MEASUREMENT OF FREQUENCY DOMAIN CONDUCTED EMISSIONS USING AN OSCILLOSCOPE

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Electromagnetic interference limits are expressed in the frequency domain, and compliance test equipment operates in the frequency domain. The authors demonstrate use of an entry-level digital storage oscilloscope with PC interface to convert a time domain measurement into the frequency domain for measuring pre-compliance conducted emissions. Utility of the measurements as a diagnostic tool is shown by noting the effect on conducted emissions of various filter component installations. Comparisons of time domain derived and traditional frequency domain signatures are presented.

Introduction - The purpose of this (ongoing) investigation is to minimize the cost and schedule impact of electromagnetic interference (EMI) qualification for the engineer who is only occasionally called upon to take on the role of EMI designer/tester. Excellent full and pre-compliance test equipment addresses the needs of the commercial test facility, as well as those of the information technology equipment (ITE) designer. Return-on-investment (ROI) considerations determine what level of equipment is appropriate. This paper would be of interest to those for whom ROI considerations rule out the purchase of special EMI test equipment.

ITE is designed based on purely *time domain* (signal voltage vs. time) considerations. Electronic test equipment used in the design/troubleshoot of ITE consists of oscilloscopes, logic analyzers, and equipment supporting firmware/software development.

The purpose of EMI qualification is to protect radio (including broadcast television) reception. Radios are *tunable*, or *frequency domain* instruments. They monitor a signal as a function of its frequency. Test equipment used to measure EMI is also tunable, operating in the frequency domain. A tunable spectrum analyzer or EMI meter is the heart of any EMI measurement set-up.

Because the ITE designer has no use for frequency domain test equipment during the design process, the acquisition of such is an added expense, and EMI test equipment is likely to sit on a shelf for much of its life. (However, the cost/schedule impact of EMI qualification is minimized by designing the proper measures into the ITE, rather than attempting bandaids during qualification.) In the last several years, many low-cost pre-compliance type spectrum analyzers have been introduced. Such analyzers range in cost from $7000 to $20,000, and one manufacturer provides a software driven complete turnkey diagnostic system for $13,000.[1] These are excellent values relative to ten or fifteen years ago. Given that the use of a commercial EMI test site costs a minimum of $1000 per day, it can be seen that a $13,000 system pays for itself once it saves two weeks at a test facility. This is above and beyond the important schedule advantage of qualifying the first time and not having to redesign.

Notwithstanding such advantages, there will be manufacturers who cannot justify the purchase of such pre-compliance systems. Reasons might be the initial cost, or the fact that very few of the manufacturer's products actually require EMI qualification. Then it would be difficult to recoup the investment in the EMI test equipment.

The author's have experimented with the use of a digital storage oscilloscope (DSO) with Fast Fourier Transform (FFT) capability. The primary purpose is to allow the use of test equipment the designer already owns in making conducted emission pre-compliance measurements. The reader should be forewarned that such testing is cumbersome compared to the use of spectrum analyzers. The authors do not recommend such testing as a replacement for traditional techniques, if the reader has the funds to purchase tunable equipment.[2] A secondary reason for using a DSO for conducted emission measurements is

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[1] The Farnell EASY-1 system, based on the Farnell SSA1000A spectrum analyzer. Wayne Kerr/Farnell, Woburn, MA. 800/933-9319. The swept frequency data in this paper are taken with portions of the EASY-1 system.

[2] With one important exception. The ability to see conducted emissions in the time domain can yield important information regarding the nature of the emissions source. The special test equipment described herein is very useful in diagnosing, and thus containing, the sources of conducted emissions in a switched-mode power supply.

that it allows the purchase of a very inexpensive ($1000 - $3000) analyzer suitable for radiated emissions measurements. A "radiated emission only" analyzer covering 30 MHz - 1 GHz is less expensive than a 9 kHz or 150 kHz - 1 GHz analyzer because the International Special Committee on Radio Interference (CISPR) bandwidth requirement is looser above 30 MHz than below. Specifically, a CISPR receiver must have the following intermediate frequency (IF) bandwidths:

Tunable range (Hz)	Measurement (IF) BW (Hz)
9 k - 150 k	200
150 k - 30 M	9 k
30 M - 1 G	120 k

The larger the bandwidth, the more phase noise and residual frequency modulation is allowable in the analyzer's local oscillator. Local oscillator stability is a cost driver in analyzer design.

Fast Fourier Transform Considerations for Conducted Emissions Testing[3,4] **-** Performing FFT signal analysis requires sampling a waveform at an even number of points and applying the FFT algorithm. The FFT algorithm assumes the time sample is the period of a periodic waveform. Two problems, aliasing and leakage, are important. Aliasing occurs when the sampling rate is slow compared to the bandwidth desired (30 MHz for CE testing). A DSO with a sampling rate at least twice 30 MHz takes care of aliasing worries. Leakage cannot be cavalierly dismissed by throwing money at it. Leakage occurs when the time period of the measurement is finite. The effect is that the amplitude associated with a given frequency spreads out across the spectrum. Lower amplitude frequency components may be masked by leakage from larger signal components. Windowing is used to limit leakage. Windowing is a weighting function used to emphasize/de-emphasize various portions of the time domain waveform. Many windows have been developed which aid a particular type of signal analysis. A very general statement is that window selection tends to trade off resolution bandwidth (RBW) and shape factor. Figure 1 qualitatively shows the trade-off. The spectral lines represent the real signal. The real signal would be measured if the sample time period exactly coincided with the period of the waveform. The light dashed line depicts what happens if there is not a precise synchronization of the two periods, with flat-top (no) windowing. The solid dark line shows the effect of using Hamming or Blackman windows. For diagnostic or pre-compliance EMI testing, it is preferable to minimize leakage at the expense of increasing RBW. The goal is to maintain the dynamic range required to make EMI measurements. Loss of accurate frequency identification of a given component is not as important as determining that all frequency components are below the specification limit. In other words, we choose amplitude over frequency accuracy.

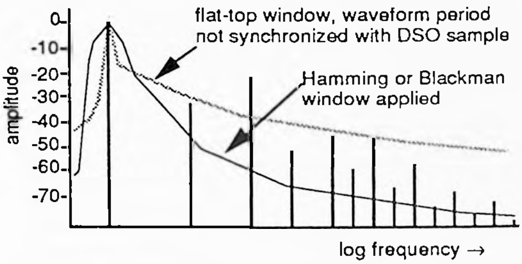

Figure 1: *Comparison of the effect of windowing (adapted from the reference of footnote 4).*

A problem related to leakage occurs if the duty-cycle of a waveform is very small. If the resolution and/or record length of the DSO is not sufficient to faithfully record the entire waveform period, then errors are introduced. The FFT assumes that the record length to be transformed represents the period of a periodic waveform. If the record length, τ, is, however, shorter than the real period, T, it overestimates the amplitude and the correction is:

$$Amplitude_{real} = Amplitude_{short\ period} \cdot \frac{\tau}{T} \qquad \text{Eqn.1}$$

Conducted Emission Measurement Test Equipment and Set-Up - Whether testing to CISPR 22 for European Community (EC) certification or American National Standards Institute (ANSI) C63.4 for Federal Communications Commission (FCC) certification, the basic pre-compliance set-up is the same. As shown in Figure 2, the equipment-under-test (EUT) is supported on a non conducting

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[3] Hewlett Packard Application Note 243, "The Fundamentals of Signal Analysis," contains a practical discussion of FFT fundamentals.

[4] An excellent source on windowing is: Harris, F. J., "On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform," Proceedings of the IEEE, Vol. 66, No.1, January 1978. page 51ff.

table 80 cm above a ground plane. Line Impedance Stabilizing Networks (LISN), defined in CISPR 22 and ANSI C63.4 are electrically bonded to a metallic ground plane.[5,6] Electrical power is fed through the LISNs to the EUT. The purpose of the LISN is implied by its name. One should be able to perform a conducted emission test anywhere and get the same results. Beyond acting as an impedance stabilizer, the LISN also provides an EMI port at which to measure the conducted emissions.

In Figure 2, one LISN is being polled by an EMI meter, while the other LISN's EMI port is dummy-loaded with 50 Ω. Each LISN requires a 50 Ω load at the EMI port at all times.

The only difference between Figure 2 and a test using a DSO is the replacement of the EMI meter by the DSO. In case the DSO cannot internally supply a 50 Ω termination to the LISN port, an external 50 Ω feedthrough connector must be provided.

A cost breakdown of the test set-up is as follows:

Spectrum analyzer:	$7 k - $20 k
LISN (5 Amp at power frequency):	$500 - $1 k
Cu ground plane:	$200
Differential Mode Rejection Network (special equipment discussed later)	$500
Common Mode Rejection Network (special equipment discussed later)	$500
Table:	(not priced)

Table, LISN, and copper ground plane are necessities, and the total cost is under $1500. Minimizing the investment cost begins and ends with the spectrum analyzer.

Time vs. Frequency Domain Instruments - Traditionally, the spectrum analyzer is swept over the frequency range of interest, 150 kHz to 30 MHz. The radio frequency (rf) input is mixed with a local oscillator to provide an intermediate frequency (IF), which is band-passed and amplified. Typically, this frequency conversion process is repeated more than once. Finally, the last IF signal is detected; that is, the modulation is stripped off the IF and this low frequency signal drives the CRT vertical deflection (while a voltage ramp generator drives the local oscillator, which is a voltage controlled oscillator - VCO).

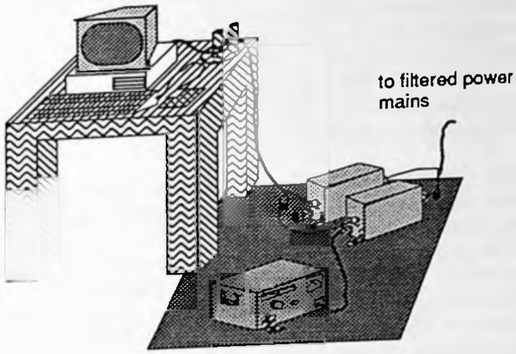

Figure 2: *Commercial conducted emission test set-up*

The DSO operates in the time domain, measuring the voltage at the LISN port as a function of time. FFT software routines, either internal to the DSO, or programmed into a personal computer (PC) convert this voltage vs. time data into voltage vs. frequency. Ideally, one would want DSO sample rates of at least 60 Megasamples per second, in order to provide adequate single-shot bandwidth to cover the required frequency span. Further, a DSO internal real-time FFT is desirable because we can observe a trace qualitatively similar to an analyzer display. We need at least 8 bit resolution, which corresponds to 48 dB dynamic range (not as good as a spectrum analyzer, but sufficient to allow measurement of signals 20 dB above and below European Community (EC) CE limits. Finally, we need enough memory to store a waveform with a period corresponding to the lowest frequency of our limit, or that which will yield a usable resolution bandwidth (RBW). For a limit starting at 150 kHz, we would want to store a waveform at least 10 μs long. However, to get a 9 kHz bandwidth, we need a record length on the order of 100 μs (RBW is inversely proportional to record length). Actually, for pre-compliance testing all that is necessary is that the RBW be small enough to resolve separate harmonics of the SMPS waveform. At 120 Megasamples per second (desirable, not necessary), a 9 kHz RBW implies a memory requirement of about 12000 samples. Such a machine is the Tektronix TDS 520. Testing performed by Javor using this DSO proved eminently satisfactory. However, the TDS 520 costs more than the typical pre-compliance analyzer. If the

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[5] CISPR 22 "Limits and methods of measurement of radio interference characteristics of information technology equipment"

[6] ANSI C63.4 " Methods of Measurement of Radio Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 10 kHz to 1 GHz"

designer already has one, he is all set; if he needs a high performance DSO and adding the FFT capability isn't a big cost driver, the TDS 520 gives the added advantage of enabling pre-compliance conducted emission testing. However, if the TDS 520 or equivalent is not in the budget, there are much less expensive alternatives. The authors investigated a low end approach; a middle of the road solution might be a LeCroy 9310A oscilloscope with WP02 Waveform Processing Package, which is approximately $6200. This DSO provides up to 100 Megasamples/s, and 50 K record length.

Brief Discussion of Conducted Emissions from SMPS[7,8] - The major challenge in meeting CE limits are the emissions of the EUT switched-mode power supply (SMPS). By their nature, SMPS emissions are periodic, lending themselves to evaluation via a DSO's repetitive bandwidth, which is higher than its single-shot bandwidth. The balance of this paper explains the nature of conducted emissions from SMPS, and the challenges in using the selected DSO to measure such emissions.

SMPS generate two types of conducted emissions, differential (dm) and common mode (cm). Figure 3 shows the paths of the two different types of emissions. The dm current is the actual current needed by the SMPS in order to function properly. The cm current is due to parasitic capacitances between SMPS components and system ground. Any technique which reduces cm noise is acceptable, subject to safety regulations (limits on line-to-ground filter capacity values, prohibition against bifilar cm choke windings). However, dm current may not be arbitrarily filtered; the SMPS must be allowed to draw dm current from a low impedance source internal to the ITE, the bulk storage capacitor.

Note that in Figure 3, the total conducted emissions on the feeder or phase conductor is the sum of dm and cm emissions, while the total CE on the return or neutral are the difference between dm and cm emissions. The footnote 8 reference presented a technique for separating the dm and cm noise contributions so that one mode could be attacked at a time. This is an extremely useful filter design technique because the filter element values and topology depend on which mode is to be filtered. Figure 4 shows the operation of a differential mode rejection network (DMRN). It adds the two noise voltages measured at the LISN EMI ports, and divides the result by two, leaving only the cm component.

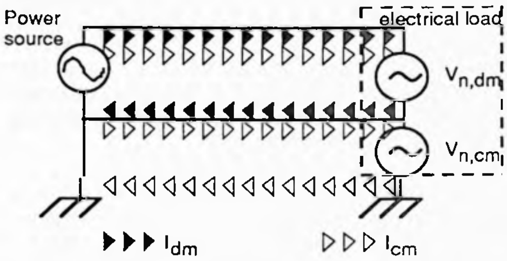

Figure 3: *Differential & common mode current flow*[9]

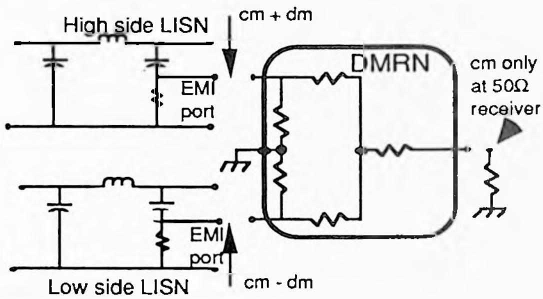

Figure 4: *Principle of the differential mode rejection network*[10]

A common mode rejection network (CMRN) is a similar device which attenuates the cm emissions by 50 dB while passing the dm emissions without attenuation.[11] Both the DMRN and CMRN are three port devices: two input ports connect to each LISN, and the output port connects to an EMI meter.

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[7] For design aspects, see: Vincent W. Greb. "Controlling Conducted Emissions from DC-DC Converters," *1993 EMC/ESD International Symposium Record*, pp.173ff.

[8] For test aspects see: K. Javor and V. Greb, "LISN-Based Conduction Mode Isolation for Power-Line EMI Filter Design," *1994 EMC/ESD International Symposium Record*, pp. 173ff.

[9] Ibid.

[10] LISNMATE. US. Patent #4,849,685. "Measuring and limiting EMI with a differential mode rejection network." 1989. Available from EMC Services, P.O. Box 2504, Huntsville, AL 35804-2504. Ph. 205/461-0241

[11] LISNMARK, Availability per footnote 10.

Description of Authors' Technique - The authors investigated a low cost alternative: an entry-level DSO with RS-232 serial interface. The FFT is performed by a PC operating under MS DOS, on a captured waveform. The technique does not provide real-time capability. The DSO was a Fluke 97 Scopemeter (~$2100 w/interface and all necessary software) sampling at 25 Megasamples per second, and storing 512 samples. Single-shot bandwidth is insufficient to the task. Repetitive bandwidth is 50 MHz, which means that it is suitable for measuring periodic waveforms up to 30 MHz.

Making the FFT Measurement - Mode rejection techniques are also valuable aids in identifying periodic waveforms for Fourier analysis. Although both dm and cm emissions are caused by the switching action of the power supply, they originate in different parts of the switching waveform. The dm component is due to currents drawn at the fundamental switching frequency and its associated rise/fall-times. The cm component arises from a fast change in voltage across a parasitic capacitance which drives current into the ground plane. The cm time domain waveform occurs at the edges of the dm waveform. Because the cm waveform is associated with the rise/fall-time of the switched waveform, it requires a much faster sweep than the dm waveform. If either memory or screen resolution is a limitation, then separate sweeps are necessary to accurately capture all necessary waveforms. For the dc-dc converter which is the subject of this paper, two sweeps were required, one to capture the dm waveform with a period of 4 μs, and one to capture the cm waveform which required a 100 ns/division sweep speed. Viewing the time domain in any detail requires even faster sweeps, but these provide unsuitable frequency domain resolution. A 400 ns record length (20 divisions at 20 ns/division) yields excellent time domain detail, but large measurement bandwidths which reveal only gross amplitudes. Another effect of using a faster sweep on the cm waveform is an over-estimation of the frequency domain amplitudes. The 400 ns record length is small relative to the actual repetition rate or period of 4 μs. The FFT algorithm (when using a 400 ns record length) over-estimated the amplitudes by 14 dB (calculated correction factor = 20 dB). Use of a 2 μs record length resulted in a reasonable correction factor of 6 dB, which tracked accurately with spectrum analyzer data. Corrected values have been recorded next to the FFT computed values in the test data.

The subject of this investigation was a Lambda Advanced Analog 28 Vdc to 5 Vdc converter. It is a 15 Watt device with a 10 W load. It is identical to that used in the papers cited in footnotes 7 and 8. EN55022, Class B, shown in Figure 5, is the CE limit against which performance is compared.

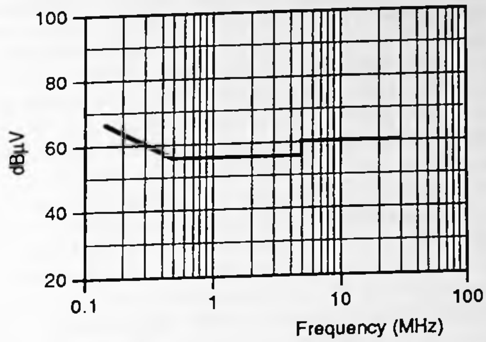


Figure 5: *EN 55022 Class B CE limit.*

Baseline emissions taken at the hot LISN are shown in Figure DSO-1a,b,c. [All FFT data is numbered DSO-Xa,b,c (if necessary); with a the original time domain record, and b,c the FFT. All spectrum analyzer data is numbered SA-X. The SA-X number corresponds to the appropriate DSO FFT plot, therefore the SA figure numbers do not run consecutively.] Figure DSO-1a (taken at the HOT LISN port) shows the triangle waveform associated with drawing switched current through an inductive source impedance (LISN). Faster sweeps reveal shorter duration spikes at the current waveform rise and fall transitions. Figure DSO-1b is the FFT. Note that the Y-axis is linear. This is not terribly useful. A future project is to modify the print out to a dB scale. However, the full dynamic range is present, and any user desired (linear) Y-axis range is available. Figure DSO-1c expands the y-axis for harmonics of the fundamental. Figure SA-1 is provided for comparison. Correlation is adequate for pre-compliance techniques. Figure DSO-2a, taken with the CMRN trade-named LISNMARK, is the differential mode component of the waveform shown in Figure DSO-1a,b,c. The dm amplitude is greater than at the HOT LISN. This is indicative of a significant cm component which is attenuated by the CMRN. Figure SA-2 bears this out by showing a different spectrum measured at the return LISN. Figure DSO-3a is dm CE taken with a 10 μF capacitor placed across the dc-to-dc converter input. The harmonics making up the triangle wave of Figures DSO-1a and DSO-2a are largely gone, leaving a sinusoidal waveform. (The sinusoid vs. triangle nature is more evident at faster sweep speeds.) Figure DSO-3b is the FFT. Only the fundamental is still out of specification, all the harmonics are well under the limit. Figure SA-3 shows the close correlation with a pre-compliance spectrum analyzer sweep. Speeding up the sweep speed of the DSO allowed analysis of the common mode spikes visible at the transition points of Figures DSO-1a (if a faster sweep speed is used than that necessitated by RBW considerations). The waveform is too short in duration to be captured using the single shot bandwidth of the DSO. Repetitive sampling is required. But repetitive sampling necessitates triggering on the same point of the waveform for each retrace. This is much easier to do using a DMRN. The DMRN attenuates the dm signal which causes waveform jitter, and allows capture of a clean waveform. Furthermore, attenuation of the dm waveform permitted the frequency domain structure of the cm waveform to be much more accurately depicted. Figure DSO-4a shows the cm waveform. It is a damped sinusoid of fundamental frequency about 24 MHz. Because the cm waveform appears at the edges of the dm waveform, the period is about 4 μs. With the DSO used, it was not possible to capture an entire period with the resolution necessary to accurately record the 24 MHz waveform. Only 2 μs was captured. Therefore the FFT algorithm assumes that a new 24 MHz waveform occurs every 2 μs, and consequently over-estimates the frequency domain components of the time domain signal. Per equation 1, the real amplitude scale must be calculated from the FFT ordinate scale as:

$$\text{Amplitude}_{real} = \text{Amplitude}_{short\ period} * [\frac{2}{4}]$$

The y-axis scale of Figure DSO-4b must be reduced a factor of 2, or 6 dB. Figure SA-4 correlates well with the adjusted FFT data of Figure DSO-4b.

A cm choke was installed at the 28 Vdc converter input. Figure DSO-5a shows the attenuated time domain waveform. Both Figures DSO-5a,b may be compared to Figures DSO-4a,b to assess the resultant attenuation. Figure SA-5 confirms that cm emissions are well below the limit. The DMRN is very effective in isolating the contribution of a filter element, whose contribution, measured directly at a LISN port, might be masked by dm noise.

One other measurement technique is important. When testing an off-line converter, the power frequency waveform is not entirely attenuated at the LISN EMI port. It is much larger in amplitude than the EMI to be measured, and hence can desensitize the DSO measurement. A filter which reduces 60 Hz voltages to negligible levels while introducing no insertion loss from 150 kHz to 30 MHz is shown in Figure 6. The inductor has 17 turns of AWG 20 wire wound on a Phillips 502T300-3E2A (≈ 1" dia.) toroid. Only milliamps of current flow in the inductor, so any wire gauge will suffice. DSO measurements of the power-line ambient with the filter in place reveal only DSO internal noise. The effect of using the filter when measuring CE from an off-line converter is demonstrated in Figures DSO-6 and DSO-7. Figure DSO-6 is data taken directly from the hot LISN. Note the non-sinusoidal nature of the waveform. This is due to the power-line harmonics being less attenuated by the LISN blocking capacitor than is the fundamental frequency. The waveform is almost identical to an ambient (unloaded) 60 Hz ac waveform measured at the LISN port. The FFT of this waveform could only be computed to 60 kHz, well below the lowest frequency of interest for CE limits. It is impossible (using the entry level DSO) to measure the desired spectrum when starting with a 60 Hz fundamental frequency.

Figures DSO-7a,b,c taken with the filter, show desired time and frequency domain information. Figure SA-7 shows the corresponding analyzer data. Close correlation is found using the filter, because we have greatly increased the DSO's dynamic range. This brings up a related benefit of the filter.

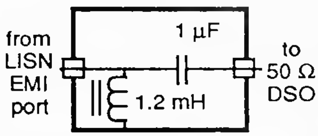


Figure 6: *Power-line filter for LISN port*

The filter of Figure 6 has broader applicability than simply time domain CE measurements. It is particularly suited for the DSO measurement because the DSO has equal sensitivity from dc to its maximum bandwidth rating, and because CE limits control voltage ripple to levels more than 60 dB below the amplitude of the power frequency waveform at the EMI port. However, this power frequency voltage can have a similar dynamic range limiting effect on spectrum analyzers as well. The typical analyzer built for commercial EMI testing has a lower tuning limit of 9 kHz. However, many analyzers do not high-pass the input port to desensitize the mixer to the 50/60 Hz voltage found at the LISN EMI port. The mixer itself may be desensitized due to having an RF transformer input, but many analyzers require significant front-end attenuation when connected to a LISN port. Attenuation reduces dynamic range because it is constant over all frequencies. The filter of Figure 6 can restore lost dynamic range by providing a high-pass front-end to the analyzer.

Conclusion - It is possible to use a digital storage oscilloscope to take conducted emission EMI measurements under the following conditions:

- repetitive bandwidth is at least 30 MHz

- 8 bit resolution is provided, and enough record length (memory) to hold from 10 - 100 µs worth of 8 bit words taken at the sample rate, depending on SMPS fundamental

- DSO has either built-in FFT capability, or has a PC interface allowing for FFT of data ported to PC.

Depending upon the sophistication of the DSO available, additional inexpensive test aids may be necessary or advantageous in the accurate measurement and control of conducted emissions.

Acknowledgments - The authors wish to thank Mr. Mark Nave of EMC Services and Mr. Vincent W. Greb of EMC Integrity for their time and invaluable contributions to the development of the techniques described herein.

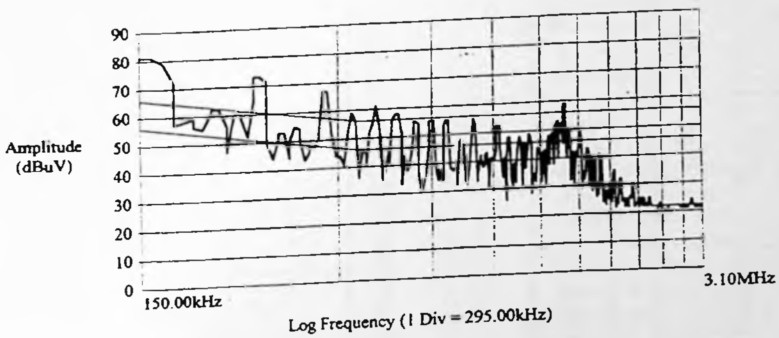


Figure SA-7: Spectrum analyzer plot of off-line converter emissions (for comparison with Figures DSO-7b,c on last page of this paper).

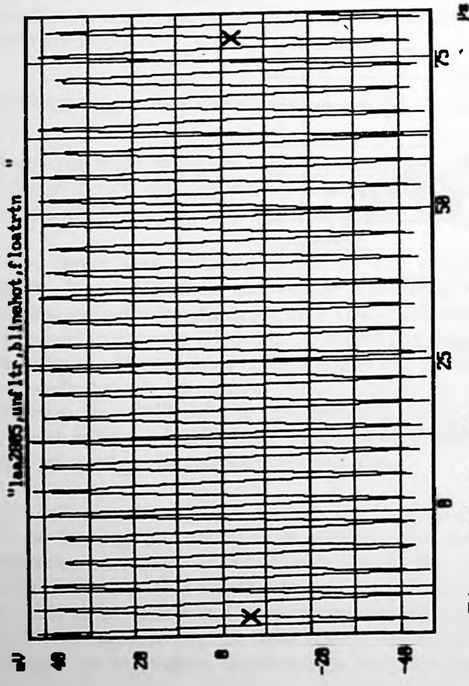


Figure DSO-1a: dc-dc converter unfiltered

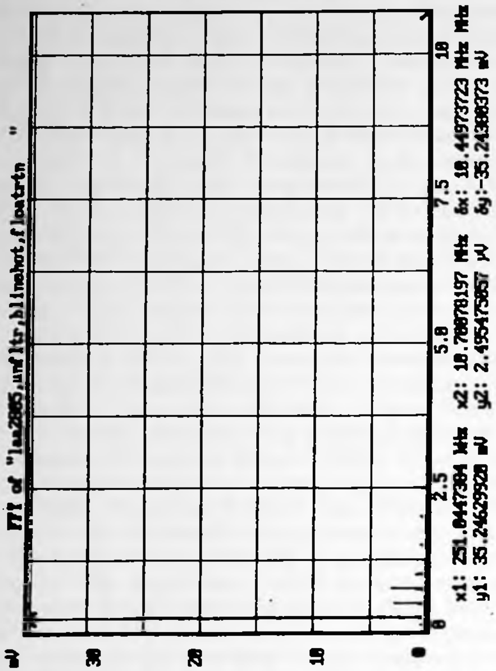


Figure DSO-1b: FFT of Figure DSO-1a

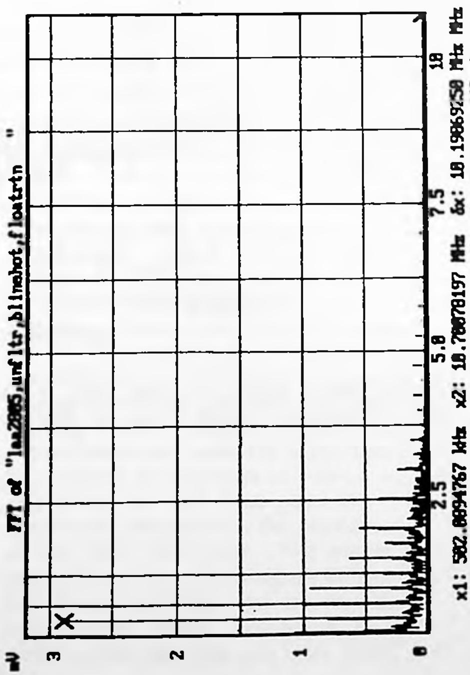


Figure DSO-1c: Expanded view of Figure DSO-1c

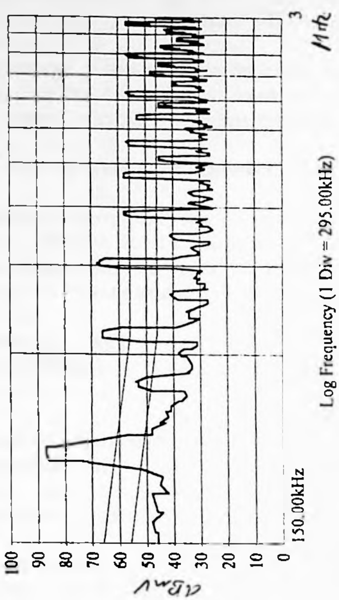


Figure SA-1: Spectrum analyzer plot of same

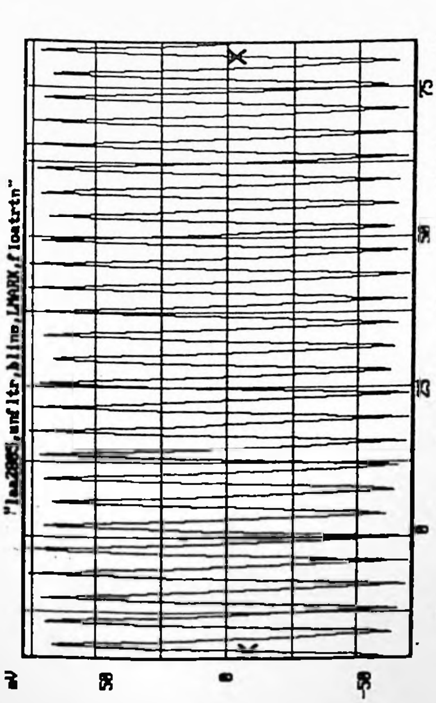


Figure DSO-2a: DM component of Figure DSO-1a

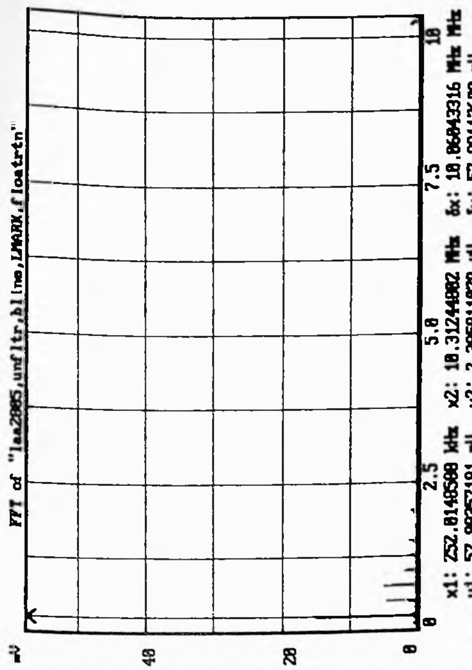


Figure DSO-2b: FFT of Figure DSO-2a

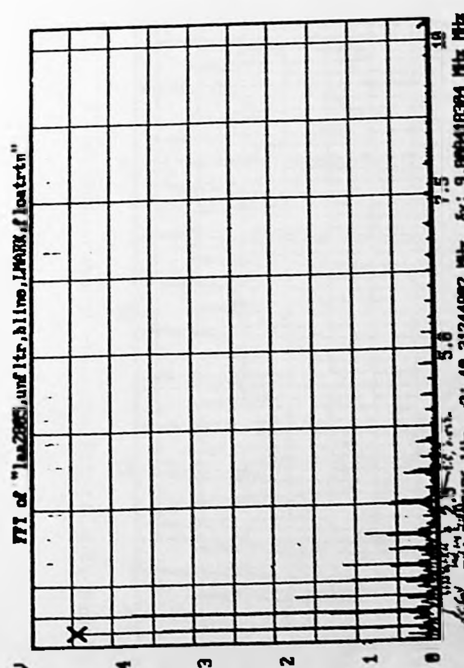


Figure DSO-2c: Expanded view of Figure DSO-2b

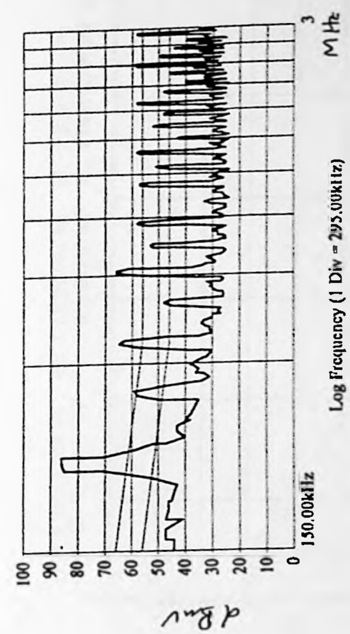


Figure SA-2: Spectrum analyzer plot of same

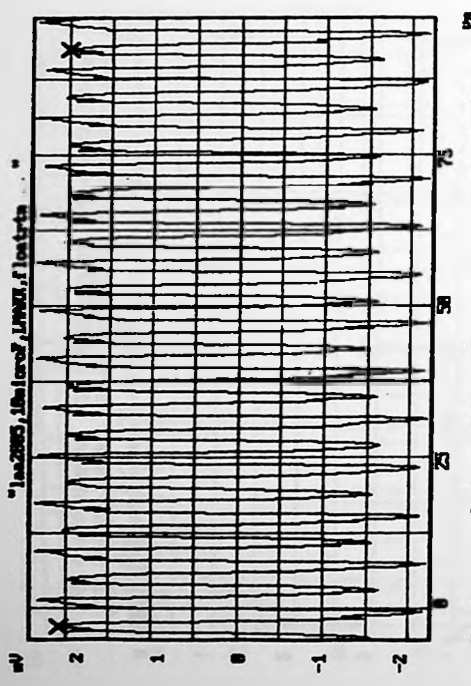


Figure DSO-3a: Filtered dc-dc converter dm CE

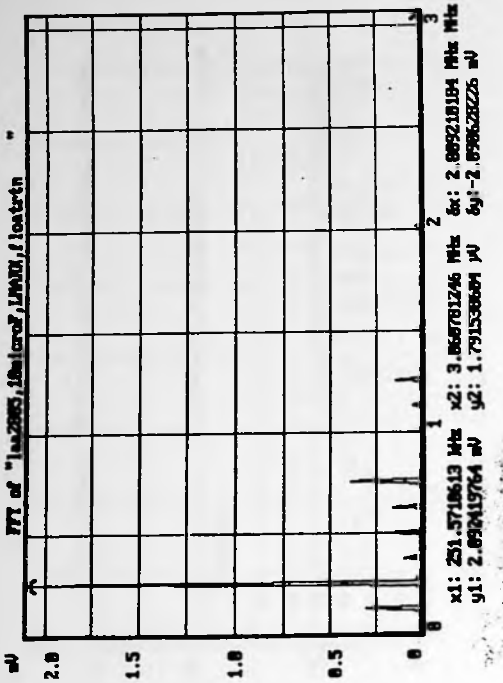


Figure DSO-3b: FFT of Figure DSO-3a

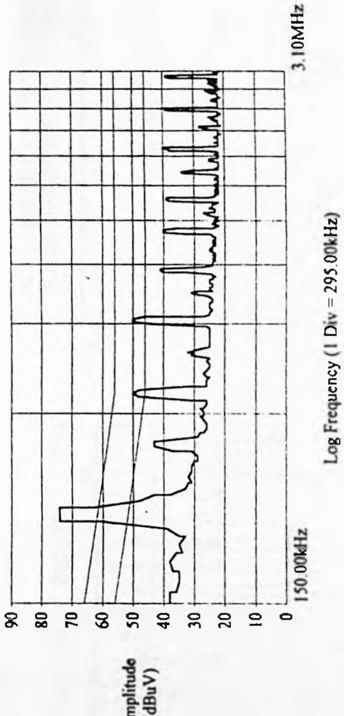


Figure SA-3: Spectrum analyzer plot of same

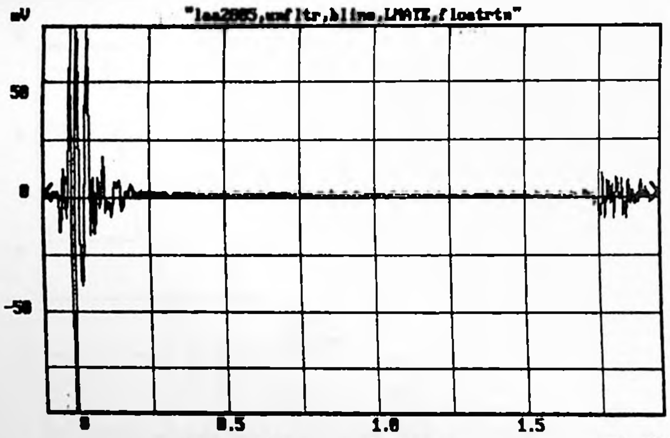


Figure DSO-4a: Unfiltered dc-dc converter cm CE

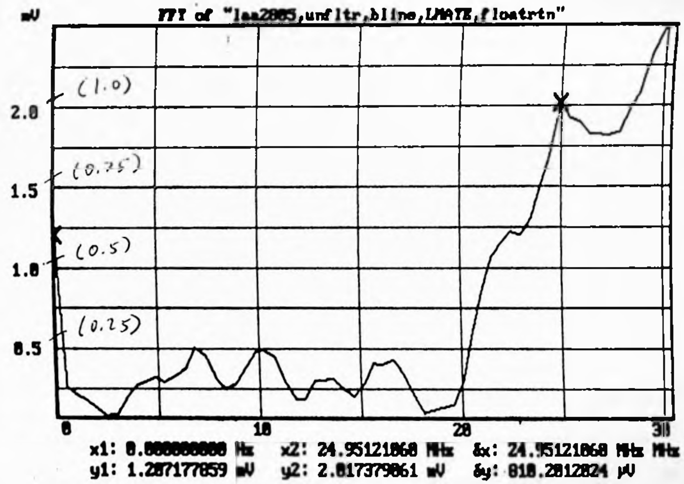
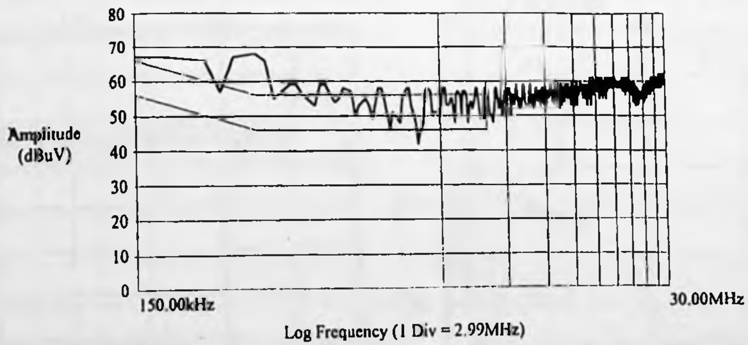


Figure DSO-4b: FFT of Figure DSO-4a



120 kHz RBW: low frequency data unreliable

Figure SA-4: Spectrum analyzer plot of same

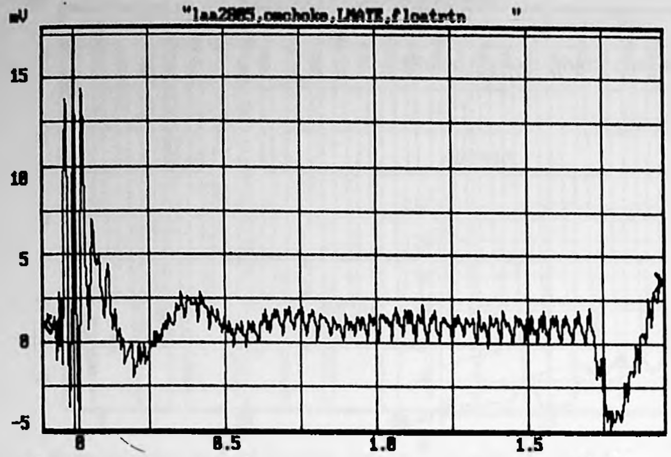


Figure DSO-5a: Filtered dc-dc converter cm CE

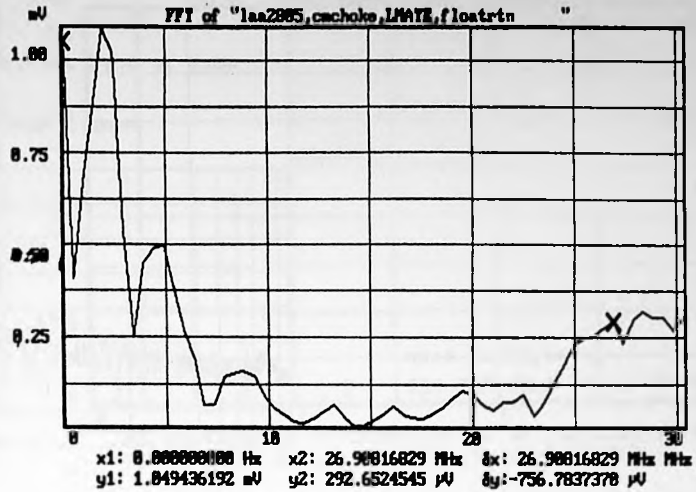


Figure DSO-5b: FFT of Figure DSO-5a

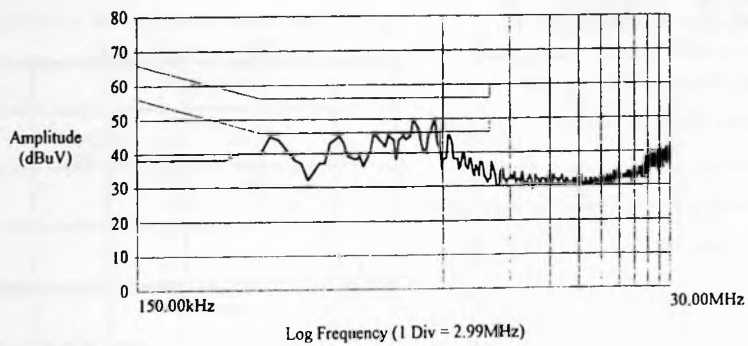


Figure SA-5: Spectrum analyzer plot of same

120 kHz RBW: low frequency data unreliable

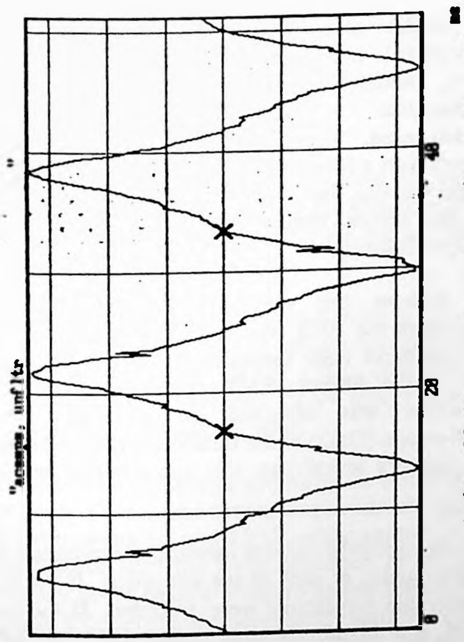


Figure DSO-6: Off-line converter CE (ac line @ LISN)

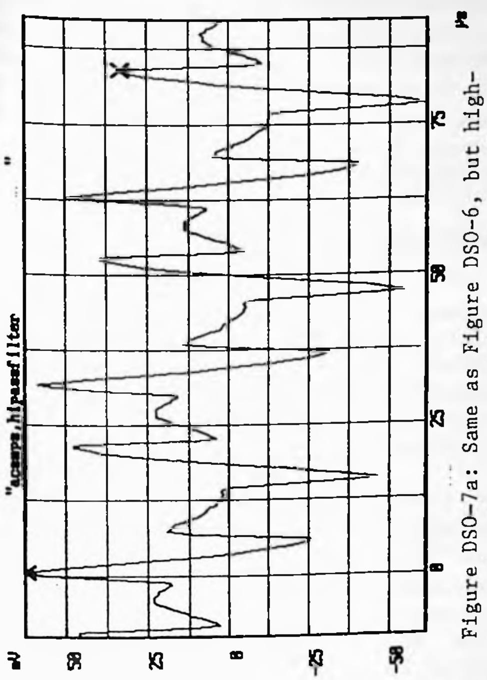


Figure DSO-7a: Same as Figure DSO-6, but high-pass filter used to block line frequency)

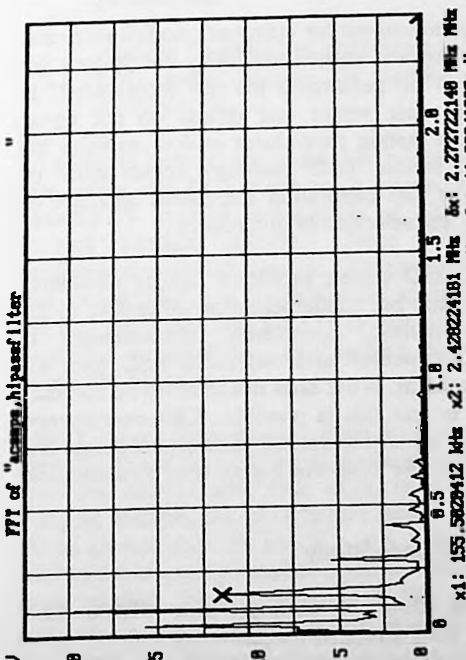


Figure DSO-7b: FFT of Figure DSO-7a

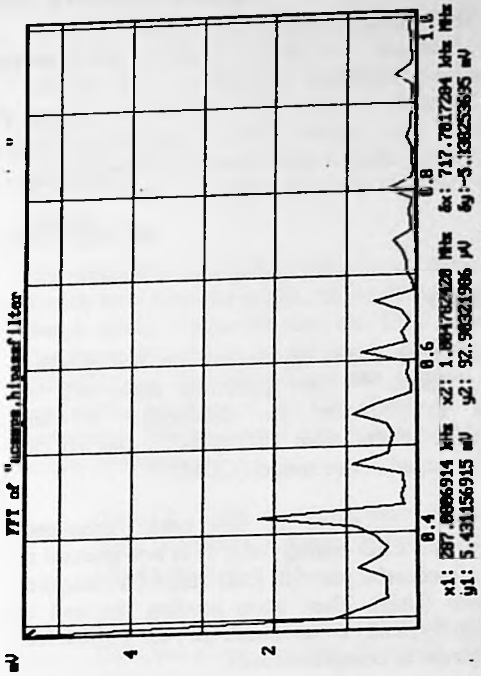


Figure DSO-7c: Expanded view of Figure DSO-7b