A Software Program for Characterizing & Designing EMI Filters

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INTRODUCTION

EMI filter designers are often faced with the problem of designing or selecting an EMI filter from a catalog without knowledge of the specific source and the load impedance between which the filter will be inserted. The insertion loss of filters in catalogs is usually specified into a 50 Ω source/load impedance as per MIL-STD-220. An impedance measuring system has been designed to determine the optimum filter.

The software program uses a network analyzer, an S-parameter test set and a technical computer to design EMI filters. This measurement system does the following:

- It measures the device under test (DUT) source and load impedances between which a custom or off-the-shelf EMI filter is to be inserted.
- It determines the frequency response of a candidate EMI filter with a network analyzer, S-parameter test set and technical computer into 50 ohms.
- It recalls the DUT impedances from the technical computer memory, computes and prints out the frequency response that the candidate EMI filter would have when placed between the actual impedances.

The system is best described by presenting an example of the manner in which it was used to design an EMI filter to render a DUT EMI compatible.

Filter design without specific knowledge of the DUT source and load impedance is now possible.

AN EXAMPLE OF EMI FILTER DESIGN

While performing conducted emissions tests on a system, a circuit module failed to pass the MIL-STD 461/462 conducted emissions (CE) test specification. The DUT was out of specification at several points in the region from 1 MHz to 3 MHz. A spectrum analyzer print-out is shown in Figure 1. The specification limit line is superimposed over the DUT emission levels. The plot shown in Figure 1 is in the standard spectrum analyzer units (dBm = dBμV - 107 dB). The module's conducted emissions level was above the specification limit by up to 10 dB over most of the frequency span between 1 MHz and 3 MHz.

The electronic module in question was a 24-volt/± 15-volt/ dc/dc converter that drew 3 amperes from a remote 24-volt battery source. A power filter was clearly required.

An examination of Figure 1 indicated the need for an EMI filter having a maximum attenuation of at least 10 dB at 1.43 MHz. The next step was to measure the source impedance to the filter at connector B and the filter load impedance at connector C (Figure 2). Then the network design approach could commence.

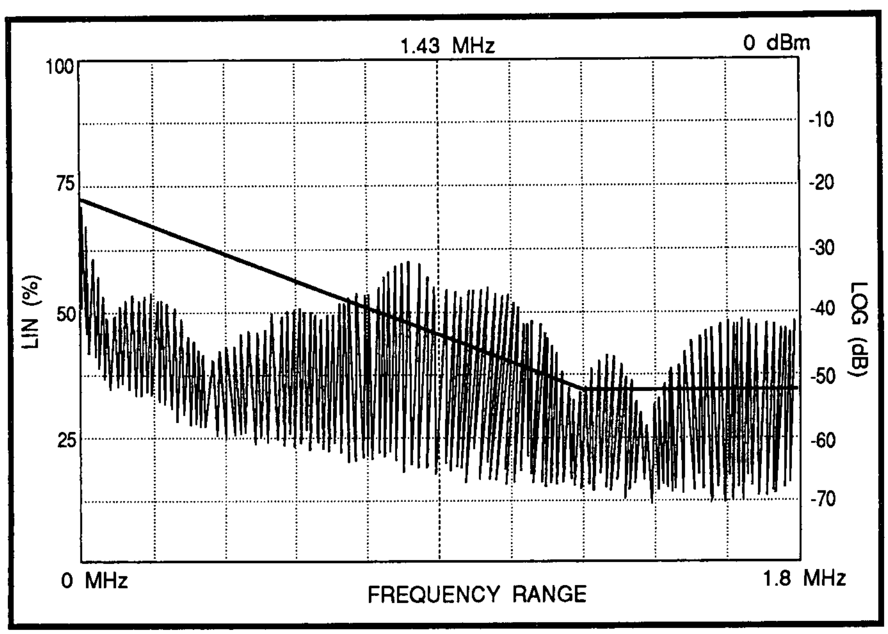

FIGURE 1. *Conducted Emission Levels.*

The impedance measurement system then was employed to measure the source and load impedances between which the EMI filter was to be inserted.

SYSTEM COMPONENTS

The impedance measurement system consists of the components listed below (Figure 2).

- A monitor screen that directs the user in a step-by-step test procedure for testing and evaluating filters
- A technical computer for operating the impedance measurement system, storing impedance data and performing analytical filter performance calculations
- A floppy disk drive
- An HP network analyzer that operates between 10 Hz and 200 MHz
- An S-parameter test set
- A harness probe for measuring filter source and load impedances
- System, program and memory disks
- A printer for plotting DUT impedances, EMI filter response curves, and power flow efficiencies
- A reflection/transmission test set for performing impedance measurements between 10 Hz and 100 kHz.

The components listed above are interconnected by a HP interface bus cable.

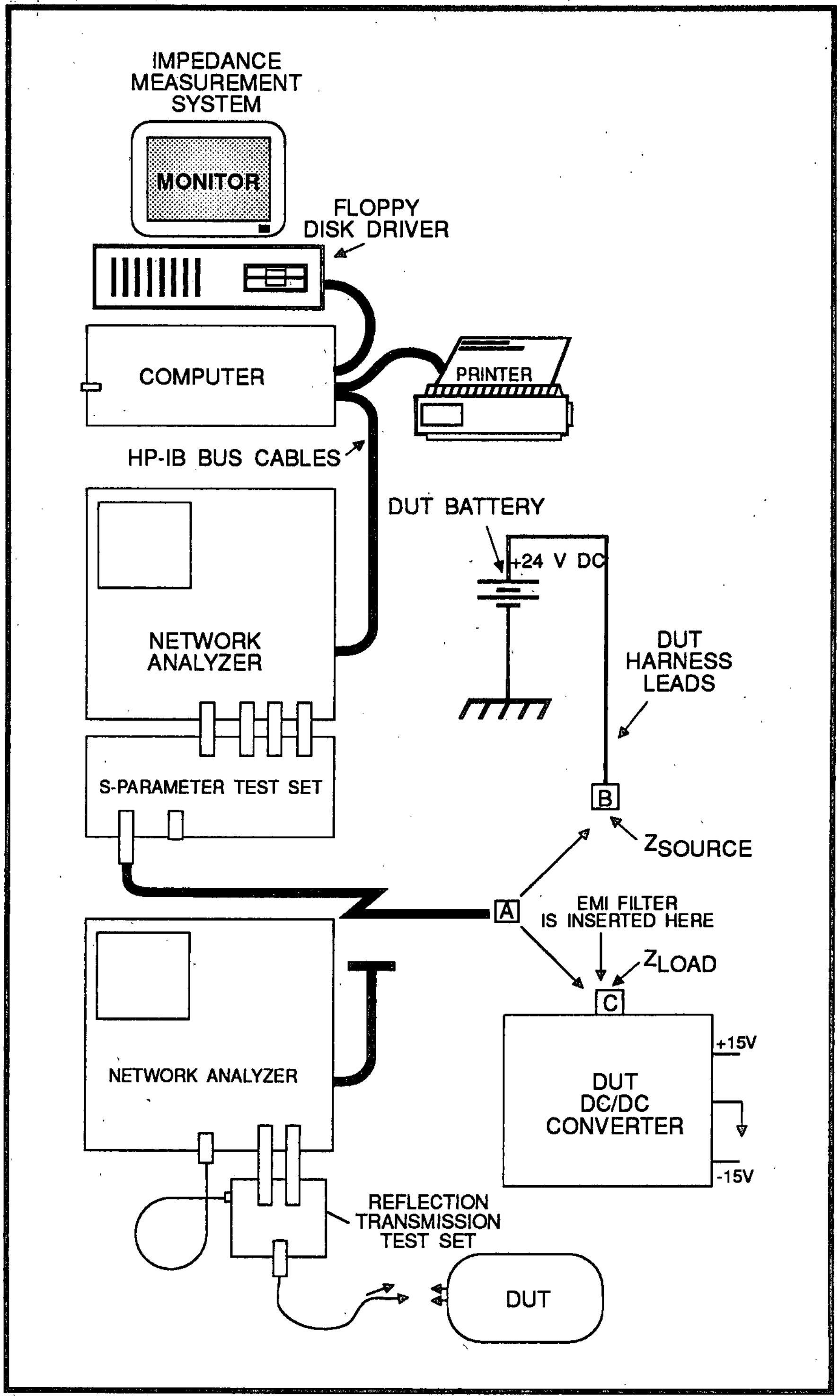

***FIGURE 2.** DUT Impedance Measurement System.*

STEPS FOR FILTER SOURCE AND LOAD IMPEDANCE MEASUREMENTS

The impedance measurement system disk is inserted in the floppy disk drive and the program is loaded. A data analysis and storage floppy disk is then inserted. The monitor then provides step-by-step instructions for calibrating the impedance of the test probe shown in Figure 2. The user is then prompted to connect the test probe connector A to connector B at the open end of the DUT remote battery harness cable.

The impedances of the remote power source and DUT harness are empirically measured by the system at connector B, on the basis of the reflection coefficient measurement procedure described below. Four-hundred measurements, under the control of the measurement system software, are made over the frequency range 100 kHz to 200 MHz using the S-parameter test set and network analyzer indicated in Figures 3 and 4.

Frequency measurements between 10 Hz and 100 kHz can also be made by connecting a reflection / transmission test kit to the network analyzer as indicated at the bottom of Figure 2.

The DUT source impedance measurements at each frequency are made by measuring the voltage injected into the source impedance and the voltage reflected from this impedance. The ratio of reflected voltage divided by incident voltage is termed the reflection coefficient.

The DUT source impedance is obtained from the normalized network analyzer reflection coefficient as follows:

$$Z_n = \frac{1 + R}{1 - T}$$

where

R = reflection coefficient, and

Z_n = is the network analyzer DUT impedance measurement normalized to 50 + j0 ohms.

$Z_{out} = 50 \cdot Z_n$

where

Z_{out} is the non-normalized DUT impedance.

A detailed description of impedance measurements and reflection coefficient is provided by the Hewlett Packard Product Note 3577A-1, titled "User's Guide to the HP 3577A Network Analyzer." The system monitor then instructs the user to measure the input impedance of the DUT dc/dc converter in the same manner.

The EMI filter source and load impedance measurements made at connectors B and C in Figure 2 are then transferred from the technical computer RAM onto the memory and stored on the analysis floppy disk. Print-outs of the DUT source and load impedances are shown in Figures 3 and 4 respectively. Four-hundred point tabular print-outs of the real and imaginary impedance vectors versus frequency in Figures 3 and 4 are presented in Tables 1 and 2 respectively.

The magnitude of the real impedance terms in Figures 3 and 4 is indicated on the left ordinate and the imaginary terms on the right ordinate. The high impedance resonances in Figure 3 are primarily due to harness resonance rather than rises in battery impedance. Table 1 lists only 400 impedance readings between 100 kHz and 200 MHz. Consequently, the real and imaginary impedance vector values listed in Tables 1 and 2 may miss the resonant peaks indicated in Figures 3 and 4.

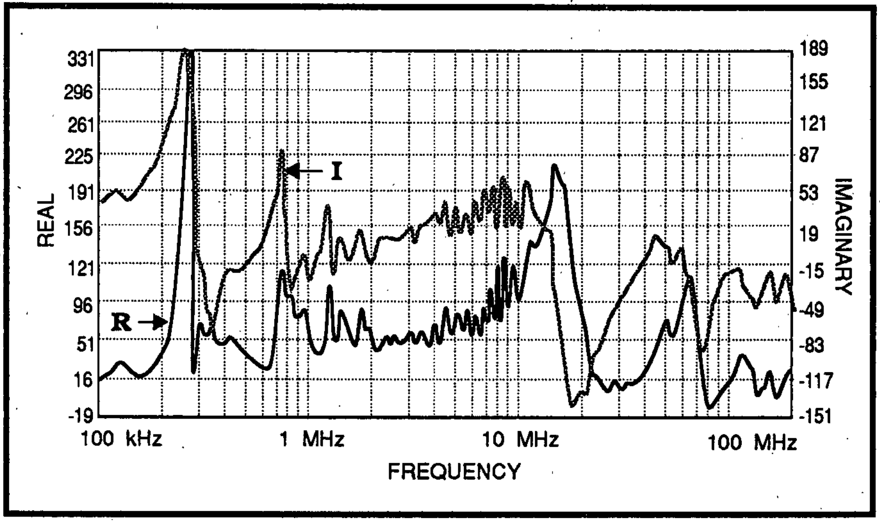

FIGURE 3. *Real and Imaginary DUT Source Impedance Terms.*

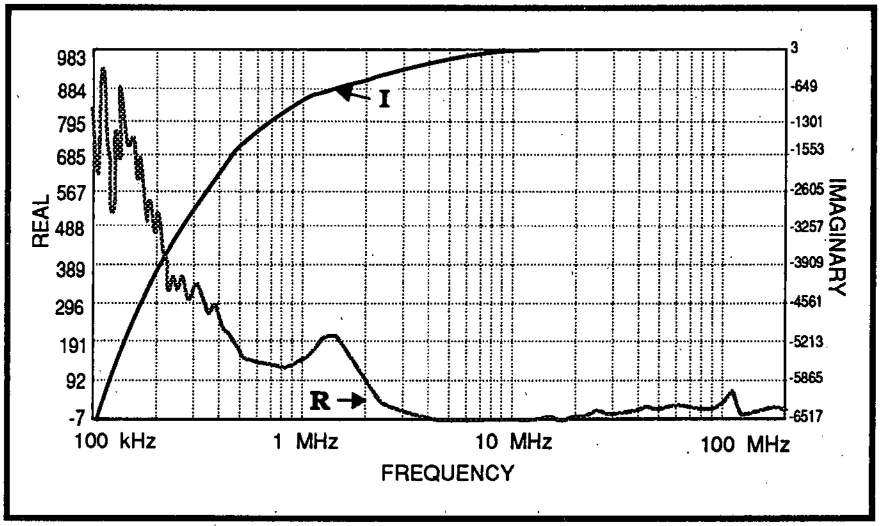

FIGURE 4. *Real and Imaginary DUT Load Impedance Terms.*

The real impedance of the battery and series harness line between 100 kHz and 10 MHz is due primarily to battery internal impedance changes as higher radiated field frequencies couple onto the harness lead between connector B and the battery in Figure 2.

The software program then instructs the measurement program to analytically measure the power flow between the remote

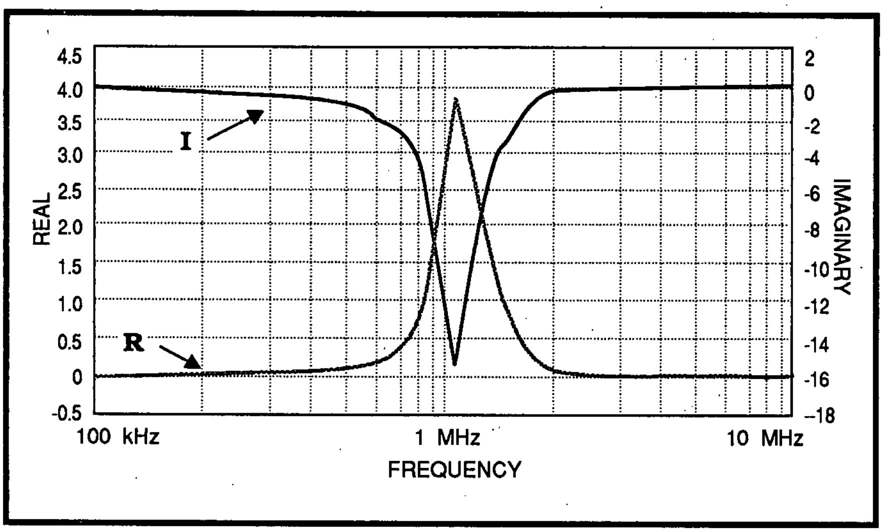

FIGURE 5. *Power Flow Plot without Filter.*

battery source impedance at connector B and the input impedance of the dc/dc converter at connector C, shown on the right side of Figure 2. The power flow curve is shown in Figure 5.

A harness lead will couple with a radiated field at frequencies where it acts like an efficient transmission line, which is where the source and load impedances are complex conjugates. Note the 4-watt peak in power transfer at 1.43 MHz, which is where the highest DUT emissions occur (Figure 1).

X SCALE (0-400)	FREQ. IN MHz	REAL	IMAGINARY
0.000	.100	9.956	37.999
10.000	.121	21.029	48.229
20.000	.146	15.422	47.976
30.000	.177	19.292	73.490
40.000	.214	45.038	124.219
50.000	.259	285.281	101.264
60.000	.313	108.326	-82.168
70.000	.378	44.107	-25.692
80.000	.457	42.352	-22.071
90.000	.553	25.909	.422
100.000	.669	31.040	63.571
110.000	.809	128.191	-16.409
120.000	.978	56.987	-30.968
130.000	1.180	71.443	39.246
140.000	1.430	68.314	-5.721
150.000	1.730	68.852	20.458
160.000	2.090	39.503	6.426
170.000	2.530	47.930	7.834
180.000	3.060	54.288	12.199
190.000	3.700	45.039	29.507
200.000	4.470	83.256	30.946
210.000	5.410	60.609	28.540
220.000	6.540	58.037	41.833
230.000	7.910	124.063	42.725
240.000	9.560	125.381	35.170
250.000	11.600	138.332	27.810
260.000	14.000	195.750	8.430
270.000	16.900	163.934	-143.645
280.000	20.500	69.744	-129.426
290.000	24.700	12.672	-82.006
300.000	29.900	9.403	-45.962
310.000	36.200	14.340	-14.366
320.000	43.700	37.010	11.691
330.000	52.900	56.812	-12.181
340.000	64.000	115.625	-54.495
350.000	77.300	-8.983	-68.852
360.000	93.500	9.151	-19.725
370.000	113.000	40.003	-29.573
380.000	137.000	1.857	-33.431
390.000	165.000	3.030	-31.941
400.000	200.000	15.402	-60.805

TABLE 1. *Actual Source Impedance (Real and Imaginary).*

X SCALE (0-400)	FREQ. IN MHz	REAL	IMAGINARY
0.000	.100	978.203	-6512.750
10.000	.121	558.516	-5615.625
20.000	.146	743.141	-4751.500
30.000	.177	620.578	-4040.313
40.000	.214	454.445	-3456.063
50.000	.259	379.938	-2917.438
60.000	.313	350.625	-2441.313
70.000	.378	296.320	-2040.187
80.000	.457	206.105	-1709.031
90.000	.553	170.734	-1413.313
100.000	.669	152.395	-1162.906
110.000	.809	153.336	-949.578
120.000	.978	182.387	-778.000
130.000	1.180	226.020	-678.563
140.000	1.430	229.570	-660.469
150.000	1.730	139.293	-624.891
160.000	2.090	68.420	-527.109
170.000	2.530	33.449	-430.203
180.000	3.060	18.209	-349.820
190.000	3.700	10.926	-286.281
200.000	4.470	4.987	-235.578
210.000	5.410	.985	-192.035
220.000	6.540	1.308	-155.555
230.000	7.910	2.415	-124.738
240.000	9.560	1.807	-98.551
250.000	11.600	2.016	-76.859
260.000	14.000	1.206	-61.816
270.000	16.900	5.499	-45.773
280.000	20.500	8.424	-33.294
290.000	24.700	15.178	-27.634
300.000	29.900	10.634	-15.986
310.000	36.200	19.127	-10.150
320.000	43.700	25.035	-14.429
330.000	52.900	33.904	-8.948
340.000	64.000	30.902	-16.900
350.000	77.300	20.534	-12.499
360.000	93.500	35.496	-1.853
370.000	113.000	11.761	-49.915
380.000	137.000	12.767	-14.662
390.000	165.000	24.307	-16.734
400.000	200.000	22.023	-21.459

TABLE 2. *Actual Load Impedance (Real and Imaginary).*

The next step is to design a candidate EMI filter based upon the impedance and power flow information provided above. A Butterworth notch filter (Figure 6) can be designed as described below to provide maximum attenuation at 1.43 MHz between the remote battery source and dc/dc input impedance. The Butterworth filter is chosen for its maximal flat frequency response characteristic.

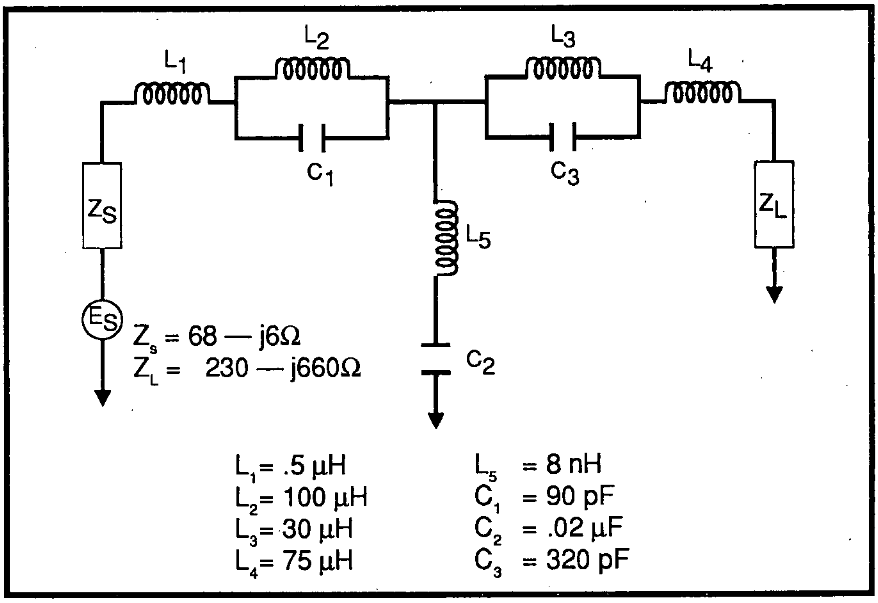

FIGURE 6. *1.43 MHz Butterworth Notch Filter.*

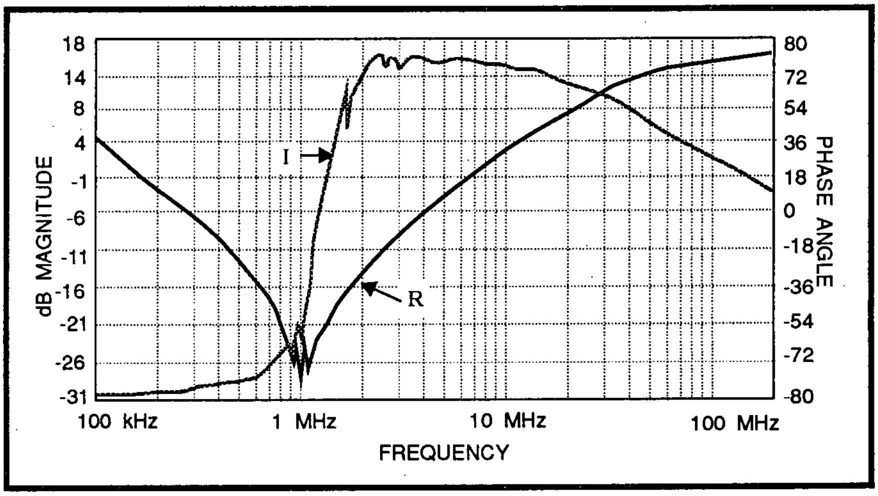

FIGURE 7. *Filter Frequency Response with DUT Source and Load Impedances.*

The design is initiated by determining these impedances from Tables 1 and 2 respectively. Table 1 is used to obtain the real and imaginary components of the source impedance at 1.43 MHz.

Z_{source} = 68 - j 6 ohms

The load impedance at 1.43 MHz is obtained from Table 2 as follows.

Z_{load} = 229 - j 660 ohms

These source and load impedance terms are used to determine the component values shown in Figure 6. The Butterworth function is synthesized from the Butterworth lowpass transfer function ($T = 1/(1 + \omega^{2n})$. The standard procedure is to determine the poles of the driving point impedance (1-T). The driving point impedance is then expressed in terms of the poles. Synthetic division of this expression produces a continuous fraction expansion whose values are standard normalized component values for a given value of n (number of elements). These component values may be scaled to the cutoff frequency and impedance level of interest. The highpass filter is derived from the lowpass by changing capacitors to inductors and vice versa and then using the reciprocals of the component values. The band reject filter combines both types.

The filter in Figure 6 also includes two outer inductors L_1 and L_5 to resonate out the capacitive reactance in the measured source and load impedances at the notch frequency. Off-the-shelf notch filters that do not compensate for the reactive part of the impedances could easily lose the entire notch.

The analytical filter design was breadboarded and tested using the software to control the network analyzer and S - Tran impedance measurement test set. The S11, S22, S12 and S21 filter parameters, normalized to 50 ohms by the network analyzer, were measured and stored on the analysis disk.

The filter frequency attenuation in the forward direction, S21, was selected for analysis purposes. The impedance measurement software analytically combined the measured filter S-parameters with the DUT source and load impedance curves shown in Figures 3 and 4. The standard transfer power gain equation is used. The resultant response curve is shown in Figure 7. A software program combined the response curves over 400 frequency points between 100 kHz and 200 MHz to obtain the resultant curve.

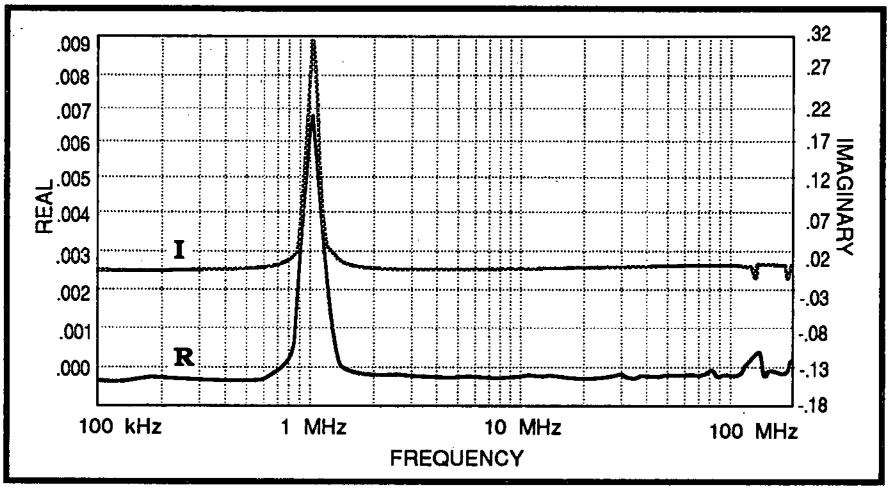

FIGURE 8. *Peak Power Flow Level.*

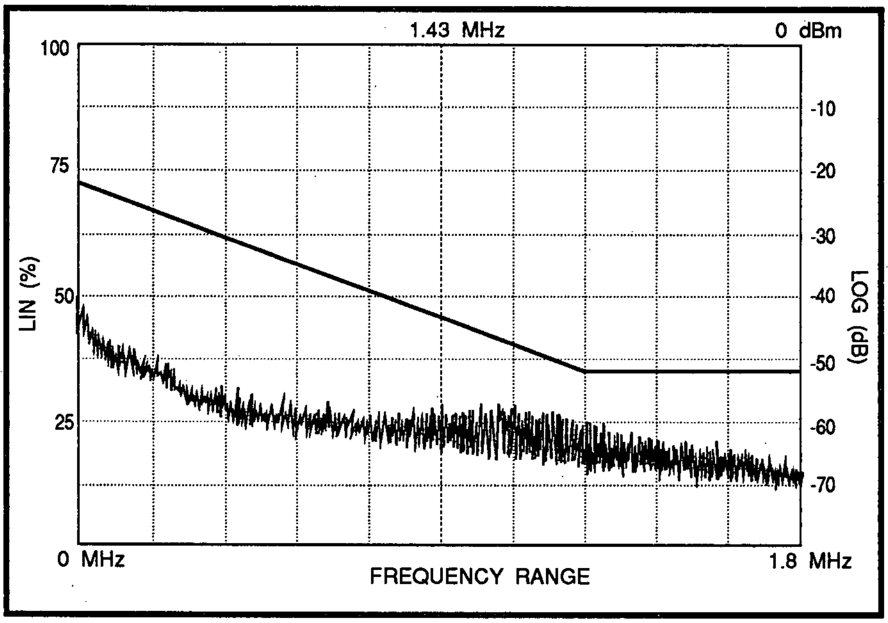

FIGURE 9. *Power Flow Plot with Filter.*

In this instance, which is why this example was selected, the filter maximum band reject point corresponds to 1.43 MHz where it is designed to be. In most cases, slight filter parameter adjustments must be made to accomplish this. When adjustments are required, the breadboard filter is connected between the network analyzer source and receiver ports while the adjustments are made. The S21 frequency response curve, when the filter is inserted between source and load impedances, can be continually viewed on the monitor screen while filter parameters are adjusted. This is a design advantage not easily realized without the aid of this measurement system.

The response in Figure 7 indicates that the EMI filter will provide 26 dB of attenuation at 1.43 MHz when inserted between the remote battery and dc/dc converter input terminal. This is sufficient to lower the DUT emissions level below the limit line over the frequency range shown in Figure 1.

Before constructing a prototype filter the impedance measurement system calculates the new power flow response curve that will occur when the filter is inserted in the DUT. The power flow response curve in Figure 5 indicates a peak power flow level of 4 watts at 1.43 MHz before the EMI filter is inserted.

The power flow curve in Figure 8 indicates a calculated power reduction from 4 to 0.009 watts at 1.43 MHz with the EMI filter inserted. By mismatching source and load impedances, the breadboard filter reduced the ability of the harness lead to conduct on the line between 100 kHz and 200 MHz. The reduction in power at 1.43 MHz is given by

$$A = 10 \text{ LOG } [0.009/4] = -26 \text{ dB}$$

In one case, a prototype filter was designed and inserted in series with the dc/dc converter DUT 24-volt dc input terminal. The impedance measurement system designed a filter which reduced the converter emission level below the limit line, as indicated in Figure 9, thus rendering the DUT electromagnetically compatible over the required frequency range.

CONCLUSION

Filter design without specific knowledge of the DUT source and the load impedance presents real challenges. An impedance measurement system can be used to expedite the filter selection or design process.

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