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A Study of

COMMON MODE SENSITIVITY OF ELECTRONIC EQUIPMENT

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Abstract

Many technical papers have raised issues regarding the susceptibility of electronic equipment to electrical interference. Often the papers base argument and conclusions upon the calculated and assumed attenuation properties of switch mode power supplies. Two divergent themes appear in these papers: low amplitude common mode interference passes through a switch mode power supply affecting the operation of internal logic circuitry, or sufficient attenuation is available in a switch mode power supply to prevent low amplitude common mode interference from affecting the performance of logic circuits powered from the power supply.

This paper attempts to explain this divergence by addressing the effect of common mode interference upon electronic equipment. The general topics covered in the paper are

- power supply design and susceptibility to common mode interference,
- the paths for common mode surge currents into electronic equipment,
- the effect of common mode surge current on data circuitry.

To investigate the effect of common mode interference upon electronic equipment a review of power supply and emissions filter design was performed along with a range of tests, both time and frequency domain, to confirm or rule out various suppositions regarding the immunity of electronic equipment to interfering signals.

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COMMON MODE SENSITIVITY OF ELECTRONIC EQUIPMENT

1. Introduction

The role of electrical interference and the sensitivity of electronic equipment has received a great deal of attention during the past few decades. Numerous test standards have been developed both domestically and internationally to guide equipment designers. The test standards normally describe the mode of injection into a device and the coupling parameters of the test signal (amplitude, frequency and energy). The mode of injection is important because the effect of interference is a function of the path(s) which an interfering signal takes as it passes through a device. The size and shape of an interfering signal determine the ability of a signal to pass (couple) into and throughout a device.

1.1. Interference Injection Mode

The four modes of interference injection for a single phase circuit are line-to-neutral, line-to-ground, neutral-to-ground, and line plus neutral with respect to ground. There are generally accepted terms for two of these modes. Events which are injected between line and neutral are called normal mode (symmetrical mode in some international standards). Events which are injected between all current-carrying conductors and ground are called common mode (asymmetrical mode internationally). By using different modes of injection, controlling the means of injection and the path for interference to follow into and out of a device, a designer can examine the impact and take steps to harden the equipment.

In North America, the neutral conductor is bonded to earth at the electrical service entrance. Theoretically, the bond should limit interference within a facility to events which are measurable between line-to-line or line-to-neutral (normal mode) and many surge suppressor designs and power supply filters are designed to address only normal mode interference. Unfortunately, this is not the case. Common mode interference may exist within a facility because the bond at service entrance is missing or poorly implemented. As a result, interference signals may be found on all current-carrying conductors (equal in phase and approximately equal in amplitude as measured from a ground reference). Even with a well-implemented bond, coupling between wires and lead inductance in the neutral-to-ground bond and in the tie to earth ground permits the propagation of high frequency common mode signals throughout a facility. In addition, interference signals are not one way events. Interference like all electricity flows in a loop and will follow each and every path available to complete a loop. The current in any path is inversely proportional to the impedance of the paths . (Kirchhoff's laws and Ohm's law still prevail).

In practice, the distinction between normal mode and common mode becomes a bit fuzzy. The grounding conductor of a device (by code requirement) is parallel and contiguous with the phase and neutral conductors. Because of the bond between neutral and ground at the service entrance, the grounding conductor becomes an additional path for normal mode surge current and serves as the principal path for common mode surge current. The issue ceases to be normal versus common mode orientation and becomes common return provided by the grounded (neutral) and grounding (ground) conductors. This is mode conversion. Figure 1 illustrates this condition. For instance, if a common mode surge enters a facility the bond between neutral, equipment ground and earth ground at the service entrance will provide a path to earth for much of the applied surge current. This assumes that earth ground is the source or part of the path for the surge current. The surge current on the hot conductor has no discharge path and therefore enters the facility without impediment. When the load is close to the bond at the service entrance, voltage differentials due to surge return current are limited. However, as the distance between the service entrance and the load increases, the impedance of the return path interacts with the surge return current creating large voltage differentials. The interaction increases proportionally with increased frequency.

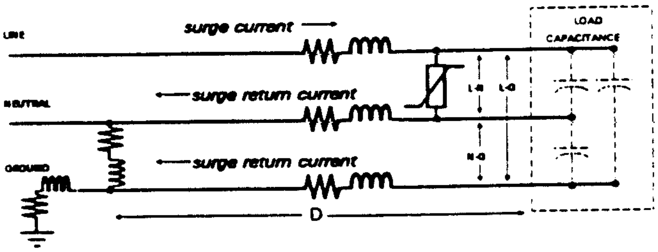

Figure 1 - Branch Circuit

To verify the development of voltage differentials, a branch circuit test was performed using a Velonex 587 surge generator. As shown in figure 2, the isolation network of the Velonex surge generator was connected with a bond between neutral and ground on the output of the isolation network to replicate the neutral-to-ground bonding condition of a typical service entrance. A normal mode surge (2000 volt, 8X20 unipolar impulse) was then applied to the test circuit. The voltage differentials were measured from line-to-neutral (L/N), line-to-ground (L/G) and neutral-to-ground (N/G) with a digital storage oscilloscope and 100X probes (differential measurement). A metal oxide varistor (V130LA20B) was connected from line-to-neutral to replicate the surge protection for a typical power supply.

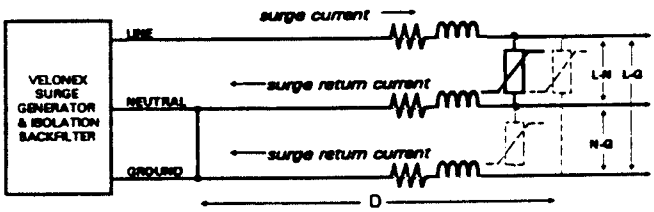

Figure 2 - Branch Circuit Surge Test

Table 1 shows the test results with the metal oxide varistor (MOV) placed 0.5 meters and 60 meters away from the surge generator. The data shows that when a load is very close to the neutral-to-ground bond, the surge voltages are uniformly limited by the combination of surge suppressor and neutral-to- ground bond. However, at the end of the 60 meter circuit (200 feet of 12 gauge, Type NM-R non-metallic sheathed cable, with integral grounding conductor), the impedance of the wiring interacts with the surge return current creating very large voltage differentials.

Table 1- Branch Circuit Test

One MOV (L-N)		
Wire Length (D)	Measurement	Volts
0.5 Meters	L/N	385
	L/G	420
	N/G	22
60 Meters	L/N	333
	L/G	1260
	N/G	963
Three MOVs (L-N, L-G, N-G)		
Wire Length (D)	Measurement	Volts
0.5 Meters	L/N	368
	L/G	350
	N/G	3
60 Meters	L/N	315
	L/G	315
	N/G	158

It is important to note that all ground referenced capacitive paths (stray capacitance, capacitors and semiconductor chips) inside a device powered from the circuit will be forced by the voltage differentials to carry surge current. As a result, surge current will flow in the grounding conductor back to the neutral-to-ground bond at service entrance.

Voltage differentials across semiconductors and the resulting surge current flowing through the semiconductors can cause operational problems or damage. As a result, multiple MOV arrays are often used in surge suppressors to limit voltage differentials. A common configuration for a multiple element surge suppressor adds MOVs between line and ground, and between neutral and ground (dashed MOVs in figure 2). The branch circuit test was repeated with three MOVs (V130LA20B) connected L/N, L/G, and N/G. Table 1 shows the test results from this configuration. The surge voltage levels are now fairly uniform, however, the grounding conductor is now an active current- carrying path for surge current. Common mode voltage differential (neutral-to-ground) is still quite high at the end of the 60 meter branch circuit.

François Martzloff of the National Institute of Standards and Technology (NIST) published surge test data in 1985 which documented the performance of surge suppressors placed at the end of a 75 meter branch circuit.[1] Table 2 contains test data which Martzloff recorded for a single MOV (L/N) and for three MOVs (L/N, L/G, N/G).

Table 2 - Branch Circuit Test With 75 Meters Wire Length

Mode	1 MOV (L/N)	3 MOVs (L/N, L/G, N/G)
L/N	360 V	360 V
L/G	1100 V	380 V
N/G	780 V	100 V

The test data prepared for this report and the test data published by Martzloff show that large voltage differentials can be created at the end of a long branch circuit through the use of nonbalanced surge suppression devices (single element). One important fact emerges from an examination of interference modes and paths. The path for interference which is provided by equipment ground must dominate in all considerations of equipment sensitivity and cannot be separated or ignored.

1.2. Coupling Parameters

The amplitude, frequency, duration and energy of an interference signal determine the capability of a signal to affect an electronic device. The degree of impact, however, is also a function of clock speed, equipment activity and data connections. Test standards exist both domestically and internationally to aid equipment designers in the development and testing of new equipment. These standards cover a wide range of interference signals. However, for the past decade a slower type of interference, the high energy electrical surge caused by lightning, has received the majority of attention. This is due in large part to the fact that electrical surges destroy equipment. As a result, companies specializing in test or power monitoring have produced systems to replicate or record electrical surge events and a host of companies have emerged with a wide range of surge suppression products. The focus of these products, for the most part, is electrical surge with frequency components ranging from kHz to low MHz.

As the focus of equipment design and protection moved toward the use of equipment tailored to address electrical surge, a unique development occurred. Computer systems became faster, power supplies grew smaller, usage became increasingly critical and computer equipment moved out of the computer room and onto the office and factory floor. Many of the electrical problems associated with the new environment were recognized: voltage fluctuations, power dropouts, and electrical surge. As a result, power supplies and aftermarket power protection products offered features and capabilities which revolved

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[1] F.D. Martzloff, The Protection of Computer and Electronic Systems Against Power Supply and Data Lines Disturbances (Schenectady, N.Y. General Electric Company, 1985), p. 32.

around the identified problems. For the most part, this approach has been satisfactory. However, problems still occur even after diligent efforts to create a suitable electrical environment for the equipment.

One of the reasons that problems persist despite precautions is that the move out of the computer room environment brought electronic equipment closer to random sources of high frequency interference. Worse yet, the equipment which was moved out to this less-than-friendly environment was connected to the computer room via data networks. The result is increased opportunity for interference to affect equipment. This is especially true for high frequency interference where coupling is an important factor. Over the past few years several test standards have been modified to address the issue of high frequency interference. Two standards, ANSI/IEEE C62.41-1991 and IEC 801, now contain test standards for electrical fast transients (EFT) and specify coupling modes.

2. Interference Coupling Within Switch Mode Power Supplies

The ability of a power supply to attenuate common mode interference is related to the coupling between the AC input and the DC output of the power supply. Figure 3 illustrates a functional block diagram for a power supply. The high frequency transformer of the pulse width modulation (PWM) inverter inside the power supply provides some common mode reduction, although the attenuation properties of the transformer are related to size and operating frequency. Some of the other determinants of attenuation are the emissions filter, output filter and random coupling throughout the power supply.

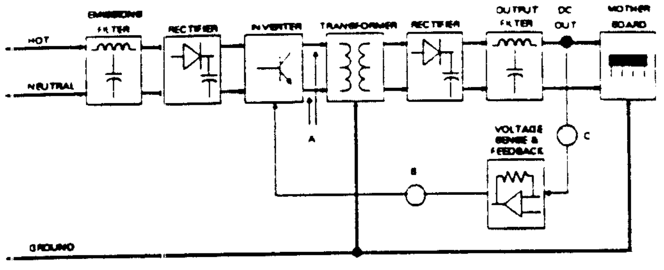

Figure 3 - Switch Mode Power Supply Block Diagram

The coupling capacitance of a PWM transformer for a switch mode power supply (personal computer size) is approximately 100 pF. As the size and operating frequency increase, the coupling increases. Figure 4 shows the attenuation characteristics of a PWM inverter transformer with 70 pF of coupling capacitance (series insertion loss of the transformer measured with a Hewlett-Packard 3585A spectrum analyzer equipped with a tracking generator). As shown in figure 4, the small signal attenuation of the PWM inverter transformer appears fairly good below 1 to 2 MHz, although the real attenuation will vary with layout and signal amplitude. Above 10 MHz, the transformer attenuation is quite limited. At 30 MHz, the attenuation is only 15.9 dB or 6:1 (referenced to the 0 dBm output of the tracking generator).

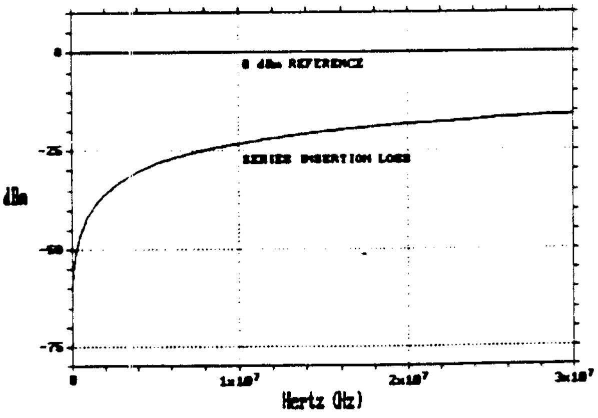

Figure 4 - PWM Transformer Attenuation

When intentional physical separation is provided between the high voltage DC portion of the power supply and the low voltage DC output, the intent is safety and not noise reduction. Figure 5 illustrates two different design characteristics for power supplies. In configuration A the drive transistors are isolated with optical isolators inside the control module. In configuration B the drive transistors are electrically isolated with pulse transformers.

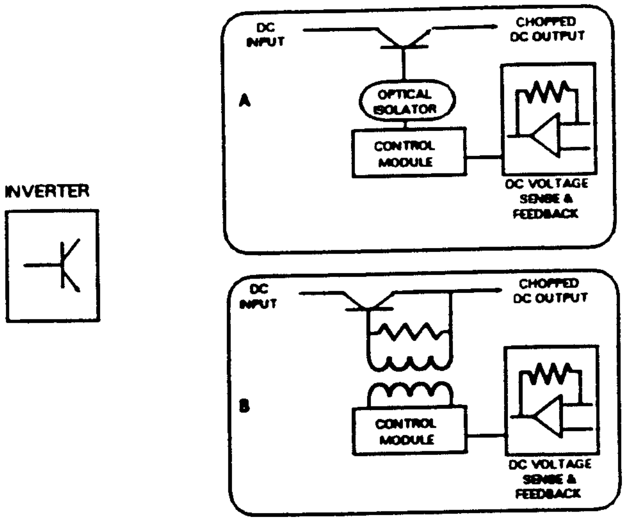

Figure 5 - PWM Drive Designs

Referring back to figure 3, isolation is normally added at either points B or C, or both, to isolate the input AC related circuitry from the output DC circuitry. The intent in either case is 60 Hz isolation from input to output to ensure safety. The 50/60 Hz safety isolation can limit paths for interference if circuit layout, wire routing and circuit board placement do not create sneak paths for interference. In one instance, a clone computer exhibited poor attenuation properties. A physical inspection revealed that the power switch on the front panel controlled the AC power for the system. Unfortunately, the power cord was routed alongside the motherboard and the floppy disc for the system. As the power cord was fairly long and was placed close to the motherboard, surge energy and high frequency interference were free to radiate throughout the system and to couple capacitively and inductively into sensitive circuitry. In this instance, the attenuation capabilities of the power supply were immaterial. Even if the power supply had excellent attenuation properties, the overall system would still be sensitive to interference. In other words, even with deliberate effort to select a quality power supply, an assembly error can create an unintentional path for common mode interference into the system. If the system is not tested after assembly, or if the system is electrically quiet and therefore passes emissions testing, then the completed unit will reach the field where interference will determine the ultimate reliability of the system.

3. Filtering for Switch Mode Power Supplies

Switch mode power supplies are inherently noisy devices. Figure 6 shows the switching voltages across each side of the center- tapped PWM drive transformer with respect to chassis ground (point A of figure 3). The signals are equal and opposite in polarity indicating a normal mode orientation. Accordingly, input and output filter capacitors for a power supply are generally connected between line and neutral and between DC supply and DC return in a normal mode configuration to control the

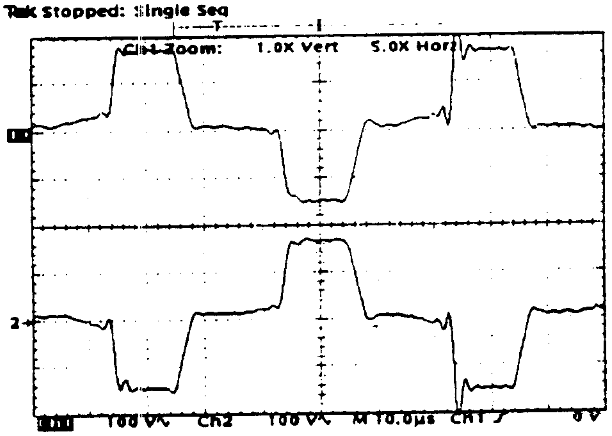

Figure 6 - PWM Inverter Drive Voltage Levels

emissions from the PWM inverter of the power supply and to control ripple voltage on the output of the power supply.

The fast edges of the switched voltage couple into adjacent wiring and sheet metal assemblies. Any imbalance in the coupling creates common mode voltage and current. Internal to a system, twisted pair wiring, shielding and ground plane technology are used to control common mode coupling. However, some coupling imbalance occurs, so emissions filters incorporate common mode chokes to control the coupled signals. The magnitude of the coupling determines the size and complexity of the emissions filter. Equipment with poor internal coupling controls will require an extensive emissions filter while equipment with good internal controls will require much less filtering. This creates a unique paradox: While the internal coupling controls improve the overall emissions profile of the system, the reduced filtering requirements can lead to the selection of a small, simple input emissions filter and a reduction in common mode filtering on the output of the power supply. The system may meet emissions requirements, but this may actually reduce both the common mode input impedance and the common mode bypass filtering for the system.

Figure 7 illustrates several types of emissions filters for power supplies. Configuration A is a simple filter with common mode chokes and a normal mode bypass capacitor. Configuration B is a multiple stage filter with common mode chokes and normal mode bypass capacitors. This style of filter might be well suited for a noisy power supply, however, the filter has no common mode bypass capacitance. Configuration C uses a common mode choke and both normal and common mode capacitors. Configuration C should provide the best overall input attenuation, however, cost, space limitations, insufficient need (perceived or actual) or leakage current concerns may preclude its use.

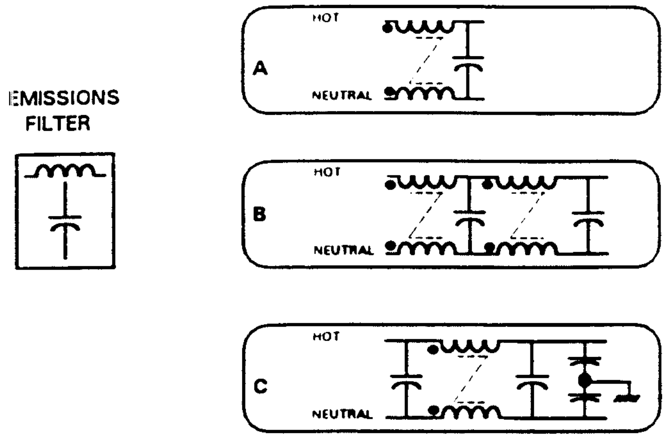

Figure 7 - Emissions Filter Configurations

The type of filtering found inside a power supply depends upon its intended usage and regulatory concerns. Obviously, if a power supply is not required to meet any governmental limitations for conducted emissions (radio frequency interference or RFI), then filter components otherwise required are usually not present. Government regulations inside the United States require testing and certification to ensure compliance, but, some types of equipment are never tested. For instance, personal computers assembled inside the country by value added resellers (VAR) are seldom tested. The VAR often buys assemblies which are integrated into a final package. The chassis, power supply, drives and circuit boards may be purchased from different suppliers. If the chassis and power supply are purchased as an assembly, then FCC certification for the enclosure may be available. Regardless, the final system is often not tested and the VAR relies upon FCC certification from component and assembly vendors. If the power supply is not built or tested to any emissions standards or the installation of the assemblies compromises the FCC certification, then the finished assembly will lack sufficient filtering and may be vulnerable to interference.

As a case in point, a value added supplier of electronic systems used an off-shore origin external SCSI assembly in conjunction with a top-of-the-line computer. The computer was extremely well built and tested to FCC class B and VDE standards. However, the final assembly was prone to lockup and reset errors. The external drive assembly did not carry any type of FCC labeling. During testing, impulses as small as 180 volts caused system reset. An examination of the power supply inside the drive assembly revealed that a single common mode choke with a normal mode bypass capacitor comprised the entire input filter (figure 7, configuration A). A replacement drive which carried FCC class B and VDE certification was subsequently selected and tested. The finished assembly then tolerated 1000 volt impulses (5ns X 50ns) without lockup or reset problems.

The type of emissions certification can affect the performance of a device. Although FCC compliance is mandated for electronic equipment operating at frequencies higher than 9 kHz, FCC class B testing for conducted emissions actually begins at 450 kHz. As a result, a filter design may not address frequencies below 450 kHz; it is a low pass filter. Frequencies well below the cutoff frequency may pass through the filter with little or no attenuation. As surge voltage inside a facility oscillates at approximately 100 kHz, a power supply incorporating input filtering with a very low frequency response may provide better attenuation for some forms of conducted interference. Some European tests for conducted emissions, for instance, begin at 9 kHz (Vfg 243/1991). However, as the name implies, an emissions filter controls noise generated within a device and it is not intended to stop interference with large amounts of energy which enter the system from the power line. The energy handling capability (instantaneous and long term) is limited. For example, when a surge event is applied to an emissions filter, the inductors inside the filter may saturate and pass the surge on to the power supply, or the interference signal may force the filter to interact with the capacitance and inductance of the power supply and create a resonant condition. In either case, the operation of the power supply and the electronics powered from the supply will be jeopardized.

4. Referencing DC Common To Chassis Ground

Almost all electronic equipment tie the DC common to chassis (and in turn to the AC ground wire) somewhere inside the system. The tie usually occurs at the motherboard or backplane for a system. Even without a deliberate tie to chassis ground, capacitive paths throughout the system effectively ground it at high frequencies. Some devices such as small external disc and tape drives may have a bond to chassis ground at the DC output of the power supply. Large power supplies are seldom bonded to ground inside the supply.

The effect of power supply grounding is subtle. Where a bond (tie) is provided between DC common and chassis ground inside the power supply, the normal mode output filtering of the power supply can aid in the process of coupled interference attenuation, if the bond and filters are properly coordinated. The tie to ground rarely occurs within the power supply if the designer uses multiple power supplies and wishes to maintain a single DC grounding point within a cabinet or if control circuitry (voltage or current sense) preclude the practice. Where a bond is not incorporated into the power supply, additional filtering is necessary if common mode interference is a concern.

If common mode interference is not bypassed to ground or attenuated by the input emissions filter, it may couple inductively or capacitively throughout the power supply and associated wiring. The interference is then free to reach logic circuitry within the system. Interference does not distinguish between logic circuitry within the system and the control circuitry of the power supply: A power supply may be just as vulnerable internally as the circuitry powered from it. The effect of interference varies with the point of injection, frequency, energy, the amount and type of bypass capacitance within the system, and second order filter characteristics. Lockup, data integrity problems, system reboot and component failure are common consequences if interference reaches logic or control circuitry within the system.

5. Common Mode Attenuation Tests - Frequency Domain

Two personal computers were tested with conducted RF (150 kHz to 30 MHz) to determine the relative immunity of the computers to conducted interference: An IBM PS2 model 30 and a 286 clone. The 286 clone was assembled inside the United States by a value added reseller; its power supply was made in Taiwan. The IBM PS2 was built inside the United States; its power supply was made in Hong Kong. The reputation of the IBM PS2 is well-known. The 286 clone is also a quality product (20 MHz processor with 4 MB of memory in a tower chassis). The point of this comparison is simple. The tested products were not selected because they were inexpensive or might test poorly: These products represent equipment which is commonly used in an office environment.

The frequency components of interference are random and vary with source, distribution impedance and load characteristics. Continuous wave signals and frequency domain measurements were performed with a spectrum analyzer to determine broadband load sensitivity and to identify frequency response of the load via spectral plots. The amplitude of the applied signals used to derive attenuation characteristics correspond to measured amplitudes of common mode noise (burst) recorded in commercial facilities. The equipment was tested with and without power to verify coupling characteristics and to remove the possibility of measurement error caused by normal computer operation. The computers were also tested on a stand-alone basis and with keyboards and monitors attached. The test results show the performance of a single system. Personal computers attached to data networks would no doubt test very differently. The derived attenuation capabilities for each computer reflect power supply and installation characteristics.

5.1. Attenuation Test Without AC Power

Figure 8 shows the test layout used to determine attenuation capability. A HP3585A spectrum analyzer equipped with a tracking generator was used to simultaneously drive a linear amplifier to inject high frequency common mode current into a personal computer and to record the attenuated test current at the +5 volt bus of the personal computer with a high frequency current probe. The amplifier was an ENI440LA rated for 35 watts of power and 45 dB gain (measured gain is 51 dB). The high frequency current probe was manufactured by Singer (Model 94430-2 calibrated at 1mV/mA). The current probe was placed around the combined +5 volt wires of the power supply which extend from the power supply to the motherboard, disc and floppy drives.

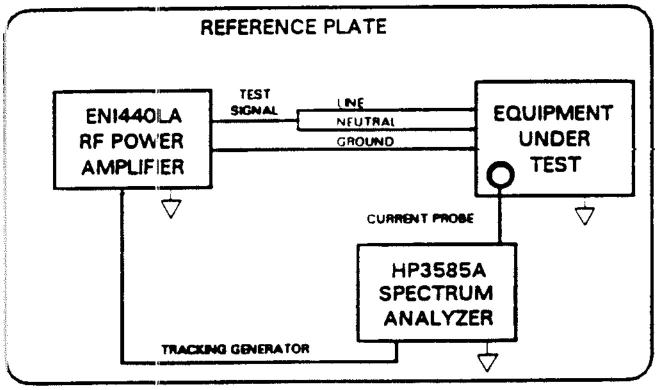

Figure 8 - Attenuation Test Setup (No Power)

A measurement reference was obtained by setting the output of the amplifier to provide a zero dB reference. The 0 dB reference corresponds to the current probe measurement of the current supplied by the amplifier to a 50 ohm, 50 watt load (Philco model 160-50D). The current at the +5 volt bus inside the device-under-test was compared to the 0 dB reference to derive attenuation data. The 50 ohm (0 dB) reference provides a means to compare the performance of a power supply with a known load. All measurements were performed with a copper ground plane and all test equipment, including the device under test, were connected to the ground plane with one inch wide copper tape. The power switch for the device-under-test was placed in the on position.

The computers were tested on a nonpowered, stand-alone basis to rule out the possibility that the measurements might be influenced by internal noise or interaction with other equipment. Keyboards and monitors were not attached. Figure 9 shows the current traces for the IBM PS2 and for the 286 clone. The figure shows the 0 dB reference and the current at the +5 volt bus for the 286 clone and the IBM PS2. The attenuation for the 286 clone ranged 20 to 51 dB (36 dB average) whereas the IBM PS2 attenuation ranged from 43 dB to 66 dB (57 dB average). The output of the RF amplifier was the same for each system (11.75 volts delivered into a 50 ohm load with approximately 3 watts power).

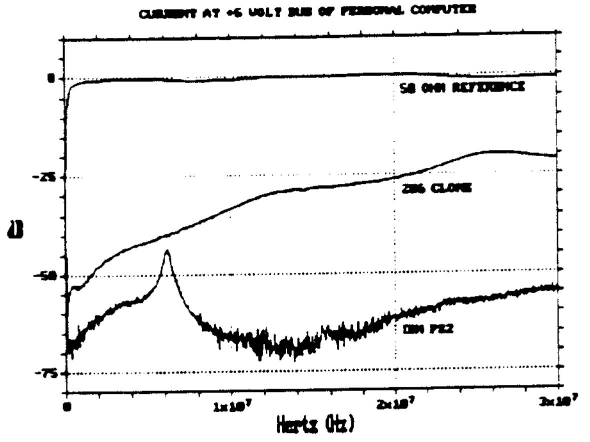

Figure 9 - Attenuation Traces (No Power)

Measurements of current were chosen as the primary indication of attenuation, rather than voltage, because capacitance within the device under test (at the motherboard or backplane) can attenuate test voltages and provide a false indication of attenuation capabilities. Coupled interference current flows through the capacitance of the motherboard (or backplane) creating localized voltage where ESR problems exist (equivalent series resistance or second order effect). The localized voltage might not be measurable at another location. Therefore, the measurement of current was chosen to determine the magnitude of interference current that might flow through a system.

Table 3 shows the attenuation levels for each computer. While the attenuation traces from the spectrum analyzer visually display the differences in attenuation, the numeric data in the table make the difference very plain. The IBM PS2 consistently provided small signal attenuation ratios which were significantly better than those provided by the 286 clone. In fact, at 30 MHz the 286 clone attenuation ratio dropped to only 10:1! One aspect of the testing must be stressed. All tests were performed with equipment and the device being tested placed on the reference plate and tied to the reference plate with one inch copper tape. The reference plate and ties to the reference plate reduce unwanted resonances and ensure accurate measurements. The reference plate and ties to the plate also ensure a low impedance return path which is probably better than would exist in real applications. As a result, the attenuation characteristics may represent best case conditions.

Table 3 - Common Mode Attenuation Test Results - No Power

MHz	IBM PS2		286 CLONE	
	Attenuation		Attenuation	
	dB	Ratio	dB	Ratio
1	64	1585:1	51	355:1
2	60	1000:1	47	224:1
5	54	316:1	41	112:1
6.17	43	141:1	39	89:1
10	66	1995:1	32	32:1
20	61	1122:1	26	20:1
30	53	447:1	20	10:1

5.2. Attenuation Test With AC Power

Figure 10 shows the test setup used to verify the attenuation capabilities while the computers were powered and operating. The same amplifier, spectrum analyzer and current probe were used for this test. An isolation back filter and signal insertion network were added to provide a means of injecting the signal and to control the direction of signal propagation. A VGA monitor and keyboard were connected to the personal computer under test. The monitor was powered from the back filter and the same monitor was used for each system.

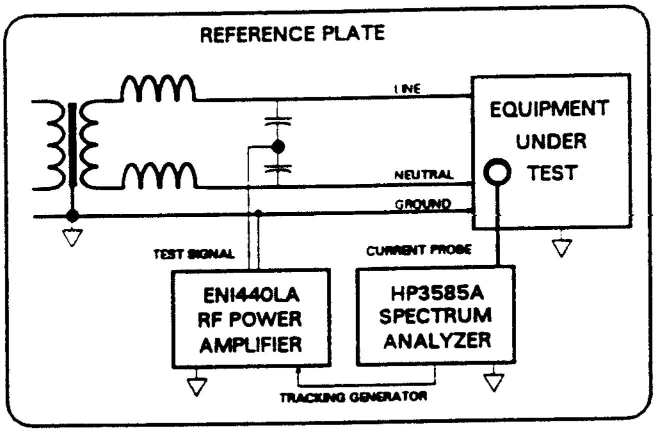

Figure 10 - Attenuation Test Setup (With Power)

The back filter elements included a Xentek isolation transformer (no neutral-to-ground bond), 90 microhenries of common mode inductance (air wound), and Tokin ferrite cores. The total attenuation provided by the back filter from the test point back to the power line was 60 dB or better across the test band (the tracking generator sweep is 20 Hz to 30 MHz and the amplifier output is 150 kHz to 300 MHz). The test signal was coupled onto line and neutral as a common mode signal via 0.1 microfarad Rifa capacitors.

Figures 11 and 12 show the test data for the IBM PS2 and the 286 clone, respectively. As before, the output from the tracking generator was attenuated with a step attenuator until the amplifier output into a 50 ohm load measured 0 dB. The current probe was connected to the +5 volt bus of the computer-under-test. The 0 dB reference was compared to this trace to derive the attenuation characteristics. In addition, in a second test the output from the tracking generator was increased until the computer-under-test exhibited functional problems. The higher trace in each figure reflects the current at the +5 volt bus for the second test. At 33.8 volts rms the 286 clone locked up. The IBM PS2 withstood 39 volts rms without lockup, although the monitor display (non-IBM) exhibited violent jitter.

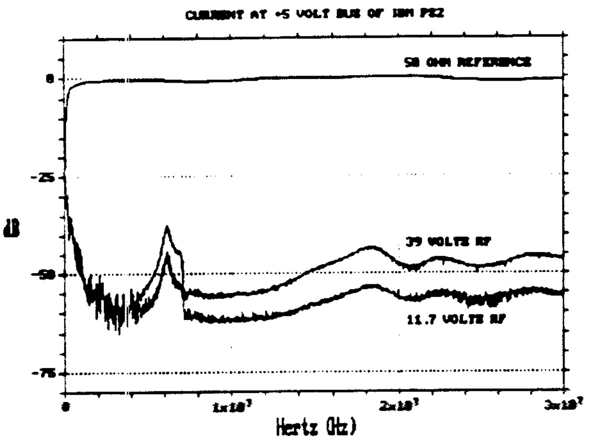

Figure 11 - IBM PS2

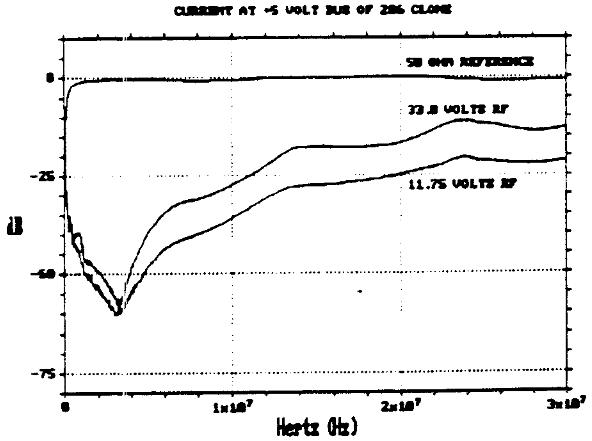

Figure 12 - 286 Clone

Table 4 shows the numeric data derived from the powered testing. The data trends established with the nonpowered testing were generally confirmed and maintained with the powered testing.

Table 4 - Common Mode Attenuation Test

MHz	IBM PS2		286 CLONE	
	Attenuation		Attenuation	
	dB	Ratio	dB	Ratio
1	52	398:1	47	224:1
2	58	794:1	53	447:1
5	57	708:1	41	112:1
6.17	44	158:1	42	126:1
10	61	1122:1	35	56:1
20	56	631:1	25	18:1
30	55	562:1	21	11:1

Because the VGA monitor provided a supplemental path for the applied common mode interference, it would seem logical that the measurements of interference within the test computer should indicate improved attenuation. At a few frequencies the test data did show an improvement, but, at other frequencies the attenuation decreased. This was true for the IBM PS2: Attenuation at 10 to 20 MHz decreased. Apparently, the data cable from the VGA monitor provided a backdoor path for interference to follow into the test computer even though the cable was shielded.

To determine if the low impedance return path provided by the copper reference plane and copper straps helped the device under test withstand the common mode test signal, the 286 clone was isolated from the table with a one quarter inch acrylic sheet and the copper tape bonds to the reference plate were removed. After the unit was isolated, 26.8 volts rms caused memory errors and strange characters on the monitor. At 27 volts rms the 286 clone exhibited several different responses: It either locked up, lost video control, lost DC bus voltages or rebooted. Momentary bursts of RF, rather than continuous signals, also caused similar problems.

6. Common Mode Surge Tests - Time Domain

The attenuation data derived during the frequency domain testing apply only to small amplitude signals. The withstand capability of a load may decrease with larger amounts of interference and energy. Two common mode surge tests were performed to determine the response of electronic equipment to larger interference signals. These tests were performed with time domain recording equipment to ensure capture of peak interference levels.

6.1. Common Mode Surge Test (Schaffner)

To verify if the attenuation level would change with higher power signals, a Schaffner surge generator (model NSG-200D with a NSG- 223 surge module) was used to inject a 500 volt common mode surge into the 286 clone. The surge current was recorded at the +5 volt wiring for the 286 clone and for the IBM PS2 with the Singer current probe (94430-2) and a digital storage oscilloscope (Tektronix TDS 540). Figure 13 shows the test setup.

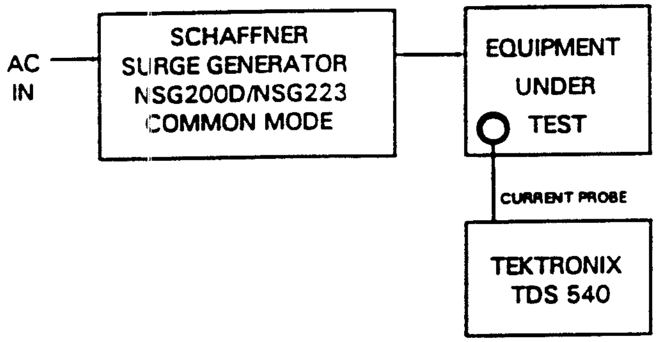

Figure 13 - Common Mode Surge Test (Schaffner)

The surge current at the +5 volt bus was 504 milliamperes for the 286 clone and was not measurable for the IBM PS2. The ambient operating current inside the IBM PS2 was 61 milliamperes peak and the surge remnant could not be extracted from the background current. Compared to the calculated surge current (500 volt surge delivered from a 45 ohm source impedance), the attenuation for the 286 clone is 26.8 dB. The test impulse was 50 microseconds in duration with 580 ns rise time. The surge remnant measured inside the 286 clone oscillated at 2 MHz.

This test demonstrates two important points. First, the attenuation was lower than would be indicated by the frequency domain attenuation testing. Second, the surge remnant was oscillatory while the applied pulse was unipolar (i.e., it was AC coupled). These conditions show that larger surge voltages can reduce input filter attenuation by saturating filter inductors.

6.2. Common Mode Surge Test (ANSI/IEEE C62.41-1991 Category A)

One test was performed to determine if the surge remnant from a three element surge suppressor could couple through a device and into connected data circuits (TVSS or transient voltage surge suppressor with MOVs between line-to-ground, line-to-neutral and neutral-to-ground). Although not intended, the test also determined if sufficient energy could be coupled through the surge suppressor to damage a protected device. Figure 14 shows the test setup. The test device was a standard dot matrix printer. The common mode surge was applied every five minutes. Differential scope probes were connected from data to signal ground (pins 2 to 7 on the serial port of the printer) to record the let-through voltage. The printer was not connected to other equipment.

The printer was tested for functionality after 10 common mode surge events. The measured let-through voltage indicated that there was a problem, and indeed, the I/O chip for the printer had failed. Figures 15 and 16 show the surge remnant, respectively, before and after failure occurred. The remnant voltage increased from around 15 volts peak to about 500 volts peak. Obviously, the printer was no longer functional at this point.

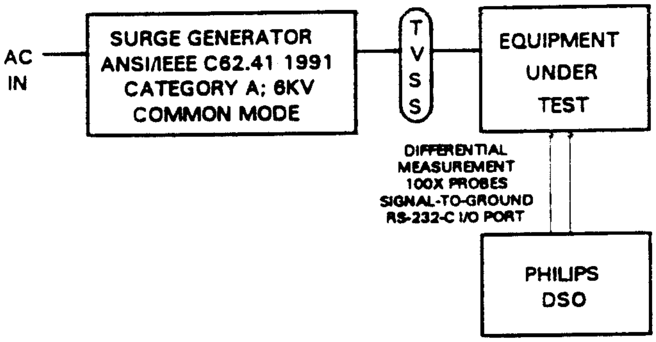

Figure 14 - Common Mode Surge Test (ANSI/IEEE C62.41-1991)

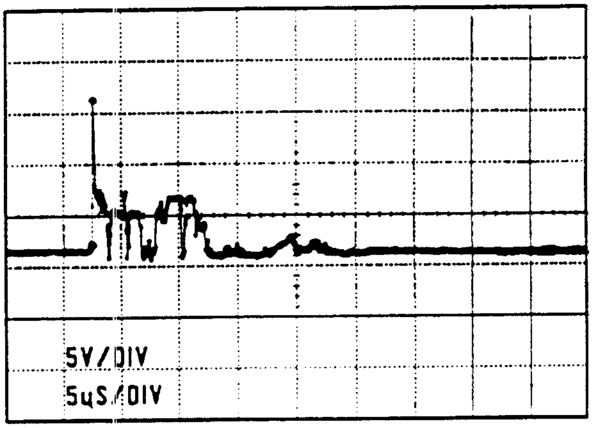

Figure 15 - Pin 2 Before Failure

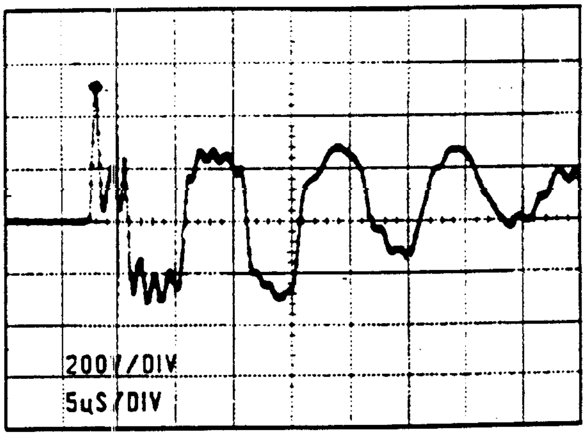

Figure 16 - Pin 2 After Failure

The surge test indicates a weakness in the design of the printer to withstand surge current remnants and points out an important consideration. Simple surge suppressors protect a load by creating a low impedance shunt path for surge energy to follow: The surge energy will pass through the impedance of the surge suppressor rather than continuing into the load provided the load presents sufficient impedance to the surge and surge remnant. If sufficient impedance is not present in the load then surge energy will enter the load and follow any path available to complete its journey. Similarly, common mode surge current remnants which do pass into a load are most likely to affect ground referenced circuitry (i.e., data circuits).

7. Interference Coupling Into Data Circuits

Data circuits and common mode surge currents share a common connection to ground. Data circuits use ground as a reference either directly or indirectly. Nonbalanced data circuits (e.g., EIA-232-D or more commonly called RS-232-C) measure data signals with respect to ground and use ground as a path for data return current. For this reason, pin 7 is commonly tied to the chassis of both the sending and receiving station. Balanced data circuits (e.g., RS-422) reference data drivers and receivers to ground, although the data signal is measured differentially between two wires. Similarly, common mode surge currents use ground as a path and can either induce current flow in the connecting cables of a nonbalanced data circuit or force a voltage differential across a balanced data circuit.

Due to the commonality of grounding, a surge condition does not require direct injection to induce a failure in a data circuit or to compromise the operation of electronic equipment. Figure 17 shows a test configuration used to verify the ability of power line related surge current to couple into data circuits. A surge generator was used to inject a normal mode surge into an isolation transformer with a bond on the secondary between neutral and ground. The resulting surge on the output was normal mode from a classic sense. However, the bond between neutral and ground on the secondary turned the branch circuit grounding conductors into supplemental paths back to the transformer (refer to figure 1 for an illustration). Two branch circuits, 50 and 150 feet in length, were powered from the transformer. An EIA- 232-D circuit (25 ft.) connected a personal computer at the end of the 150 foot branch circuit and a printer at the end of the 50 foot branch circuit. A 3 element transient voltage surge suppressor (TVSS) was installed in the 150 foot branch circuit at the personal computer.

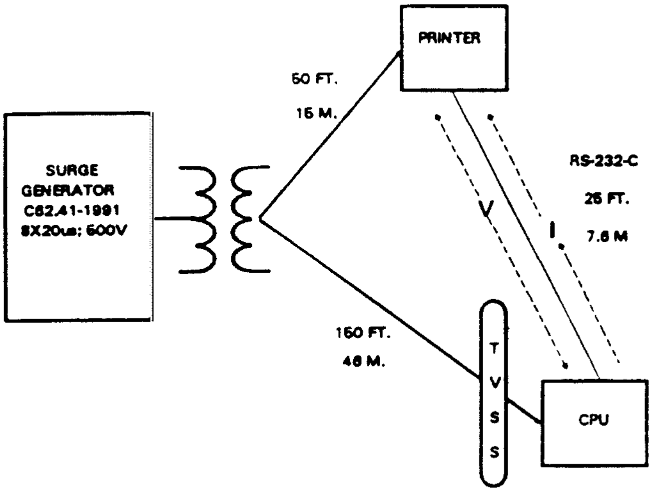

Figure 17 - Data Circuit Coupling Test

Figure 18 displays the current measurable in the ground referenced conductor of the data cable. The current occurs because the surge suppressor uses ground as a return path and the data cable is just another path. Coupling and impedance differences between branch circuits may also cause current in the data cable because the surge current interacts with the impedance of each branch circuit creating a transient voltage gradient (skew or reference shift) between the branch circuits. In nonbalanced data circuits (e.g., EIA-232-D) and in balanced data circuits (e.g., RS-422) the ground referenced voltage differential develops across

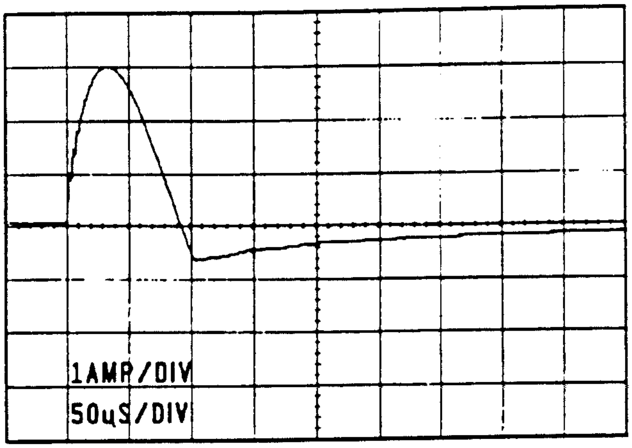

Figure 18 - Surge Current In Data Cable

the input and output data ports of the data-linked systems and, if large enough, causes data errors or damage to the data ports.

The effects of reference skew are not limited to the data ports. A very large transient voltage gradient in the grounding means may cause enough current in the grounded conductor of the data cable to induce appreciable voltage in the signal conductors. The data chip may then pass the energy into the system. Figure 19 shows a schematic for a popular data driver chip (DS1488).[2]

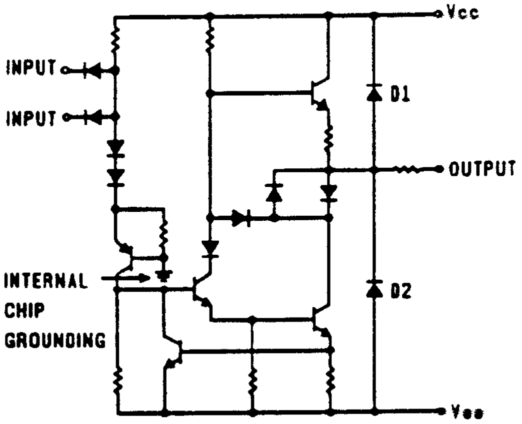

Figure 19 - I/O Drive Chip Schematic

Protective diodes are built into the chip. If surge voltage exceeds Vcc or Vee, then diodes D1 and D2 conduct and pass surge current into the power bus of the system. Inside the system, the effect of the surge current depends upon internal protective measures. However, systems with limited internal protection can experience lockup, reset and even internal circuit board failures.

8. Sources of High Frequency Common Mode Interference

High frequency interference can be generated by a wide range of equipment or conditions. Worn brushes on AC motors or loose arcing contacts in an electrical distribution system are the most common sources. Credit card embossers (found in stores, restaurants and even throughout hospitals), electric drills, heat guns, vacuums and floor polishers are also excellent sources. Some equipment, however, is unique in its ability to generate high frequency interference. Within a hospital, the Bovie cauterizing equipment commonly found in operating rooms and in industrial settings, its cousin the high frequency arc welder are spectacular sources of high frequency interference. Some equipment radiates high frequency interference as a byproduct of its normal function. Within a semiconductor manufacturing facility, epitaxial reactors and sputterers are well-documented sources of interference. Hand held radio transmitters, cellular phones and digital radio pagers and terminals also induce high frequency interference into unshielded power and data lines.

The problems caused by high frequency interference are not new, but the presence of these

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[2] Interface Databook (National Semiconductor, 1988), p. 1-13.

problems may be difficult to detect and diagnose. Power monitors simply do not possess sufficient bandwidth or sampling rates to record high frequency interference. For example, a power monitor which samples at 2 megasamples per second will record events which are 2 MHz and faster as low kHz events unless sufficient bandwidth limitation and aliasing filters are built into the design. In this case the monitor cannot respond to the event. Further, the threshold levels for the monitors may be too high to capture low amplitude signals.

The presence of low sample rates and high thresholds in monitoring equipment are due to the assumption that the power line surge is the dominant problem for electronic equipment, and that electrical surges tend to be very large and fairly slow. The results are often extremely confusing for the user of monitoring equipment. In one instance where high frequency common mode was a problem, processors throughout a major data center would reset or lockup without any apparent cause or reaction from power monitors installed at the site. An indication of the nature of the interference was finally captured, but only after the power monitors at the site were supplemented with high frequency storage oscilloscopes.

Figures 20 and 21 show common mode, high frequency interference events which were recorded in an office environment. An inspection of the circuit revealed that a refrigerator and a water bottle cooler were powered from the circuit. The events were recorded with a Tektronix TDS540 digital storage oscilloscope, an ONEAC LV103 line decoupler and were stored with a computer based data acquisition and analysis system. The events were recorded randomly throughout the day. A closer inspection revealed that the timing of the events coincided with the power-off cycle of the refrigerator. Apparently, the energy stored in the inductance of the refrigerator motor was injected into the power line causing the events.

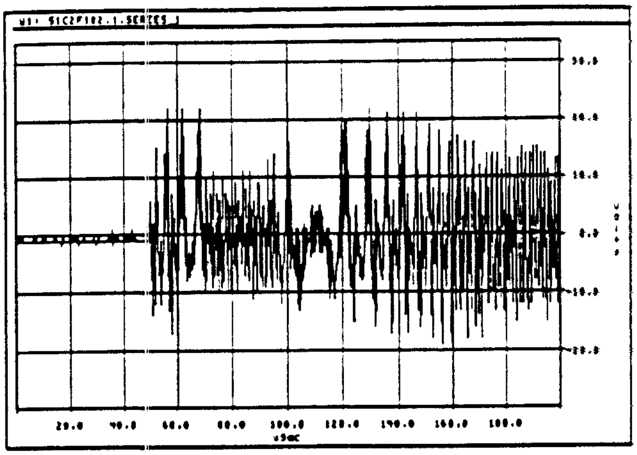

Figure 20 - Event 182 - Common Mode Interference

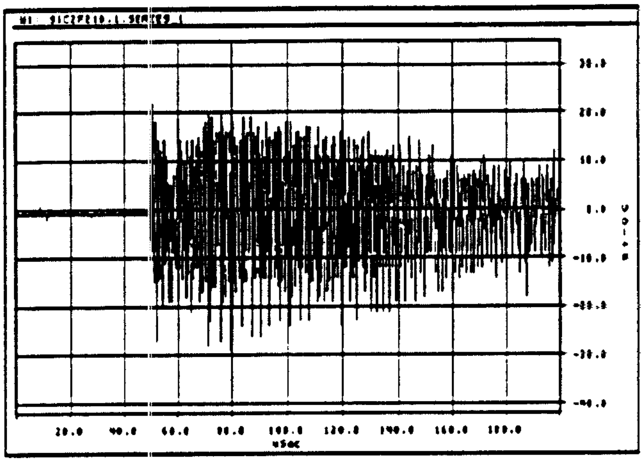

Figure 21 - Event 210 - Common Mode Interference

In another case, the cycling of a refrigerator caused large popping noises in a music system. The owner, fearing damage to the system, added an isolation transformer to protect the amplifier. Unfortunately, the transformer did not stop the interference and the tweeters in the system were destroyed. The amplifier, just like sensitive test equipment, is a small signal, large gain device. Interestingly, a power monitor used at the site was not able to capture and record the interference. Due to the sampling rate of power monitors, the interference would be missed or recorded incorrectly if the refrigerator interference was fast enough.

Figures 22 and 23 show the Fourier analysis of the office related refrigerator events. The Fourier analysis reveals three important points. First, the events show that high frequency common mode signals can occur in normal commercial environments. Second, the fast Fourier transform (FFT) analysis shows that the waveforms have frequency components which range from kHz to several MHz and the FFT transforms require several hundred volt potentials to reconstruct the original waveform. The concern raised by the FFT analysis is that the waveforms might cause current flow through an impedance which reflects the FFT potential and not the actual amplitude. Actually, sensitivity of the load to the individual frequency components is the most important factor. Third, the waveform in event 182 shows a unique beat pattern which may be caused by aliased signal processing and may help to explain why the monitor in the earlier example missed the interference.

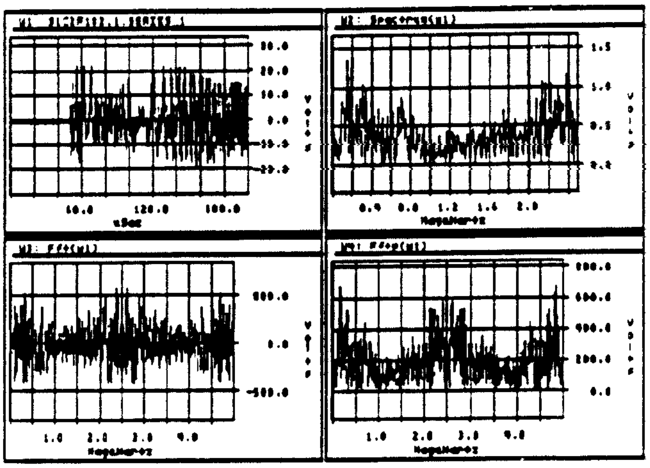

Figure 22 - FFT Analysis of Event 182

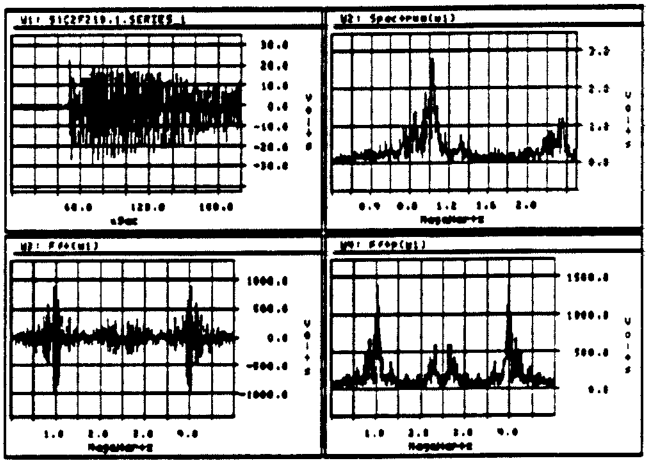

Figure 23 - FFT Analysis of Event 210

Figures 22 and 23 show events 182 and 210, respectively. Both events were analyzed and displayed to permit comparison. In each figure, the individual windows represent a different analytical process.

- W1 - The original waveform
- W2 - A spectrum plot of the original waveform (W1)
- W3 - A FFT plot of the original waveform (W1)
- W4 - A FFT and phase plot of the original waveform (W1)

The contrast between events 182 and 210 is quite striking. Event 182 shows a wide range of frequencies (low kHz to several MHz) and null periods without any significant frequency components. In contrast, event 210, while also exhibiting a wide range of frequencies does not show the same null periods and the highest frequencies do not approach the sampling limitations imposed by the oscilloscope settings.

Event 182 (figures 20 and 22) is a good example of an aliased signal. The Fourier analysis shows an almost equal concentration of low kHz and high MHz (2.5 MHz) components. As the oscilloscope was set for 10 microseconds per division capture rate, the sampling rate is five megasamples per second. Per the Nyquist theorems for data analysis, the sample rate must be at least two times faster than the frequency of the recorded waveform. Where the applied signal equals or exceeds the Nyquist point, the original signal cannot be displayed correctly. The resulting signal will be lower in frequency, and may actually approach zero frequency.

The term aliasing is used to describe this condition. A sample rate which is 5 to 10 times the anticipated frequency is really needed to capture and display signals with accuracy.

9. Conclusions

This paper has addressed the paths and processes by which common mode interference couples into electronic equipment and has demonstrated that power supplies, and the subsequent operation of electronic equipment, can be upset by relatively low levels of high frequency interference. The general belief that interference signals must be hundreds of volts in amplitude before system upset can occur is only true when the frequency of the interfering event is low. Segmenting interference into categories of normal versus common mode ignores the issues of mode conversion and the role which the electrical distribution system plays in the creation of ground referenced interference. Just as important, electronic equipment is increasingly used in potentially hostile electrical environments and interconnected with data circuits.

The solution to the problems posed by interference may be addressed through equipment design and test. The susceptibility of a device varies with design. The physical determinants are:

- emissions filter style, frequency response and input impedance,
- bypass capacitance for common mode interference,
- data interconnection, filtering and protection of data I/O ports,
- wiring and circuit board layout,
- and grounding within the system.

The type and speed of process also plays a role in the susceptibility of a device to interference. Equipment with large signal gain, or equipment which operates at extremely fast speeds, conceptually, are at greater risk. With large signal gain, even small amounts of interference can be amplified to objectionable levels. With fast operating speeds, the potential for interference to coincide with a critical process event is much greater.

Extremely fast interference is not a new subject. Test standards exist both domestically and internationally to aid equipment designers. For the past decade high energy electrical surge caused by lightning has received the majority of attention. Modern test standards, both domestic and international, have recently added tests which incorporate fast frequencies with common mode injection and common mode coupling as a means to test electronic equipment. However, the application of these standards will take time and will only be of benefit if used. Unfortunately, time, cost, and an inability or unwillingness to test equipment will leave users with equipment which may let them down and cost untold financial loss. Even when well designed and tested, however, the data circuits may prove to be the weak link providing the path for damaging interference.

Testing or field experience can indicate if a device may be susceptible to common mode interference. Testing a product for interference sensitivity can be expensive. When a company has the time, budget, resources and ability to test and harden their equipment against surge voltages and high frequency interference, the resulting improvement in reliability can be impressive. Even with large companies there is no guarantee of consistency of design across product lines or between various divisions within large multi-national organizations. It is common practice for both large and small companies to integrate equipment from a variety of suppliers into complete systems which may not be tested or hardened against surge voltages and high frequency interference.

If cost were an indication of final performance, then the solution would be obvious. Unfortunately, cost is not necessarily an accurate indicator. Field experience or testing remain the only real methods to verify if a system possesses the ability to withstand a wide range of interference. In the absence of testing or field data to guide a user, precaution must be the rule. In many environments it would be prudent for the user to consider some form of ancillary (add-on) product to supplement and enhance the withstand capability of electronic equipment to low levels of high frequency common mode electrical interference.

About the author:

Tom Shaughnessy is Vice President and co-founder (1986) of *PowerCET Corporation.* Previously he held positions of engineering and product management, applications support and field engineering. Tom is a graduate of the University of Montana, a member of IEEE and NFPA has over 12 years experience in the areas of equipment service and protection. Tom is a co-author of PowerCET's publication: *Power, Grounding and Protection of Electronic Equipment II.*

About PowerCET Corporation:

PowerCET Corporation is an independent consulting company which is focused at understanding the electrical environment and its impact upon the operation of electronic equipment. PowerCET's unique background brings a wealth of experience and knowledge to its range of training courses and consulting activities. In this regard, PowerCET Corporation provides the power quality training courses for Dranetz Technologies and offers other education programs on the electrical enviorment. In addition, PowerCET has developed custom software and monitoring systems to facilitate network troubleshooting and has published manuals and papers on the electrical environment and its impact on electronic equipment.