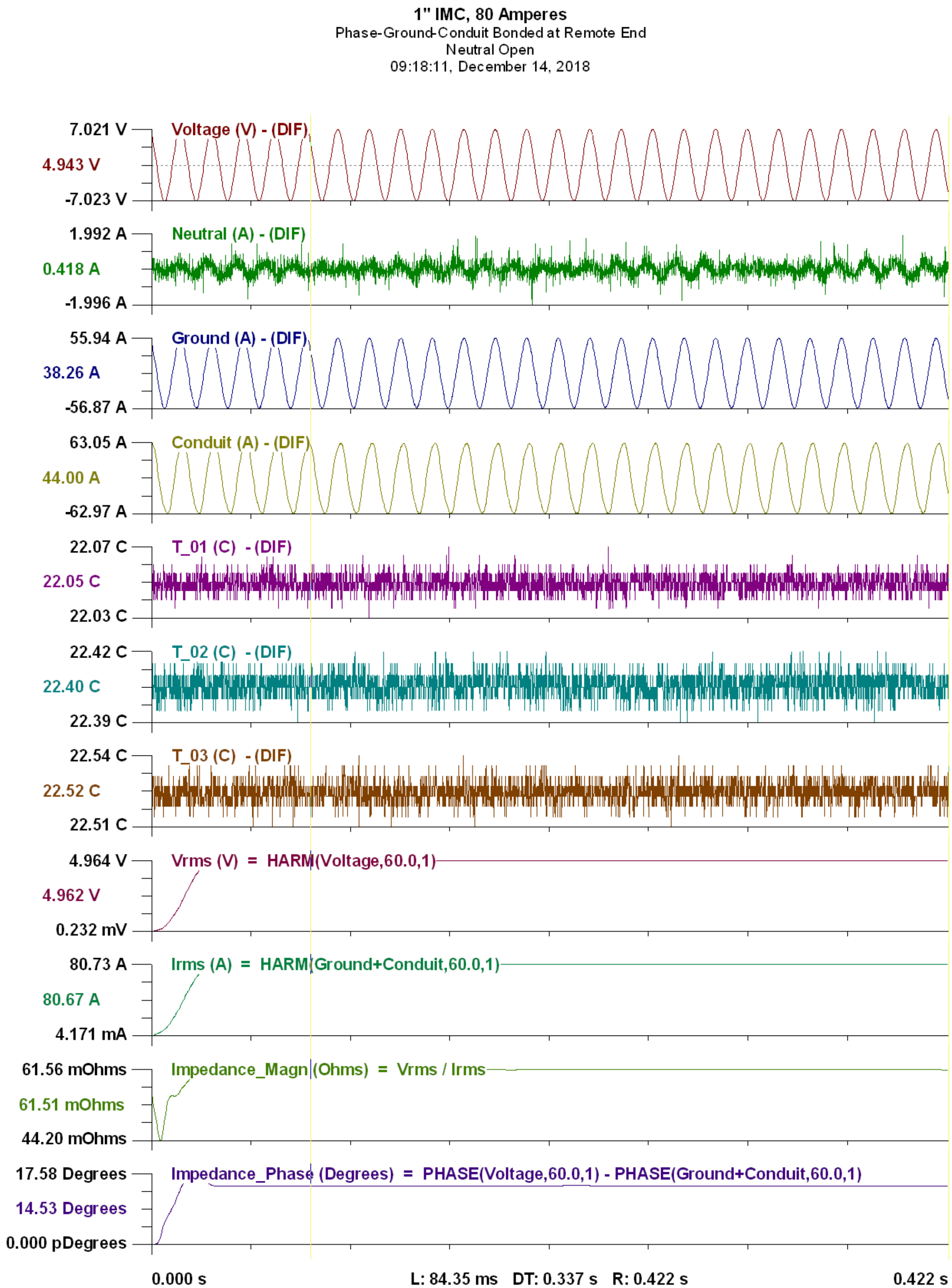


Figure J-1: Case Name IMC100_006

1" IMC, 240 Amperes
Phase-Ground-Conduit Bonded at Remote End
Neutral Open
09:19:11, December 14, 2018

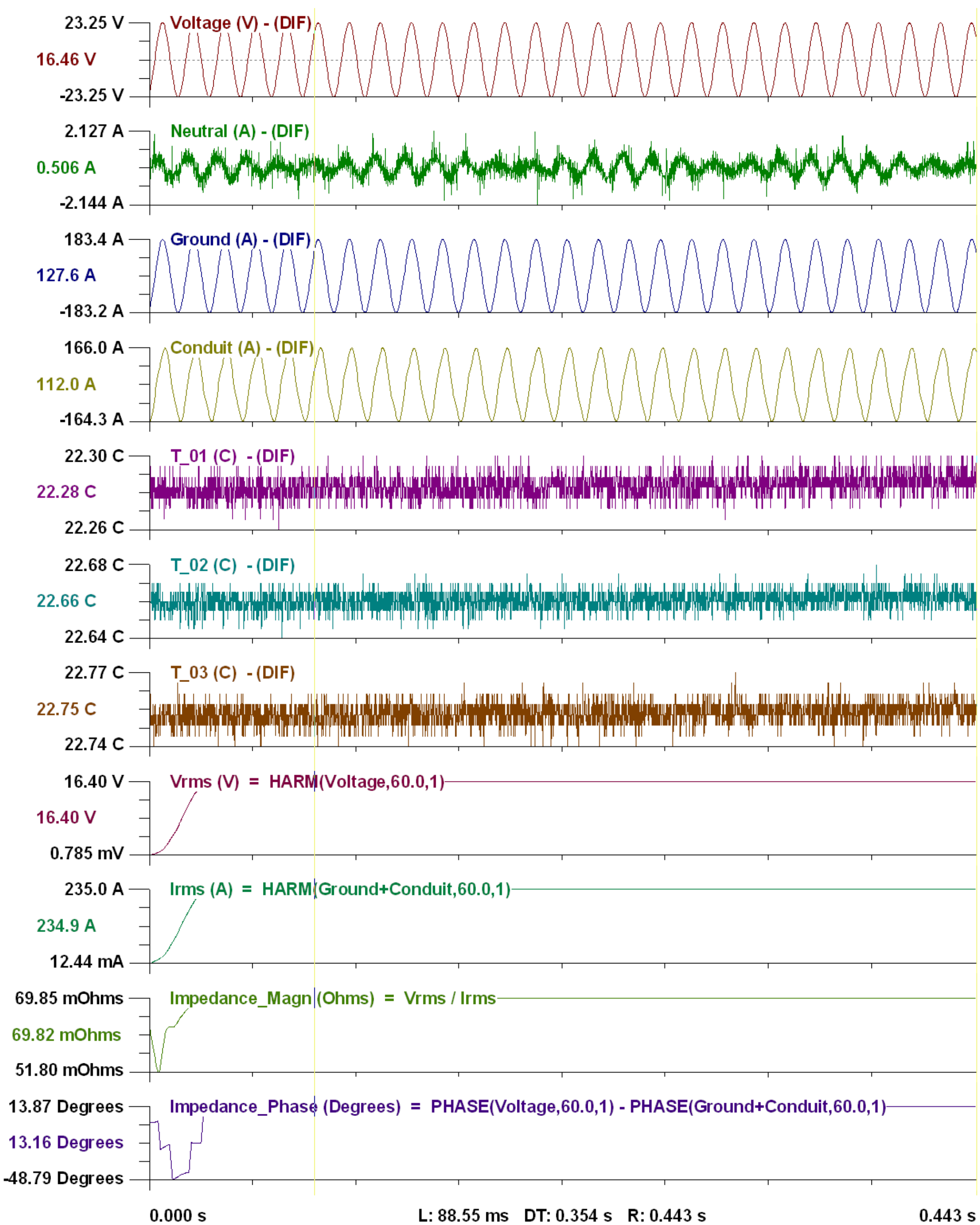


Figure J-1: Case Name IMC100_007

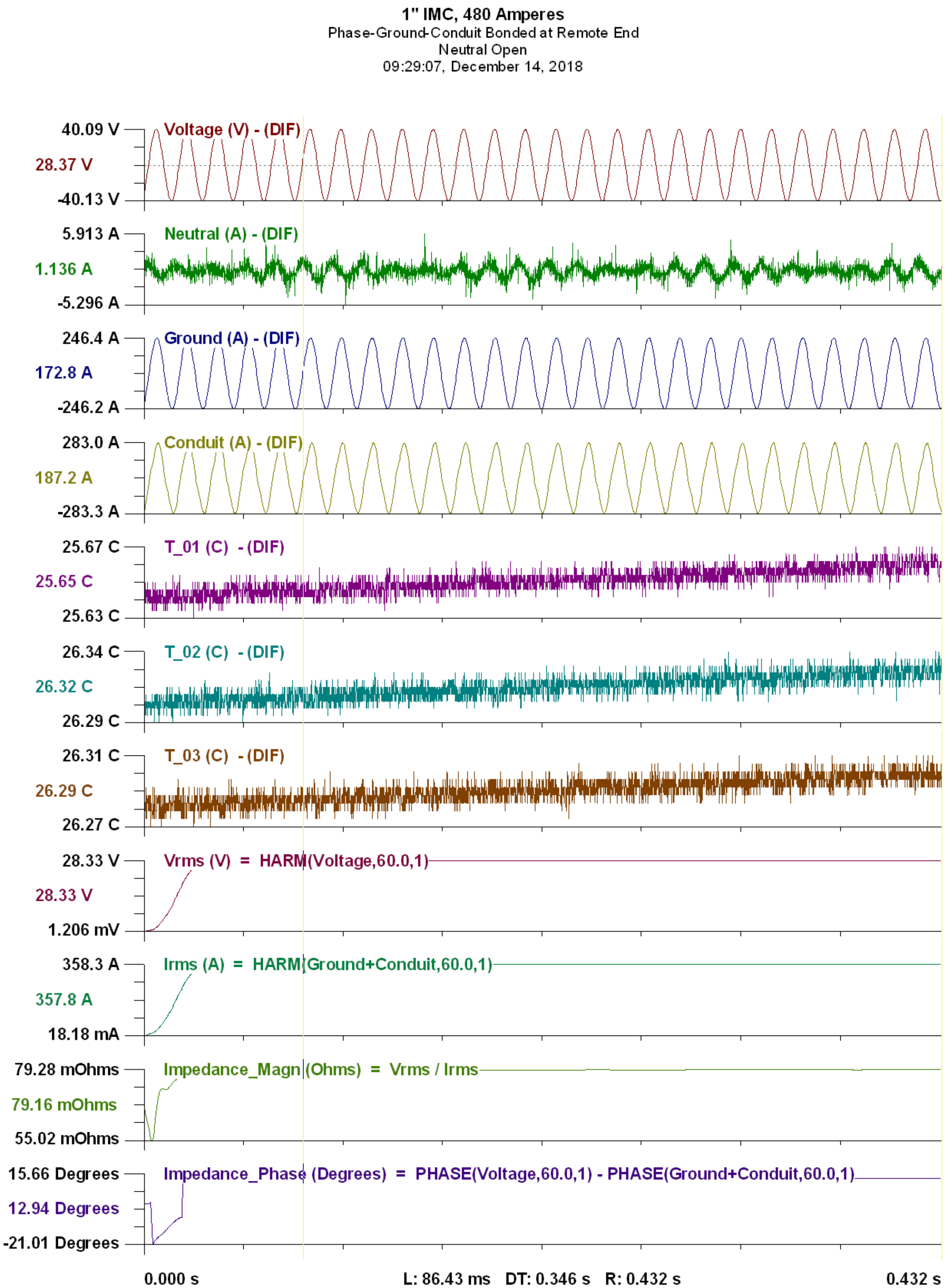


Figure J-1: Case Name IMC100_008

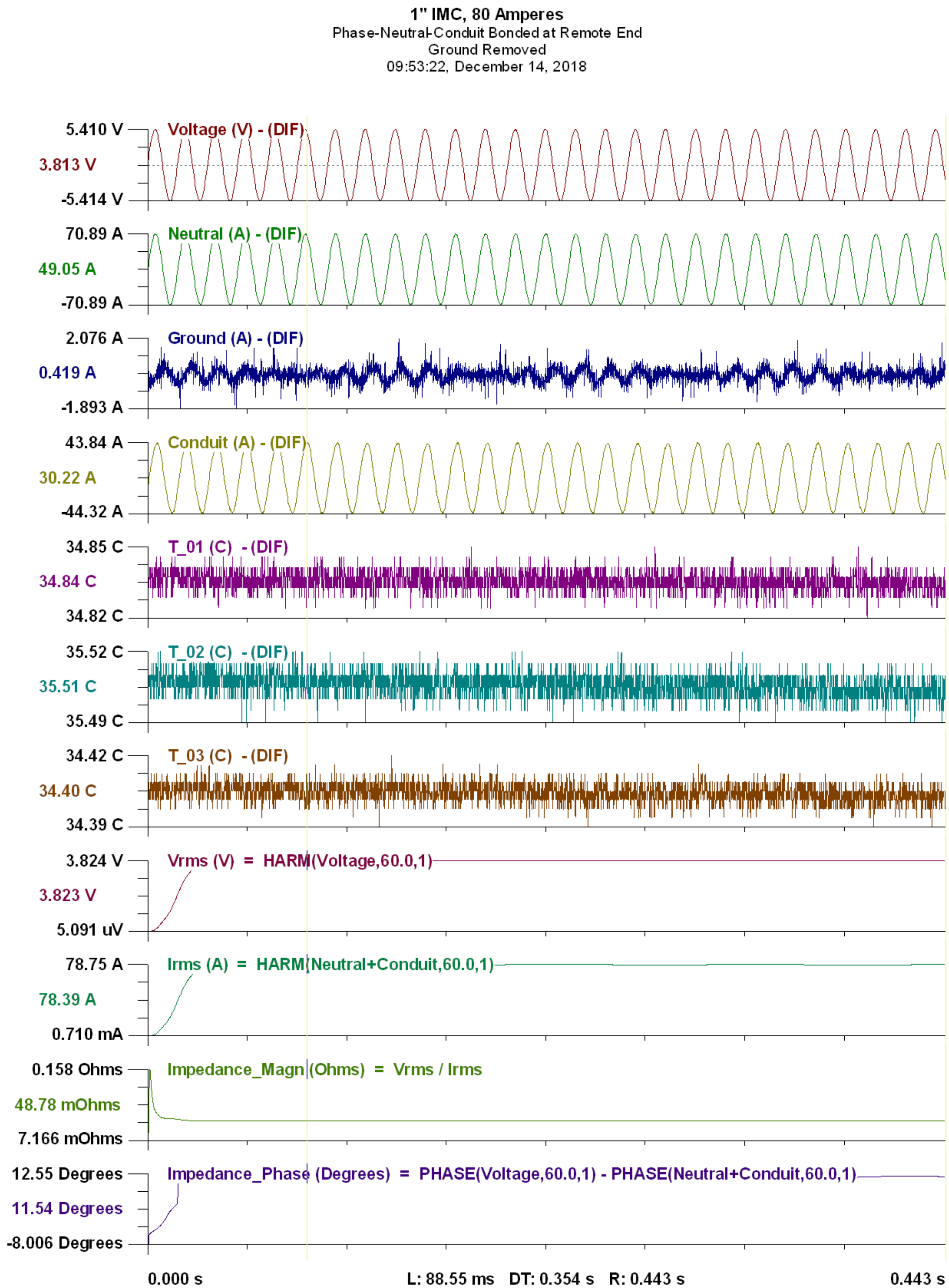


Figure J-1: Case Name IMC100_009

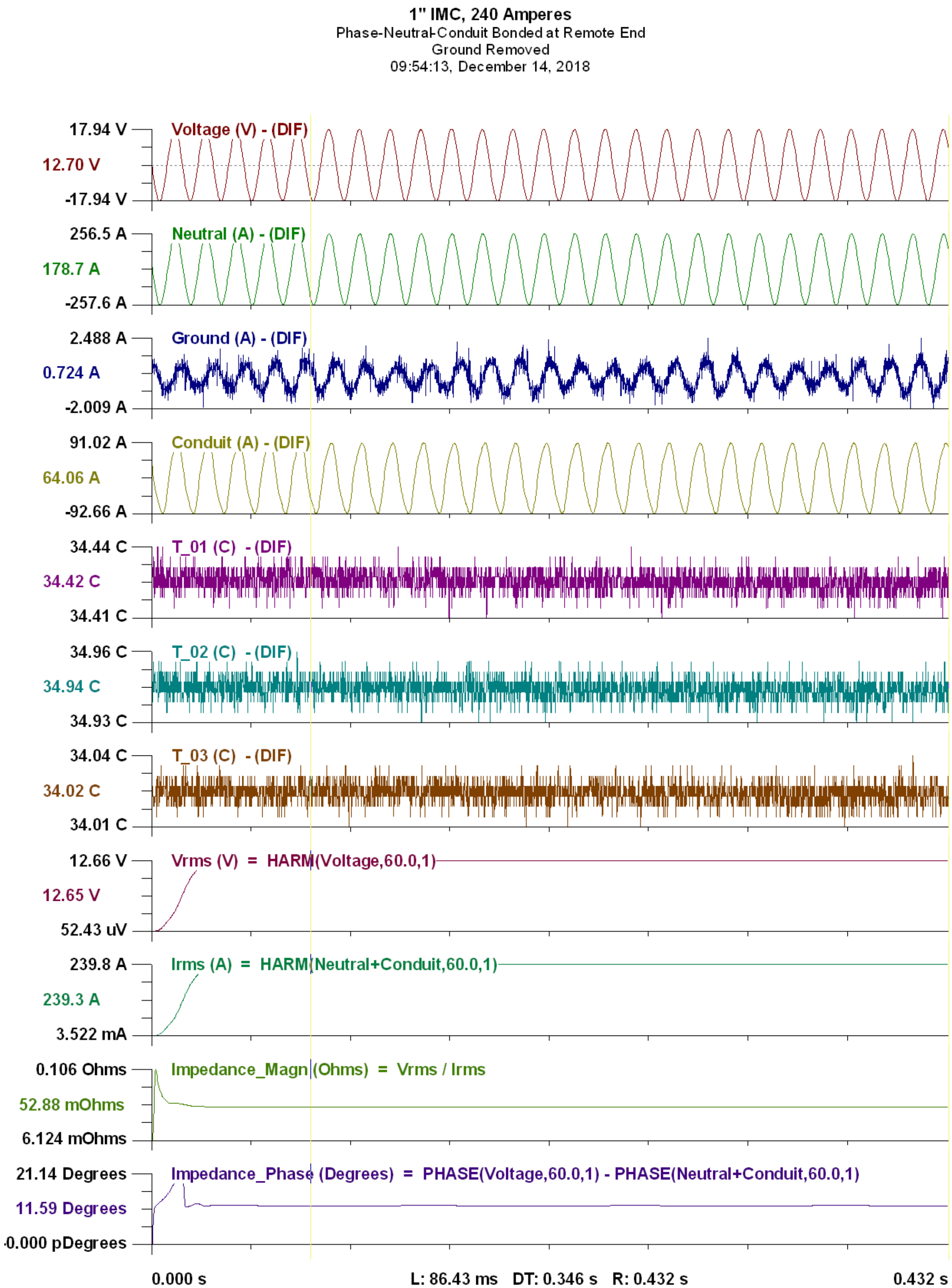


Figure J-1: Case Name IMC100_010

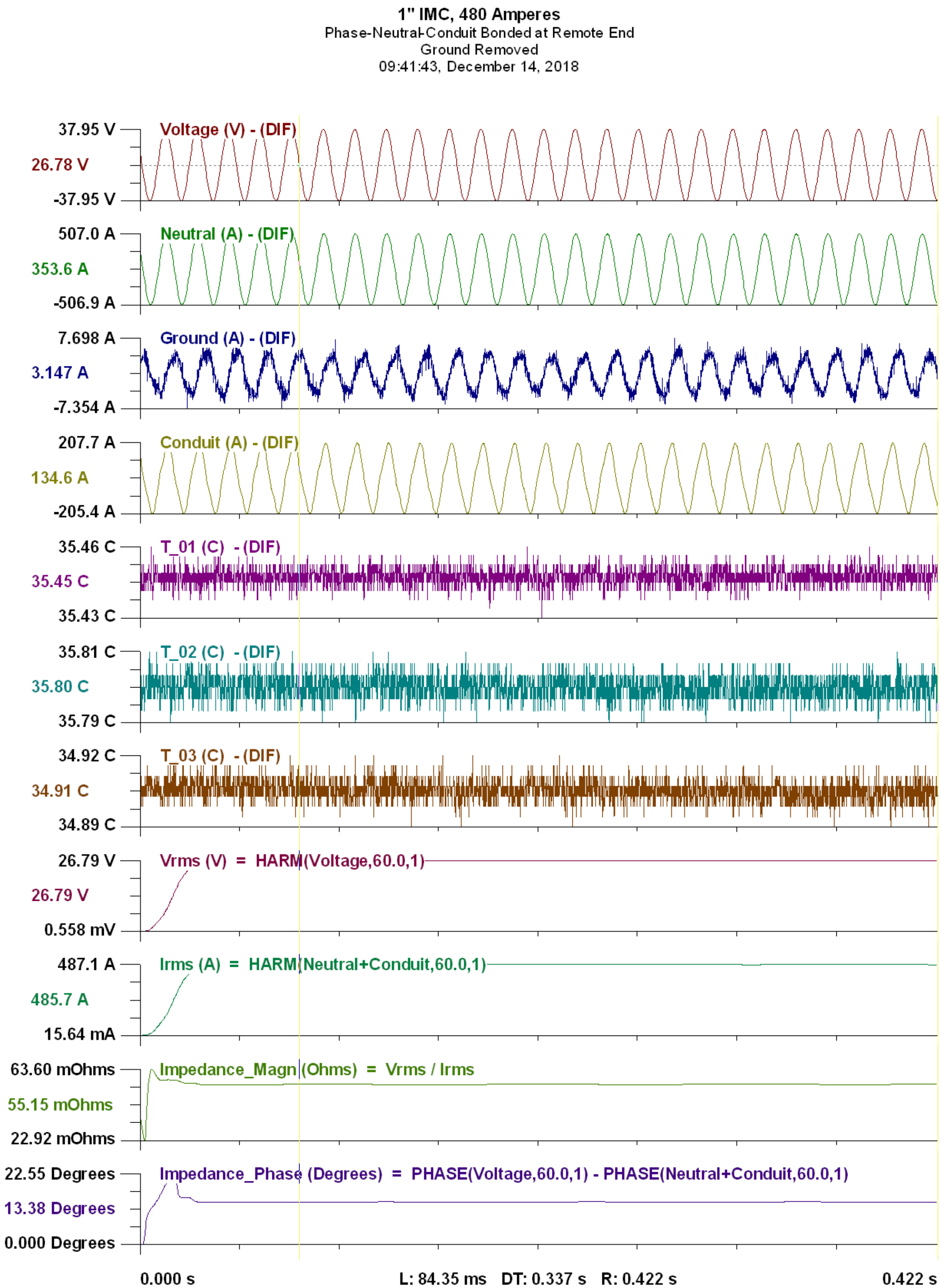


Figure J-1: Case Name IMC100_011

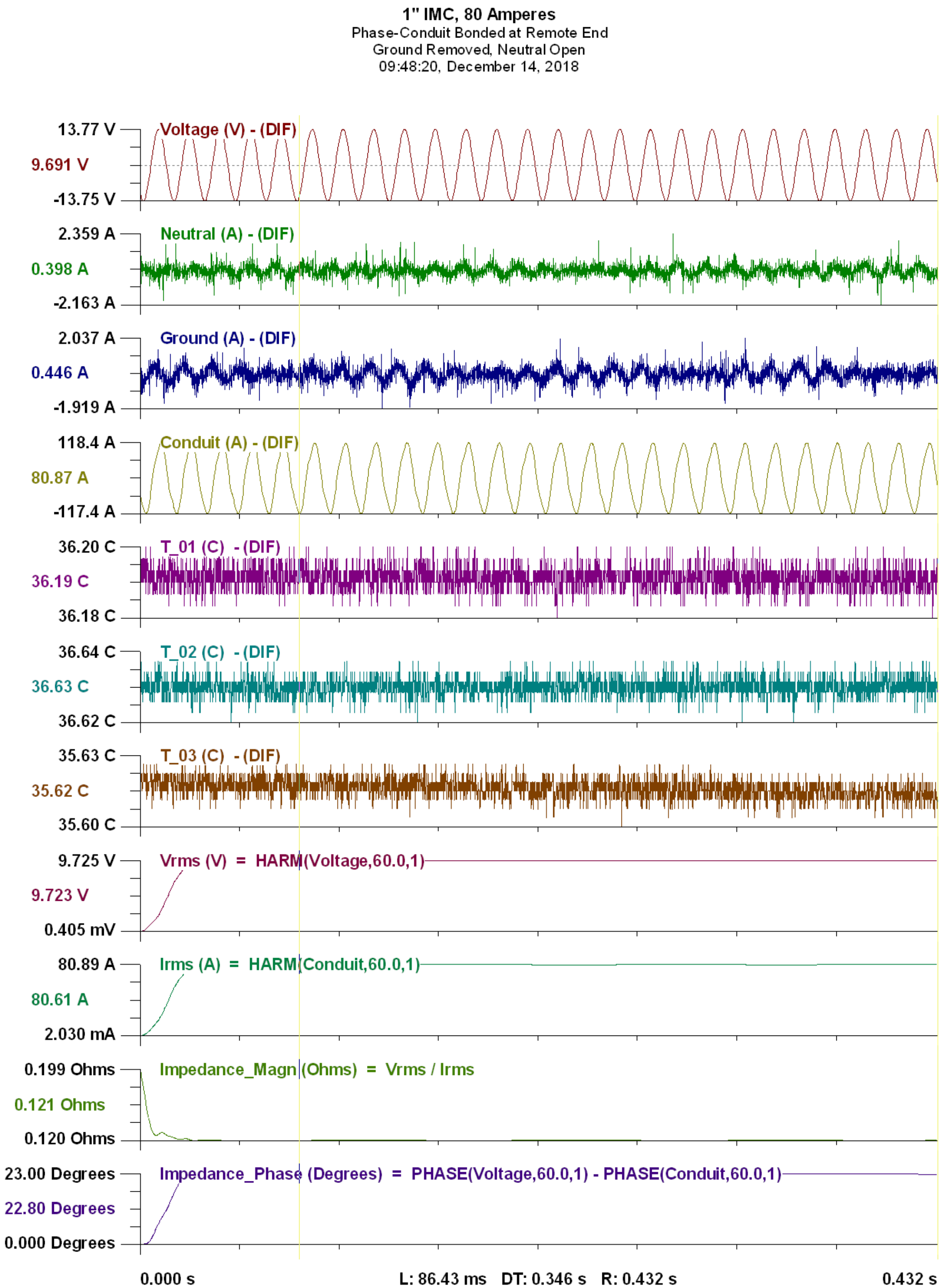


Figure J-1: Case Name IMC100_012

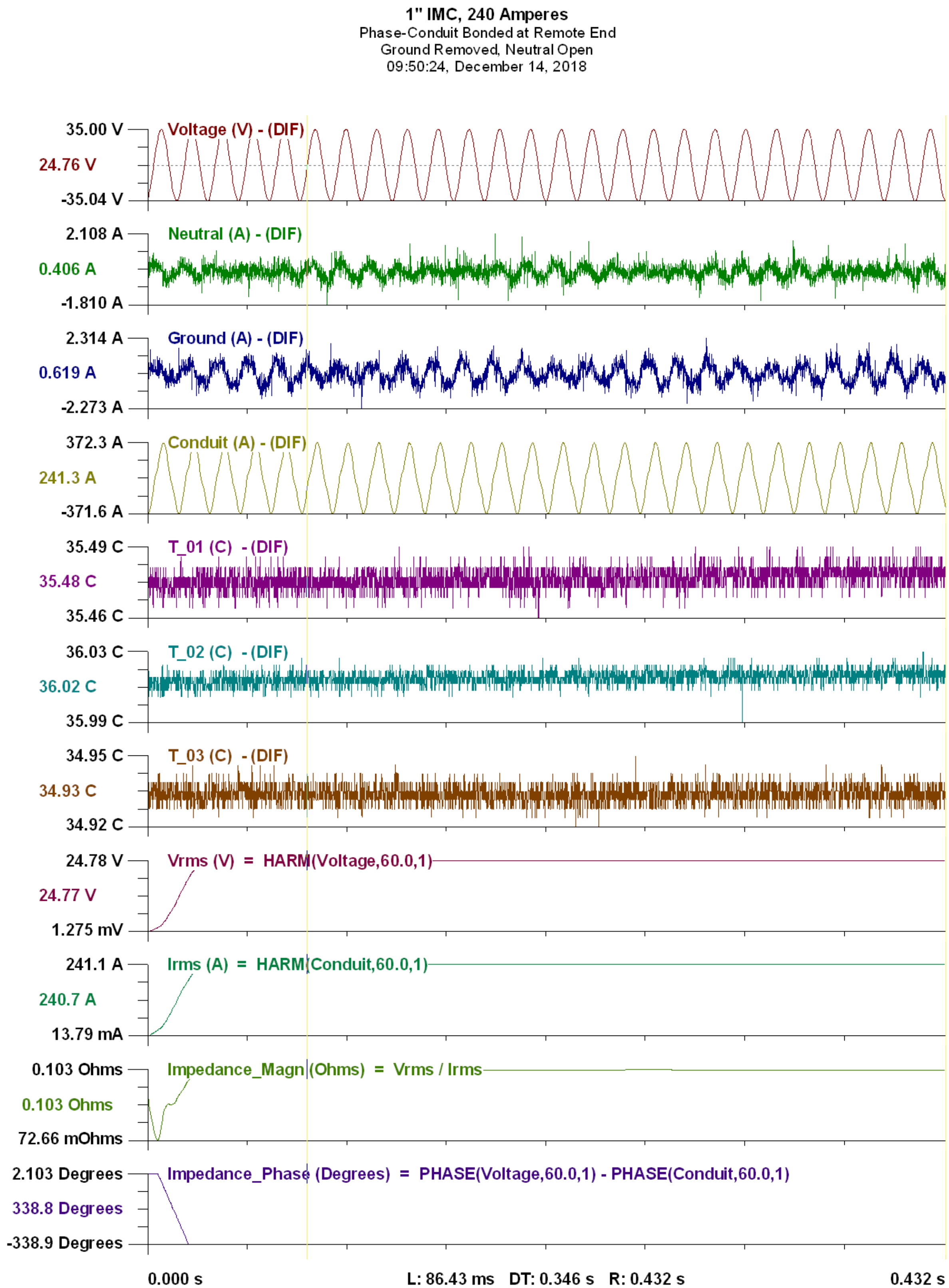


Figure J-1: Case Name IMC100_013

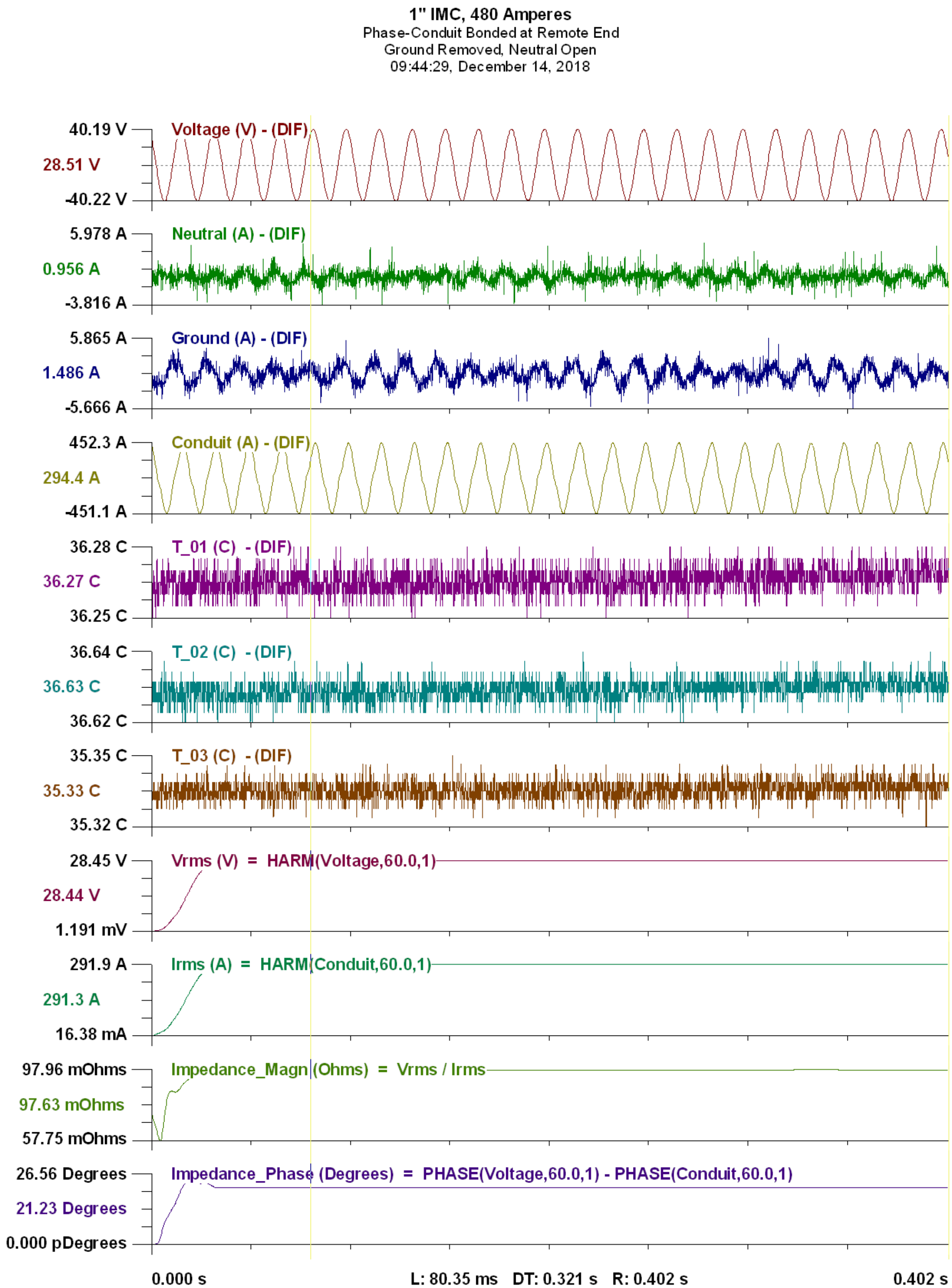


Figure J-1: Case Name IMC100_014

Appendix K – 1” Stainless-Steel Raw Data Plots

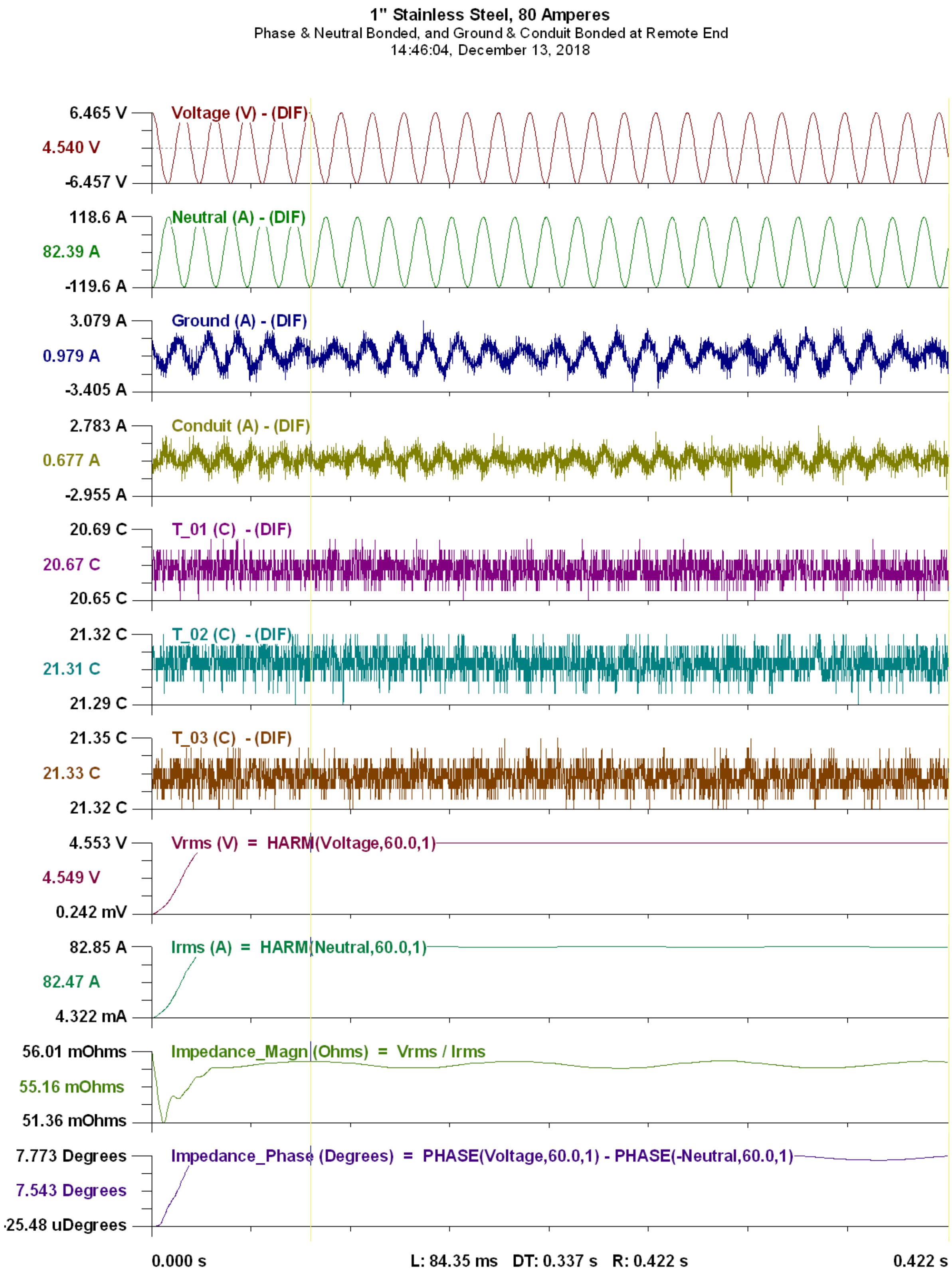


Figure K-1: Case Name STAINLESS100_001

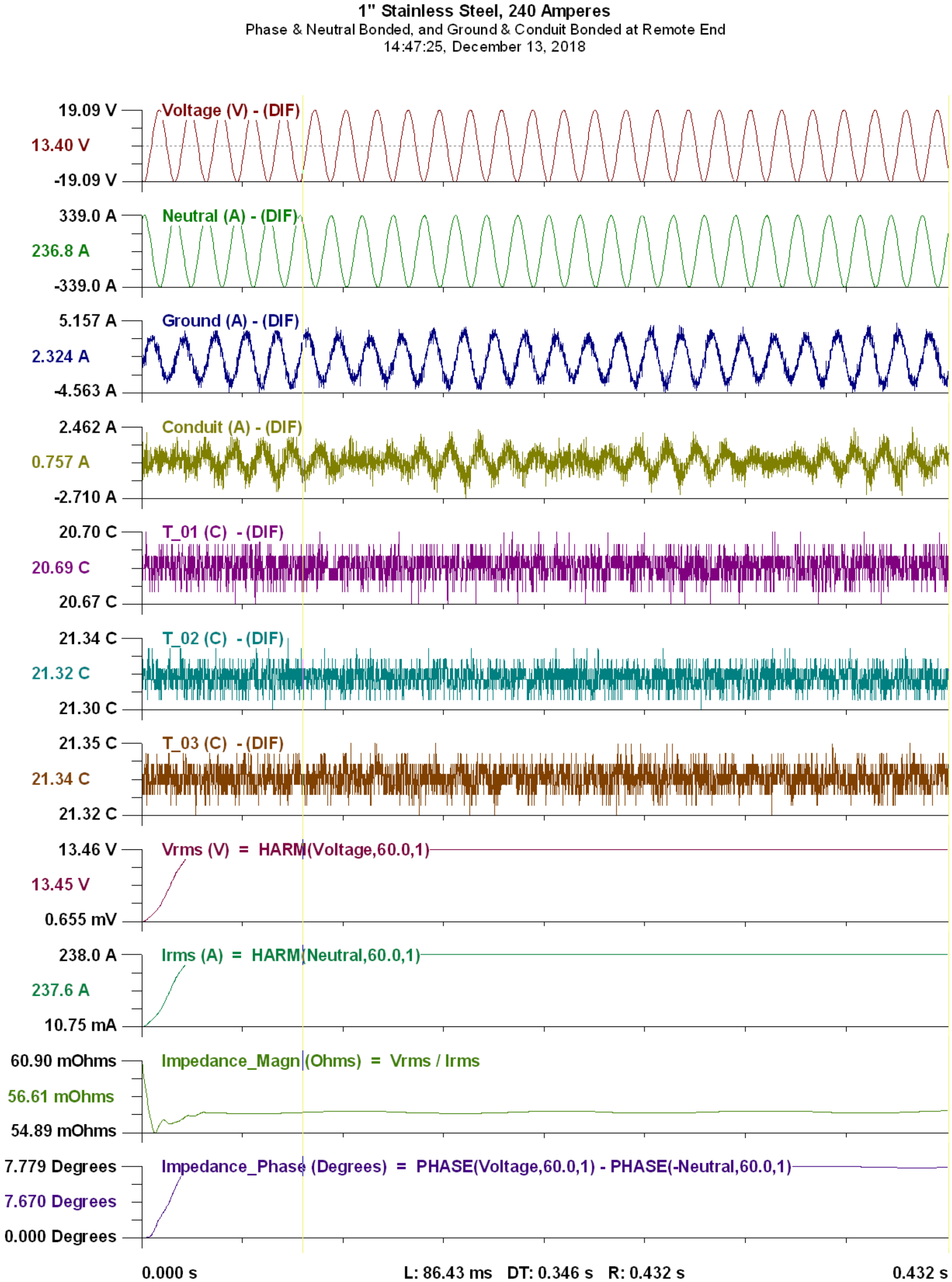


Figure K-2: Case Name STAINLESS100_002

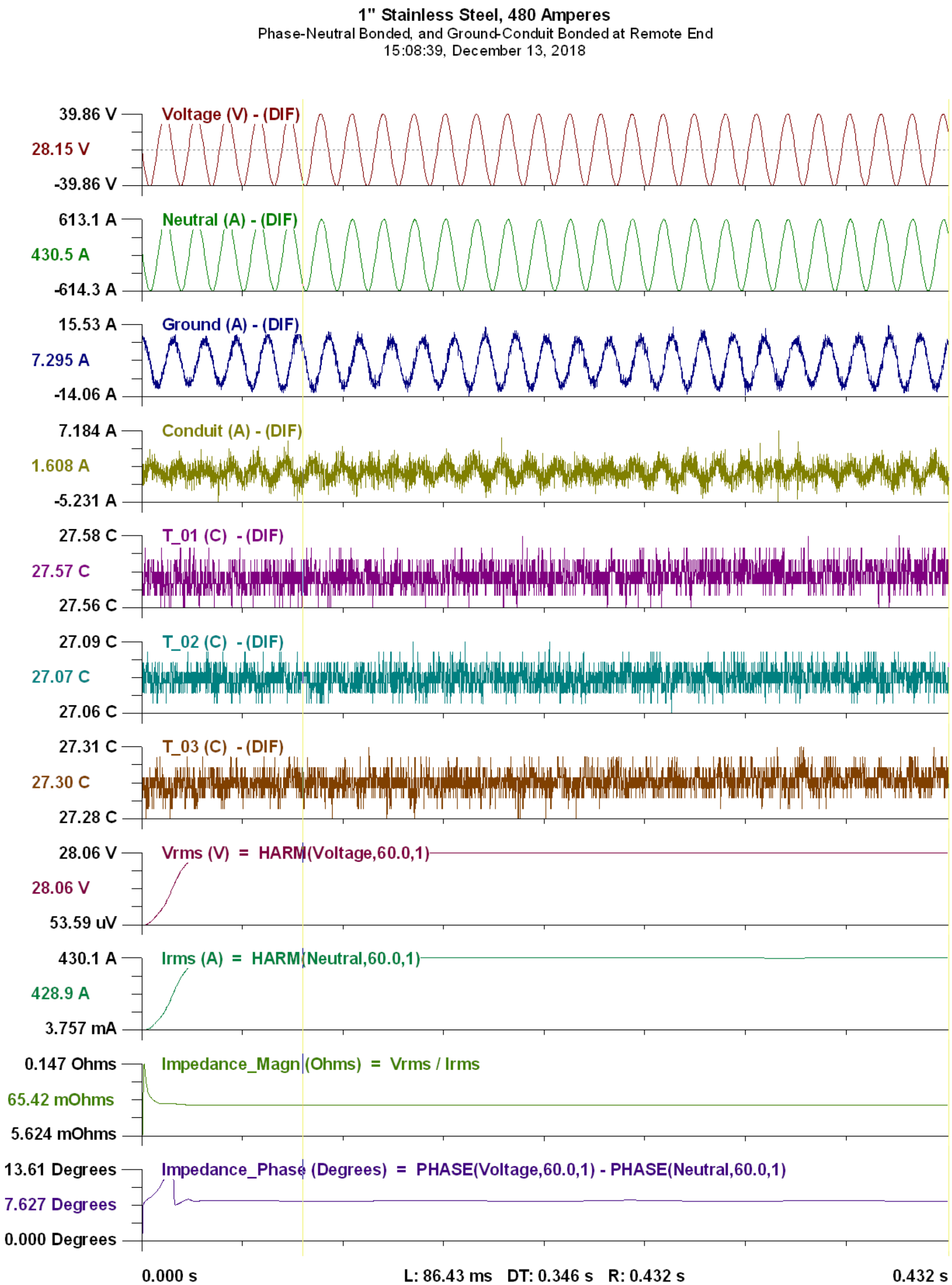


Figure K-3: Case Name STAINLESS100_003

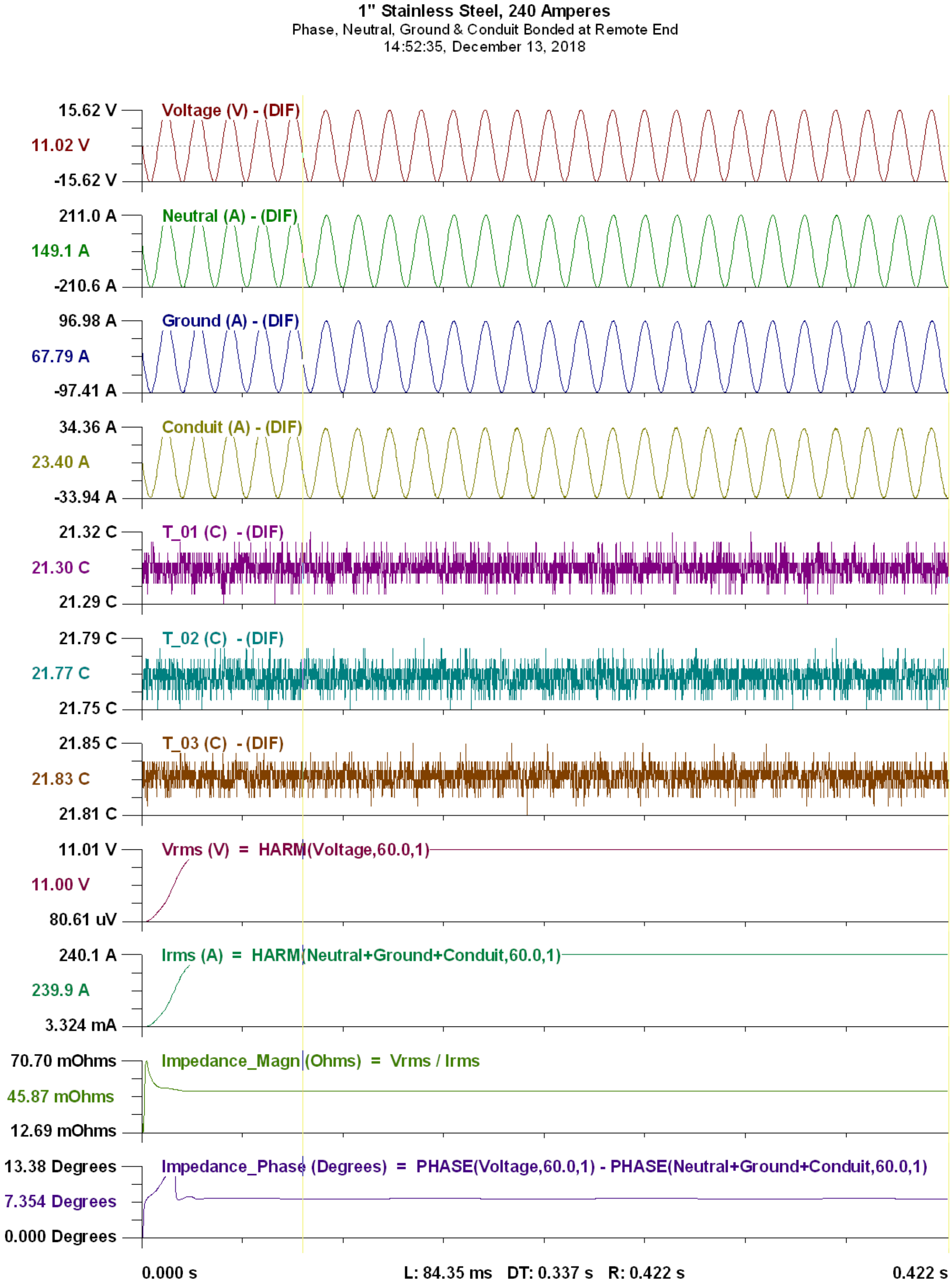


Figure K-4: Case Name STAINLESS100_004

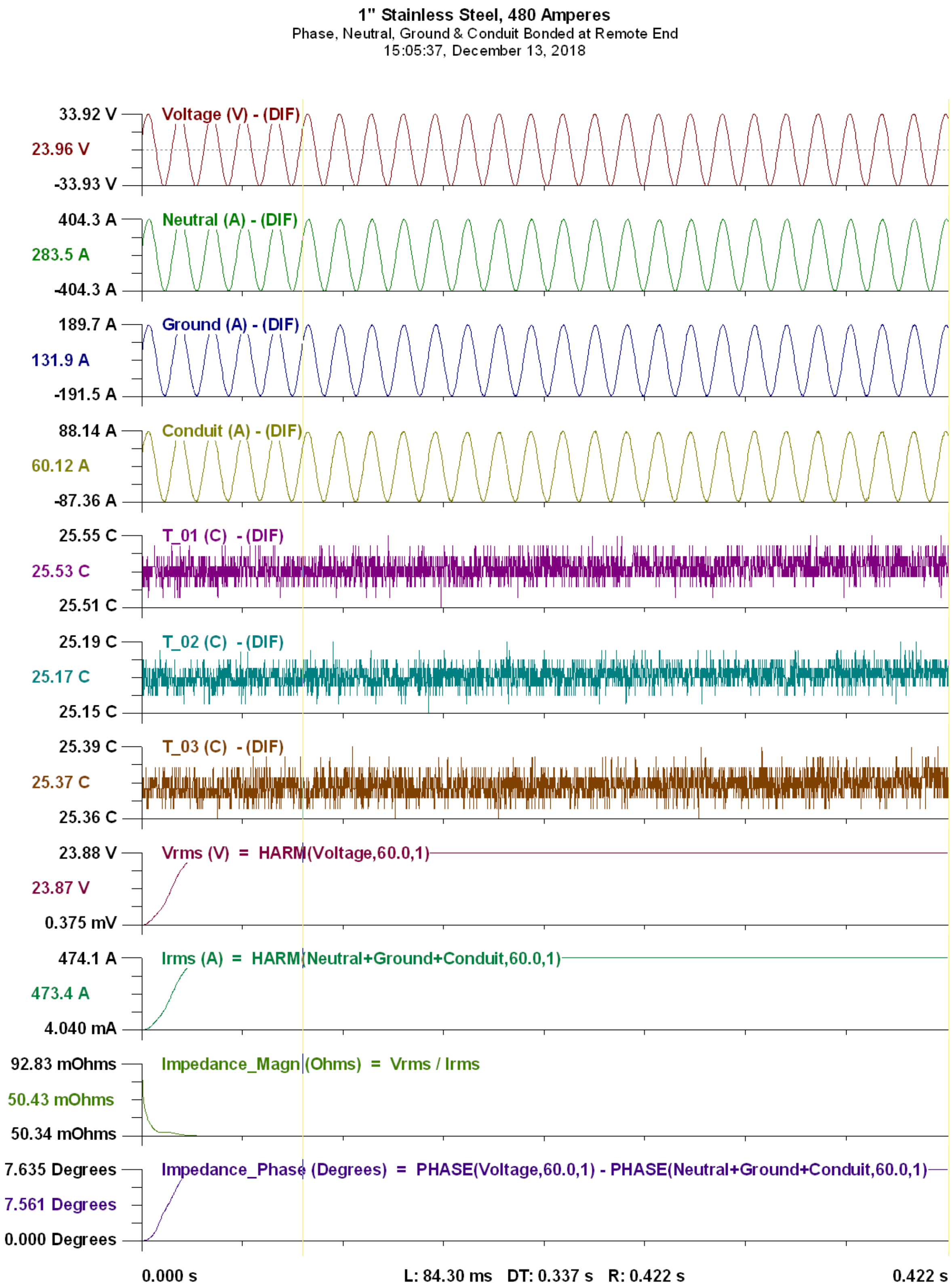


Figure K-5: Case Name STAINLESS100_005

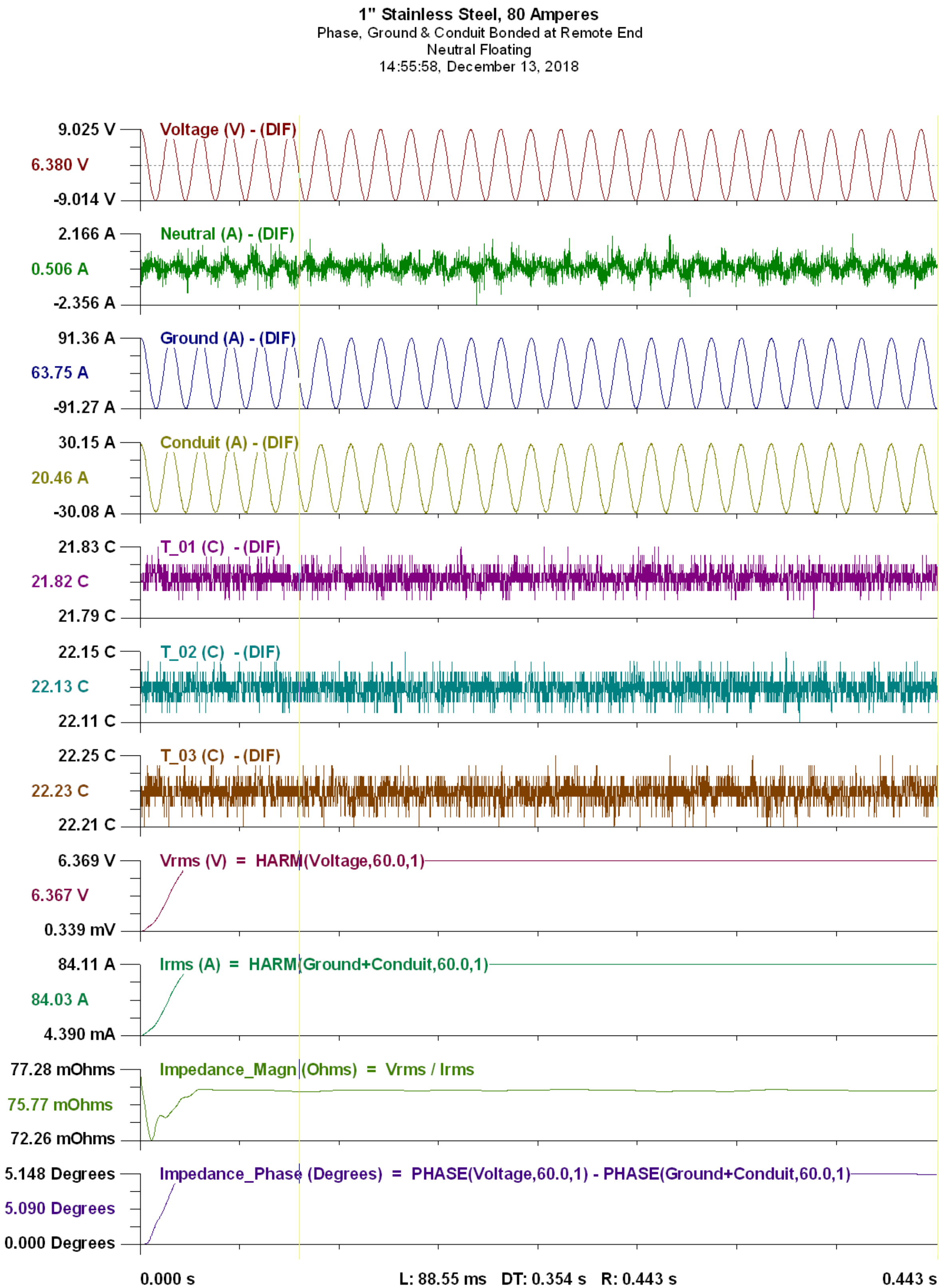


Figure K-6: Case Name STAINLESS100_006

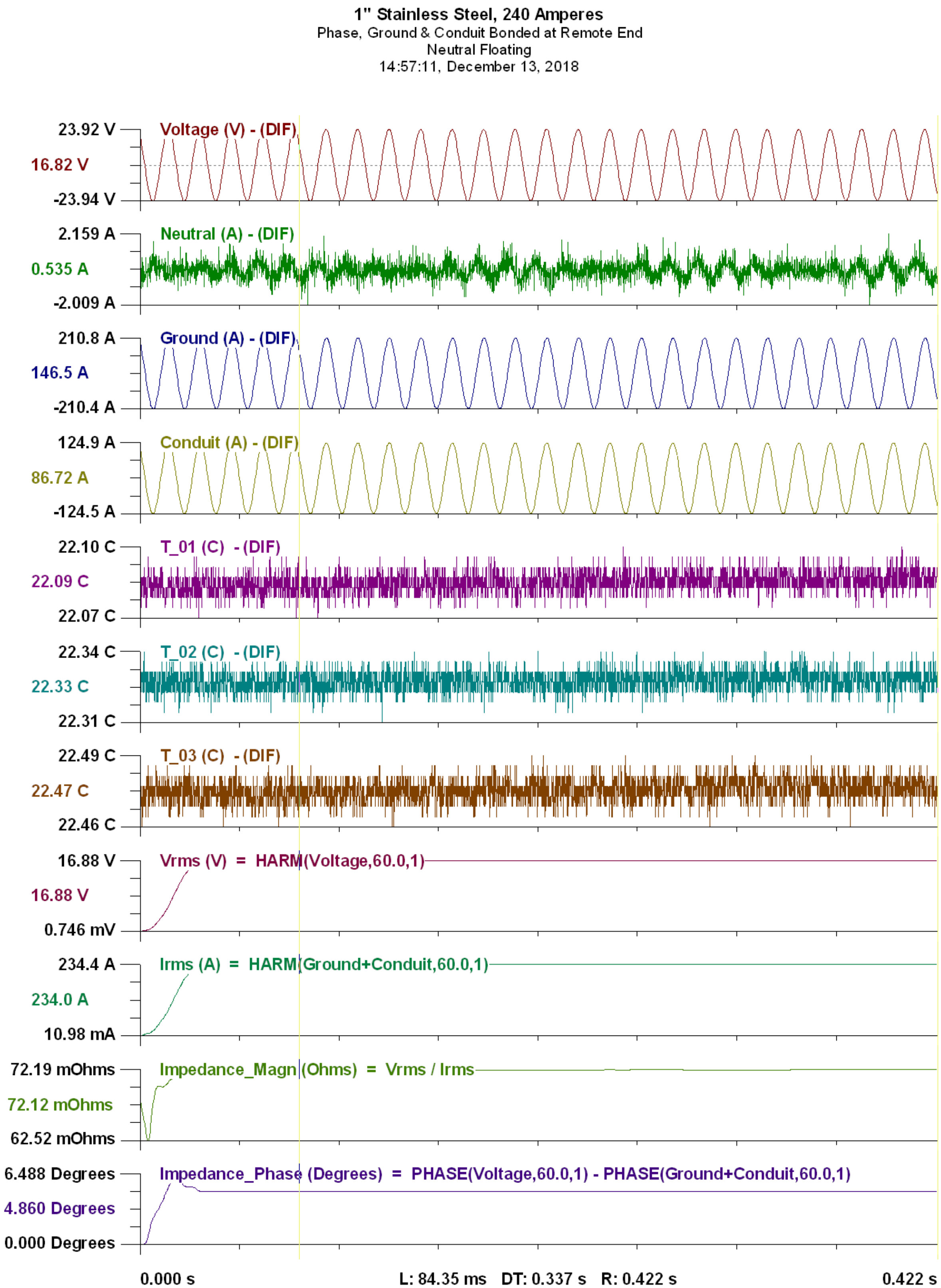


Figure K-7: Case Name STAINLESS100_007

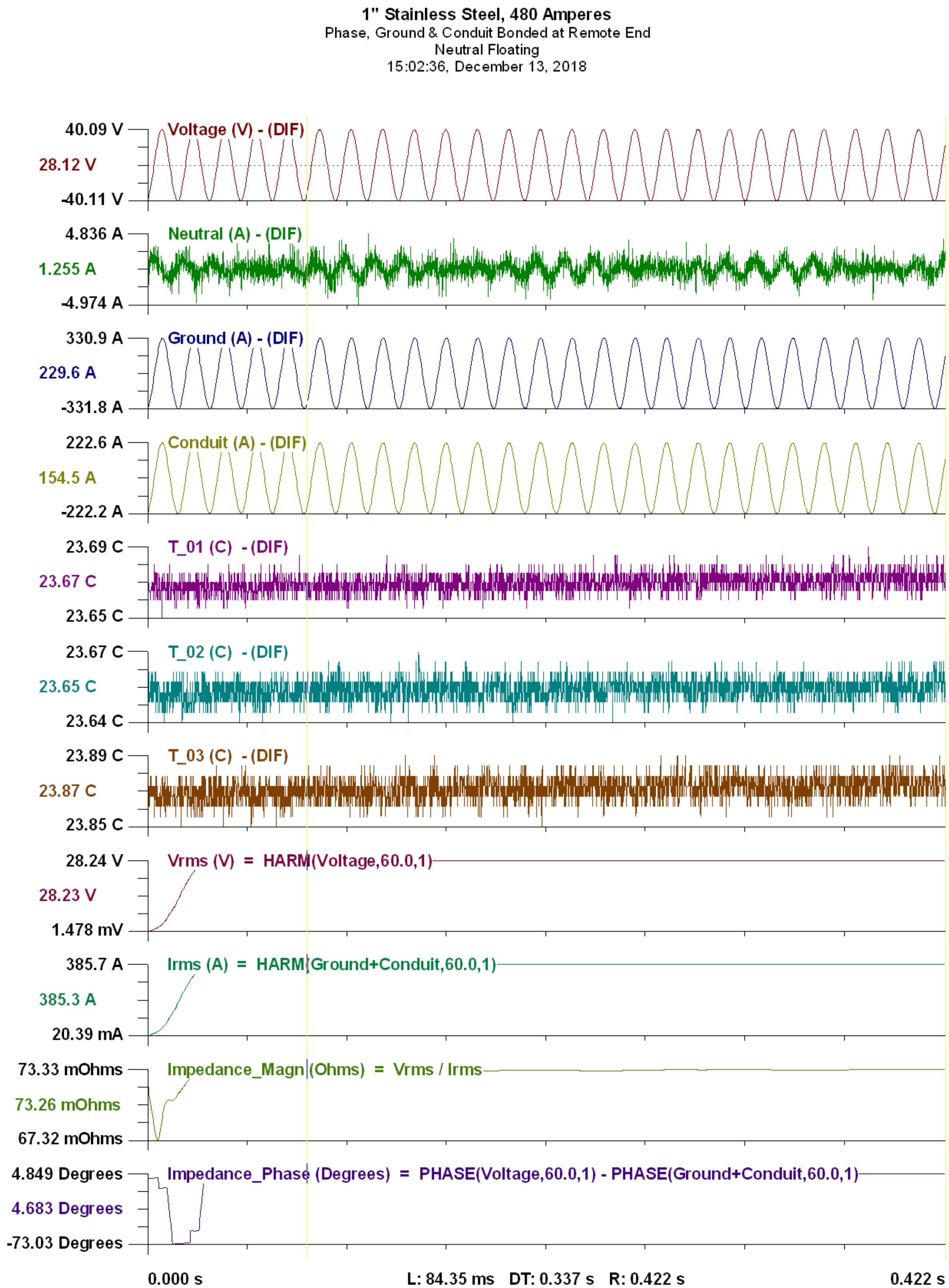


Figure K-8: Case Name STAINLESS100_008

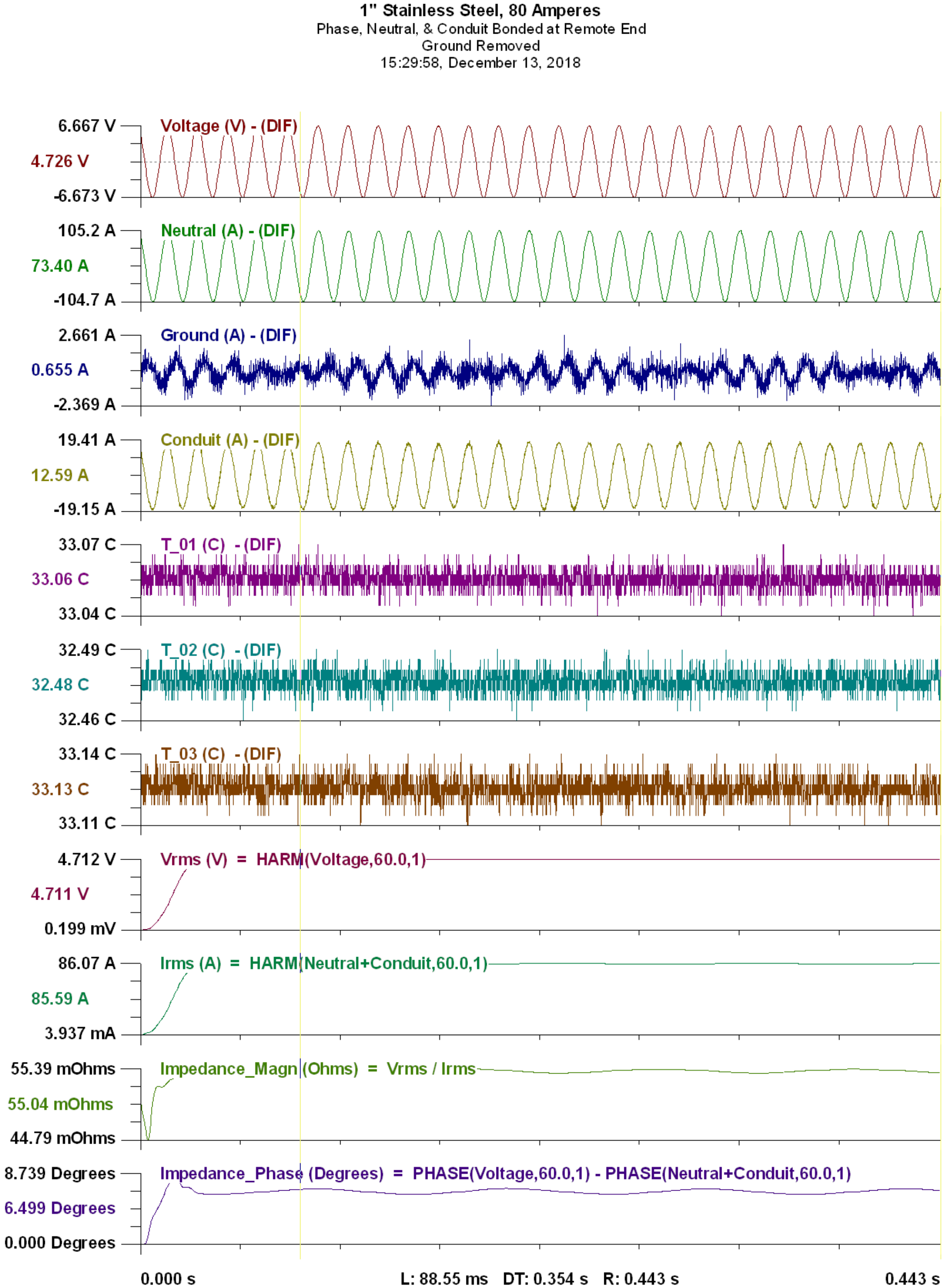


Figure K-9: Case Name STAINLESS100_009

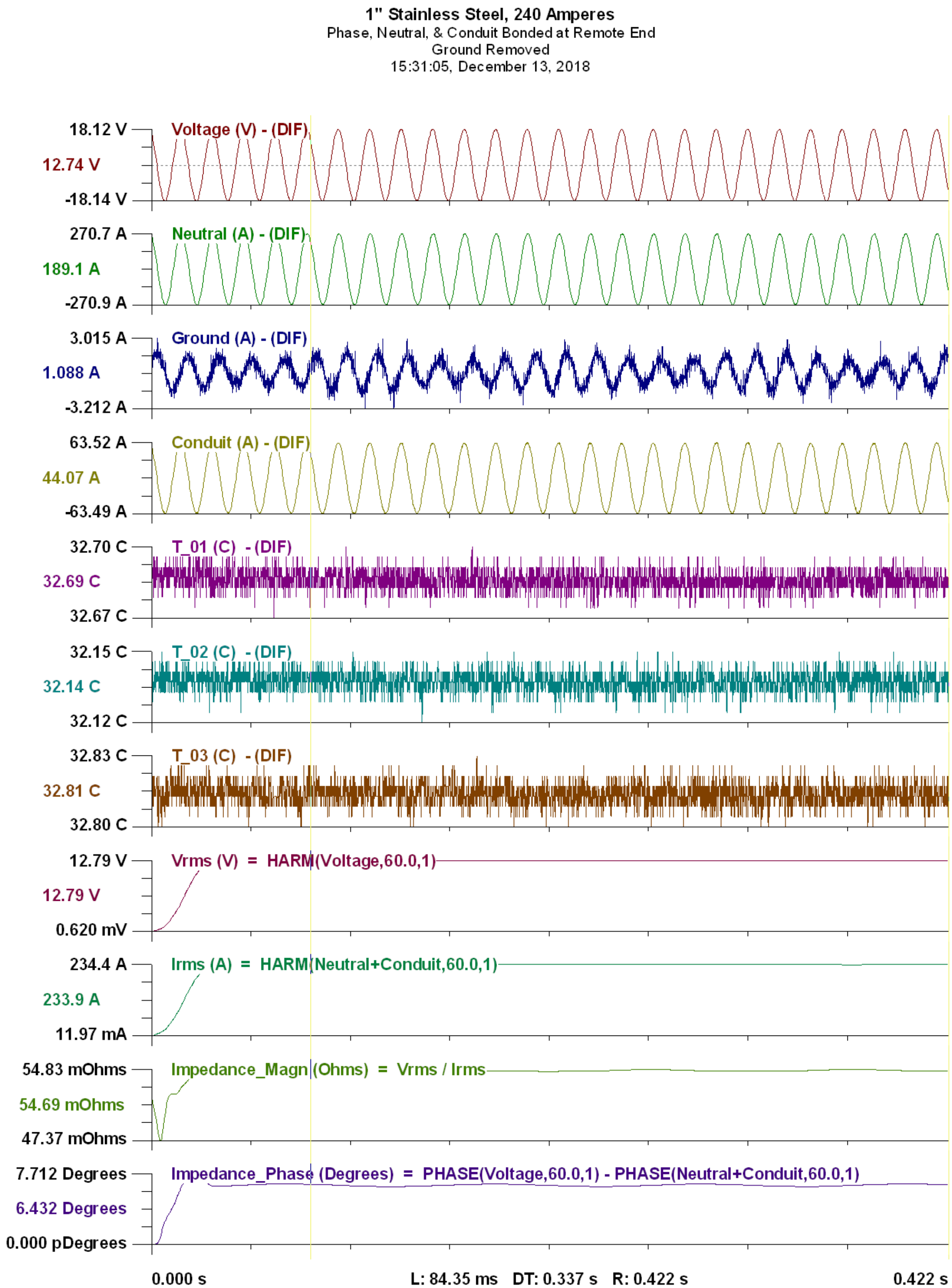


Figure K-10: Case Name STAINLESS100_010

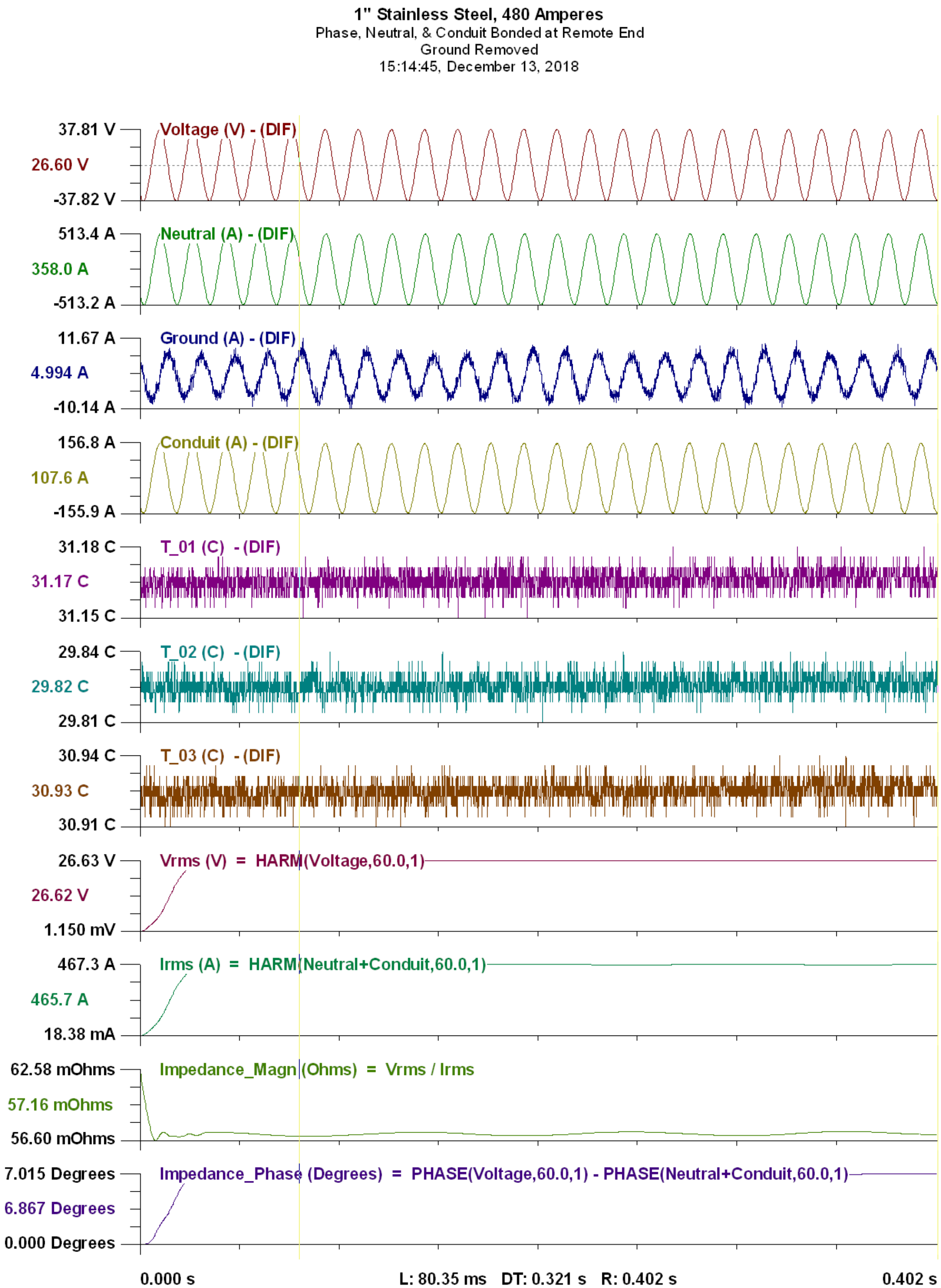


Figure K-11: Case Name STAINLESS100_011

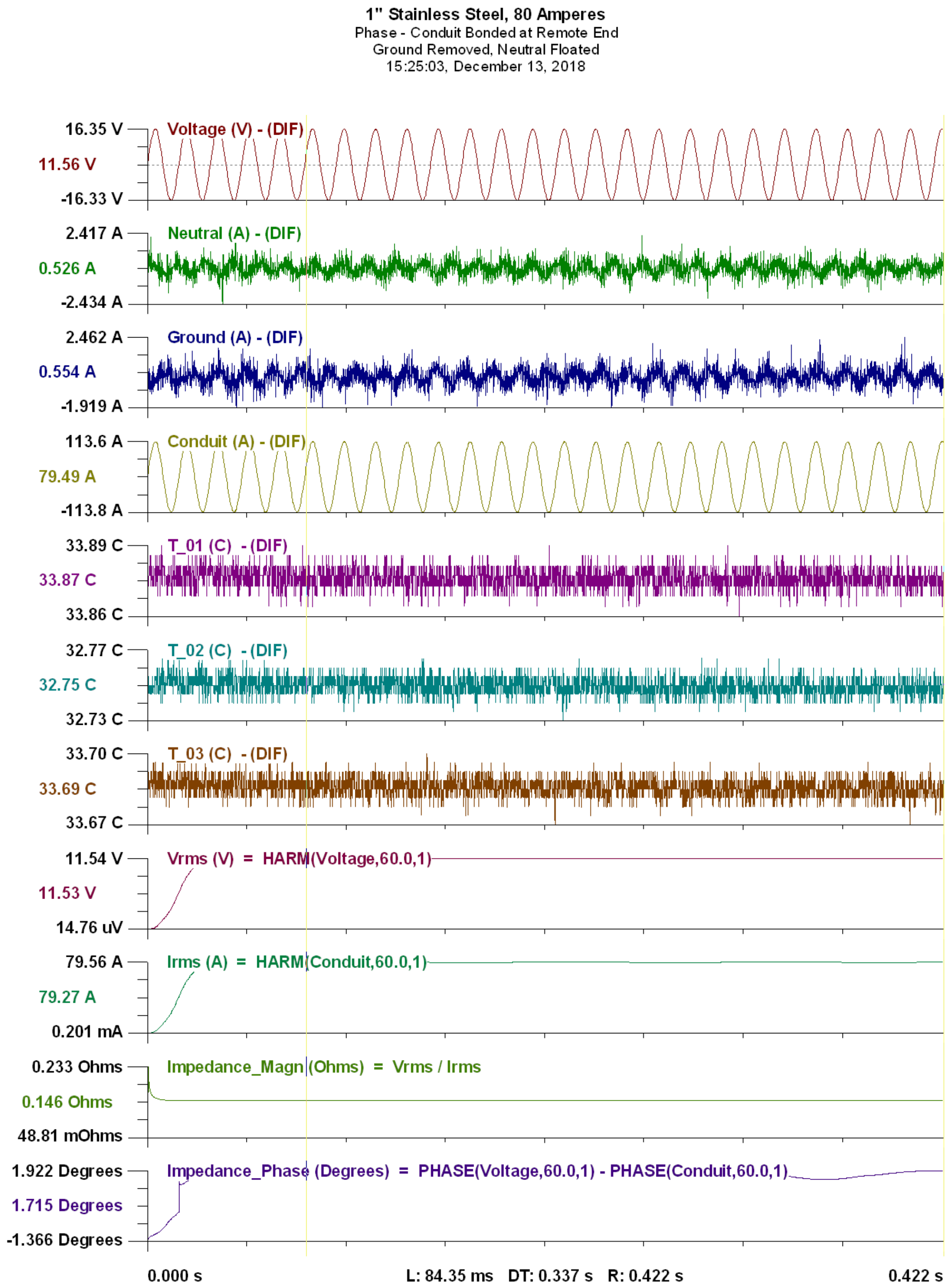


Figure K-12: Case Name STAINLESS100_012

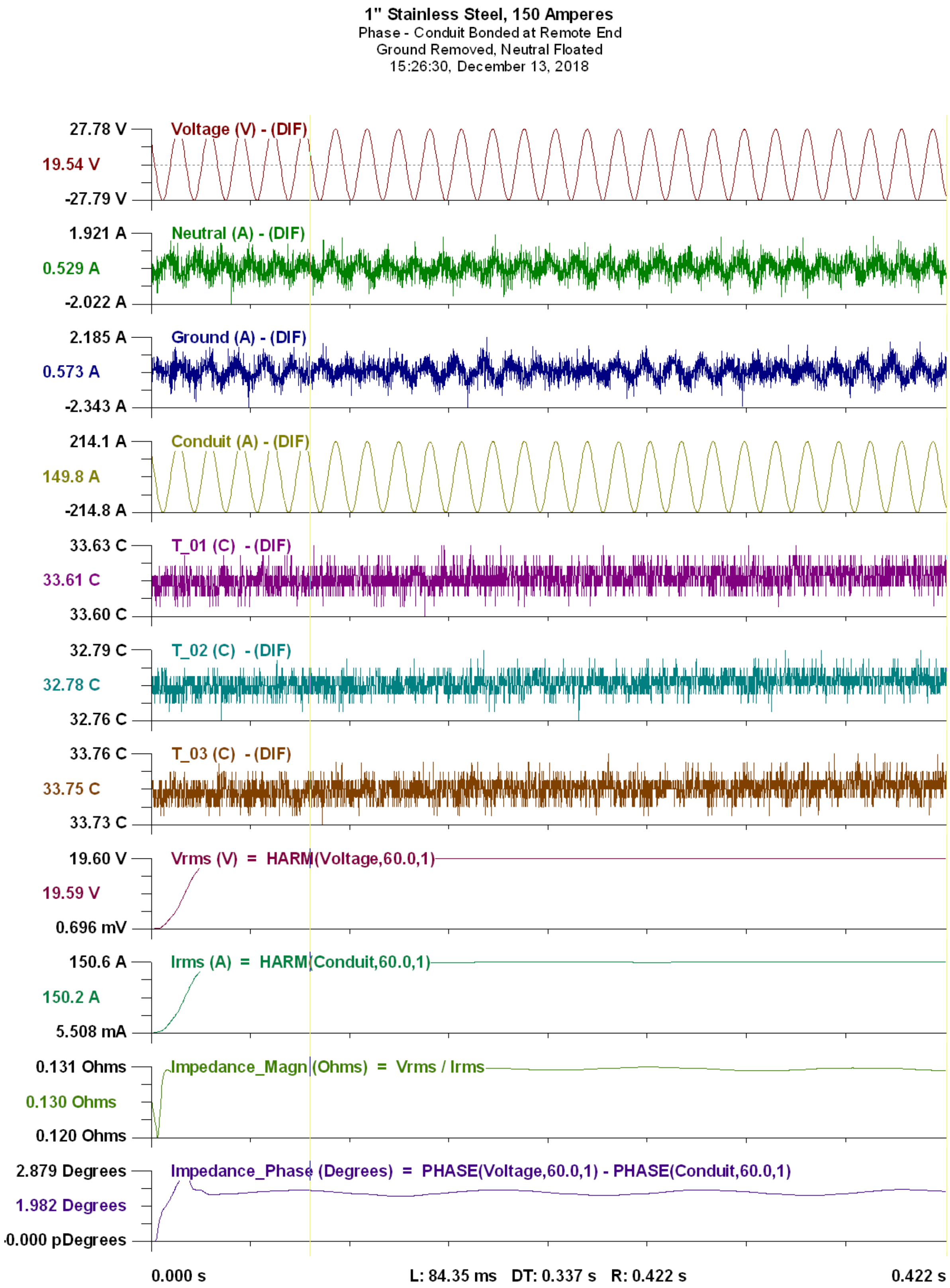


Figure K-13: Case Name STAINLESS100_013

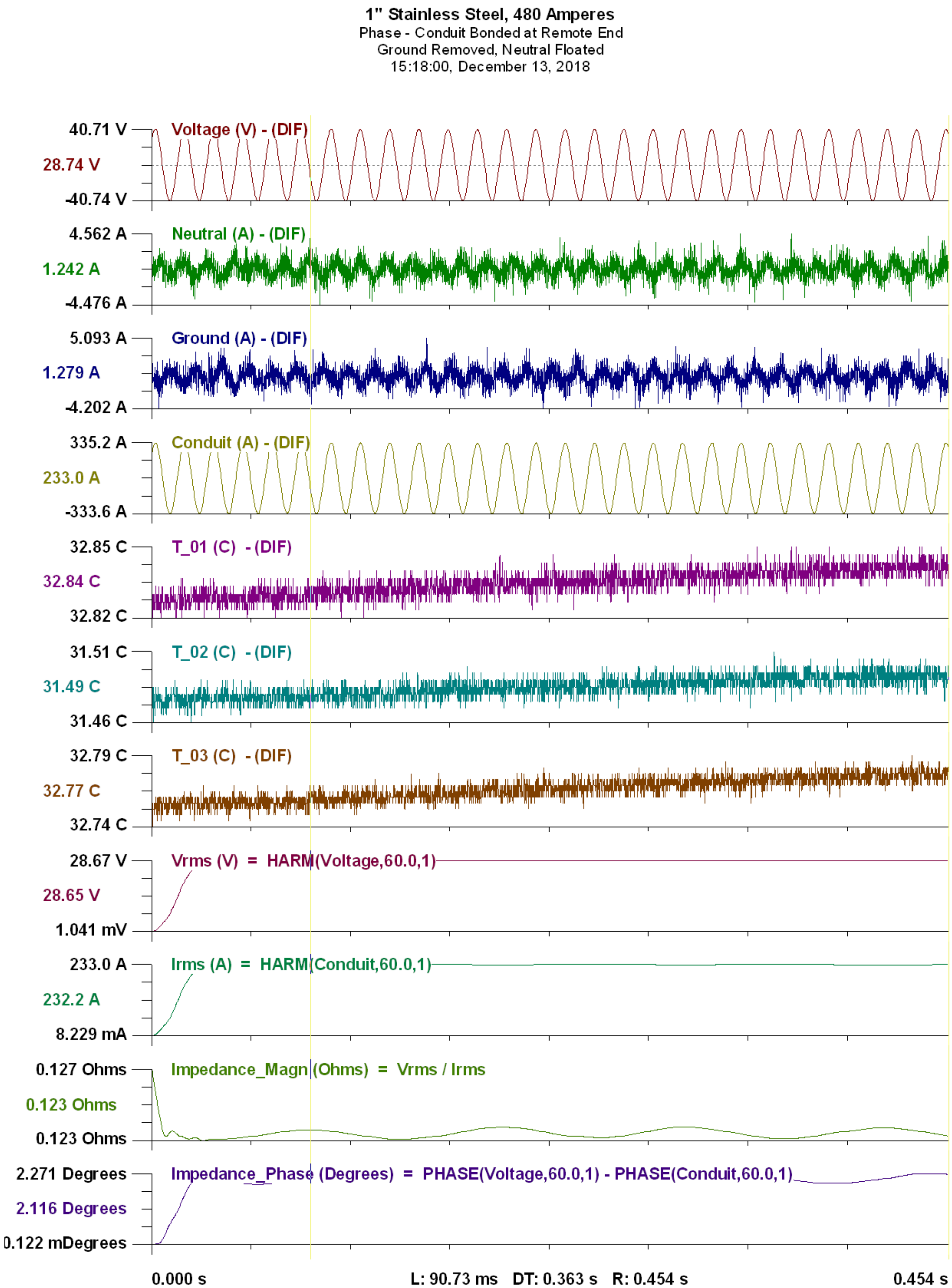


Figure K-14: Case Name STAINLESS100_014

Appendix L – ¾" EMT Raw Data Plots

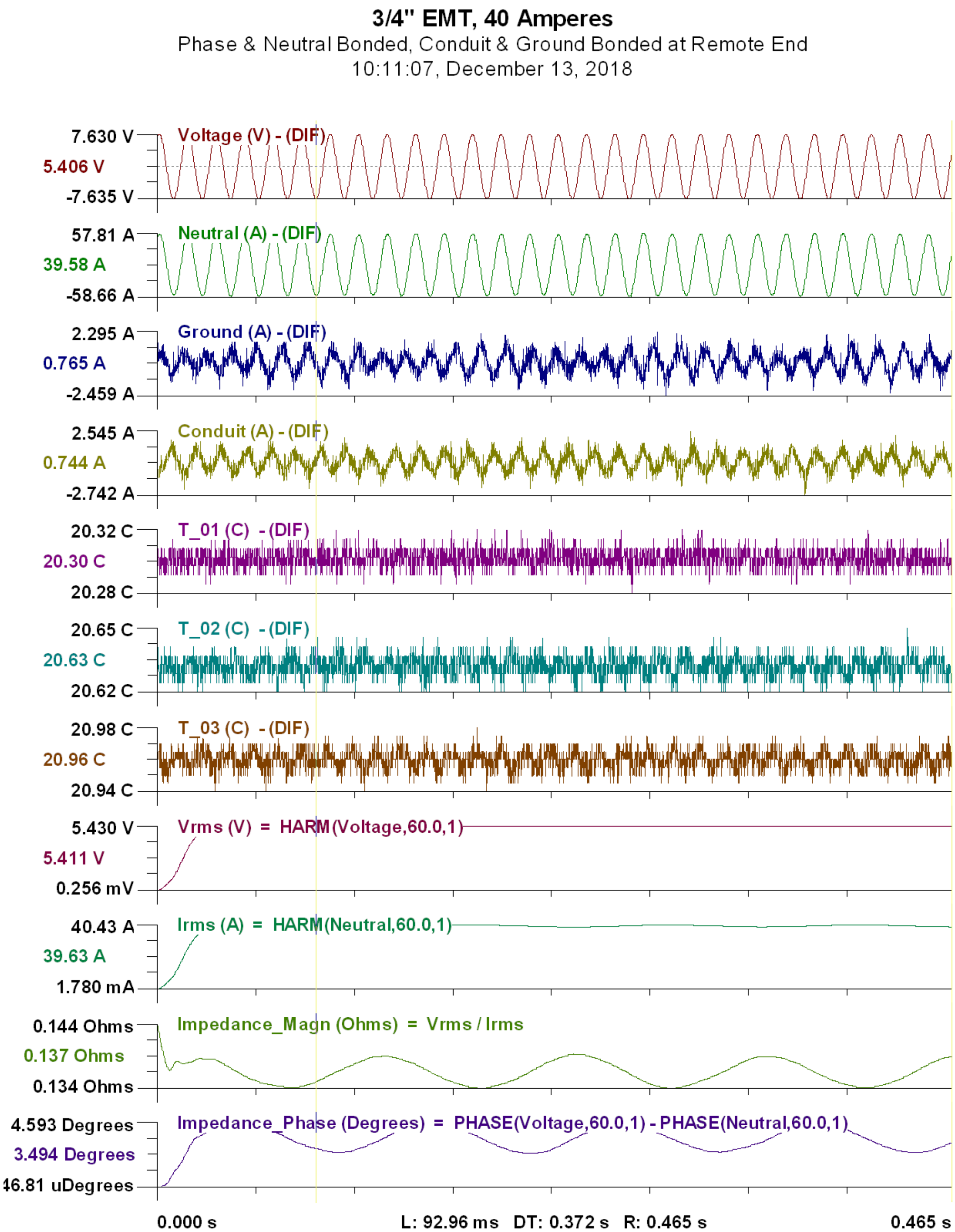


Figure L-1: Case Name EMT075_001

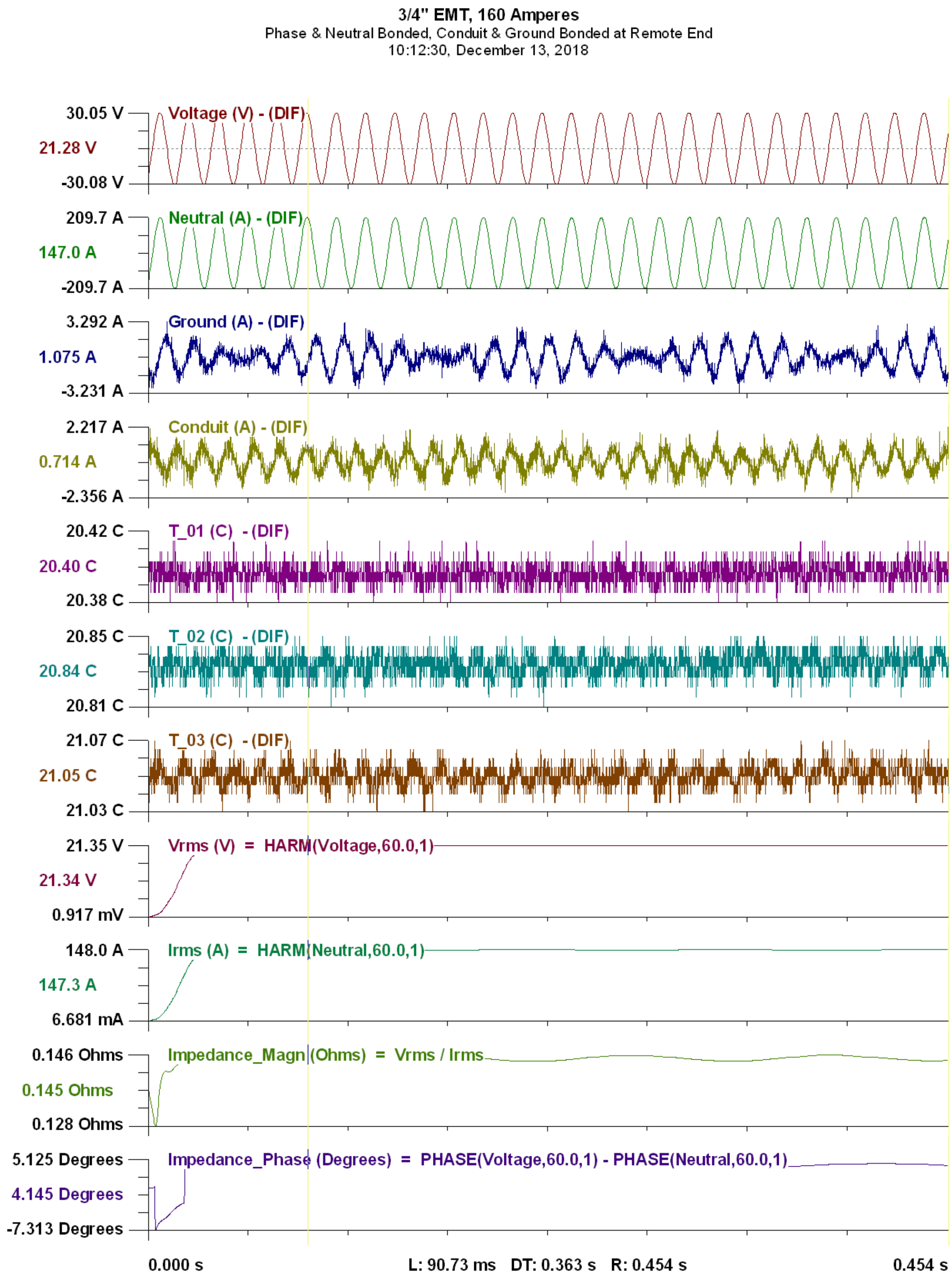


Figure L-2: Case Name EMT075_002

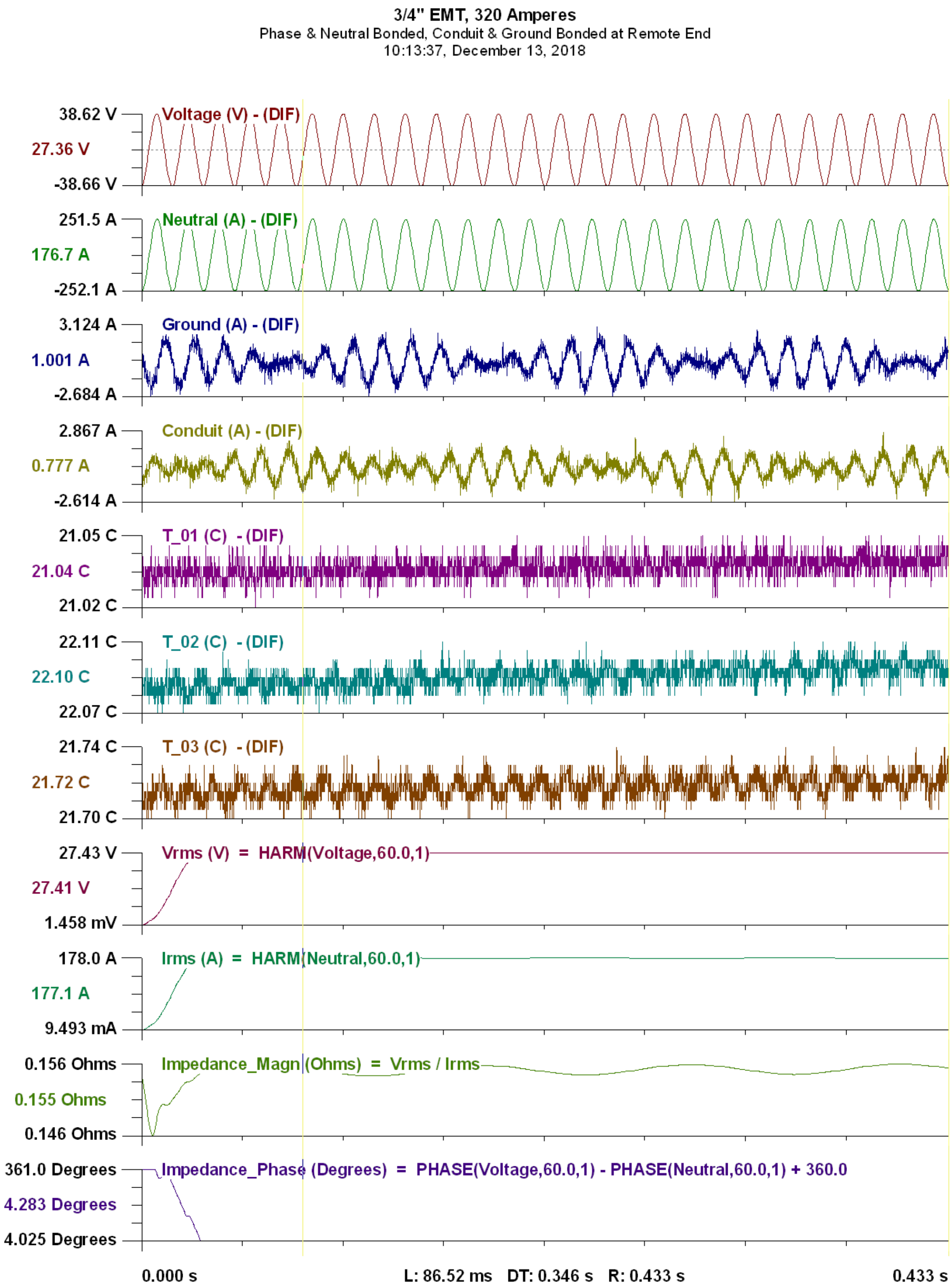


Figure L-3: Case Name EMT075_003

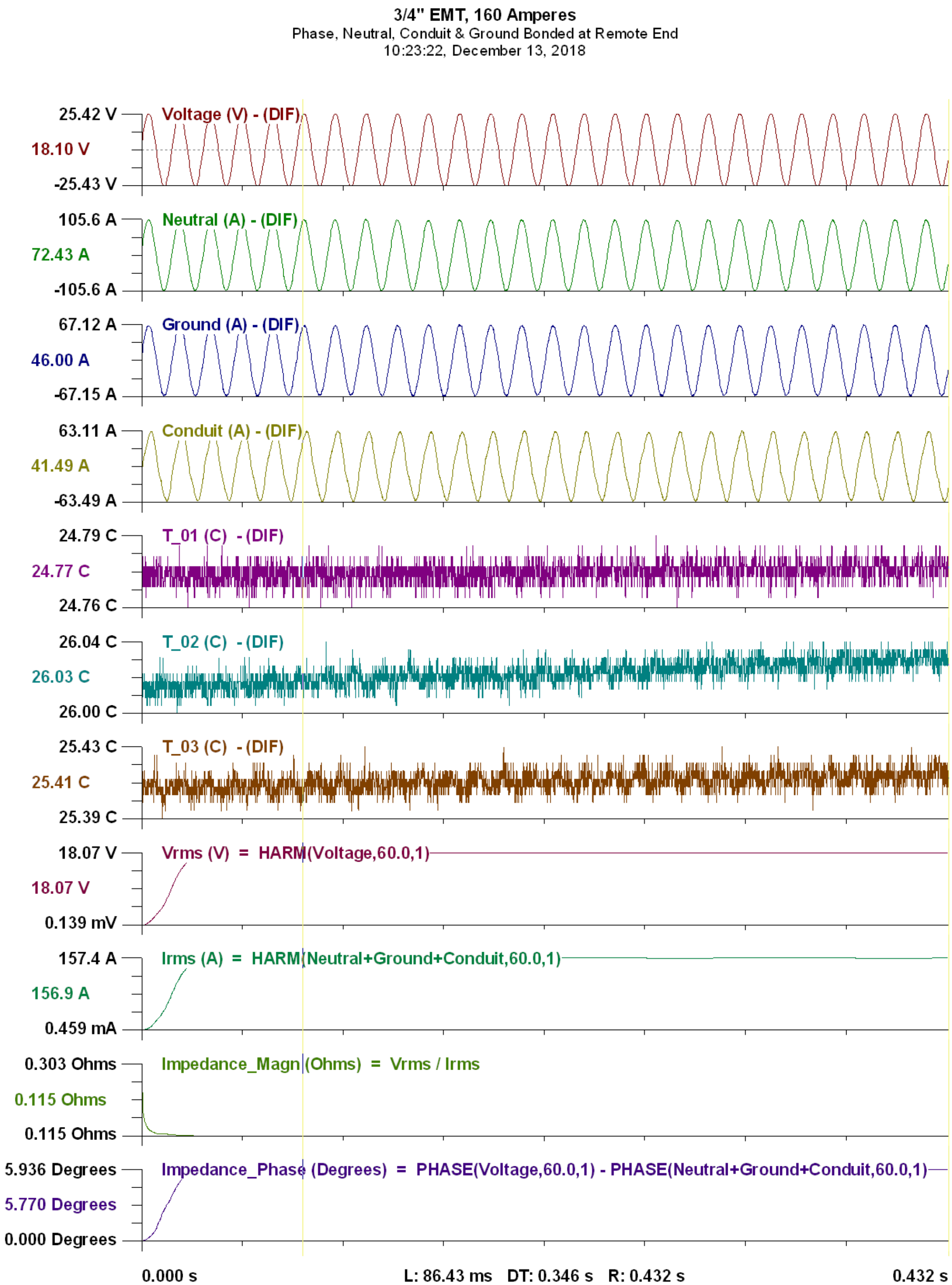


Figure L-4: Case Name EMT075_004

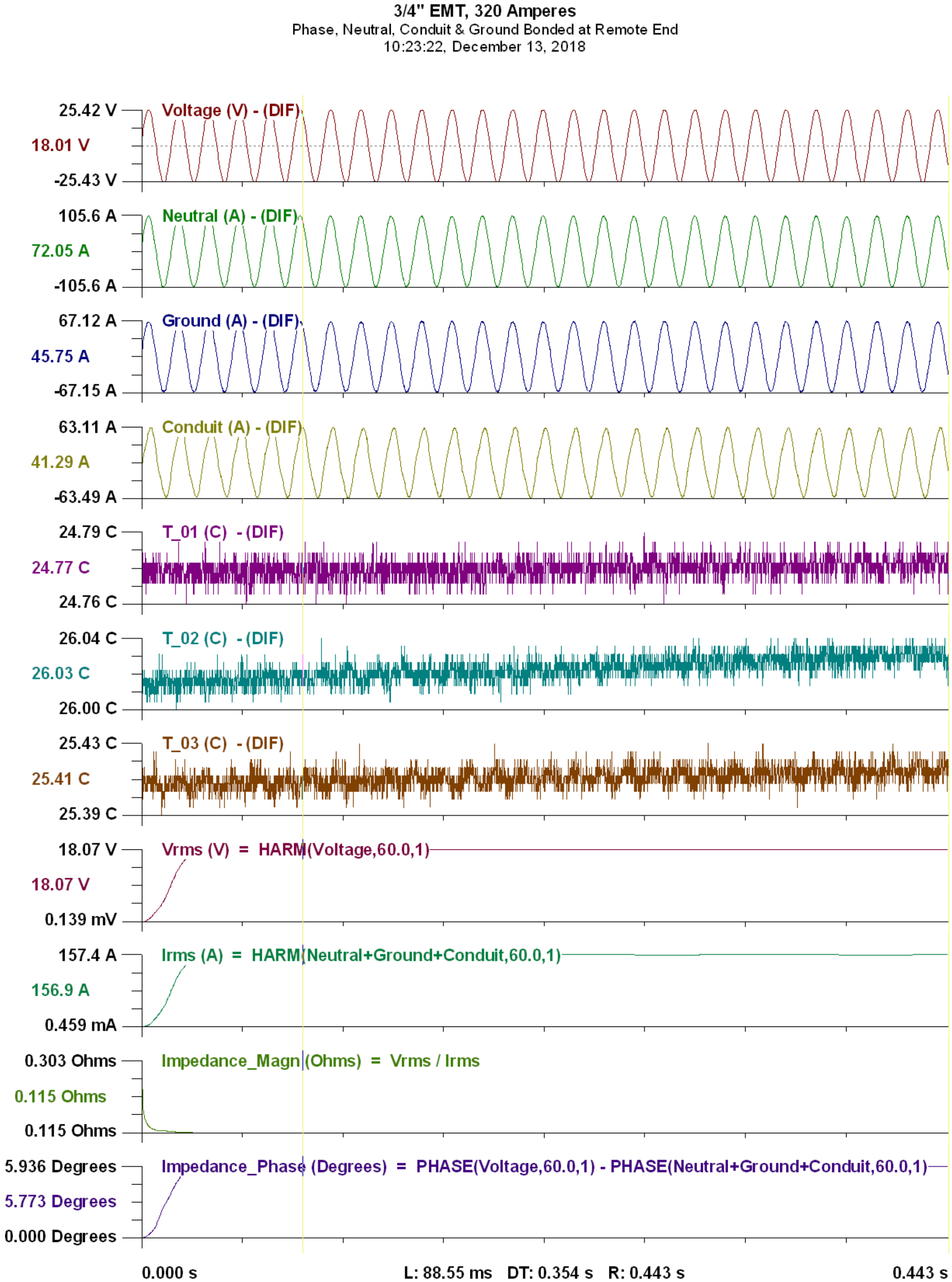


Figure L-5: Case Name EMT075_005

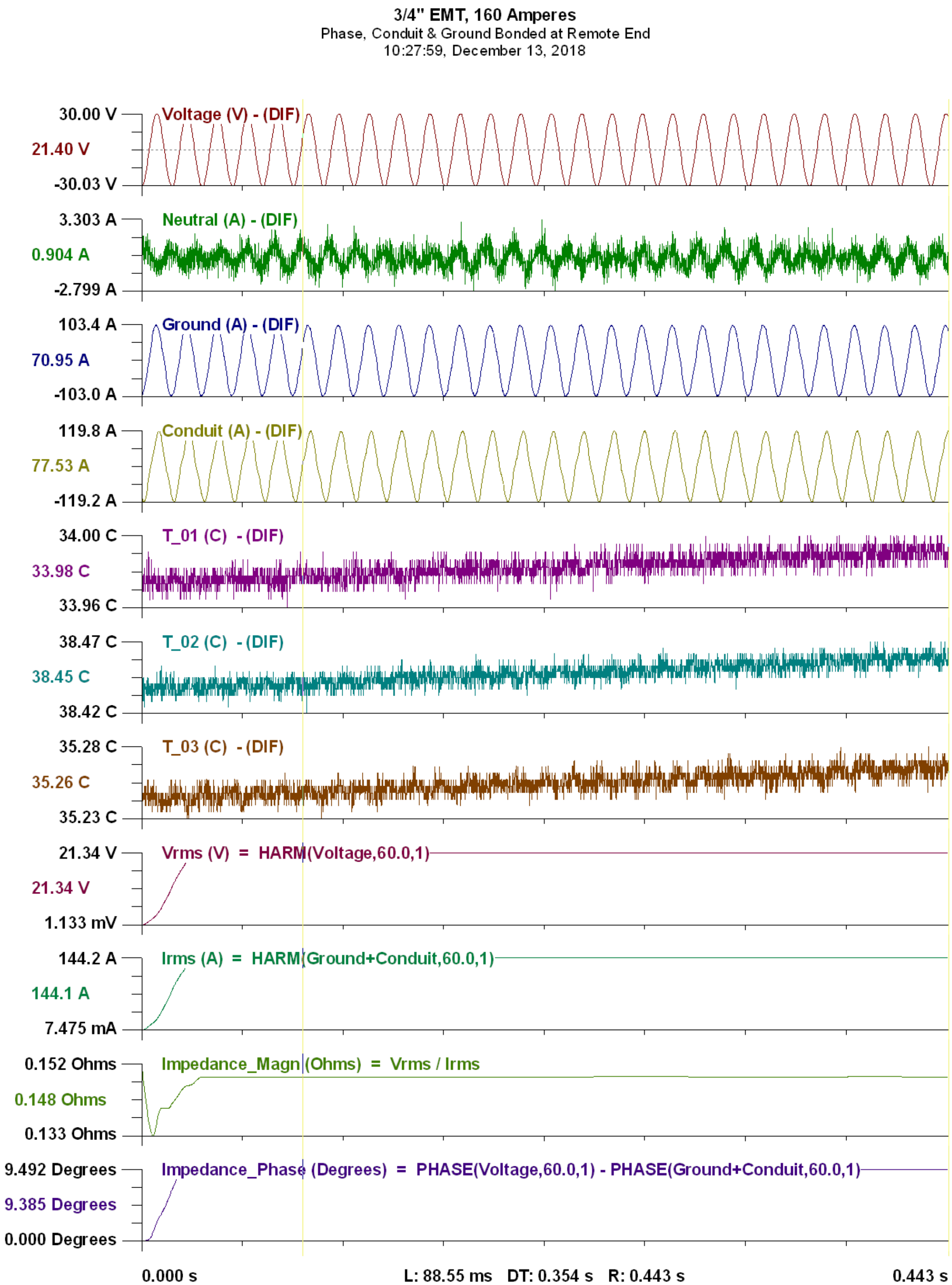


Figure L-6: Case Name EMT075_006

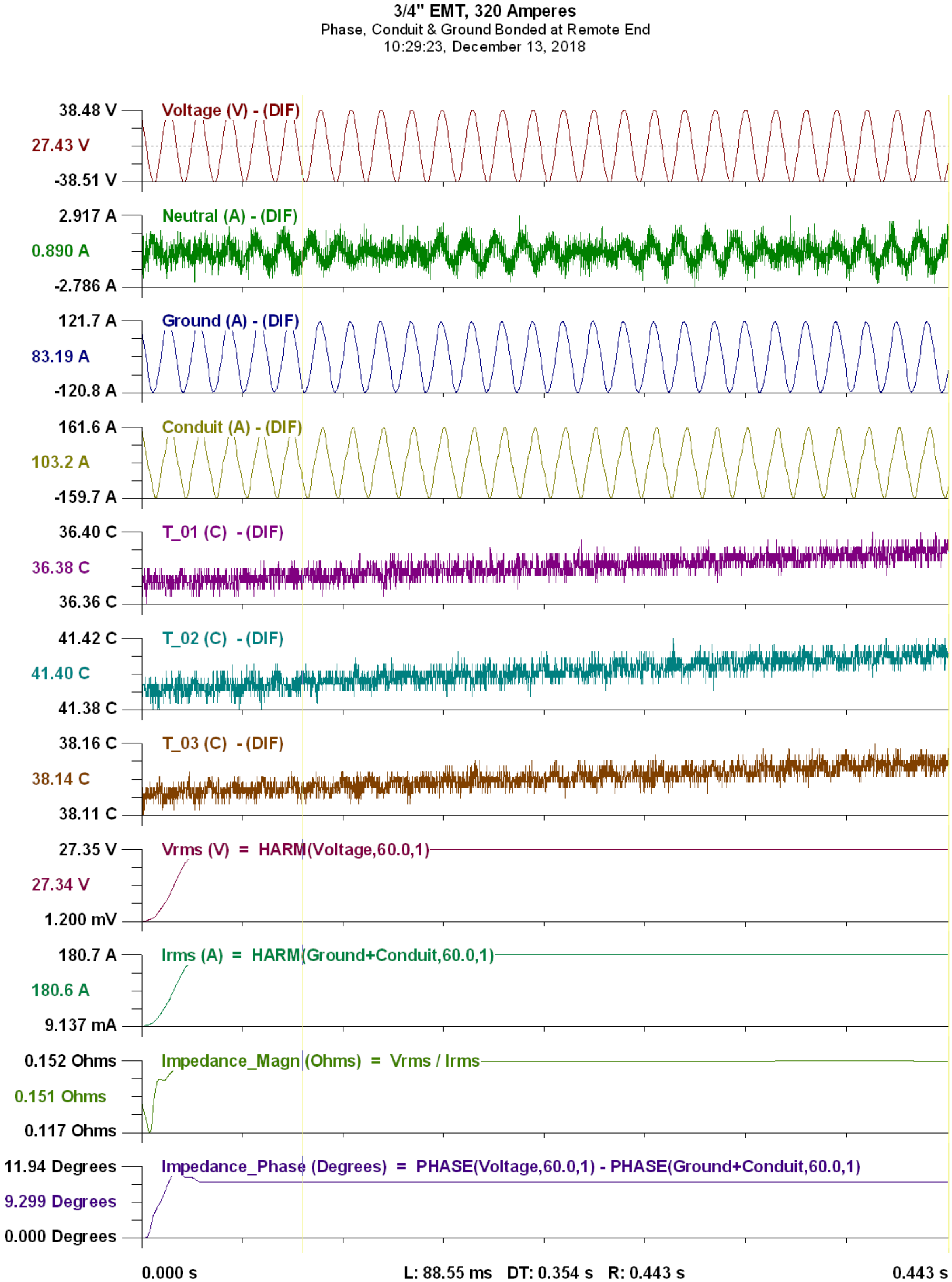


Figure L-7: Case Name EMT075_007

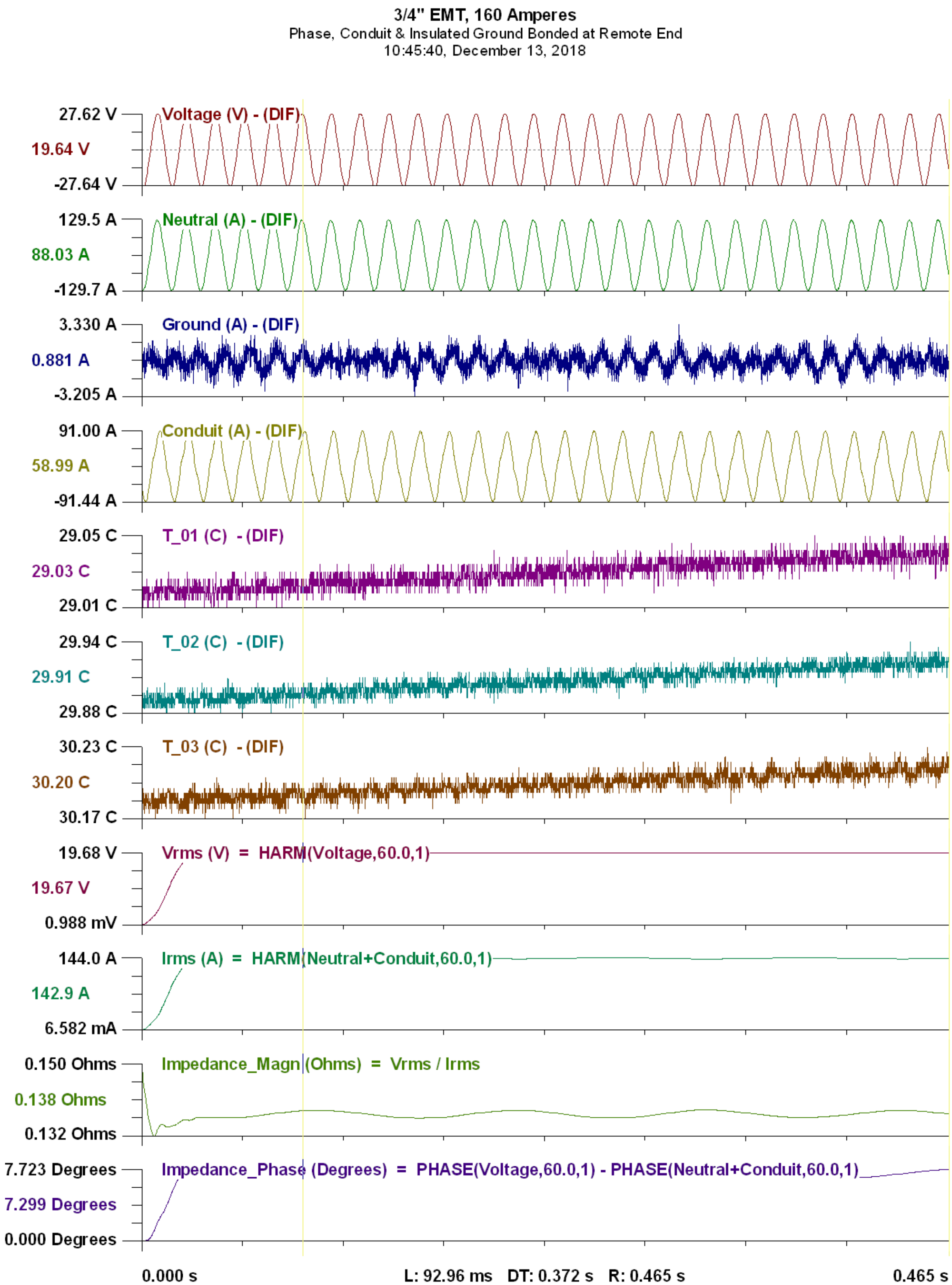


Figure L-8: Case Name EMT075_008

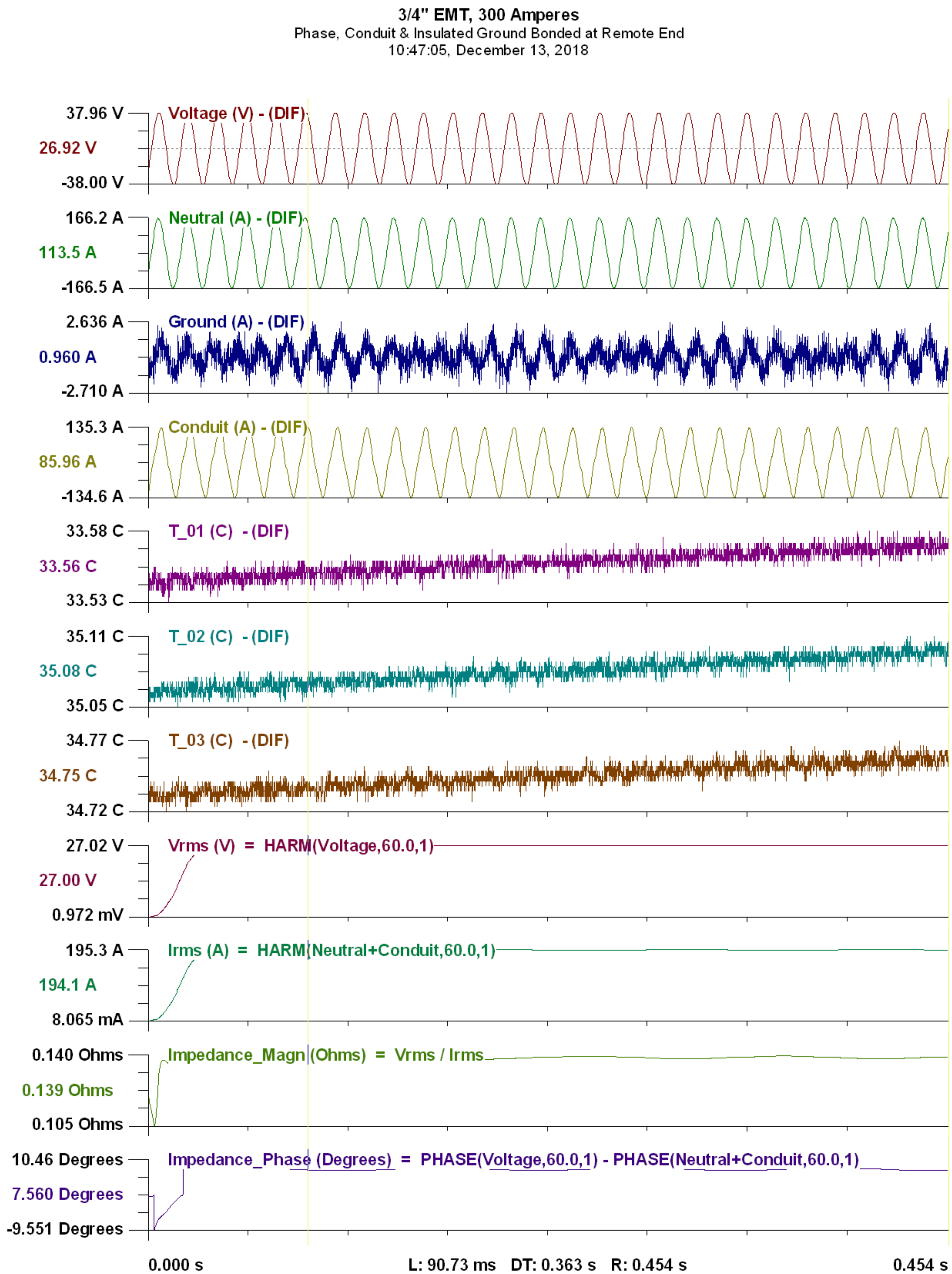


Figure L-9: Case Name EMT075_009

Appendix M – ¾" GRC Raw Data Plots

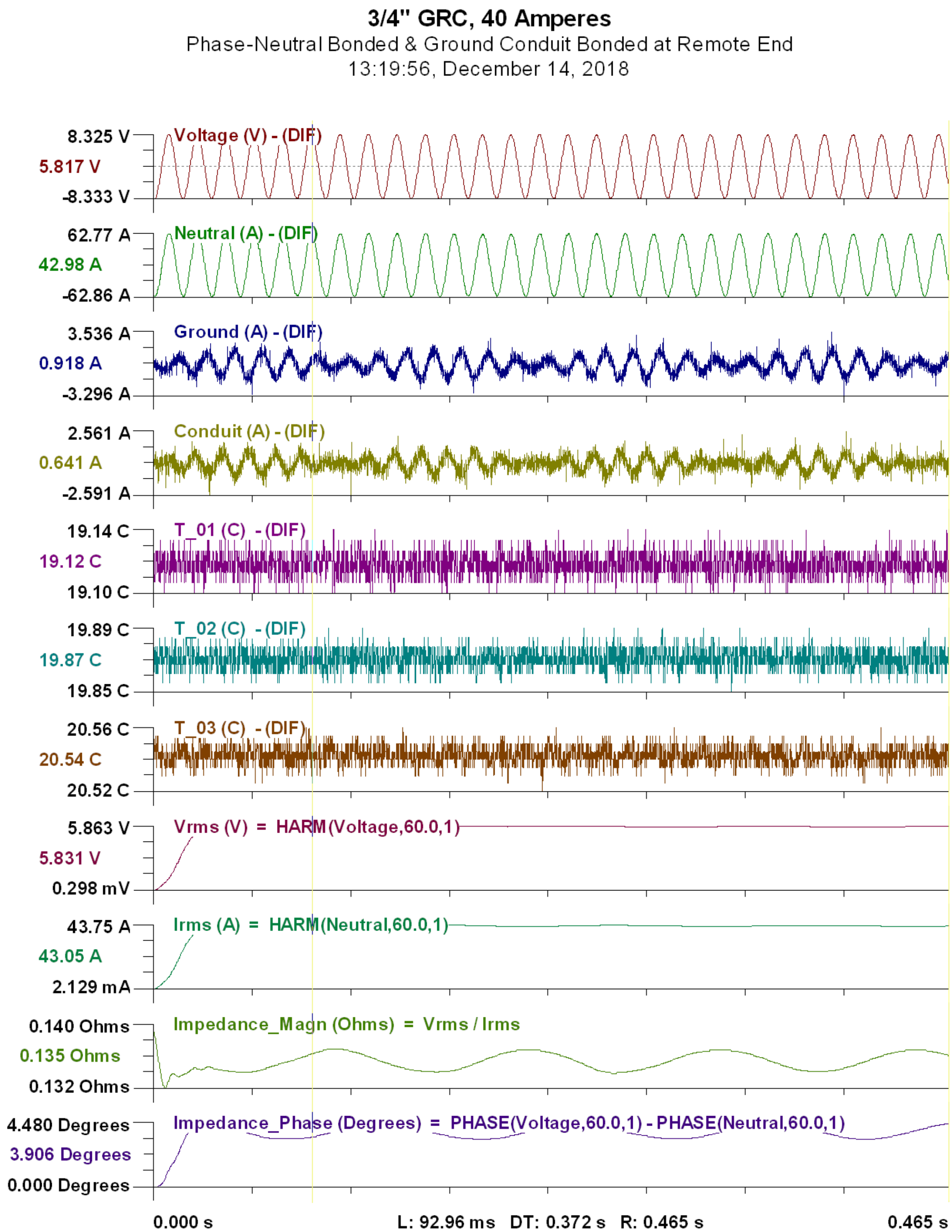


Figure M-1: Case Name GRC075_001

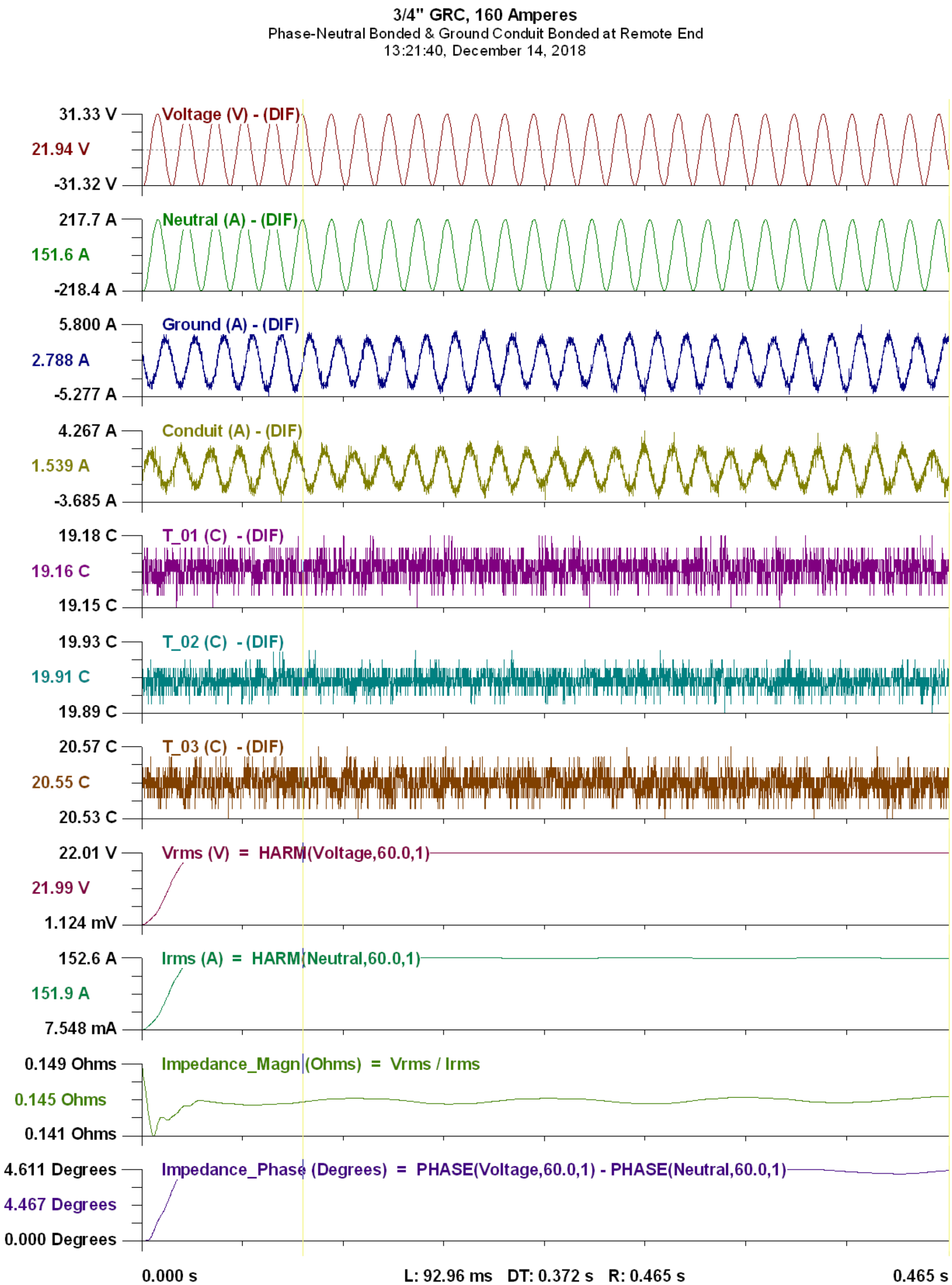


Figure M-2: Case Name GRC075_002

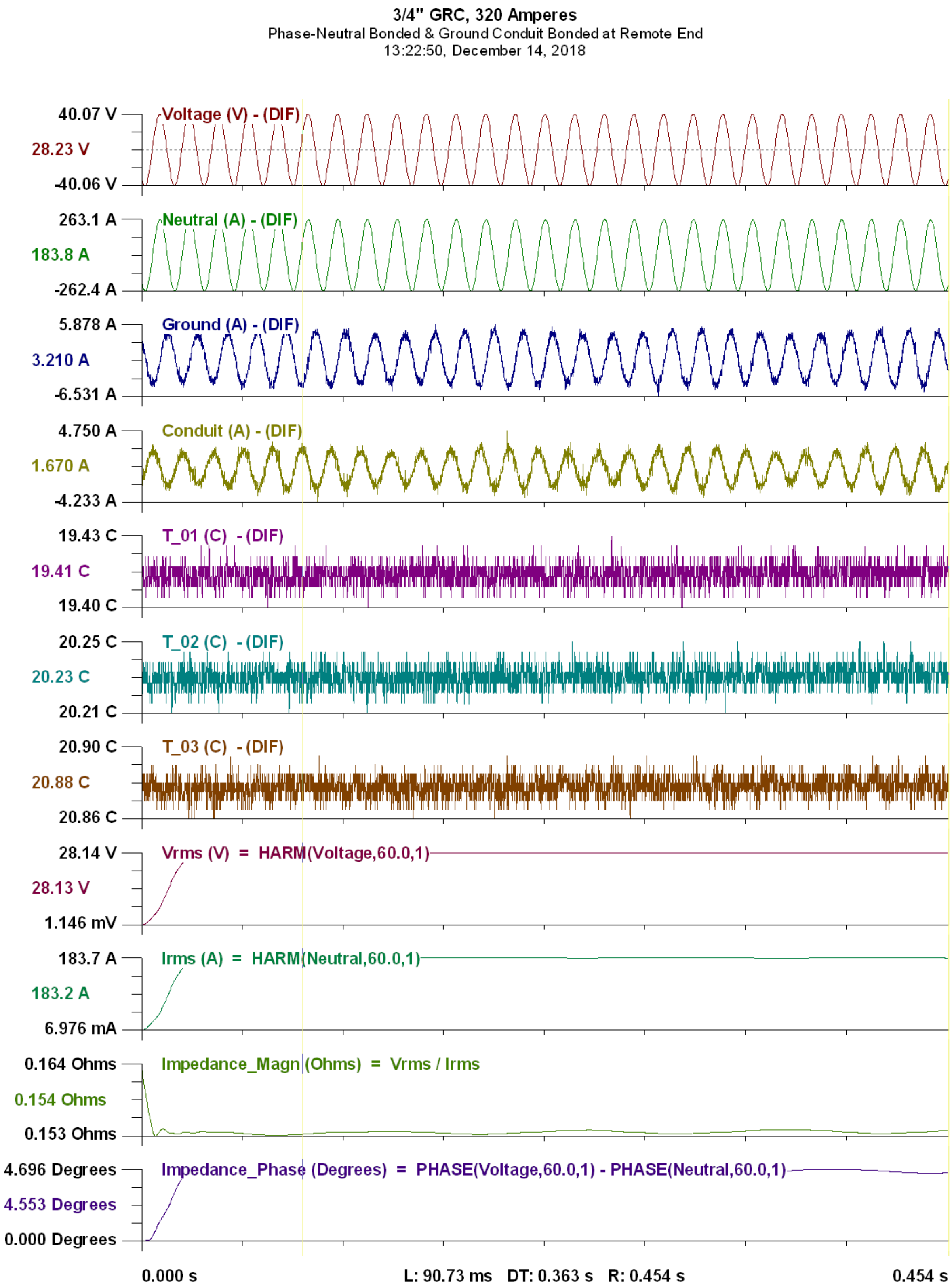


Figure M-3: Case Name GRC075_003

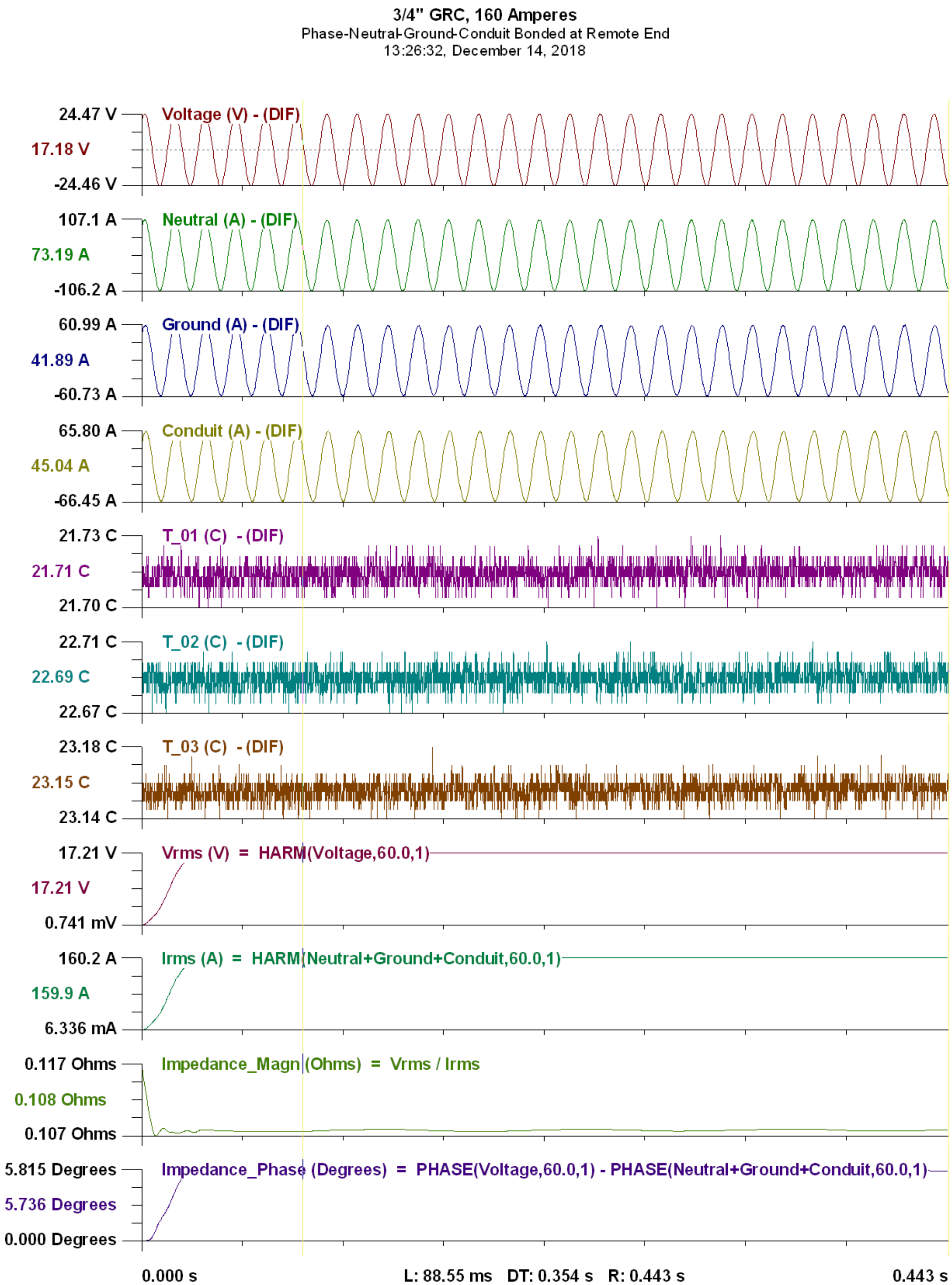


Figure M-4: Case Name GRC075_004

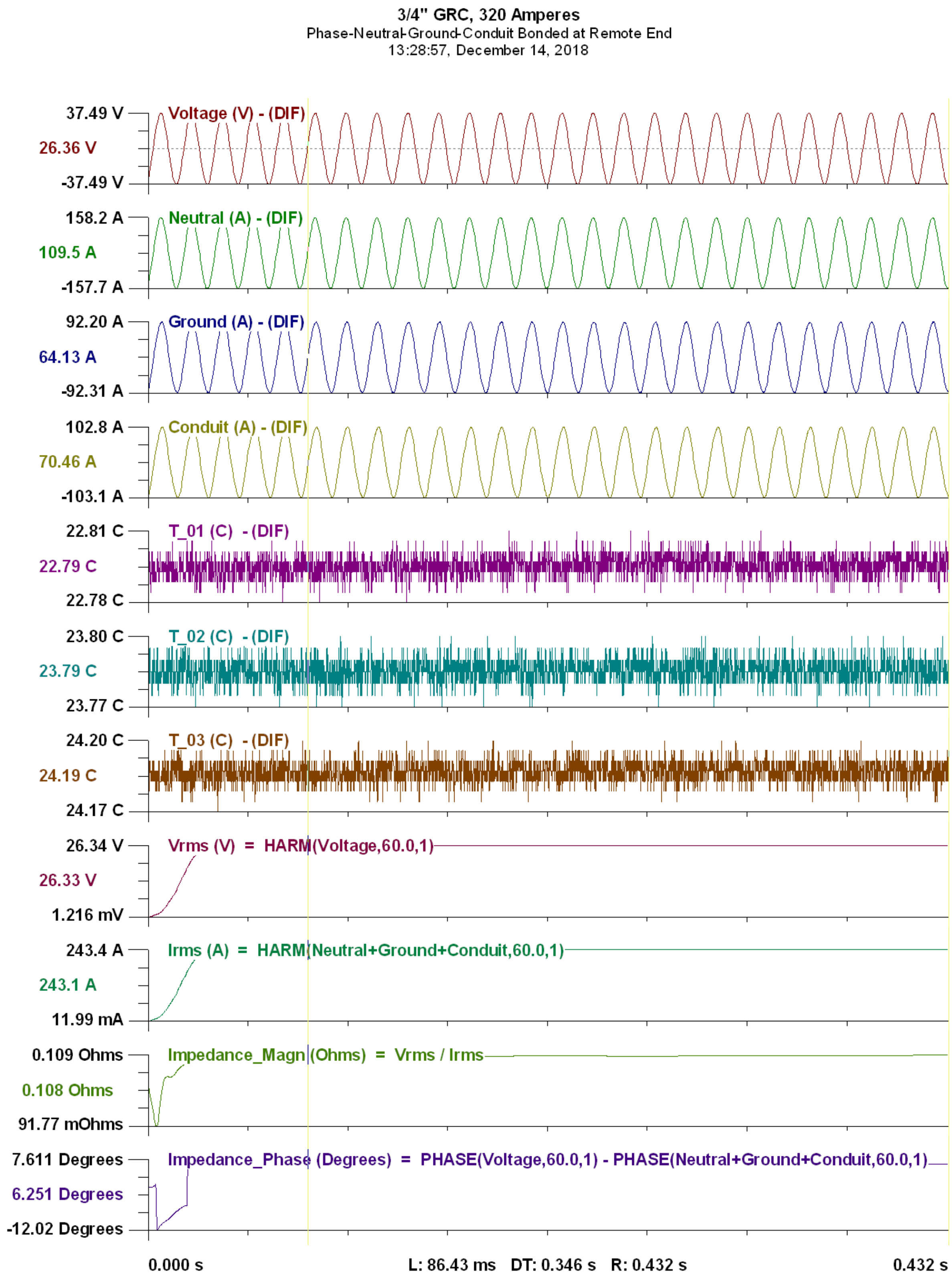


Figure M-5: Case Name GRC075_005

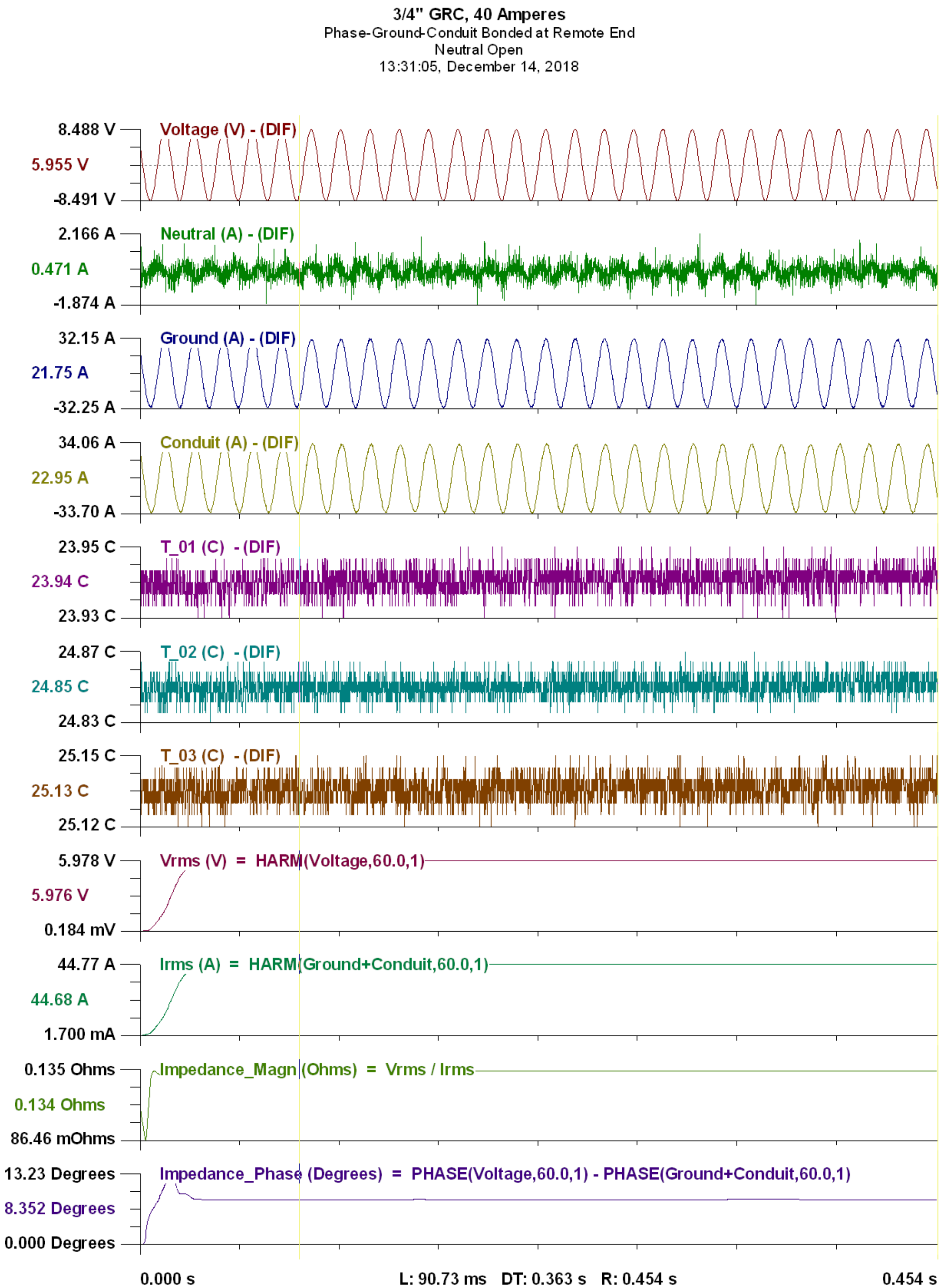


Figure M-6: Case Name GRC075_006

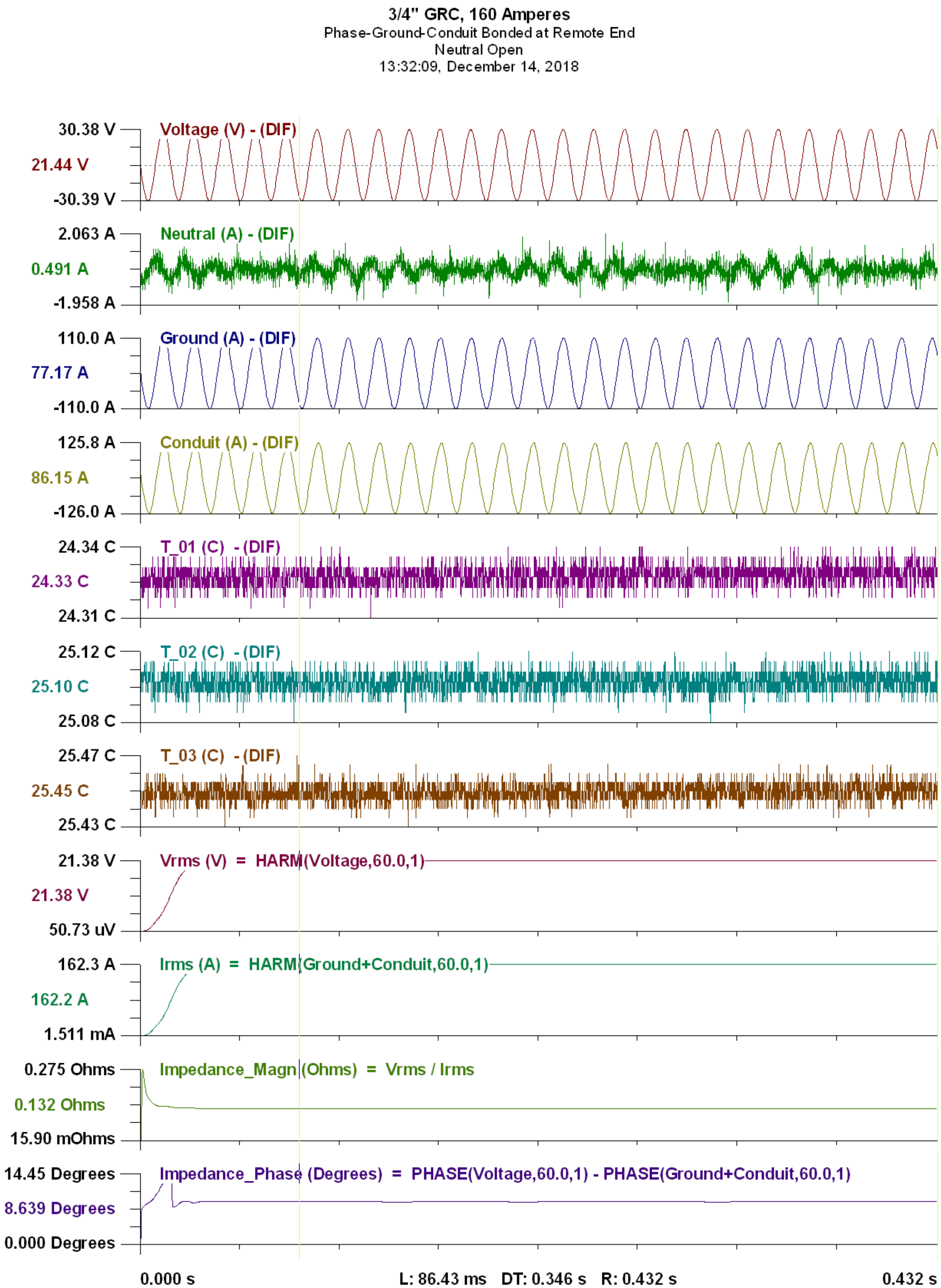


Figure M-7: Case Name GRC075_007

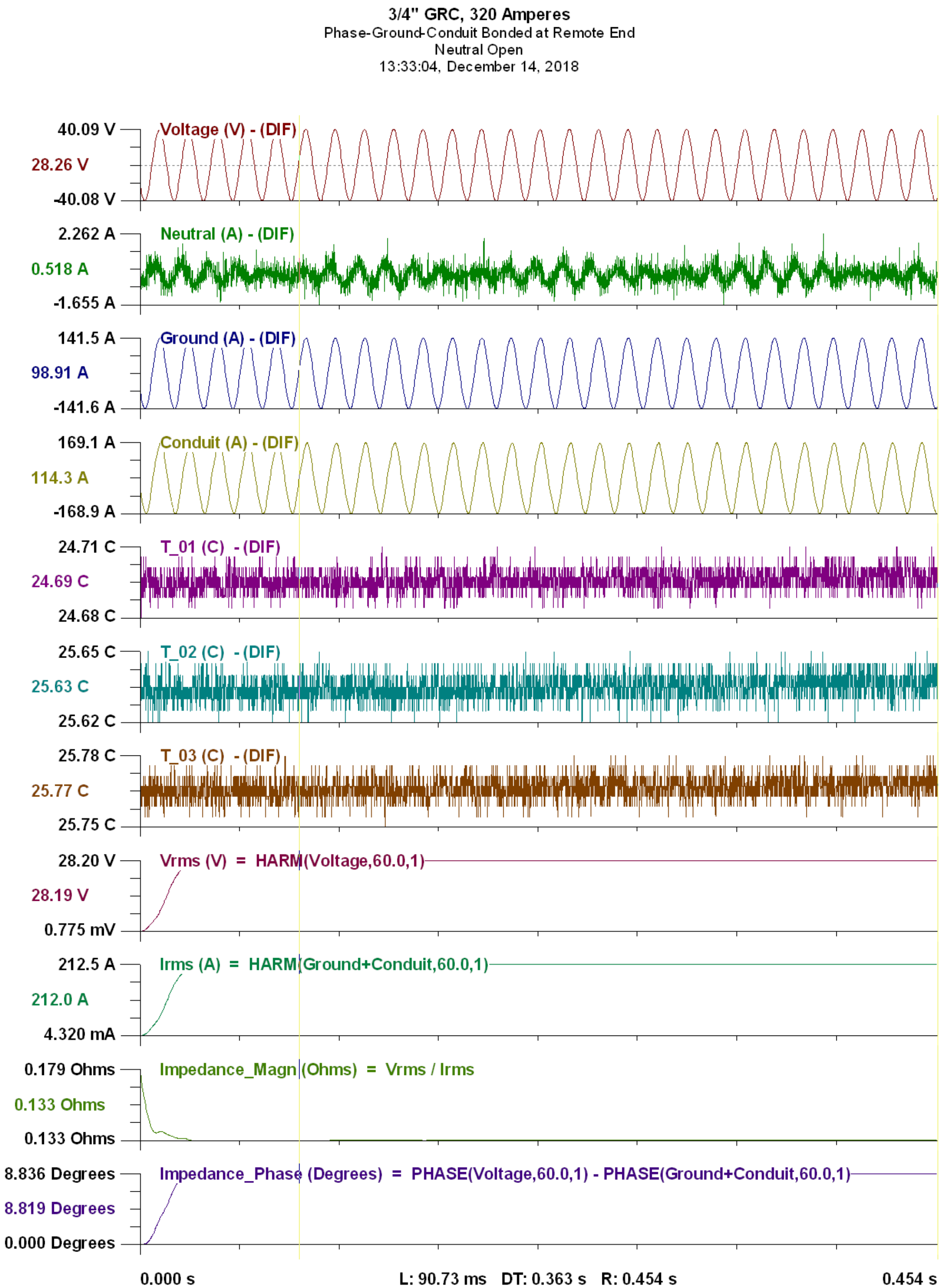


Figure M-8: Case Name GRC075_008

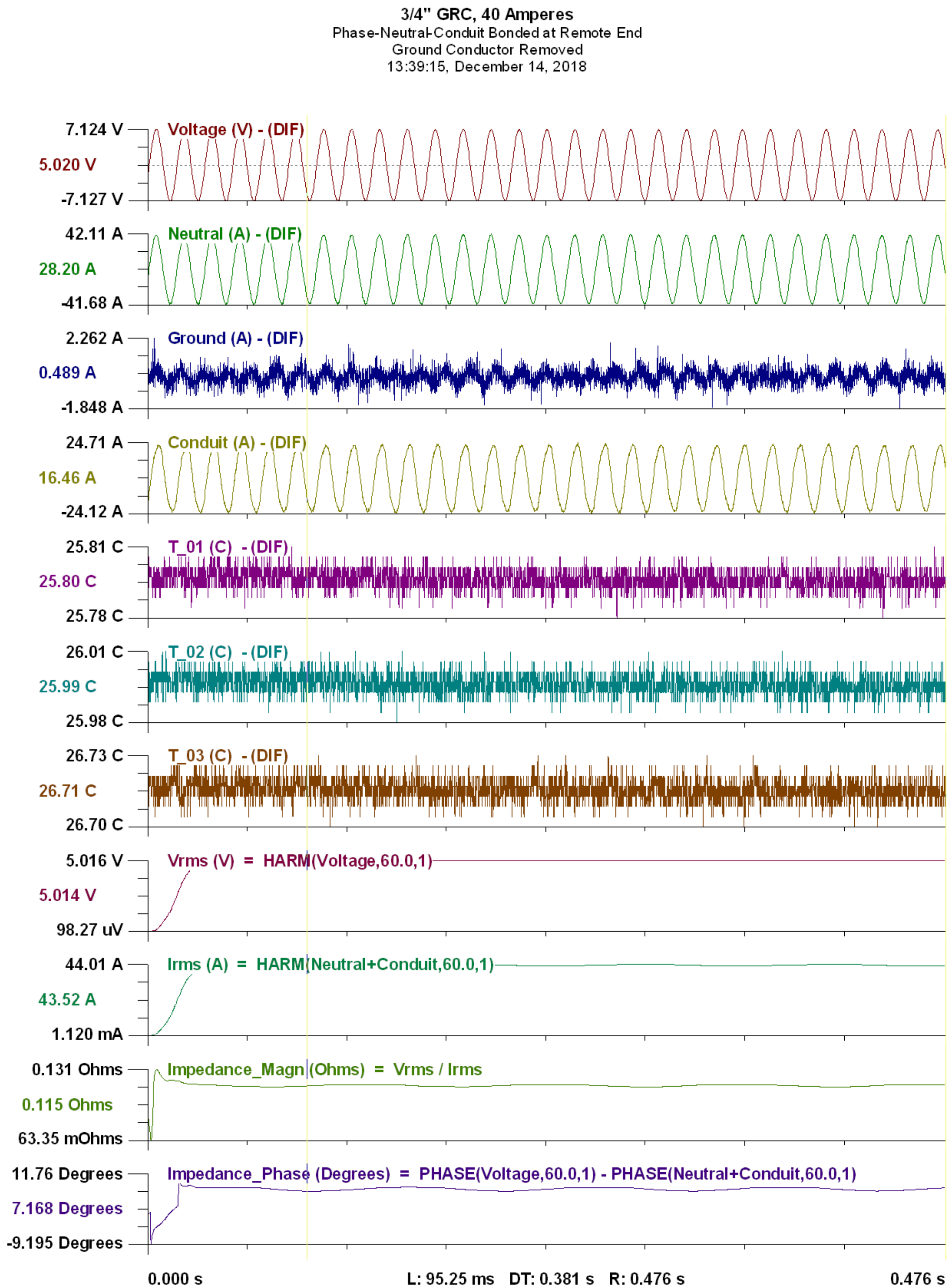


Figure M-9: Case Name GRC075_009

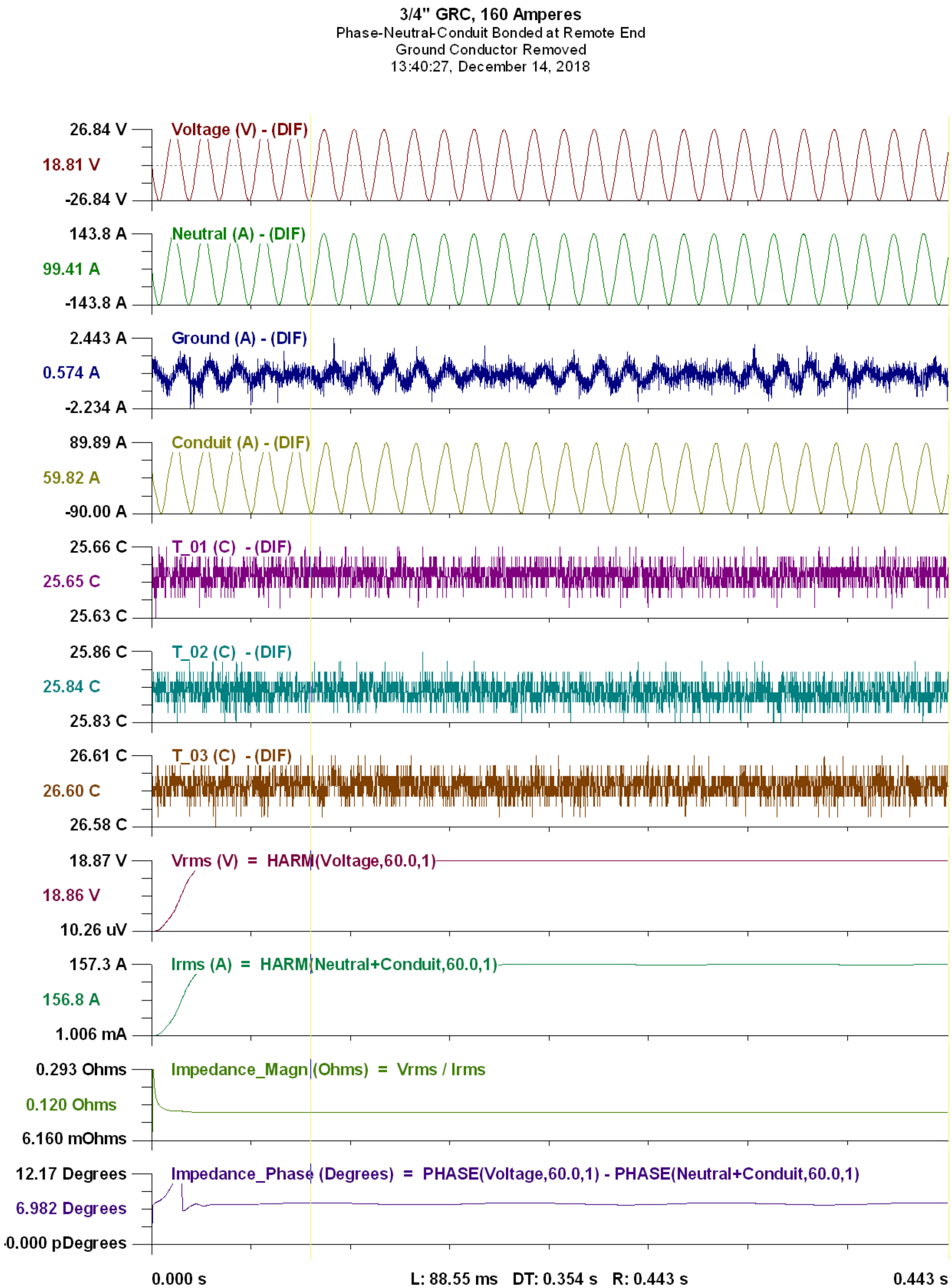


Figure M-10: Case Name GRC075_010

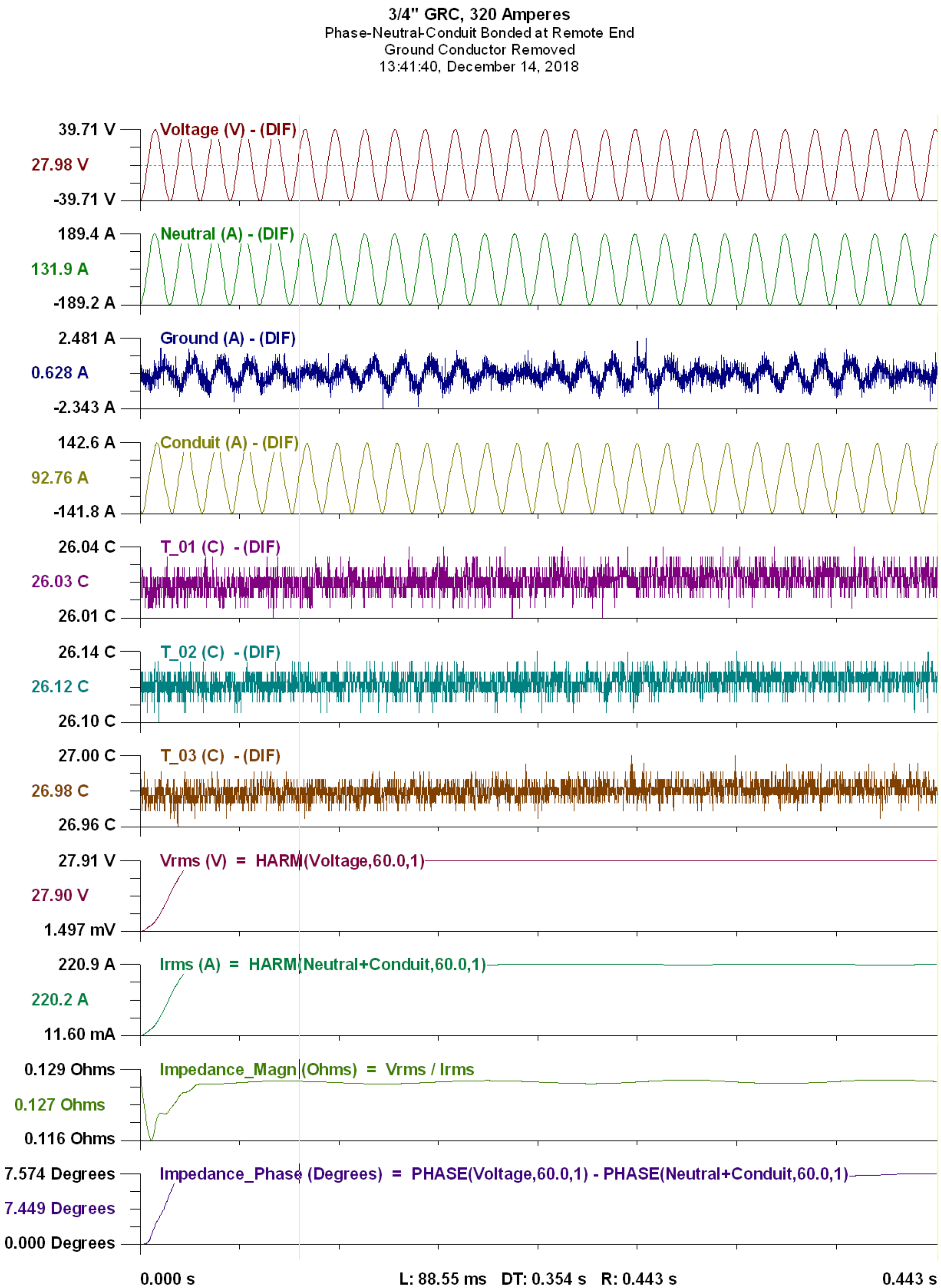


Figure M-11: Case Name GRC075_011

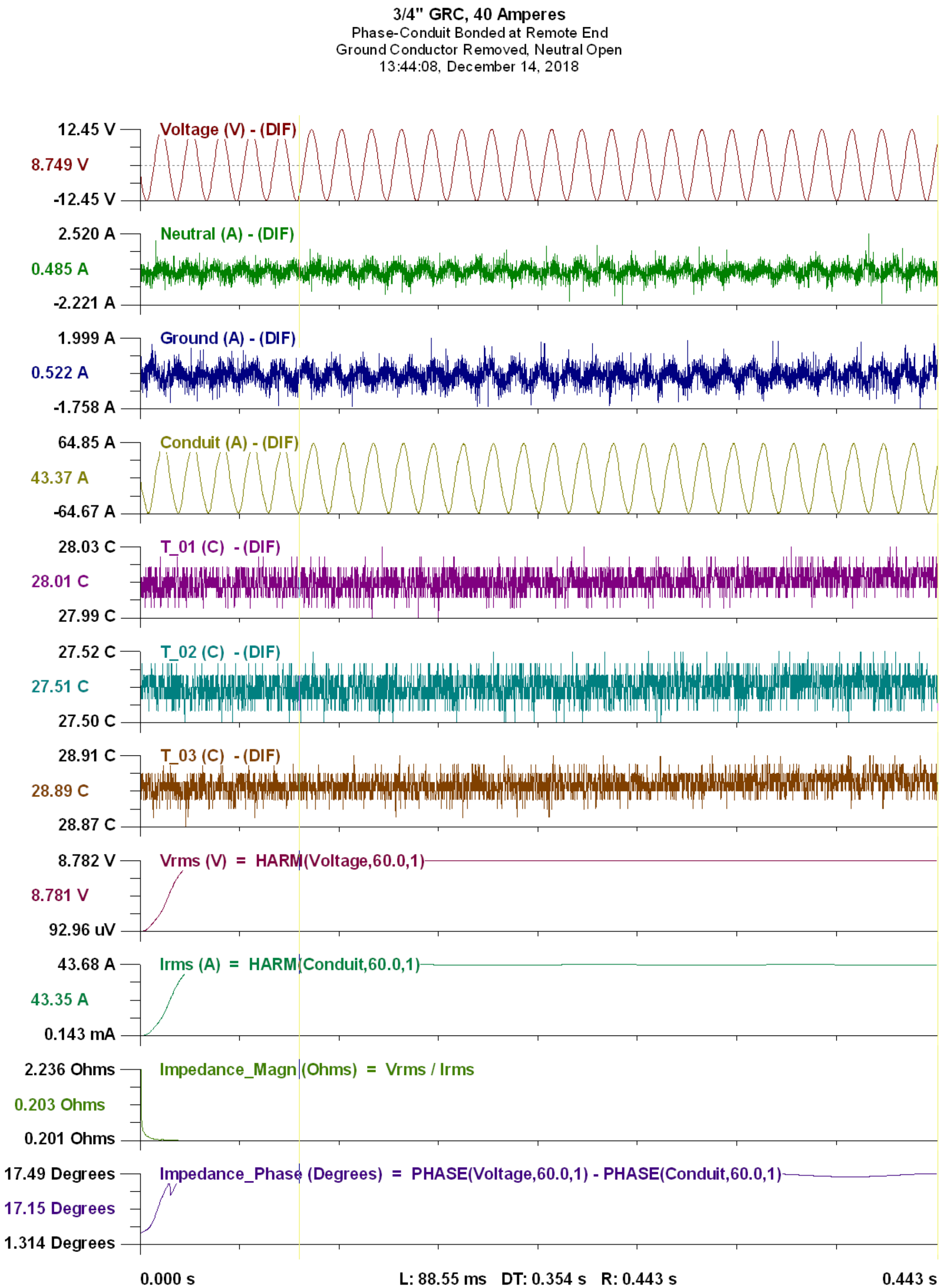


Figure M-12: Case Name GRC075_012

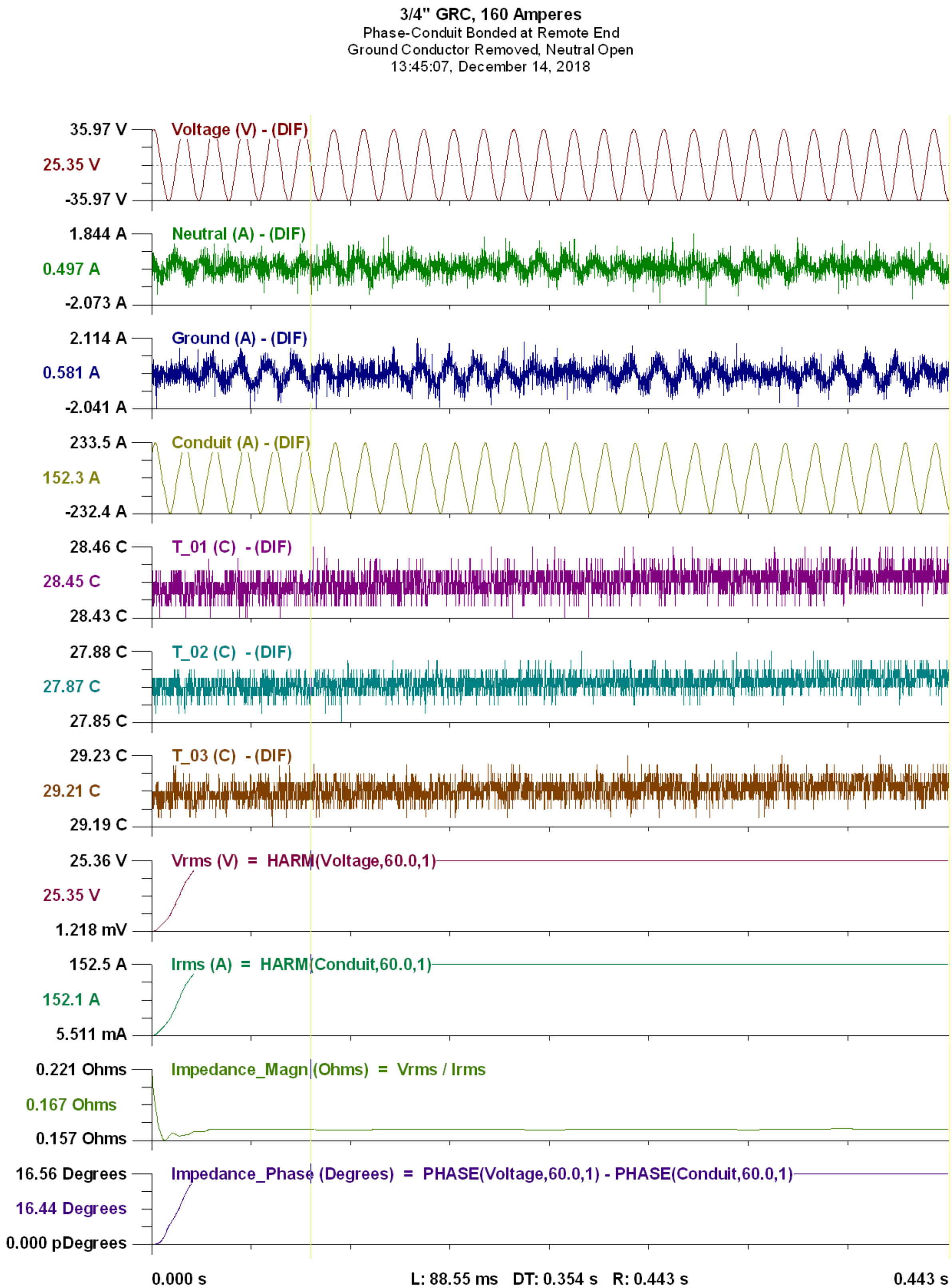


Figure M-13: Case Name GRC075_013

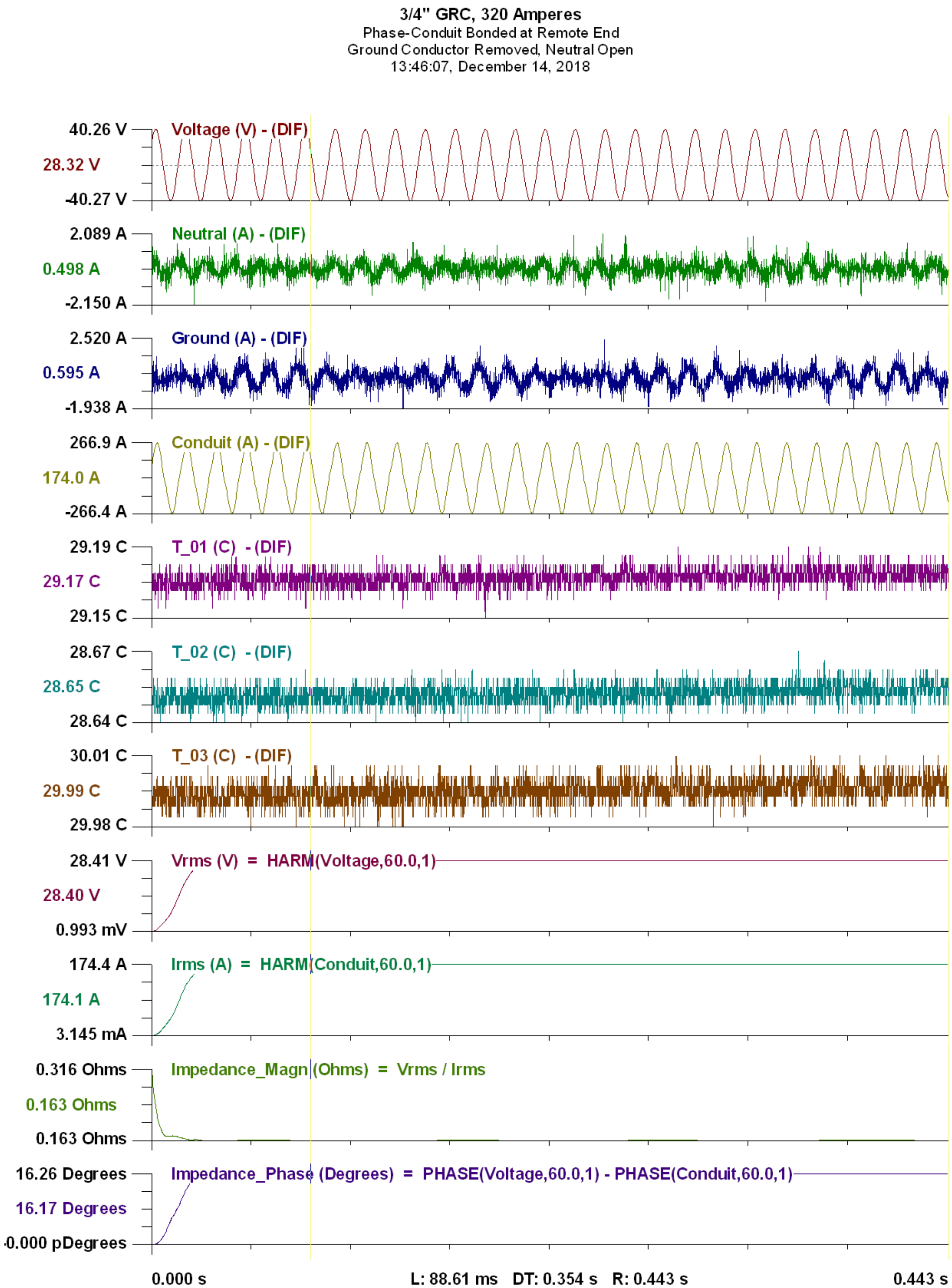


Figure M-14: Case Name GRC075_014

Appendix N – ¾” IMC Raw Data Plots

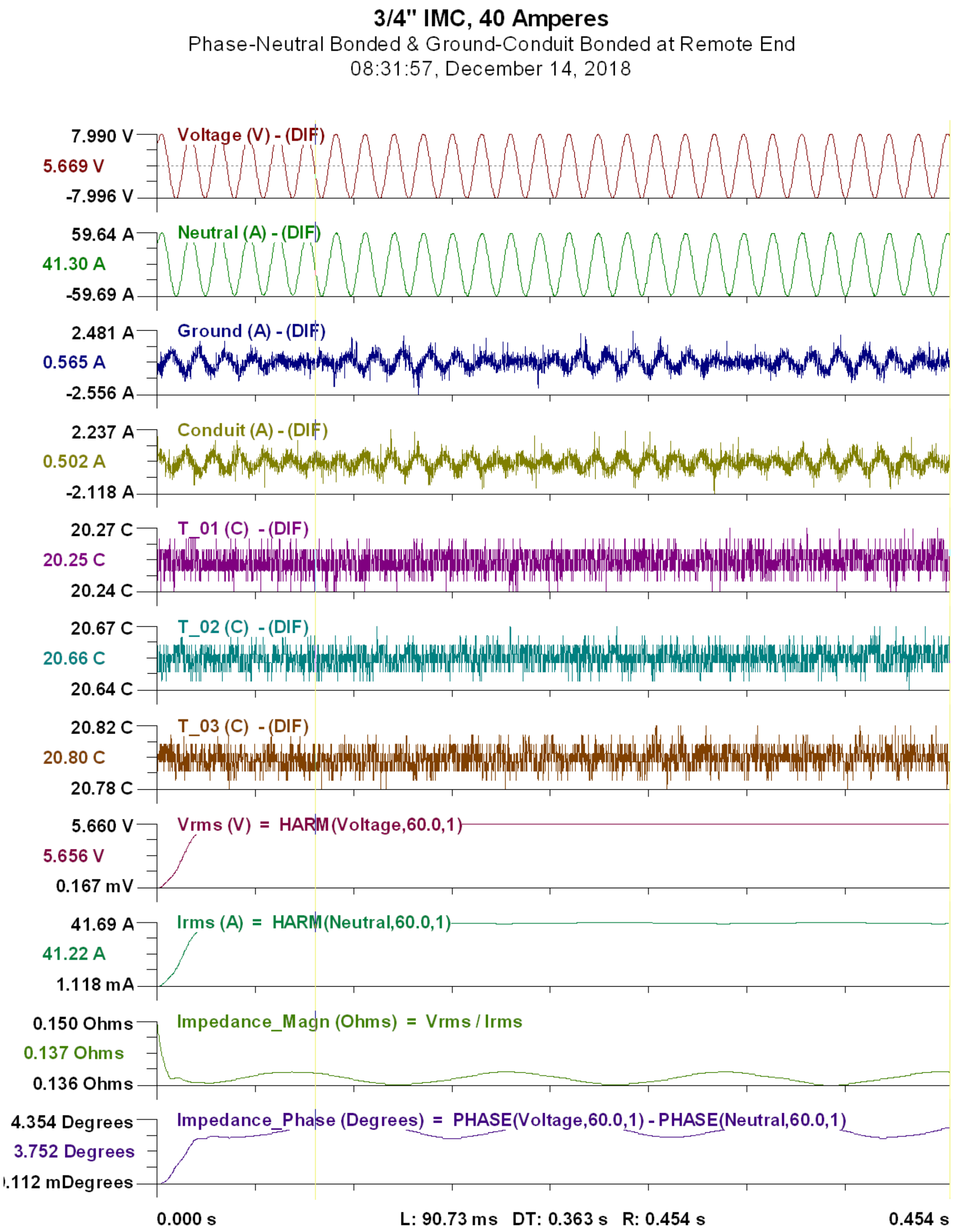


Figure N-1: Case Name IMC075_001

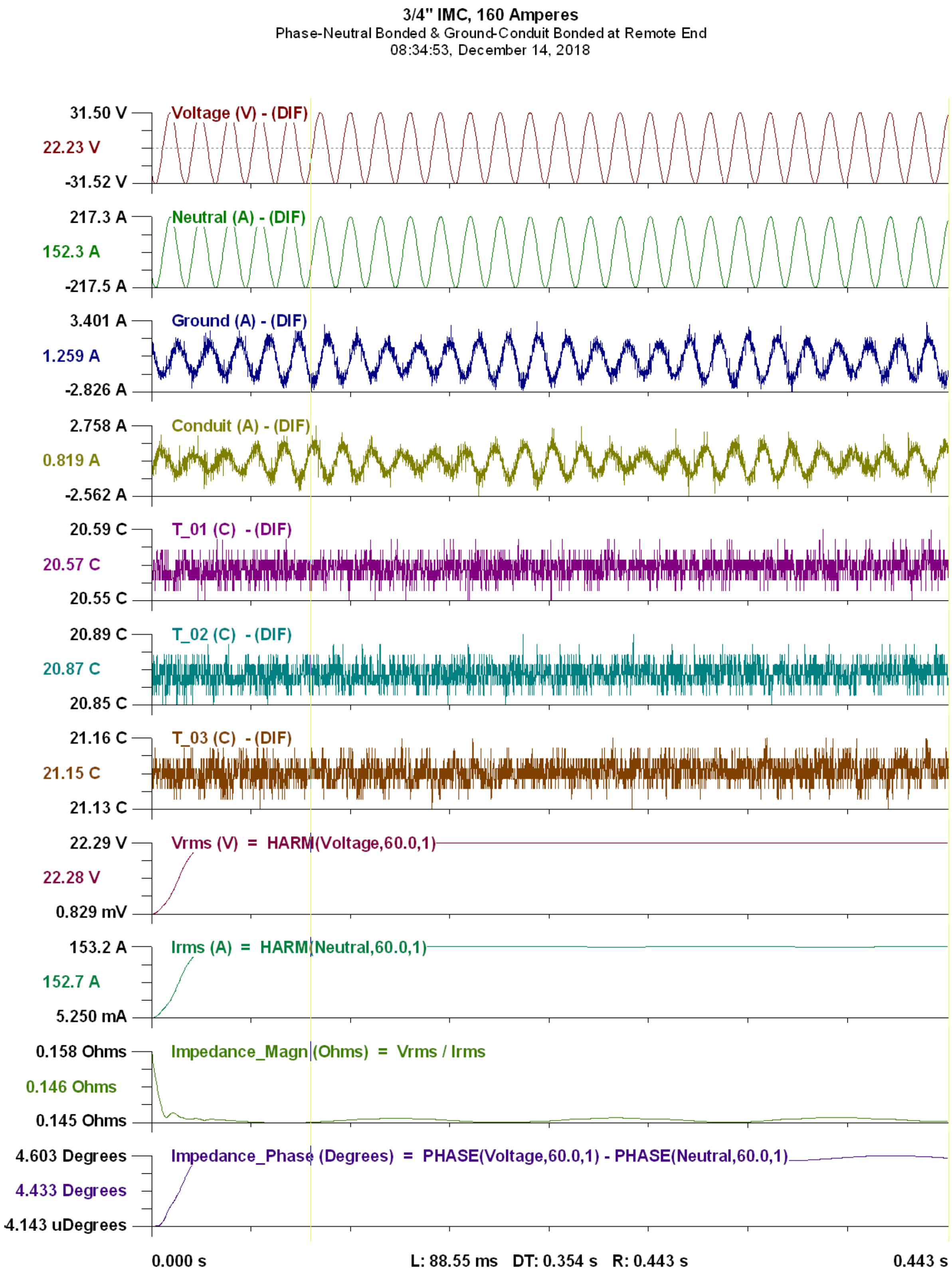


Figure N-2: Case Name IMC075_002

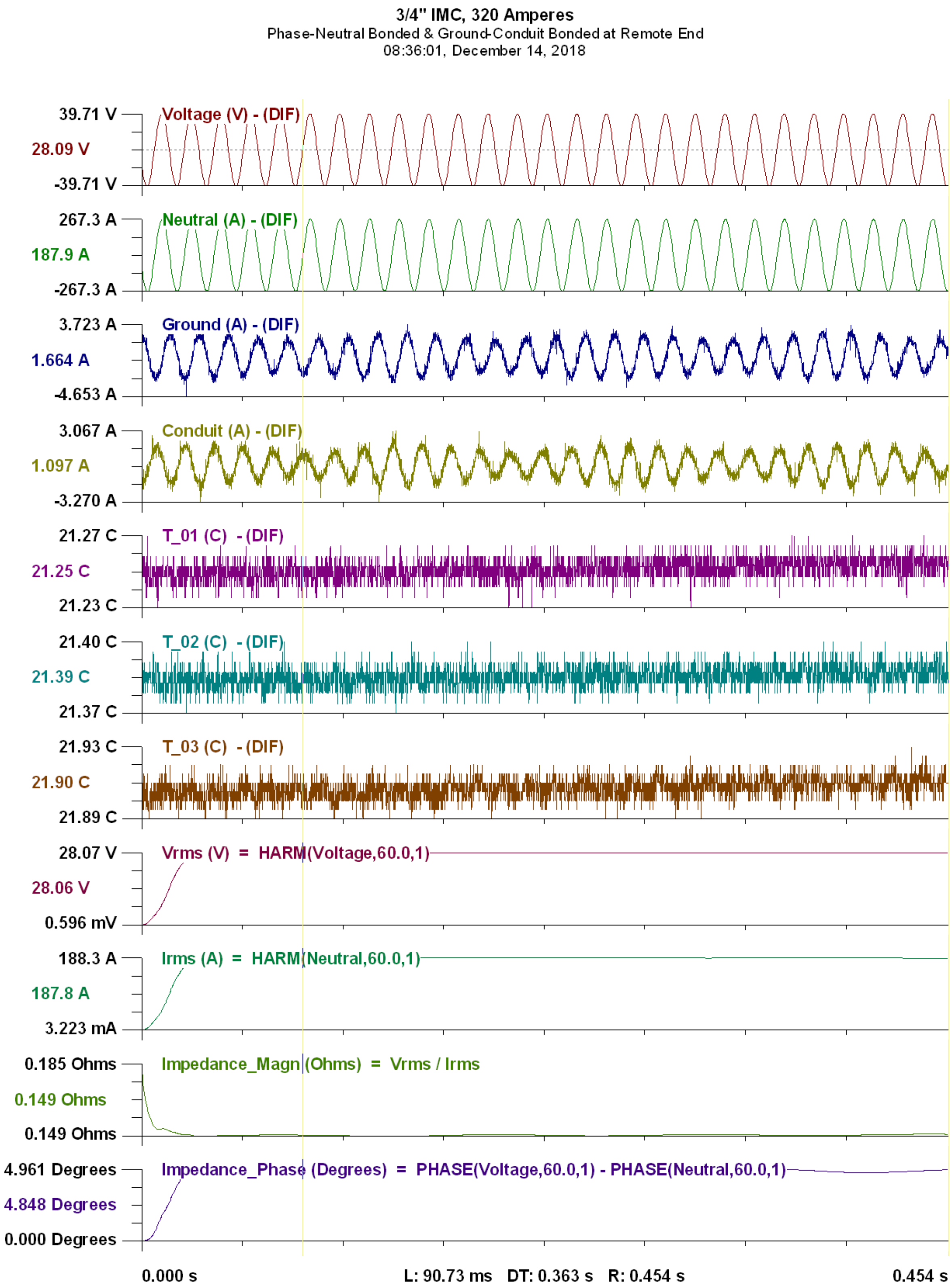


Figure N-3: Case Name IMC075_003

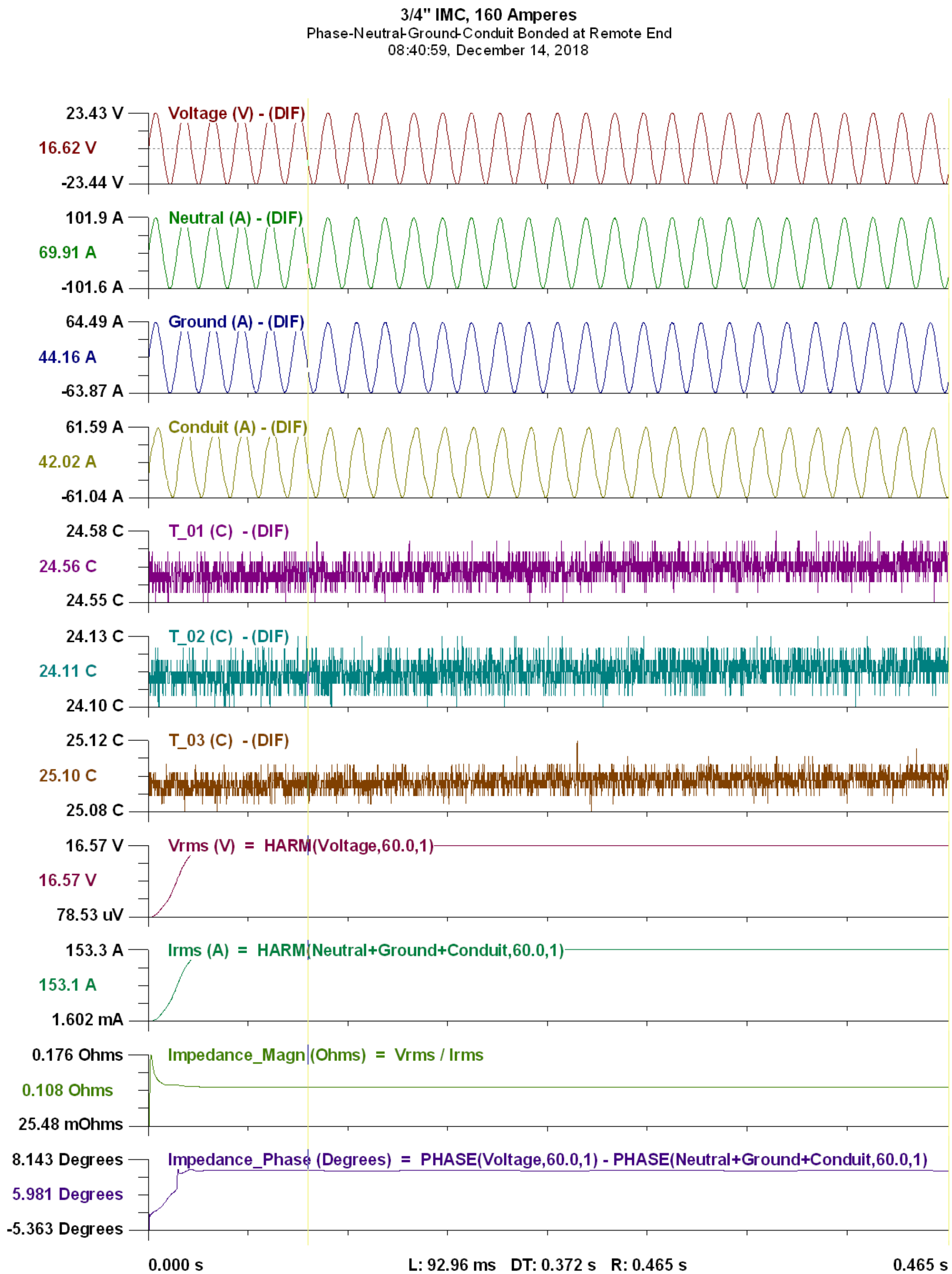


Figure N-4: Case Name IMC075_004

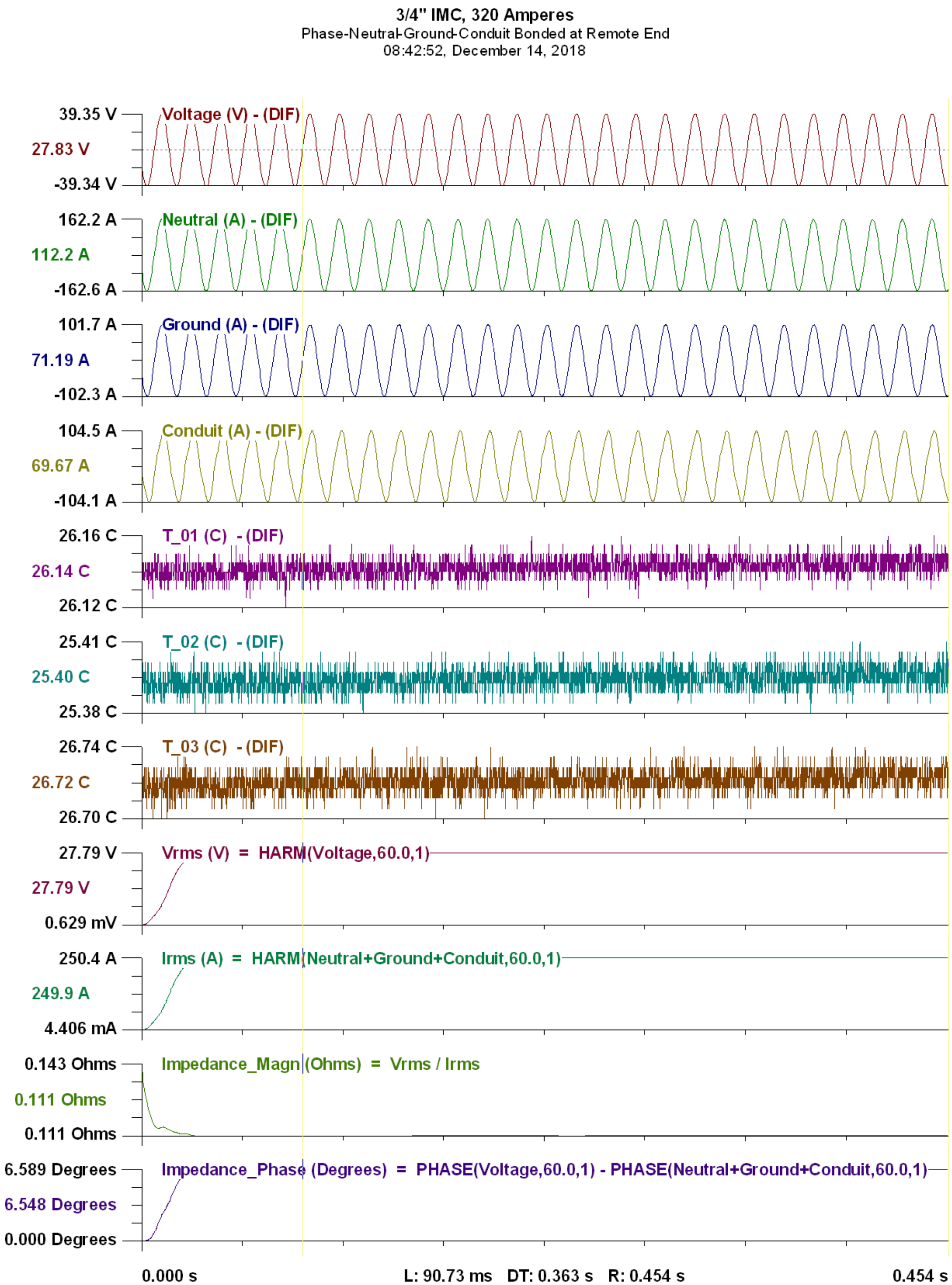


Figure N-5: Case Name IMC075_005

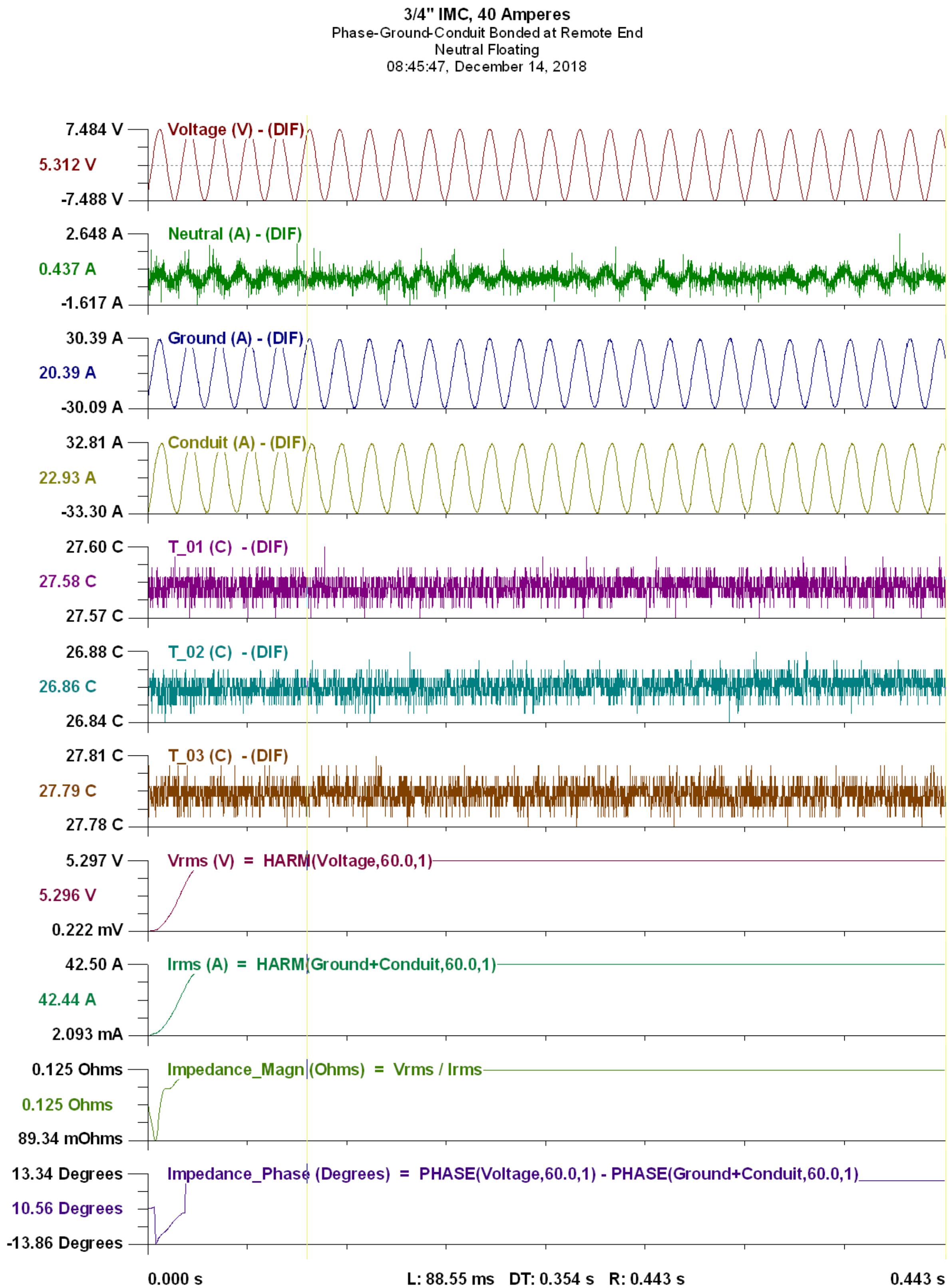


Figure N-6: Case Name IMC075_006

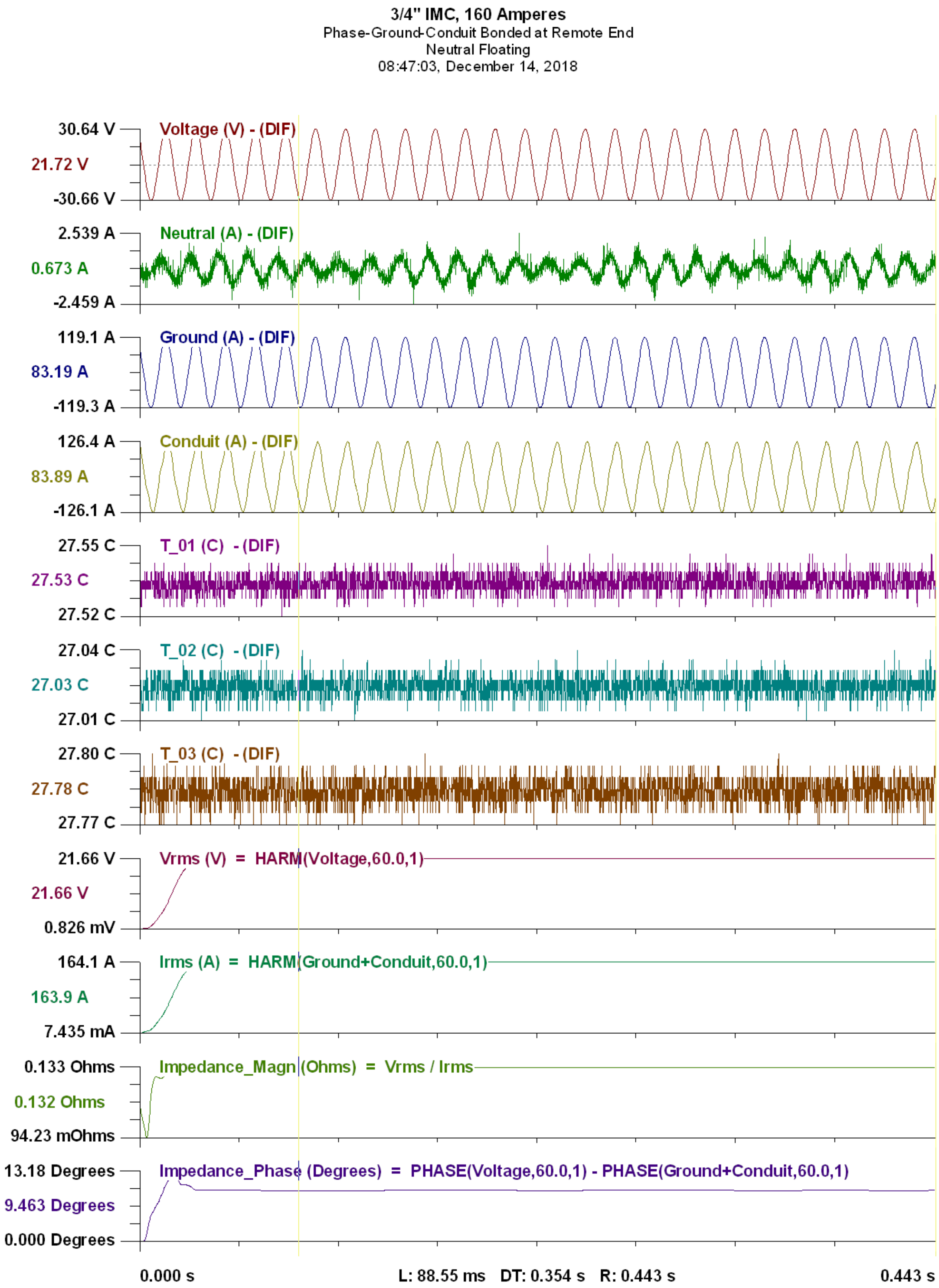


Figure N-7: Case Name IMC075_007

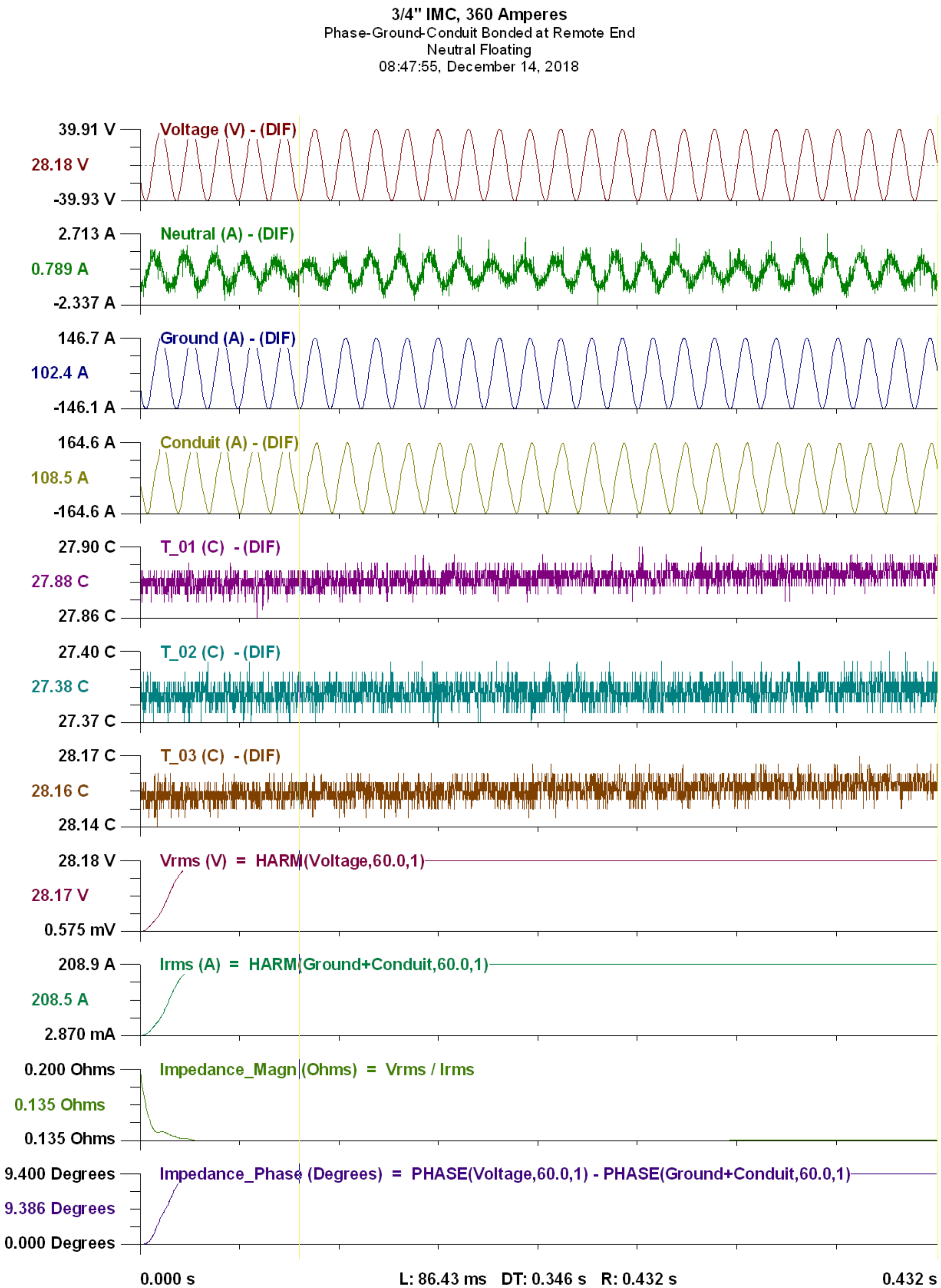


Figure N-8: Case Name IMC075_008

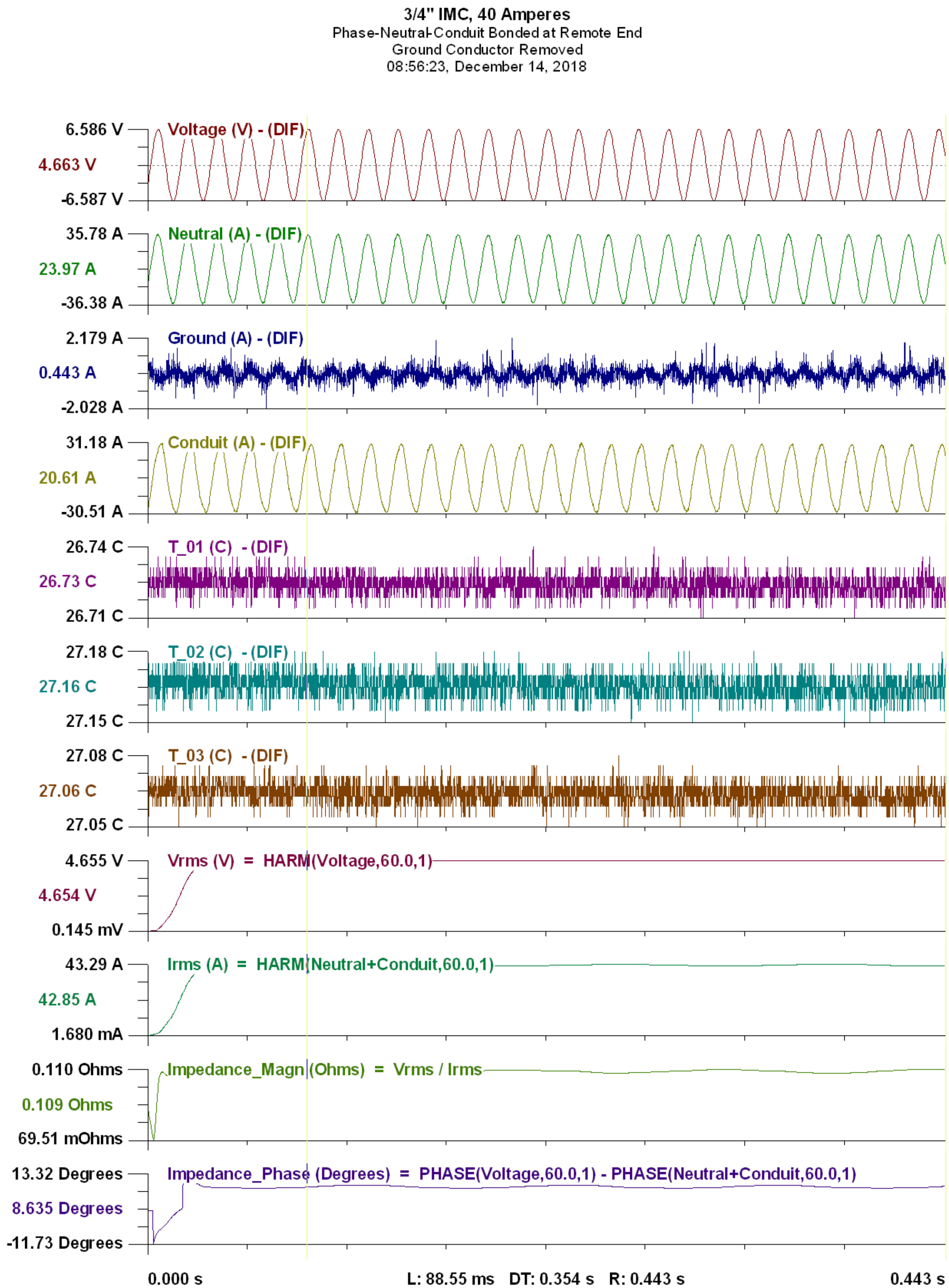


Figure N-9: Case Name IMC075_009

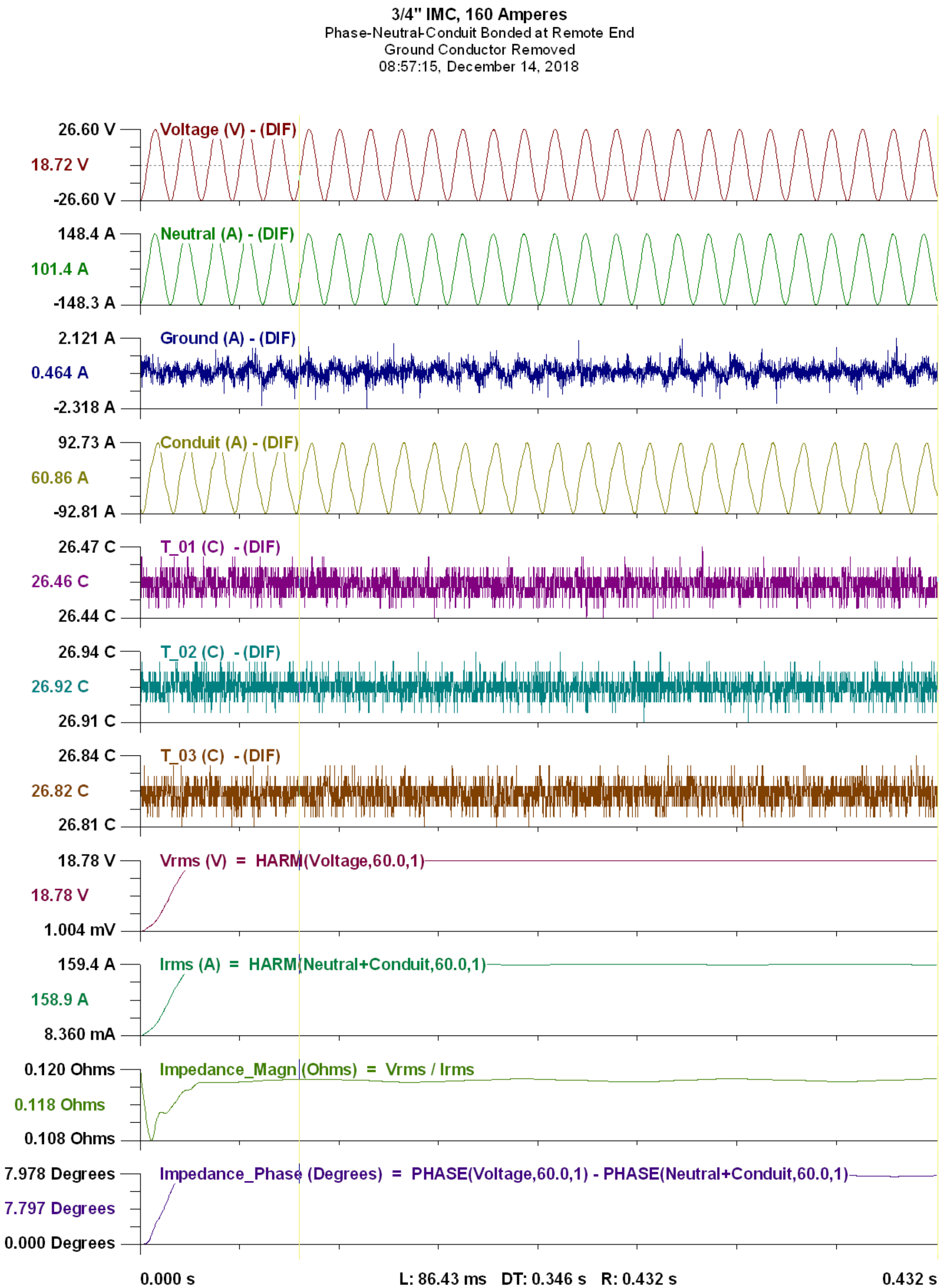


Figure N-10: Case Name IMC075_010

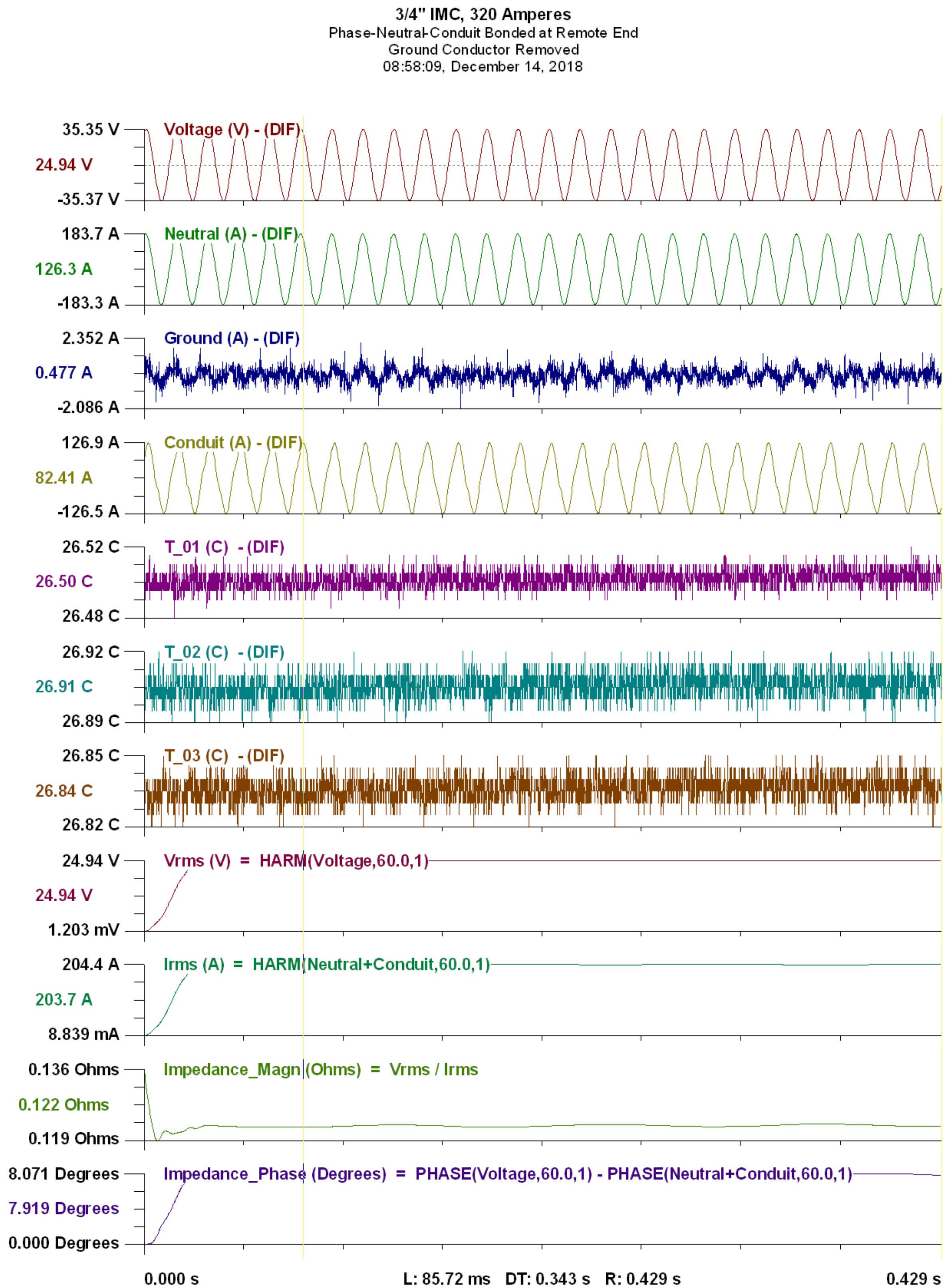


Figure N-11: Case Name IMC075_011

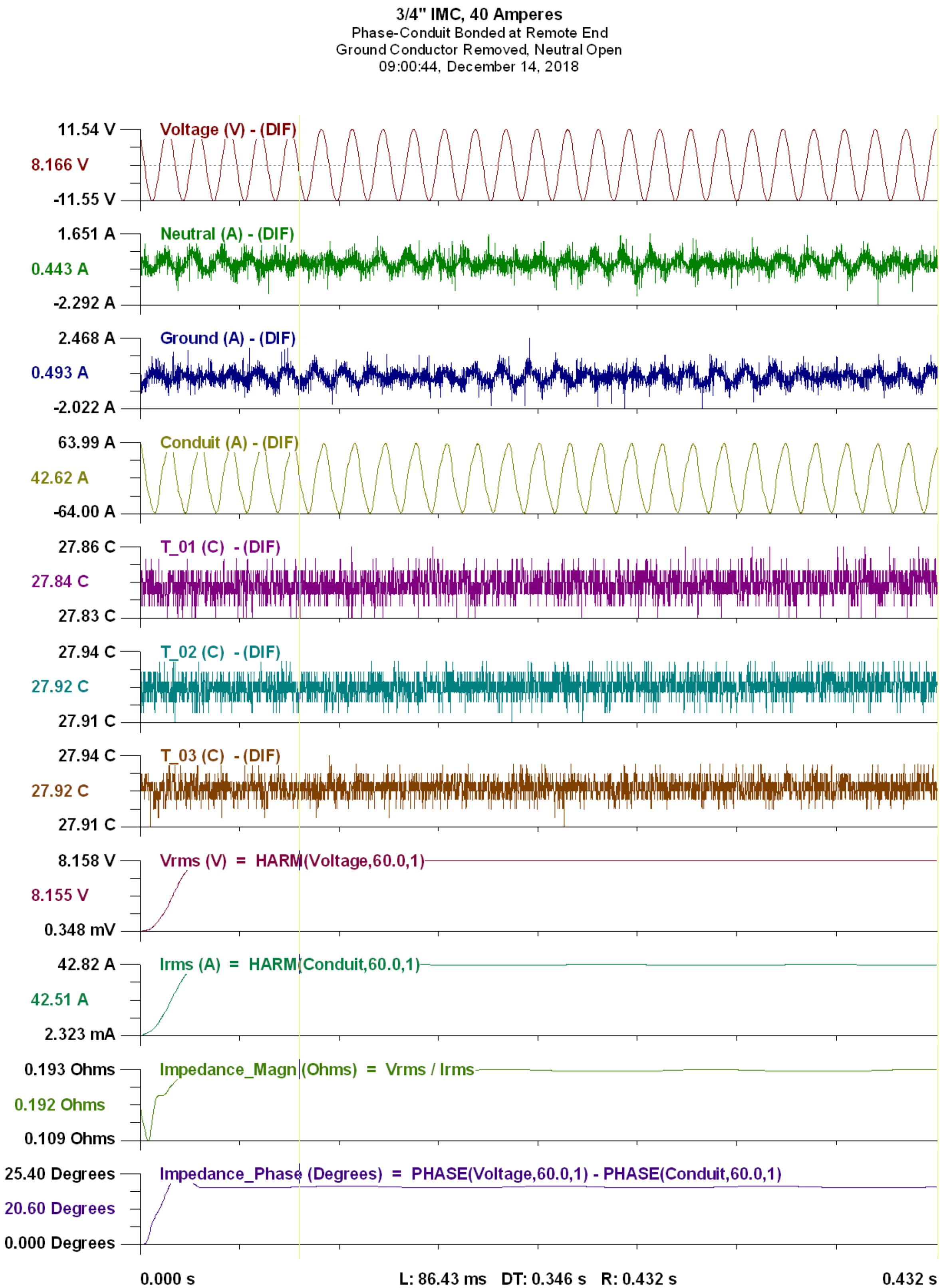


Figure N-12: Case Name IMC075_012

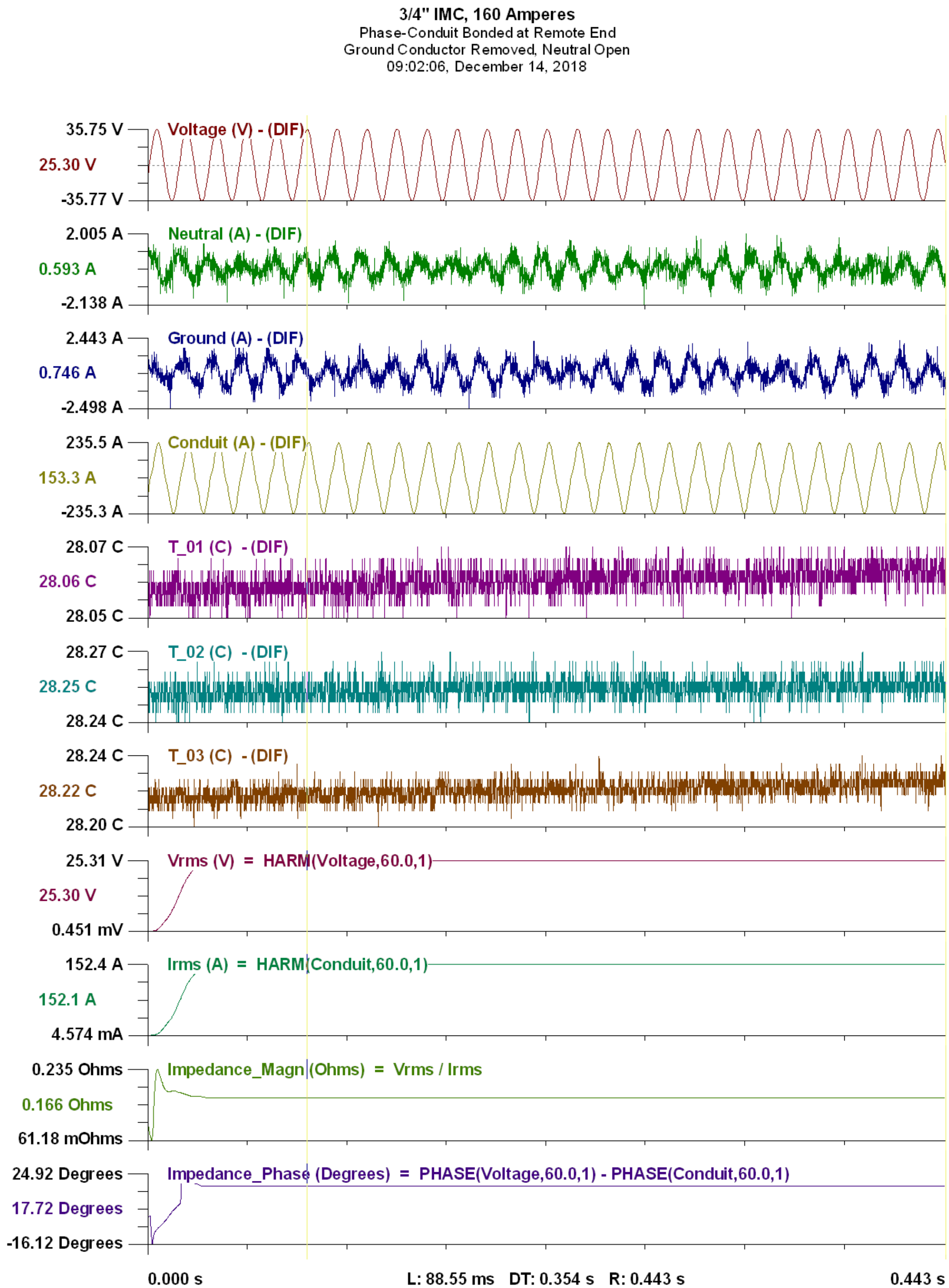


Figure N-13: Case Name IMC075_013

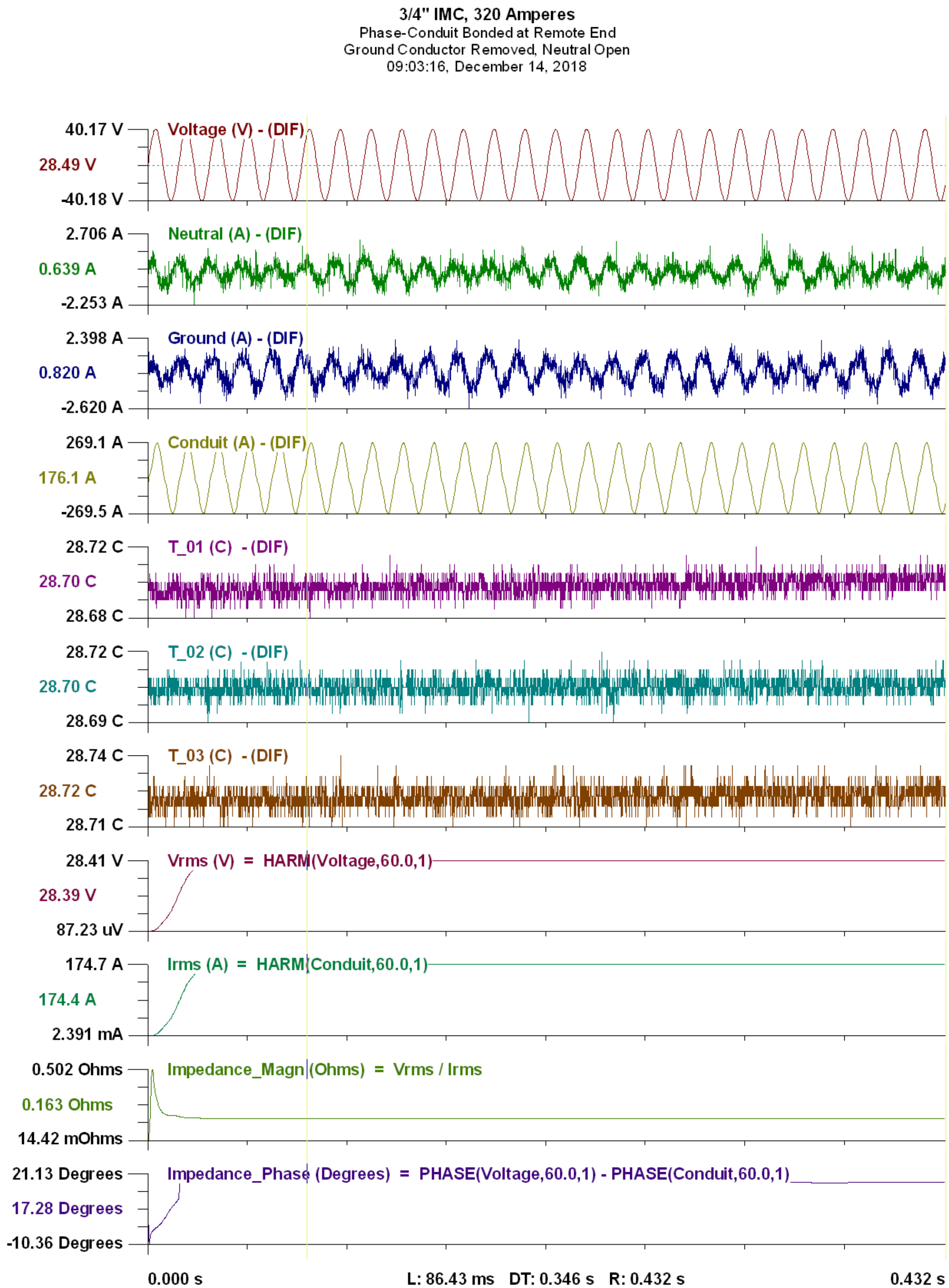


Figure N-14: Case Name IMC075_014

Appendix O – 2” Stainless-Steel Conduit Impedance Measurements (2019)

Impedance Tests on 2” Stainless-Steel conduits were repeated on December 22, 2019 since some of the stainless-steel conduit results obtained during the December 2018 tests yielded unexpectedly high impedances. The test description and results on the 2” Stainless-Steel conduit are presented in this Appendix. The 1” Stainless-Steel conduit tests are presented in the following Appendix (Appendix P).

The test setup is illustrated in Figures O-1 and O-2. Two sections of 2” conduit were connected using the provided screw-coupler. Care was taken to insure that the both conduit sections were secured tightly into the coupler to ensure good electrical connection.

Figure O-1 : Test Setup for the Stainless-Steel conduit (Overall View)

The current source consists of four 3000-Ampere current transformers with the high current secondary windings connected in series. The current transformer primary windings are in parallel and driven by a 1kVA 120 V-max Variable Transformer. The Data acquisition equipment consisted of a custom designed hardware based on the National Instruments 16 channel 16-bit DAQ (same equipment used during the 2018 tests). The data acquisition and analysis procedure are done using the WinXFM software running on a windows PC (See Figure O-2).

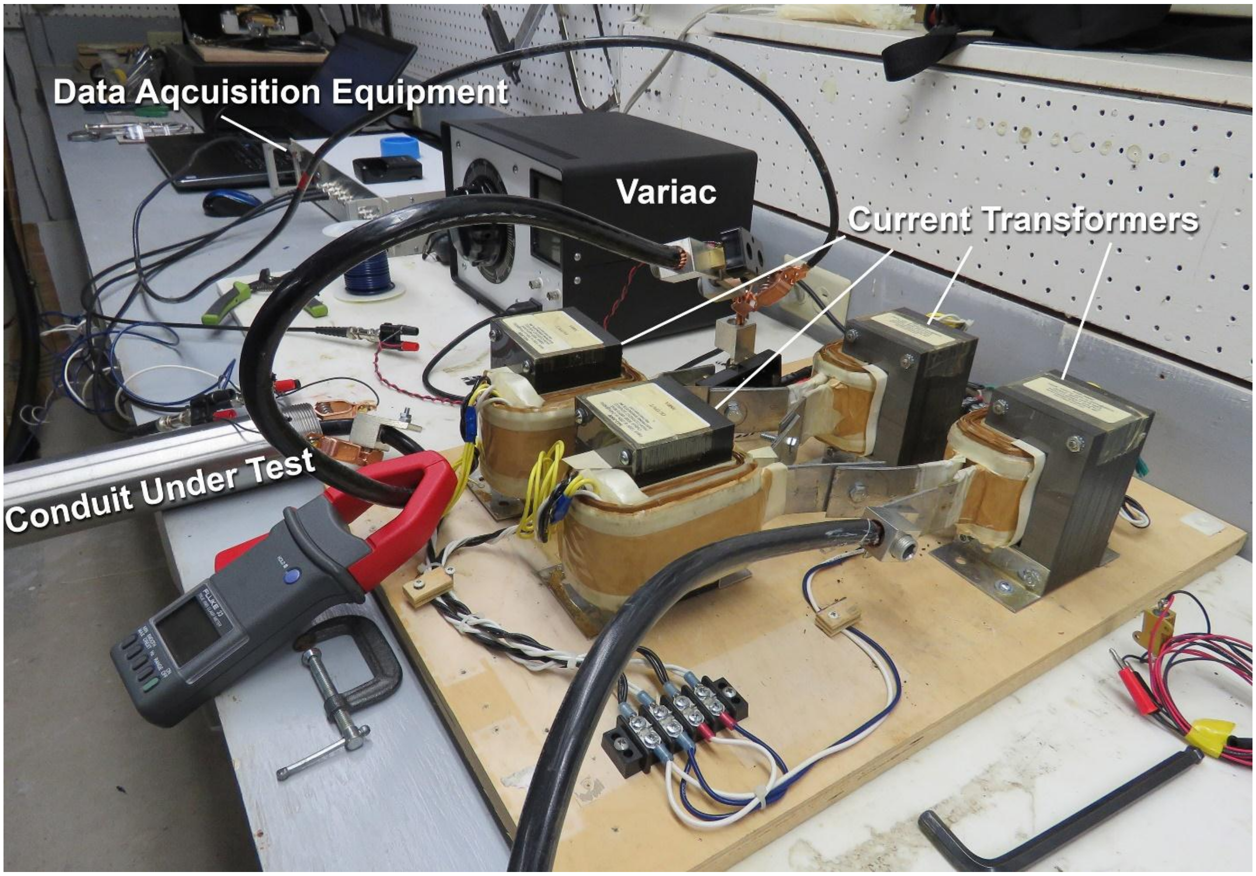
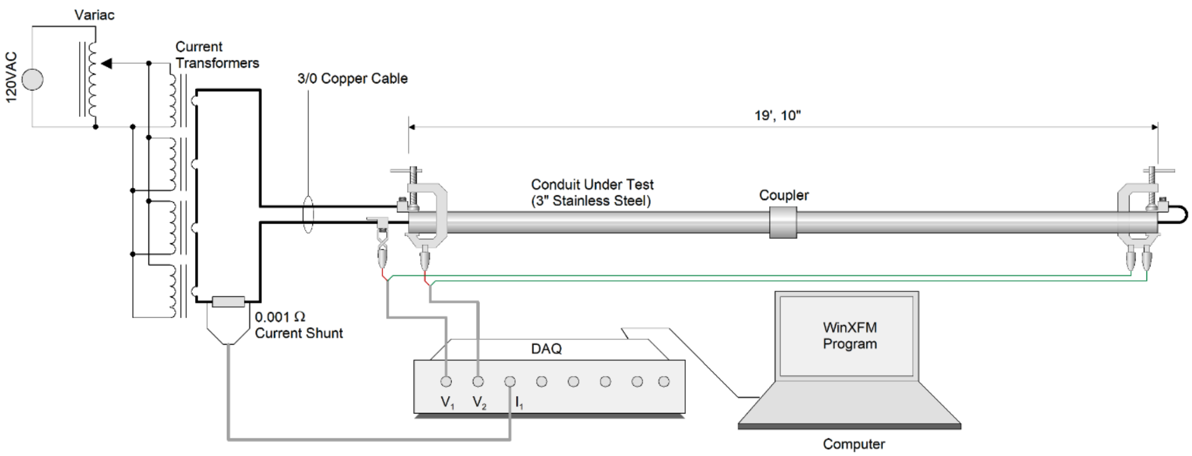


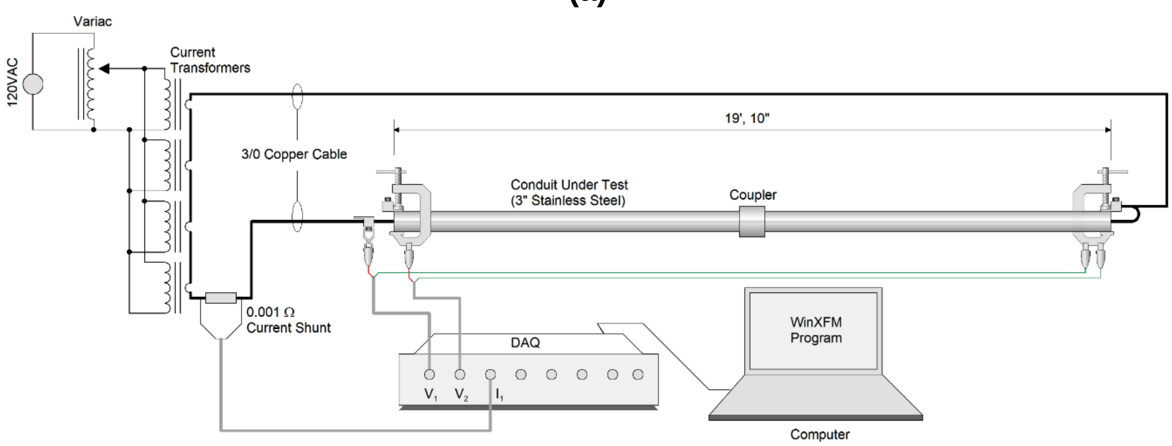
Figure O-2: Test Setup for the 2" Stainless-Steel conduit (Equipment Close-up View)

Three test configurations were used for each conduit size, which are illustrated in Figure O-3. In test configuration (a) the current flows through the conductor installed inside the conduit and returns through the conduit. This test captures the self-impedances of both conductor and conduit. In test configuration (b) the current flows through the conductor installed inside the conduit and returns through an external conductor. This test captures the mutual-impedance between conductor and conduit by measuring the voltage induced along the conduit due to the internal conductor current. In test configuration (c) the current flows through the conduit and returns through an external conductor. This test captures the mutual-impedance between conductor and conduit by measuring the voltage induced along the internal conductor due to the conduit current.

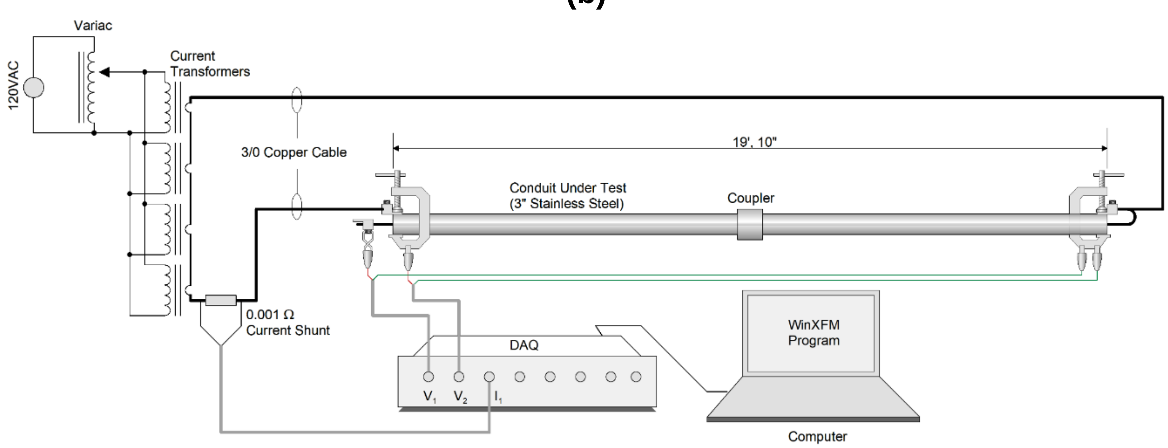
The results of the above-described tests are shown if Figures O-6 through O-8. The results are also summarized in Table O-1



(a)



(b)



(c)

Figure O-3: Test Configurations

(a) Self-Impedance Test
(b) Mutual Impedance Test 1 – Induced Voltage on Conduit
(c) Mutual Impedance Test 2 – Induced Voltage on Phase Conductor

Table O-1: 60 Hz Impedance Test Results (Two Sections)

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

Next, the impedance was measured on a single section. The conduit self-impedance results are listed in the Table below:

Table O-2: 60 Hz Impedance Test Results (One Section)

Current Amperes	Voltage Volts	Zrms milliOhms	Z60 milliOhms	Phase Degrees
66.24	0.220	3.321	3.298	1.044
95.57	0.316	3.306	3.298	1.074
128.70	0.424	3.294	3.297	0.981
162.40	0.536	3.300	3.297	1.053
193.30	0.638	3.301	3.299	0.966
229.10	0.756	3.300	3.299	1.038
261.70	0.864	3.301	3.299	1.003
292.90	0.966	3.298	3.299	1.025
324.70	1.072	3.302	3.301	1.023

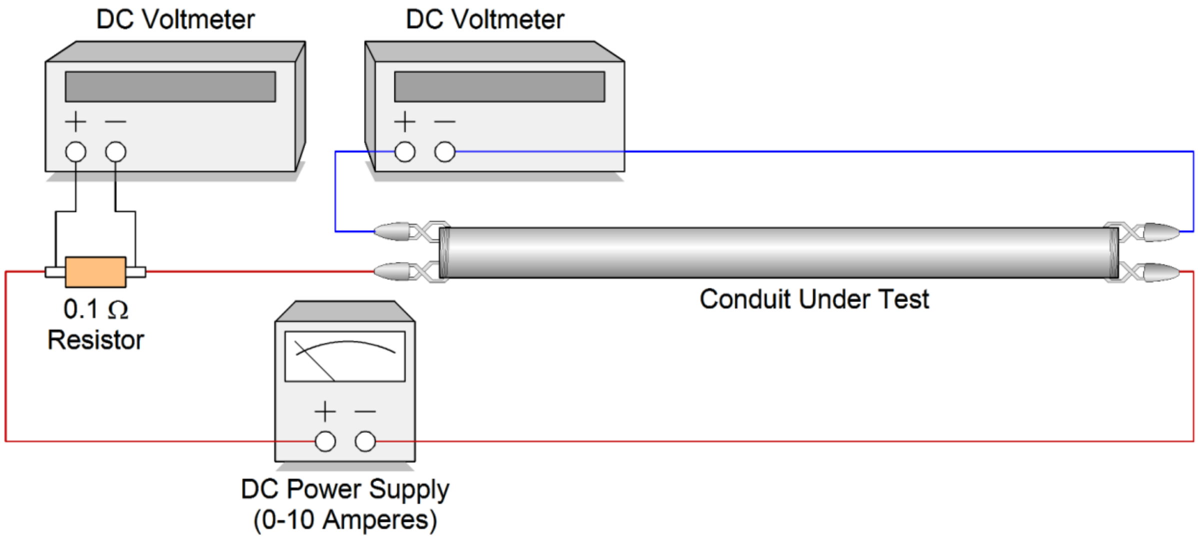
Note that these single section results are consistent with the two-section measurements over the entire range of current levels (66 to 324 Amperes).

Coupling Resistance Computation

$$Z_c = 7.159\ \text{m}\Omega\ - 2 \times 3.300\ \text{m}\Omega = 0.56\ \text{m}\Omega$$

DC Measurements

The DC resistance of 2” stainless steel conduit was measured using the arrangement illustrated in Figure O-4



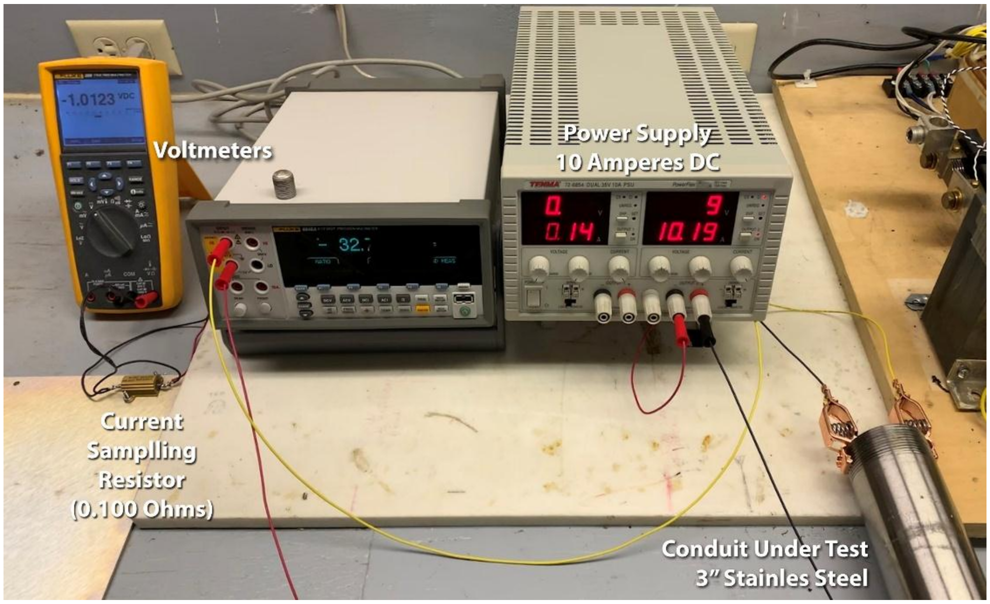


Figure O-4: DC Resistance Measurement Setup

Table O-2: 2" Stainless Steel Conduit DC Resistance Measurements

$V_{conduit}$ (milliVolts)	V_r (Volts)	Current (Amperes)	Resistance (mΩ)
32.8000	1.0126	10.1260	3.2392
16.3100	0.5042	5.0420	3.2348
-16.3200	-0.5043	-5.0430	3.2362
-32.7900	-1.0130	-10.1300	3.2369
		Average	**3.2368**
		STD	0.0018

Table O-3: DC Resistivity Computation

Outside Diameter	2.37600	inches
Inside Diameter	2.06500	inches
Wall Thickness	0.14500	inches
Computed Wall Thickness	0.15550	inches
Cross Section Area	1.08475	$inches^2$
Cross Section Area	0.00070	m^2
Length	3.048	m
Resistance per Mile	1.708	Ω/mile
Resistance	3.2368	mΩ
Conductivity	**1,345,552**	**S/m**

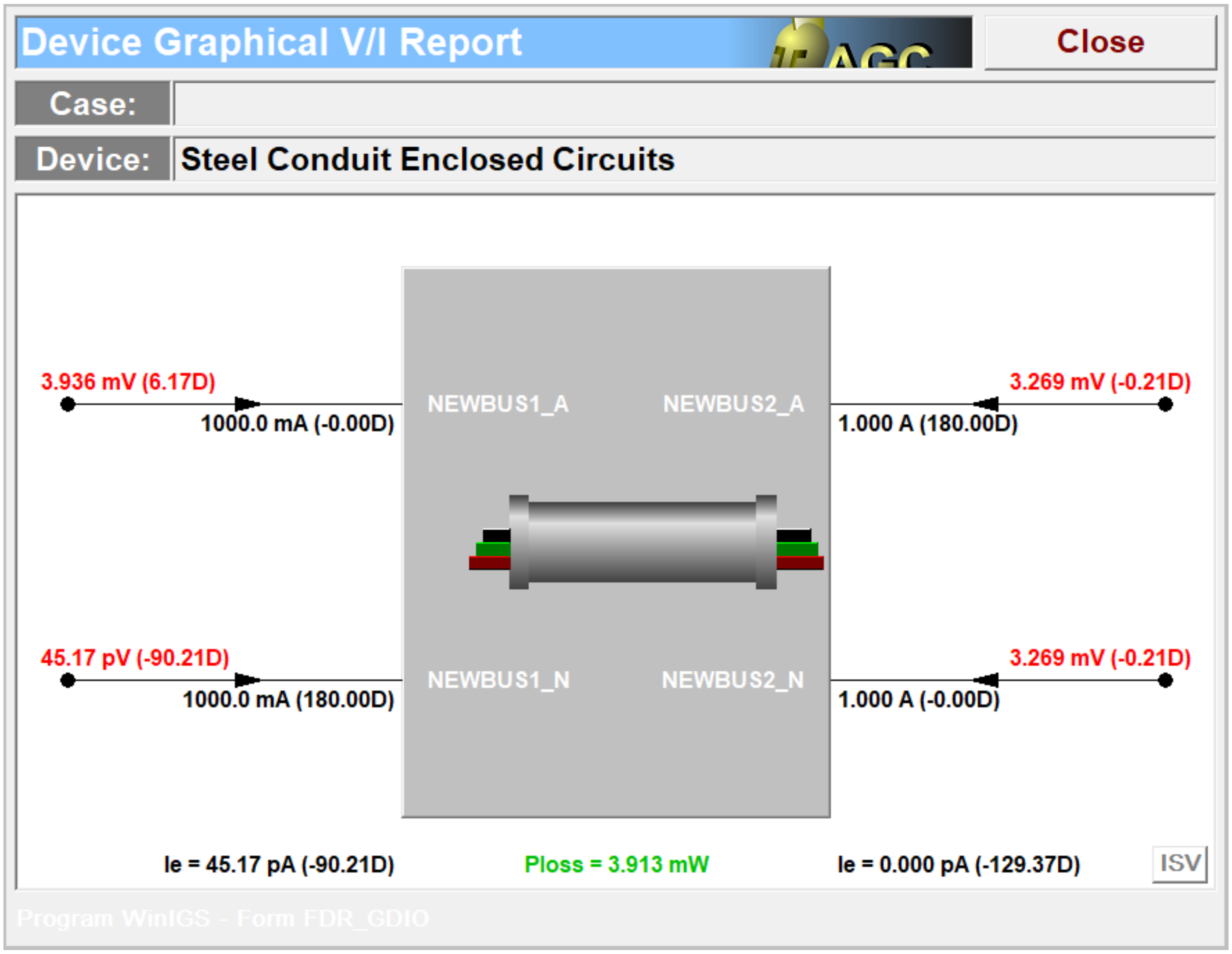


Figure O-5: WinIGS/GEMI Model Result

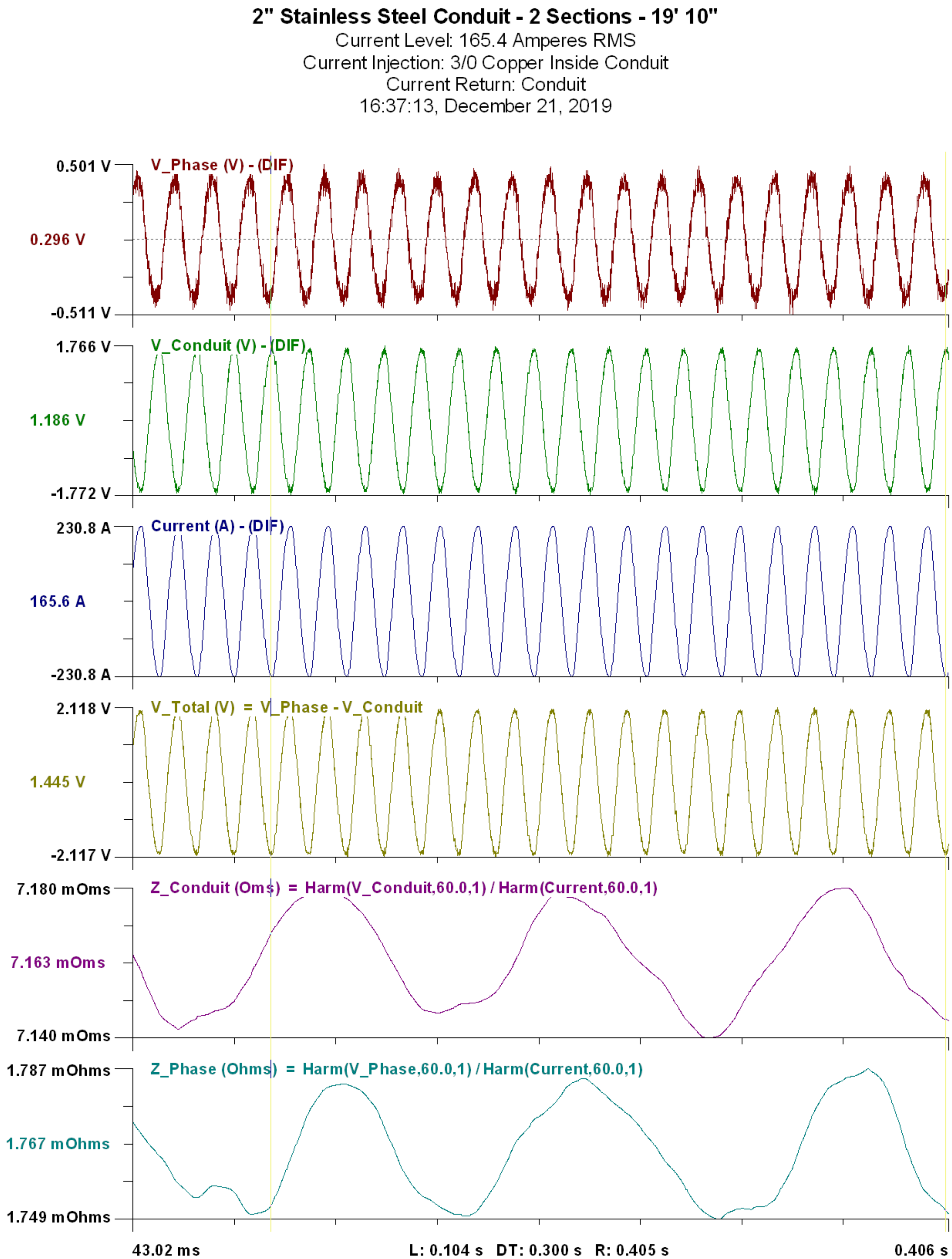


Figure O-6: Measurement Results for Test Configuration (a)

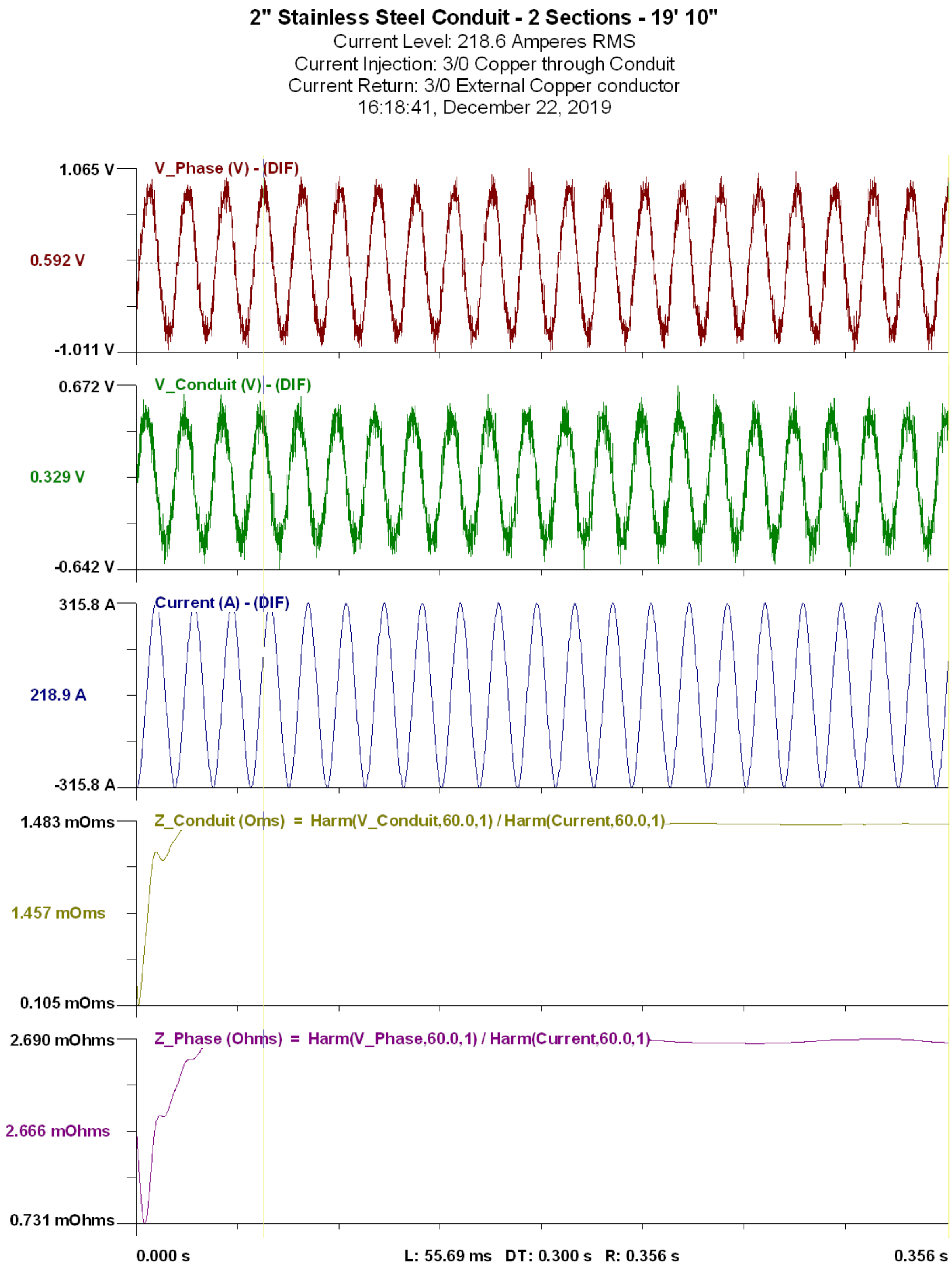


Figure O-7: Measurement Results for Test Configuration (b)

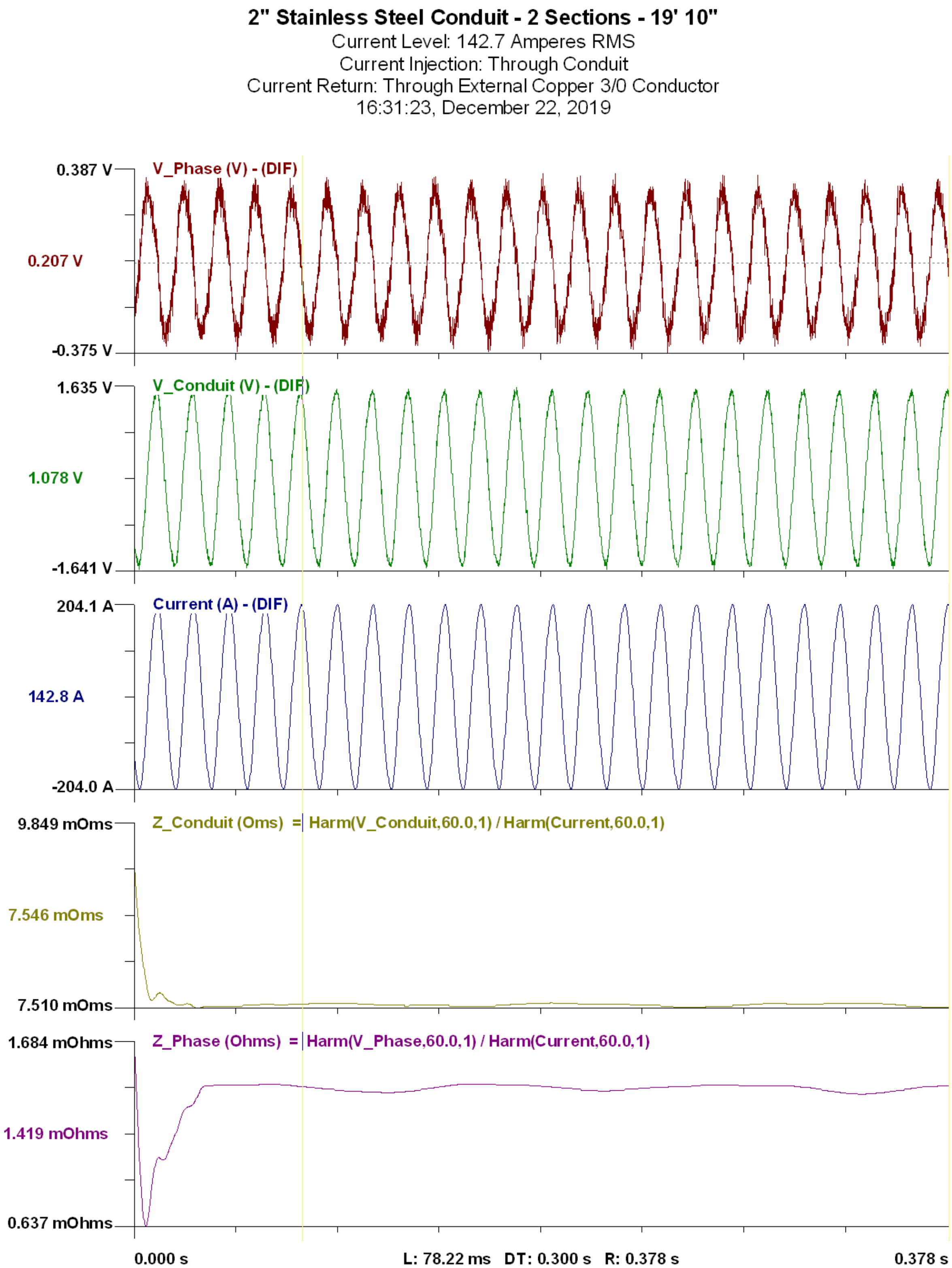


Figure O-8: Measurement Results for Test Configuration (c)

Appendix P – 1” Stainless-Steel Conduit Impedance Measurements (2019)

Impedance Tests on 1” Stainless-Steel conduits were repeated on December 22, 2019 since some of the results obtained during the December 2018 tests yielded unexpectedly high impedances. The test description and results on the 1” Stainless-Steel conduit are presented in this Appendix.

The test setup is illustrated in Figures P-1 and P-2. Two sections of 1” conduit were connected using the provided screw-coupler. Care was taken to insure that the both conduit sections were secured tightly into the coupler to ensure good electrical connection.

Figure P-1 : Test Setup for the Stainless-Steel conduit (Overall View)

The current source consists of four 3000-Ampere current transformers with the high current secondary windings connected in series. The current transformer primary windings are in parallel and driven by a 1kVA 120 V-max Variable Transformer. The Data acquisition equipment consisted of a custom designed hardware based on the National Instruments 16 channel 16-bit DAQ (same equipment used during the 2018 tests). The data acquisition and analysis procedure are done using the WinXFM software running on a windows PC (See Figure P-2).

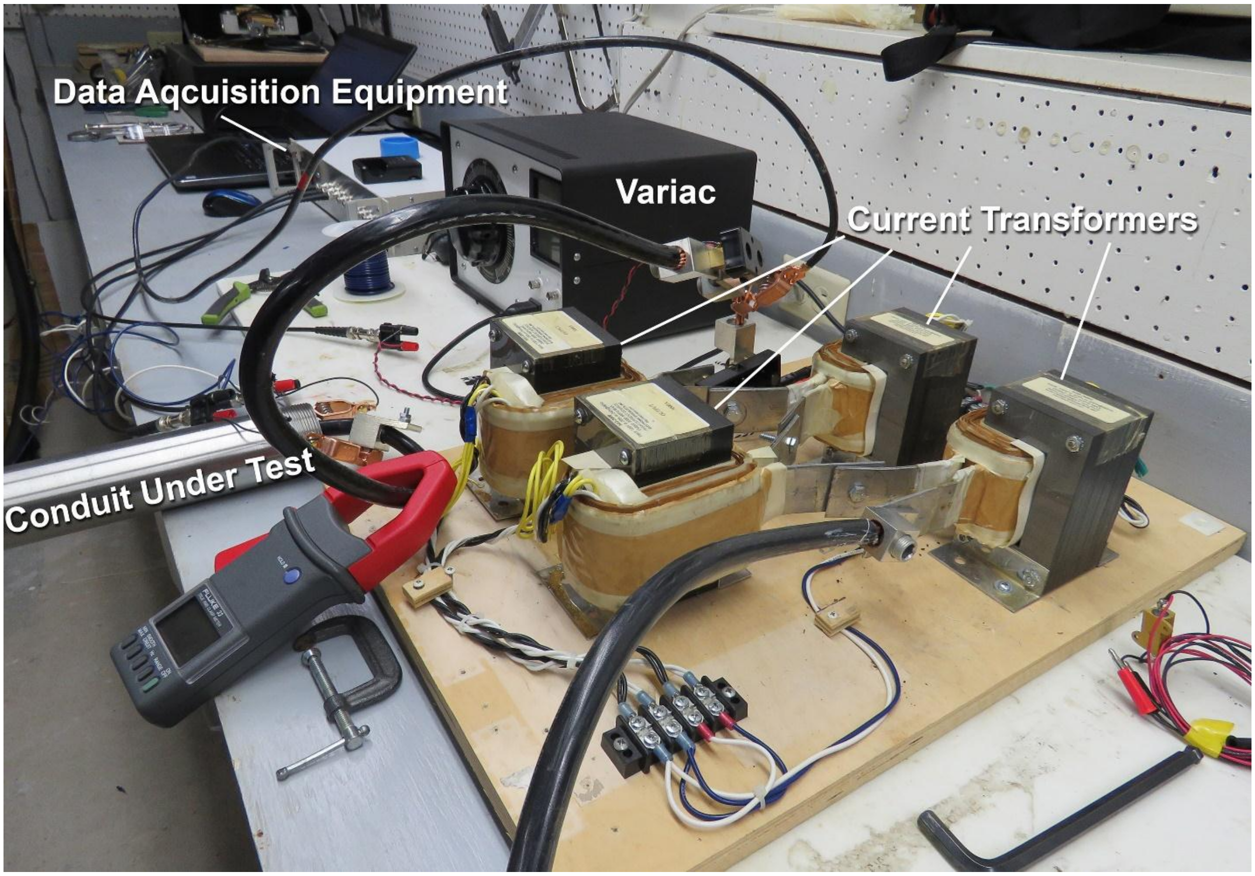
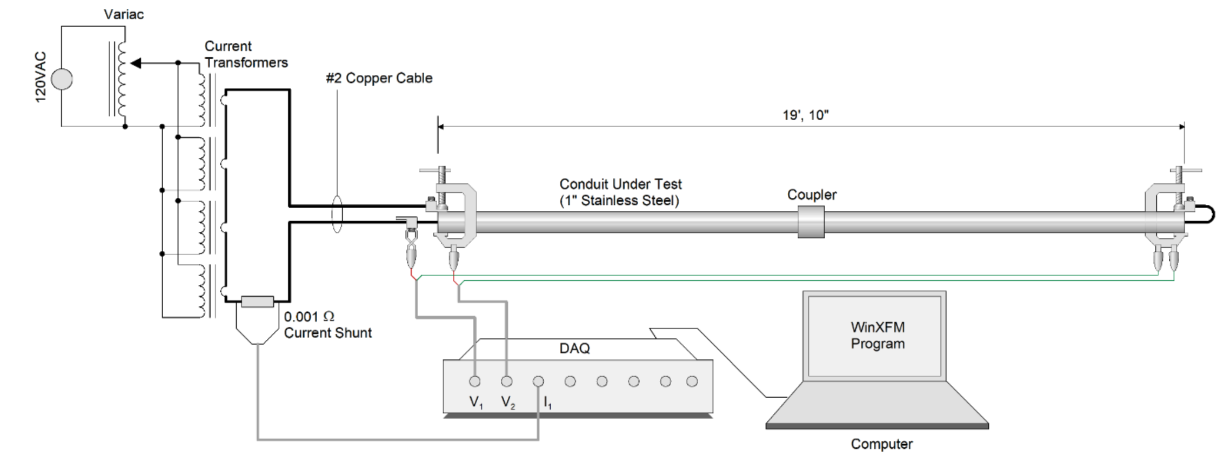


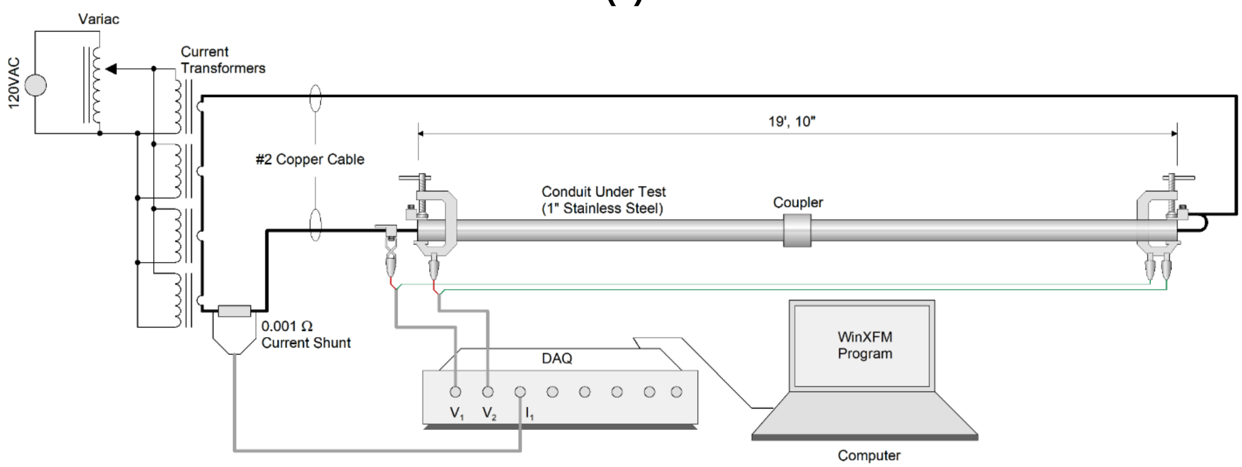
Figure P-2: Test Setup for the Stainless-Steel conduit (Equipment Close-up View)

Three test configurations were used for each conduit size, which are illustrated in Figure P-3. In test configuration (a) the current flows through the conductor installed inside the conduit and returns through the conduit. This test captures the self-impedances of both conductor and conduit. In test configuration (b) the current flows through the conductor installed inside the conduit and returns through an external conductor. This test captures the mutual-impedance between conductor and conduit by measuring the voltage induced along the conduit due to the internal conductor current. In test configuration (c) the current flows through the conduit and returns through an external conductor. This test captures the mutual-impedance between conductor and conduit by measuring the voltage induced along the internal conductor due to the conduit current.

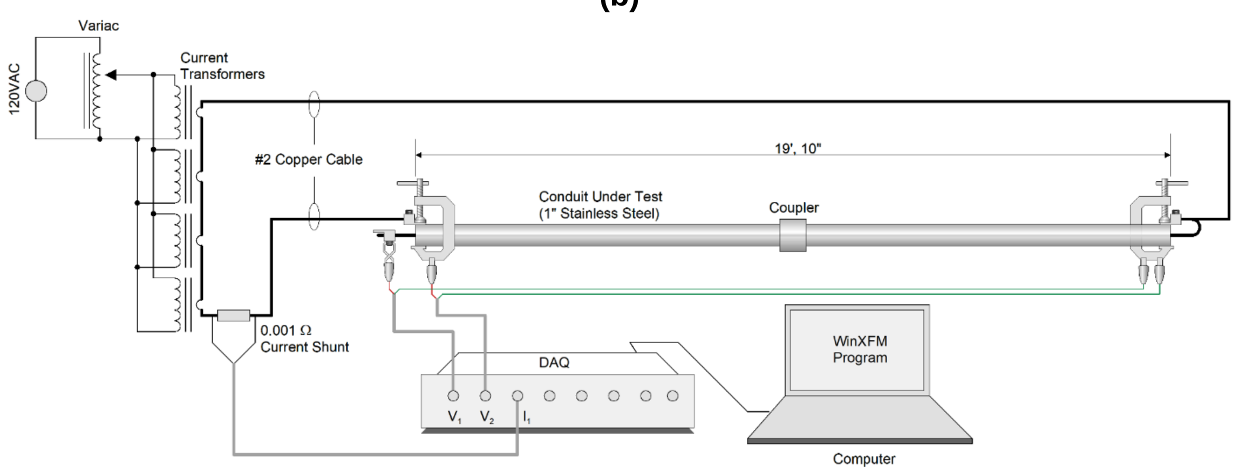
The results of the above-described tests are shown if Figures P-6 through P-8. The results are also summarized in Table P-1.



(a)



(b)



(c)

Figure P-3: Test Configurations

(a) Self-Impedance Test
(b) Mutual Impedance Test 1 – Induced Voltage on Conduit
(c) Mutual Impedance Test 2 – Induced Voltage on Phase Conductor

Table P-1: 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

The above result is close to the December 2018 test result. Specifically the total loop impedance (phase conductor + conduit) in the new result is

$$Z = 1.670 \text{ V} / 64.82 \text{ A} = 25.76 \text{ m}\Omega$$

The above result was for 20’ length of conduits, thus for 100’ length the total impedance will be:

$$25.76 \times 5 = \mathbf{128.8\ m\Omega}$$

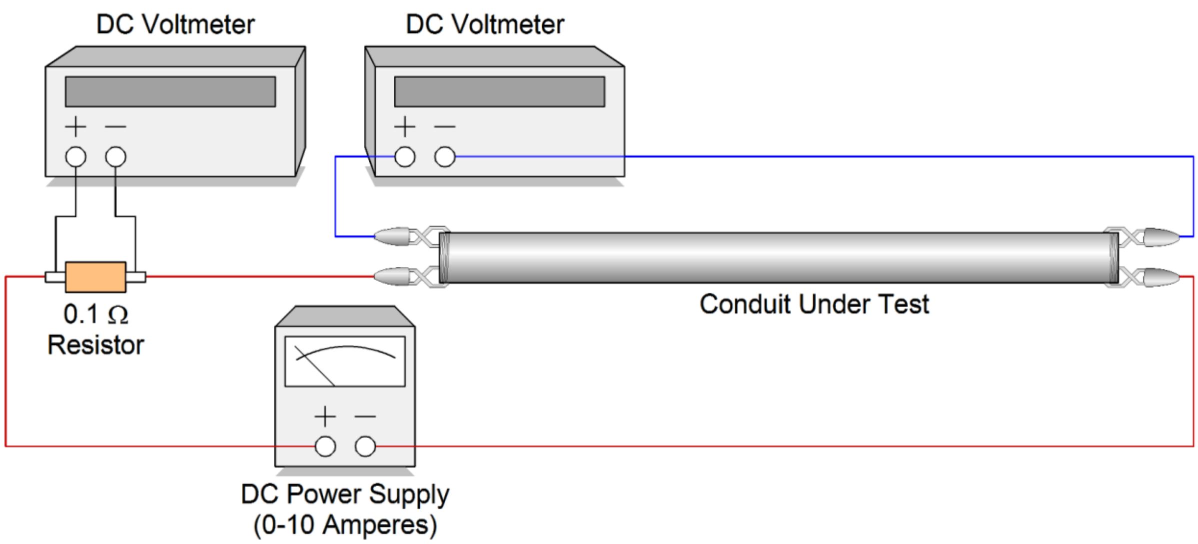
The values measured during the 2018 tests were from **123 to 146 mΩ.**

Coupling Resistance Computation

$$Z_c = 22.53 \text{ m}\Omega - 2 \times 10.6342 \text{ m}\Omega = \mathbf{1.262\ m\Omega}$$

DC Measurements

The DC resistance of 1” stainless steel conduit was measured using the arrangement illustrated in Figure P-4



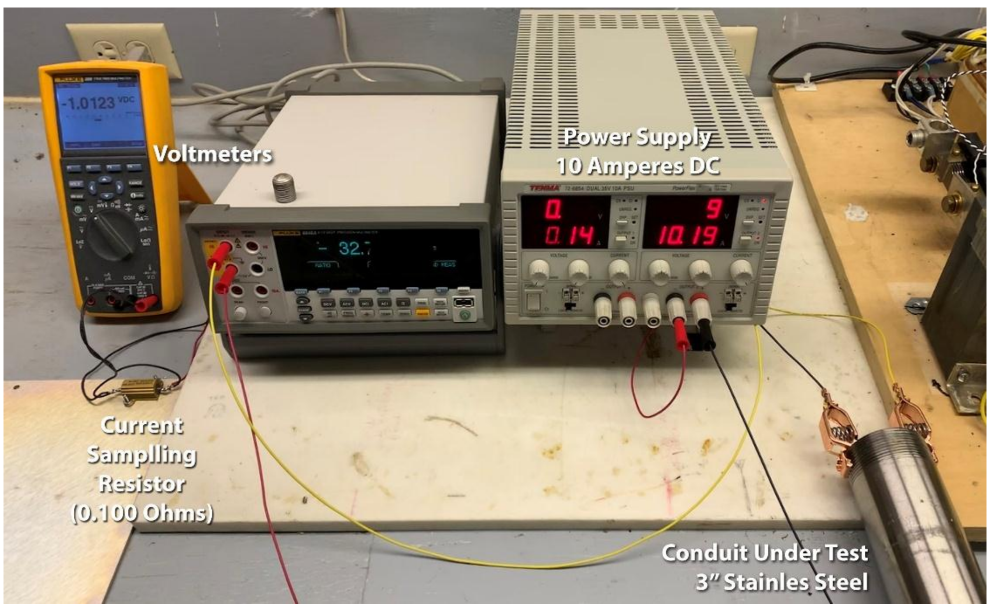


Figure P-4: DC Resistance Measurement Setup

Table P-2: 1" Stainless Steel Conduit DC Resistance Measurements

$V_{conduit}$ (milliVolts)	V_r (Volts)	Current (Amperes)	Resistance (mΩ)
107.65	1.0122	10.122	10.6352
-107.65	-1.0124	-10.124	10.6331
		Average	**10.6342**

Table P-3: DC Resistivity Computation

Outside Diameter	1.06000	inches
Inside Diameter	0.82850	inches
Wall Thickness	0.11000	inches
Computed Wall Thickness	0.11575	inches
Cross Section Area	0.34337	$inches^2$
Cross Section Area	0.00022	m^2
Length	3.048	m
Resistance	10.6342	mΩ
Resistance per mile	5.613	Ω/mi
Conductivity	**1,293,853**	**S/m**

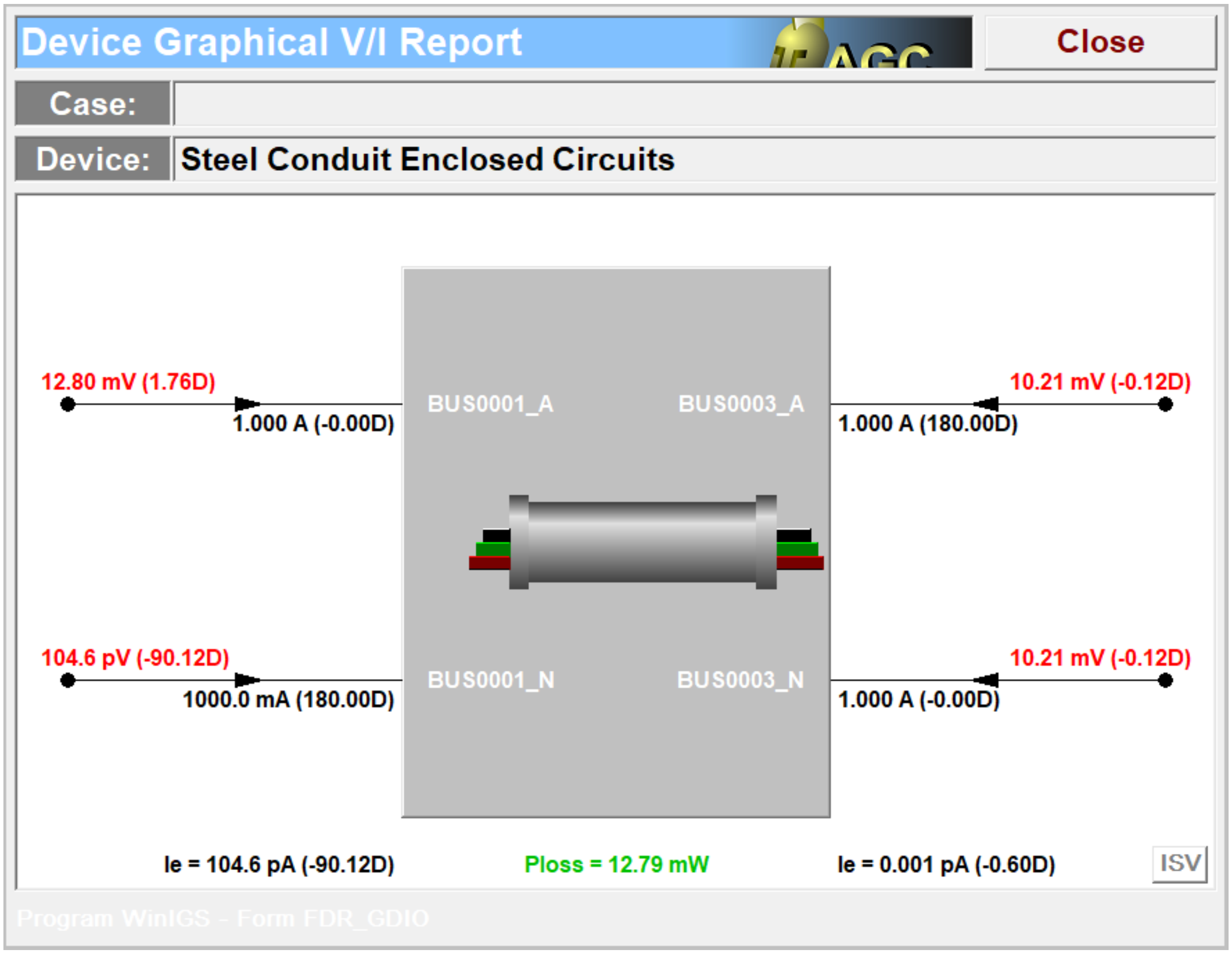


Figure P-4: WinIGS/GEMI Simulation Result

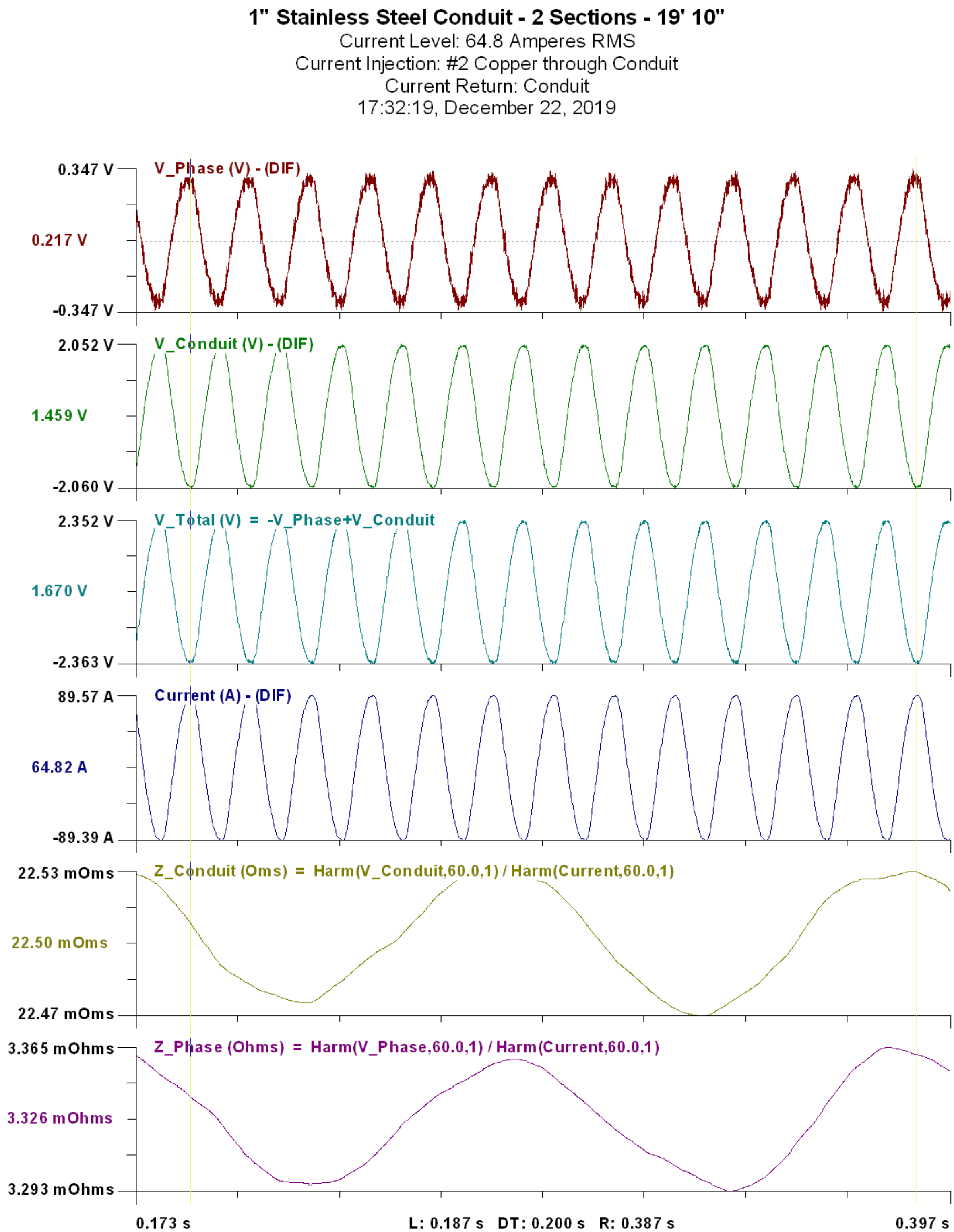


Figure P-6: Measurement Results for Test Configuration (a)

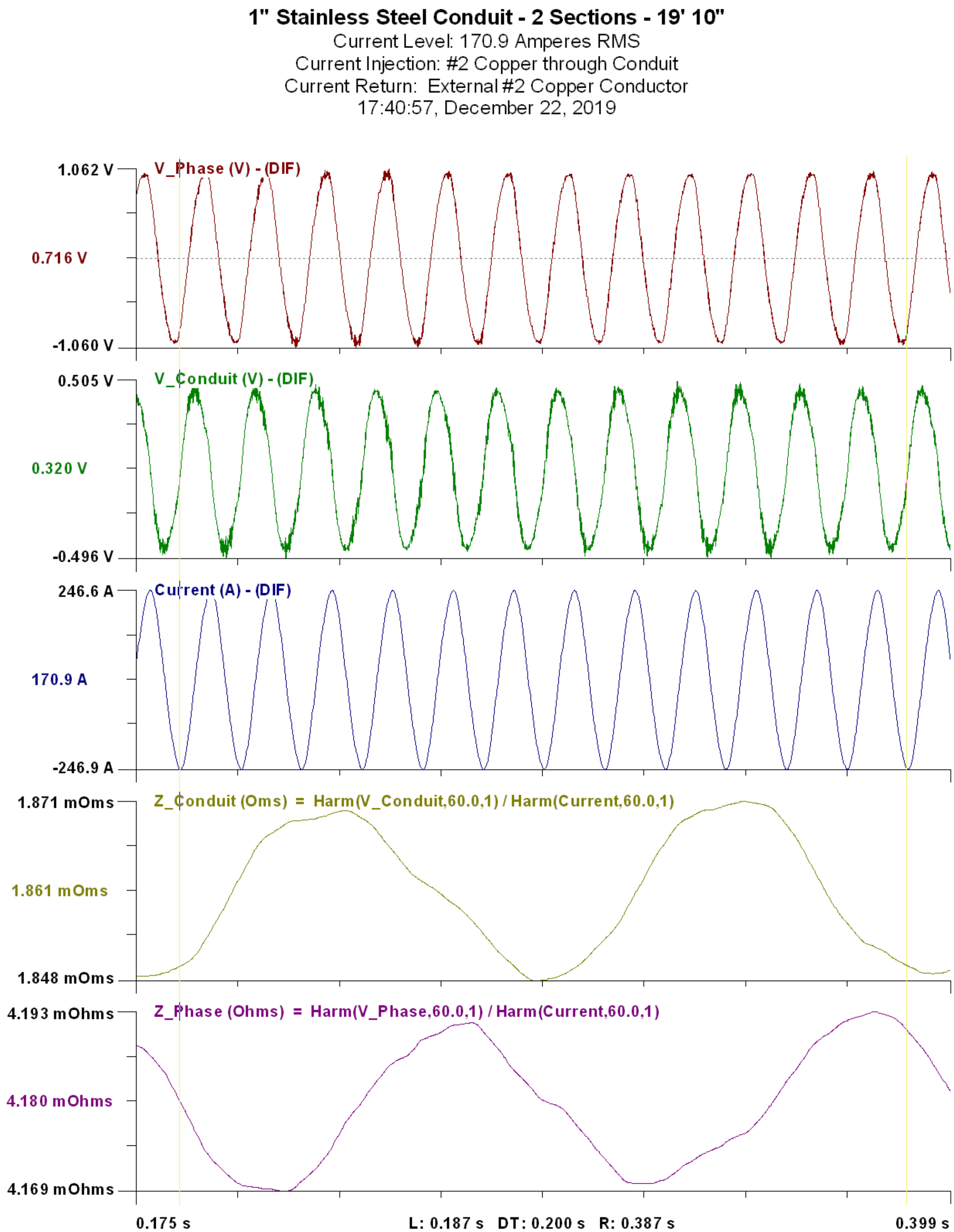


Figure P-7: Measurement Results for Test Configuration (b)

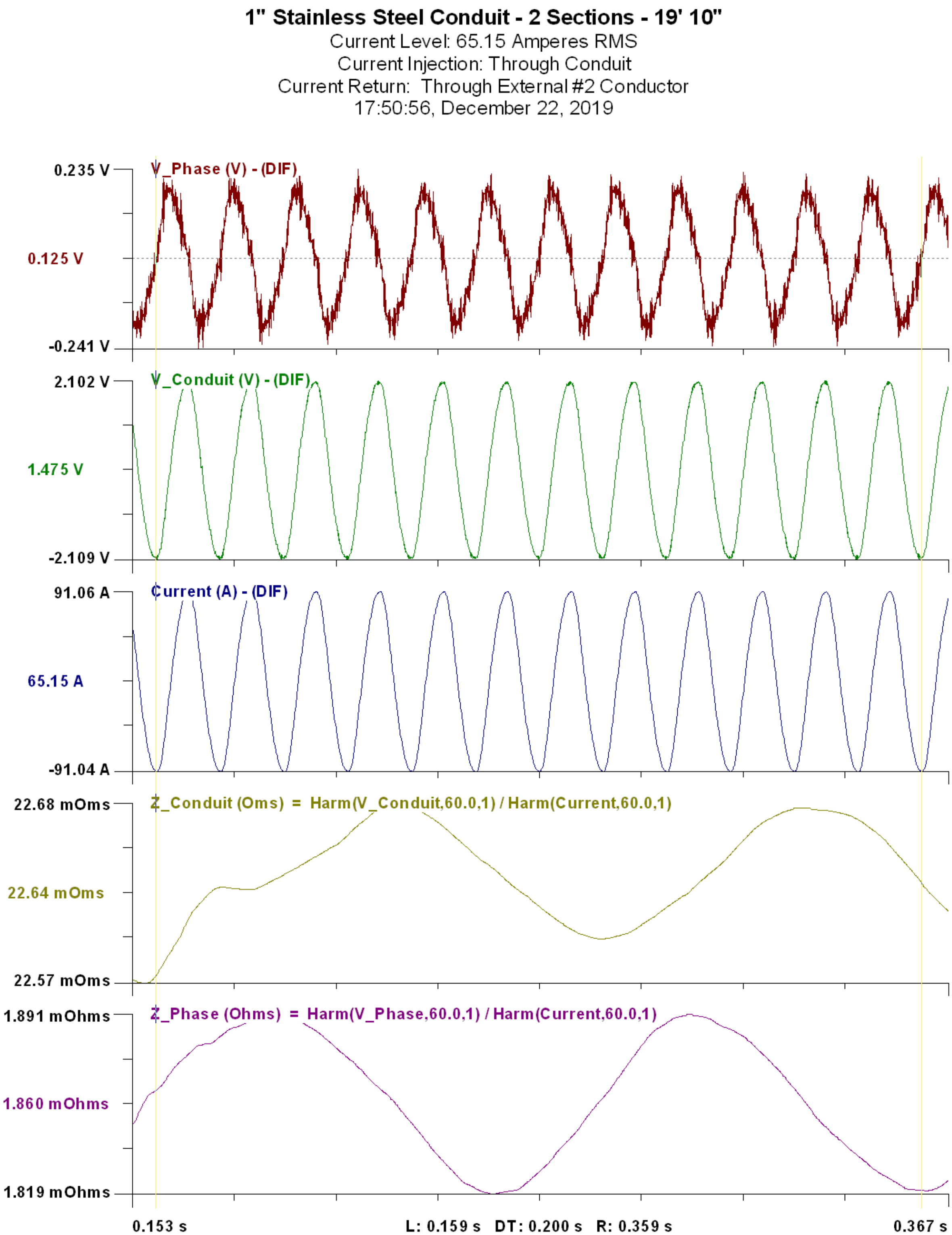


Figure P-8: Measurement Results for Test Configuration (c)

Appendix Q – SGM Tests

The impedance of EMT, IMC, GRC and Stainless Steel conduits wat measured at low excitation current (4 Amperes) using the Smart Ground Multimeter. The results are summarized in Table Q-1. Detailed measurement data are given in Figures Q-2 through Q-20.

Table Q-1: Conduit Impedance Test Result Summary (Resistance and Impedance at 60 Hz)

Case #	Test Description	Resistance (mΩ)	Impedance @ 60 Hz (mΩ)
1	EMT 3/4 Conduit Test, High Current	43.88	48.33
2	EMT 3/4 Conduit Test	43.63	48.01
3	EMT 3/4 Conduit Test	71.78	90.18
4	EMT 3/4 Conduit Test	31.59	36.27
5	EMT 3/4 Conduit Test	29.40	50.49
6	EMT 3/4 Conduit Test	16.20	21.71
7	EMT 3/4 Conduit Test	9.030	33.62
8	EMT 3/4 Conduit Test	7.794	16.23
9	EMT 3/4 Conduit Test	8.934	16.07
10	EMT 3/4 Conduit Test	4.803	26.96
11	1" Stainless Steel Conduit	587.5	587.6
12	3" Stainless Steel Conduit	22.94	25.10
13	3/4" IMC Conduit	29.84	39.38
14	1" IMC Conduit	27.86	35.31
15	2" IMC Conduit	12.99	24.59
16	3" IMC Conduit	7.608	17.52
17	3/4" GRC Conduit	43.74	61.38
18	1" GRC Conduit	73.62	79.91
19	2" GRC Conduit	12.44	24.34
20	3" GRC Conduit	10.92	20.47

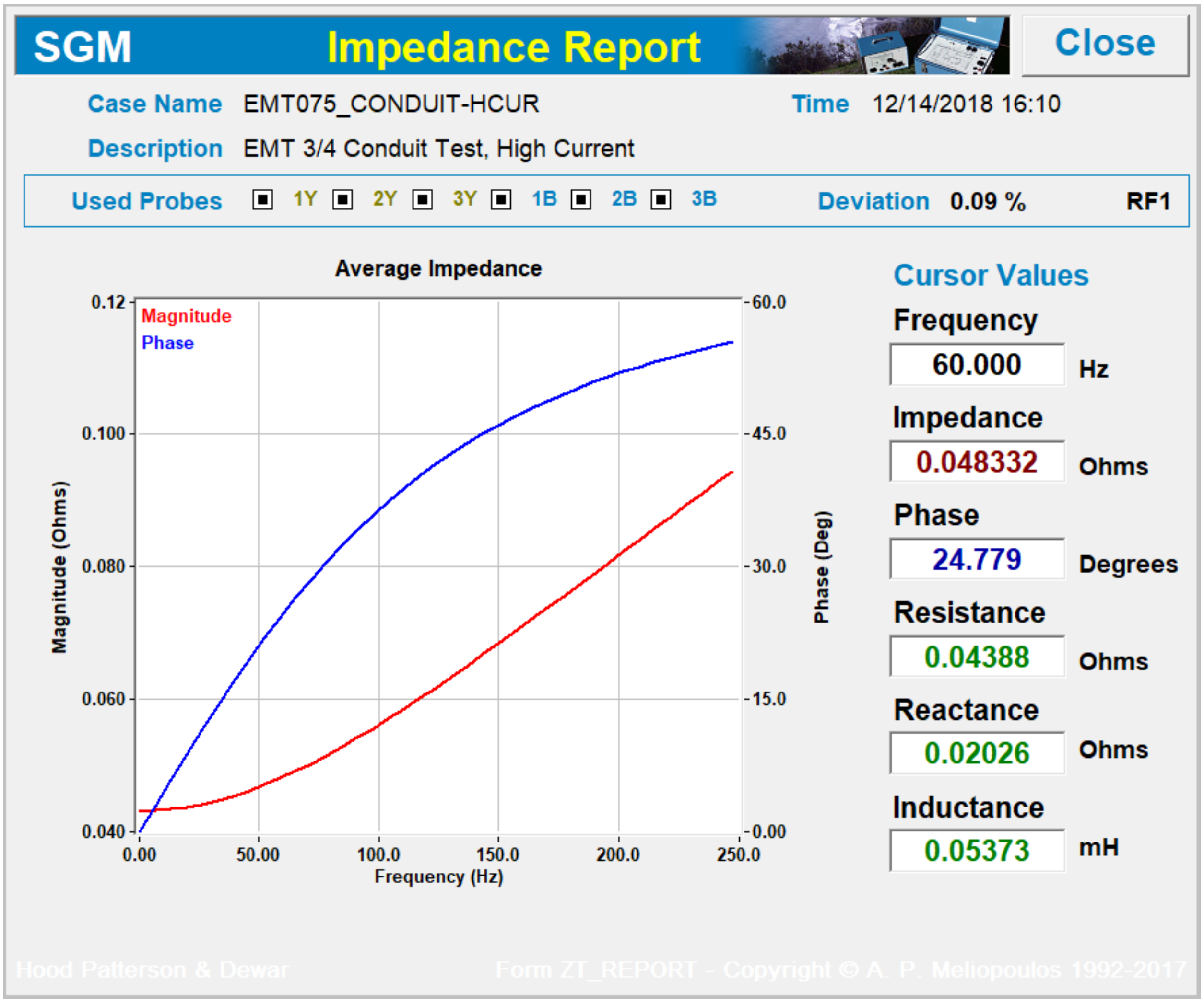


Figure Q-1: EMT 3/4 Conduit Test, High Current

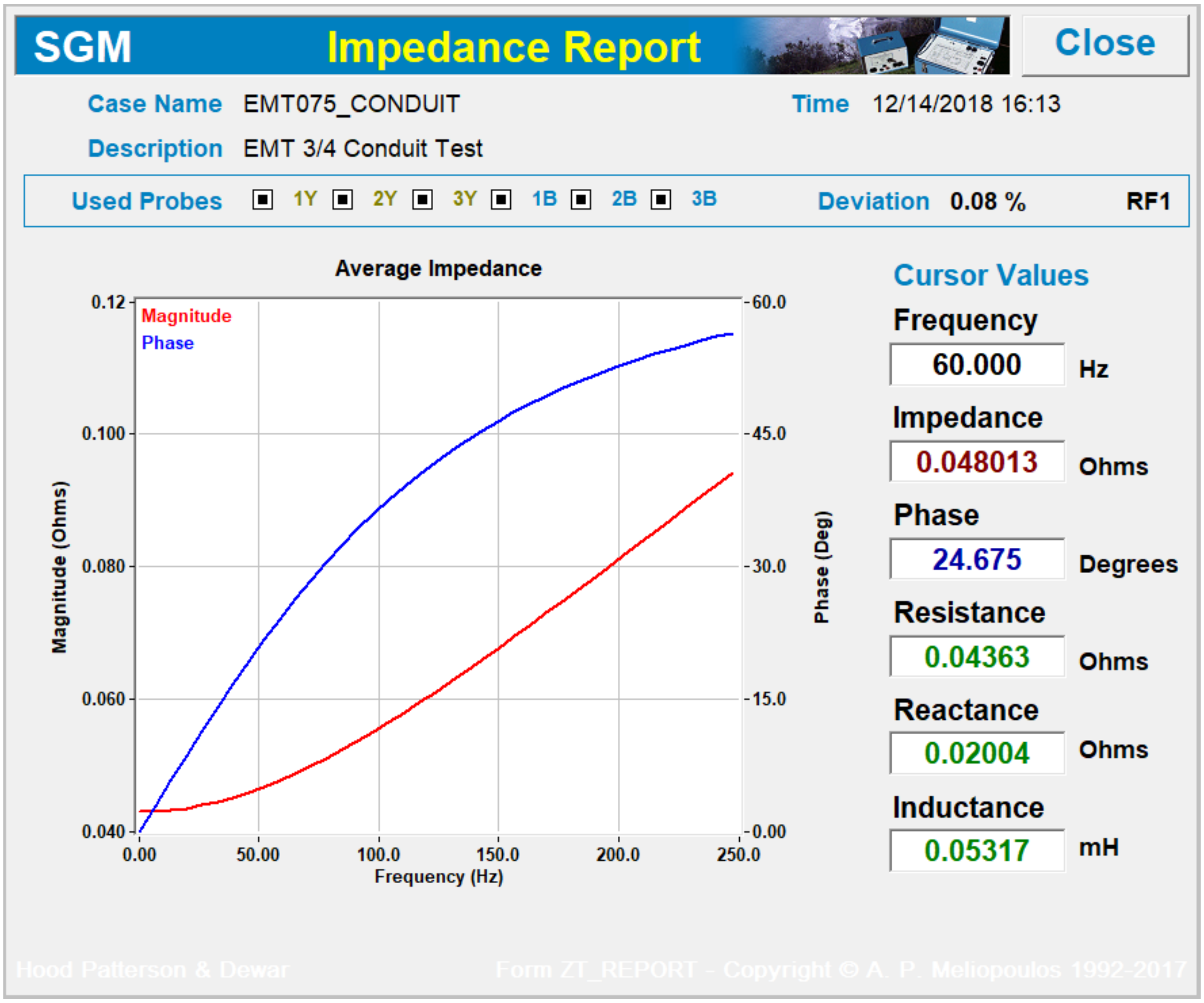


Figure Q-2: EMT 3/4 Conduit Test

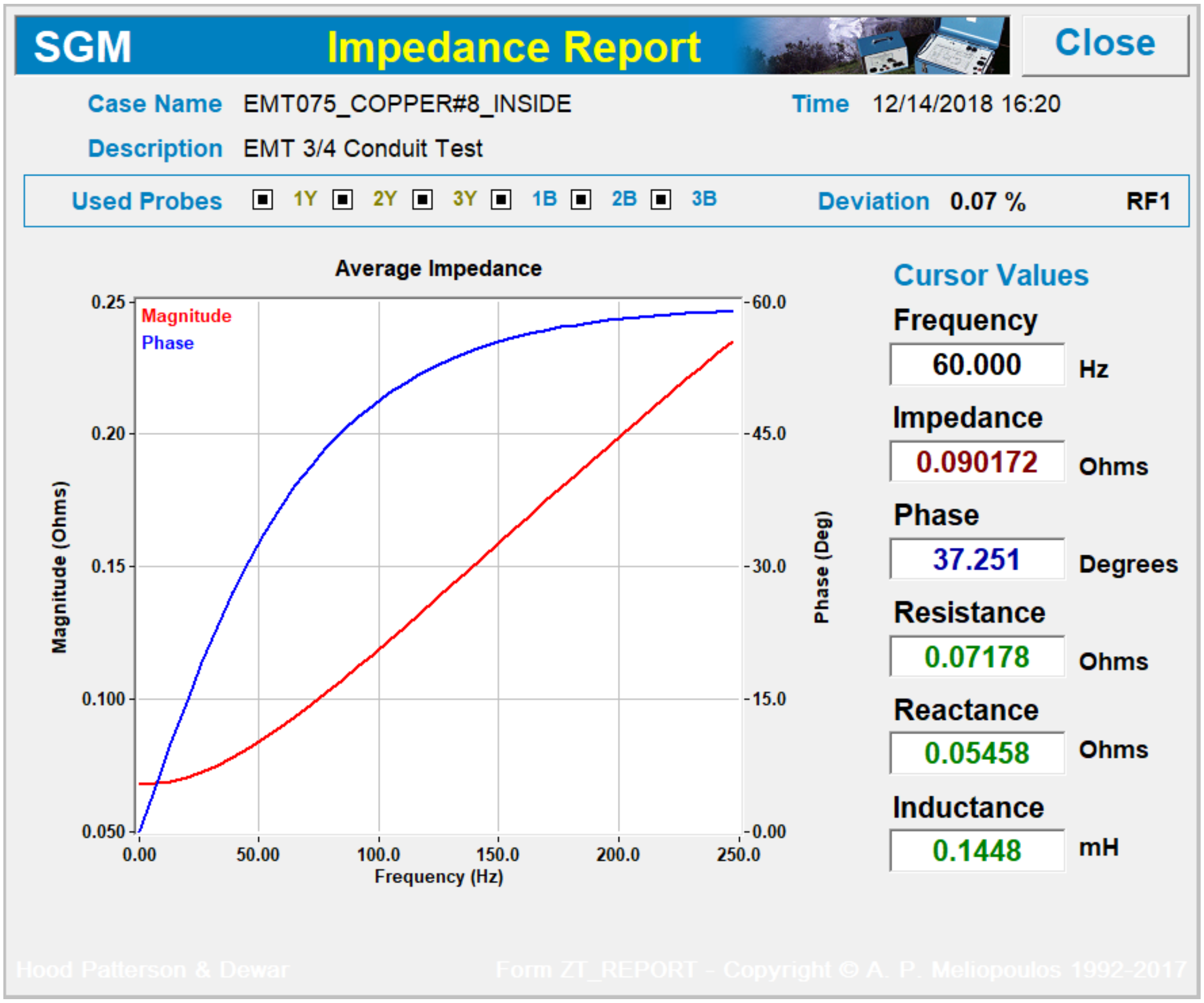


Figure Q-3: EMT 3/4 Conduit Test

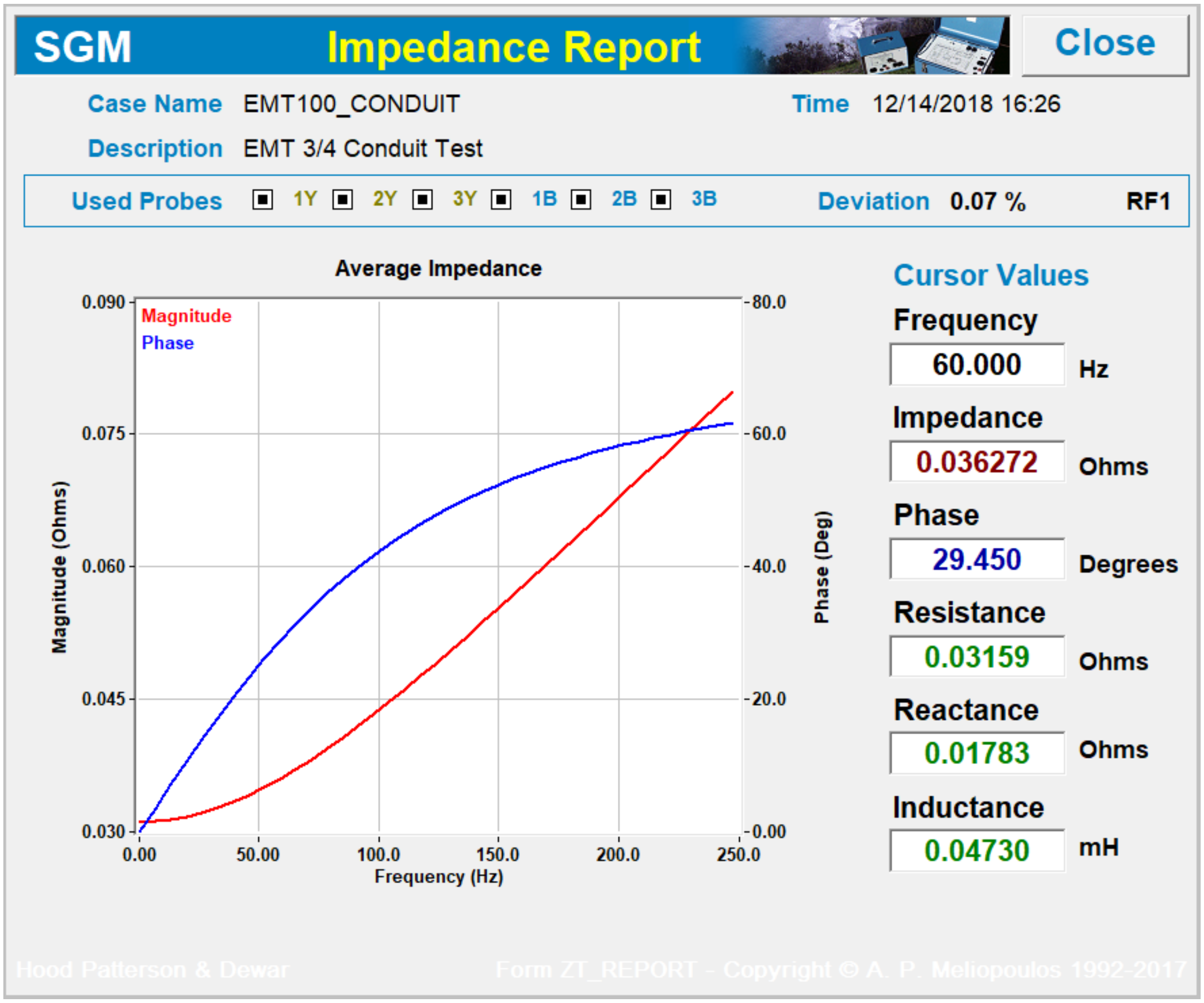


Figure Q-4: EMT 3/4 Conduit Test

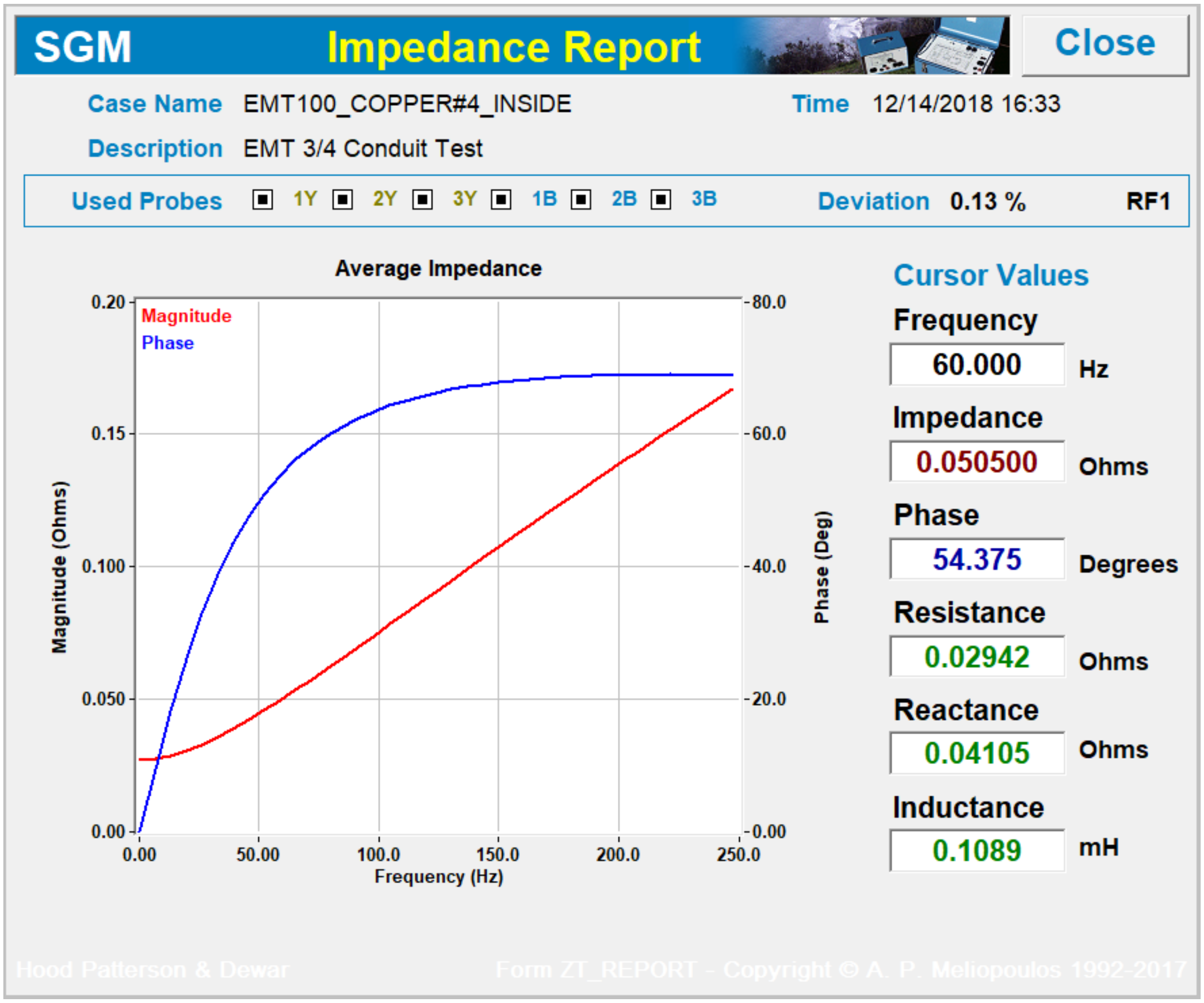


Figure Q-5: EMT 3/4 Conduit Test

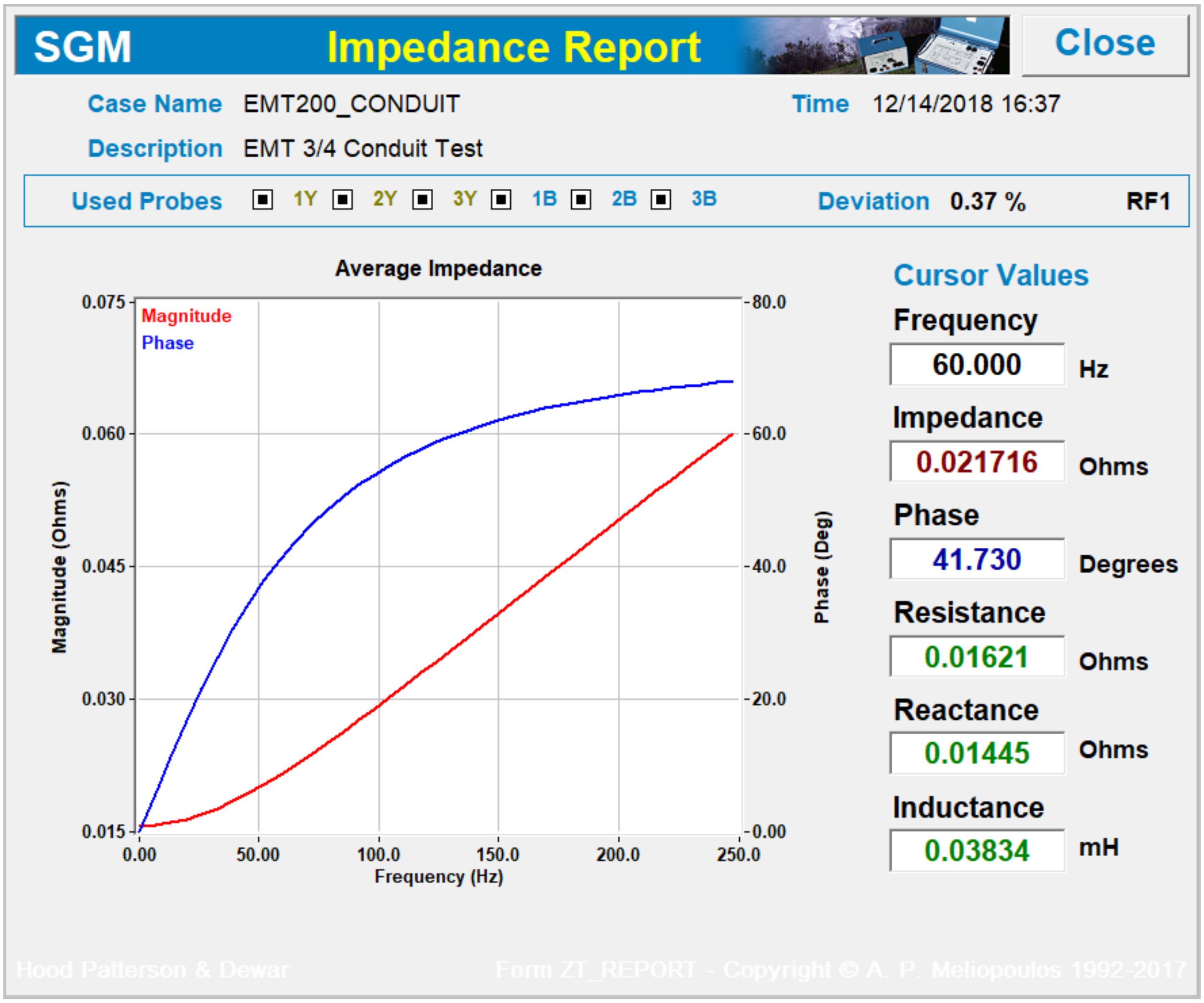


Figure Q-6: EMT 3/4 Conduit Test

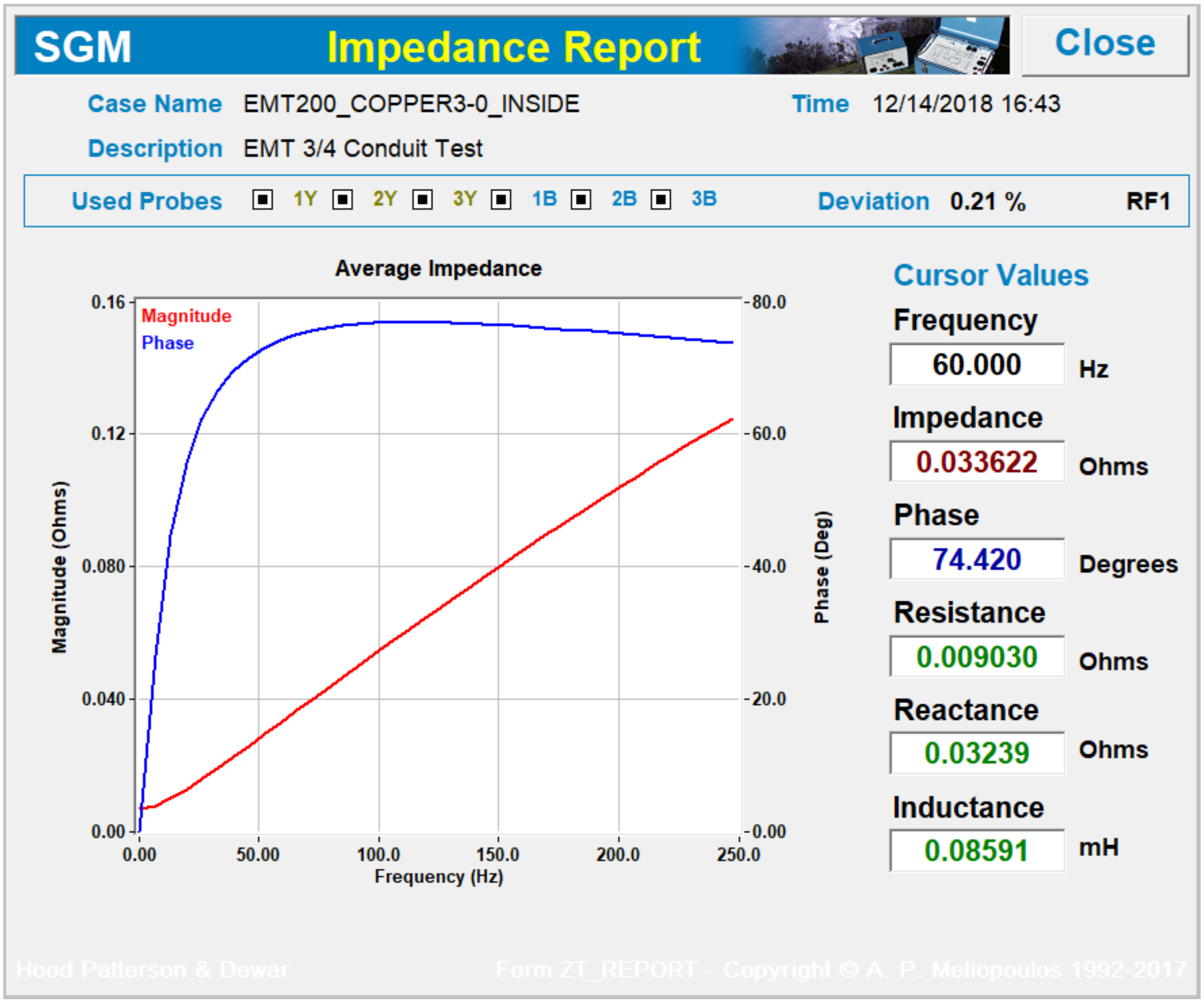


Figure Q-7: EMT 3/4 Conduit Test

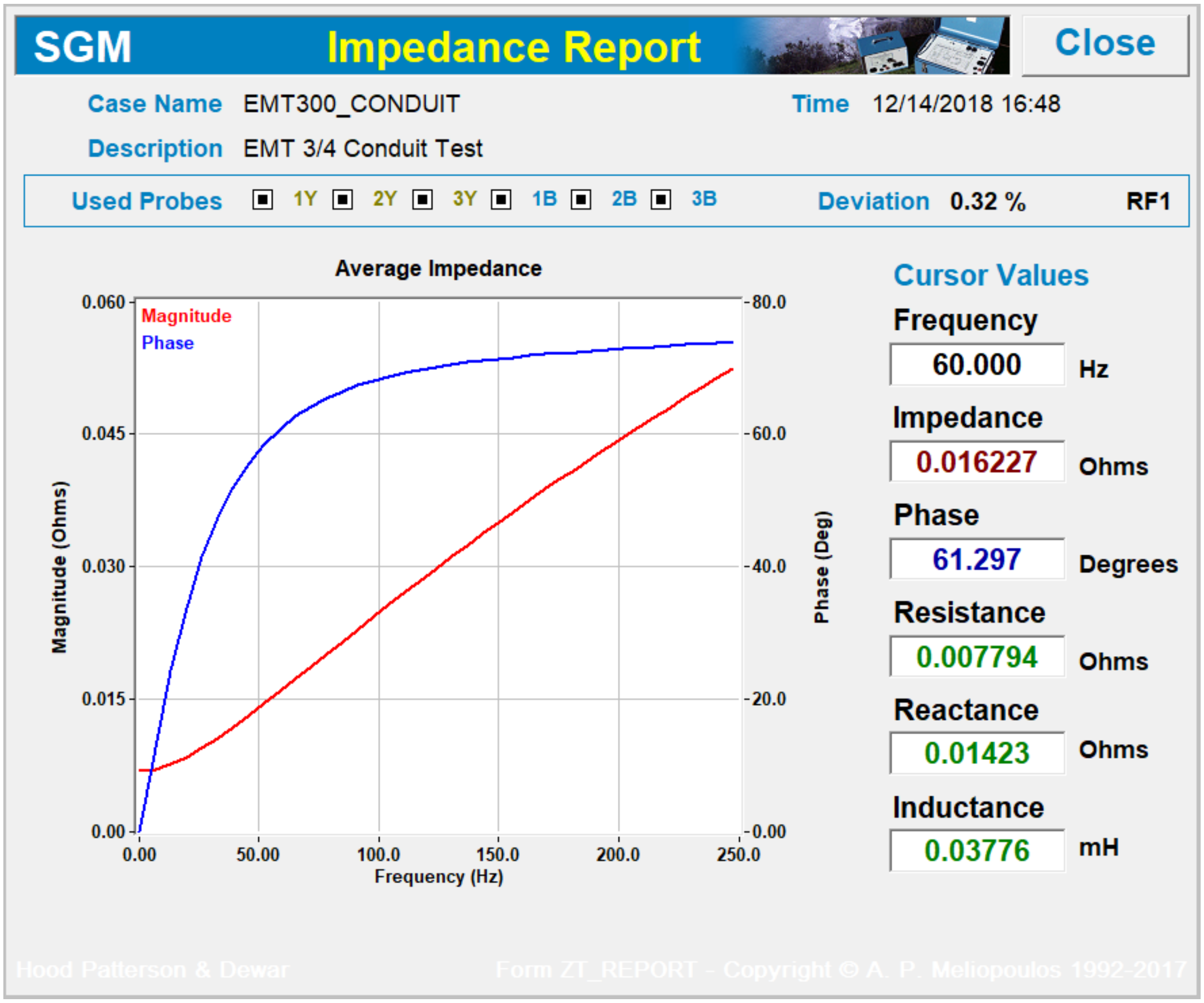


Figure Q-8: EMT 3/4 Conduit Test

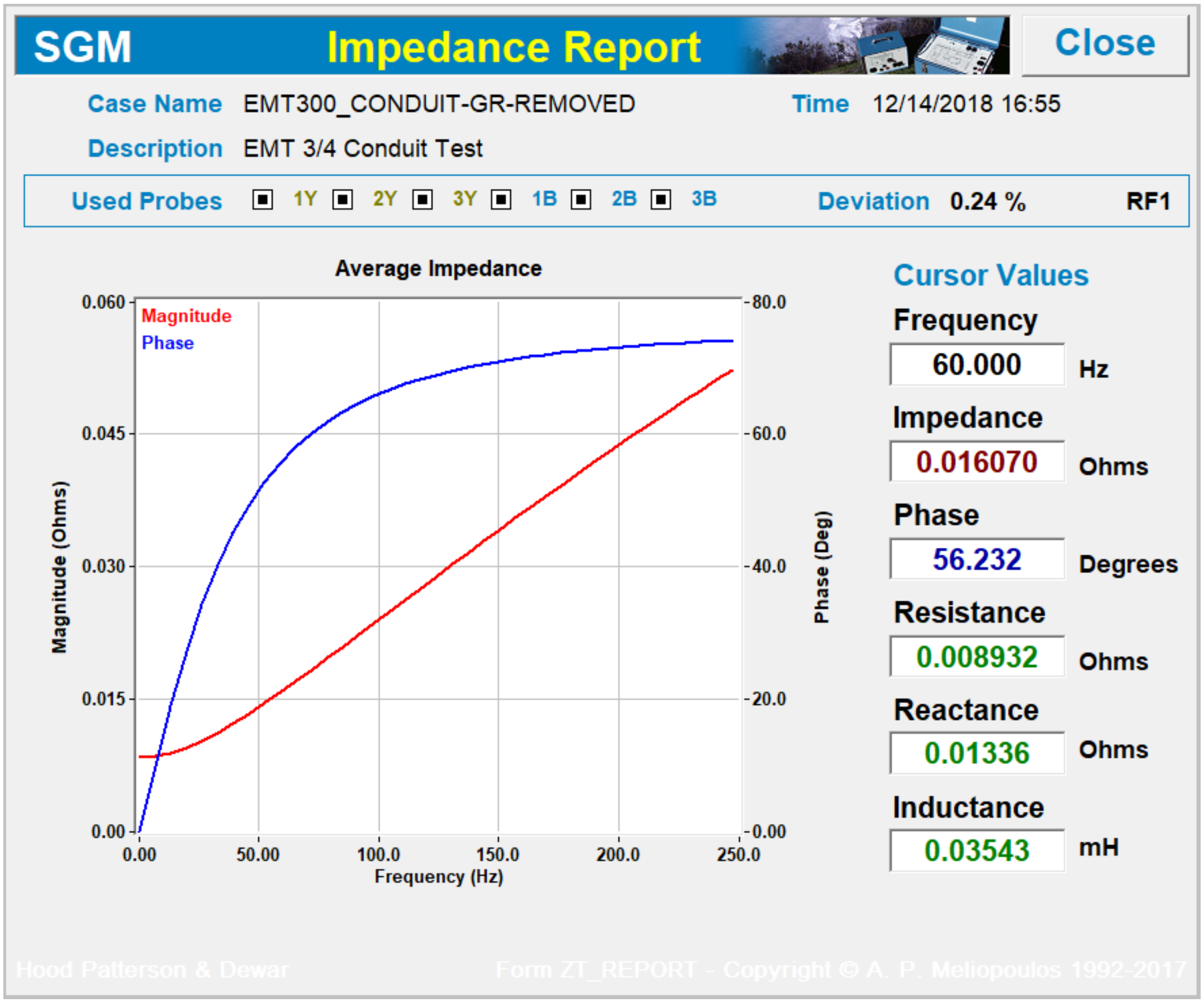


Figure Q-9: EMT 3/4 Conduit Test

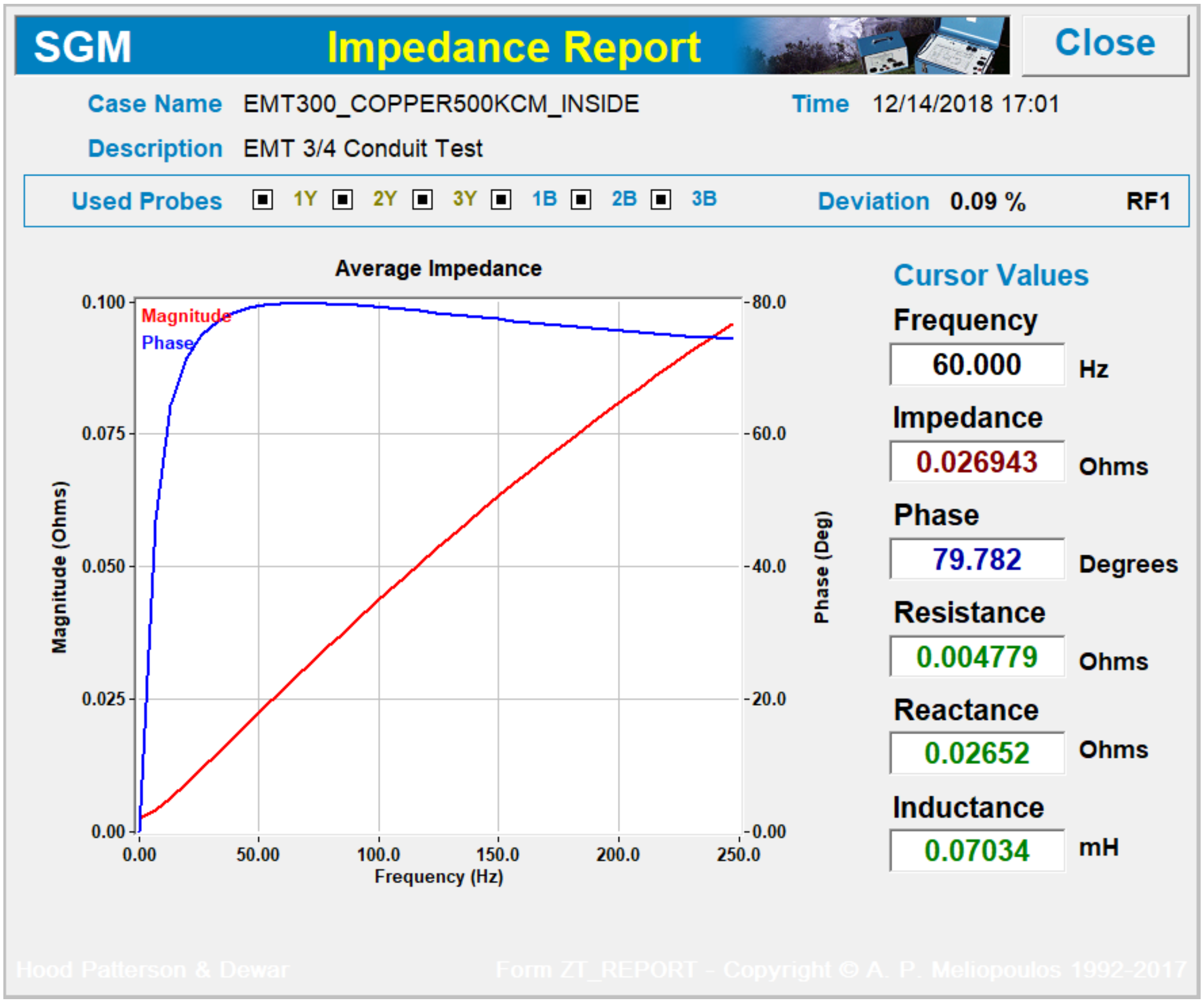


Figure Q-10: EMT 3/4 Conduit Test

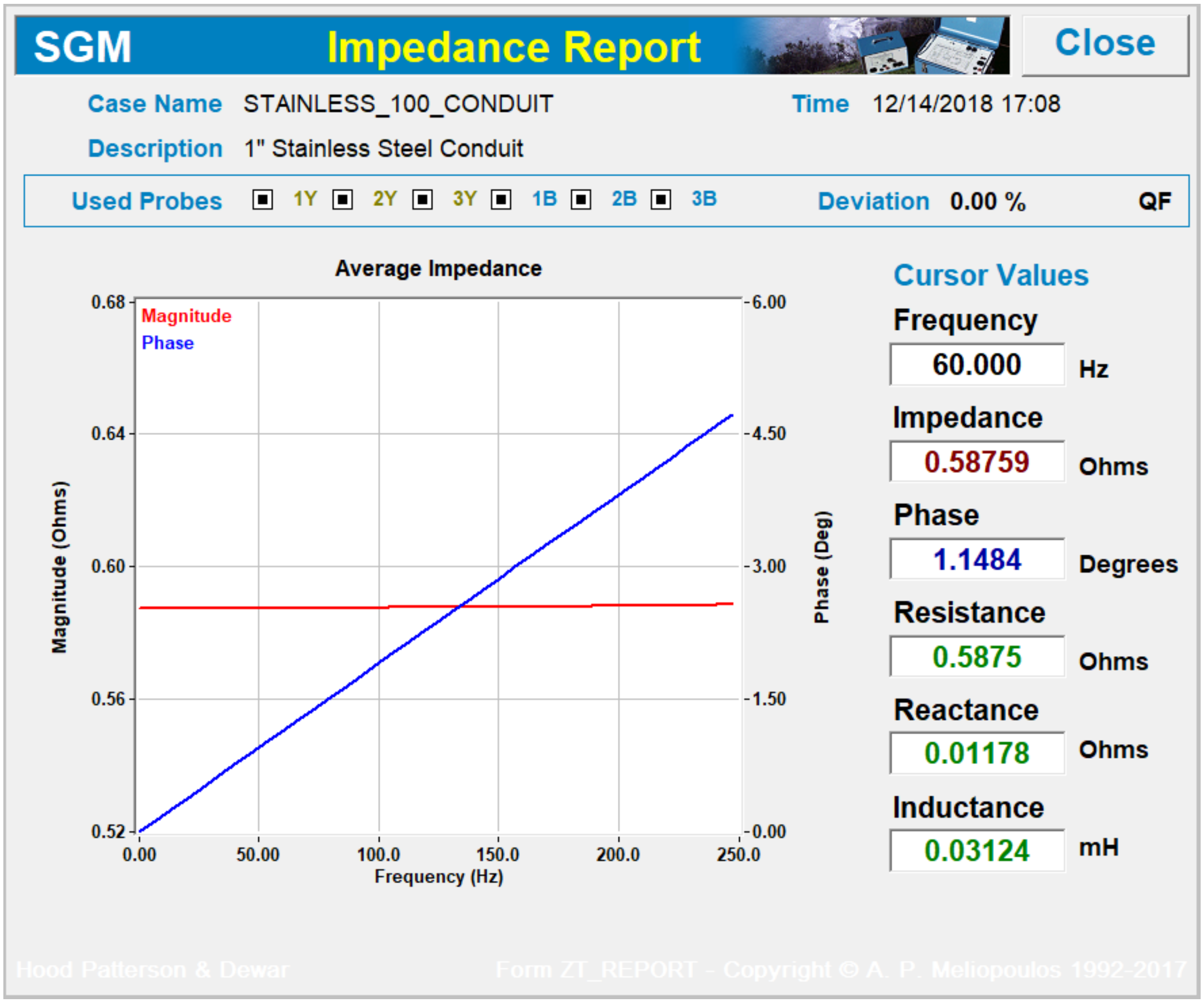


Figure Q-11: 1" Stainless Steel Conduit

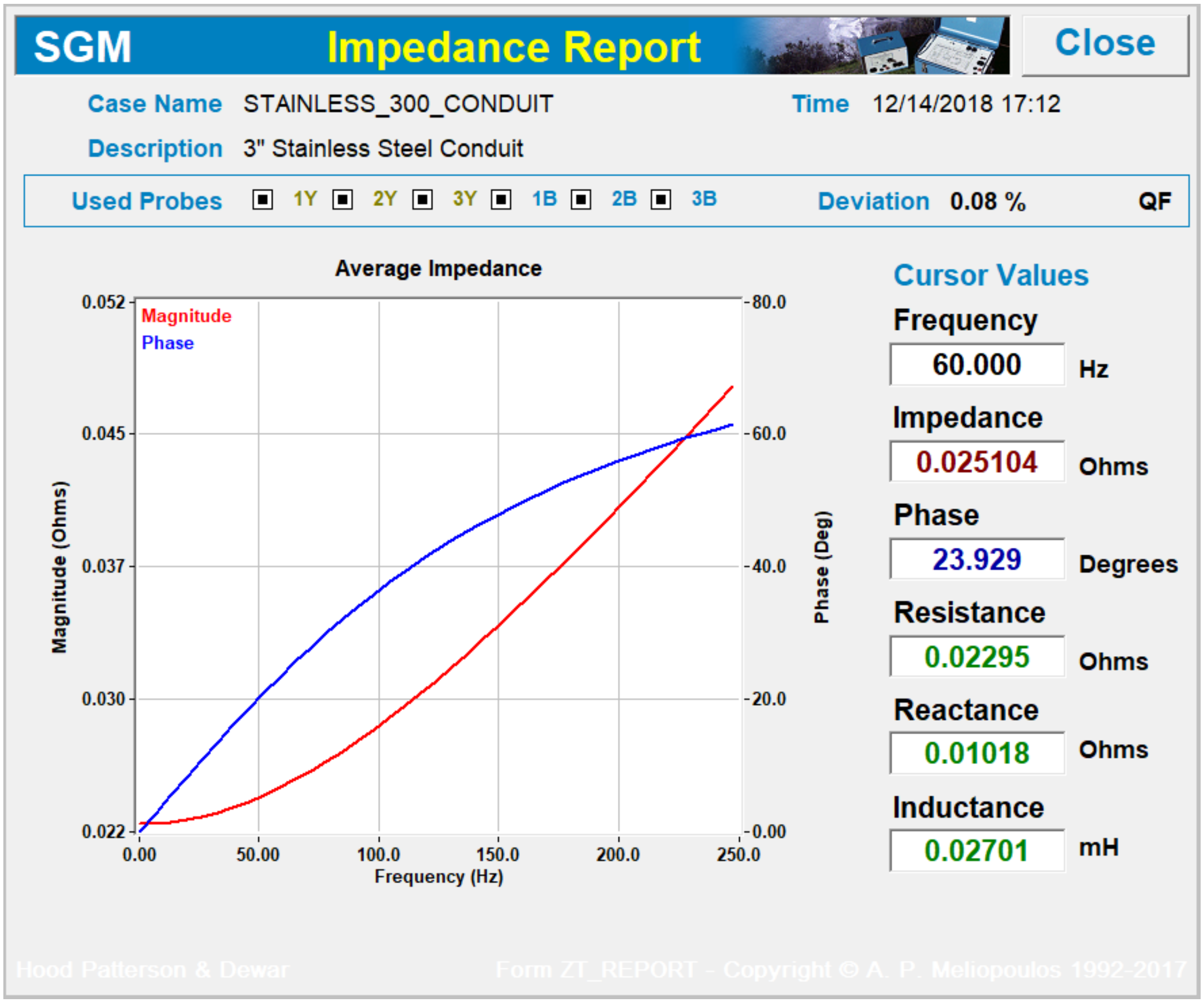


Figure Q-12: 3" Stainless Steel Conduit

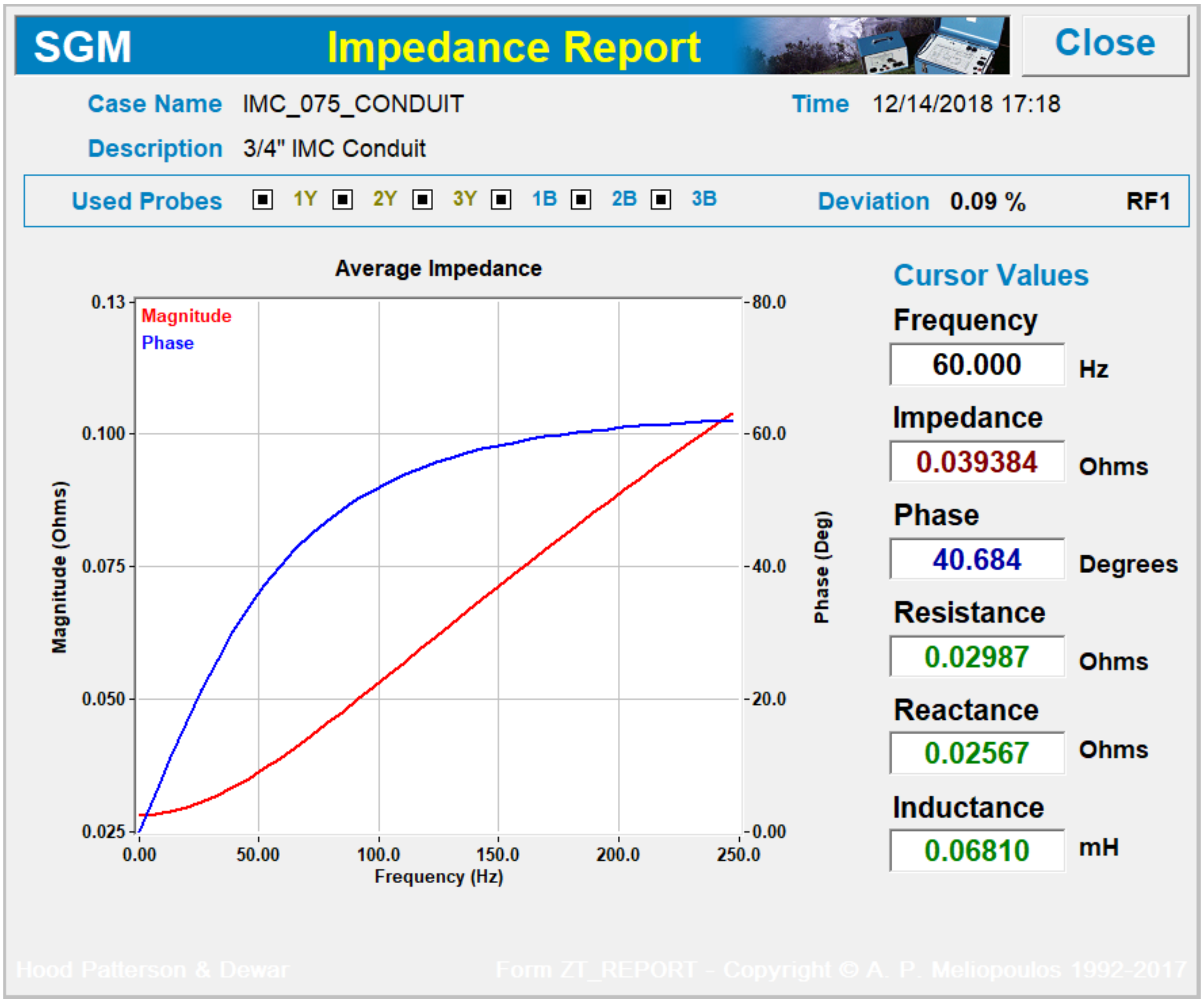


Figure Q-13: 3/4" IMC Conduit

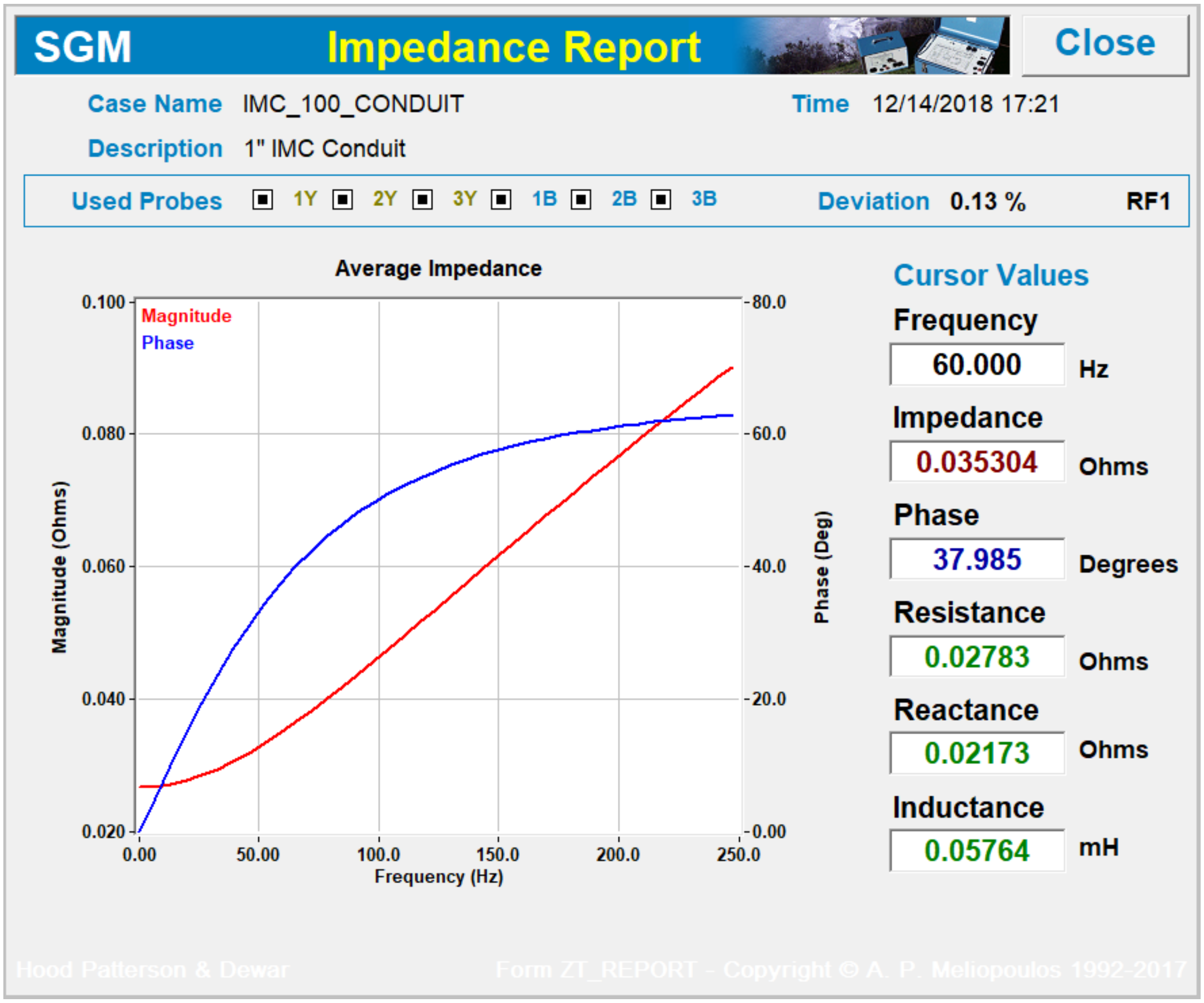


Figure Q-14: 1" IMC Conduit

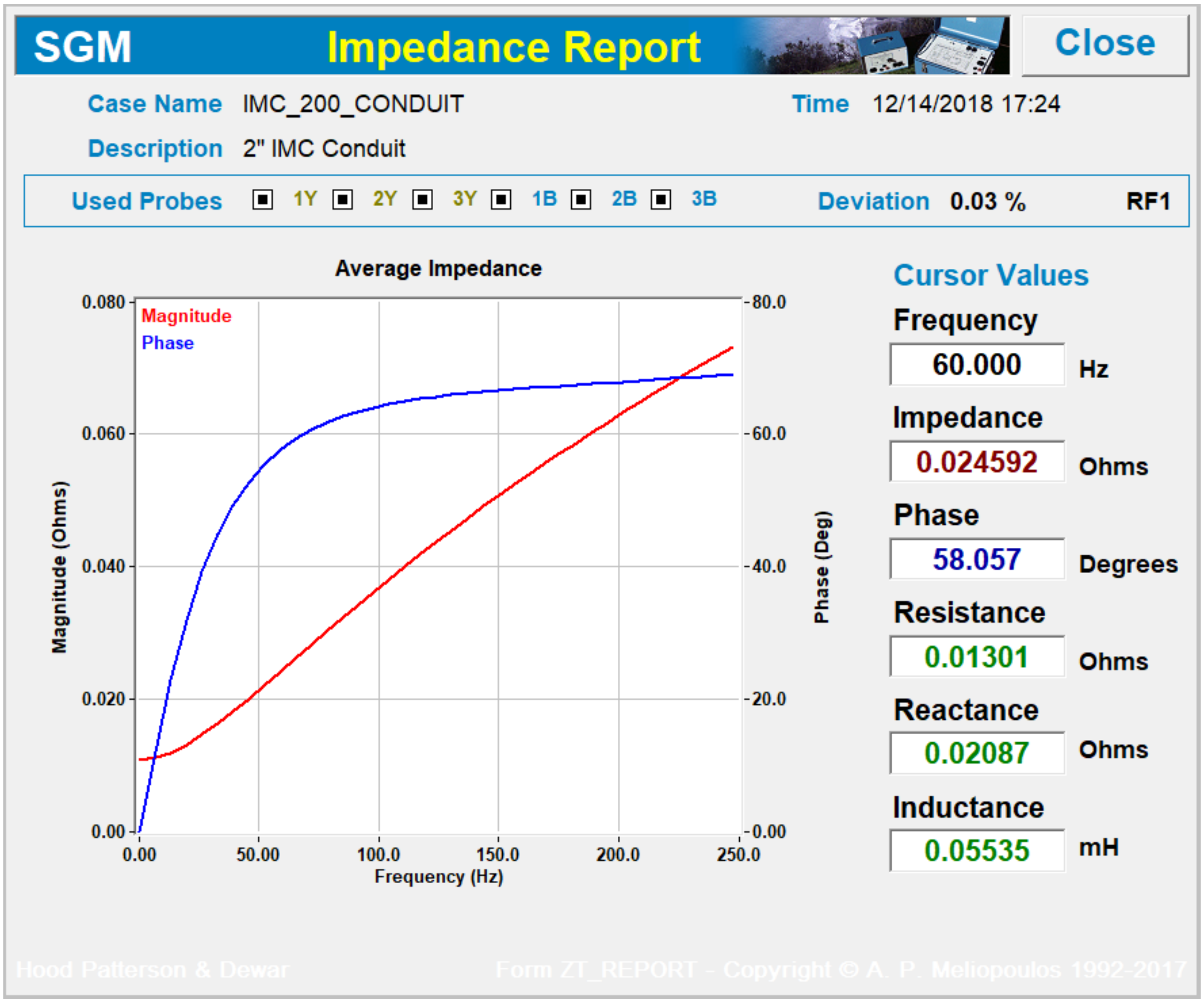


Figure Q-15: 2" IMC Conduit

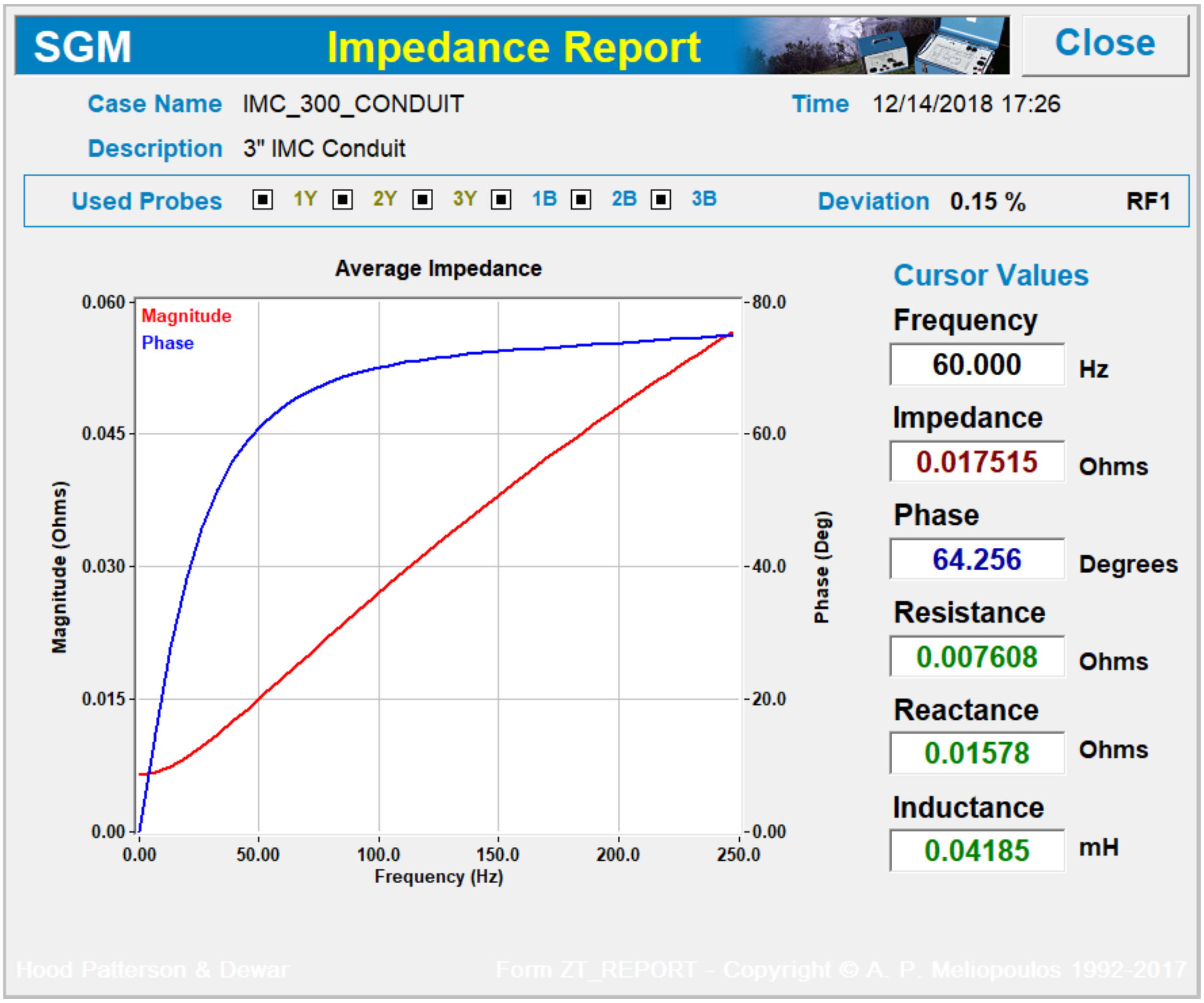


Figure Q-16: 3" IMC Conduit

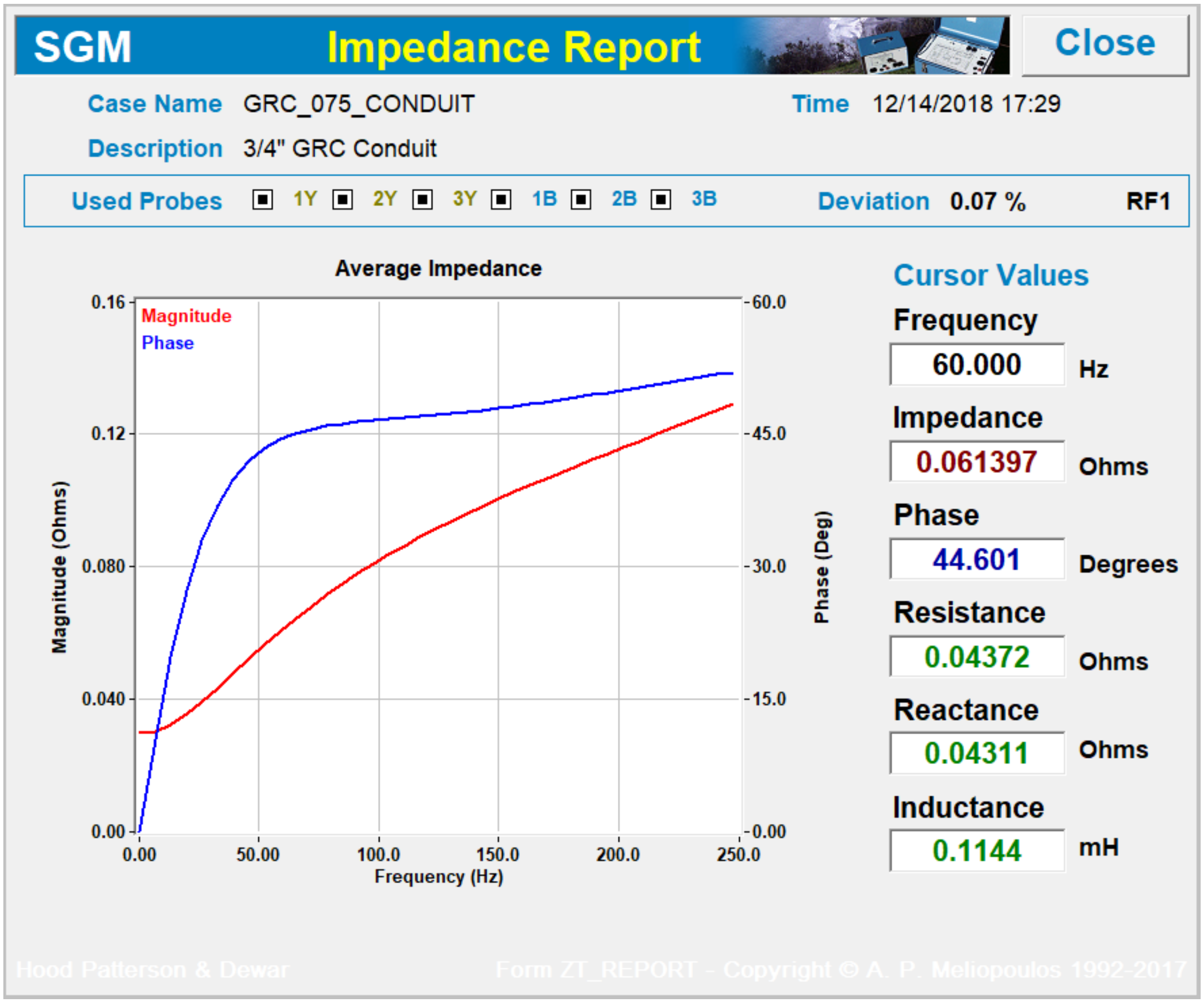


Figure Q-17: 3/4" GRC Conduit

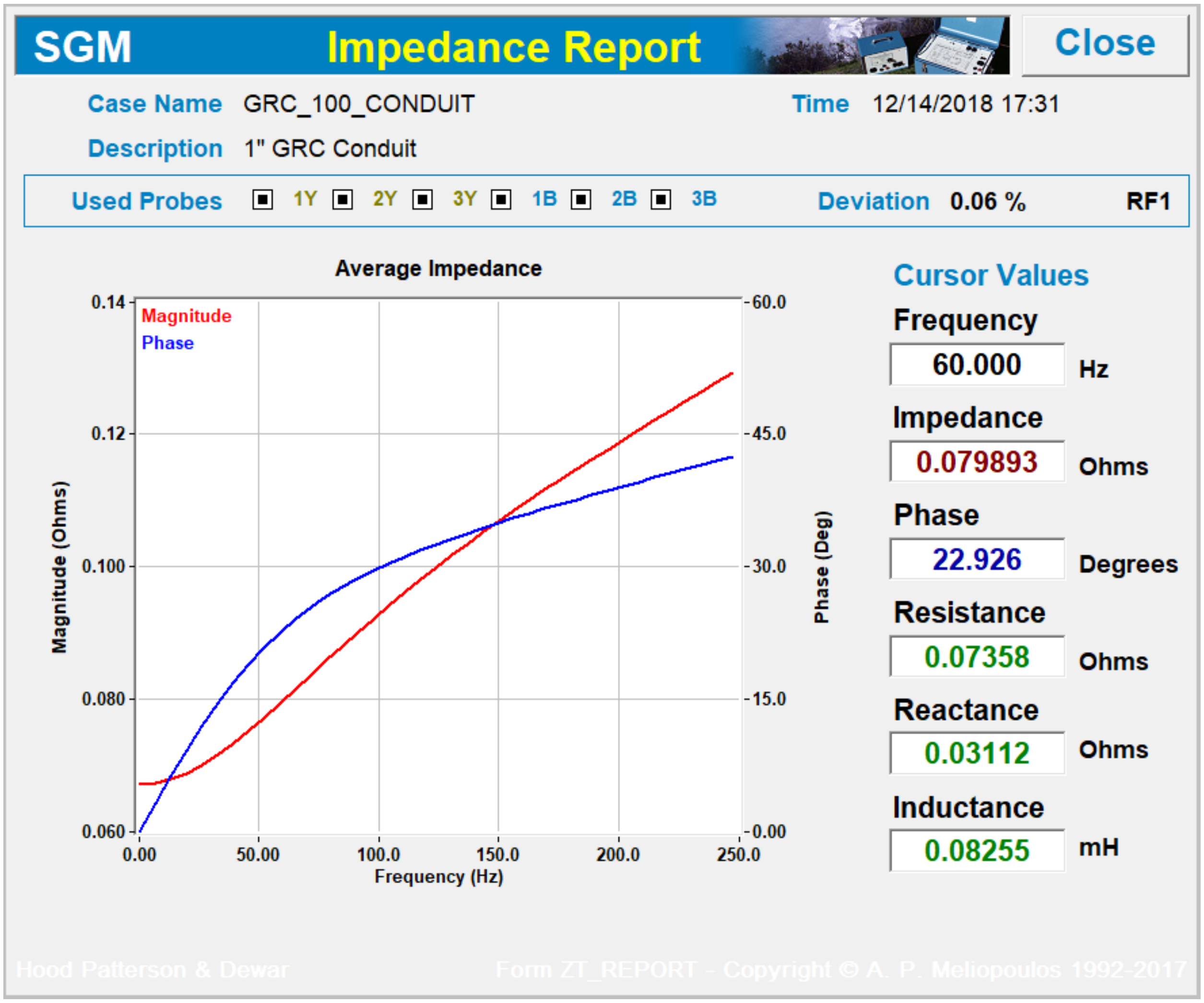


Figure Q-18: 1" GRC Conduit

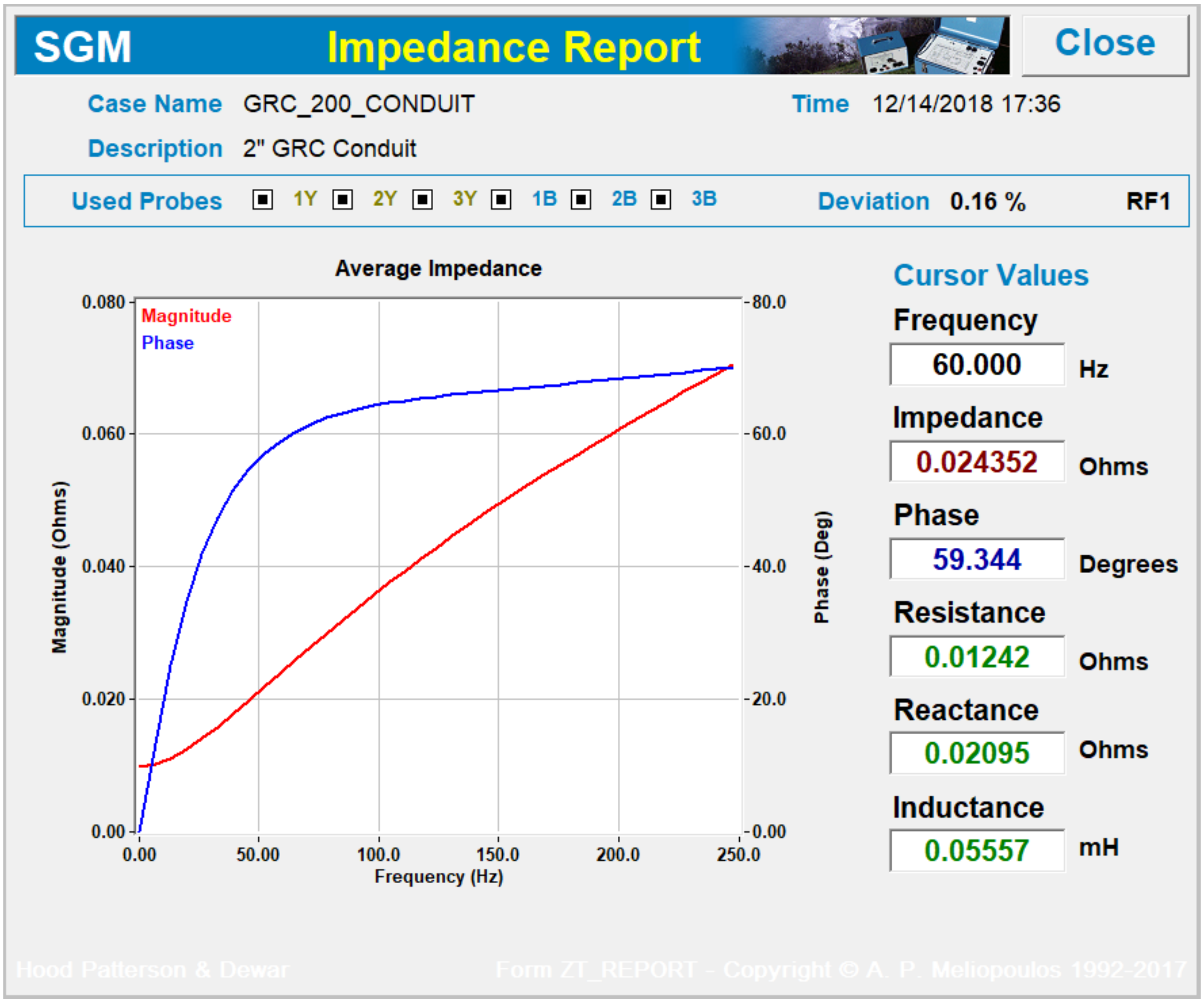


Figure Q-19: 2" GRC Conduit

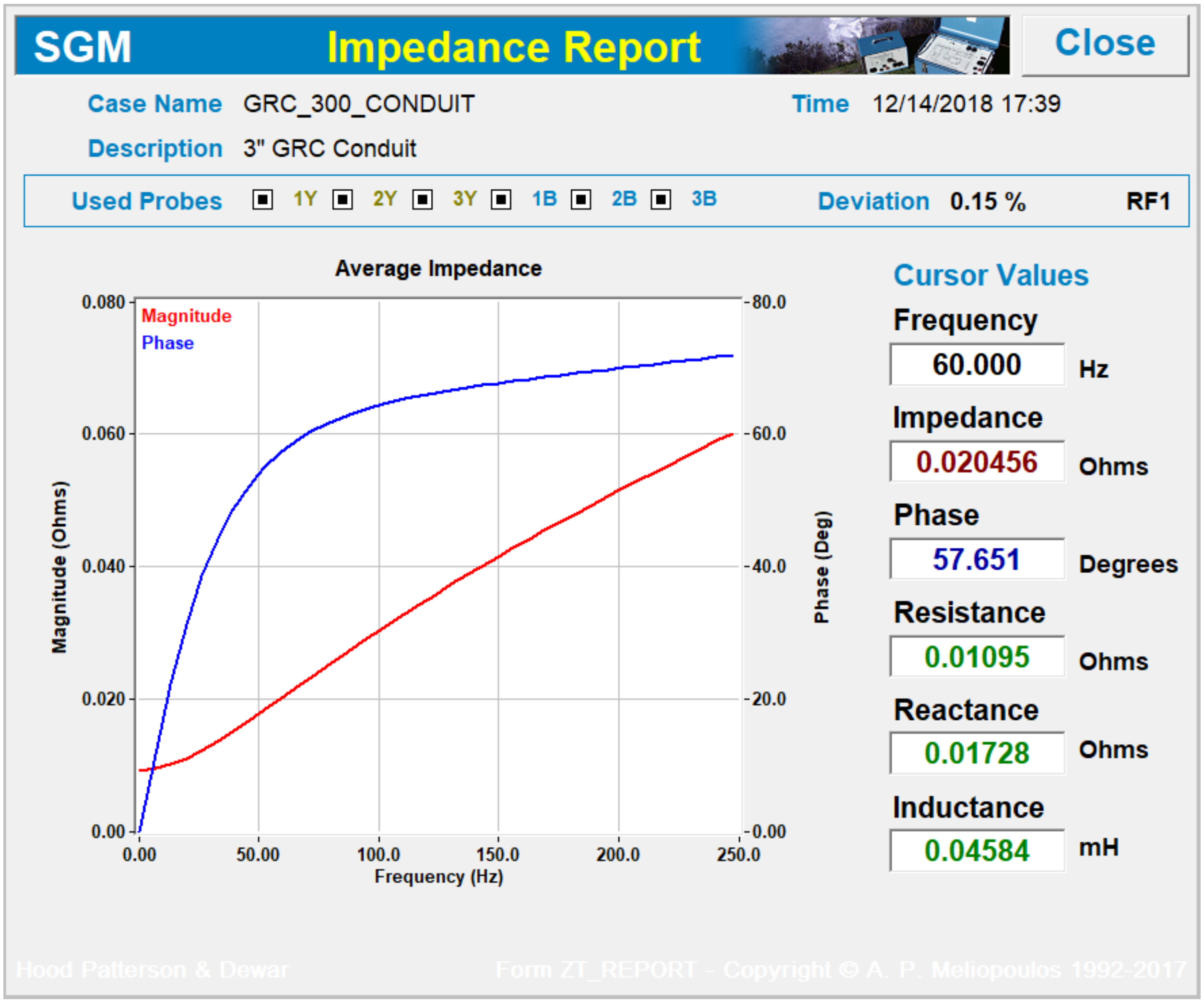


Figure Q-20: 3" GRC Conduit

Appendix R – Permeability Measurements

Measurement Setup

The permeability of the steel used in the various conduit types was measured in the lab. A measurement setup was constructed that allows measurement of the material permeability over a range of magnetic field intensities which extends into complete magnetic saturation. The measurement setup is illustrated in Figure R-1. It consists of a set of transformers that implement an electrically isolated 60 Hz variable voltage source. The source drives the primary winding which has been added on each conduit sample. A data acquisition system records the primary winding current waveform, as well as the voltage across both primary and secondary conduit sample windings.

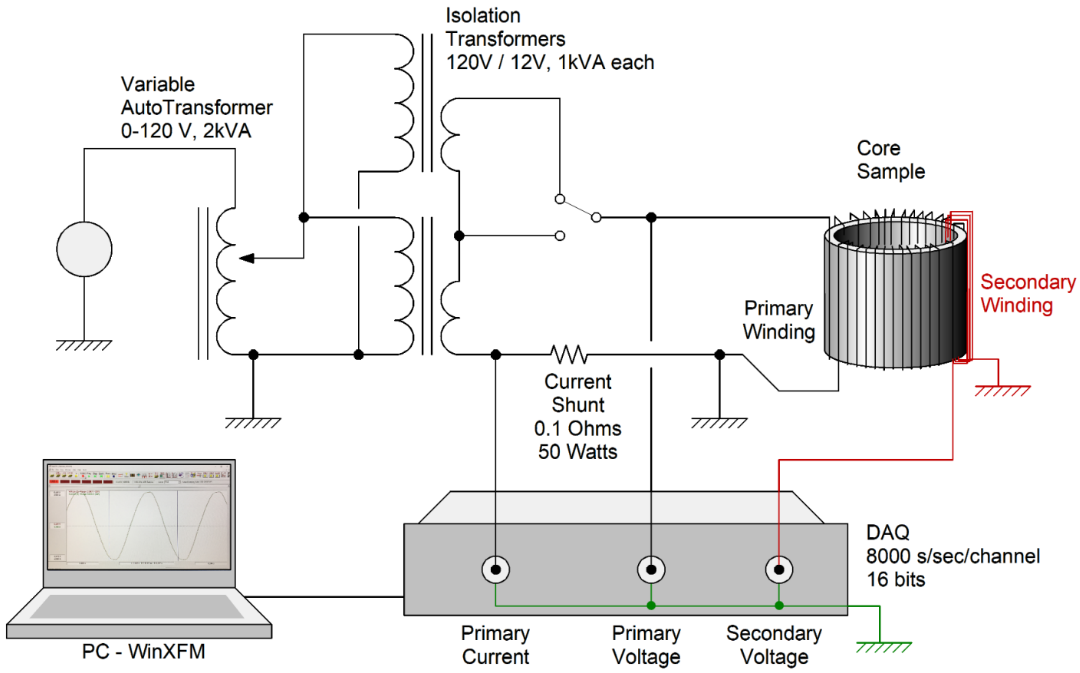


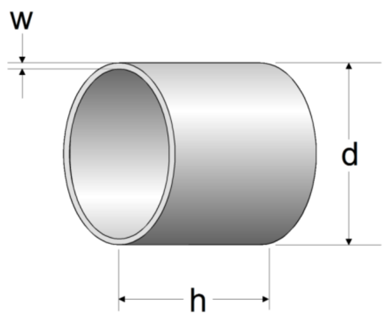
Figure R-1: Measurement Setup

Conduit samples were obtained from 1”, 2”, and 3” EMT, IMC, and GRC conduits. Two windings were added on each sample (referred to as primary and secondary windings). The primary consists of a single layer evenly distributed along the entire circumference of the sample. The secondary winding is concentrated. The conduit sample dimensions and winding specifications are given in Table R-1. Figure R-2 shows several conduit samples with the added primary and secondary windings.

Figures R-3 and R-4 show the overall lab setup, and a close-up view of the isolated source transformers, current sampling resistor and test sample.

Table R-1: Conduit Sample Dimensions

#	Material	Size	d - Outside Diameter (inches)	w – Width (inches)	h – Height (inches)	Weight (g)	Turns Prim/Sec	DC Resistance (Ω)
1	EMT	3”						
2		2”	2.20”	0.068”	2.25”	123 g	84/20	
3	IMC	3”						
4		2”	2.36”	0.111”	1.83”	174 g	88/20	
5	GRC	3”	3.52”	0.192”	2.295”	591 g	135/20	
6		2”	2.38”	0.145”	2.03”	255 g	90/20	
7	Stainless Steel	1”	1.33”	0.138”	1.347”	110 g	44	0.0863
8		2”						



Conduit Sample Dimension Diagram

Representative Samples **Samples with Added Windings**

Figure R-2: Conduit Test Samples

Figure R-3: Conduit Test Samples

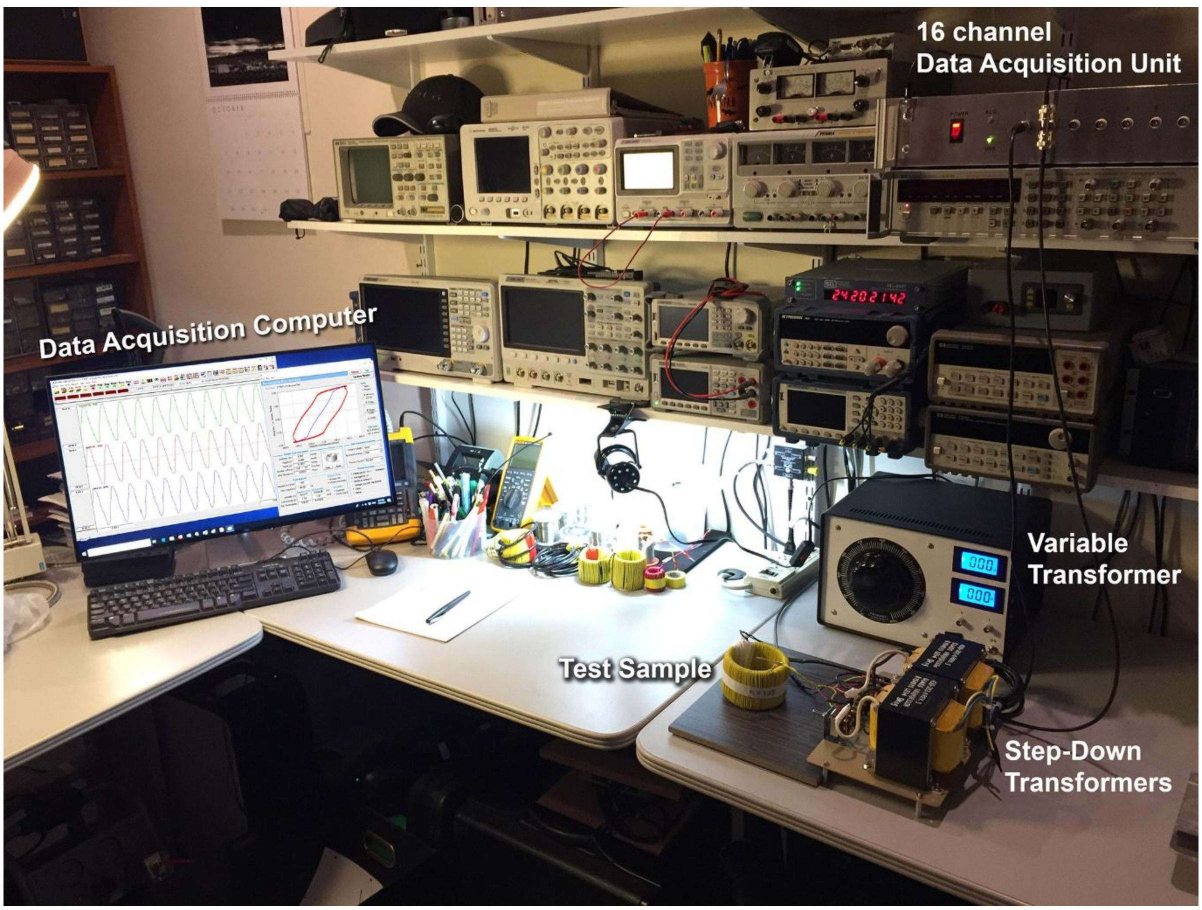


Figure R-4: Overall Lab Test Setup

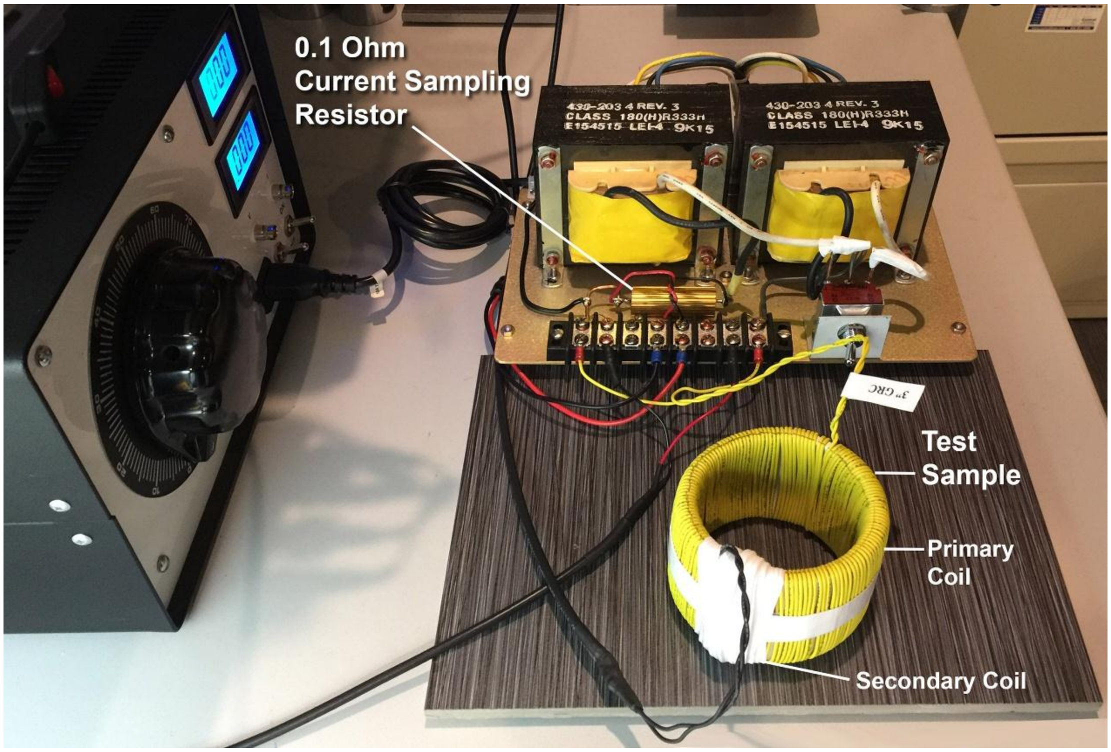


Figure R-5: Lab Test Setup Detailed View

The Test setup illustrated in Figures R-4 and R-5 was used to collect data using 2” conduit samples of EMT, IMC and GRC types. Two measurement and corresponding analysis methods were used:

(a) Time domain voltage and current measurements (point of time waveform data)
(b) RMS voltage and current measurements

The Time domain and RMS measurement and analysis methods are presented in the following tso sections.

Permeability Data from Time Domain Measurements

An example of time domain measurement data are illustrated in Figures R-6, R-7, and R-8 for EMT, GRC and IMC materials respectively. The plotted measurement data consist of the primary winding current waveform and the primary and secondary winding voltage waveforms (note that the secondary winding current is nearly zero).

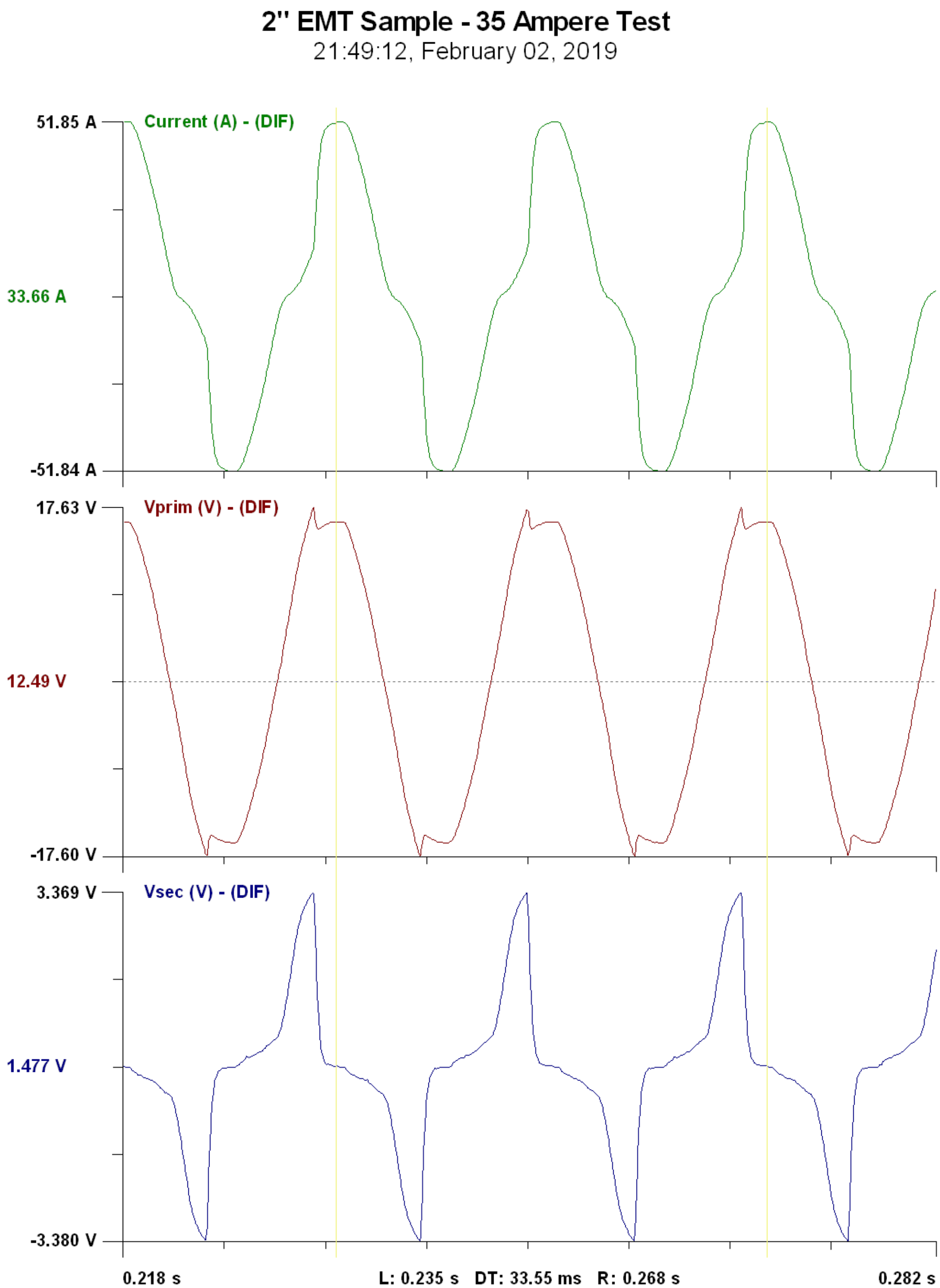


Figure R-6: 2" EMT Sample Measurement Results

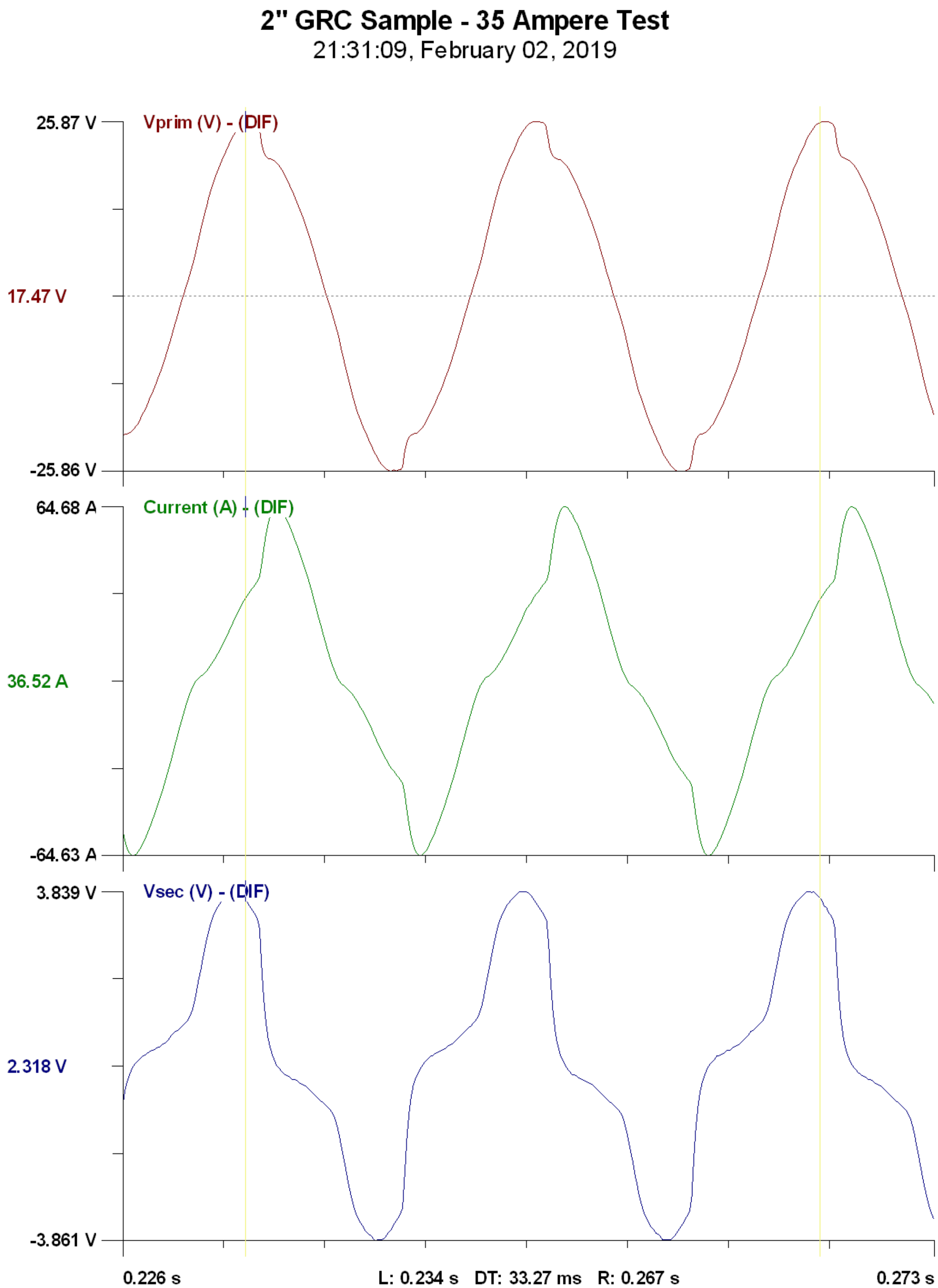


Figure R-7: 2” GRC Sample Measurement Results

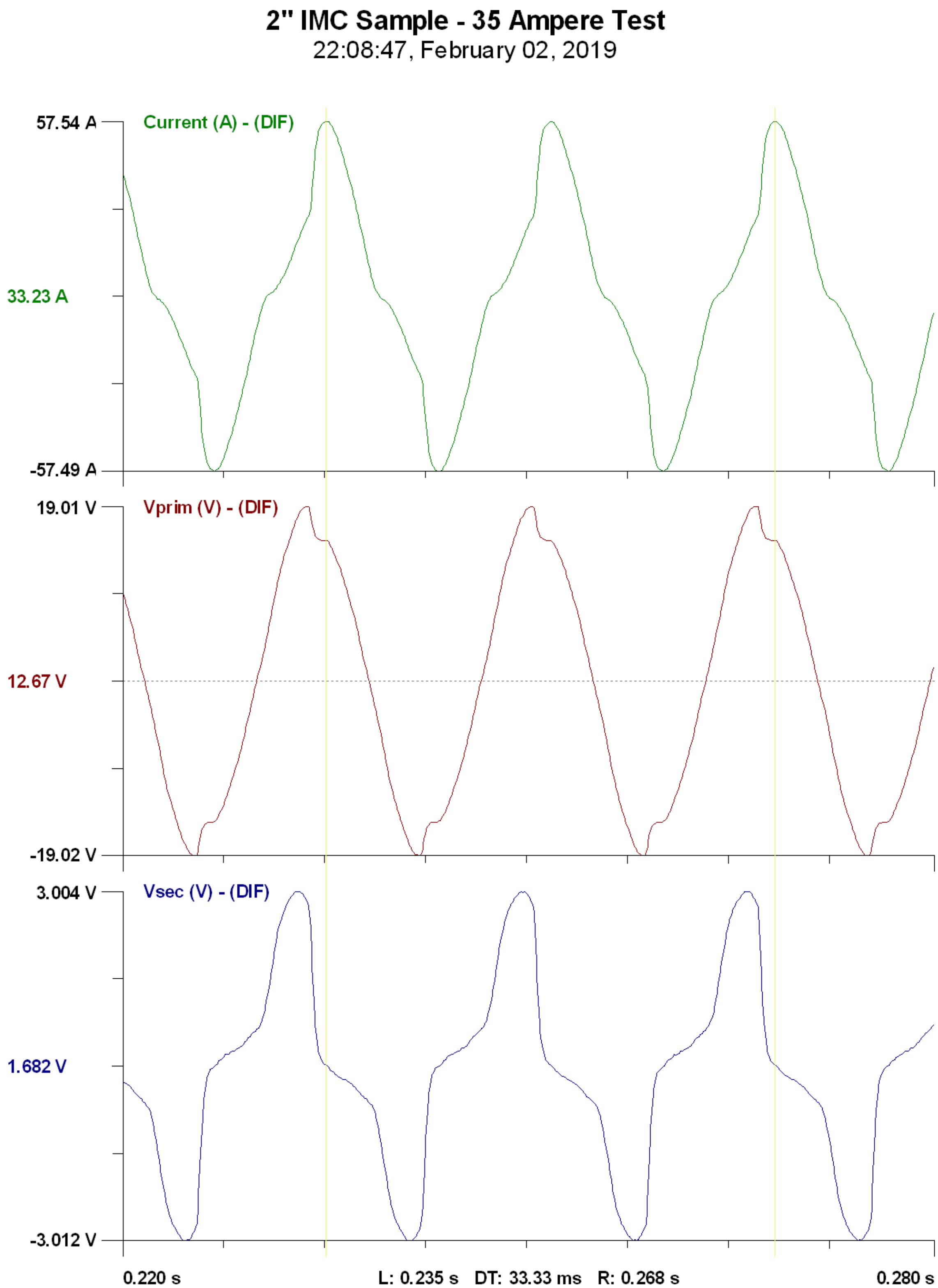


Figure R-8: 2” IMC Sample Measurement Results

Using the measured voltage and current waveform data, the magnetic field intensity H(t) and the magnetic field intensity B(t) within the steel are computed as follows:

$$H(t) = \frac{n \cdot i(t)}{\pi(d-a)}$$

See Figure R-9 for the definition of terms n, a and d.

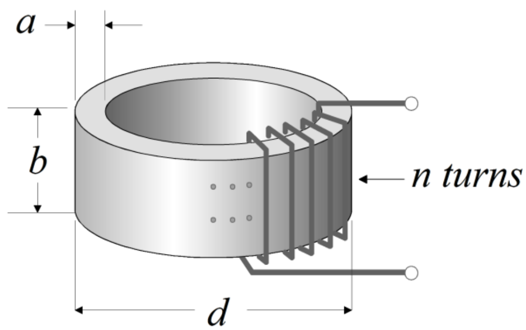


Figure R-9: Conduit Sample Dimensions

The magnetic flux density B(t) within the steel is computed by solving the following equation for B(t):

$$v(t) = R_w \cdot i(t) + \frac{d}{dt}\left(n \cdot \Phi(t)\right) = R_w \cdot i(t) + n \cdot a \cdot b \cdot \frac{d}{dt} B(t)$$

Where R_w is the winding resistance and *i(t)* is the current flowing through the winding. Using a second winding dedicated to magnetic flux monitoring, the second winding current is zero, thus the above equation solved for B(t) assuming *i(t)* = 0 becomes:

$$B(t) = \int \frac{v(t)}{n \cdot a \cdot b} dt$$

Subsequently, the relationship between B and H (excluding the hysteresis component) is approximated with a piecewise linear-quadratic function. Specifically, the B-H curve can be accurately described with two piecewise linear and one quadratic function, as illustrated in the Figure R-10.

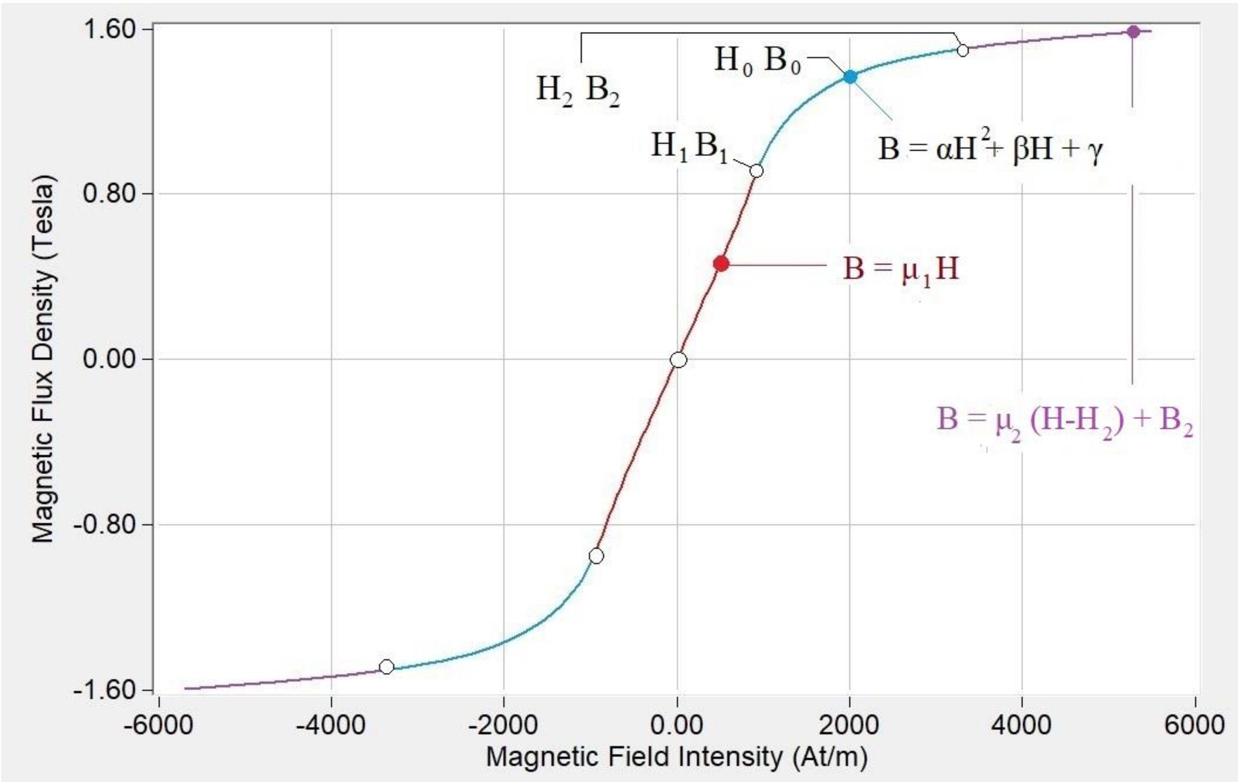


Figure R-10: B versus H function definition

Assuming μ_1 μ_2, H_0, H_1, H_2, B_0, B_1, and B_2 are known, the parameters α, β, γ, must be determined so as to match the quadratic function to the measured B-H data. To ensure continuity the following equations must be satisfied:

$$\alpha H_0^{\,2} + \beta H_0 + \gamma = B_0 / \mu_0$$

$$\alpha H_1^{\,2} + \beta H_1 + \gamma = B_1 / \mu_0$$

$$\alpha H_2^{\,2} + \beta H_2 + \gamma = B_2 / \mu_0$$

The above equations can be solved to provide the parameters α, β, γ as follows

Let $A = \begin{bmatrix} H_0^{\,2} & H_0 & 1 \\ H_1^{\,2} & H_1 & 1 \\ H_2^{\,2} & H_2 & 1 \end{bmatrix}$ and $B = \begin{bmatrix} B_0 / \mu_0 \\ B_1 / \mu_0 \\ B_2 / \mu_0 \end{bmatrix}$

$$\begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} = \begin{bmatrix} H_0^{\,2} & H_0 & 1 \\ H_1^{\,2} & H_1 & 1 \\ H_2^{\,2} & H_2 & 1 \end{bmatrix}^{-1} \begin{bmatrix} B_0 / \mu_0 \\ B_1 / \mu_0 \\ B_2 / \mu_0 \end{bmatrix}$$

However to ensure that the derivative of B(H) is also continuous, the following additional equations must be satisfied:

$$2\alpha H_1 + \beta = \mu_1$$

$$2\alpha H_2 + \beta = \mu_2$$

The above can be achieved by changing the constants H_1 and H_2 to unknown variables, resulting in a set of 5 equations and 5 unknowns. The equations are now nonlinear so Newton's method is used for the solution. We define a function set $f_1..f_5$ as follows:

Differentiability at point 1: $f_1 = 2\alpha H_1 + \beta - \mu_1$

Differentiability at point 2: $f_2 = 2\alpha H_2 + \beta - \mu_2$

Passing through point 0: $f_3 = \alpha H_0{}^2 + \beta H_0 + \gamma - B_0 / \mu_0$

Continuity at point 1: $f_4 = \alpha H_1{}^2 + (\beta - \mu_1) H_1 + \gamma$

Continuity at point 2: $f_5 = \alpha H_2{}^2 + (\beta - \mu_2) H_2 + \gamma - \delta$

Where $\delta = B_2 / \mu_0 - H_2 \mu_2$ computed from initial values of B_2 and H_2.

The Jacobean matrix is defined using the partial derivatives of the above functions with respect to α, β, γ, H_1, and H_2, yielding:

$$\begin{array}{cc} & \begin{array}{ccccc} \alpha & \beta & \gamma & H1 & H2 \end{array} \\ J = & \begin{bmatrix} 2H_1 & 1 & 0 & 2\alpha & 0 \\ 2H_2 & 1 & 0 & 0 & 2\alpha \\ H_0^2 & H_0 & 1 & 0 & 0 \\ H_1^2 & H_1 & 1 & 2\alpha + \beta - \mu_1 & 0 \\ H_2^2 & H_2 & 1 & 0 & 2\alpha + \beta - \mu_2 \end{bmatrix} \end{array}$$

The solution vector is initialized using the parameters α, β, γ obtained from arbitrary set of H_1, H_2, B_1, B_2, then iteratively adjusted as follows:

$$\begin{bmatrix} \alpha \\ \beta \\ \gamma \\ H_1 \\ H_2 \end{bmatrix}_{\nu+1} = \begin{bmatrix} \alpha \\ \beta \\ \gamma \\ H_1 \\ H_2 \end{bmatrix}_{\nu} + \begin{bmatrix} 2H_1 & 1 & 0 & 2\alpha & 0 \\ 2H_2 & 1 & 0 & 0 & 2\alpha \\ H_0^2 & H_0 & 1 & 0 & 0 \\ H_1^2 & H_1 & 1 & 2\alpha + \beta - \mu_1 & 0 \\ H_2^2 & H_2 & 1 & 0 & 2\alpha + \beta - \mu_2 \end{bmatrix}^{-1} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \end{bmatrix}$$

Given the parameters H_0, H_1, H_2, B_0, B_1, B_2, α, β, γ, the following equations provide B(H) and H(B):

$$B = \begin{cases} \mu_0 \mu_1 H & for\ H < H_1 \\ \mu_0(\alpha H^2 + \beta H + \gamma) & for\ H_1 < H < H_2 \\ \mu_0 \mu_2 (H - H_2) + B_2 & for\ H_2 < H \end{cases}$$

The inverse function is as follows:

$$H = \begin{cases} B/(\mu_1 \mu_0) & for\ B < B_1 \\ \dfrac{-\beta + \sqrt{\beta^2 + 4\alpha(B/\mu_0 - \gamma)}}{2a} & for\ B_1 < B < B_2 \\ (B - B_2)/(\mu_0 \mu_2) + H_2 & for\ B_2 < B \end{cases}$$

$$B = \begin{cases} H\mu_0 \mu_1 & for\ H < H_1 \\ \dfrac{-\beta + \sqrt{\beta^2 + 4\alpha(H\mu_0 - \gamma)}}{2\alpha} & for\ H_1 < H < H_2 \\ (H\mu_0 - \delta)\mu_2 & for\ H_2 < H \end{cases}$$

The above described analysis methodology has been implemented within the WinXFM program. The implementation uses the measured voltage and current waveform data, along with the core sample geometric parameters, and automatically computes the piecewise linear-quadratic parameters. The user interface of the WinXFM permeability analysis module is illustrated in Figures R-11, R-12 and R-13 showing the sample results for GRC, IMC and EMT materials respectively.

The program generates a text files containing the permeability parameters. An example of the permeability parameter file is illustrated in Table R-2. These data are added to the GEMI program material library, and used in conduit enclosed circuit simulations.

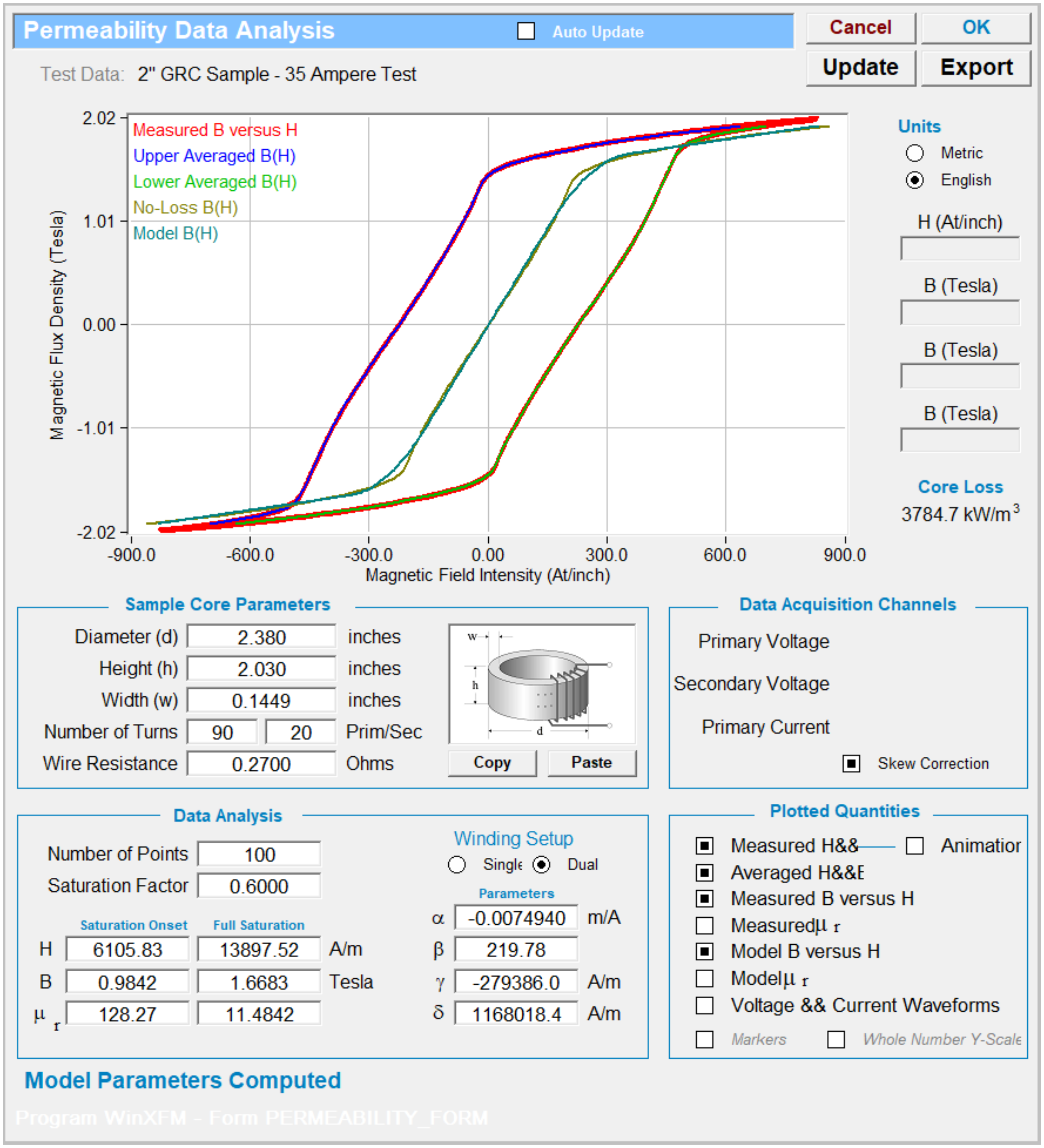


Figure R-11: GRC Permeability Measurement

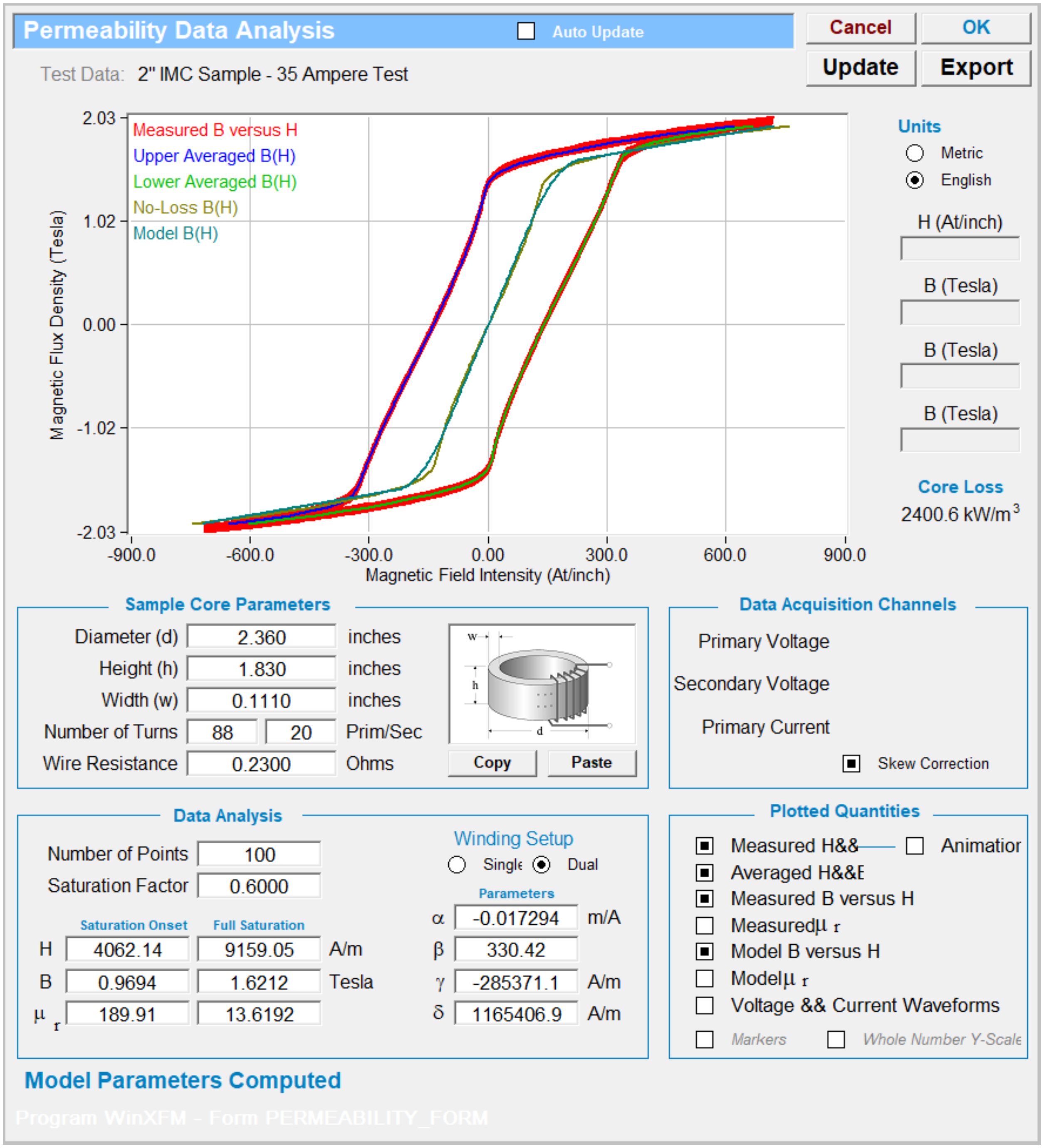


Figure R-12: IMC Permeability Measurement

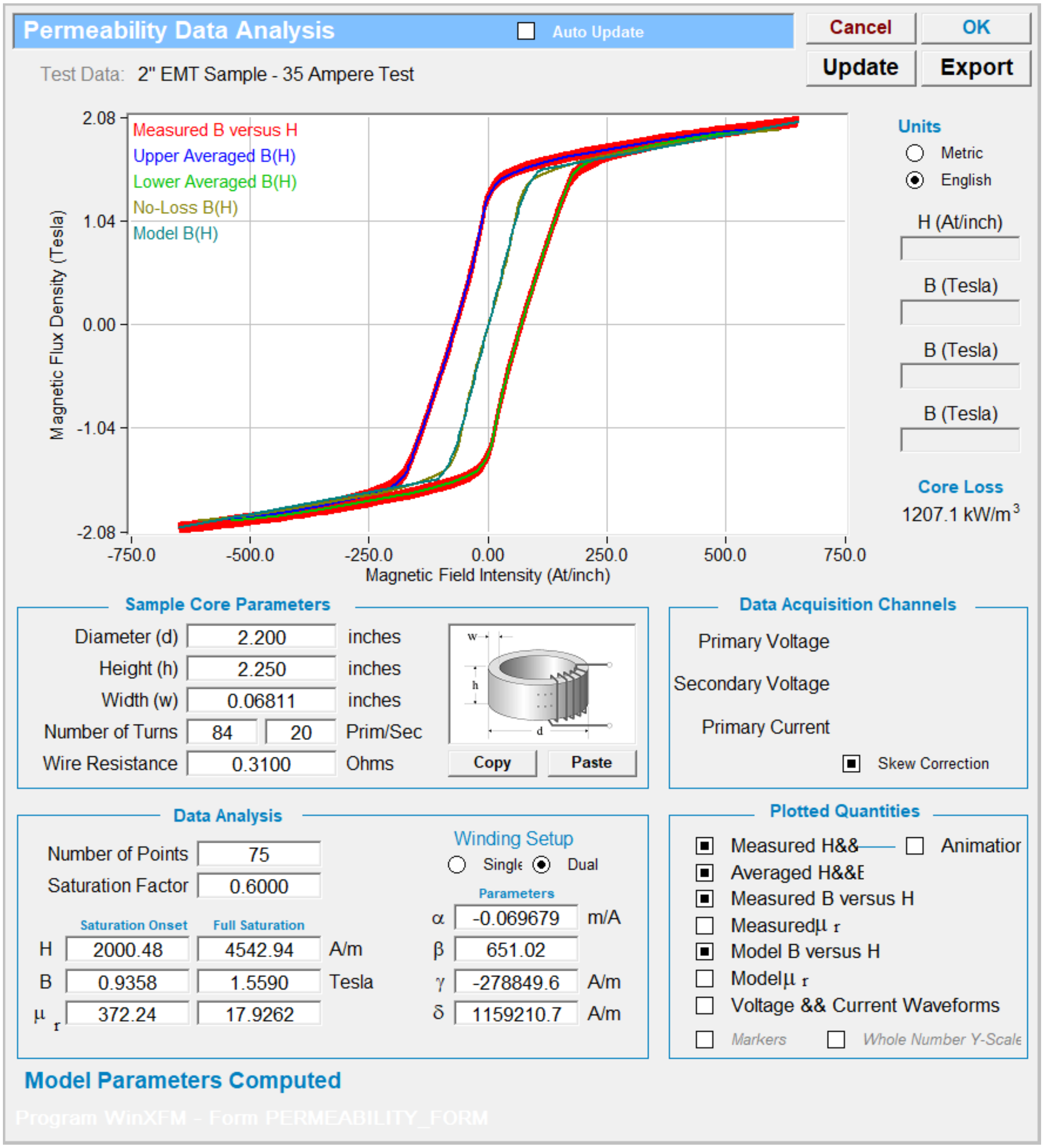


Figure R-13: EMT Permeability Measurement

Table R-2: Permeability Measurement Summary

```
PERMEABILITY MODEL
TITLE 2" EMT Sample - 35 Ampere Test
REL_PERM 372.239 17.9261
DELTA 1159206.67
H_SAT 2000.48 4542.94
QUAD_COEF -0.069679 651.0209 -278848.66
CORE_LOSS 1207139.22
END

PERMEABILITY MODEL
TITLE 2" GRC Sample - 35 Ampere Test
REL_PERM 128.266 11.4842
DELTA 1168018.36
H_SAT 6105.83 13897.52
QUAD_COEF -0.007494 219.7810 -279386.00
CORE_LOSS 3784657.76
END

PERMEABILITY MODEL
TITLE 2" IMC Sample - 35 Ampere Test
REL_PERM 189.913 13.6192
DELTA 1165406.93
H_SAT 4062.14 9159.05
QUAD_COEF -0.017294 330.4157 -285371.12
CORE_LOSS 2400560.09
END
```

Permeability Data from RMS Voltage and Current Measurements

The permeability characterization for IMC, EMT and GRC materials was repeated using RMS voltage and current measurements. This approach yielded a more accurate model because it made possible separation of the hysteresis effect from the magnetic saturation effect. 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)

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*.

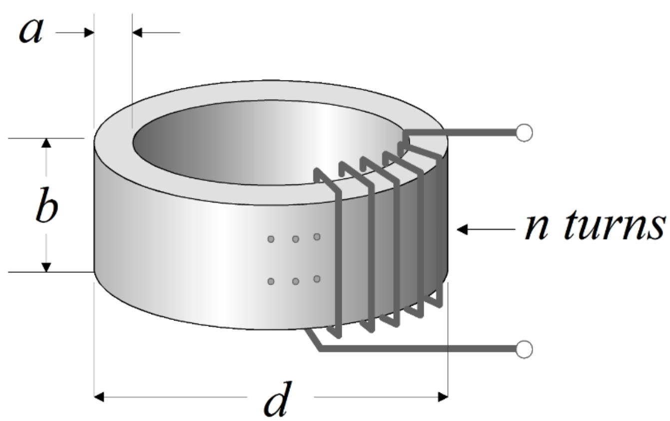


Figure R-14: Conduit Sample Geometric Data

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:

$$v(t) = \frac{d}{dt}\lambda(t) = \frac{d}{dt}\frac{ab\mu_0\mu_{rel}N_1N_2i(t)}{\pi(d-a)}$$

Assuming sinusoidal conditions, and converting to the frequency domain:

$$V = \frac{\omega ab\mu_0\mu_{rel}N_1N_2I}{\pi(d-a)}$$

Or:

$$\mu_{rel} = \frac{\pi(d-a)\mathrm{V}}{\omega ab\mu_0N_1N_2I}$$

The above formula can be used to compute the material permeability before saturation onset.

Figures R-15, R-16, and R-17 provide the measurement data for IMC material in plot form. Figure R-18 provides the parametric representation of the permeability data in terms of a piece-wise linear-quadratic curve. Similarly, Figures R-19 through R-26 provide the same information for the EMT and GRC materials.

Table R-3: 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 R-4: 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 R-5: 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

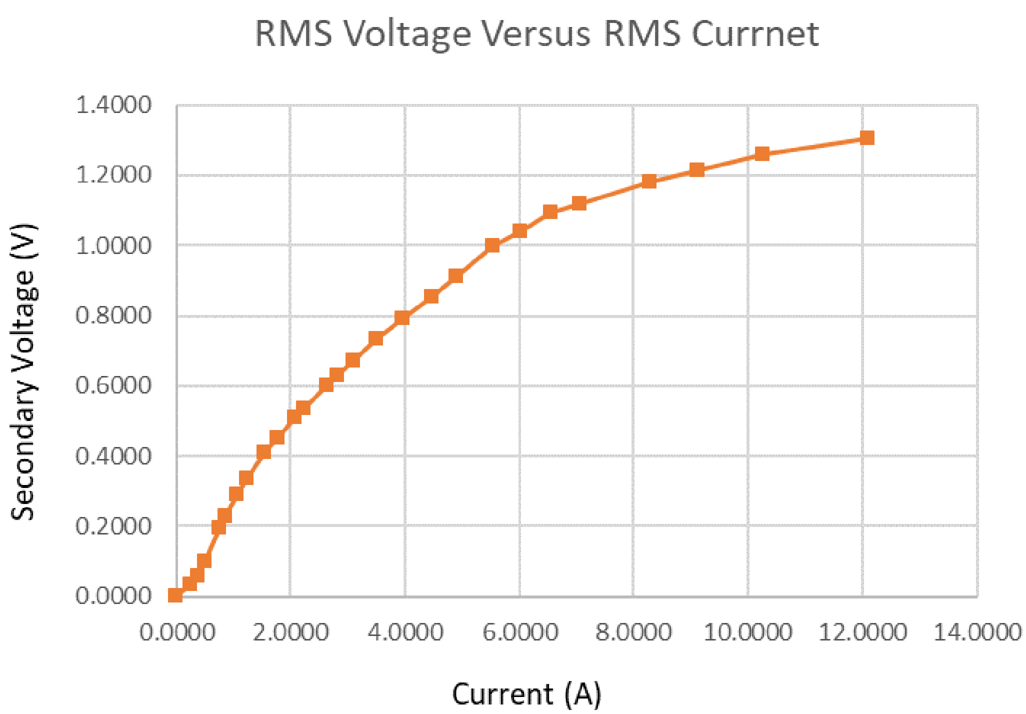


Figure R-15: RMS Voltage vs Current for IMC 2" Sample

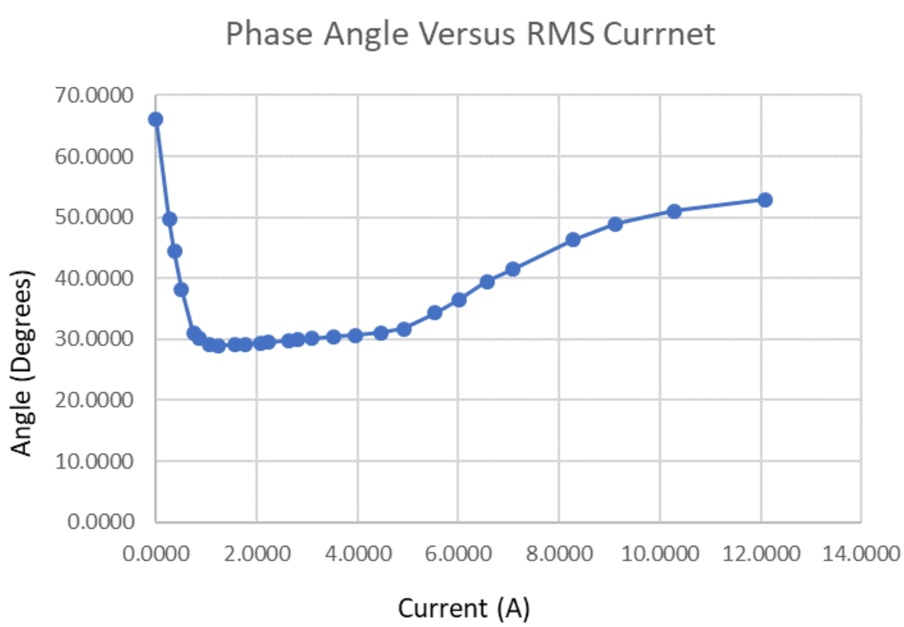


Figure R-16: V-I Phase Angle vs Current for IMC 2" Sample

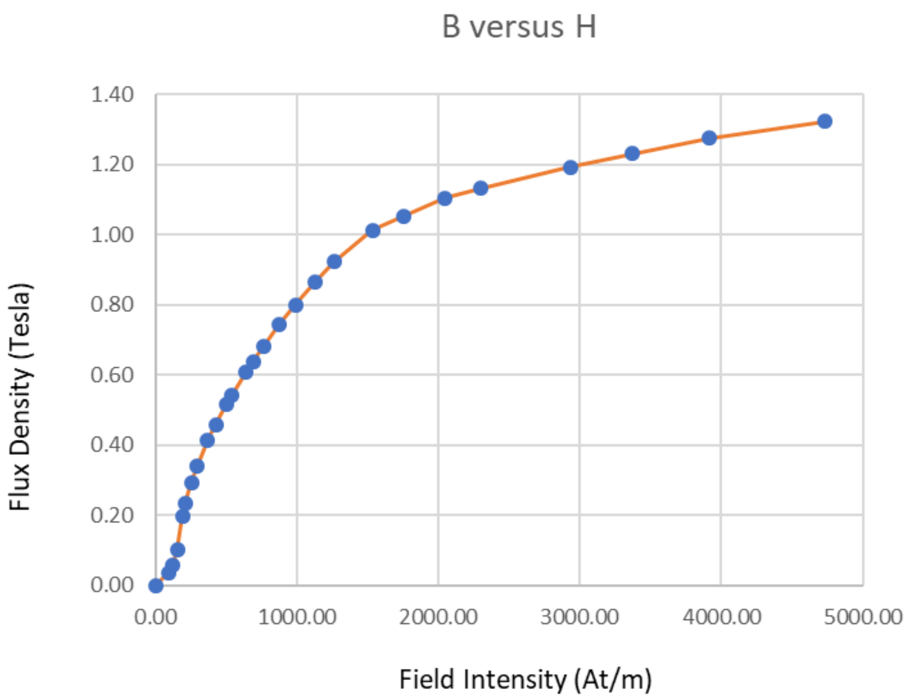


Figure R-17: B vs H for IMC 2" Sample

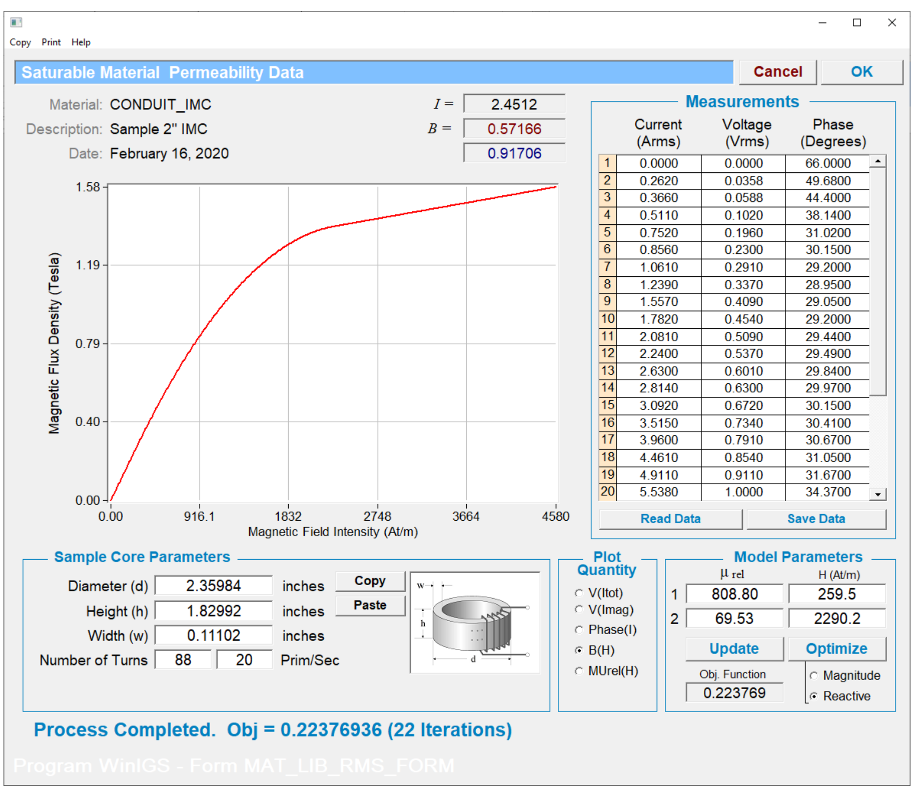


Figure R-18: PWLQ model of B vs H for IMC Material

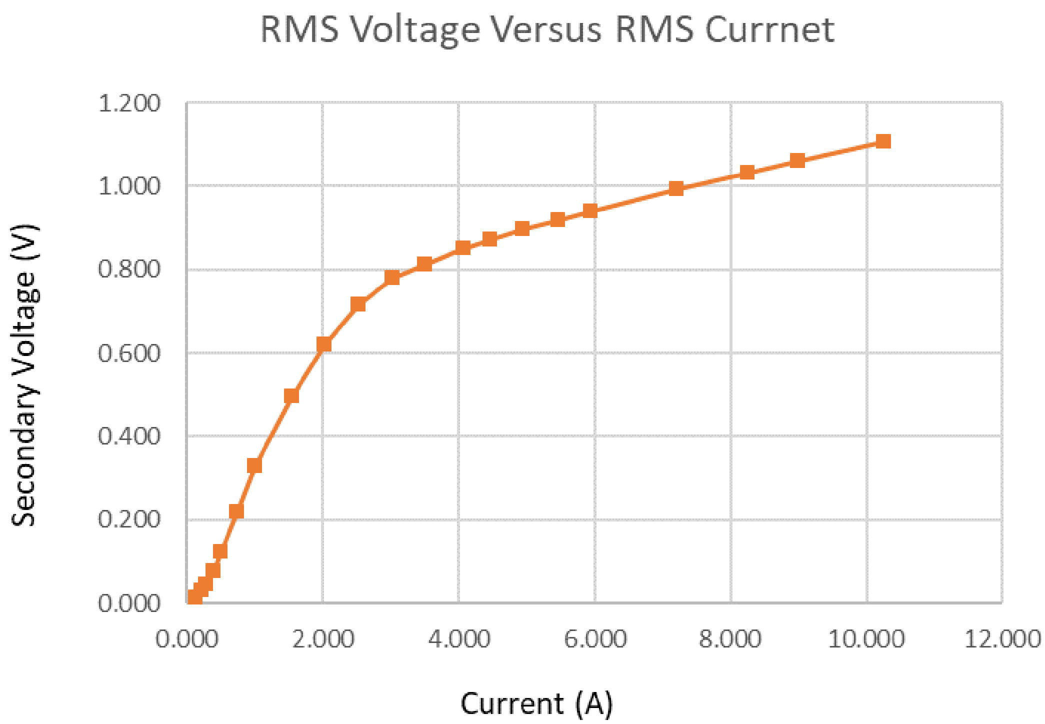


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Figure R-19: RMS Voltage vs Current for EMT 2” Sample

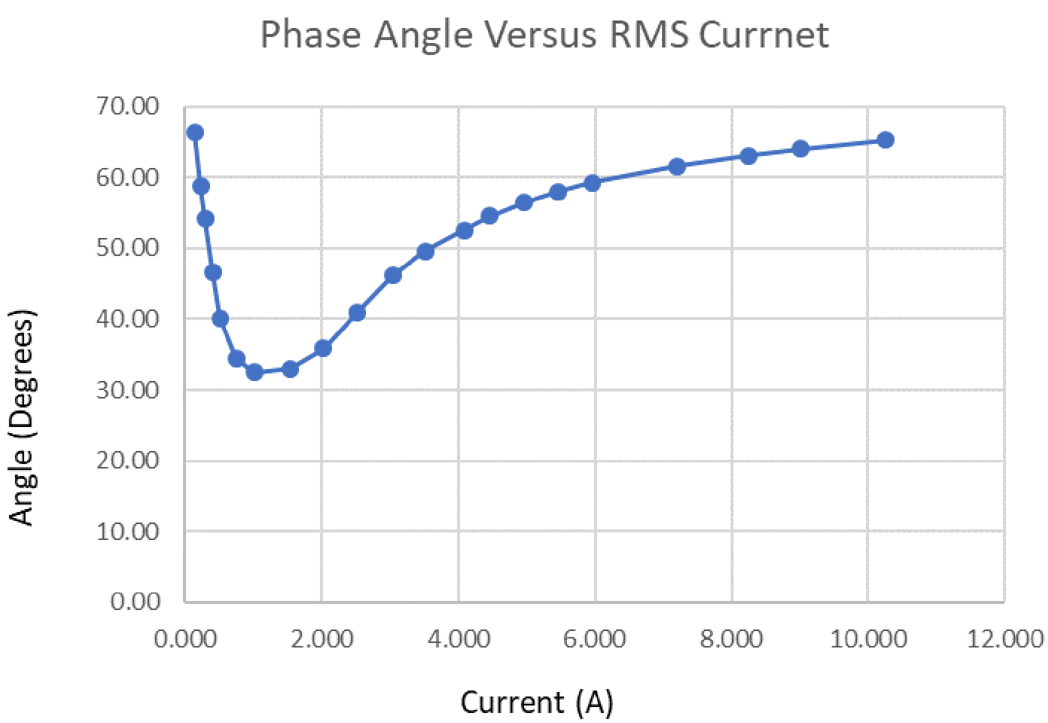

Figure R-20: V-I Phase Angle vs Current for EMT 2” Sample

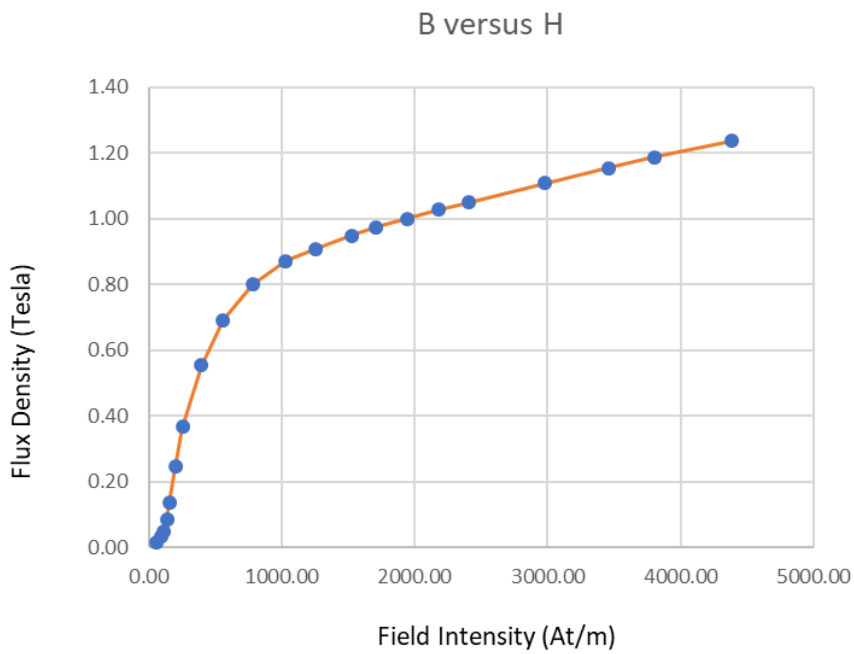

Figure R-21: B vs H for EMT 2" Sample

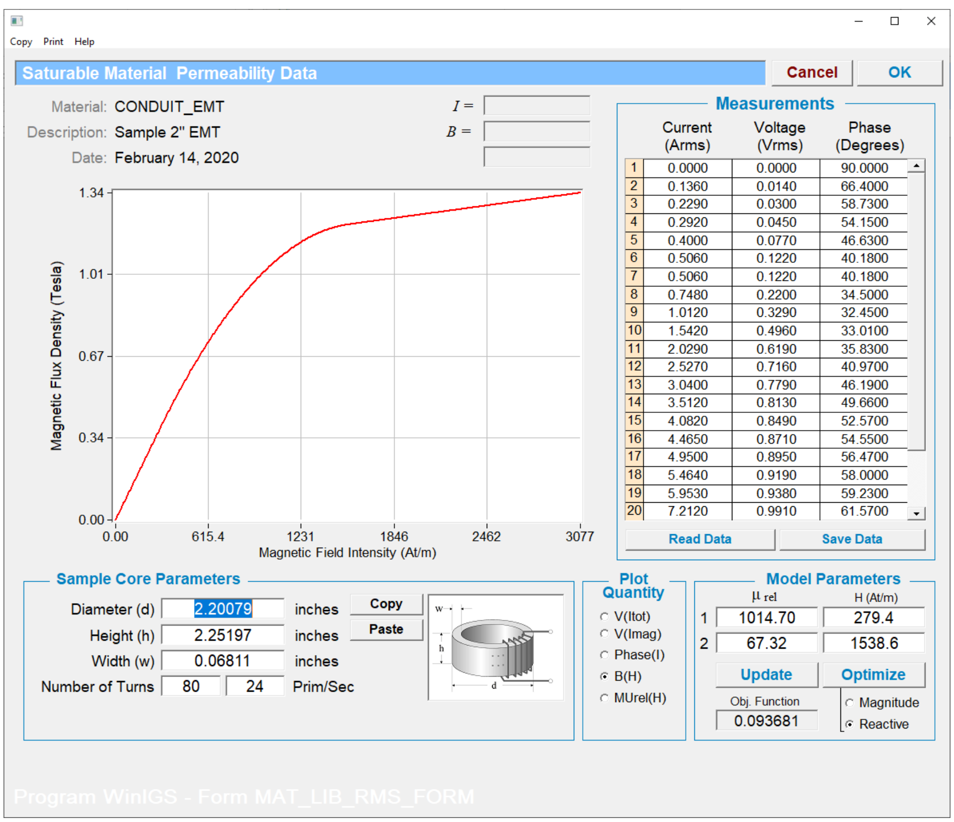

Figure R-22: PWLQ model of B vs H for EMT Material

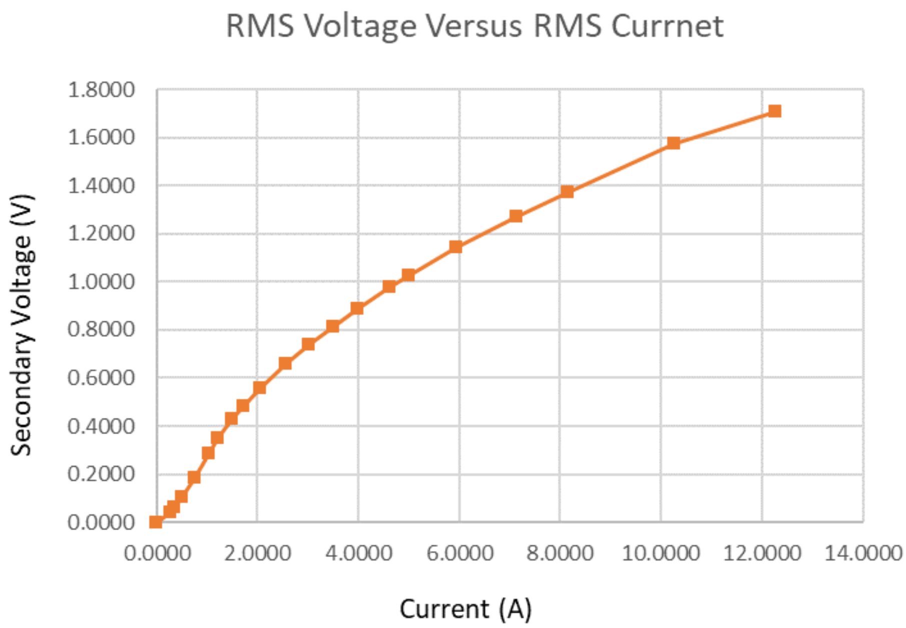

Figure R-23: RMS Voltage vs Current for GRC 2” Sample

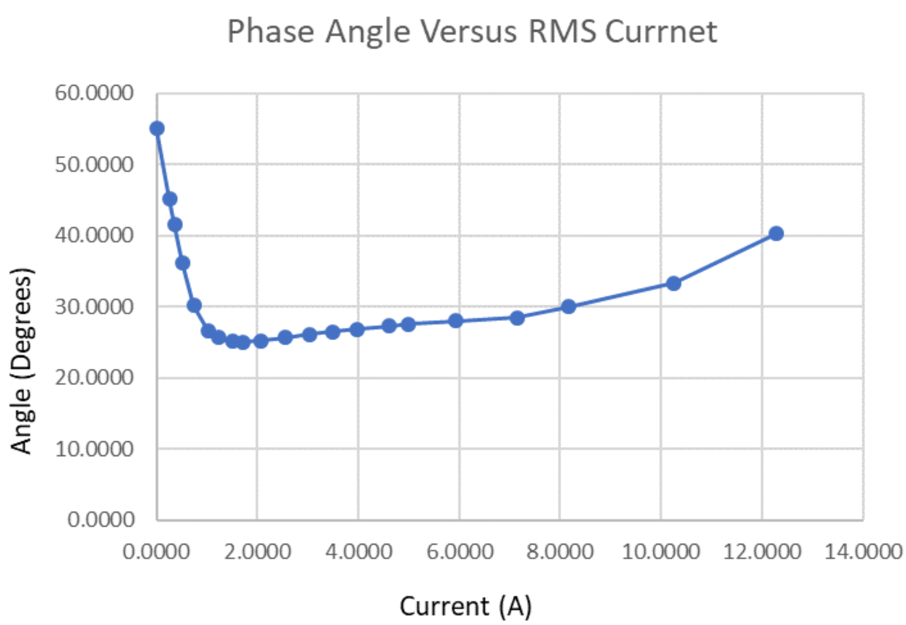

Figure R-24: V-I Phase Angle vs Current for GRC 2” Sample

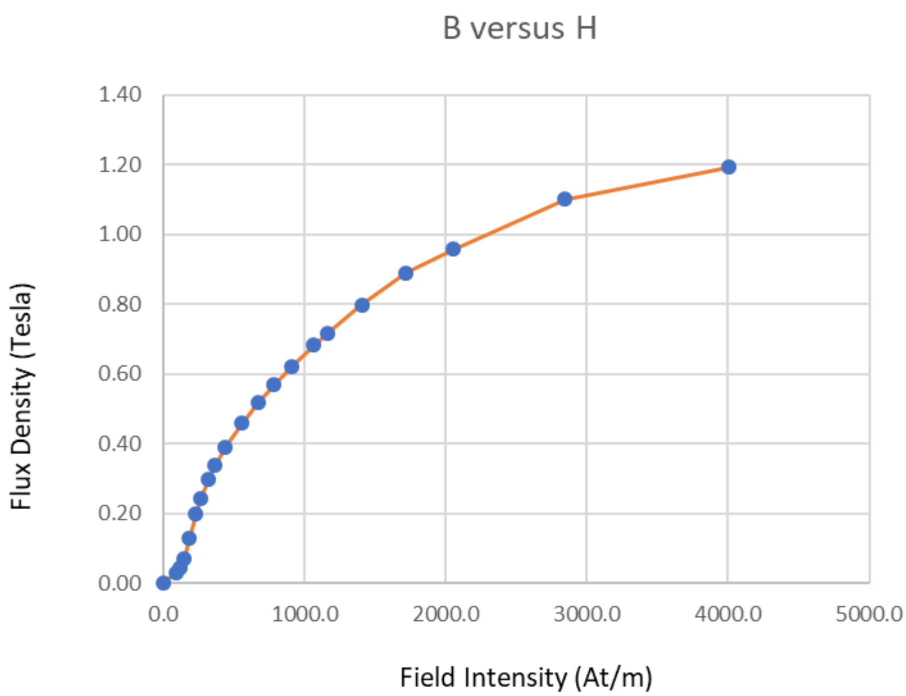

Figure R-25: B vs H for GRC 2” Sample

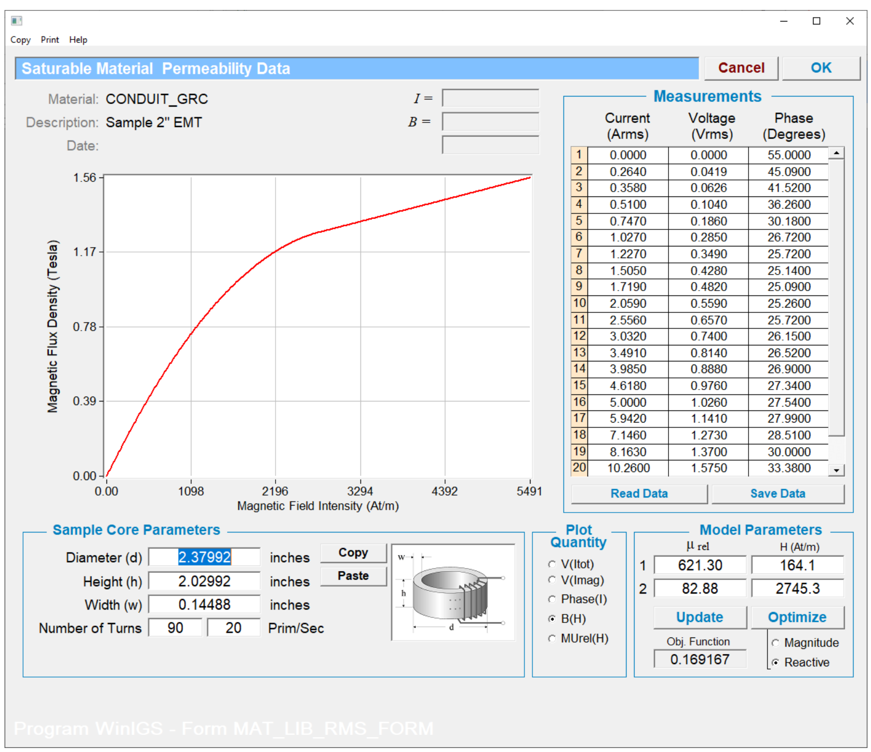

Figure R-26: PWLQ model of B vs H for GRC Material

Appendix S – Permeability Comparison of Various Metals

Figure S-1 shows the measured B-H curve obtained from a 2" EMT sample. As illustrated in this Figure, the saturation relative permeability is approximately 14.1.

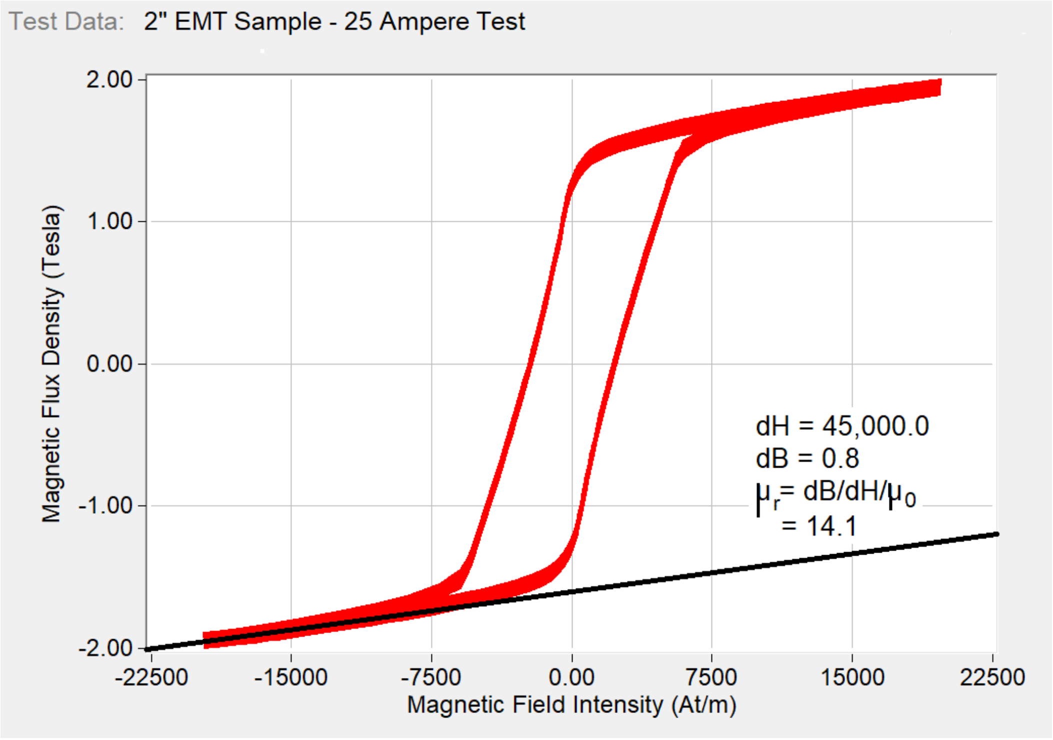

Figure S-1: Measured B-H curve obtained from a 2" EMT sample

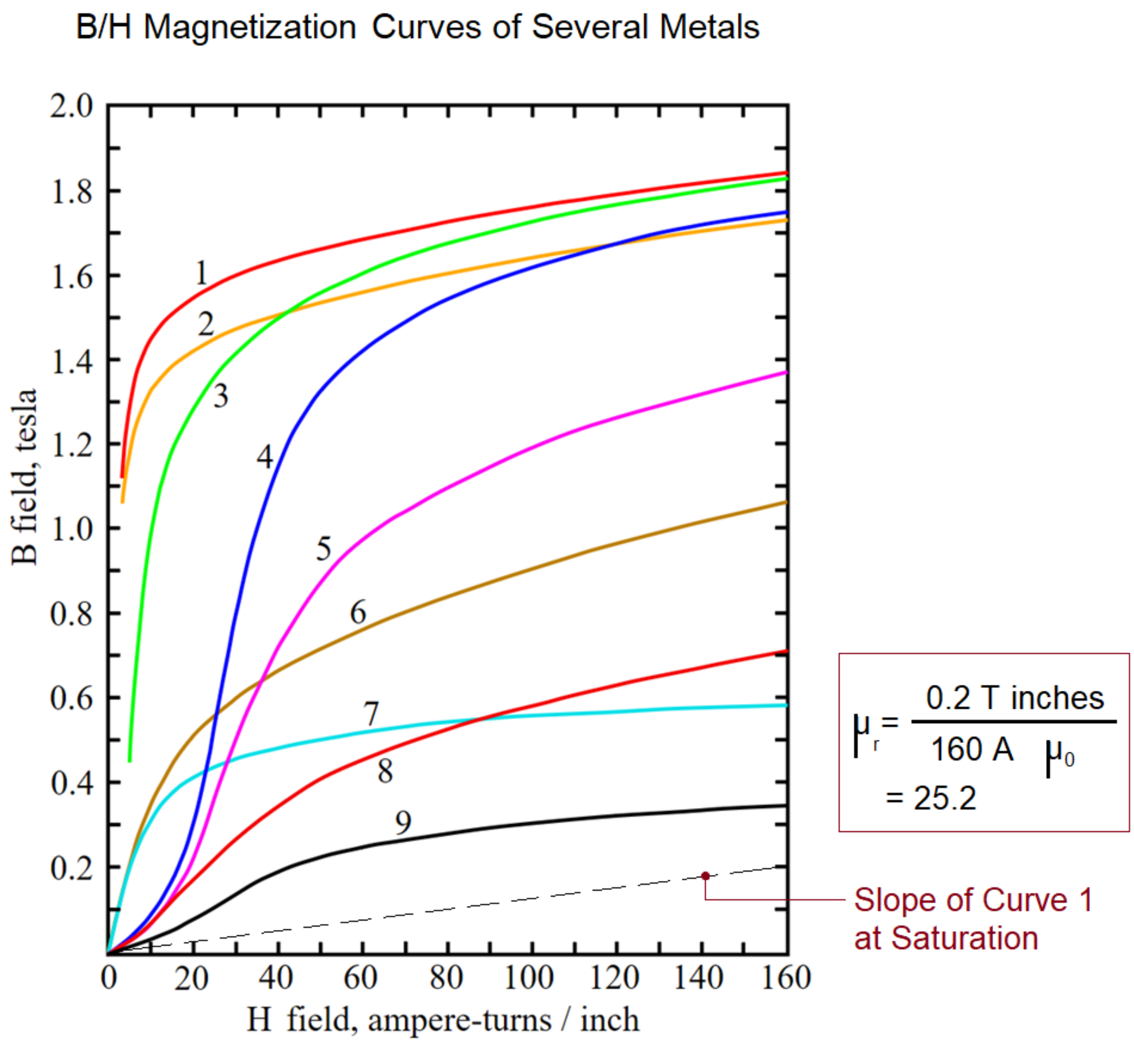

Figure S-2: B/H Magnetization Curves of Several Metals
Magnetization curves of 9 ferromagnetic materials, showing saturation.
1. Sheet steel, 2. Silicon steel, 3. Cast steel, 4. Tungsten steel,
5. Magnet steel, 6. Cast iron, 7. Nickel, 8. Cobalt, 9. Magnetite

Appendix T – Stainless Steel Permeability Measurement

Measurements performed using a stainless steel conduit sample indicated that the relative permeability of the stainless steel conduit material is very close to 1.0, i.e. this material is not magnetic.

Figure T-1 shows the voltage and current measurements performed on a 1” steel conduit sample (illustrated in Figure T-2). Note that the measured voltage and current are very nearly in phase (top 2 traces). The 3d trace was derived by subtracting the component of the voltage which is in phase with the current from the total voltage, yielding the inductive voltage component. Note that the inductive part is only 3.4 % of the total voltage.

Figure T-3 shows the time domain analysis method applied to the stainless steel measurement results. Note that there is no trace of saturation and the estimated relative permeability is 1.0.

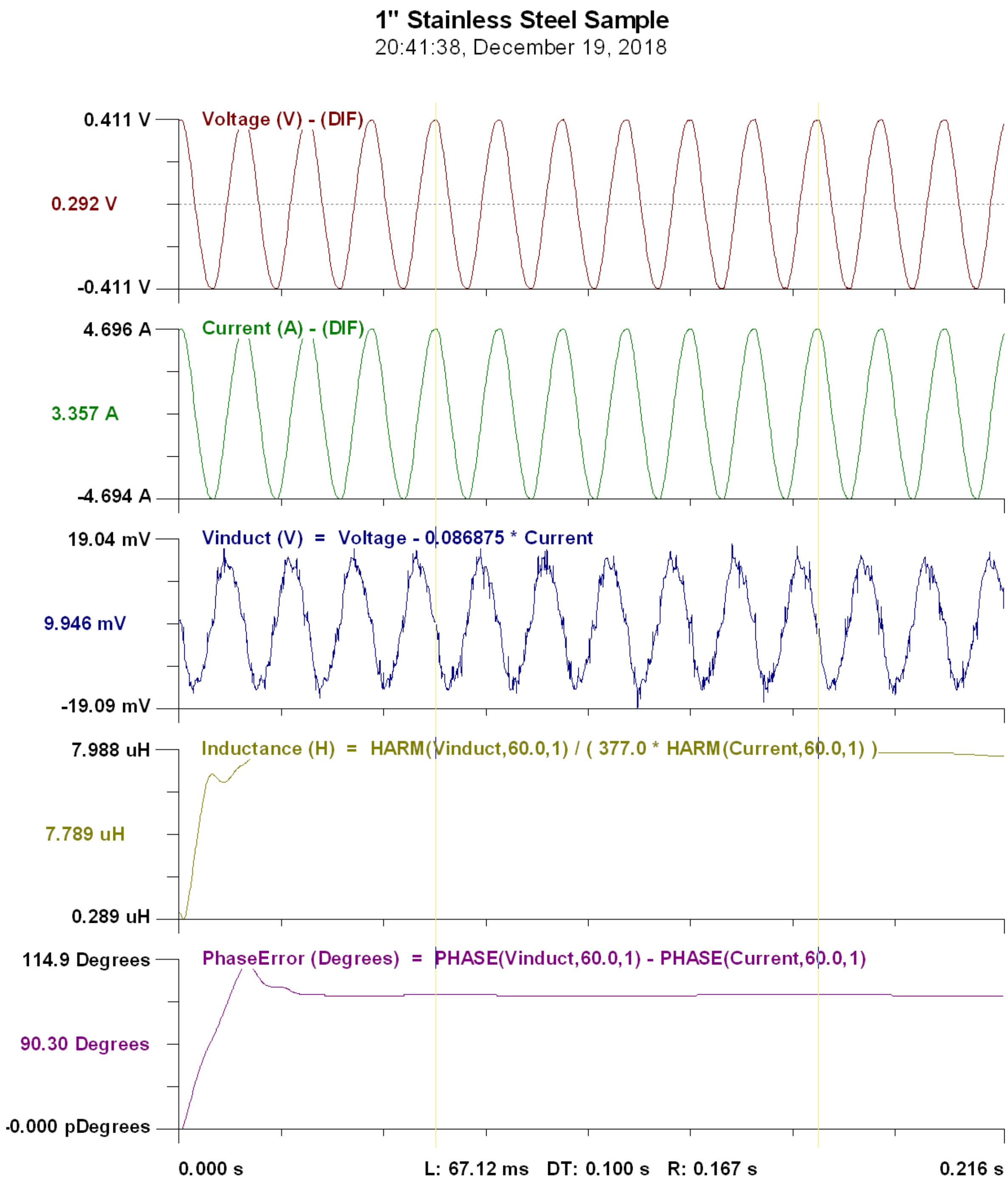

Figure T-1: 2” Stainless Steel Sample Measurement Results

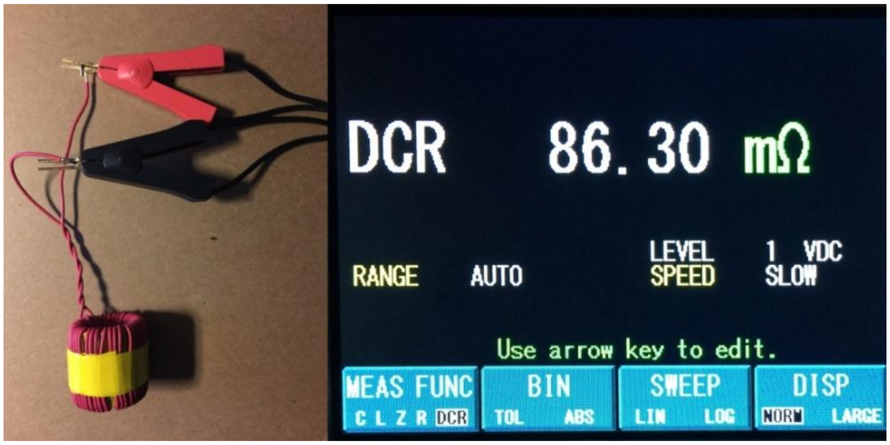

Figure T-2: Coil DC Resistance Measurement (4-Wire Test)

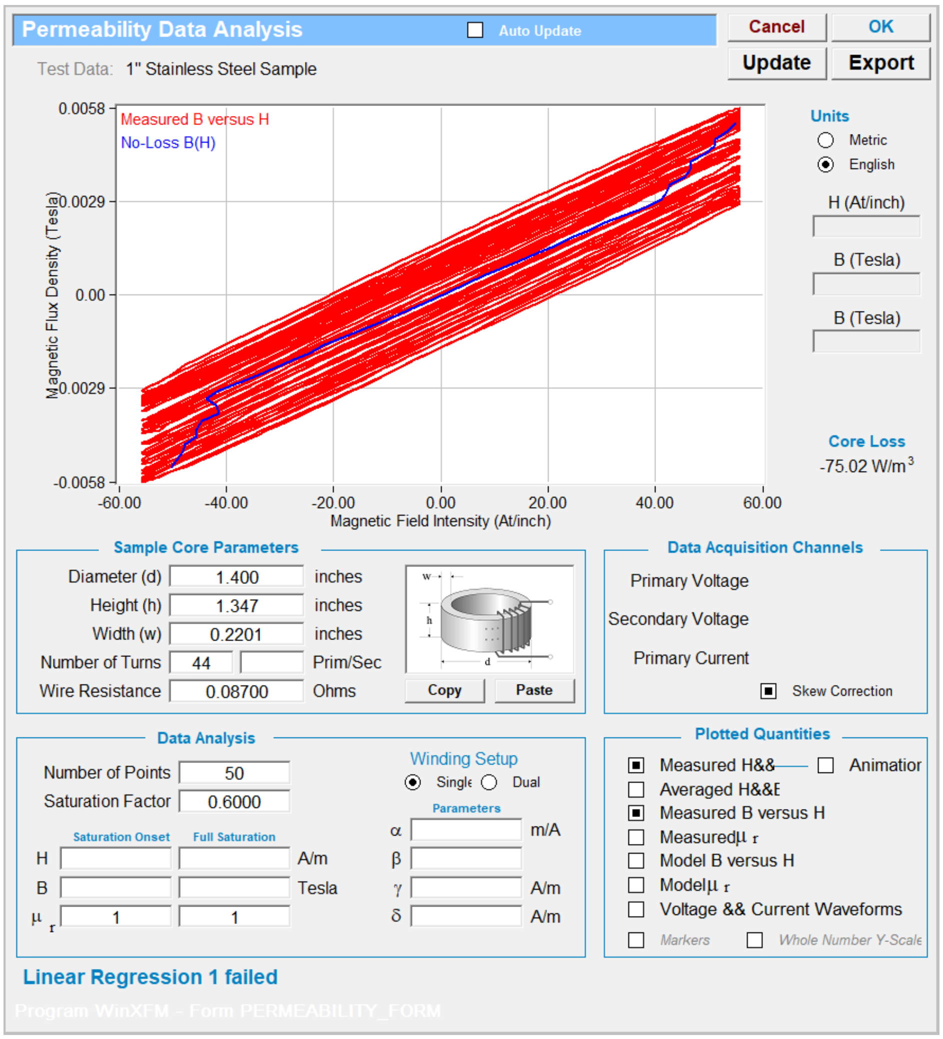

Figure T-3: Analysis of Permeability Data for a 1" Stainless Steel Sample