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**MITIGATION OF EMI GENERATED BY A
VARIABLE-FREQUENCY-DRIVE CONTROLLER
FOR AN AC INDUCTION MOTOR**

by

Philip E. VanWiltburg

September, 1994

Thesis Advisor:

Richard W. Adler

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**MITIGATION OF EMI GENERATED BY A VARIABLE FREQUENCY DRIVE
CONTROLLER FOR AN AC INDUCTION MOTOR**

by

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Submitted in partial fulfillment
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ABSTRACT

In recent years a significant number of digital devices and systems have been added to receiving and data-processing sites. These additions have enhanced the ability of the sites to accomplish their mission. They have also introduced new kinds of electromagnetic interference (EMI) into these sites along with accompanying performance degradation problems. In this thesis one specific case of EMI is considered. It is EMI from a digital climate-control system of a building housing a data-processing facility. The digital system generated excessive amounts of EMI. The EMI was conducted throughout the site over power and control conductors. Electromagnetic fields from EMI current flowing in these conductors coupled the EMI into other nearby conductors. Integrated barrier, filter, and ground techniques were used to reduce the conducted and radiated EMI to harmless levels.

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I. INTRODUCTION

The electromagnetic spectrum is divided into a number of separate bands, and these bands are used for a number of purposes. Typical uses include point-to-point radio communications, mobile-radio communications, satellite communications, radar, navigation aids, and many other uses. All such applications of the radio spectrum employ antennas and receivers to convert extremely weak electromagnetic fields into useable analog or digital signals. Unfortunately, some electronic equipment and devices generate significant levels of radio interference. In some cases this interference is sufficiently large to degrade the ability of receivers to detect desired signals. Sometimes the interference is strong enough to adversely affect the operation of other electronic devices and systems.

An increasing number of modern digital devices and systems are being introduced into receiving and data processing sites. While these systems result in significant improvements in work efficiency, they sometimes generate excessive levels of radio interference to radio receivers and other electronic systems. Typical examples of interference sources include digital power-control systems, microwave ovens, computers, printers, copy machines, digital-telephone systems, uninterruptible power supplies (UPS), and other similar devices and systems.

This thesis describes a solution to one specific case of electromagnetic interference (EMI) from a digitally-based, variable-frequency induction-motor controller. The

controller and induction motor were used in the air-handling system of a building housing sensitive data-processing equipment.

A. BACKGROUND

Most receiving sites and data-processing centers require a controlled climate. For most of these sites, air conditioners are used to maintain the climate at a near constant temperature and humidity. The standard motor for most high-volume air-conditioning systems (HVAC) is a 460-volt, 3-phase, AC induction motor which operates at a constant speed. When the HVAC services more than one room, the amount of cooling the facility requires will vary. By using a variable-frequency-drive (VFD) controller to run the HVAC's motor at different speeds, the HVAC provides the exact amount of cooling needed for the facility. Variable-frequency drives take a fixed voltage and frequency and convert it into a variable voltage and frequency, hence the variable speed. The Halmar-Robicon ID-PWM 454 series VFD used for this thesis is typical of the VFD drives available today.

B. OBJECTIVE

This thesis investigates the electromagnetic interference generated by a variable-frequency drive in the 1-kHz to 100-MHz portion of the electromagnetic spectrum and recommends modifications to minimize these problems. Chapter 2 describes EMI sources and various EMI standards. Chapter 3 describes barrier, filter, and ground design. Chapter 4 describes the ID-PWM 454 VFD and its operation. Chapter 5 describes the performance of an unmodified VFD. Chapter 6 describes the performance

of a VFD modified to reduce EMI. Chapter 7 states conclusions and recommendations for placing modified VFDs in service and the advantages of having an electromagnetic compatibility (EMC) plan.

C. RELATED WORK

Electromagnetic compatibility studies have been ongoing throughout the world for many years. However, several problems remain including confusing and conflicting standards, poor measurement equipment, and incorrect perceptions about the control of EMI. As a result, many mitigation efforts fail to solve EMI problems, and in some cases they exacerbate EMC problems. An exception is the Signal-to-Noise Enhancement Program (SNEP). Organized at the Naval Postgraduate School, a SNEP team conducts EMI surveys and defines steps to mitigate EMI problems. The SNEP teams use specialized equipment to define EMI problems, set limits for EMI emissions at receiving sites, and recommend solutions. Both the U.S. Navy and the U.S. Army use SNEP teams to conduct EMI surveys at receiving and data processing sites.

Some progress has been made in the control of EMI at receiving and data processing sites by the SNEP. SNEP teams, consisting of experienced personnel and specialized instrumentation from the Naval Postgraduate School, have investigated and mitigated a number of complex EMI problems. These teams have proposed maximum EMI current limits for all conductors that enter, leave, or support digital devices and systems.

II. ELECTROMAGNETIC COMPATIBILITY

Electromagnetic compatibility is more important in today's dense electromagnetic environment than anytime in the past. An electronic device or system is electromagnetically compatible if it does not interfere with other systems, it is not susceptible to EMI from other systems, and it does not interfere with itself. While portions of the radio spectrum have been very crowded for many years, the increased numbers and operating speed of today's digital devices greatly compound interference problems in the HF, VHF, and UHF bands.

Digital devices and equipment have been widely installed in receiving and data processing sites to increase productivity. But much of this equipment was installed with little regard or understanding for EMC. As a result, some digital equipment degrades mission effectiveness by adding EMI. As new digital equipment is added to sites, noise increases. In addition, the area surrounding these sites often has digital equipment, which can add to the EMI levels affecting receiving and data processing sites.

A. ELECTROMAGNETIC-INTERFERENCE SOURCES

EMI, both natural and man-made, has degraded the performance of radio systems since the early days of radio. Examples of early systems degraded by EMI include telegraphs and radios. EMI comes from two sources; (1) sources external to the facility

housing the system in question and (2) sources within the facility, including noise created within electronic and electrical systems.

1. External Noise Sources

Unwanted electromagnetic waves that enter a site through antennas, or any other conductor, are from external noise sources. Most of these waves can be classified as radio-frequency interference (RFI). Examples of RFI sources include natural phenomenon such as lightning, static from charged rain drops and static from dust/sand storms. Lightning is major source of RFI up to 50 MHz. Static charge builds up when charged raindrops, dust, or sand strike isolated conductive surfaces. When the charge becomes large enough, corona discharge can occur at sharp projecting points on the charged surfaces. Noise associated with power-line hardware is a significant man-made source of external noise. Any power line within the line-of-sight of a receiving site is a potential source of RFI. The most common examples of power-line noise include gap noise, hardware noise, lightning-arrester noise, cable-head sparking, and corona noise.

[Ref. 1]

2. Internal Electromagnetic-Interference Sources

Internal EMI sources include microscopic sources, electrical devices, and electrical circuits. EMI generated from microscopic sources include thermal noise and shot noise. Random velocity fluctuations of charge carriers in a resistive material produces thermal noise. Shot noise occurs as a current passes a potential barrier (this occurs in solid-state circuits). Electrical circuits and devices are another major source

of internal noise. Circuits that cause a significant amount of EMI/RFI include mixers and oscillators. Heterodyning and signal modulation/demodulation also produce EMI/RFI. Switching devices such as diodes, SCRs, and integrated circuits also generate EMI. Computers, UPS, motor speed controls, and equipment with sliding contacts generate broadband EMI. [Ref 1]

B. ELECTROMAGNETIC-INTERFERENCE STANDARDS

Limiting EMI current on site conductors to harmless levels will eliminate most EMI problems. Many modern digital systems inject high levels of EMI current into grounds, power wires, cable shields, and other conductors. The electromagnetic fields associated with the EMI current can interfere with the reception of signals-of-interest (SOI) at receiving sites. While data processing systems tolerate higher EMI currents than receiving equipment, no suitable documentation exists for a maximum acceptable EMI limit for either.

1. SNEP Electromagnetic Interference Standards

The staff and students of the Naval Postgraduate School, in cooperation with other government and civil agencies, have informally proposed maximum levels of EMI currents for large HF, VHF, and UHF receiving sites. Large receiving sites are fixed multi-room facilities containing numerous conductive paths. The suggested maximum levels for large sites are: 2 mA of EMI current at any frequency from 10 Hz to 10 kHz and 10 μ A of EMI current at any frequency from 100 kHz to 100 MHz. A straight line

can be used to connect the 2-mA and 10- μ A levels. These guidelines are shown graphically in Figure 1 below.

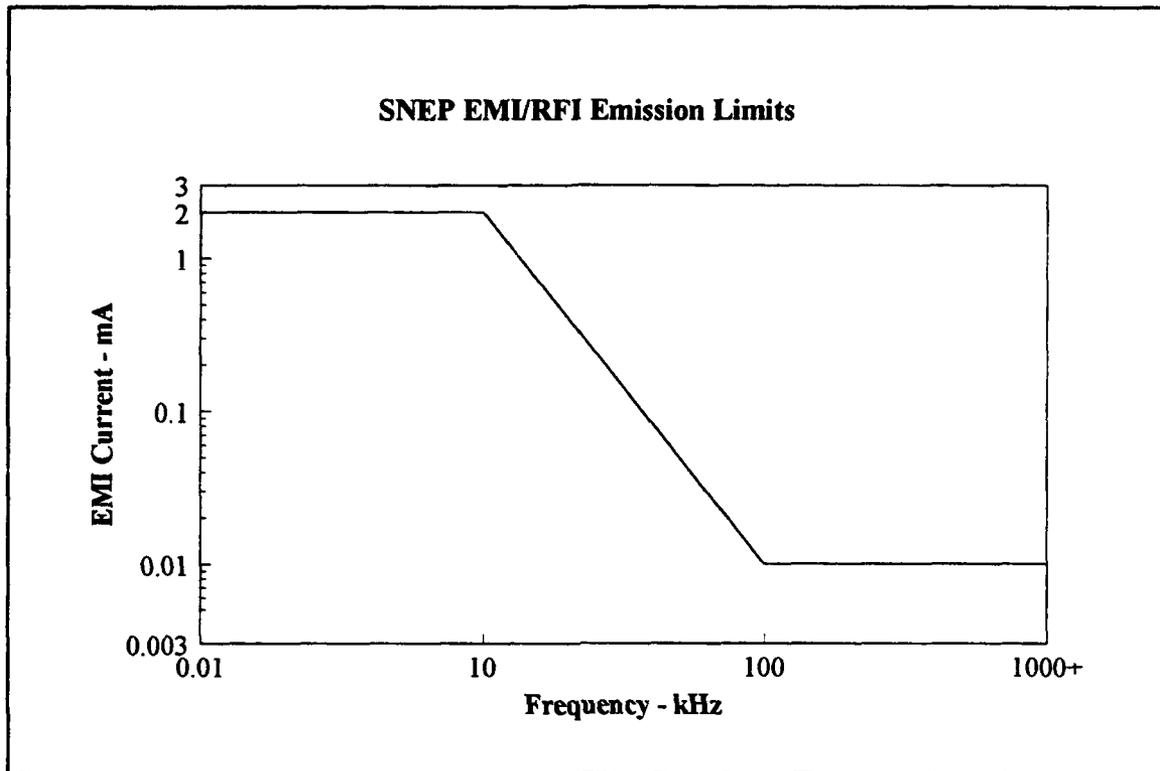


Figure 1. SNEP Maximum EMI Current Level

For a small field receiving site, the suggested maximum value of EMI current from 100 kHz to 100 MHz is reduced from 10 μ A to 2 μ A. [Ref. 2]

2. Federal Communications Commission EMI Standards

The Federal Communications Commission (FCC) regulates the use of radio frequencies from 9 kHz to 3000 GHz under Title 47, Part 15 of the Code of Federal Regulations. Any electronic system with digital circuits using clock signals or other signals over 9 kHz must comply with the FCC limits for radiated and conducted emissions. The FCC divides these digital devices into Class A and Class B. Class A

digital devices are for business, commercial, and industrial use while Class B digital devices are for residential use. The Class B conducted emission limit is $48 \text{ dB}\mu\text{V}$ for the 0.45-30 MHz frequency range, while the Class A conducted emission limit is $60 \text{ dB}\mu\text{V}$ between 0.45-1.705 MHz and $69.5 \text{ dB}\mu\text{V}$ between 1.705-30 MHz [Ref. 3]. The FCC measurements for conducted emissions are verified by the use of a line-impedance-stabilization-network (LISN) inserted in the unit's AC power cord as shown in Figure 2.

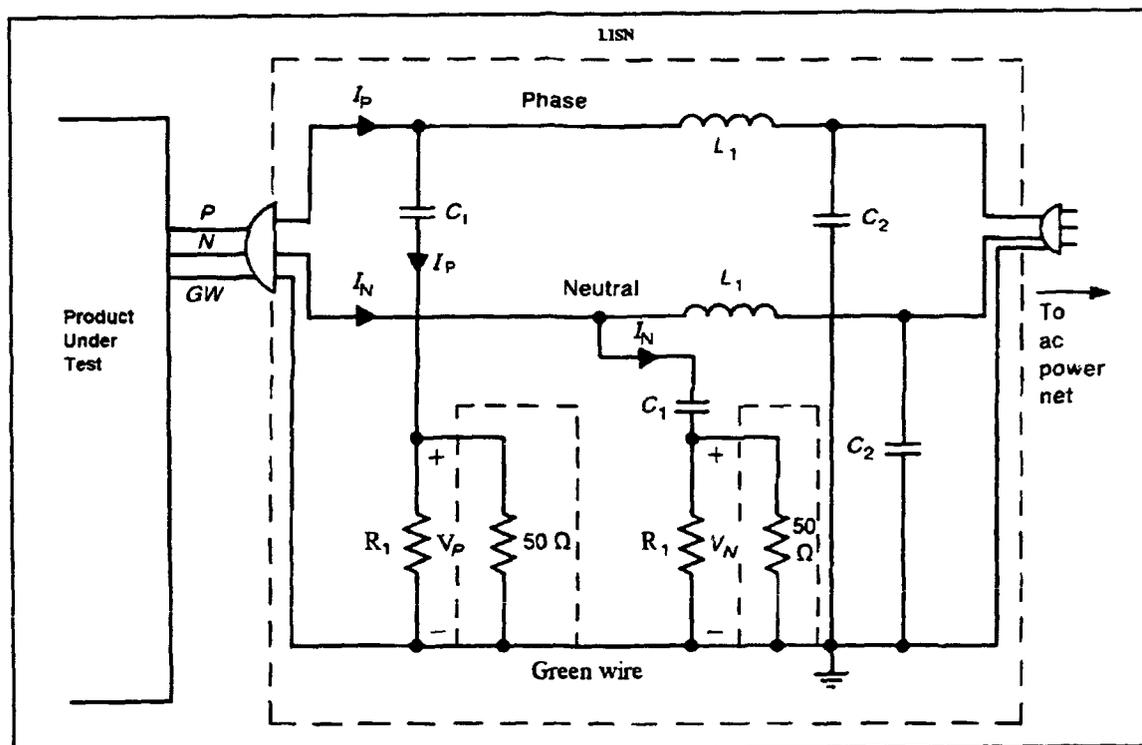


Figure 2. FCC LISN Measurement Device

Inserting the LISN into the power line does not result in an accurate representation of the EMI current. The LISN measures voltage which is approximately related to the interference current [Ref. 4]. Unfortunately, this measurement method induces errors from the use of various LISN devices and the random effects of power

wiring impedance. These measurements can be converted to approximate values of current in μA using the following relationships:

$$P_{mW} = V_{\mu V}^2 * 1 \times 10^{-9} / R_1 \quad (1)$$

and

$$I_{\mu A} = \sqrt{P_{mW} * 5 \times 10^{10}}. \quad (2)$$

The maximum allowable EMI current of the FCC EMI standard is shown in Figure 3.

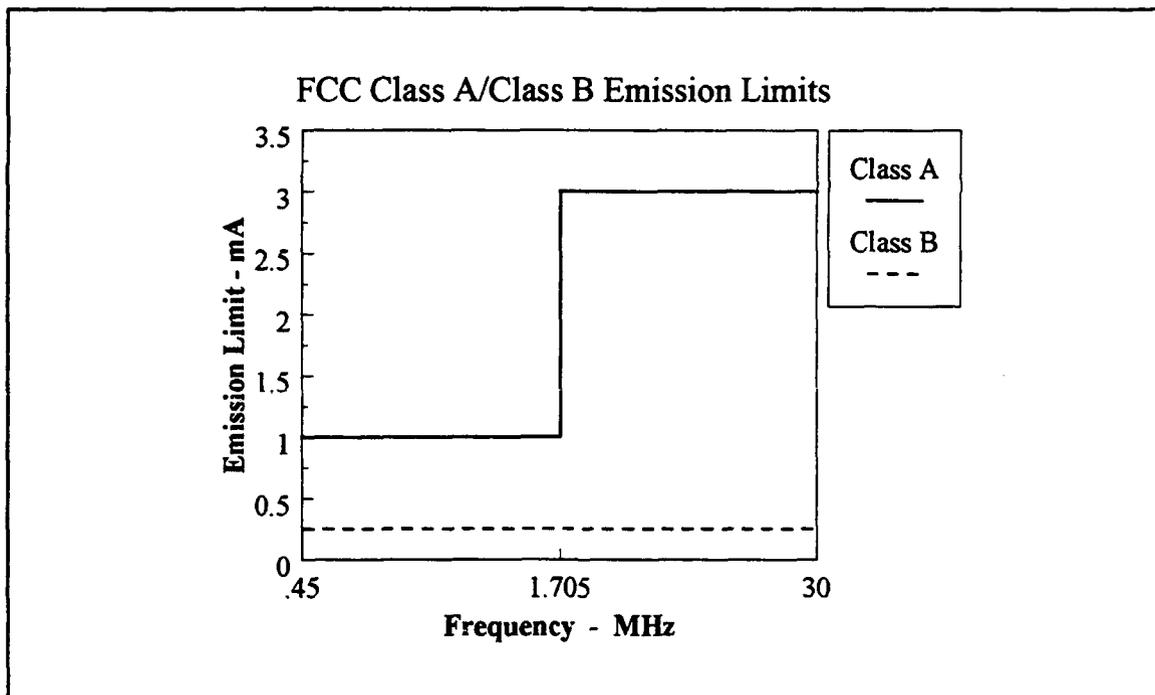


Figure 3. FCC Class A/B Emission Limits

Figure 3 shows that the FCC Class A and Class B levels are much higher than the SNEP levels shown earlier. The FCC standards also do not cover a frequency range as wide as the SNEP-suggested levels.

3. Department of Defense MIL-STD-461B EMI Standards

Within the Department of Defense, imposed limits on electromagnetic emissions are specified in MIL-STD-461B for most electrical systems. These standards vary for different types of equipment, but even the most stringent limit (Class A), ranges from 20 mA at 14 kHz and 10 μ A from 2 to 50 MHz for conducted emissions as shown in Figure 4.

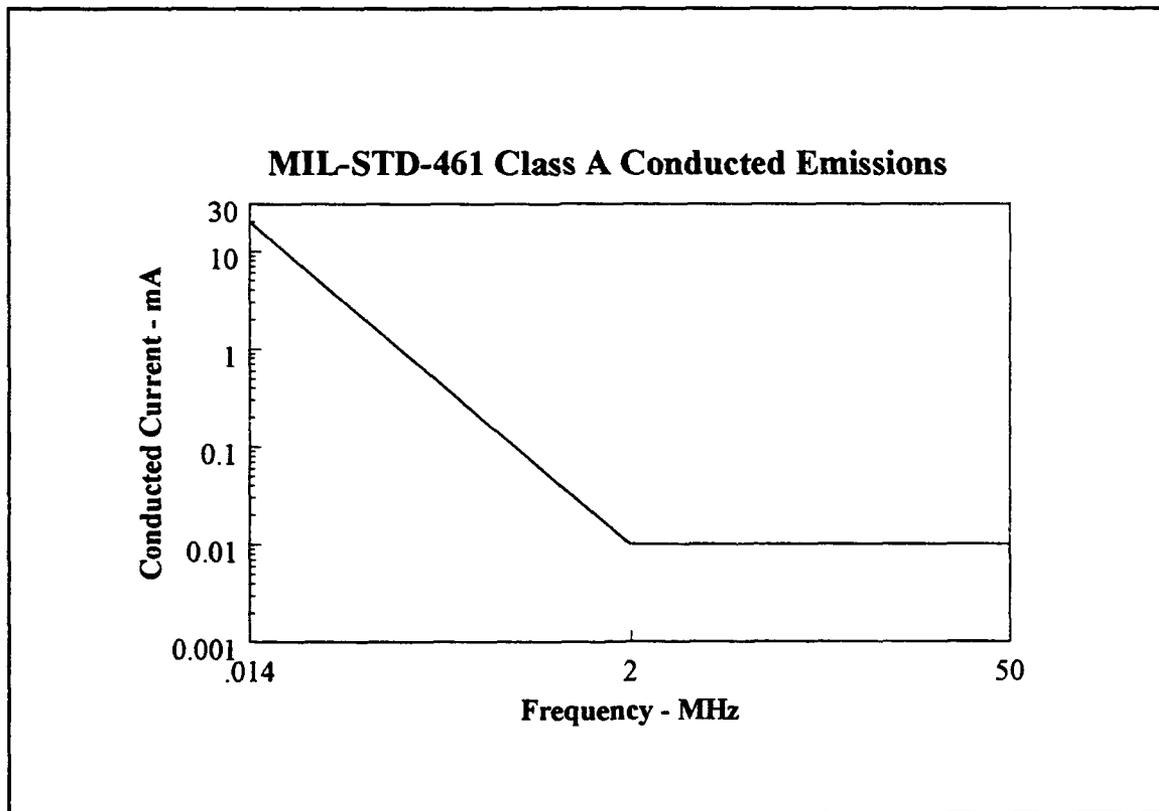


Figure 4. MIL-STD-461B CE03 Conducted Emission Limit for Class A Equipment

The MIL-STD-461B Class A emission limits shown in Figure 4 apply to equipment which must operate when installed in critical areas such as aircraft, submarines, surface ships, and ground facilities. MIL-STD-461B also controls the susceptibility of equipment to EMI emissions from other electronic equipment. Key differences between MIL-STD-461B and the FCC standards include a much wider class of products covered by MIL-STD-461B. Compliance with MIL-STD-461B can be waived by the military agency procuring the system. [Ref 4]

While MIL-STD-461's EMI standards are closer to those of the SNEP proposed guidelines, they still do not cover a frequency range as wide as the SNEP. The waiverability of these standards make them practically useless as any EMI standard must be strictly adhered to for effective implementation.

4. Institute of Electrical and Electronics Engineers EMI Standards

The Institute of Electrical and Electronics Engineers (IEEE) P1155 standard sets new limits of EMI/RFI emission and susceptibility for the VXibus architecture. The VXibus systems consist of a mainframe with a varied number of slots for plug-in modules. Oscilloscope, multimeter, multiplexer, and computer modules are examples of modules that can be plugged into a mainframe. Both the mainframe and the modules are required to meet the EMC standards shown in Figure 5. The mainframe's output maximum-rated peak current and dynamic current determine the EMI limits for the mainframe, while each module's maximum-rated peak current and dynamic current determine the EMI limits for the module.

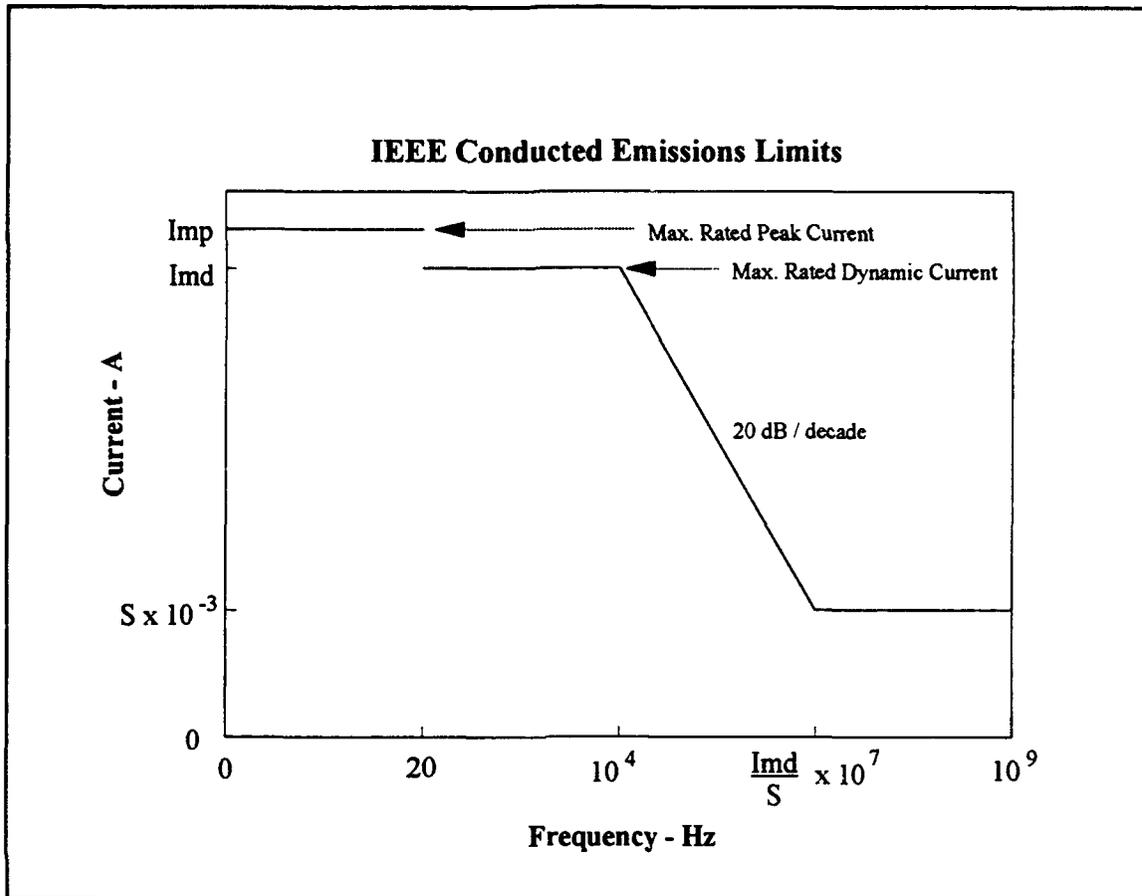


Figure 5. IEEE EMC Standards for VXibus [Ref. 5]

The number of slots in the mainframe multiplied by 1 mA is the maximum EMI current level from

$$\frac{I_{md}}{\text{no. Slots}} * 10^7 \text{ Hz} \quad (3)$$

to 1 GHz. If a VXibus mainframe has 13 slots, a maximum-rated peak current of 3 A, and a maximum-rated dynamic current of 1 A then the maximum EMI current from 770 kHz to 1 GHz would be 3 mA. [Ref. 5]

The IEEE P1155 EMI standard for the VXIbus is also very high when compared to the SNEP recommended values. The lowest allowed level for EMI current under the VXIbus standard is still measured in milliamperes. The VXIbus standard does address a wider range of frequencies than the SNEP-recommended levels.

5. Proposed Standard

An arbitrary guideline is the SNEP 2-mA level of current from 10 Hz to 10 kHz and the 10- μ A value of current from 100 kHz to 100 MHz. These EMI current levels are significantly lower than the FCC EMI standards or the IEEE P1155 EMI standard. The SNEP standard also covers a wider frequency range than the FCC EMI standard and the MIL-STD-461 EMI standards. While the SNEP emission limits should prevent large EMI problems, they may not be sufficiently low to prevent all EMI problems [Ref 2]. The severity of any EMI problem depends on the susceptibility of the equipment installed in the facility. Data-processing equipment is less susceptible to EMI than receiving equipment, but the exact level that a specific piece of data-processing equipment can accept without errors occurring must be measured.

III. BARRIER, FILTER, GROUND DESIGN FOR EMC

Kirkoff's law of current flow states that the sum of all currents flowing out of any point in a network at any instant equals zero [Ref. 6]. Thus, any current eventually must return back to its source. This implies that EMI current flowing from a source will return to that source over any available path. Barriers, filters, and grounds are commonly used in an attempt to control EMI/RFI. Unfortunately, unified guidelines and standards do not exist for barrier, filter, and ground techniques. As a result, attempts to control EMI/RFI sometimes aggravate the problem. This chapter describes an integrated approach to barriers, filters, and grounds for the control of EMI/RFI.

A. BARRIER, FILTER, GROUND PRINCIPLES

The primary function of barriers, filters, and grounds is to prevent EMI/RFI generated by an electrical device from leaving an enclosure containing the device and to prevent external EMI/RFI from entering the enclosure. Figure 6 shows all three components of a BFG design that must be included in any design for reducing EMI current. [Ref. 7]

A common mistake in BFG design is that "better" grounds will help control site generated EMI. These "better" grounds generally consist of ground grids, ground plates, and other expensive multi-element systems. There is no ground system that, by itself, helps control EMI current. "Better" grounds, when used by themselves, increase the

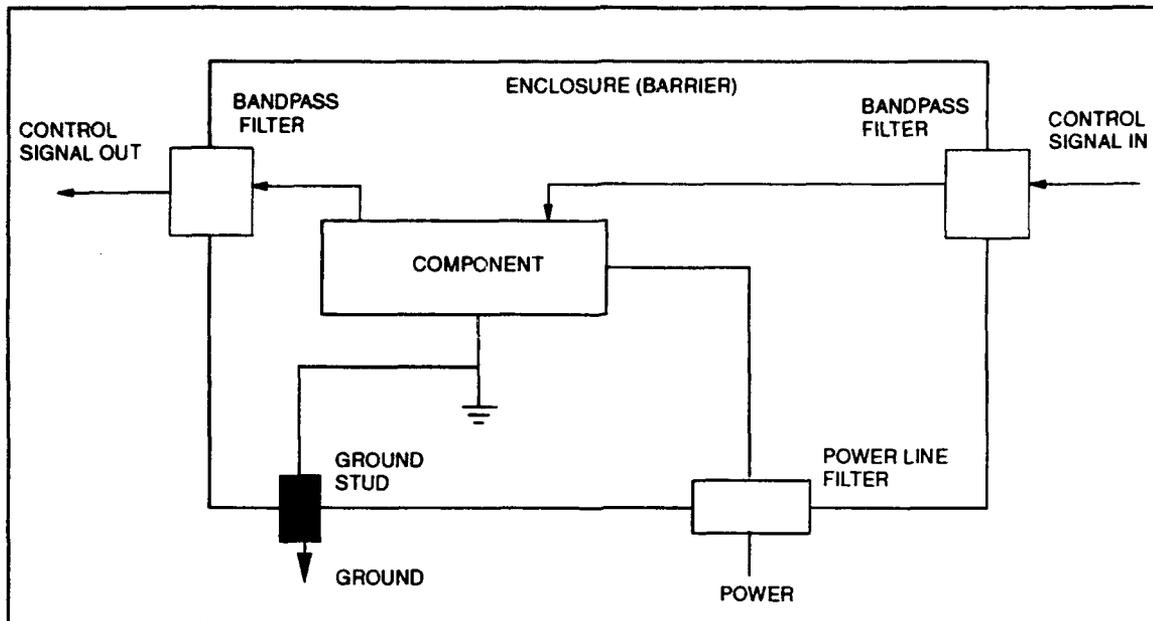


Figure 6. Basic Barrier, Filter, Ground Components

EMI problems in many situations. A complex ground system will usually increase the EMI problem by increasing the number of paths over which the EMI current can travel. A ground stud used as shown in Figure 6 ensures the equipment will be properly grounded for safety reasons and also keeps the EMI current created by the electrical component inside the enclosure. [Ref. 7]

Barriers keep internally-generated EMI/RFI from intruding into other system components and external EMI/RFI out. The use of filters allow power and control signals to access the electrical components inside the barrier while keeping EMI current at other frequencies out. If an uncontrolled conductor penetrates a barrier, the barrier's effectiveness is negated. The barrier does not have to be a completely solid enclosure. Because the electronic equipment inside the barrier needs cooling, modest holes in the barrier are allowed. The maximum diameter of the holes in the barrier must be less than

about three tenths of the shortest wavelength being controlled with a waveguide three times the holes' diameter in length attached. To be an effective barrier, the surface of the enclosure must be electrically bonded with all structural elements. [Ref. 1]

B. INTEGRATED BARRIER, FILTER, GROUND DESIGN

A single simple barrier can reduce EMI/RFI levels by 30-40 dB or more. This improvement increases when multiple levels of barriers, filters, and grounds are employed. Each level of BFG isolation further reduces the EMI/RFI by a similar single-level amount. Figure 7 shows incorrect and correct implementations of multiple levels of barriers and filters. [Ref. 7]

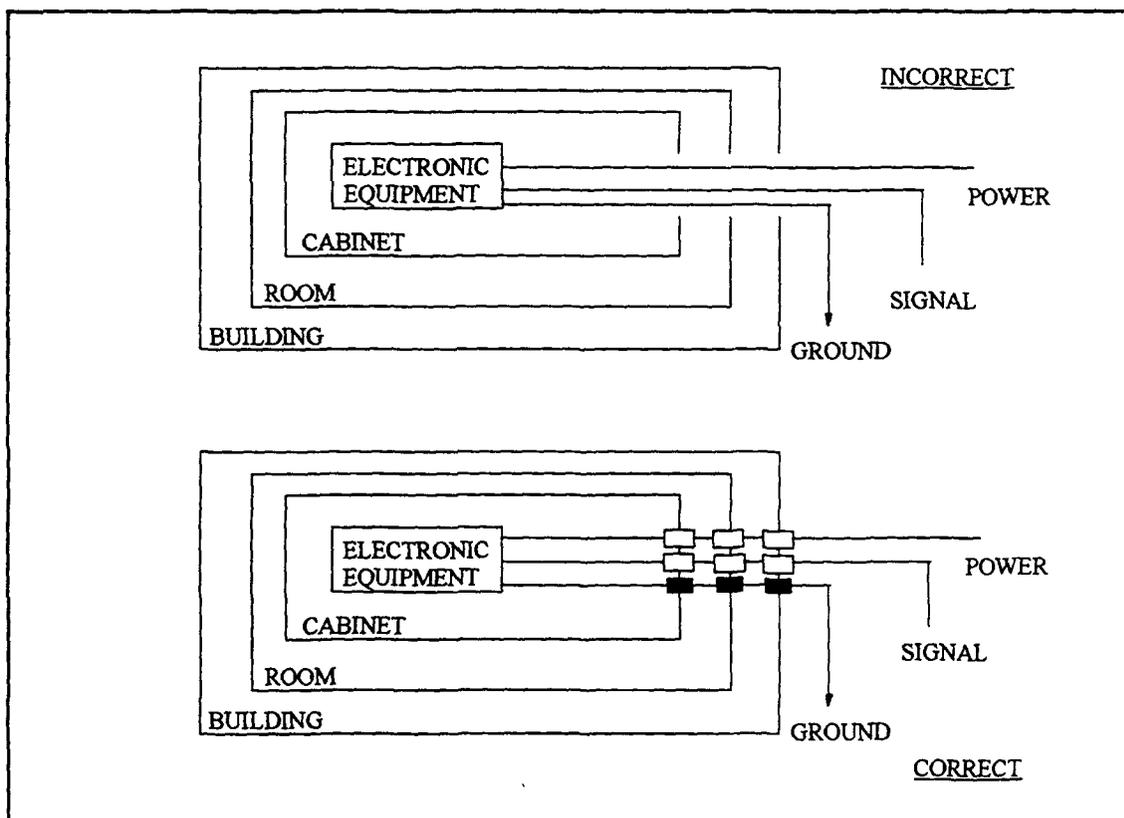


Figure 7. Multiple Barrier Levels

In Figure 7, the incorrect implementation has conductors passing through multiple barriers without being filtered, or without the grounds being terminated on the inside and outside surfaces of the barriers. This negates the effectiveness of the barriers in controlling EMI currents. [Ref. 7] Figure 8 shows various methods of coping with barrier penetrations and openings (marked with asterisks) as well as typical discontinuities in shielded enclosures that must be avoided. Low-pass power-line filters allow power to reach the equipment, but keep the unwanted EMI current from entering or leaving the equipment via the power conductors. Other control lines entering the enclosure must also pass through bandpass filters, permitting the required signals to pass while filtering EMI currents at other frequencies. The filters that are installed must provide a low-impedance path to return EMI current to its source and a high-impedance path inhibiting the flow of EMI current across the barrier. The filters must always be installed on the barrier's surface and be electrically bonded to the surface of the barrier. Any penetration of the barrier that is not filtered creates a discontinuity that allows EMI/RFI emissions to escape. [Ref. 1]

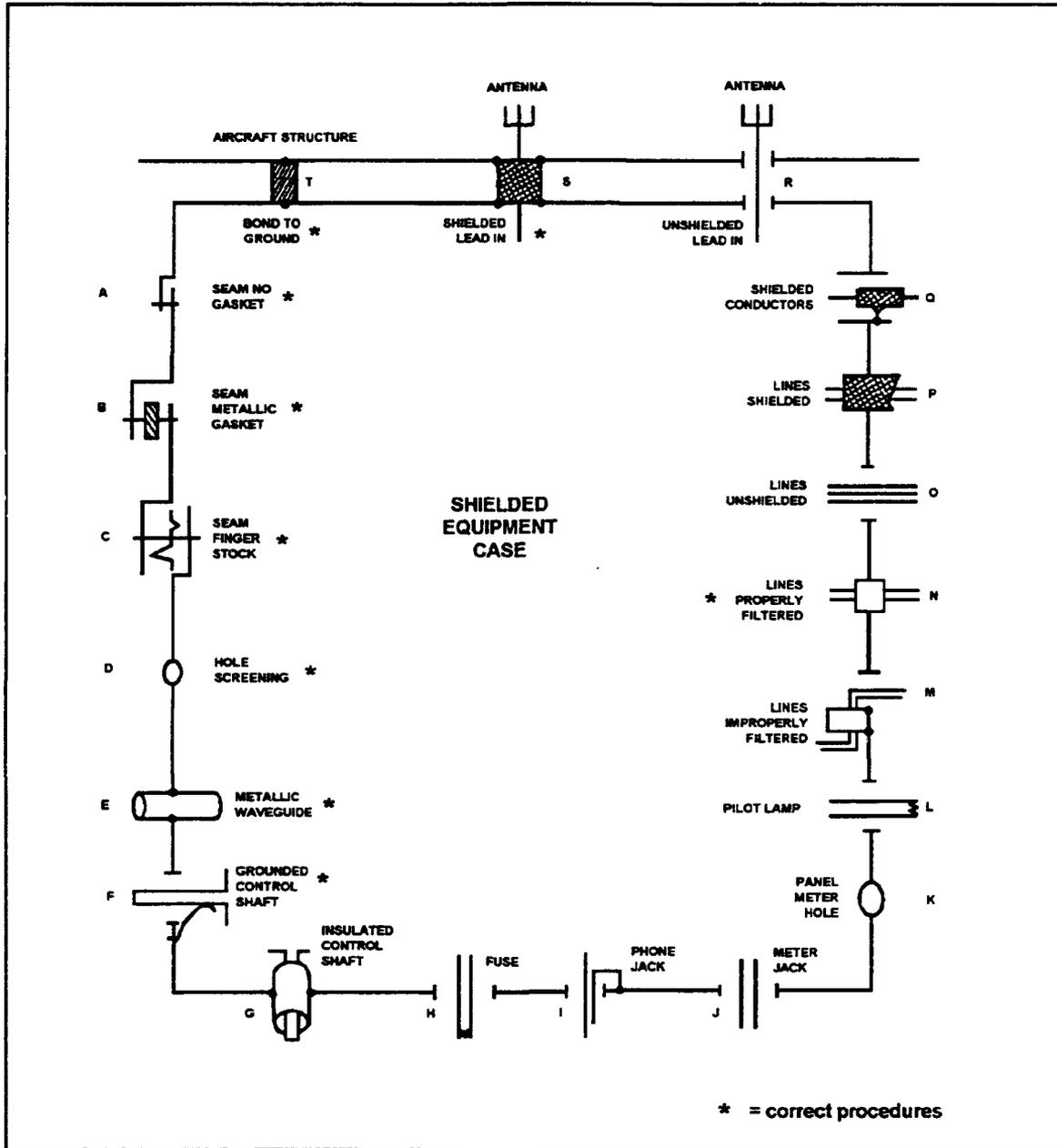


Figure 8. Barrier Penetrations

IV. VARIABLE-FREQUENCY-DRIVE INDUCTION-MOTOR CONTROLLER

The Halmar-Robicon ID-PWM 454 series VFD is an updated model of the Halmar-Robicon ID-PWM 455 series VFDs currently installed at Fort Gordon's Luketina Hall facility. The major difference between these drives is that the 454 series VFD is modularized for easier component replacement.

A. APPLICATIONS OF VARIABLE-FREQUENCY DRIVES

The Halmar-Robicon ID-PWM 454 series of variable-frequency drives are modular, compact, transistor-based, pulse-width-modulated (PWM) drives. They have digital controls for the precise control of the speed of three-phase induction motors and a serial communications port for interfacing with programmable controllers and computers. The Halmar-Robicon ID-PWM 454 series VFDs are available from 3-1000 horsepower at 460 VAC. Variable-frequency drives are designed for speed control of induction motors in positive-displacement pumps, supply/return fans, conveyors, cooling-tower fans/pumps, and high-capacity air-conditioning systems. [Ref. 8]

A VFD allows a single-speed induction motor to run at 0-100% of the motor's rated speed. For example, if an HVAC system had an induction motor running at 1800 rpm, the amount of cooling capacity provided by the HVAC system is fixed. If only a small amount of cooling is needed, the HVAC cools areas that don't require cooling or wastes the excess amount of cooling by shunting it elsewhere. With a VFD the motor

rotates from less than 400 up to 1800 rpm, depending on the amount of cooling required. The VFD receives the percentage capacity that is needed through the serial communications port and drives the induction motor of the HVAC at the speed required to provide the correct amount of cooling. [Ref. 9]

B. OPERATION OF VARIABLE-FREQUENCY DRIVES

Variable-frequency drives convert a fixed frequency and voltage into a variable-voltage, variable-frequency output. The VFDs examined in this thesis are voltage source, pulse-width-modulated VFDs, using a diode front-end with output transistors. The variable speed is obtained by a three-stage process in the VFD as shown in Figure 9. [Ref. 9]

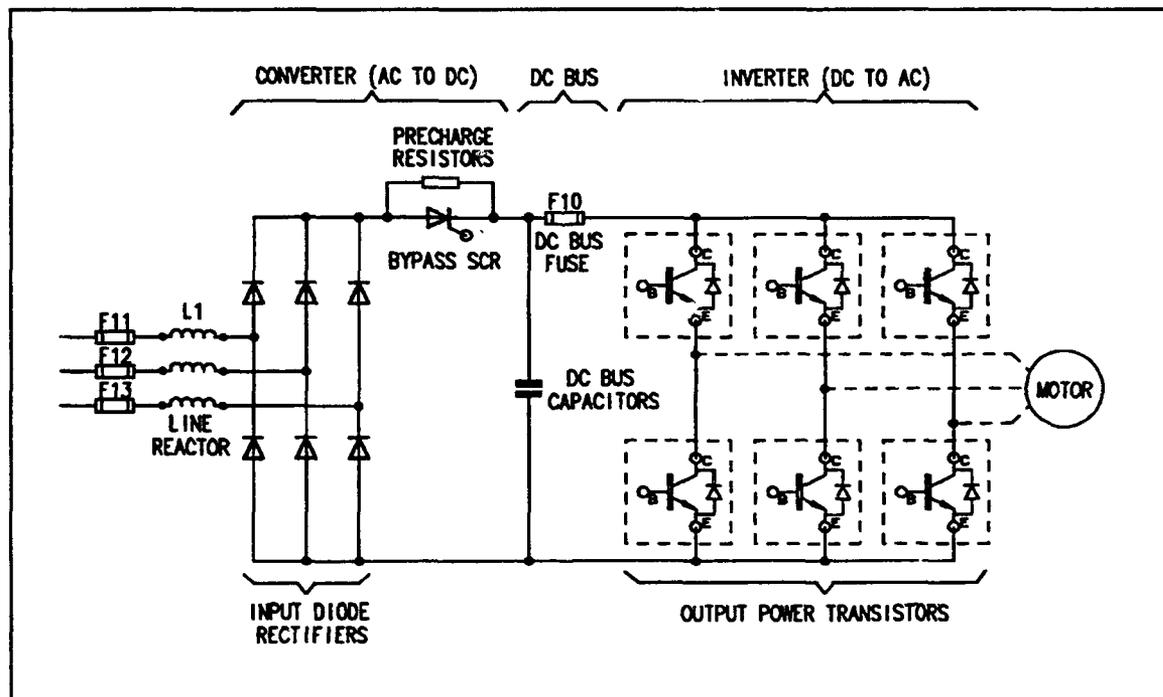


Figure 9. Stages of ID-PWM 454 VFD

The converter section, a three-phase full-wave diode bridge, converts the 460-V, 60-Hz AC input into DC. This provides an improved power factor, phase-sequence insensitivity, and lower harmonic content over the traditional phase-controlled front-end.

The second stage is a DC bus composed of electrolytic capacitors with a parallel SCR and resistor arrangement. The bus charges through the resistors at currents less than 50% of the drive rating. When the DC bus is charged, the SCR is switched on, enabling full current operation.

The inverter section converts filtered DC bus voltage into AC. Six output transistors are switched in the correct sequence to obtain an AC output voltage of the desired "fundamental" frequency and output voltage. Voltage and current waveforms of normal AC power to a resistive load are sinusoidal. Waveforms from an AC inverter contain spectral components from switching that distort the waveforms. The extent of this distortion is determined by the design of the inverter. Motor voltage from the VFD is regulated by a proprietary algorithm in a dedicated, high-speed, digital processor. The algorithm also compensates for varying supply voltage and motor load.

The control circuitry of the Halmar-Robicon ID-PWM 454 series VFD uses 120-VAC, 60-Hz power. This VFD does not require a separate AC line for this power; instead, the VFD contains a small transformer to convert the available 460-VAC, 60-Hz power to 120-VAC, 60-Hz power for the processor power supply. [Ref. 9]

C. LAYOUT OF EXPERIMENTAL VARIABLE-FREQUENCY DRIVE

Figure 10 shows the configuration of the Halmar-Robicon ID-PWM 454 series VFD as well as the supporting equipment. This system was installed in room 543 of Spanagel Hall with a four wire (three phase and one ground) power line supplying the VFD's 460-VAC, 60-Hz power. A blower assembly provided a load for the induction motor. The unmodified VFD included all parts in Figure 10 except for the filters.

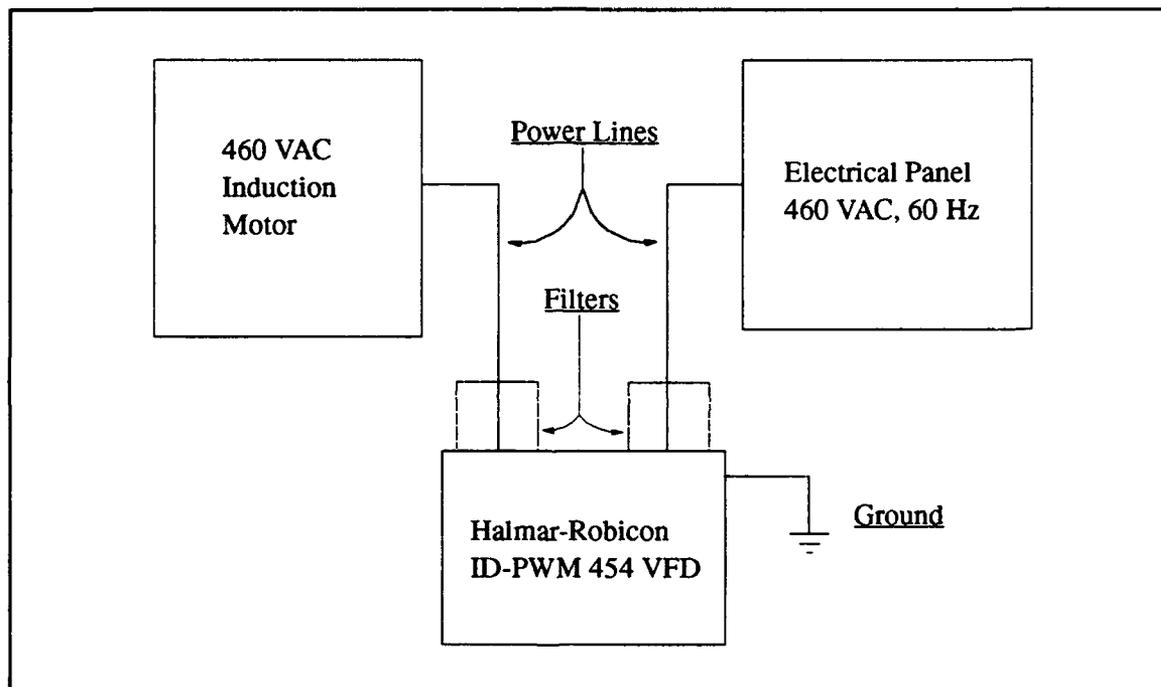


Figure 10. Halmar-Robicon ID-PWM 454 VFD Setup

The Halmar-Robicon ID-PWM 455 series VFD at Fort Gordon's Luketina Hall was similarly configured with the only difference being an emergency cutoff switch next to the VFD (due to the long distance from the electrical panel) and a smaller motor used in the experimental setup in Spanagel Hall.

V. UNMODIFIED VARIABLE-FREQUENCY DRIVE PERFORMANCE

Initial performance data was collected at Fort Gordon's Luketina Hall in December, 1993 on the Halmar-Robicon ID-PWM 455 series VFD. Because of the high ambient EMI current at Luketina Hall, an additional VFD was acquired for experimental work. The older 455 series VFD was no longer in production, so the newer model ID-PWM 454 series VFD was used for experimentation. Initial tests indicated that the newer ID-PWM 454 and the ID-PWM 455 had approximately the same EMI characteristics.

A. INSTRUMENTATION

The experiments included EMI current measurement on power and ground lines from the electrical panel to the VFD and from the VFD to the motor over the 100-kHz to 100-MHz frequency range. The measurement instrumentation included a Hewlett Packard 141T Spectrum Analyzer, a Develco Model 7200B 3-Axis Display, and a Fischer F-70 RF Current Probe (see Figure 11).

The Hewlett Packard 141T Spectrum Analyzer allows observations of signals and EMI currents using the Fischer F-70 RF Current Probe. The F-70 probe measures current flowing on conductors and has a flat output above 100 kHz. The 3-axis display provides a means to observe the spectral and temporal properties of EMI and signals over a wide bandwidth and a period of time. The 3-axis display can be frozen with the present and previous scans stored in memory. Controls on the 3-axis display allow the

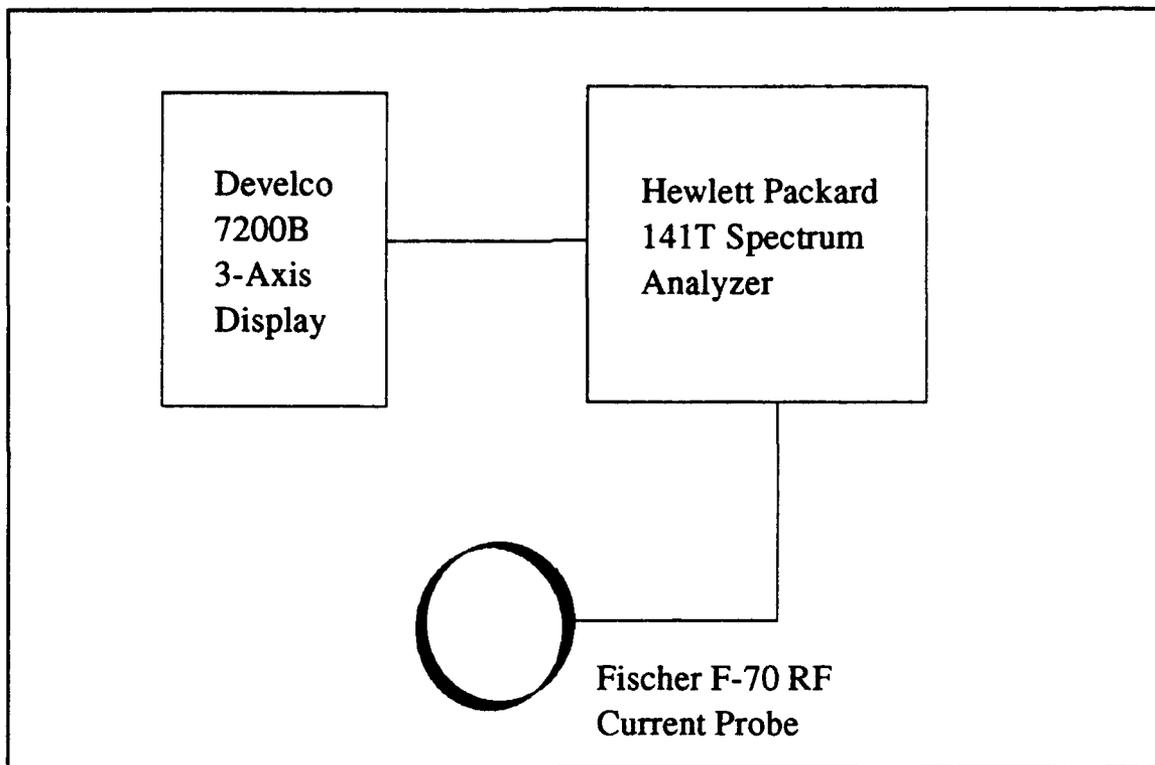


Figure 11. Instrumentation for EMI Measurement

operator to vary the viewing angles for maximum visual perception of the observed data. Four, eight, 16, or 32 lines can be extracted from the view for expanded views of portions of the time axis. [Ref. 10]

The lower left corner of each figure containing photos of EMI current provides the following information:

- Date, Time
- Location, Device being tested
- Center frequency, Frequency span, IF bandwidth, Scan time
- Probe identification, Amplification gain (dB), RF attenuation (dB), Reference level (dBm)

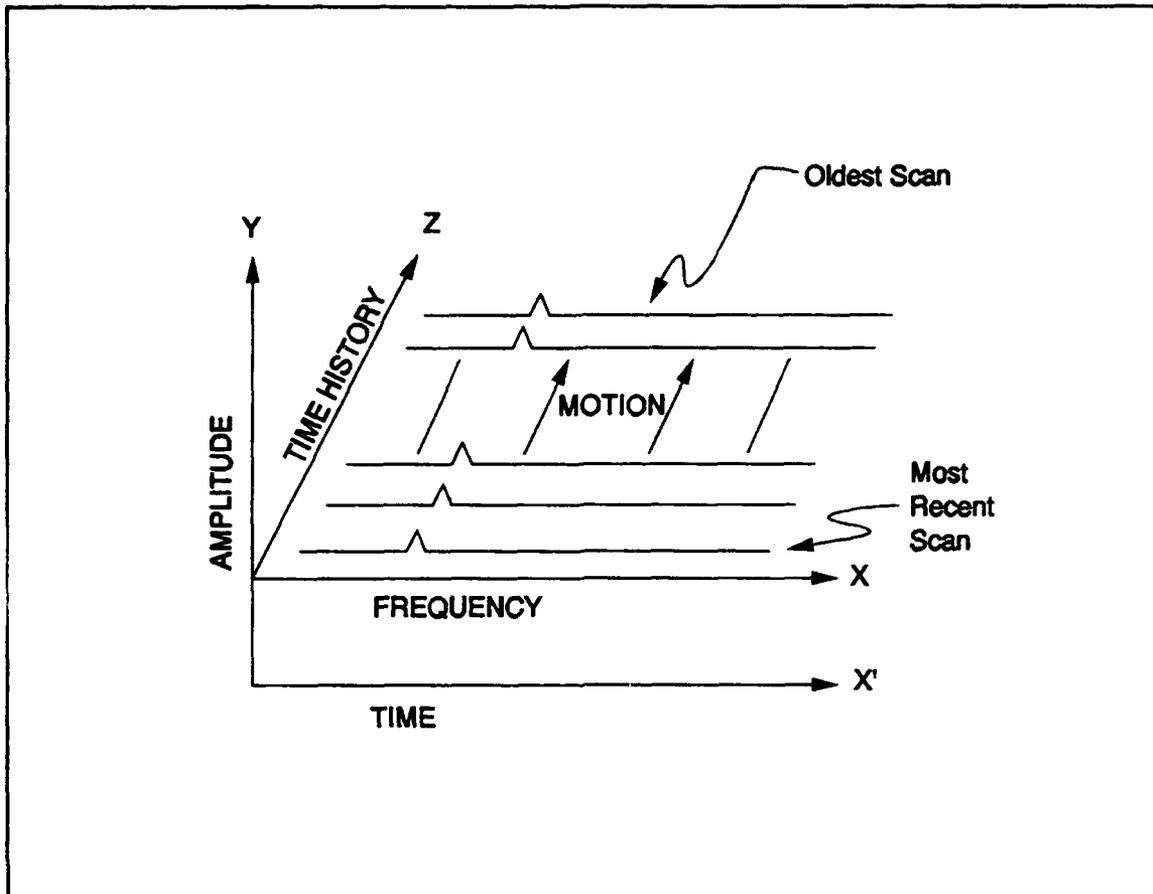


Figure 12. 3-Axis Display

To calculate the EMI current levels on the right of the photos, use the reference level minus 80 dB and use this power (in mW) in Equation 2 to determine the lowest current level. The power value can be modified by the amplification gain (subtract the dB gain from the reference level). If the reference level was -20 dBm, the lowest power shown would be -100 dBm. Putting this power (in mW) in Equation 2 yields $2.24 \mu\text{A}$ as the lowest current level.

B. DATA COLLECTION

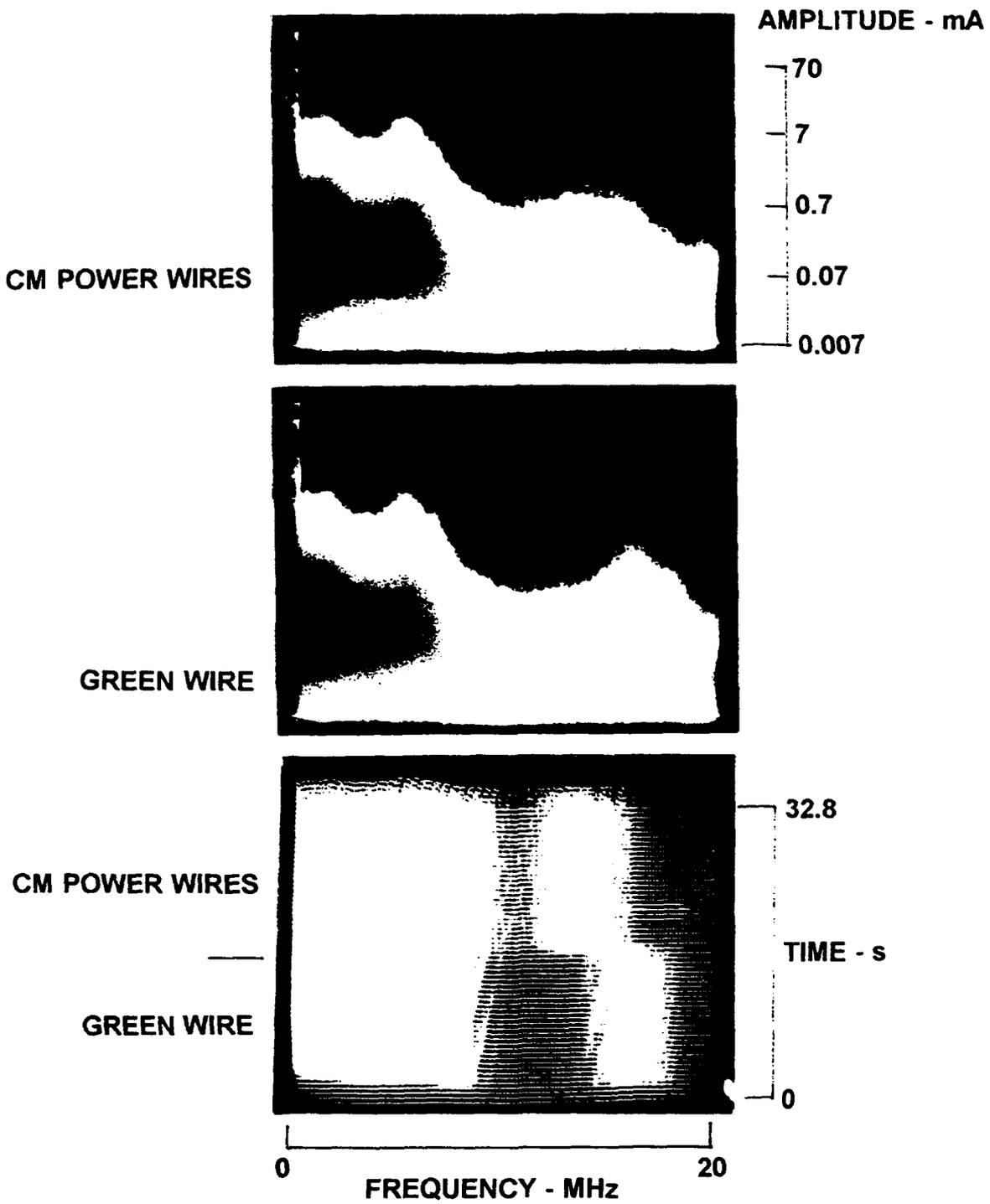
1. Data Collection at Luketina Hall, Fort Gordon

Luketina Hall, Fort Gordon had two Halmar-Robicon ID-PWM 455 series variable-frequency drives controlling two separate high-volume air conditioners for the facility. A third HVAC in the facility did not have a VFD because it served administrative areas that did not require precise temperature settings. Figure 13 shows EMI current inserted into the power wires and the green wire (ground) by one of the VFDs. The EMI current is over 7 mA from 100 kHz through 6 MHz and is 200 μ A at 20 MHz [Ref. 11].

Figure 14 shows the EMI current from 0-10 MHz caused by the two VFDs at the electrical panel [Ref. 11]. Turning off VFD #2 had little effect on the EMI current. Turning off the remaining VFD dropped the EMI current level to that shown in Figure 14 labeled 'ALL 3 AHU OFF'. With the VFDs turned off, the ambient EMI current was below 10 μ A at frequencies above 7.5 MHz. The two VFDs raised the EMI current level by more than 20 dB at electrical panel PU from 0-10 MHz. Another HVAC system without a VFD was present, but it had a negligible effect on the EMI current levels and is not included in this analysis.

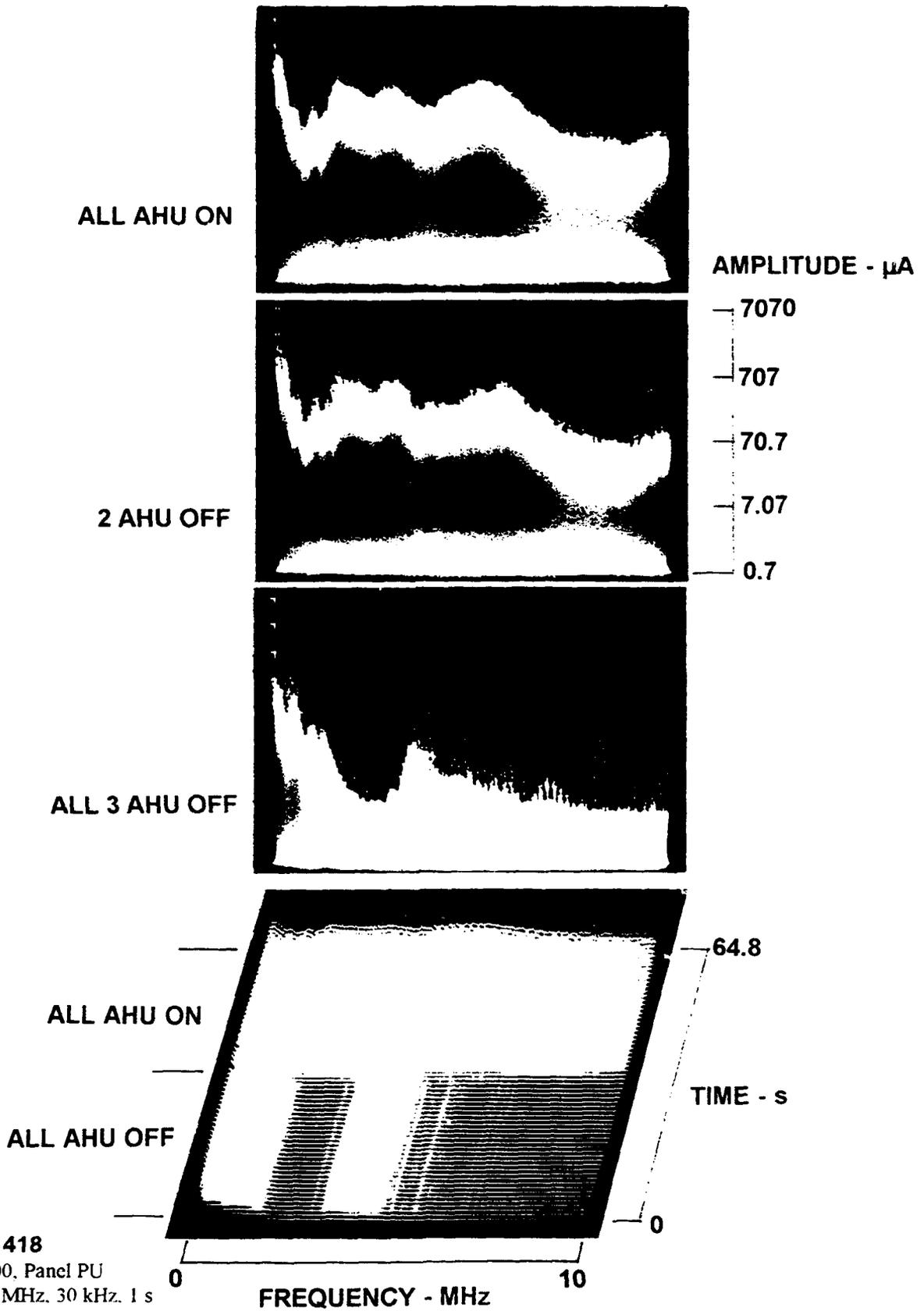
2. Unmodified Experimental Variable-Frequency-Drive Data Collection

The Halmar-Robicon ID-PWM 454 Series VFD had the same performance characteristics as the series 455 VFD at Luketina Hall, but is modularized for cost



931215 1351
 GOR, 20400, Mech Rm, AHU-2,
 Green wire in on bottom: power in common mode
 10 MHz, 20 MHz, 30 kHz, 500 ms
 F70, 0, -30, -10

Figure 13. Luketina Hall VFD #2 EMI Current (0-20 MHz) Input Line



931214 1418
 GOR. 20400, Panel PU
 5 MHz, 10 MHz, 30 kHz, 1 s
 F70', 0, 0, -30

Figure 14. Luketina Hall VFDs EMI Current (0-10 MHz) at Electrical Panel

effective and rapid repair of faulty components. This VFD was connected and passed the diagnostic checks as detailed in the instruction manual.

The motor-idle portion of Figures 15 through 23 and 25 through 28 show the VFD receiving power but not providing power to the induction motor. Much of the ambient EMI current shown from 0-4.5 MHz in the motor-idle section is EMI caused by Spanagel Hall's elevators, which are on the same circuit. The display shows an increased EMI current level in this frequency range when the elevator was moving. The motor running portion of these figures were when the VFD supplied power to its induction motor. Little variation in EMI levels occurred when varying the speed of the VFD.

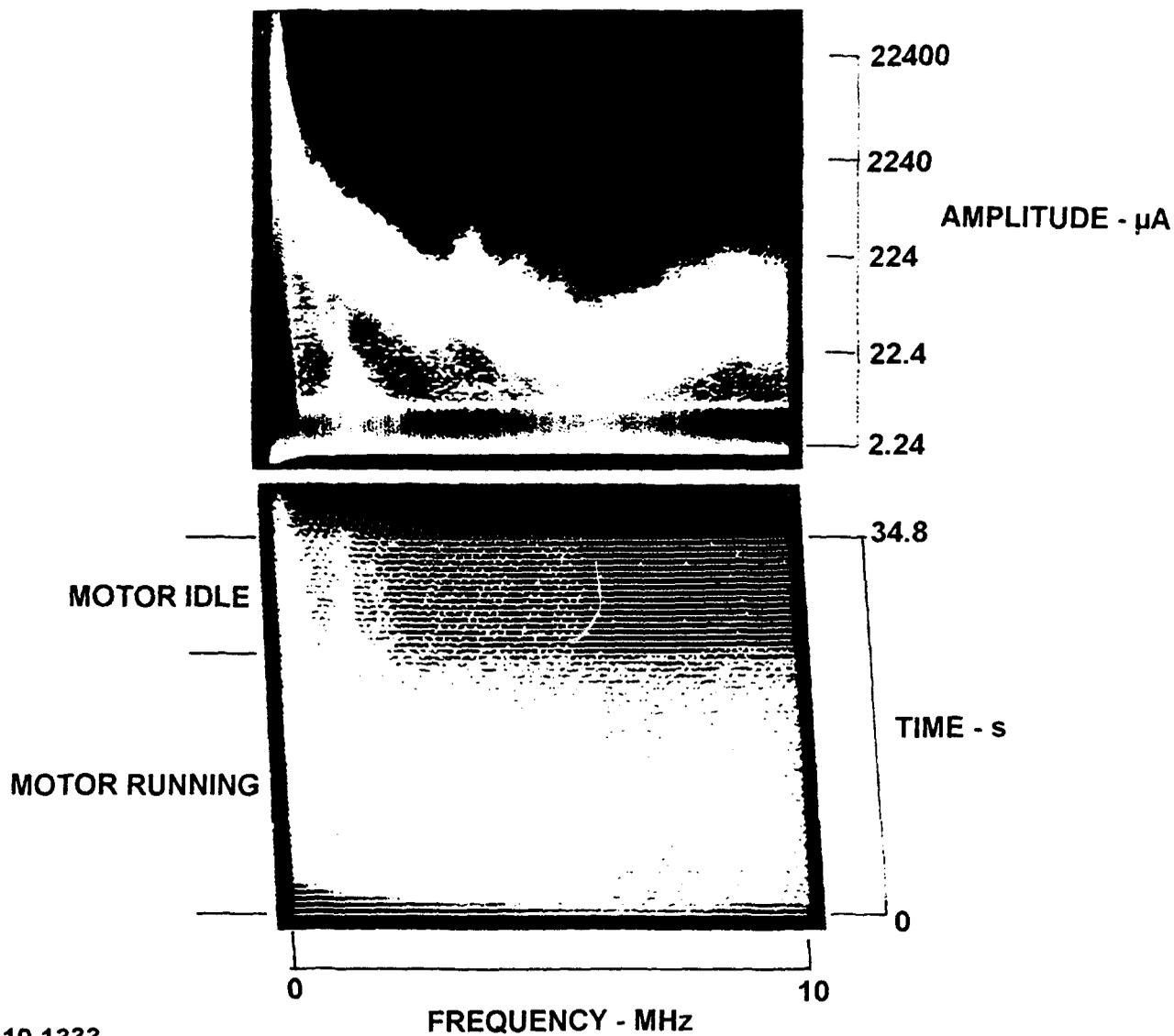
Figure 15 shows initial measurements of the unmodified drive with a peak of about 500 μ A at 4 MHz on one phase wire between the electrical panel and the VFD's input terminal over a frequency range of 0-10 MHz. The experimental VFD's EMI current level was lower than the EMI current caused by the Luketina Hall VFDs. A lower noise floor in the experimental setup accounts for some of the variation in EMI current levels between the two models of VFDs. The modular design of the experimental VFD probably accounts for the remaining difference between these measurements. In Figure 16 the average EMI current level is greater than 2 mA between 0-5 MHz with a peak of approximately 10 mA at 4 MHz on one of the phase wires. The EMI current level drops as the frequency increases after the peak. The other phase lines had similar characteristics. The EMI current pictured in Figure 16 has few, if any, peaks and nulls due to impedance variations with frequency. The lower EMI current in Figure 15

demonstrates that current division occurred at several junctions and some EMI current returned to its source before reaching the phase line.

Figure 17 illustrates the EMI current injected by the experimental VFD from 0-50 MHz into the electrical panel. The EMI current at an output phase wire of the test VFD is portrayed in Figure 18 for the frequency range of 0 to 100 MHz is pictured. The four signals in Figure 18 from 90-100 MHz are FM radio stations received by the wire connecting the VFD to the motor. Both of these figures show spectral peaks at 4 MHz with EMI current decreasing as frequency increases.

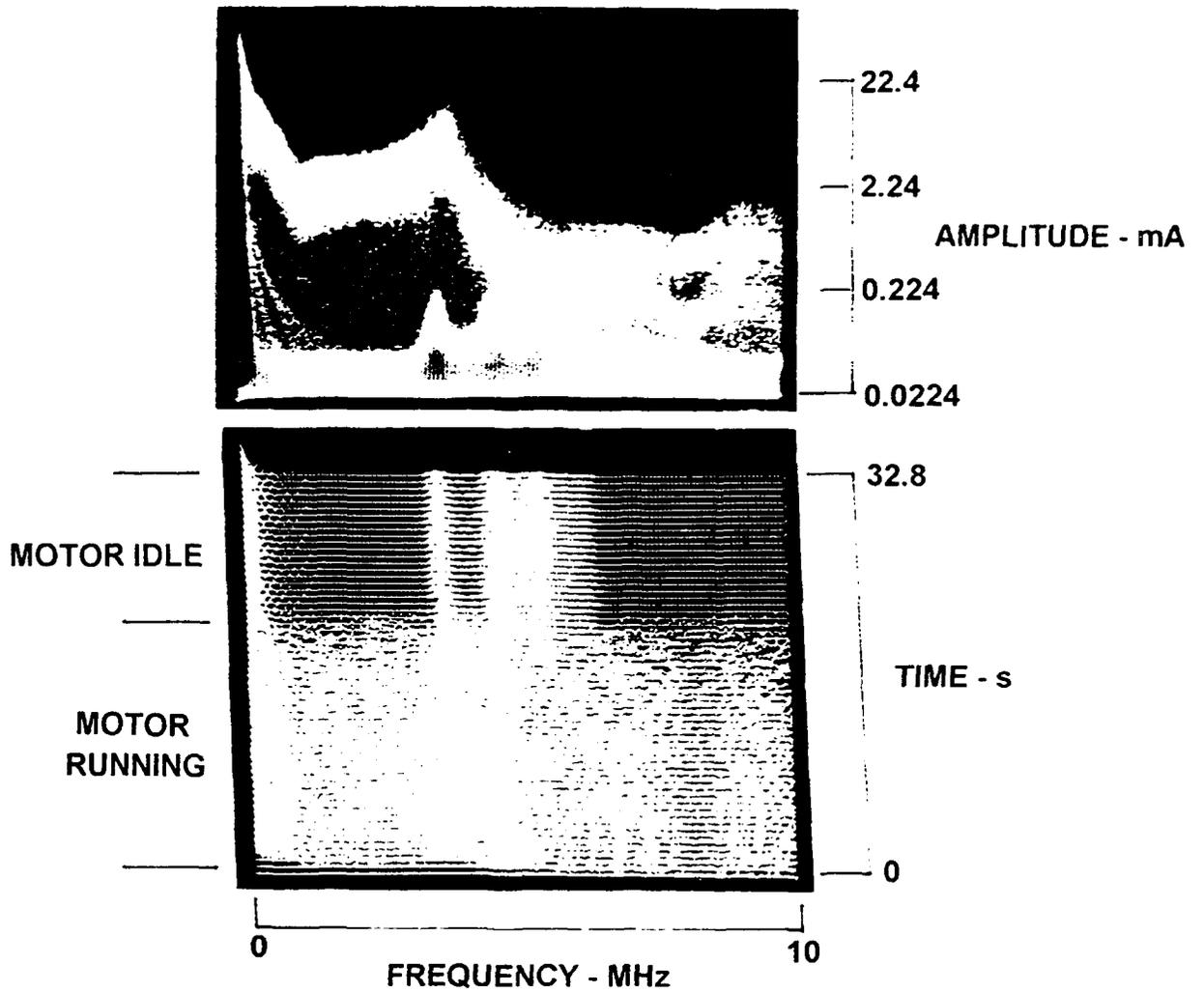
The likely source of EMI current is the inverter stage of the VFD. In the process of converting DC to AC, harmonics are created across the frequency spectrum similar to the harmonics produced by an uninterruptible power supply. However, the VFD's harmonics are based on the frequency provided to the motor. The output lines of the VFD had a larger EMI current level than the input lines. The EMI current produced by the inverter stage had few junctions prior to coupling with the output conductors, but had to travel through many junctions in the DC bus and AC-to-DC converter stages to reach the input conductors.

Figures 19 and 20 are provided for later comparison with a modified VFD. Figure 19 shows the EMI current from 0-20 MHz on a phase wire from the electrical panel to the VFD input terminal. The EMI current level drops from a high of 500 μ A at 4 MHz to under 100 μ A at 20 MHz. Figure 20 shows the EMI current from 0-20 MHz on a phase wire from the VFD output terminal to the motor. The EMI current level drops from a high of 10 mA at 4 MHz to 200 μ A at 20 MHz.



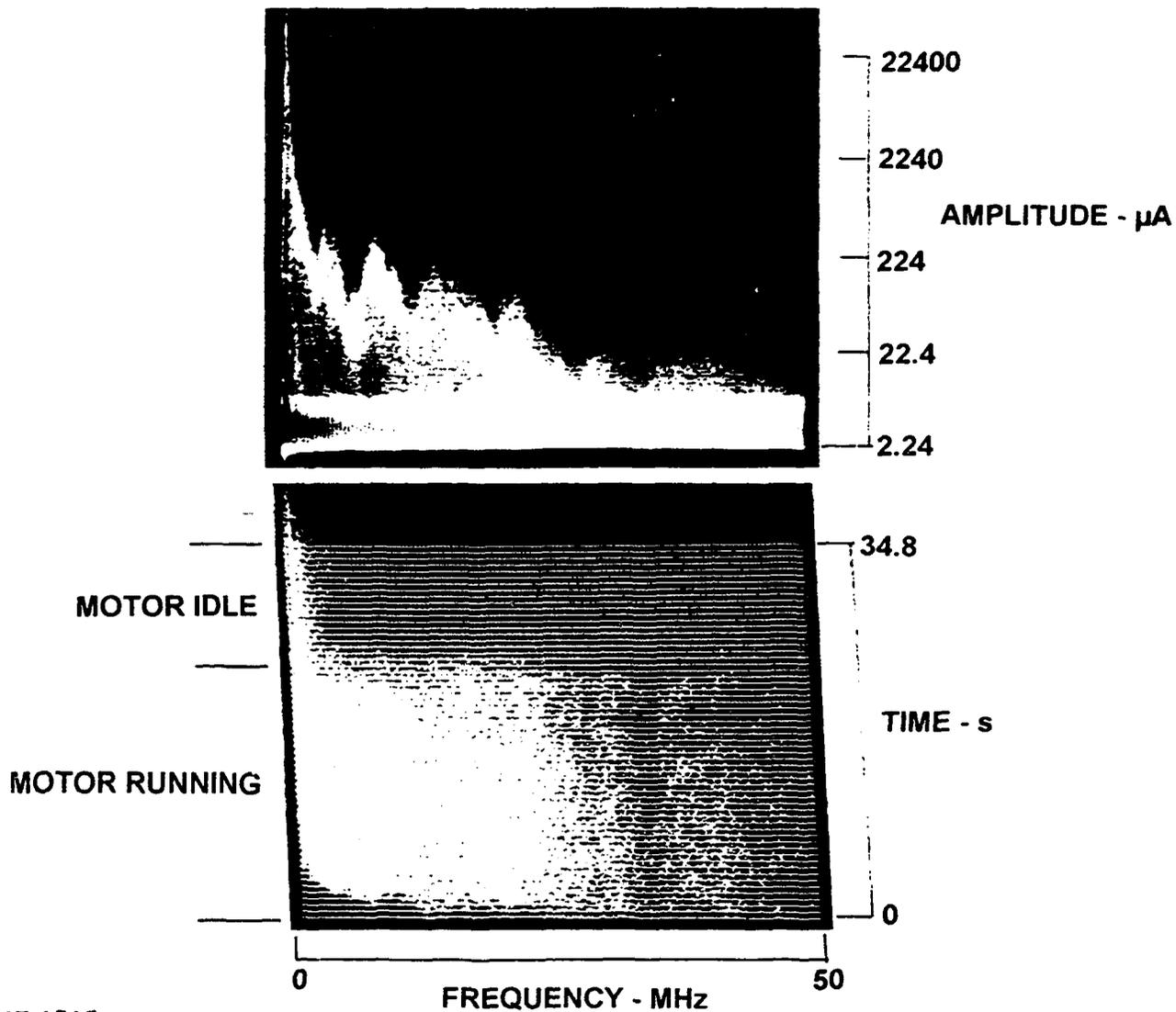
940810 1333
 SP-543. Phase Line.
 electrical panel to VFD input
 5 MHz, 10 MHz, 100 kHz, 500 ms
 F70, 0, 0, -20

Figure 15. Unmodified Experimental VFD EMI Current (0-10 MHz) Electrical Panel



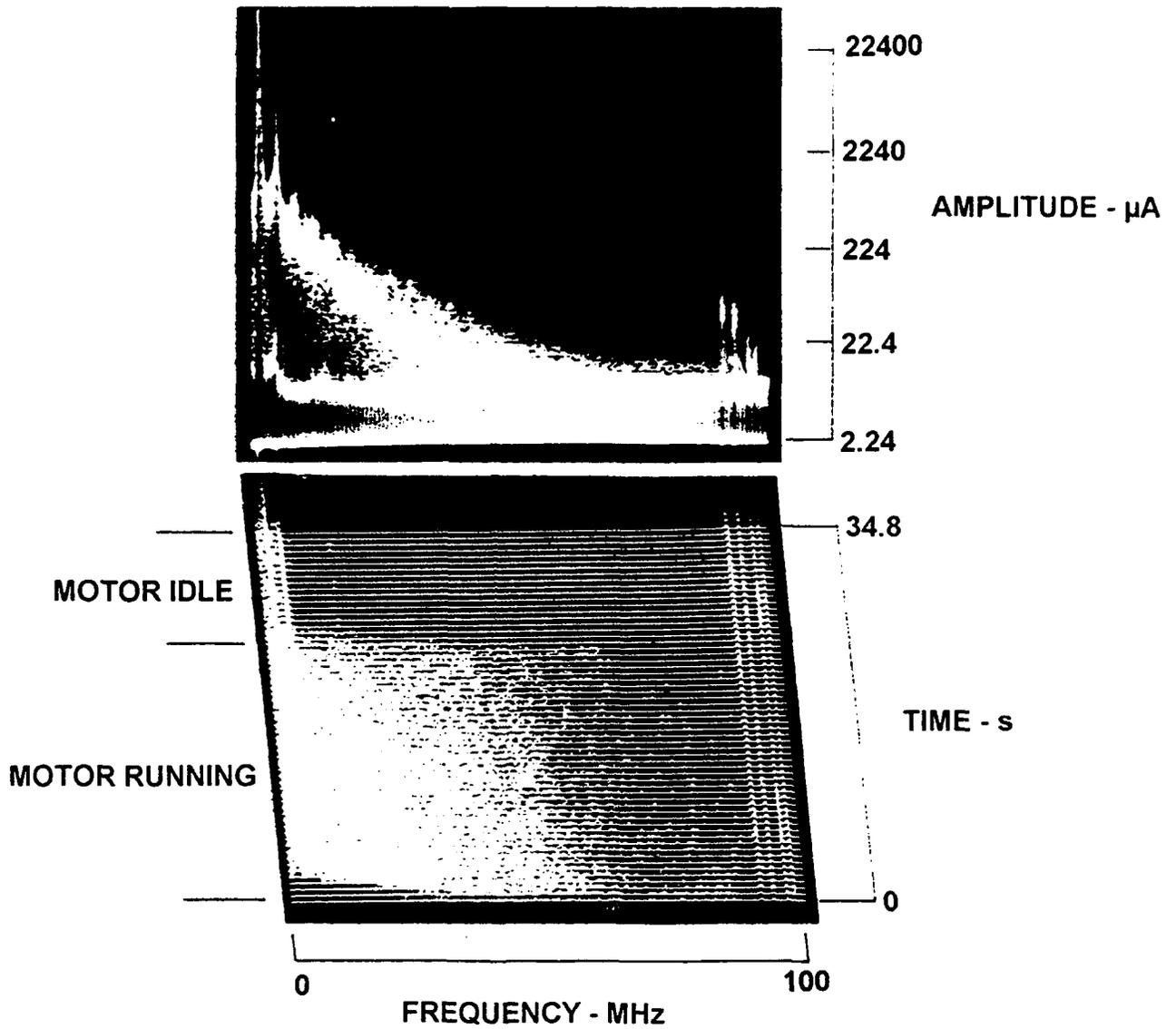
940801 1255
 SP. Rm 543. VFD. Output to Motor
 5 MHz. 10 MHz. 100 kHz. 500 ms
 F70. 0. -20. 0

Figure 16. Unmodified Experimental VFD EMI Current (0-10 MHz) Output Line



940817 1515
 SP-543, Phase Line,
 electrical panel to VFD input
 25 MHz, 50 MHz, 100 kHz, 500 ms
 F70, 0, 0, -20

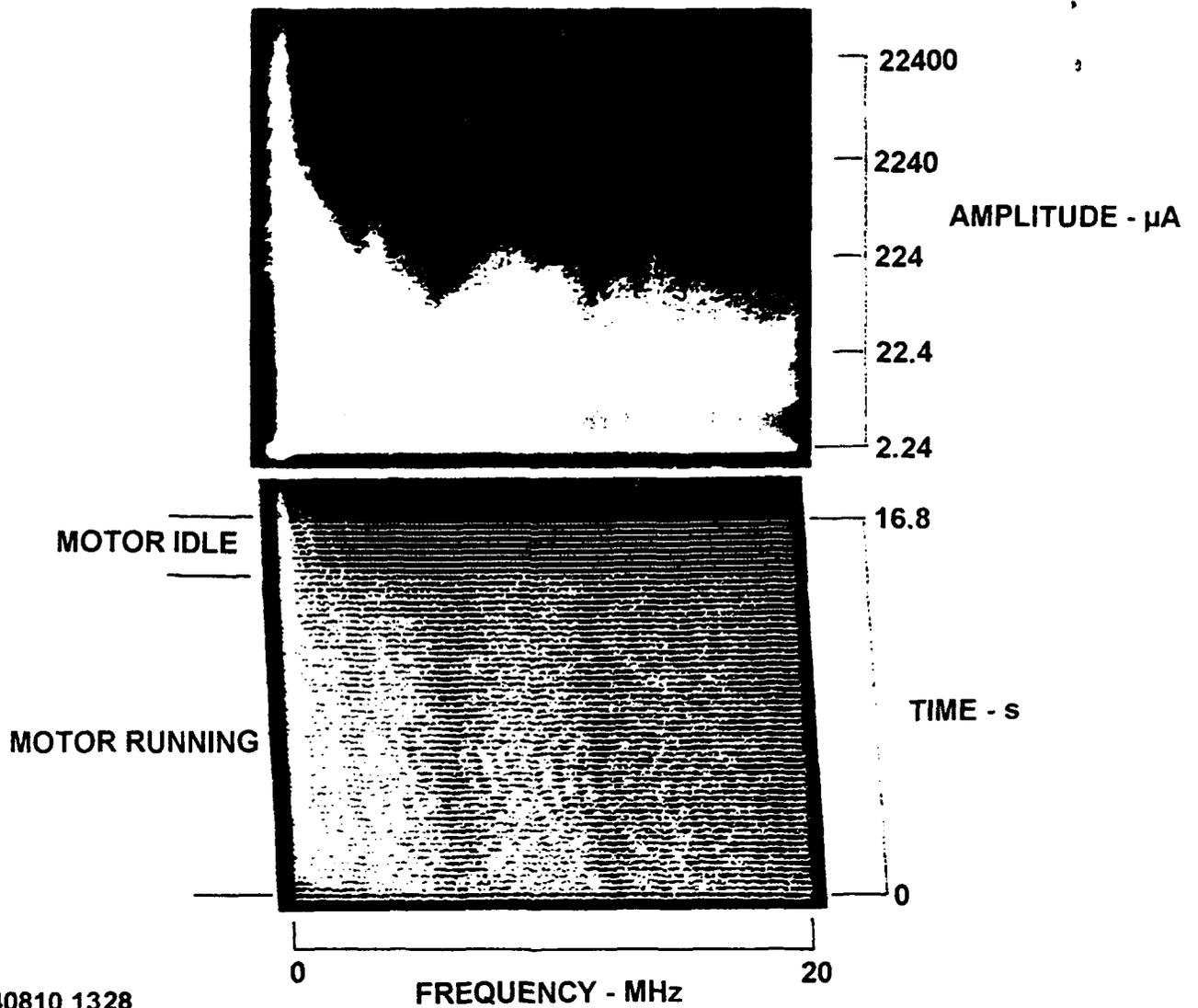
Figure 17. Unmodified Experimental VFD EMI Current (0-50 MHz) Input Line



940817 1525

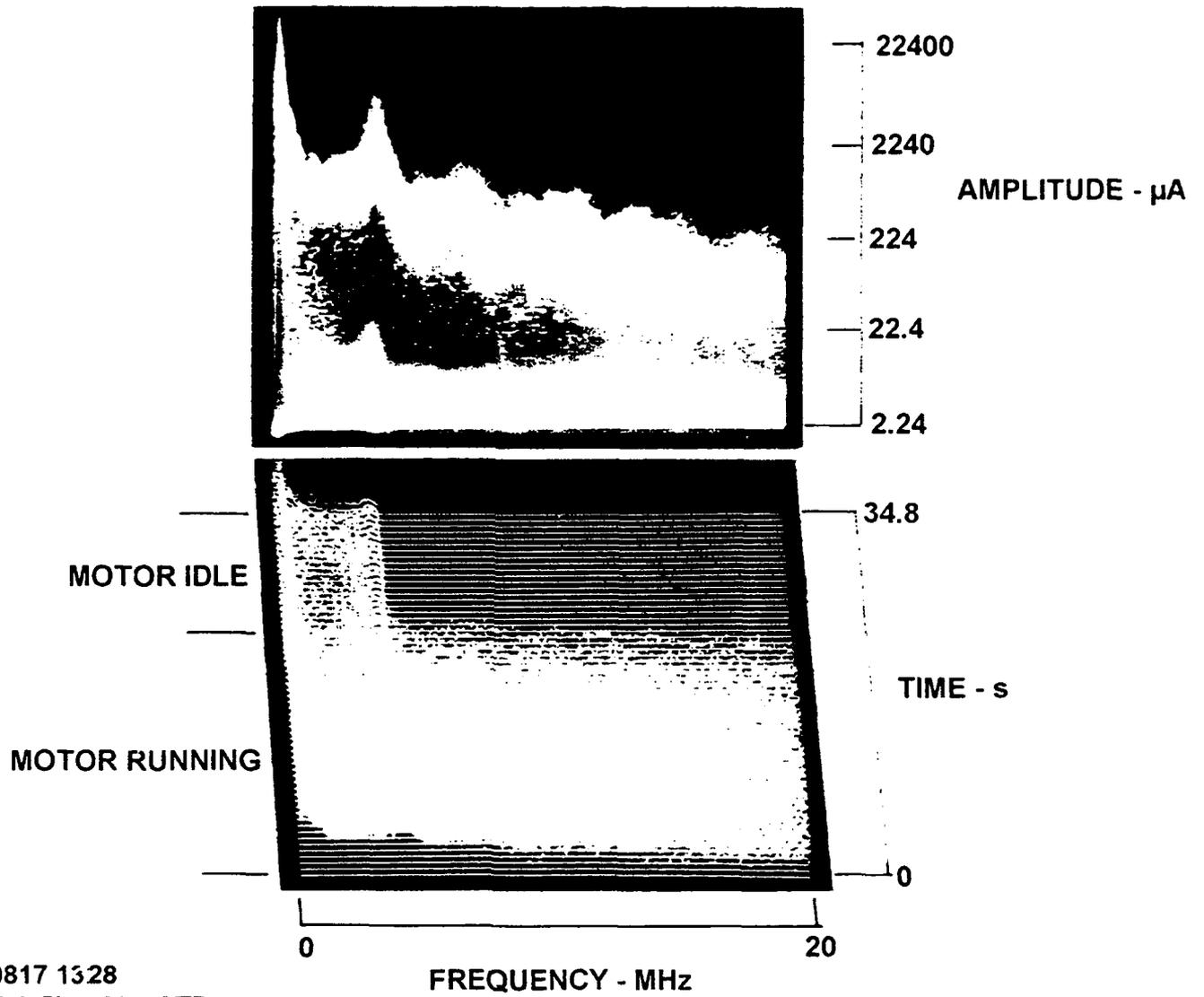
SP-543. Phase Line. VFD output to motor
 50 MHz. 100 MHz. 100 kHz. 500 ms
 F70. 0. 0. -20

Figure 18. Unmodified Experimental VFD EMI Current (0-100 MHz) Output Line



940810 1328
 SP-543, Phase Linc.
 electrical panel to VFD input
 10 MHz, 20 MHz, 100 kHz, 200 ms
 F70, 0, 0, -20

Figure 19. Unmodified Experimental VFD EMI Current (0-20 MHz) Input Line



940817 1328
 SP-543, Phase Line, VFD output to motor
 10 MHz, 20 MHz, 100 kHz, 500 ms
 F70, 0, 0, -20

Figure 20. Unmodified Experimental VFD EMI Current (0-20 MHz) Output Line

VI. MODIFIED VARIABLE-FREQUENCY DRIVE PERFORMANCE

Because of the high EMI current levels from the Luketina Hall variable-frequency drives and the experimental VFD, modifications to the case housing the experimental VFD were made using the barrier, filter, ground techniques described in chapter 3. The experimental VFD will be the only VFD referred to in this chapter.

A. INITIAL VARIABLE-FREQUENCY DRIVE MODIFICATIONS

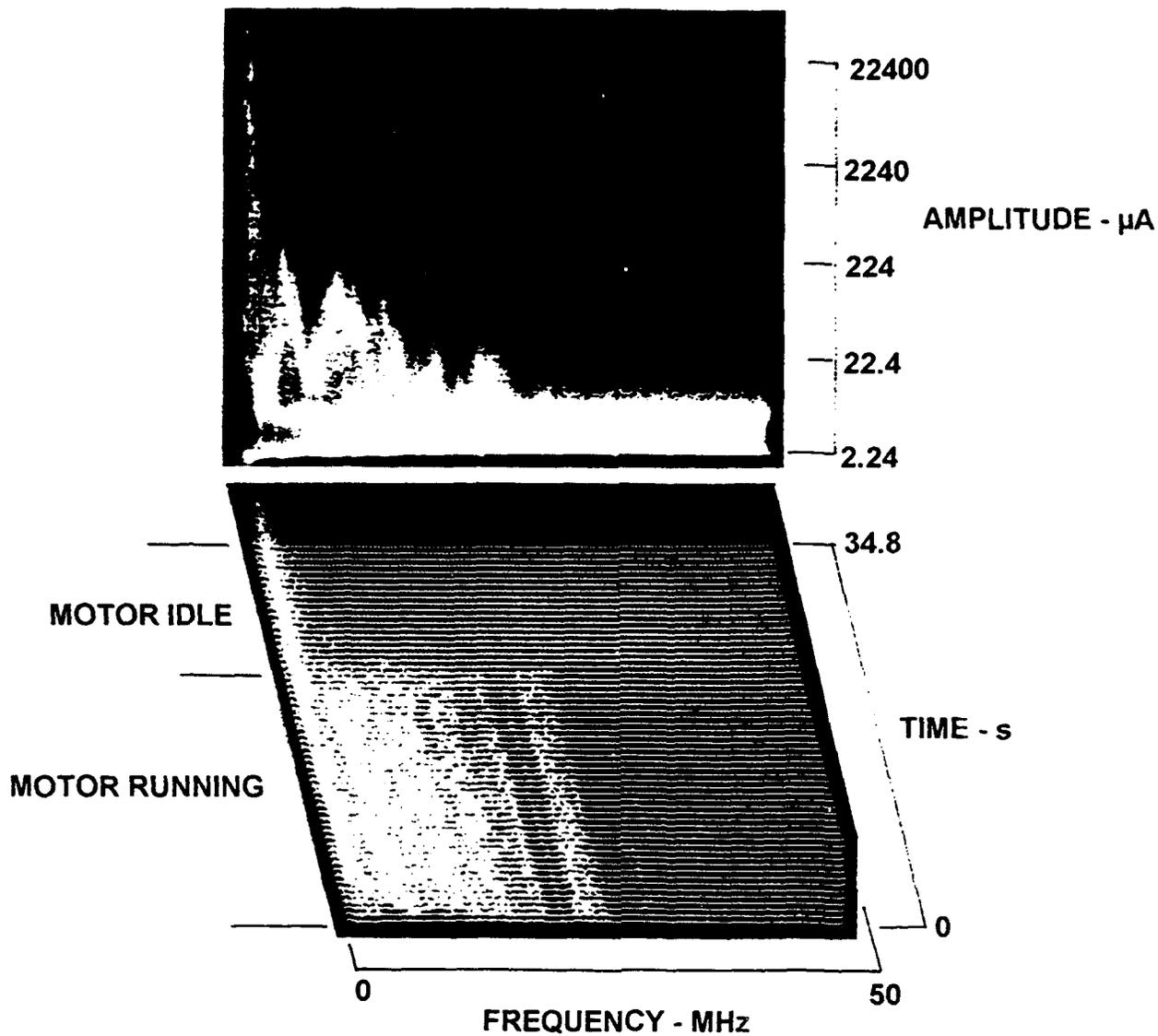
The initial modifications made to the VFD were as follows. The VFD cabinet was an adequate barrier after the paint was sanded off the edges that were bolted together to provide a good electrical bond. The rubber seal on the door was stripped off. The internal ground for the system was adequate with the use of a ground stud to connect the internal grounds inside the cabinet with the external ground. Both the input and output lines were filtered using CORCOM 30T48 power-line filters which have a 460 volt, 31 ampere capacity which filter out frequencies over 18 kHz. These Pi-section filters have a capacitor input to keep high frequency impedance low at the input. These filters keep EMI potentials low on the short wires from the drive's terminals to the filter. The VFD's layout was as pictured in Figure 10, including the filters.

Unfortunately, the VFD did not work with a filter on the power line from the VFD's output terminal to the motor. The VFD shut down when any current was delivered to the motor, displaying an "out-of-saturate" message on the VFD's message

panel. The VFD apparently required the inductive impedance of an induction motor; the filter disrupted this impedance, causing the error. Removing the filter between the VFD and the motor allowed full operation of the VFD.

Measurements were taken with a filter on only the input line to the VFD. Figures 21 and 22 shows the EMI current from 0-50 MHz. In Figure 21 the EMI current from the filter to the VFD's input terminal drops below $10 \mu\text{A}$ above 20.5 MHz and below 4 MHz, which is significantly lower than the unfiltered EMI current shown in Figure 17. EMI current levels between 4 and 17 MHz ranged between $240 \mu\text{A}$ and $22.4 \mu\text{A}$, a 6-dB improvement. Figure 22 shows an EMI current level of $224 \mu\text{A}$ at 14 MHz between the filter and the VFD's input terminal and above $10 \mu\text{A}$ across the entire 0-50 MHz region. Figures 17 and 22 show that the EMI current level is actually higher between the filter and VFD input terminal than before the filter was installed. This is caused by the reflection of the EMI current back into the VFD, which is the purpose of the filter. Figure 23 shows more clearly the effect of the filter from 0-4 MHz (the light shading above $10 \mu\text{A}$ is due to the building's elevator).

To resolve the VFD's failure to operate with a filter on the output power line, a new capacitive load filter with a frequency cutoff of 100 kHz was built. With this filter the VFD still shut down when any current was supplied to the motor. At this point an alternative approach was tried.



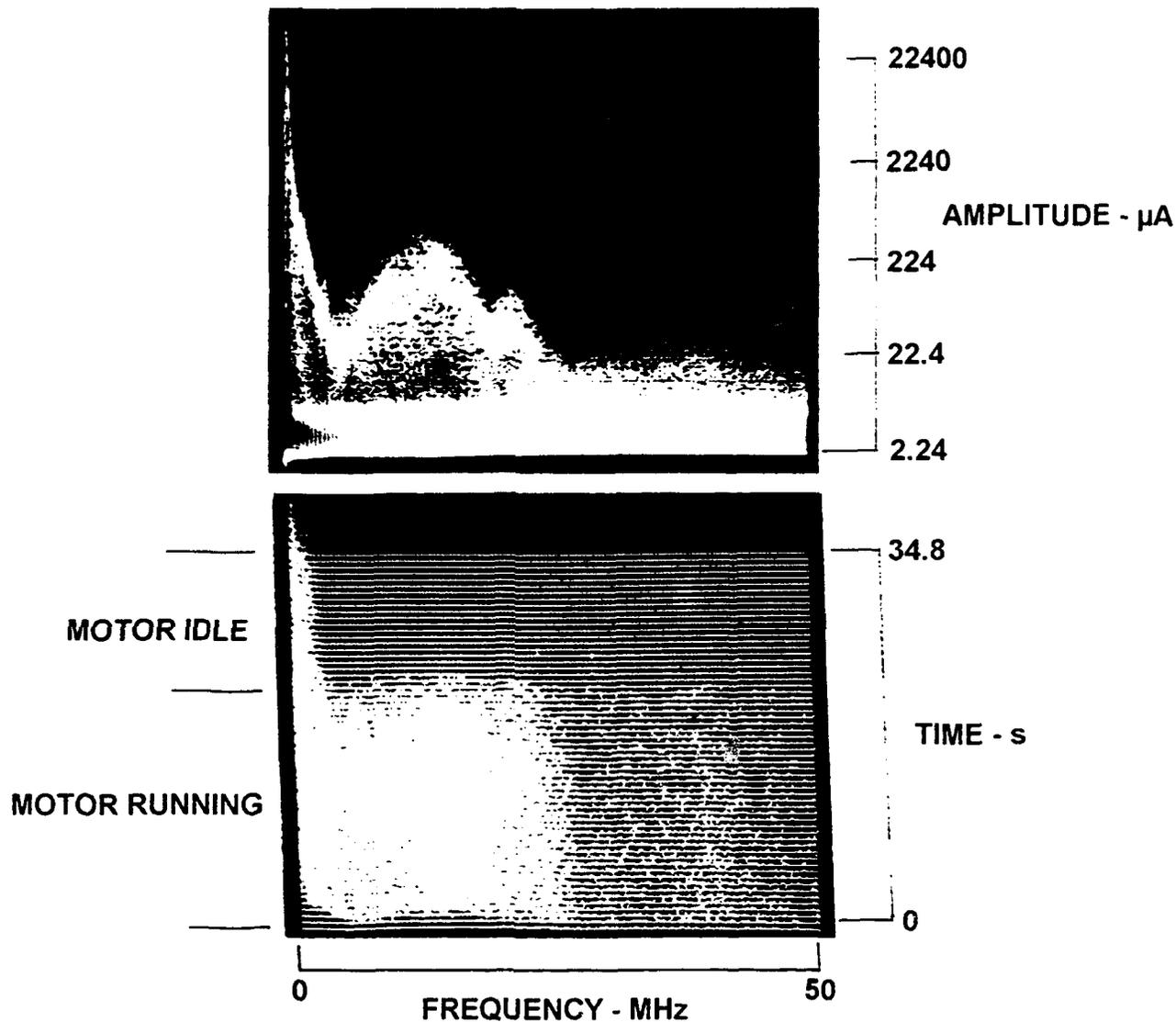
940817 1349

SP-543. Phase Line. electrical panel to filter

25 MHz. 50 MHz. 100 kHz. 500 ms

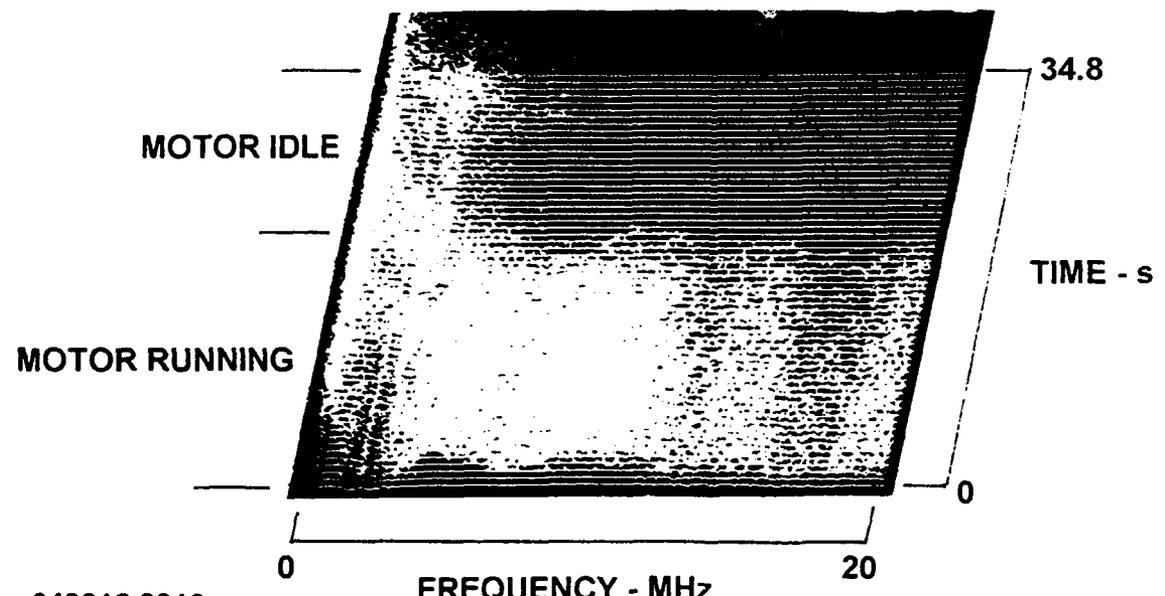
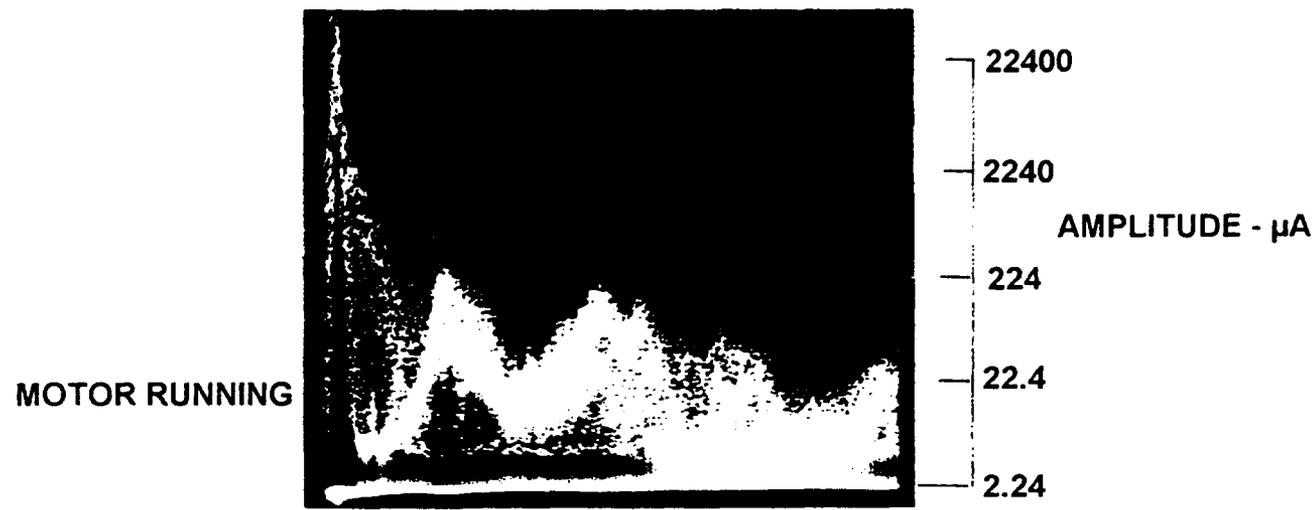
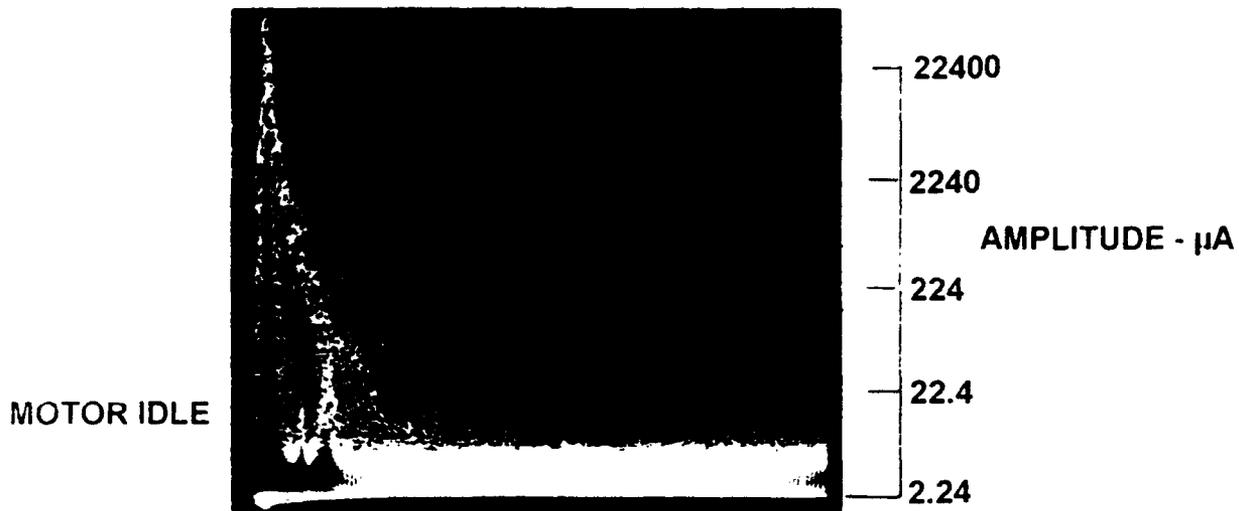
F70. 0. 0. -20

Figure 21. Modified VFD EMI Current (0-50 MHz) Electrical Panel to Filter



940817 1406
 SP-543. Phase Line. filter to VFD input
 25 MHz. 50 MHz. 100 kHz. 500 ms
 F70. 0. 0. -20

Figure 22. Modified VFD EMI Current (0-50 MHz) Filter to VFD Input Terminal



940812 0910
 SP-543. Phase Line. electrical panel to filter
 10 MHz, 20 MHz, 100 kHz, 500 ms
 F70, 0, 0, -20

Figure 23. Modified VFD EMI Current (0-20 MHz) Electrical Panel to Filter

B. FURTHER MODIFICATION TO THE BARRIER, FILTER, GROUND PLAN

Because the available filters prevented the VFD's operation when placed on the output line, a different approach was attempted. The input and output wires were unshielded in the previous measurements. When installed in a permanent location, metallic conduit will enclose the input and output lines. To model this, the wires from the VFD's output terminal to the motor were strung through BX cable. Typical connectors secured the BX cable to the VFD's cabinet and the motor casing. The VFD and motor cases were sanded where the connectors were attached. The wire was placed in BX cable and the BX cable was secured to the motor, providing barrier protection and preventing EMI current from radiating. This configuration is shown in Figure 24.

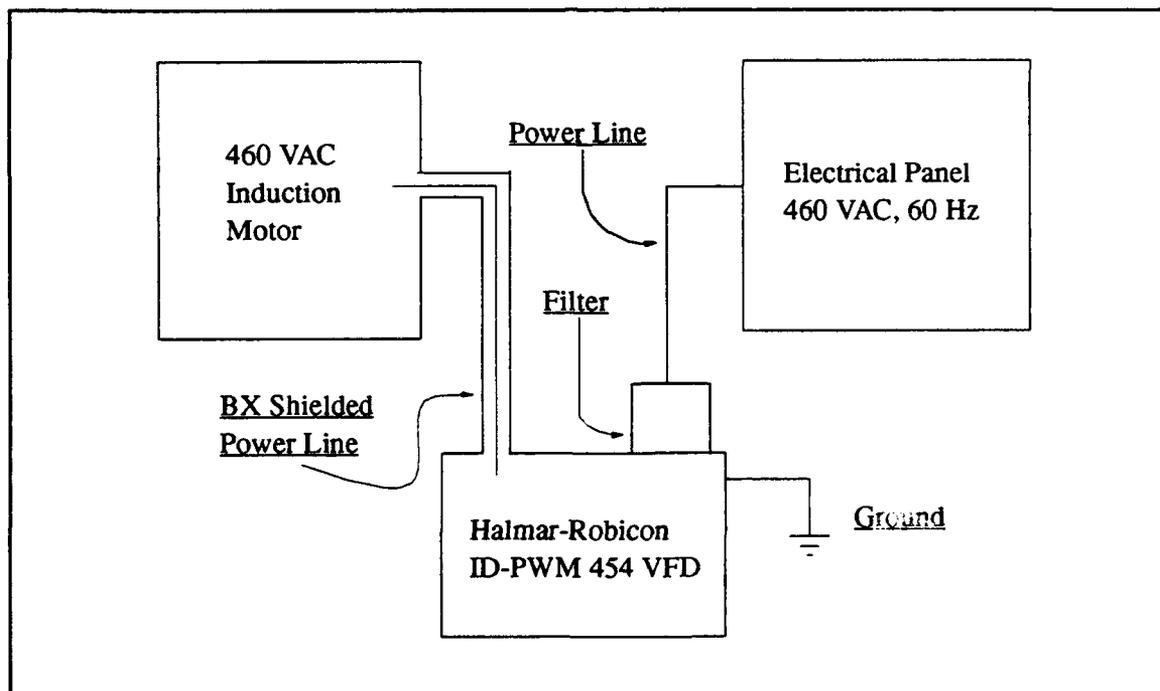
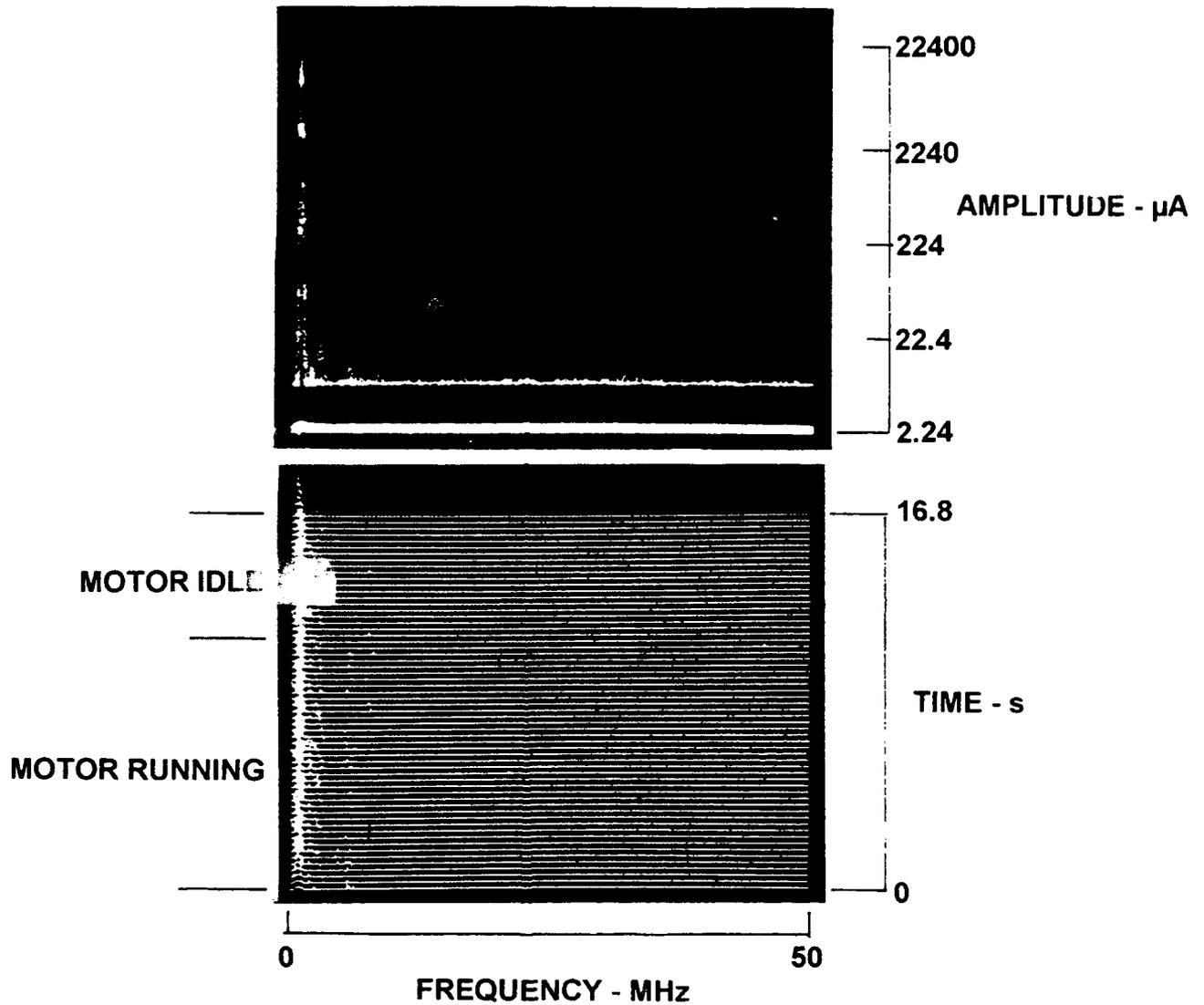


Figure 24. Final Configuration of Modified VFD

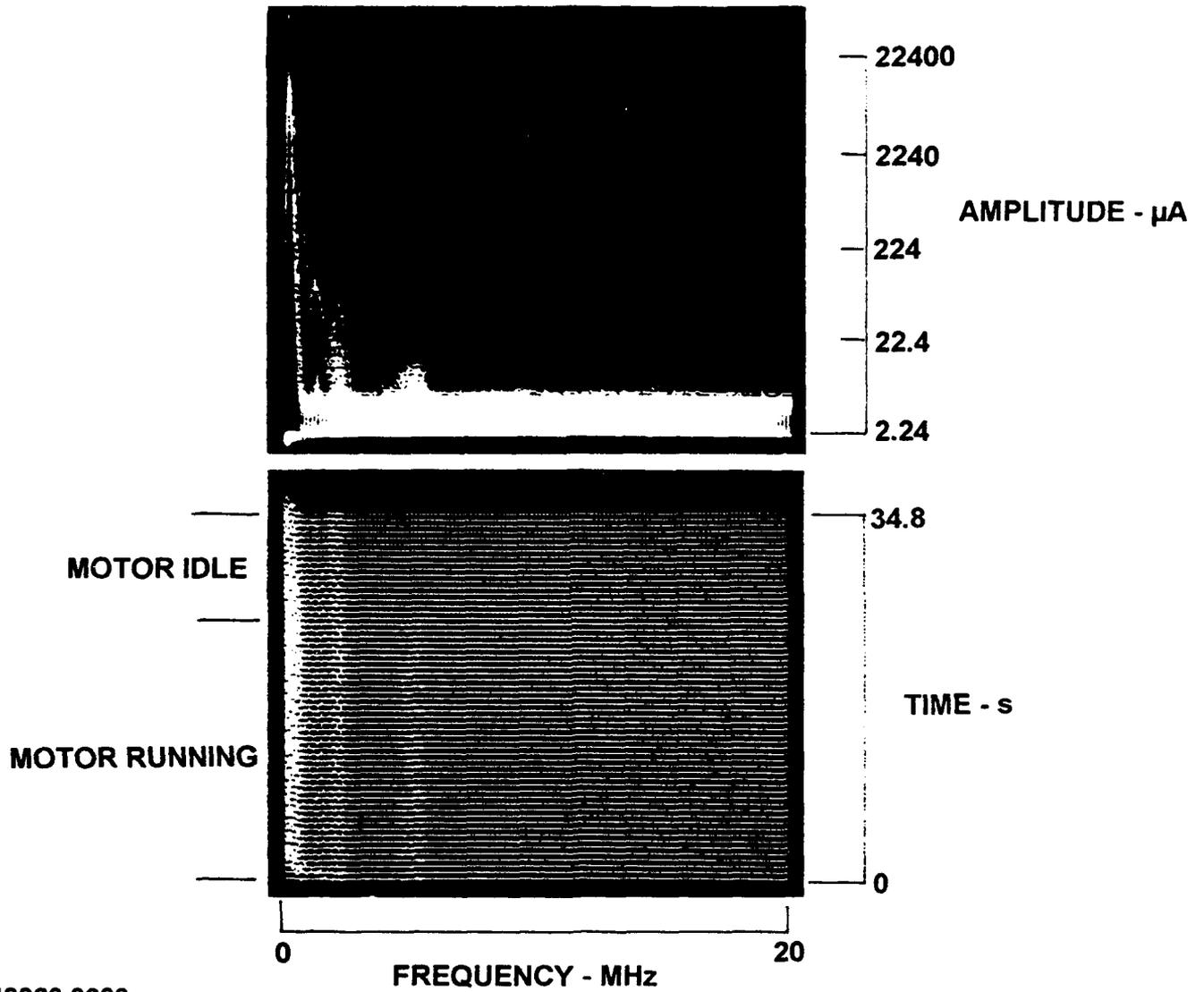
The results of inserting the output wires in BX cable are shown in Figures 25 to 28. The improvement is significant. The EMI current pictured in Figure 25 is below the noise floor of $10\ \mu\text{A}$ across the 0-50 MHz frequency range except at 4 MHz. The EMI current level was still approximately $11\ \mu\text{A}$ at 4 MHz. The original unmodified VFD measurement shown in Figure 17 showed an EMI current of approximately $500\ \mu\text{A}$. The power-line filter provided approximately 35 dB attenuation of the signal. The best that can be expected of a single filter is about 40 dB. Figure 26 shows more clearly the EMI current at 4 MHz. The remaining EMI current below 4 MHz is due to the building's elevators.

Figures 27 and 28 show the same frequency range as Figures 25 and 26 with the signal amplified by 20 dB. In Figure 27 the other parts of the EMI current that are above the $1\ \mu\text{A}$ noise floor, including components at 8 MHz, 14 MHz and 20 MHz, can be seen. The elevator EMI current are the slanting lines in the 0-15 MHz range in Figure 28, and the VFD's EMI current is apparent at 4 MHz, 8 MHz, 14 MHz, and 20 MHz. The latter three are well below the $10\ \mu\text{A}$ level and the 4 MHz signal is just over this level. The lower EMI current level, compared to the initial values, suggest that the filter prevented EMI currents from leaving the cabinet, but radiation from the output wires coupled onto the input wires.



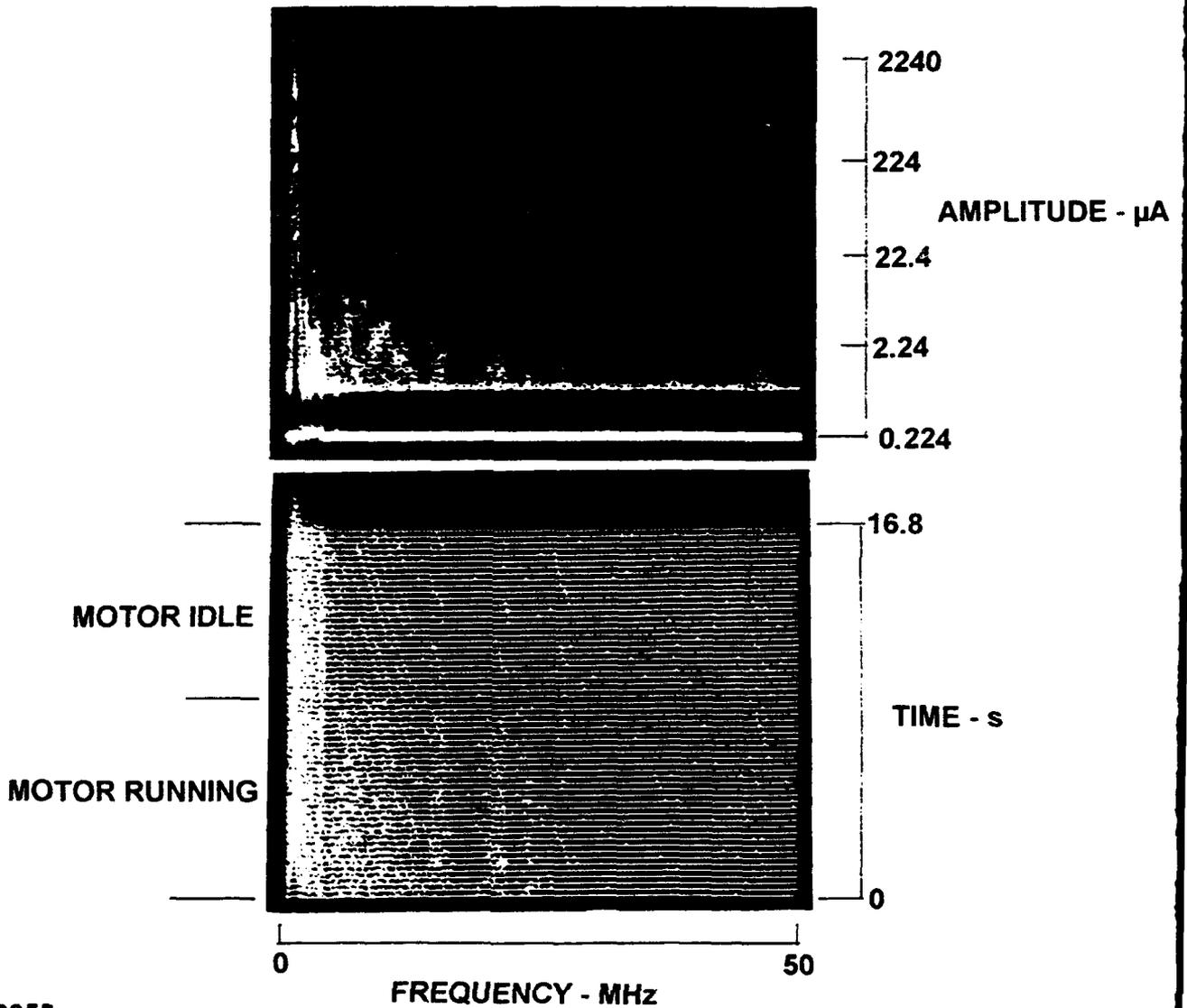
940826 0850
 SP543, Phase wire.
 Electrical panel to filter. BX on output line
 25 MHz, 50 MHz, 100 kHz, 200 ms
 F70, 0, 0, -20

Figure 25. BX Modified VFD EMI Current (0-50 MHz) Electrical Panel to Filter



940826 0830
 SP543, Phase wire.
 Electrical panel to filter. BX on output line
 10 MHz, 20 MHz, 100 kHz, 500 ms
 F70, 0, 0, -20

Figure 26. BX Modified VFD EMI Current (0-20 MHz) Electrical Panel to Filter



940826 0855

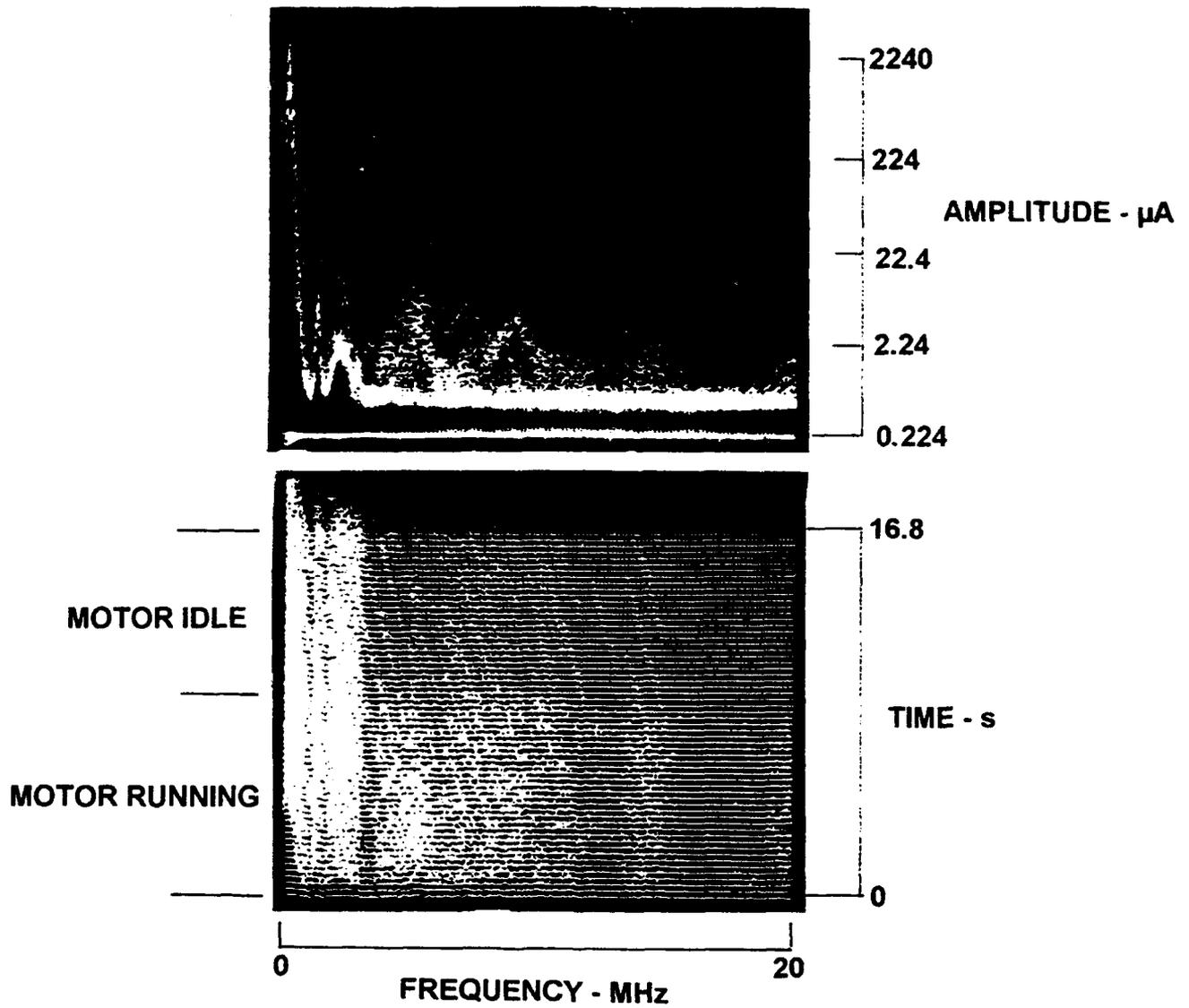
SP543. Phase wire,

Electrical panel to filter, BX on output line

25 MHz, 50 MHz, 100 kHz, 200 ms

F70, +22, 0, -20

Figure 27. BX Modified VFD EMI Current (0-50 MHz) Electrical Panel to Filter



940826 0840

SP543. Phase wire.

Electrical panel to filter. BX on output line

10 MHz, 20 MHz, 100 kHz, 200 ms

F70, +22, 0, -20

Figure 28. BX Modified VFD EMI Current (0-20 MHz) Electrical Panel to Filter

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The electromagnetic interference generated by a digital, variable-frequency, induction-motor drive was examined in this thesis. Interference mitigation techniques were explored and implemented on a VFD motor controller. Specific conclusions reached during this work are as follows:

- Existing EMI standards were reviewed for their application to receiving and data processing sites. MIL-STD-461, the VXIbus standard, and the FCC standards do not provide sufficient EMI protection for the case where digital equipment is used in receiving and data processing sites. No other appropriate standard or set of guidelines was found that provided sufficient EMI protection. The suggested maximum EMI current limitations proposed by the SNEP teams were found to be more appropriate.
- Conducted and radiated EMI from a standard digital, variable-frequency, motor controller was found to be excessive. The use of the type of digital motor controller examined in this thesis is not recommended in receiving and data processing sites unless it is modified to reduce EMI to acceptable levels.
- Integrated BFG techniques were successfully used on the metal cabinet housing the motor controller to reduce EMI to acceptable levels. No circuit changes or other modifications to the motor controller itself was required.
- A standard Pi-section power-line filter was successfully used on the input power conductors to limit conducted EMI current to SNEP-suggested maximum levels.
- A standard Pi-section power-line filter installed on the motor power conductors prevented the operation of the motor controller. The input capacitor of the filter appeared to affect the functioning of the motor controller. This was overcome by removing the filter and extending the barrier to the motor housing with standard electrical conduit.

- No uncontrolled conductors were allowed to enter or leave the cabinet housing the motor controller.
- All objectives of the thesis were met using the integrated BFG approach to the control of EMI.

B. RECOMMENDATIONS

A number of recommendations were formulated during the course of the thesis work. These are as follows:

- EMI standards, guidelines, or other document that apply to receiving and data processing sites need to be generated and made available to site designers, equipment purchasing personnel, and others involved in the operational performance of receiving and data processing sites. The SNEP-suggested maximum EMI current limits provide a starting point for the generation of a suitable document.
- Similarly, a document providing details of the integrated BFG need to be produced and made generally available to designers, manufacturers, and installation personnel.
- No new digital equipment should be procured for installation in receiving and data processing sites unless it meets appropriate EMI limits.
- Digital motor controllers of the type used in this thesis should be modified prior to installation in a receiving and data processing site.

LIST OF REFERENCES

1. Adler, R.W., Class notes for EC 3640 (Electromagnetic Environmental Effects), Naval Postgraduate School (unpublished), 1994.
2. Vincent, Wilbur R. and Adler, Richard W., "Comments About Electrical Grounds in CDAA Sites," Naval Postgraduate School note (unpublished), pp. 3-4, October 1992.
3. Code of Federal Regulations, U.S. National Archives and Records Administration, *Title 47 - Telecommunications*, p. 545, Government Printing Office, Washington, DC, October 1, 1992.
4. Paul, Clayton R., *Introduction to Electromagnetic Compatibility*, pp. 42-76, John Wiley & Sons, Inc., 1992.
5. Institute of Electrical and Electronic Engineers, Inc., IEEE Std 1155-1992, *IEEE Standard for VMEbus Extensions for Instrumentation: VXibus*, 20 September 1993.
6. Kraus, Allan D., *Circuit Analysis*, p. 38, West Publishing Company, 1991.
7. *Performance Evaluation at Cryptologic Sites Technical Course Manual*, Draft 1, Chapter 7, Signal-to-Noise Enhancement Program (SNEP) Team, April 1991.
8. Halmar-Robicon Group, *Product Data, AC Variable Frequency Drives, ID-PWM 454 Series*, 1993.
9. Halmar-Robicon Group, Instruction Manual ID-PWM 454 Series, *Intelligent Drive-Pulse Width Modulated Adjustable Speed A.C. Motor Drive, 3 through 500 HP*, 1993.
10. Ingram, V.D., *Strategies in Topological Approach to Electromagnetic Interference Control*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 1987.
11. Mantech Field Engineering Company, Contract DAAB10-91-D-0502, Delivery Order 0033, *EMI Site Survey: Luketina Hall, Ft. Gordon, Georgia*, pp. 16-21, 13 April 1994.

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