AC Ground Impedance Measurements

WESLEY A. ROGERS
Electronic Development, Inc.

INTRODUCTION

Determining how a ground path behaves at high frequencies is problematic, because a poor ground path is susceptible to radiation and will also radiate at frequencies above dc. A dc ground resistance measurement using a megohmmeter will not reveal this information. A poor ground path at high frequencies raises the noise floor level of RF enclosure test equipment, increases the susceptibility of circuitry in electronic consoles, and reduces the effectiveness of EMI filters. A ground impedance measurement system (GIMS), capable of measuring the impedance of ground paths between electronic control consoles and RF enclosures through grounding rods to earth, has been developed to address this problem.

A poor ground path is susceptible to radiation and will also radiate at frequencies above dc.

The GIMS is capable of measuring the individual impedance of three ground paths and the associated grounding rod to earth between 5 Hz and 1 MHz. The ground paths measured by the system can consist of a single grounding rod to earth, a ground grid to earth, or a combination of either in series with any type of wire or other connection from a remote location. Three typical ground-to-earth impedance paths between RF enclosures and earth (Z_1, Z_2 and Z_3) are indicated in Figure 1.

This article discusses ground path impedance measurements made with a GIMS at a customer's site and offers an analysis of the problems presented by poor ground paths at frequencies above dc.

QTY.	MODEL NO.	DESCRIPTION
1	HP3577A	Network Analyzer
1	HP35677A	S-Parameter Test Set
1	HP35676A	Trans Test Kit/Ref1
1	HP2225A	Ink Jet Printer
1	HP9122D	Dual Floppy Drive
1	HP217	Microprocessor
1	HP35721A	Video Monitor
1	HP46020A	Keyboard
3	HP10833A	HP/IB Bus Cables

TABLE 1. *S-Tran System Components.*

GROUND IMPEDANCE MEASUREMENTS USING GIMS

EQUIPMENT DESCRIPTION

The GIMS system hardware, shown in Figure 2, and listed in Table 1, can be easily transported to a measurement site. The equipment can also be rented locally if desired. The unique GIMS software required to perform the measurements is contained on a floppy disk.

Test leads between the S-Parameter Test Set and Z_1 and Z_2 shown in Figure 2 are calibrated out of the measurements by the GIMS software program. The user-friendly software program instructs the operator in a step-by-step fashion to perform the impedance measurements described below. The 50-foot long test cables, shown in Figure 1, are able to reach most ground paths at RF enclosures, electronic consoles, etc.

GROUND PATH IMPEDANCE MEASUREMENT TECHNIQUES USING GIMS

Two ground path-to-earth dc resistance measurement schemes using a megohmmeter are in general use at the present time: (1) the Three Point Measurement Method and (2) the Fall of Potential Method.

The Three Point Method measures the individual resistance of each path to earth by (1) selecting two other ground paths (building

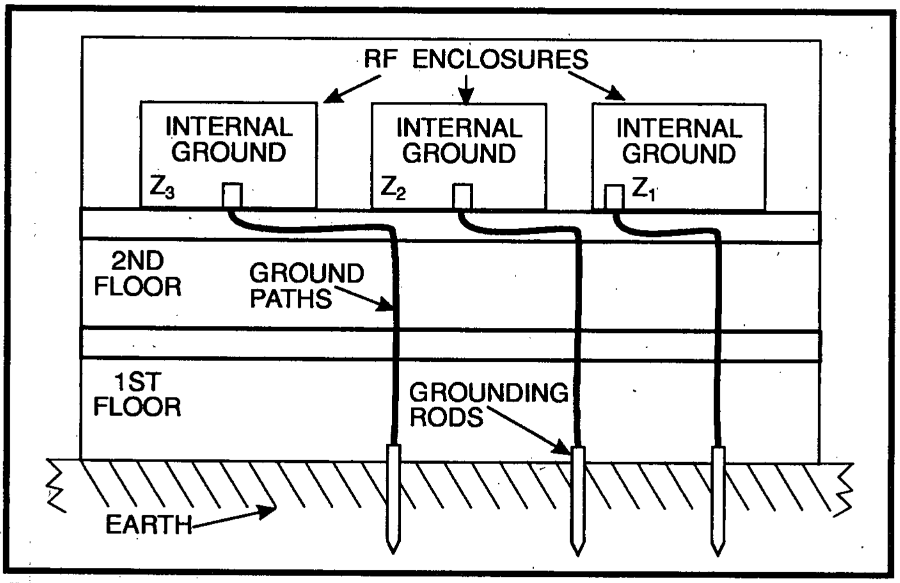

FIGURE 1. *Ground Paths and Grounding Rods to Earth.*

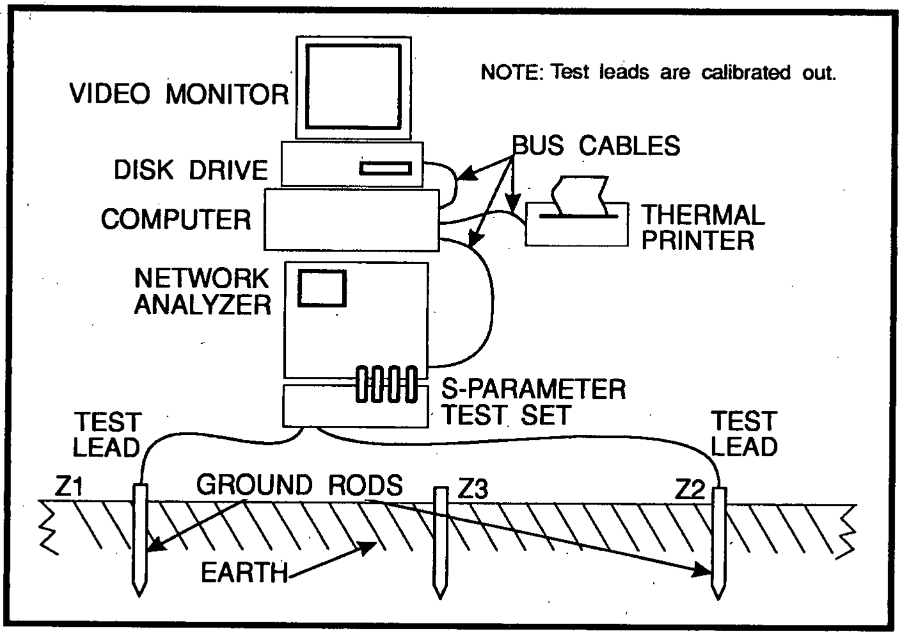

FIGURE 2. *Ground Rod Impedance-to-Earth Measurement with GIMS.*

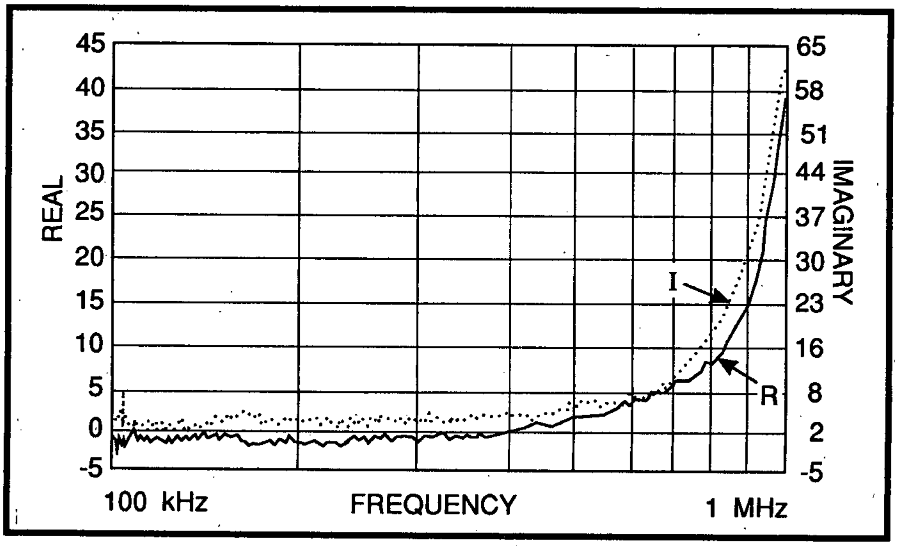

FIGURE 3. *Impedance of Ground Path Z_1 to Earth.*

FREQUENCY (MHz)	Z REAL	Z IMAGINARY	MAGNITUDE OF Z	ANGLE (DEGREE)
0.100	0.187	-2.629	2.636	85.935
0.106	0.716	0.758	1.042	46.635
0.112	0.118	0.632	0.643	79.381
0.119	0.565	0.852	1.023	56.437
0.126	0.608	0.890	1.078	55.694
0.133	0.671	0.950	1.163	54.784
0.141	1.365	1.242	1.845	42.306
0.150	2.093	0.866	2.265	22.473
0.158	1.974	-0.135	1.978	-3.501
0.168	1.353	0.426	1.418	17.491
0.178	0.487	0.450	0.663	42.728
0.188	0.887	0.082	0.891	-5.267
0.200	0.775	0.163	0.792	11.850
0.211	0.814	-0.256	0.853	17.427
0.224	0.690	0.432	0.814	32.025
0.237	0.630	0.131	0.644	11.713
0.251	0.677	0.353	0.763	27.571
0.266	1.342	0.269	1.369	11.326
0.282	0.844	0.057	0.846	3.867
0.299	0.711	0.277	0.763	21.264
0.316	0.740	0.429	0.855	30.074
0.335	0.824	0.573	1.004	34.833
0.355	0.956	0.855	1.283	41.812
0.376	1.006	1.973	2.215	62.987
0.398	1.145	1.133	1.611	44.708
0.422	1.181	1.569	1.964	53.022
0.447	1.470	2.348	2.771	57.962
0.473	1.726	2.630	3.145	56.720
0.501	2.677	3.185	4.097	51.030
0.531	2.516	3.103	3.994	50.960
0.562	2.779	3.856	4.753	54.225
0.596	2.953	4.625	5.487	57.445
0.631	3.445	6.403	7.271	61.715
0.668	3.945	8.438	9.314	64.944
0.708	4.976	12.181	13.159	67.779
0.750	6.161	14.800	16.031	67.399
0.794	7.637	18.942	20.424	68.042
0.841	10.665	25.473	27.616	67.282
0.891	15.500	34.463	37.788	65.785
0.944	26.396	47.187	54.068	60.778
1.000	40.712	61.974	74.150	56.698

TABLE 2. *Impedance Table for Z_1.*

pipes, etc.) within 50 feet of Z_1 and (2) measuring the impedance between each of the three ground paths shown, and (3) calculating the impedance of any or all of the ground paths to earth using Equations 1 through 9 below. Impedance calculations are performed by the GIMS software.

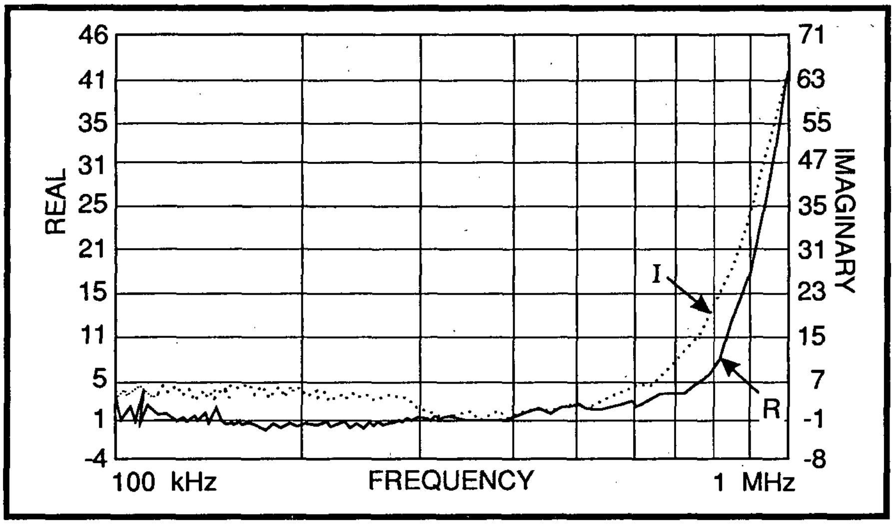

FIGURE 4. *Impedance Plot of Ground Path Z_2 to Earth.*

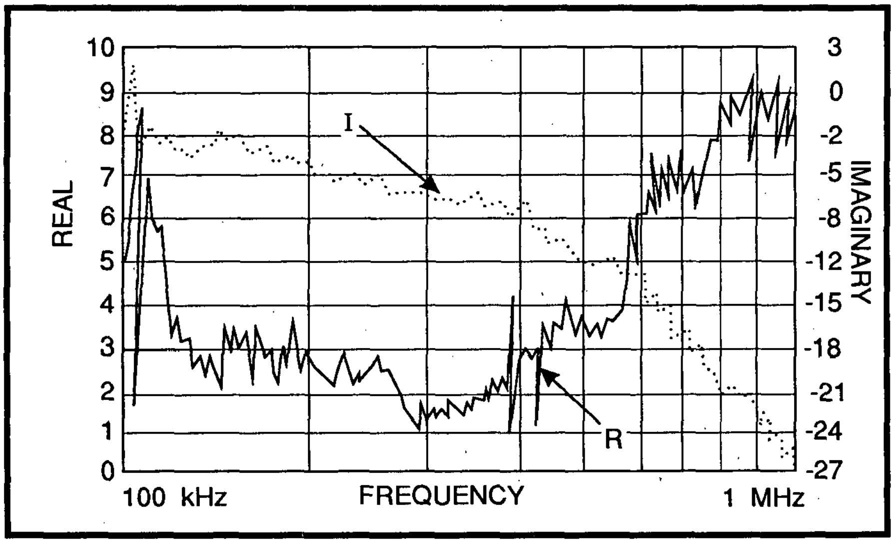

FIGURE 5. *Impedance Plot of Ground Path Z_3 to Earth.*

The ability to measure and print out the impedance to earth of a ground path between 5 Hz and 1 MHz reveals the existence of resonant points at various frequencies as a function of length, poor joints, skin effect, etc.

The GIMS follows the same approach, but measures the impedance rather than the resistance of the ground paths to earth. The GIMS software program calculates the impedance of each individual ground path to earth, or any selected path. It then calculates how the three ground path impedances change with frequency. Printouts of a client's ground paths indicating the impedance changes versus frequency measured by the GIMS over the frequency range 10 Hz and 1 MHz are shown in Figures 3 through 5 and Tables 2 through 4. The ability to measure ground path integrity at other than dc levels reveals problems that cannot be determined with resistive measurements only.

It is not possible to directly measure the impedance or resistance of a single ground path (for instance, Z_1 in Figure 1) to earth without providing a return path to the measuring equipment through a second ground path (Z_2 or Z_3).

FREQUENCY (MHz)	Z REAL	Z IMAGINARY	MAGNITUDE OF Z	ANGLE (DEGREE)
0.100	0.873	2.129	2.301	67.692
0.106	2.126	4.739	5.194	65.838
0.112	2.426	1.396	2.799	29.923
0.119	3.707	1.157	3.884	17.339
0.126	3.970	-0.004	3.970	-0.063
0.133	3.473	-0.237	3.481	-3.904
0.141	3.285	0.163	3.289	2.839
0.150	4.422	0.364	4.436	4.710
0.158	4.270	-1.347	4.477	-17.503
0.168	3.839	-2.066	4.359	-28.286
0.178	4.767	-2.262	5.277	-25.385
0.188	4.726	-2.356	5.280	-26.495
0.200	4.357	-3.409	5.532	-38.039
0.211	3.370	-3.747	5.040	-48.033
0.224	2.688	-4.200	4.987	-57.380
0.237	1.768	-3.645	4.051	-64.118
0.251	2.058	-2.680	3.379	-52.486
0.266	2.412	-3.225	4.027	-53.203
0.282	1.740	-3.700	4.089	-64.809
0.299	0.912	-3.293	3.417	-74.514
0.316	1.005	-2.721	2.901	-69.734
0.335	0.948	-2.468	2.644	-68.991
0.355	0.951	-1.987	2.203	-64.437
0.376	1.411	-2.629	2.983	-61.780
0.398	1.079	-1.428	1.790	-52.924
0.422	1.193	-0.620	1.345	-27.469
0.447	1.882	-0.280	1.903	-8.460
0.473	1.959	-0.105	1.962	-3.076
0.501	1.722	0.453	1.780	14.732
0.531	1.983	1.400	2.428	35.226
0.562	1.769	2.553	3.106	55.277
0.596	2.429	4.830	5.406	63.298
0.631	3.211	5.695	6.538	60.587
0.668	3.704	7.612	8.466	64.052
0.708	3.965	9.966	10.726	68.306
0.750	5.586	14.286	15.339	68.643
0.794	8.002	20.018	21.558	68.211
0.841	10.326	26.973	28.882	69.051
0.891	16.177	36.859	40.253	66.304
0.944	25.622	49.573	55.803	62.667
1.000	41.350	65.858	77.763	57.877

TABLE 3. *Impedance Table for Z_2.*

GIMS allows ac measurement of both the real and imaginary components of any or all of the impedance vectors associated with ground paths Z_1, Z_2 and Z_3 in Figure 1. The real component of

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FREQUENCY (MHz)	Z REAL	Z IMAGINARY	MAGNITUDE OF Z	ANGLE (DEGREE)
0.100	6.569	1.153	6.669	9.953
0.106	5.839	-4.862	7.598	-39.786
0.112	4.914	-5.310	7.235	-47.220
0.119	3.333	-5.796	6.686	-60.097
0.126	2.563	-5.352	5.934	-64.415
0.133	2.495	-4.842	5.447	-62.738
0.141	2.925	-4.648	5.491	-57.814
0.150	3.375	-4.810	5.876	-54.940
0.158	2.829	-5.742	6.401	-63.771
0.168	2.244	-6.293	6.681	-70.377
0.178	2.641	-6.300	6.831	-67.257
0.188	2.830	-6.144	6.765	-65.267
0.200	2.320	-6.194	6.614	-69.470
0.211	2.180	-6.446	6.804	-71.313
0.224	2.164	-6.667	7.009	-72.019
0.237	2.668	-7.077	7.563	-69.341
0.251	2.168	-7.868	8.162	-74.593
0.266	1.416	-8.011	8.136	-79.980
0.282	1.550	-7.525	7.683	-78.364
0.299	1.623	-7.927	8.091	-78.432
0.316	1.751	-8.027	8.216	-77.696
0.335	1.867	-8.151	8.362	-77.096
0.355	2.131	-8.311	8.580	-75.621
0.376	4.439	-7.955	9.110	-60.838
0.398	2.808	-9.401	9.811	-73.369
0.422	3.297	-9.630	10.178	-71.100
0.447	4.121	-10.589	11.363	-68.738
0.473	3.778	-11.478	12.084	-71.782
0.501	3.512	-11.546	12.068	-73.079
0.531	4.040	-11.804	12.476	-71.105
0.552	6.070	-11.549	13.047	-62.274
0.596	5.955	-13.208	14.488	-65.731
0.631	7.223	-15.236	16.861	-64.636
0.668	7.315	-16.246	17.817	-65.758
0.708	6.109	-16.428	17.527	-69.602
0.750	8.338	-17.238	19.148	-64.188
0.794	8.937	-19.227	21.203	-65.069
0.841	8.706	-19.950	21.767	-66.423
0.891	8.546	-21.092	22.758	-67.943
0.944	7.669	-22.681	23.943	-71.319

***TABLE 4.** Impedance Table for Z_3.*

the ground path impedance to earth will be defined in the discussion below as the real part of the vector Z where R = Z cos θ. The imaginary part of the impedance vector Z versus frequency is defined as X = Z sin θ. The ac resistance of the ground path to earth equals the real part of the impedance at frequencies where the phase makes the transition from negative to positive.

The unique feature associated with GIMS is a patented software program that allows the calculation and print-out of each or any one of the three ground paths to earth in Figure 2. The individual impedances to earth of Z_1, Z_2 and Z_3 are printed out in the following formats:

- Graphical plots of the real and imaginary components of Z_1, Z_2 and Z_3 in ohms to earth at 400 points between 5 Hz and 1 MHz, are shown in Figures 3, 4 and 5.

The unique feature associated with GIMS is a patented software program that allows the calculation and print-out of each or any one of the three ground paths to earth.

- Tabular plots of the magnitudes of Z_1, Z_2 and Z_3, real and imaginary components and phase angle are shown in Tables 2, 3 and 4.

The graphs in Figures 3, 4 and 5 and Tables 2, 3 and 4 were printed out for the customer in two separate measurements; the first over the frequency range 5 Hz to 100 kHz, and the second between 100 kHz and 1 MHz. For purposes of brevity, only the second set of impedance plots and tables is indicated.

Each step in the GIMS measurement procedure is displayed on the monitor screen (Figure 2). Graphical printouts of impedance plots are displayed on the monitor screen prior to print-out.

The following procedure indicates the manner in which GIMS is connected to measure the individual ground path impedances to earth of Z_1, Z_2 and Z_3 in Figure 2.

The GIMS impedance measurement leads are successively placed between Z_1 and Z_2, Z_1 and Z_3, and Z_2 and Z_3. The GIMS test leads are shown connected to Z_1 and Z_2 in Figure 2. Impedance measurements are made between 5 Hz and 1 MHz by following step-by-step instructions on the monitor screen. A rapid software calibration procedure eliminates the GIMS probe impedances from the ground path-to-earth impedance measurements.

GIMS stores the three impedance measurements Z12, Z13 and Z23 indicated in Equations 1, 2 and 3 below. The real vector components R_1, R_2 and R_3 as well as the imaginary components of X_1, X_2, X_3 of each separate impedance path Z_1, Z_2 and Z_3 are extracted from the combined impedance path measurements Z12, Z13 and Z23 by solving the following equations.

$$Z_1 \text{ to earth} = R_1 + jX1 = (Z12 + Z13 - Z23) / 2 \quad (1)$$

$$Z_2 \text{ to earth} = R_2 + jX2 = (Z12 + Z23 - Z13) / 2 \quad (2)$$

$$Z_3 \text{ to earth} = R_3 + jX2 = (Z13 + Z23 - Z12) / 2 \quad (3)$$

The terms Z12, Z13 and Z23 are complex impedances consisting of a real impedance vector component and either an inductive or capacitive component that changes in magnitude as a function of frequency. Consequently, the real and imaginary vector components of Z_1, Z_2 and Z_3 must be added separately by GIMS at points between 5 Hz and 1 MHz, by the GIMS software, to obtain the values of R_1, R_2, R_3 and X_1, X_2 and X_3 in Equations 1, 2, and 3 above. Equations 4 through 9 illustrate this operation.

$$R_1 = 1/2\,(R12 + R13 - R23)\ \Omega \quad (4)$$

$$X_1 = 1/2\,(X12 + X13 - X23)\ \Omega \quad (5)$$

$$R_2 = 1/2\,(R12 + R23 - R13)\ \Omega \quad (6)$$

$$X_2 = 1/2\,(X12 + X23 - X13)\ \Omega \quad (7)$$

$$R_3 = 1/2\,(R13 + R23 - R12)\ \Omega \quad (8)$$

$$X_3 = 1/2\,(X13 + X23 - X12)\ \Omega \quad (9)$$

The impedance of the Z_1 ground path increases in magnitude as expected at 600 kHz due mainly to the inductance of the ground path lead between the RF enclosure and grounding rod. Above a few hundred kHz the capacitive or inductive impedance vector increases rapidly. The magnitude versus frequency of the inductive or capacitive vector component depends upon the shape of the rod, the inductance, and the distributed capacitance of the ground path to the rod.

ANALYSIS OF THE GROUND PATH IMPEDANCE GRAPHS

The impedance versus frequency of ground path Z_1 to earth was fairly well behaved. The real magnitude of the impedance vector was 101 ohms when measured at dc and it increased with frequency to the resistance levels indicated in Figure 3 at 100 kHz. Note the slight resonance point that increases the resistance to 5 ohms at 100 kHz. The inductive imaginary component of the impedance vector is less than an ohm to 450 kHz and then increases rapidly above 450 kHz.

The magnitude versus frequency of the inductive or capacitive vector component depends upon the shape of the rod, the inductance, and the distributed capacitance of the ground path to the rod.

The ground path impedance to earth printouts of Z_1, Z_2 and Z_3 indicate the magnitude of the real part of the associated impedance vector along the left ordinate in ohms and the magnitude of the imaginary vector along the right ordinate in ohms. The abscissa is displaced in terms of frequency. The dotted trace represents the imaginary component of the impedance vector and the dark solid trace represents the real component of the impedance vector displayed at 40 points over the frequency range 100 kHz to 1 MHz.

The customer decided not to improve this ground path.

The real component of impedance vector Z_2 when measured at dc was 0.03 ohms. Ground path Z_2 also resonated slightly at 100 kHz and the resistive component of the impedance vector then increased to between 2 and 3 ohms between 120 and 380 kHz. A rapid rise in the inductive component of the impedance vector then occurred due to the properties of the ground path.

The customer noticed a slightly higher ground floor level on the spectrum analyzers used in the RF enclosure associated with this ground path but decided not to improve the ground.

The third ground path, Z_3, was a poor one, having a dc resistance of 0.08 ohms, and resonated badly at 100 kHz as well as at much lower frequencies not indicated on the printout. The spectrum analyzer noise ground floor level was quite high in the enclosure grounded by this rod and was the reason the customer contacted us. Note the magnitude of the real and imaginary components of impedance vector Z_3.

The ground path was replaced with one having better welds and wider ground braiding, and the ground rod was reinstalled into a bed of earth treated with a liquid compound for better conduction. The improved ground path eliminated the measurement problems associated with this enclosure.

GIMS SOFTWARE PROGRAM DESCRIPTION

The software program consists of the five main branches listed below:

A) Status Screen
B) Measure Grounds
C) File Load
D) GIMS Analysis
E) Restart

Status Screen

The status screen is the main part of the program. It controls file management and allows users to select the branch of the program which they choose to run.

Measure Grounds

This branch of the program contains many functions. It controls the network analyzer through the HP - IB bus during ground measurements. The operator is prompted through a procedure that calibrates the impedance of the test cables so that the impedance is not recorded as part of the ground path-to-earth impedance being measured.

After calibration, the ground to be measured is connected to the network analyzer and a device name is selected. The device name is the file name under which the measured data will be saved for later evaluation. The analyzer "captures" the data into one of its registers. The GIMS software then retrieves the data and stores it on a floppy disk for immediate evaluation. The operator has the option of reviewing the data. After the data is reviewed it may be stored or discarded.

File Load Option

This option allows the operator to recall a file from disk and store it in RAM. Then the operator can recall the data and assign it to an array (i.e., Y1 (X) values over a selected frequency range) for later use. The user can retrieve the ground path impedance components Z12, Z13 and Z23 data files from the disk. This data, Z12, Z13 and Z23, is manually stored in the technical computer RAM.

GIMS Analysis

After a file is retrieved from the disk and placed in RAM using the file load option, the user chooses the GIMS analysis option. At this point the program enters the GET Z subroutine. The user is asked to choose a path, Z12, Z13 or Z23. The user's choice is based upon where the data came from during measurement of the ground impedance paths. After a path is chosen, the program prompts "Do you wish to calculate impedances?" The operator responds "yes" or "no" on the keyboard. The operator responds "no" until Z12, Z13 and Z23 are assigned to corresponding arrays.

Once data has been assigned to all three paths, the user responds with a yes. The computer then calculates Z_1, Z_2 and Z_3.

After the calculations are made, the program goes to the display mode. At this point the operator has the choice of printing Z_1, Z_2 and Z_3 in both tabular and graphical formats.

Restart

The Restart option clears the current file from memory so that other data may be retrieved from the disk. Restart does not clear the array in which the data was assigned in the GET Z subroutine.

Additional Options

Other branches within the program are *Edit Header* and *New Destination*. *Edit Header* is the part of the program that creates the labels that will be displayed at the top of the plots when they are printed out.

New Destination tells the computer where to store the above data on either drive "O" or drive "1" disks.

Program Code Printout

The program code list contains 6,000 lines. It is a unique program designed to calculate the individual ground-to-earth impedances over the frequency range 10 Hz to 1 MHz of each of three ground paths in accordance with the Three Point Measurement Method.

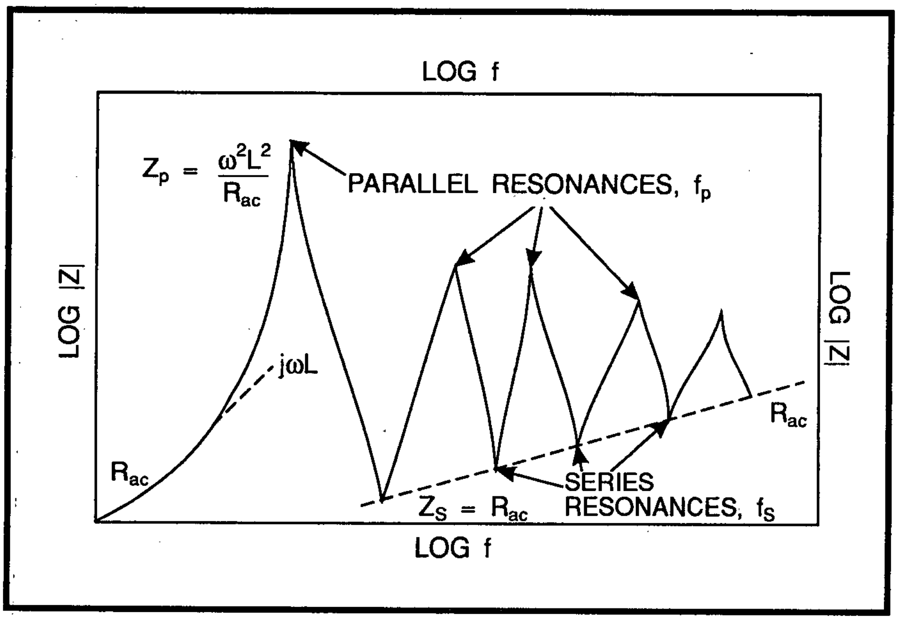


***FIGURE 6.** Typical Impedance vs. Frequency Behavior of a Grounding Conductor.*

ANALYSIS OF THE REAL AND IMAGINARY COMPONENTS OF GROUND PATH IMPEDANCE

The impedance of a grounding system is controlled by five major factors:

- Skin Effect
- Resonance
- Antenna Effect
- Bonding
- Earth Impedance

A brief discussion of each is presented below. A complete mathematical analysis is beyond the scope of this article.

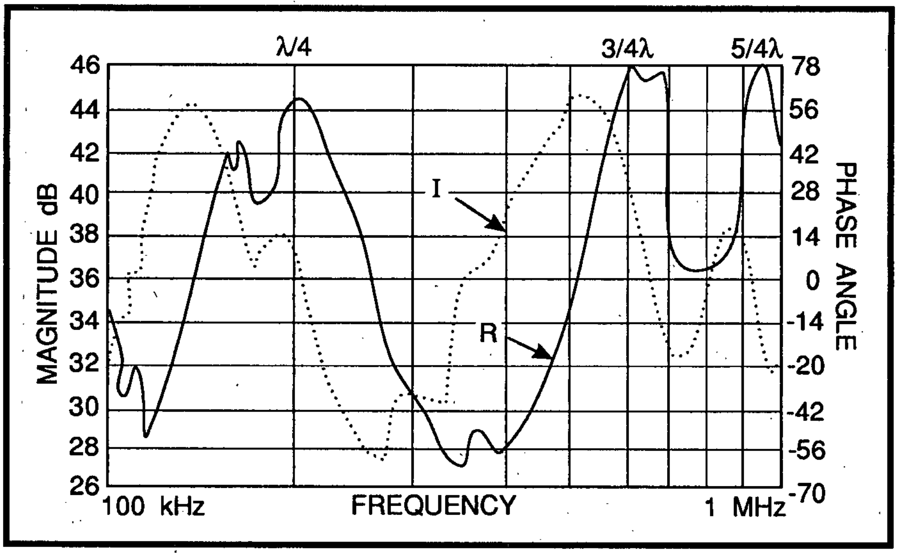


FIGURE 7. *Actual Impedance (Mag and Phase).*

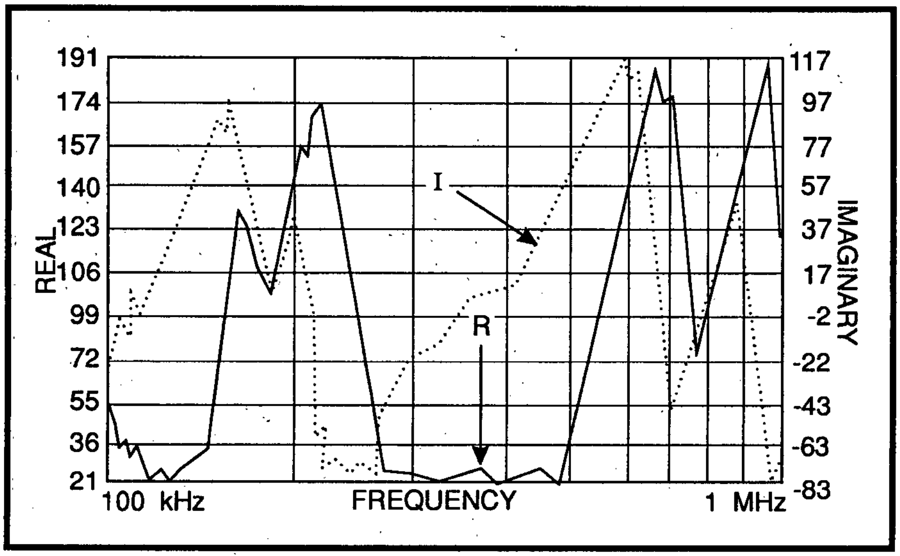


FIGURE 8. *Actual Impedance (Real and Imaginary).*

SKIN EFFECT

Skin effect is the increase in current density (J_z) near the edge of a solid conductor as frequency is increased. This phenomenon causes the real and imaginary components of conductor impedance to increase as a function of frequency.

According to electromagnetic theory, the currents and fields within a solid circular conductor are regarded as having penetrated from the outer surface toward the center. Maxwell and Bessel established a set of relationships that quantitatively specify the current density at any radius from the center as a vector, J_z. The current density vector J_z increases in proportion to a radius vector r to a maximum when the radius equals (a) — the radius to the conductor surface. This effect becomes more pronounced with increasing frequency leading to the skin effect.

The increase in the resistance of the real component of the impedance vectors in Figures 3, 4 and 5 is due to skin effect. A solid conductor looks like a hollow shell having very thin walls at frequencies above 100 kHz.

RESONANCE

Both parallel and series resonance are exhibited by ground structures as a function of frequency. Engineers have long known of their existence, but have not been able to measure the impedance characteristics of these resonances until the advent of GIMS.

Engineers generally refer to the efficiency of a ground structure in proportion to its diameter: the bigger the better. This is not necessarily so when frequencies higher than 100 kHz are carried. A solid copper grounding structure can appear as a thin hollow path to RF currents.

It can be shown that the efficiency of a ground current conductor at dc is reduced by 50 percent or more at higher frequencies due to both series and parallel resonances. These resonances are caused by distributed inductance along the conductor and parasitic capacitance to nearby metal surfaces and bonded joints along its length.

Figure 6[1] indicates a theoretical plot of parallel and series resonances versus frequency found on typical ground path conductors. Actual impedance versus frequency measurements made with GIMS at a customer's site on a resonating ground path between the RF enclosure and earth are shown in Figures 7 and 8. These measurements exhibit the same parallel and series resonant structure that was theoretically calculated in Figure 6.

At parallel resonance, the path impedance to earth is much higher than would be expected due to skin effect alone. The high ground path impedance to earth impedance at resonance isolates the equipment to be grounded from the grounding rod and earth.

ANTENNA EFFECTS

Antenna effects are related to the resonances indicated in Figures 6, 7 and 8. Ground path conductors will both radiate and pick up interference as a function of their lengths relative to a wavelength (λ/m) = 300/frequency in MHz.

The length of a ground path can be calculated by determining the first resonant point which is the quarter wavelength frequency, and substituting it in the equation below. The printouts shown in Figures 7 and 8 indicate a first quarter wave resonant point at 200 kHz. The 3/4 wave point falls at 600 kHz and the 5/4 wave resonant point falls at approximately 1 MHz as indicated in the impedance versus frequency plot for that point.

The length of this ground path is calculated as follows:

$\lambda = 300/f(\text{MHz}) = 300/0.2 = 1{,}500$ m

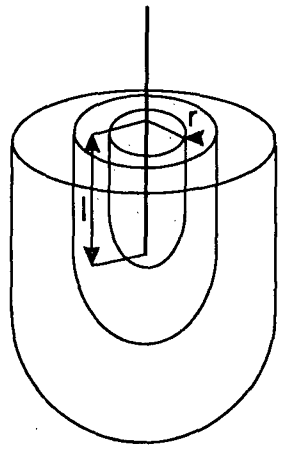
Therefore $\lambda/4 = 1{,}500/4 = 375$ m

Note that on the impedance plots for Z_3 in Figure 6 above, the sign of the imaginary part of the impedance goes from positive to negative (inductive to capacitive) at each parallel resonant point. This is characteristic of antenna resonance.

BONDING

An effective bond is said to have a bonding resistance below 2.5 milliohms. A low dc bond resistance is not, however, a good indication of the quality of the bond at high frequencies. Inherent bond inductance and stray capacitance along with associated standing wave effects determine bond impedance at high frequencies (i.e., above 100 kHz).

The equivalent high frequency circuit of the bond is indicated as an inductive impedance in parallel with a capacitor. This combination forms a parallel anti-resonant circuit. The effect of these bonds can be seen on charts of anti-resonant frequency versus inductance and capacitance. Parallel resonance in bonds, just as in ground straps, leads to poor RF ground paths that cannot be detected with dc resistance measurements.



r in m	Percent of Resistance
0.03	25
0.06	38
0.09	46
0.15	52
0.3	68
1.5	86
3.0	94

FIGURE 9. *Conceptual View of Earthing Resistance.*

EARTH IMPEDANCE

Ground resistance is calculated either by application of field theory or by empirical dc resistance, or impedance measurements with GIMS. The majority of the resistance between the grounding rod and earth is determined by earth impedance immediately adjacent to the rod. Soil resistivity is defined in ohm - meters for different types of soil and water content.

Soil resistance is presently given in terms of concentric shells of resistance at progressively larger radii from the grounding rod as shown in Figure 9.[2] Impedance measurements include both the resistance in ohms and the reactance between the soil and the ground rod.

Soil resistance is inversely proportional to the radius r from the rod due to the larger area encompassed by the circular shells as r is increased. Consequently, earth impedance is highest for small values of r close to the rod.

CONCLUSION

It is now possible to determine how a ground path acts at high frequencies where resonances due to poor bonding, nearby metallic structures, etc., reduce the ability of the ground path to provide a low ground impedance path to earth. A ground impedance measurement system (GIMS) has been developed which can be used to quickly and accurately measure the impedance of an individual ground path.

REFERENCES

1. Mardiguian, M., A Handbook Series on EMI & C, Vol. 2, "Grounding and Bonding," pg 2.7, ICT, Inc.
2. ibid, pg. 2.43.

A frequent contributor to ITEM, ***WESLEY A. ROGERS*** *is president of Electronic Development, Inc., and is an EMI consultant. Previously, Mr. Rogers was with Bell Laboratories and General Motors. While with the GM Aerospace Division, he was responsible for radiation hardening of the Titan and Sabre missiles, and for the navigation electronics for the 747 aircraft. He directed the EMI laboratory at General Motors in Warren, Michigan. (800) 334-6908.*