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An electromagnetic interference analysis of uninterruptible power supply systems in a data processing environment

Beran, Edward W.

Monterey, Calif. Naval Postgraduate School

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NAVAL POSTGRADUATE SCHOOL
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THESIS

AN ELECTROMAGNETIC INTERFERENCE ANALYSIS OF UNINTERRUPTIBLE POWER SUPPLY SYSTEMS IN A DATA PROCESSING ENVIRONMENT

by

Edward W. Beran

December 2002

Thesis Advisor:	Richard W. Adler
Second Reader:	Wilbur R. Vincent

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The results show that a significant reduction in the level of EMI can be achieved in low-to-modest size UPSs using inexpensive, standard, and commercially available filters, provided the filters are installed in an effective manner. The reduction of EMI to harmless levels at radio-receiving and data-processing sites is shown to be feasible.

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AN ELECTROMAGNETIC INTERFERENCE ANALYSIS OF UNINTERRUPTIBLE POWER SUPPLY SYSTEMS IN A DATA PROCESSING ENVIRONMENT

Edward W. Beran
Civilian, Fort Meade, Maryland
BSEE, University of Maryland, 1973

Submitted in partial fulfillment of the
requirements for the degree of

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December 2002

Author:
Edward W. Beran

Approved by:
Richard W. Adler
Thesis Advisor

Wilbur R. Vincent
Second Reader

Donald P. Lyons
Fort Meade Advisor

John P. Powers
Chairman, Department of Electrical and Computer Engineering

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Funding was provided for two trips to NPS by the Fort Meade National Cryptologic School (NCS). In addition, financial assistance was given from the NPS Signal-to-Noise Enhancement Program (SNEP) Laboratory for all lab supplies including camera film, lab equipment, and drafting support.

Personal thanks to Professor Vicente Garcia for allowing two visits to NPS, thus enabling completion of performance data. Additionally, gratitude for his ever-present enthusiasm and patience given to a student in dire need of guidance during an extremely taxing work - school adjustment period. Professor Garcia kept this student from giving in to despair during the initial period where reality of the enormous effort required for upcoming tasks was actually recognized.

Most importantly, the author offers profuse gratitude to Professors Richard Adler and Wilbur (Ray) Vincent for their expert guidance along with unending patience to a distraught student during the research and writing of this thesis. To Professor Adler: thanks for the overall guidance and taking on this student (however taxing he may have been). Professor Adler, this author recognizes this assistance was an additional burden to a gentleman with a constantly hectic schedule. To Professor Vincent: thank you for the intermediate guidance, constant support, and unimaginable, unending patience. Professor Vincent guided this student around many grammatical and graphical problems with unbelievable grace and kindness.

Special recognition goes to Mr. Andrew Parker for his generous assistance in all lab procedures (especially on the student's TDY weekends).

Finally, the author wishes to offer appreciation to Mr. Donald Lyons (the Fort Meade advisor) for his constructive comments for the completion of the thesis.

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EXECUTIVE SUMMARY

Electromagnetic interference (EMI) generated by small- and medium-size Uninterruptible Power Supplies (UPS) is investigated in this thesis, and a solution to minimize the impact of UPS-generated EMI at radio-receiving sites and data-processing facilities is described. The investigation was instigated by field reports of the Navy's Signal-To-Noise Enhancement program (SNEP) teams that have documented numerous cases of harmful interference to the reception of radio signals at receiving sites. In addition, cases of the corruption of digital signals in data-processing systems from UPS EMI have been noted. Since the use of small and medium UPS to prevent power interruptions to critical equipment is commonplace, a practical and effective solution to the EMI problem is considered essential.

An introduction to power quality problems and EMI is presented in Section II of the thesis. EMI can be defined as any electrical signal that adversely affects the operation of electrical, electronic, or communications equipment. EMI can be generated and radiated from many devices. The radiated electromagnetic fields can be intercepted by a victim device and interfere with its operation. Additionally, EMI can also be conducted from a source to a victim over conductors such as power wires, grounds, cable shields, and other conducting objects. Descriptions of typical sources of EMI, victim devices and equipment, and EMI standards are presented. The final discussion presented in this section concerns EMI mitigation.

In the EMI measurement section of the report, the test setup is explained in detail. The measurement configuration and test locations are discussed. The UPS measurement section was divided into two sub-sections, the unmodified (standard, no filters installed) UPS results and the modified (with EMI filters) UPS results. The modified UPS results show that EMI currents have been reduced significantly with the use of EMI filters on the input and output conductors of the UPS. The final subsection is a proposed UPS equipment specification.

Appendix A provides a “Table of Noise Sources” obtained from the United States Signals Intelligence Directive. The noise sources or emitters shown in Table A.1 of the Appendix are intended only for general guidance to planners and operational units since it is impossible to list all possible sources. While only a limited number of sources existed in past years, the recent introduction of new devices into Department of Defense facilities (especially digital power-control devices) has introduced many new kinds of sources. Each situation involving electrical and radio-noise problems must be evaluated on a case-by-case basis to identify and mitigate any adverse input on facility operations from each individual source. Existing noise sources in Department of Defense facilities cannot always be summarily removed because of overall operational considerations, but each source can and should be modified or replaced to minimize the deleterious impact of noise on the operation of electrical and electronic systems. Every effort must be made to protect against ongoing mission performance degradation created by EMI. Such actions will improve the performance of radio and data-processing systems and often results in the improved efficiency of the devices causing noise.

In Appendix B, a document search was performed to find existing EMI-related documents that identify EMI current criteria standards. This investigation of various standards was accomplished to determine the latest interference criteria at the time of the writing of this thesis. Based on several document searches, it was decided to use the SNEP interference criteria for this report.

In Appendix C, a description of UPS systems is presented. Two typical office data-processor-type UPS systems were used in the analysis of this document. The components of UPS (rectifier or charging unit, inverter, and battery bank) were briefly discussed. UPS standards and warning signs were next discussed.

In Appendix D, the test calibration methods are explained. The descriptions cover time-axis calibration of the 3-axis display test equipment, amplitude calibration, bandwidth calibration, and probe calibration techniques.

In Appendix E, an introduction to EMI filter theory is next presented. Descriptions of t- and pi-filters are discussed. For the purposes of this thesis, the discussion will be limited to the low-pass type, which allows alternating electrical power to be provided to an UPS while attenuating higher-frequency EMI being conducted out of the UPS. A brief discussion of filter characteristics, insertion loss, standards, and finally installation criteria are given.

In Appendix F, the engineering specification for a single-phase UPS system is given. Section 16611 from the MASTERSPEC DRAWING COORDINATION document issued by the American Institute of Architects (AIA) provides an overall specification for an Uninterruptible Power Supply (UPS). Suggested changes in this specification are listed in bold. These changes are directed at the use of UPS systems in radio-receiving and sensitive data-processing facilities. Of particular concern is the elimination of harmful levels of UPS generated EMI on radio signal reception and on the operation of sensitive data-processing systems.

In the summary section of the thesis, the author concluded that EMI can degrade the operation and performance of many kinds of electronic devices and radio receiving systems. The increasing use of computers, digital-data-processing devices, and power-control devices in such facilities (including UPS systems, switching power supplies, and motor controllers based on solid-state switching techniques) has resulted in many cases of EMI problems. In UPS systems, EMI is generated by the rectifier and inverter sections, which often produce noise up to and sometimes higher than 50 MHz. Also, another intermittent source of impulsive noise is load-current changes (load switching), that create voltage and current impulses and electrical noise. The EMI generated by two unmodified commercial models of UPS were examined. The units were modified in accordance with integrated Barrier, Filter, Ground techniques and again tested. Significant reductions in conducted EMI current was achieved on all conductors penetrating the UPS case including all power and ground conductors. The modifications resulted in the test units meeting all known conducted EMI current limits including those of MILSTD-461 and the suggested limits provided by the US Navy SNEP team.

The MASTER DRAWING COORDINATION document issued by the American Institute of Architects (AIA) is often used as a guide for the procurement and installation of UPS systems. This document, in its original form, does not consider the impact of

UPS-generated EMI on other systems. Based on the results of this investigation, suggested changes to the AIA document are provided in Appendix F.

In the recommendation section of the thesis, the author offered the following suggestions:

- To follow the Naval Security Group (NSG) recommendation for the use of UPS (see page 46): "Only mission-essential equipment not able to tolerate even momentary power disturbances shall be connected to UPS power." This recommendation is fully supported, and the DOD will be best served by following the NSG recommendation.
- In addition, to the above general recommendation, additional precautions need to be taken to ensure that UPS-generated EMI does not degrade the operation of other radio and electronic systems. This is especially the case in HF, VHF, and UHF radio-receiving sites where UPS-generated EMI is often found at the input terminals of the radio receivers and in sensitive data-processing facilities where UPS-generated EMI is often found on data-cable shields and grounds.
- When a determination is made that an UPS is required, or an UPS already exists, specific guidelines and critical aspects for consideration both prior to purchase and after the product has been obtained or installed should be followed.
- Although an UPS provides excellent protection for sensitive equipment from many kinds of power faults, their generation of low- and high-frequency EMI must be considered. At times, interference may exist after the UPS has been installed. During these occasions, the procedure for identifying and documenting harmful levels of EMI becomes somewhat more complicated.
- In cases where UPS noise may be a factor degrading the performance of electronic and radio devices or systems, it is recommended that UPS be procured and installed in accordance with the additions to *"The MASTER DRAWING COORDINATION document issued by the American Institute of Architects (AIA)*". These additions and changes are provided in Appendix F.

These changes apply to small and medium power UPS systems (up to about 50 kVA) where standard filters are available as COTS items.

- Finally, it is recommended that future projects be undertaken to better understand methods to control EMI caused by a medium-sized (i.e., 50 to 250 kVA) UPS and large sizes (i.e., 250 kVA and higher). A project is required to develop methods and filter configurations to lower conducted and radiated EMI from medium and high power UPS to acceptable limits.

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I. INTRODUCTION

Field experience has shown that electromagnetic interference (EMI) generated by Uninterruptible Power Supplies (UPS) and other similar solid-state-switching devices can result in the degradation of signal reception at radio-receiving sites and the contamination of data at data-processing facilities. The need for UPS systems to improve power reliability for critical devices at such sites is recognized, and this indicates the need for devising effective EMI mitigation actions. This matter is examined in this thesis.

A review of available EMI standards, specifications, and other related documents was undertaken. This included Department of Defense standards and documents as well as standards and documents of other agencies such as the Federal Communications Commission (FCC) and the Institute of Electrical and Electronic Engineers (IEEE). Although no standard was found that fully covered the UPS/EMI issue, all addressed the topic to some extent.

EMI tests were conducted on two standard UPS units over the frequency range of a few kHz and as high as 50 MHz. EMI suppression actions were then undertaken on both units and the amount of EMI reduction was measured. The method of EMI suppression is described. The results before and after suppression actions were compared to conducted-current limits suggested by available standards, specifications, and documents.

The Appendices provide supplemental information on topics associated with electrical noise and used for research in this thesis. The topics include electrical noise sources, EMI standards, UPS system descriptions, test calibrations, EMI filter characteristics, and UPS technical equipment specifications.

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II. ELECTROMAGNETIC INTERFERENCE

Factors important in the evaluation of electromagnetic interference from an Uninterruptible Power Supply are presented in this chapter.

A. BACKGROUND

The operation of sensitive electronic components and systems can typically prove to be adversely affected by a number of power-quality factors such as EMI. An understanding of these factors is required for investigation of, and solutions to EMI occurrences. Power quality issues are specifically described by the following general categories:

- Transients - Disturbances with high-speed voltage or current changes. Transients are sometimes described as spikes, impulses, and surges.
- Momentary interruptions - Referring to a loss of voltage for periods of less than a cycle to several cycles.
- Sags and swells - Variations in voltage or current, ranging from one half second to several seconds. Sags refer to reductions in voltage or current while swells refer to increases in voltage or current.
- Under voltage or over voltage - Described as sags or swells continuing for more than several seconds or at times lasting for longer than a period of hours.
- Harmonic distortion - Occurrences where the waveshape of voltage or current is not sinusoidal.

EMI is one additional factor often affecting the operation of sensitive electrical and electronic equipment. EMI can be defined as any electrical signal that adversely affects the operation of electrical, electronic, or communications equipment. EMI can be generated and radiated from many devices (or from the conductors associated with such devices). The radiated electromagnetic fields can be intercepted by a victim device and interfere with its operation. Additionally, EMI can also be conducted from a source to a victim over conductors such as power wires, grounds, cable shields, and other conducting objects. Both forms of transmission regarding EMI from a source to its victim must be considered when investigating EMI problems.

Two terms are often used to describe conducted EMI; they are known as common-mode and differential-mode. Common-mode EMI is the interference measured between a conductor (or a pair of conductors carrying a desired signal) and a reference ground. Differential-mode EMI is interference measured between two conductors carrying desired signals. Conducted EMI interference can be measured and compared with either voltage or current established criteria.

B. TYPICAL SOURCES OF EMI

EMI is often generated by a variety of electrical and electronic devices and equipment. Typical types of equipment that can create EMI are:

- Uninterruptible Power Supplies
- Telecommunication Equipment
- Personal Computers and Peripheral Equipment
- Switching Power Supplies
- Variable Frequency Induction Motor Drives
- Battery Chargers
- Electronic Dimmers
- Electronic Fluorescent Light Ballasts
- RF Stabilized Arc Welders
- Some Medical Equipment
- Power Conversion Devices Based on Switching Techniques

Additional sources [Reference 1] of EMI are provided in Appendix A and derived from the United States Signals Intelligence Directive.

C. VICTIM DEVICES AND EQUIPMENT

Most electronic devices can be adversely affected by EMI including items in the list of sources provided in Section B, but data-processing equipment, communications devices, and radio receivers located in remote facilities are the items of highest concern in this thesis.

The operating speeds of digital devices and equipment continue to increase, making them more susceptible to high-frequency EMI. In addition, the operating voltage of many solid-state devices will continue to decrease while conserving power, thereby creating susceptibility for malfunction due to transients and other forms of EMI. Of primary concern are these two trends in device and equipment design, combined with the increased usage of various devices causing EMI.

D. EMI STANDARDS

A large number of publications, references, handbooks, and standards exist addressing the topic of EMI. The pertinent handbooks and standards are listed and reviewed in Appendix B. A number of government handbooks and standards provide guidance concerning EMI. However, the enormous variety of electronic and electrical devices, ongoing introduction of new devices and equipment, and the long production times for revision of standards and handbooks causes difficulty in covering total aspects of EMI. In addition, there is an increasing tendency to rely on commercial-off-the-shelf (COTS) equipment and associated standards for the procurement and installation of electrical and electronic equipment.

Much of the equipment in today’s data-processing centers and radio-receiving facilities is purchased in accordance with COTS requirements. For example, the UPS systems of primary concern within this thesis are almost always procured as COTS equipment, where the primary standard is the Class A or Class B requirements of Part 15 of the Federal Communications Commission. The Class A requirement is directed at providing equipment to be installed and used in industrial facilities. A far more stringent Class B requirement is directed at the provision of equipment for use in residences.

E. EMI MITIGATION

A commonly used approach to EMI mitigation, better and bigger grounds (or ground impedance), was used with much success in past decades when cases of high-frequency EMI current flowing on grounds, power conductors, cable shields and other conductors at a facility was rare. Grounds provided a means to establish a voltage reference for all equipment in a facility. The more recent introduction of solid-state switching devices and other digital devices into electronic and power-control equipment greatly increased the amount and levels of both low-frequency and high-frequency EMI current and voltages. This occurs on grounds, power conductors, cable shields, equipment cases, and other conductors. In addition, the lengths of conductors associated with EMI sources, victim equipment, and the paths between the two become electrically long at higher-frequency components of EMI. Multiple wavelength paths now introduce standing waves of EMI voltage and current on these paths, which further complicates coupling mechanisms between source and victim. These factors significantly reduce the effectiveness of the grounding approach. Electrical lengths of grounds, power conductors, cable shields, and other conductors are now a key factor in the EMI problem rather than a part of the solution. Transmission line and antenna theory is now an integral part of an EMI problem.

Moreover, efficient near-zone coupling mechanisms (both inductive and capacitive) allow high-frequency EMI current and voltage from a conductor to be coupled onto other closely-spaced conductors at a facility. The near-zone coupling mechanisms and direct conduction of EMI current from a source to another location over multiple paths allows EMI current and voltage to spread far beyond its source and to seek paths of entry into victim equipment. This can result in a large number of paths for the flow of EMI current making the description and modeling of a source, its paths to a victim, and the susceptibility of a victim very difficult and often impractical to identify.

A description of UPS systems is given in Appendix C. A simplistic but effective approach to the mitigation of EMI from an UPS (or any other source) was taken during this effort. The approach was discovered in the early era of radio and telegraph communications. It consists of merely preventing EMI current from flowing on any conductor outside the case or housing of a device generating EMI along with the recognition that grounds are now a part of the EMI problem rather than a solution.

This approach is described in a number of unclassified publications by Nanevich, Vance, and Graf of SRI International [References 2 through 5]. These publications describe an EMI control technique they call the “Topological Control of EMI.” It consists of the use of shielding around a source or victim, applying meaningful bandwidth control on all conductors entering and exiting the shield, the termination of internal cable shields and grounds on the inside surface of the shield, and the termination of external cable shields and facility ground conductors on the outside surface of the shield. This concept has been extended and used by USN Signal-To-Noise-Enhancement Program teams. These teams applied usage of the electromagnetic barrier, filter, ground (BFG) technique [Reference 6] to control EMI from sources, or lowering susceptibility of victims. The BFG technique was applied to the test UPS systems examined in this thesis.

The general background and information needed for the control of harmful levels of electrical and electromagnetic interference from UPS systems has been presented above. This background has been stated in terms used by and encountered by radio-receiving site and sensitive data-processing site personnel.

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III EMI MEASUREMENTS

This Chapter describes the measurement setup and presents the results of measurements on one Interruptible Power Supply of a type frequently found in field sites and data-processing facilities.

A. TEST SETUP DISCUSSION

The test equipment utilized in this study is identical to the setup used by the NPS Signal-Enhancement Laboratory and for the Naval Security Group (NSG) Signal-to-Noise Enhancement Program (SNEP). This equipment has been used for many laboratory and field measurement programs. All tests and measurements provided in this document are based on conducted emissions from standard COTS UPS systems. The measurements provide values of conducted EMI current over broad bandwidths before and after the UPS systems were modified where the modifications were made to reduce conducted EMI current to harmless levels. Figure 3.1 shows a photograph of the primary items of instrumentation in this test setup.

Figure 3.1: The SNEP Test Setup

Figure 3.1 shows a low-frequency spectrum analyzer in the lower right part of the view, a high-frequency spectrum analyzer in the lower left part of the view, the time-history display on top of the high-frequency spectrum analyzer and line amplifiers on top of the time-history display. The current probes used to measure conducted EMI current are not shown.

The instrumentation setup provides a capability to measure low-frequency EMI current over the frequency range of 0 to 100 kHz in addition to high-frequency EMI current over the frequency range of 50 kHz up to 100 MHz. Both capabilities were used to produce the examples of data shown in this document. Figure 3.2 shows a block diagram of the instrumentation used for the low-frequency measurements.

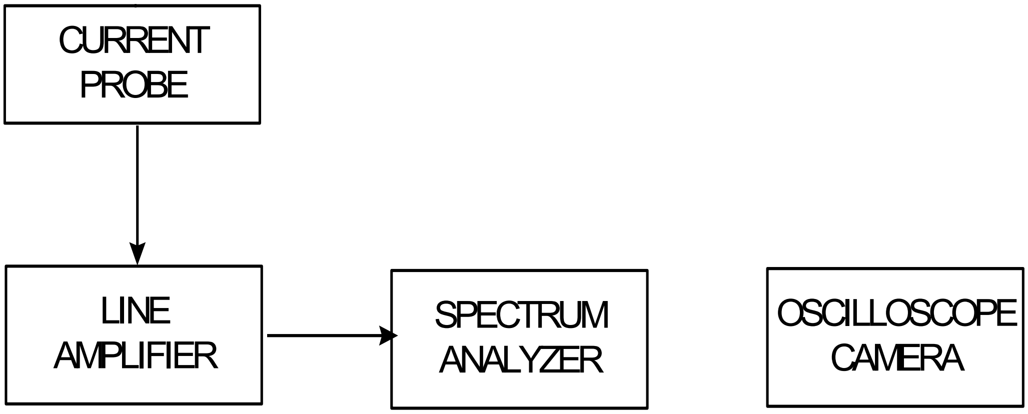


Figure 3.2: Block Diagram of the Low-Frequency Test Setup

A clamp-on Tektronix Model CT-4/P6021 current probe was provided to measure low-frequency EMI current on power and ground conductors. The frequency range of the probe was much larger than the frequency range of any measurement, but the full frequency range could not be utilized. The maximum amplitude of the low- or high-frequency components of EMI current and the lowest levels of EMI current occurring at higher frequencies exceeded the dynamic range of the instrumentation. This prevented simultaneous measurement of low- and high-frequency currents. A Hewlett-Packard Model 3561 spectrum analyzer was used to measure the amplitude of spectral components of low-frequency EMI. A WRV Model A-102 line amplifier was provided to measure very low levels of EMI current. The line amplifier was seldom used, since most components of EMI current were high enough to be examined directly by the spectrum analyzer. A Tektronix Model C-5C oscilloscope camera was used to photographically record examples of EMI current.

A second set of instrumentation was used to measure high-frequency EMI current. Figure 3.3 shows a block diagram of this instrumentation.

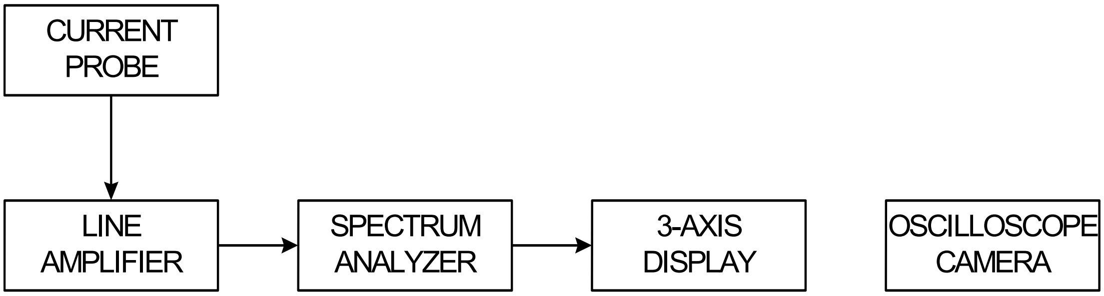


Figure 3.3: Block Diagram of High-Frequency Test Setup

A clamp-on Fischer Model F-70 current probe was used to measure EMI current over the frequency range of 100 kHz through 100 MHz. A calibration curve was provided to extend the frequency range of the probe down to 50 kHz. This provided some overlap in the frequency range of the low- and high-frequency instrumentation systems. A high dynamic-range line amplifier providing a gain of 20 dB was used to increase the measurement range of the setup to low values. A standard Hewlett Packard Model-141 spectrum analyzer was used to examine the spectral and temporal structure of conducted EMI current. An ELF Engineering 3-axis display was used to provide a time-history view of variations in the level and frequency of spectral components of EMI current and to allow examination of the temporal structure of impulsive components of the current. A Tektronix Model C-5C oscilloscope camera was used to photographically record examples of conducted EMI current.

Figure 3.4 shows the format of the time-history presentation. A small identification chart was added to each example of data presented at the lower left part of the data. The information in this chart is:

Line 1 Date of the measurement in yymmdd format, local time
Line 2 Site ID, UPS ID
Line 3 Conductor ID, UPS Load Information
Line 4 Center Frequency, Scan Width, IF Bandwidth, Scan Time
Line 5 Line Amplifier Gain, RF Attenuation, IF Gain
Line 6 Additional Information

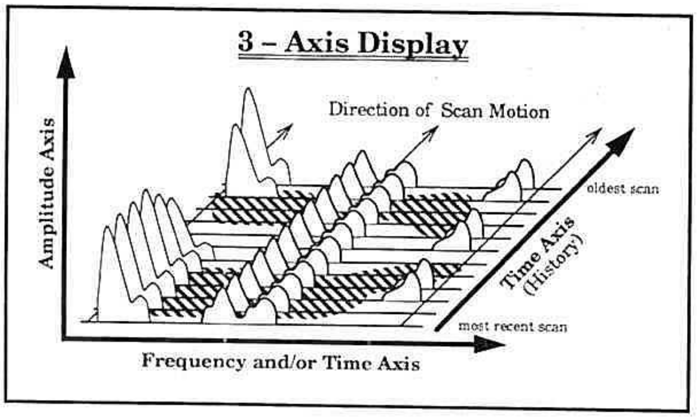


Figure 3.4: Format of the 3-Axis Display

B. MEASUREMENT CONFIGURATION

Figure 3.5 shows a photograph of the UPS under test. APPENDIX C presents a brief system description of the UPS systems. The UPS under-test is mounted on a small pallet and the input and output power conductors are shown in the photograph. Power cord adapters were used to allow for measurement of current on individual conductors of the power cord or the common-mode current on all conductors. A Fischer Model F-70 current probe is shown in the lower part of the view along with a section of cardboard used to insulate the probe from the cement floor of the test location.

Figure 3.5: UPS under Test

Combinations of tests were performed for purposes of this study. First, a calibration test was performed. A no-load test was then completed to examine the ambient current flowing on the power conductors. This was followed by an on-off test to compare the ambient levels of current with the UPS operating levels of current. Finally, a test was conducted with the UPS operating with a resistive load. These sequences of tests were performed on each UPS, first with the COTS configuration of the UPS, and second with a filter added to the UPS input and output conductors.

The detailed test procedures are provided in Appendix D. The calibration curves for the instrumentation are also provided in Appendix D.

C. TEST LOCATIONS

Two test locations in California were used for measurement. The first location was at a small, suburban, radio-receiving site located in Los Altos Hills, CA. This was a noise-quiet radio-receiving site used for special signal-reception tests. The second location was at the Signal Enhancement Laboratory in Spanagel Hall of the Naval Postgraduate School in Monterey, CA.

While the first site was considered to be a low-noise radio-receiving site, it was located fairly close to several high-power medium-frequency broadcast stations in the San Francisco region. Additionally, it was fed from overhead power lines although sources of noise from hardware on the power-line had been eliminated.

The second site was fed from underground power lines, but the facility contained laboratories with electrical and electronic equipment. Included were a large number of power-conversion devices, several motor controllers, a large number and variety of computers, data-processing equipment, and other sources. These sources impressed significant levels of ambient EMI current onto the power conductors.

D. UNMODIFIED UPS RESULTS

1. UPS Models Examined

A standard Model Ferrups FE/QFE 1.4 kVA UPS manufactured by the Best Corporation of Necedah WI was obtained for the investigation of EMI. In addition, a Model Ferrups FE/QFE 2.1 kVA was also available, as well as models from other manufacturers. All UPS units examined were new and in excellent operating condition.

Past experience with UPS units installed in field sites suggested the Model Ferrups FE/QFE 1.4 kVA generated less, but unknown amounts of EMI, compared to other models from Best or from many other manufacturers. Thus, EMI levels from the unmodified UPS presented in this thesis are ostensibly lower than many other similar units. Curiously interesting is that all UPS units investigated during this effort were advertised as meeting FCC Class A requirements. No UPS could be found meeting the more stringent FCC Class B requirements, which have stricter guidelines.

Conducted EMI was measured on all conductors penetrating the case of each UPS during normal operation. No additional conductors or test conductors were allowed to penetrate the case during the tests. The metal case provided with the UPS was in place during all measurements to minimize radiated effects. The UPS case was unmodified and it was installed in accordance with the manufacturer’s instructions.

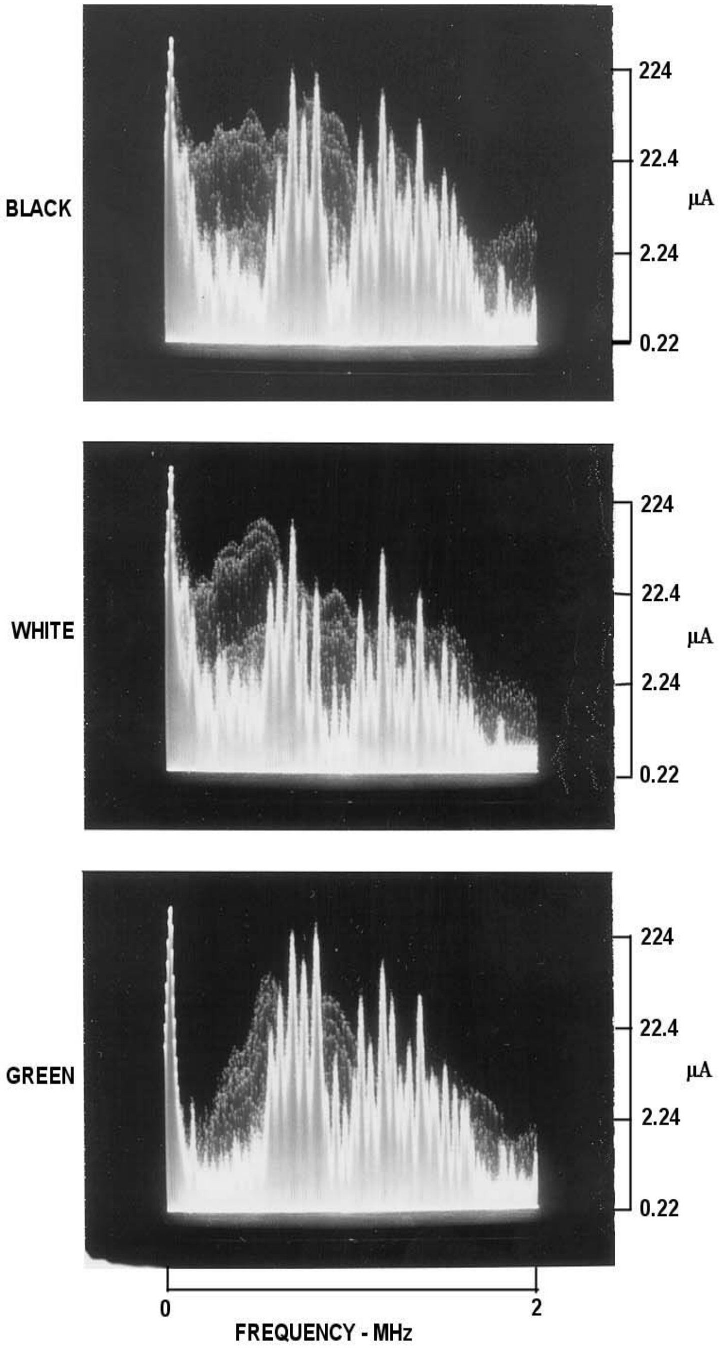
Tests were first made with the UPS as it was obtained from the manufacturer. The UPS as then modified in accordance with Barrier, Filter, Ground principles [Reference 5] and re-tested using the same instrumentation.

2. Ambient EMI Current

During the tests the ambient EMI current on the input power conductors proved very high at frequencies below 2 MHz, interfering with low-frequency measurements. Illustrating detrimental effects, EMI current was measured on input power conductors while the UPS was switched off. Figure 3.6 shows the spectral components of ambient current on the white, black, and green conductors of the UPS power cord.

The data in Figure 3.6 shows ambient current from two different sources flowing on all of the input power wires. Signals from nearby broadcast stations induced current into the overhead distribution line providing electrical power to the test facility. These signals are represented by the discrete-frequency spectral components shown in each of the three amplitude-vs.-frequency views. In addition, broadband impulsive noise current was also flowing on the power wires. The source of this current was later traced to a recently installed variable-speed drive on an air-conditioning system at a nearby residence receiving power from the same distribution line as the measurement facility.

Significant variations in the amplitude of the ambient impulsive current are shown across the 2-MHz band of the data in Figure 3.6, including peaks and nulls. The peaks and nulls suggest that resonance conditions existed in the power conductors, but this is to be expected since the conductors are electrically long at the frequency range of the data. The amplitude of the ambient current can be scaled from the data for any desired frequency, but a single value of current amplitude cannot be used to provide a meaningful or complete measure of amplitude. Thus, a meter reading of the EMI current is not feasible.



000106 1025, 1015, 10130
LAH, BEST UPS, SWITCH OFF, NO LOAD
BLACK, INPUT PWR, AMBIENT
1M, 2M, 10 k, 100 ms
F-70, +20, 0, -20

Figure 3-6: Ambient EMI Current on Input Power Cord Conductors

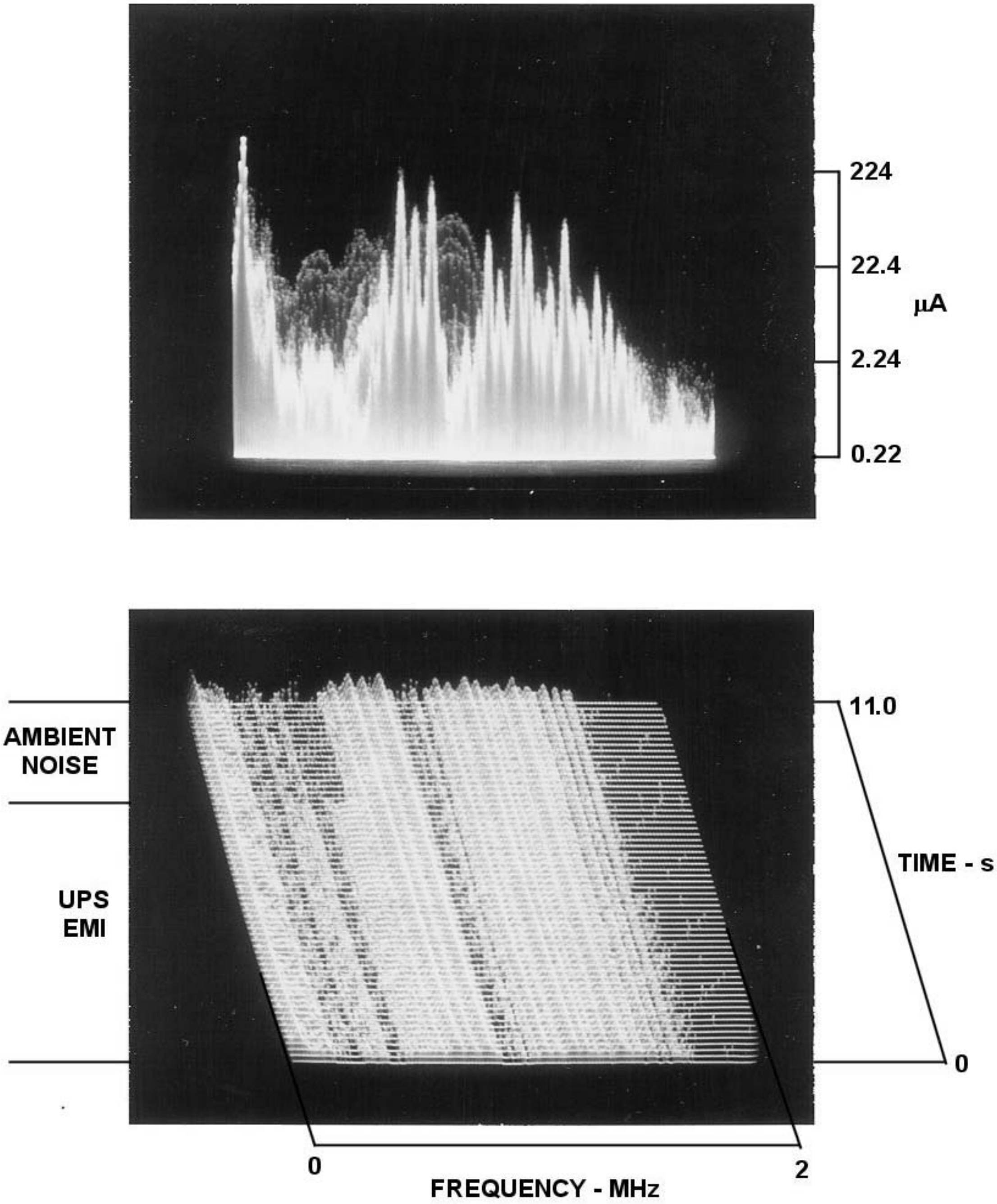
The high ambient current on power conductors is one factor that must be considered during such tests. Impulsive noise from power-conversion equipment based on solid-state switching techniques is now encountered in most facilities. For critical tests it is necessary to use a diesel-powered generator to avoid contaminated power. The amplitude of the ambient current from these two sources must be ignored in the evaluation of EMI from the UPS.

3. EMI Current, Input Conductors

The UPS was then turned on and the battery was allowed to charge to its full level. When the battery was fully charged, a 300-watt resistive load was switched on. (A resistive load was used to avoid the harmonics and impulsive EMI current generated by loads containing nonlinear devices such as switching power supplies, motor controllers, computers, and other similar devices.) A 50-ft power cord was used between the UPS and the resistive load to provide an electrically long length of conductor between the UPS and the load. EMI current was then measured on the three input power conductors and the three output conductors. The broadband impulsive current from the switching source was somewhat similar for the black and white conductors in that the amplitude was high from about 10 kHz up to 1 MHz. It decreased in amplitude and became quite low at 2 MHz. The current on the green-wire ground conductor was low at approximately 100 kHz, reaching peaks in the range of 0.5 to 1 MHz. The current then decreased in amplitude above 1 MHz and was quite low at 2 MHz.

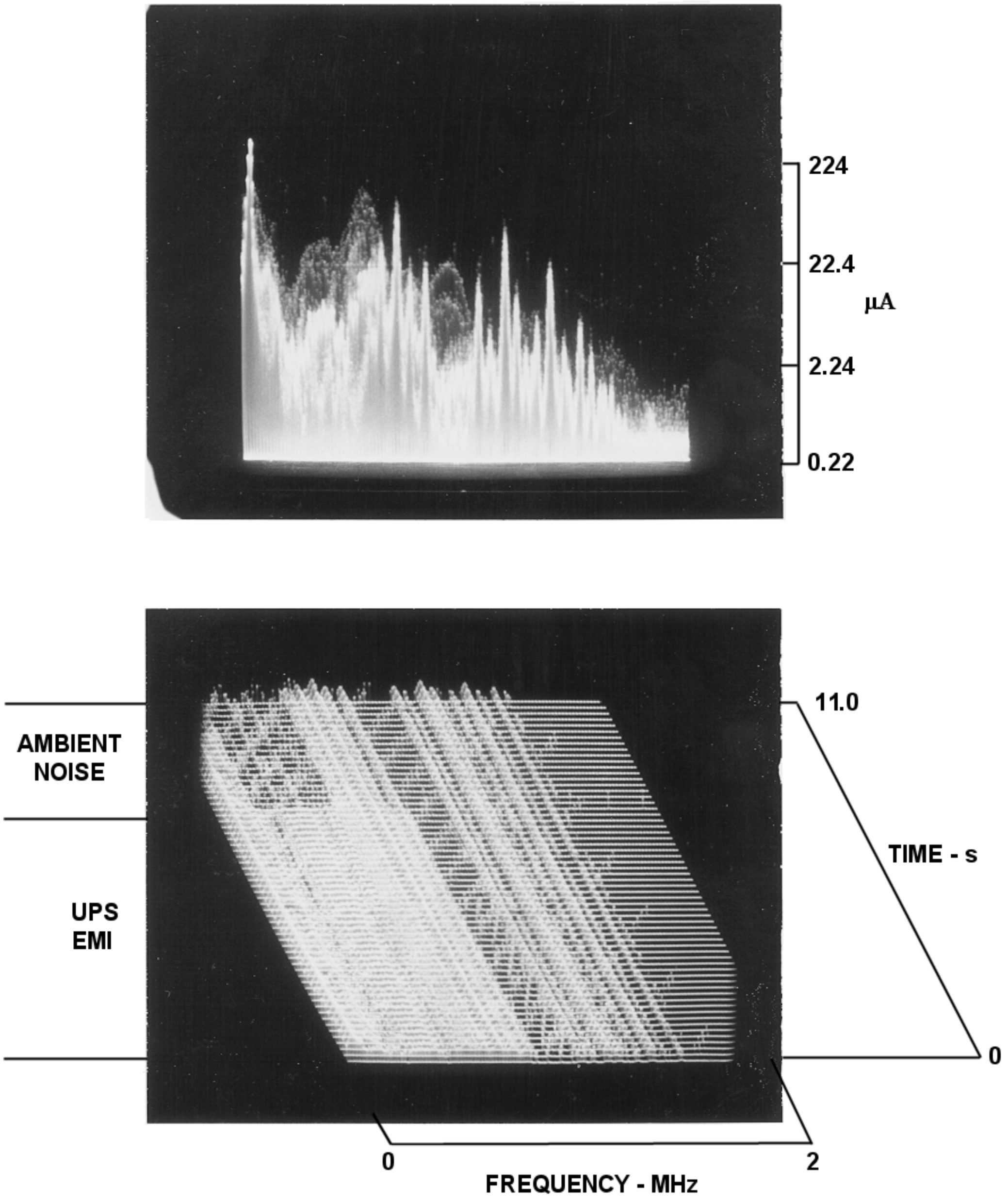
Broadcast-band signals were found on all three conductors. The presence of the broadcast-band signals suggest that a site with an underground power feed would be more suitable since an underground feed would not act as a receiving antenna for such signals.

Figures 3.7 through 3.9 show the low-frequency ambient and UPS-generated EMI current flowing on the input power conductors when the UPS was operated. Both the amplitude-vs.-frequency and the time-history views are provided to show the coarse-scale temporal of impulsive noise. The upper part of the time-history view shows the ambient



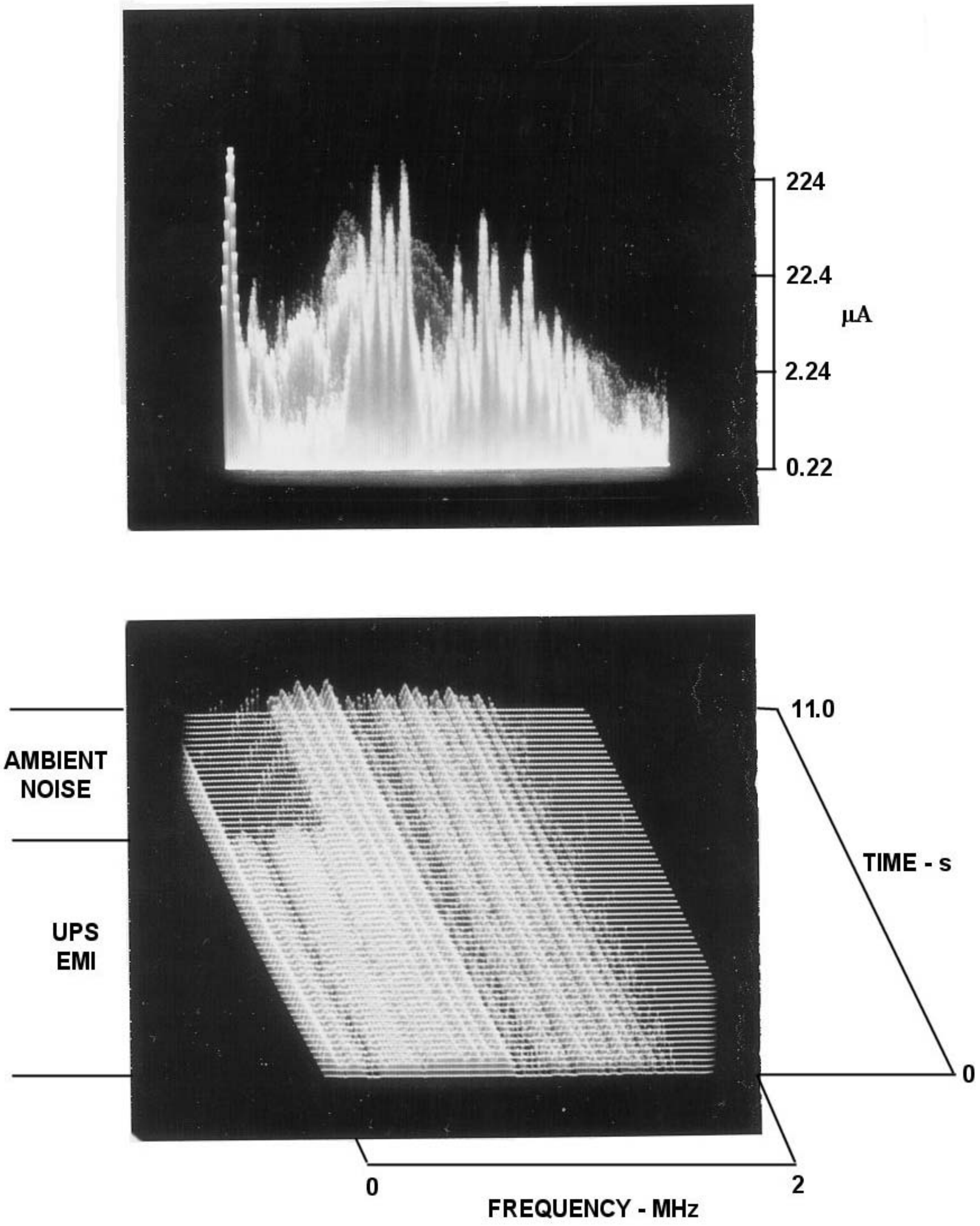
000106 1100
LAH, BEST UPS, ON, CHARGING, NO LOAD
BLACK, INPUT PWR
1M, 2M, 10 k, 100 ms
F-70. +20, 0, -20

Figure 3.7: Ambient and UPS EMI Current on the Black Conductor, Low Frequencies



000106 1050
LAH, BEST UPS, OFF/ON, CHARGING, NO LOAD
WHITE, INPUT PWR,
1 M, 2M, 10k, 100 ms
F-70, +20, 0, -20

Figure 3.8: Ambient and UPS EMI Current on the White Conductor, Low Frequencies



000106 1040
LAH, BEST UPS, OFF/ON, CHARGING, NO LOAD
GREEN, INPUT PWR,
1 M, 2M, 10k, 100 ms
F-70, +20, 0, -20

Figure 3.9: Ambient and UPS EMI Current on the Green Conductor, Low Frequencies

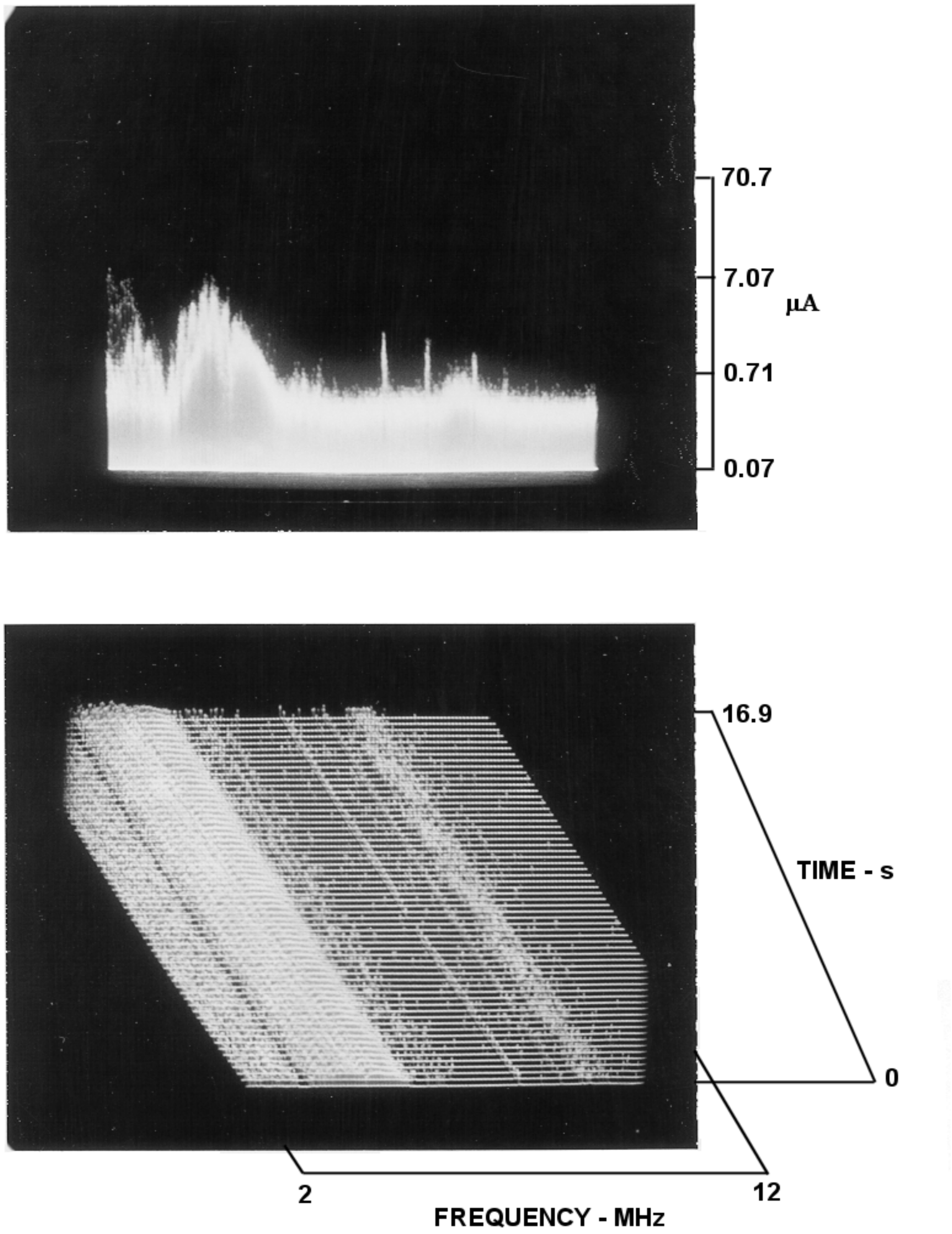
current. The display was temporarily placed into a “freeze-mode” after portraying a short period of ambient current to allow the operation of the UPS to stabilize. The display was then unfrozen to show the additional EMI current generated by the UPS. The spectral structure of both the ambient current and the UPS-generated impulsive current is shown in the amplitude-vs.-frequency view.

Figure 3.7 shows the low-frequency current flowing on the black input power conductor over the frequency range of 0 to 2 MHz. In this case, ambient noise was higher than the UPS generated noise. It reached a sharp peak of about 20 μA near 0.5 MHz. It is impossible to read the current levels in the part of the medium-wave broadcast band containing closely-packed signals with the wide frequency span used to generate the data in Figure 3.7, and it is necessary to search between broadcast-band signals by employing a narrow scan width. Figure 3.8 shows ambient and UPS-generated current on the white input conductor and Figure 3.9 shows the ambient and UPS-generated current on the green-ground conductor of the power cord.

The high-frequency components at 2 to 12 MHz of EMI current flowing on the conductors of the input power cord were examined next. In this case, the ambient currents, with minor exceptions, were well below the UPS-generated levels and in most cases below the signal-detection sensitivity of the instrumentation.

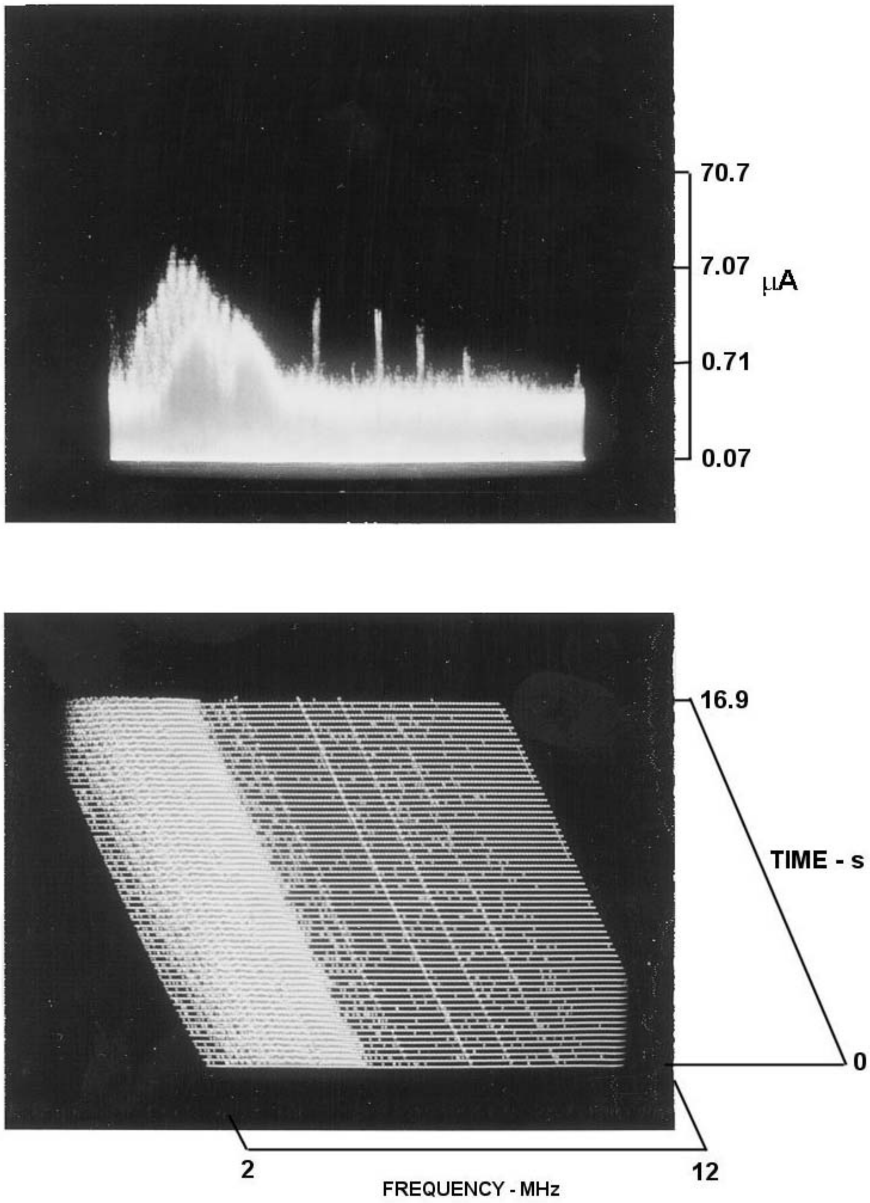
Figures 3.10 through 3.12 show EMI current levels on the black, white, and green conductors. The presentation is identical to that used for the low-frequency current measurements except for the frequency span.

Figure 3.10 shows ambient and EMI current flowing on the black conductor over the frequency range of 2-to-12 MHz. The current fell below instrumentation sensitivity at frequencies above 12 MHz for the particular model of UPS being tested, therefore higher frequency data is not shown. A small amount of ambient current is shown at the extreme left edge of the frequency range. The broad peak in current centered at about 6 MHz is from the UPS, reaching a level of about 5 μA. A smaller peak in EMI current was found near 12.5 MHz. The four discrete-frequency spectral components in the upper



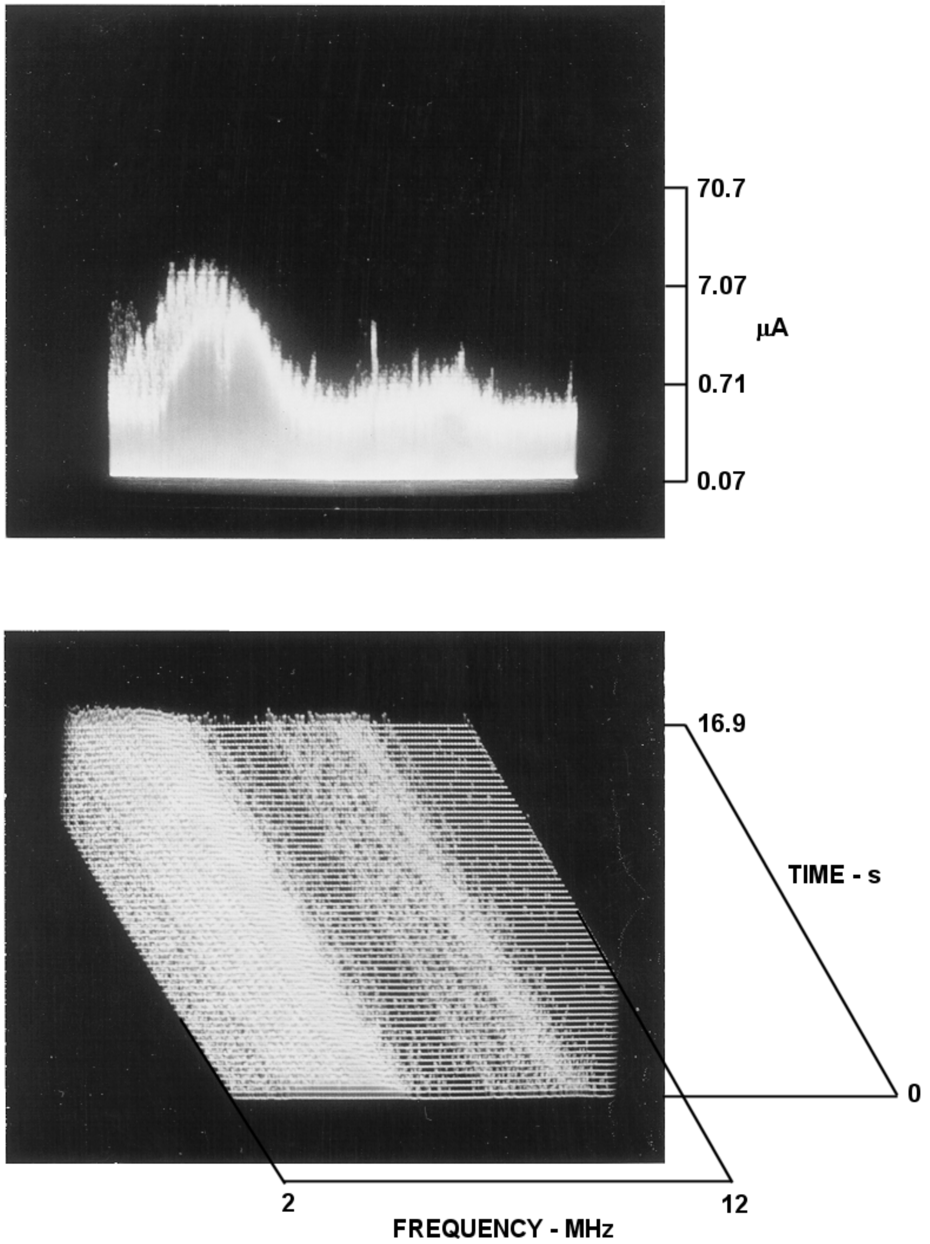
000106 1345
LAH, BEST UPS, ON, CHARGING, LOAD
BLACK, INPUT PWR
7M, 10M, 10 k, 200 ms
F-70. +20, 0, -30

Figure 3.10: Ambient and UPS EMI Current on the Black Conductor, High Frequencies



000106 1355
LAH, BEST UPS, ON, CHARGING, LOAD
WHITE, INPUT PWR
7M, 10M, 10 k, 200 ms
F-70, +20, 0, -30

Figure 3.11: Ambient and UPS EMI Current on the White Conductor, High Frequencies



000106 1350
LAH, BEST UPS, ON, CHARGING, LOAD
GREEN, INPUT PWR
7M, 10M, 10 k, 200 ms
F-70, +20, 0, -30

Figure 3.12: Ambient and UPS EMI Current on the Green Conductor, High Frequencies

half of the frequency range are HF signals collected by the power wiring. These signals were present regardless of whether the UPS was switched off, or on, while testing.

Figure 3.11 shows the ambient and EMI current flowing on the white conductor over the frequency range of 2-to-12 MHz. The ambient current at the low end of the frequency span was lower than observed with the black conductor, while the broad peak in UPS-generated EMI current was centered somewhat lower in frequency at about 4 MHz. The amplitude proved somewhat higher at 11 µA. The higher-frequency peak found on the black conductor did not appear on the white conductor. The four HF signals did appear in the data.

Figure 3.12 shows ambient and EMI current flowing on the green-wire ground conductor of the power cord. A small amount of ambient current was found at the extreme low end of the frequency scale. The broad spectral peak in EMI current shown near 4 MHz is wider than for the other conductors, and the measurable EMI current extended upward to 12 MHz. Narrow peaks and nulls in the amplitude of UPS-generated EMI current are shown for all conductors suggesting resonant conditions on the power conductors.

4. EMI Current, Output Conductors

A similar set of measurements was made on the output conductors running from the UPS to the resistive load. Figures 3.13 through 3.15 provide levels of EMI current on the output conductors running from the UPS to the resistive load. The data shows the current over the frequency range of 0 to 2 MHz although the amplitude readings are calibrated only over the 0.1 to 2 MHz portion of the data. In this case the ambient current from impulsive noise was below the levels of UPS-generated current, while discrete-frequency signals from the local medium-frequency broadcast-band stations appear in the data and must be ignored. Figure 3.13 shows EMI current flowing on the black output conductor. The slanting lines in the time-history view provide a convenient means to separate the UPS-

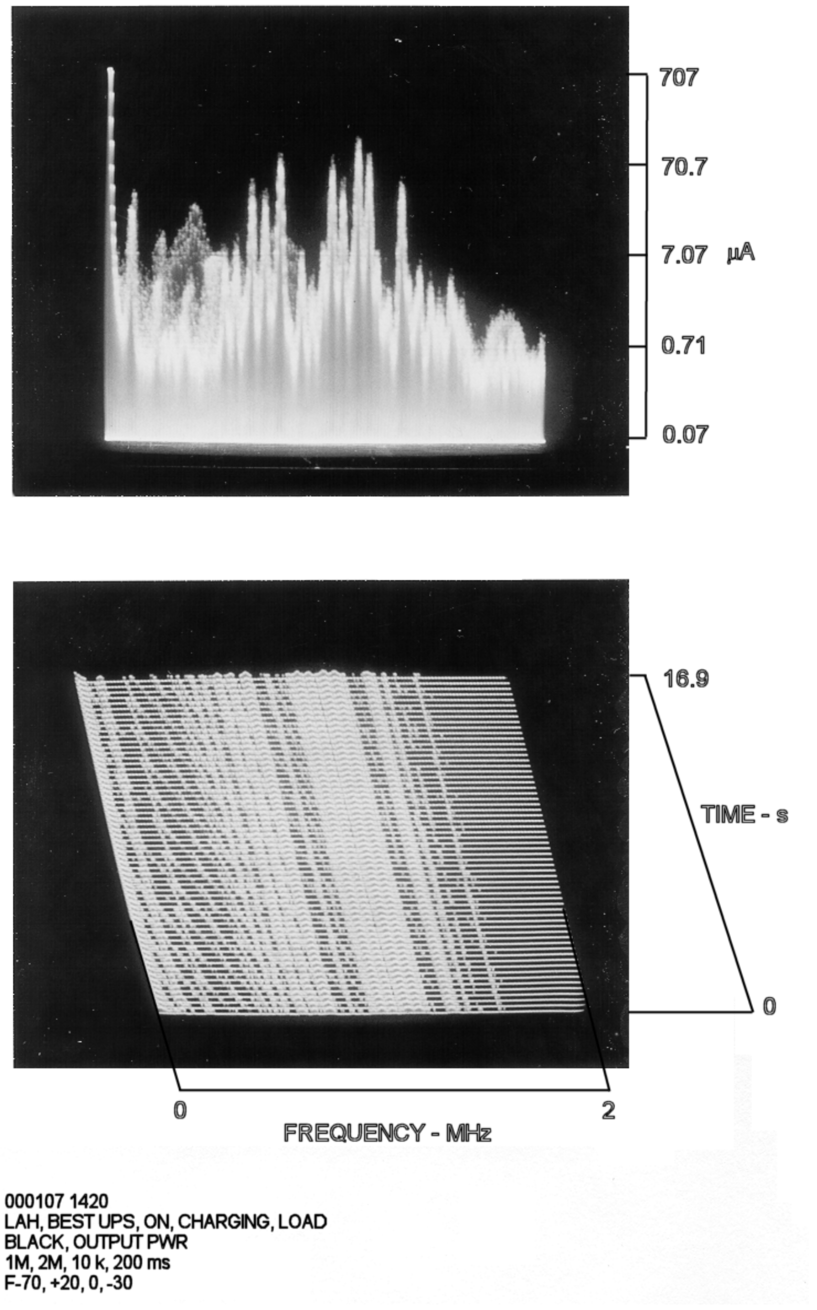
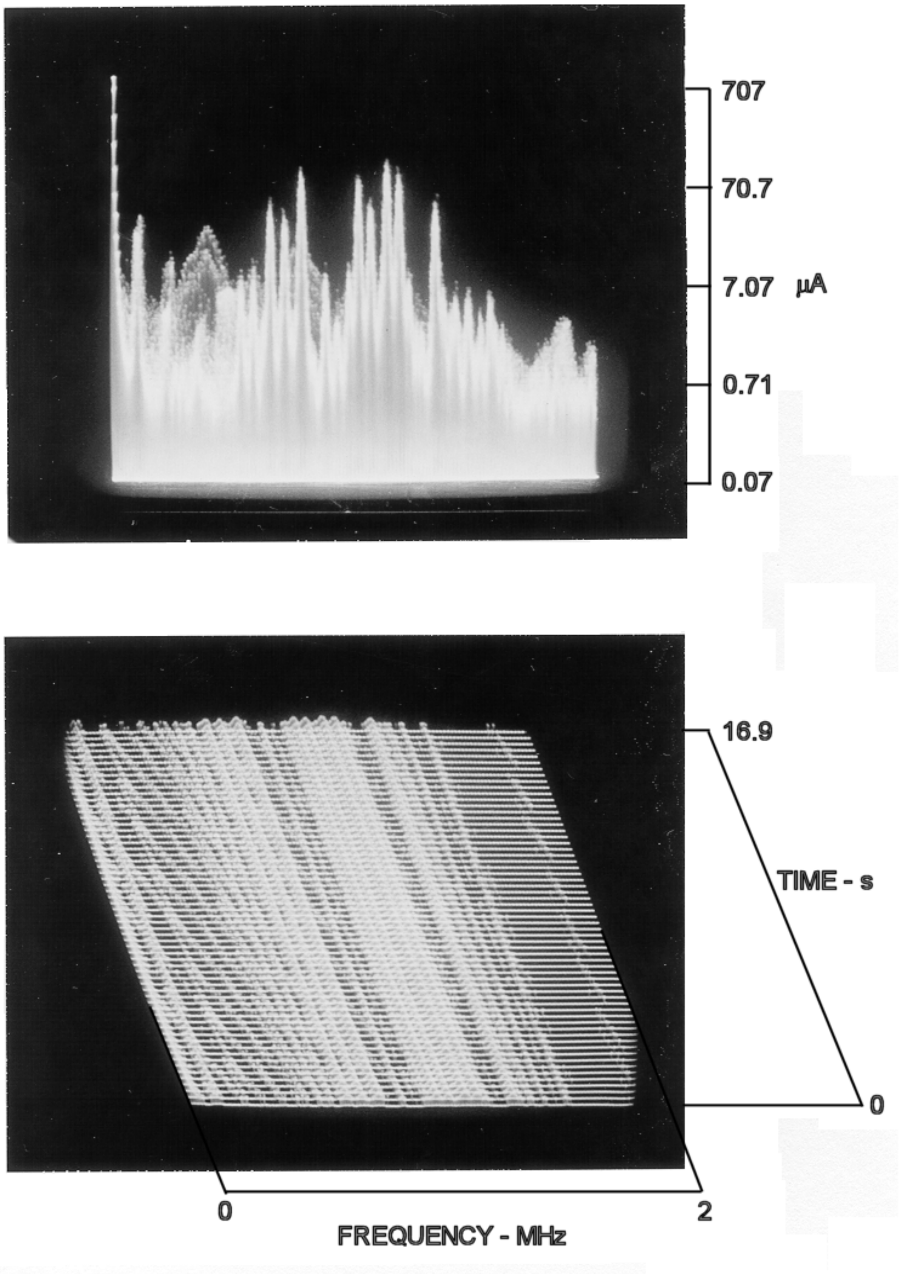
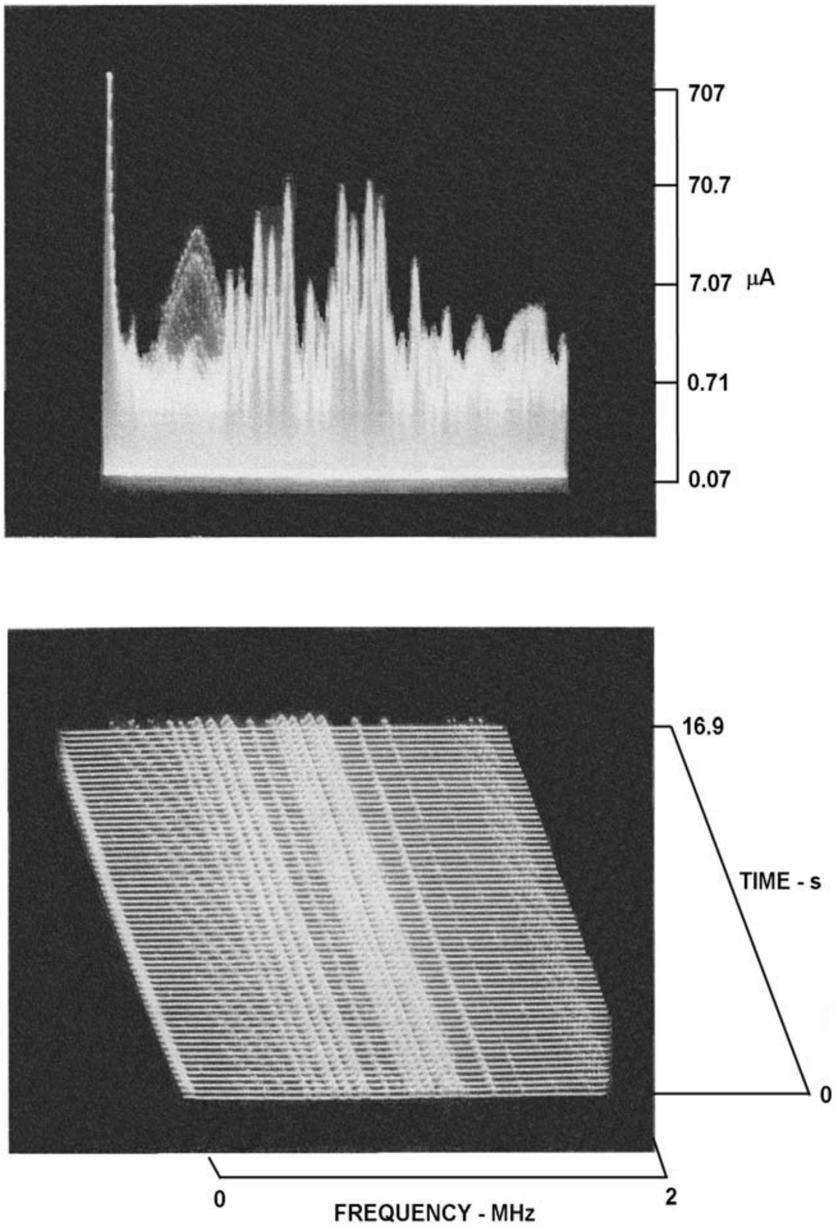


Figure 3.13: UPS EMI Current on the Black Output Conductor, Low Frequencies



000107 1410
LAH, BEST UPS, ON, CHARGING, LOAD
WHITE, OUTPUT PWR
1M, 2M, 10 k, 200 ms
F-70, +20, 0, -30

Figure 3.14: UPS EMI Current on the White Output Conductor, Low Frequencies



000107 1415
LAH, BEST UPS, ON, CHARGING, LOAD
WHITE, OUTPUT PWR
1M, 2M, 10 k, 200 ms
F-70, +20, 0, -30

Figure 3.15: UPS EMI Current on the Green Output Conductor, Low Frequencies

generated noise from the broadcast-band signals. A peak in the UPS-generated noise is shown at 0.4 MHz. Lower-level peaks in EMI current can be distinguished throughout the frequency range including a distinct peak near the upper end of the frequency scale at 1.7 to 1.8 MHz.

Figure 3.14 shows EMI current flowing on the white output power conductor. The results are similar to those obtained from the black conductor.

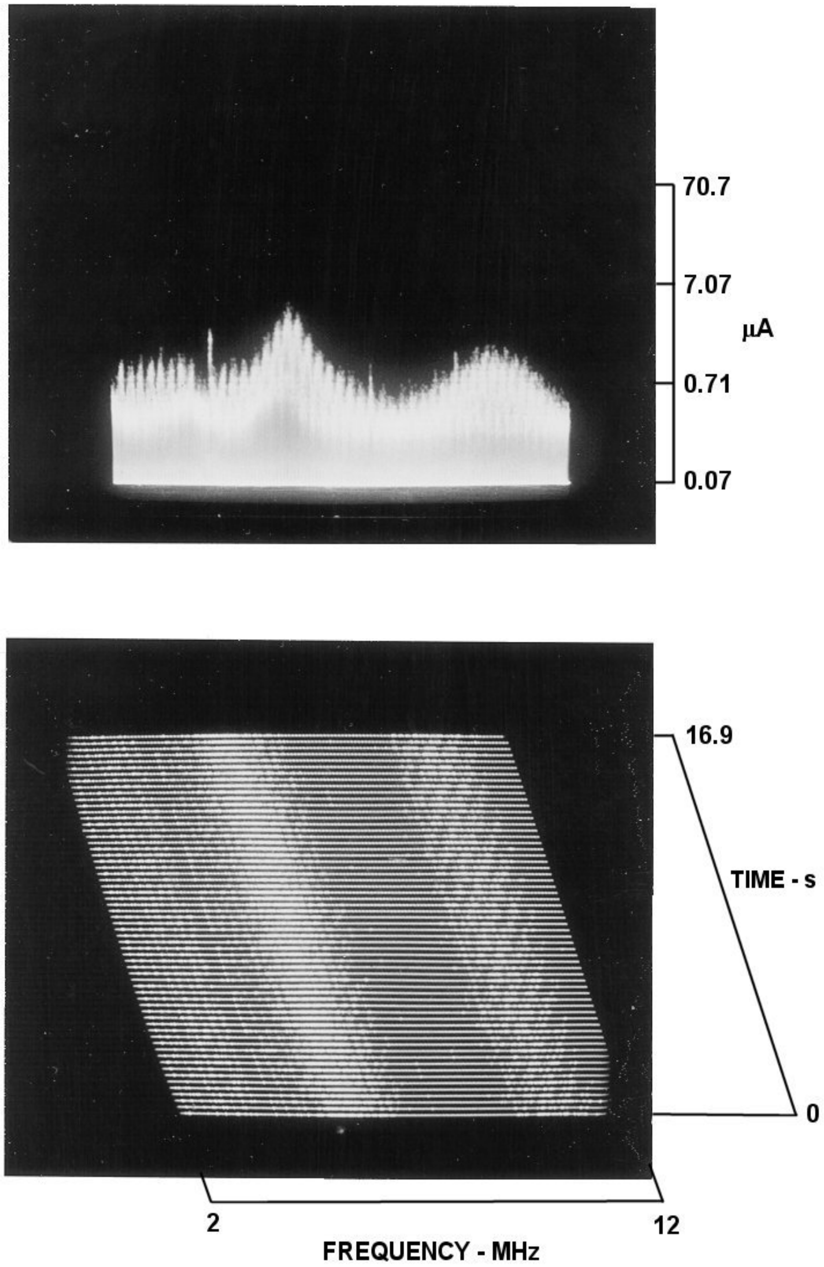
Figure 3.15 shows EMI current flowing on the green-wire ground conductor running from the UPS to the resistive load. The view is less cluttered than for the black and white conductors because less ambient current from broadcast signals is picked up by this conductor.

Distinctive spectral peaks and nulls in UPS-generated current appear on all conductors. This is an indicator that resonance conditions exist on all conductors from a combination of conductor length and the impedance of UPS components in the output paths. The peaks and nulls in the current makes it impossible to describe the amplitude of the EMI current with a single number; however, a value of UPS current can be provided at any selected frequency.

EMI and ambient current flowing on the output conductors over the frequency range of 2 to 12 MHz was also examined. Figures 3.16 through 3.18 show the UPS-generated EMI current on the conductors of the output power cord. In this case most of the ambient current was well below the UPS-generated EMI current and only a small amount of ambient current appears in the data.

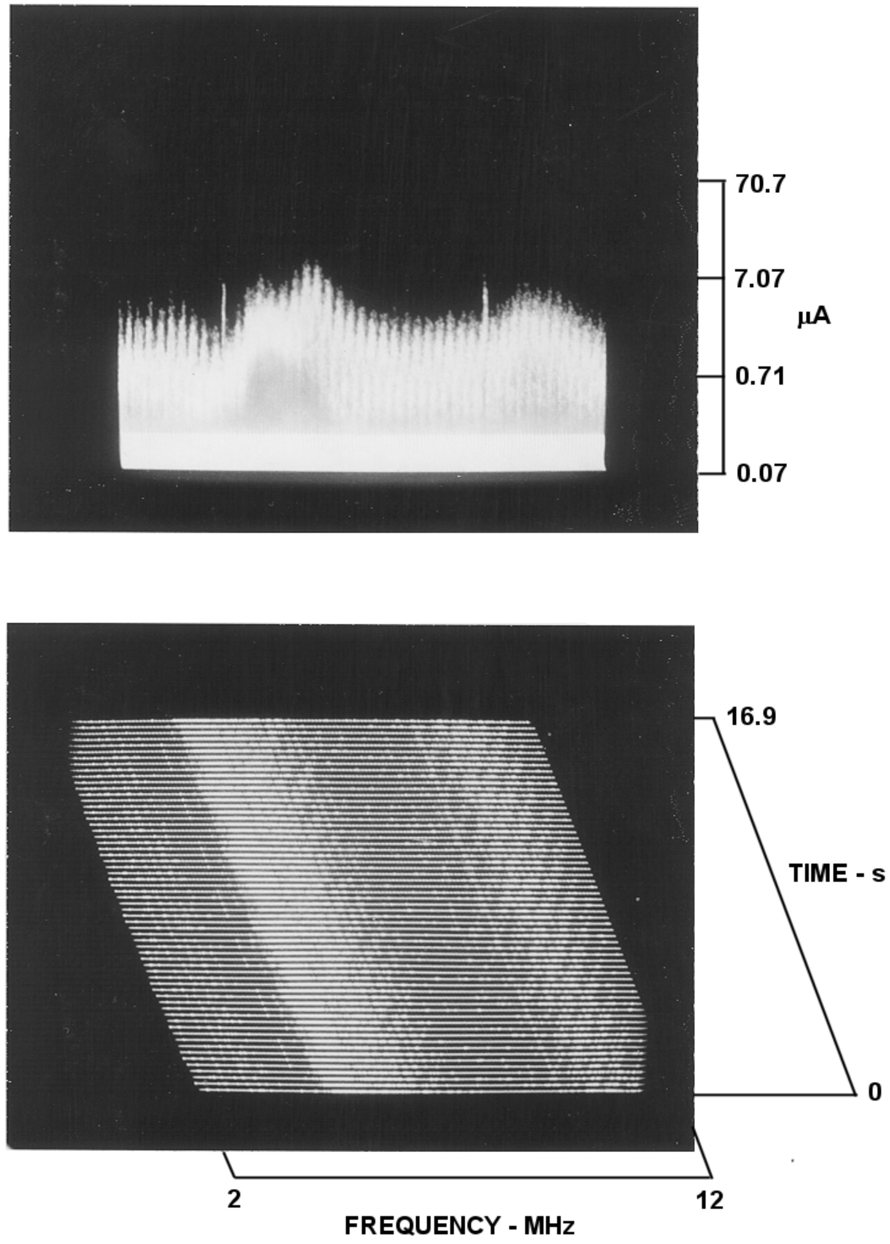
Figure 3.16 shows the current on the black output conductor over the 2- to 12-MHz frequency band. Figure 3.17 shows the current on the white output conductor and Figure 3.18 shows the current on the green-wire ground conductor.

An examination of the data from the three output power conductors shows two distinct variations in amplitude with frequency. Broad peaks and nulls in the amplitude of the UPS-generated EMI current were found on all conductors.



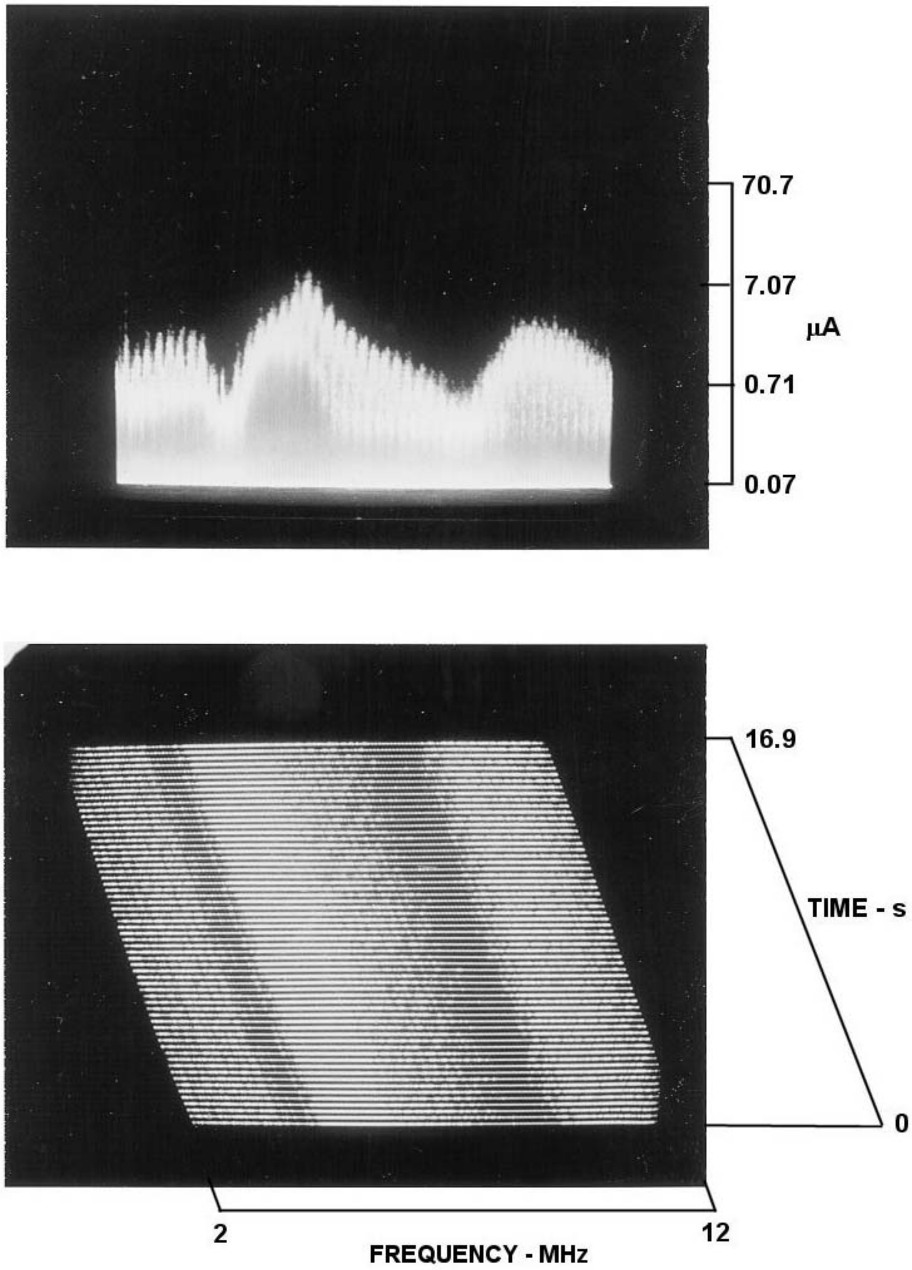
000106 1550
BEST UPS, ON, CHARGING, LOAD
BLACK, OUTPUT PWR
7M, 10M, 100 k, 200 ms
F-70, +20, 0, -30

Figure 3.16: UPS EMI Current on the Black Output Conductor, High Frequencies



000106 1535
LAH, BEST UPS, ON, CHARGING, LOAD
WHITE, OUTPUT PWR
7M, 10M, 10 k, 200 ms
F-70, +20, 0, -30

Figure 3.17: UPS EMI Current on the White Output Conductor, High Frequencies



000106 1555
BEST UPS, ON, CHARGING, LOAD
GREEN, OUTPUT PWR
7M, 10M, 100 k, 200 ms
F-70, +20, 0, -30

Figure 3.18: UPS EMI Current on the Green Output Conductor, High Frequencies

In addition, narrow peaks and nulls also exist in the data. This indicates that two distinct resonance phenomena exist on the output conductors. These peaks and nulls prevent providing a single number for the UPS-generated EMI current although a value can be provided for any specific frequency. Two discrete-frequency peaks in ambient current appear on the black and white conductors at frequencies near 4 and 8 MHz. These signals were from nearby HF transmitter facilities; therefore, they can be ignored.

E. MODIFIED UPS RESULTS

1. Modifications

Standard COTS filters were added to the input and output power conductors in a Barrier, Filter, Ground (BFG) Configuration. A description of EMI filters is given in Appendix E. Figure 3.19 shows the configuration employed to allow 60-Hz current to flow into and out of the UPS.

The filters provided high impedance to the flow of high-frequency EMI current through and then out of the UPS on the black and white power conductors at frequencies above its cutoff frequency. Of special concern was the prevention of UPS-generated EMI current from escaping the UPS case on the green-wire ground while still maintaining the required electrical safety requirements of the National Electric Code. If EMI current was allowed to flow on the green-wire ground, it would be inductively coupled back onto the black, white, and other conductors thereby negating the effectiveness of the filtering provided on the black and white conductors.

The flow of current on the green wire was limited to low frequencies by connecting the external green-wire ground to the outside surface of the UPS case and the internal green-wire ground to the interior of the UPS Case. This type of connection was provided by the metal shell of the COTS filters.

Figure 3-20 shows a photograph of the modified UPS. Both the input and the output filters were added to the back panel of the UPS. Since there was room inside the UPS case for the filters, the modification was easy to implement.

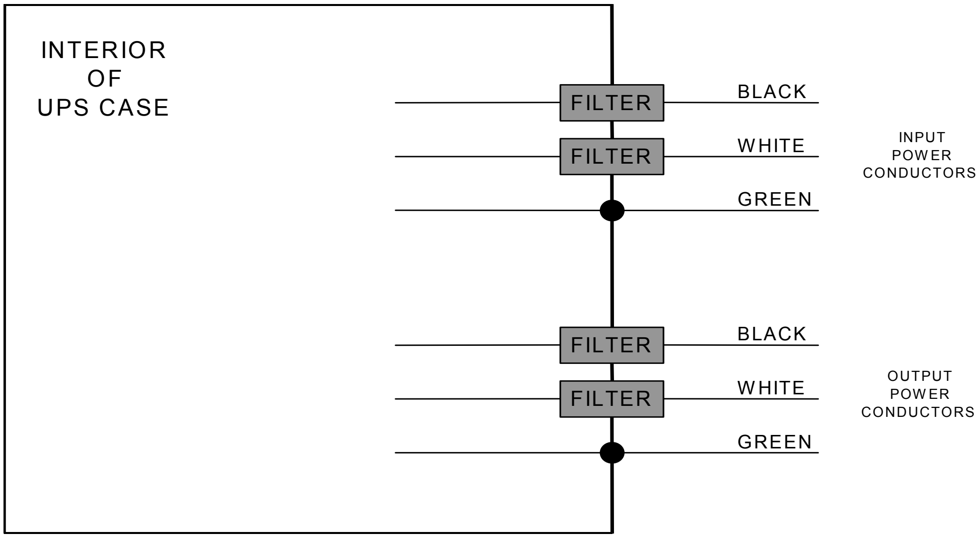


Figure 3.19: Filter Configuration

Figure 3.20: Rear Panel of the Modified UPS

2. Modified UPS Results

Measurements on the modified UPS were made at the laboratory facilities of the Signal Enhancement Laboratory of the Naval Postgraduate School. Unfortunately, the ambient EMI level at this facility was too high to obtain good low-frequency EMI data.

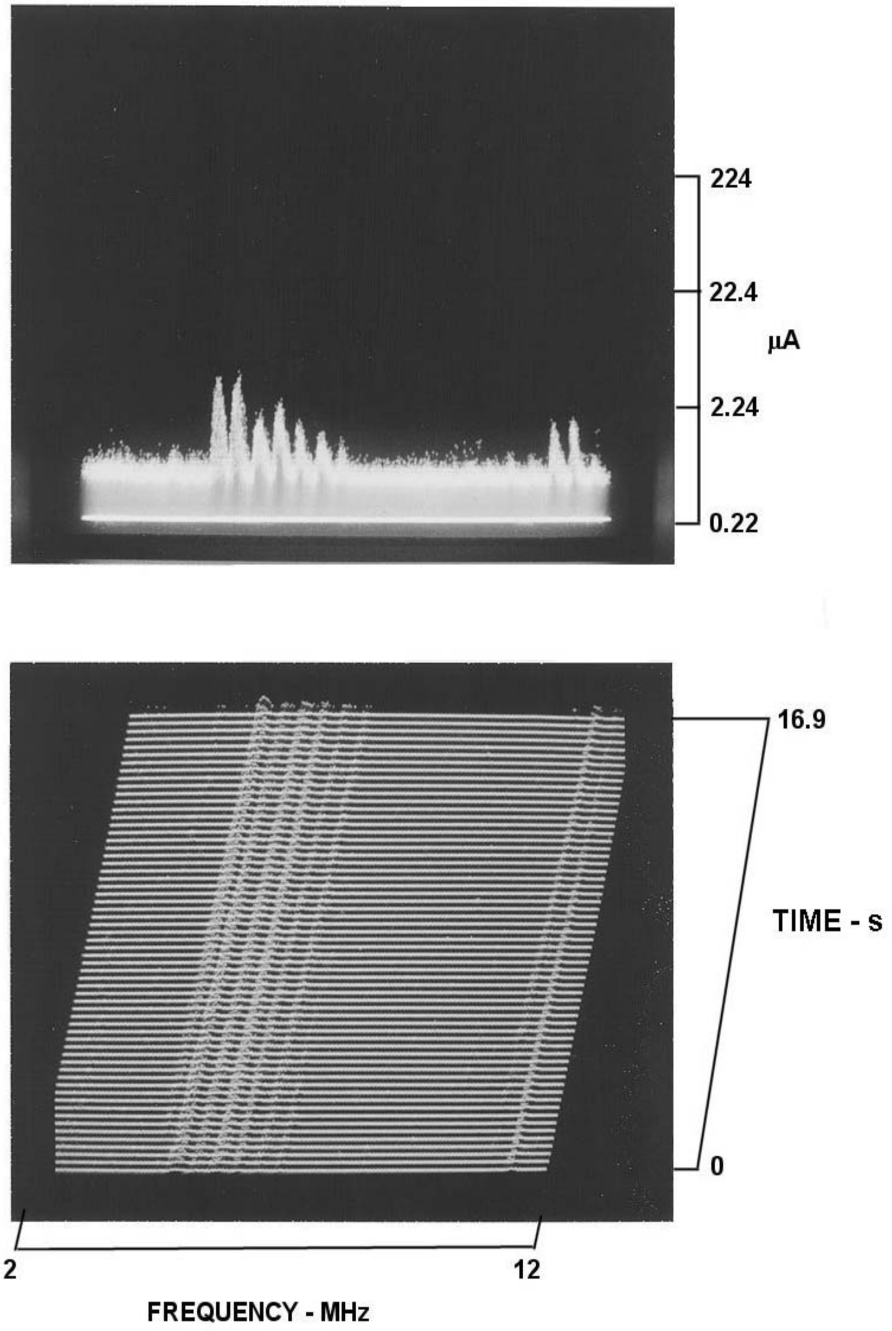
The presence of many other sources of EMI in the building including variable-speed motor controllers, many computers, switching power supplies, and other digital devices prevented low-frequency data from being obtained. The ambient interference was sufficiently high, making the normal reception of radio signals impossible from very low frequencies to above 30 MHz. In addition, instances of the corruption of data lines with COTS type data-processing equipment was common in the facility when certain power-conversion devices were operated. Reasonable high-frequency data was obtained in spite of the high ambient EMI levels. Figures 3.21 through 3.23 shows the high-frequency EMI current on the UPS input conductors over the 2- to 12-MHz band.

Figure 3.21 shows current flowing on the black input conductor. Some small peaks in current are shown in the data, but these were all ambient current which was present whether the UPS was switched on or off during testing.

Figure 3.22 shows the high-frequency EMI current flowing in the white input conductor. Again, all spectral components shown in this view were caused by other devices operating in the test facility and not from the UPS under test. No low-level spectral-component of current could be traced to the UPS.

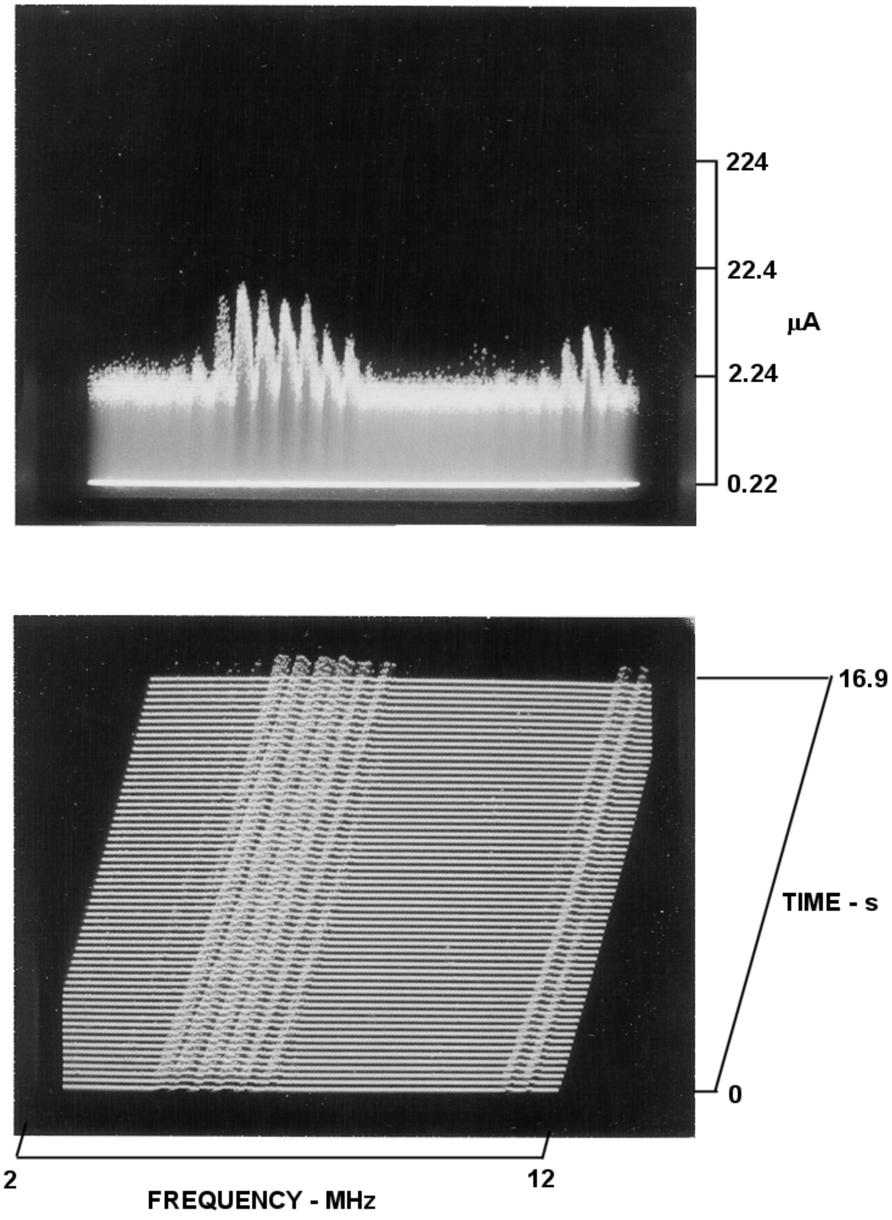
Figure 3.23 shows the high-frequency EMI current flowing on the input green-wire ground conductor of the UPS power cord. Once again, the current shown in the data was from other sources, and no spectral component could be traced to the UPS under test. The lack of high-frequency UPS-generated current on the green-wire ground shows the effectiveness of the green-wire ground connection employed in the UPS modifications. This connection provided a conducting path at low-frequencies, meeting the requirements of the National Electric Code, and it employed the shielding provided by the metal UPS case to prevent the flow of UPS-generated EMI current to the outside green-wire ground conductor.

Figures 3.24 through 3.26 shows the high-frequency EMI current flowing on the output conductors of the modified UPS. Figure 3.24 shows the current flowing on the



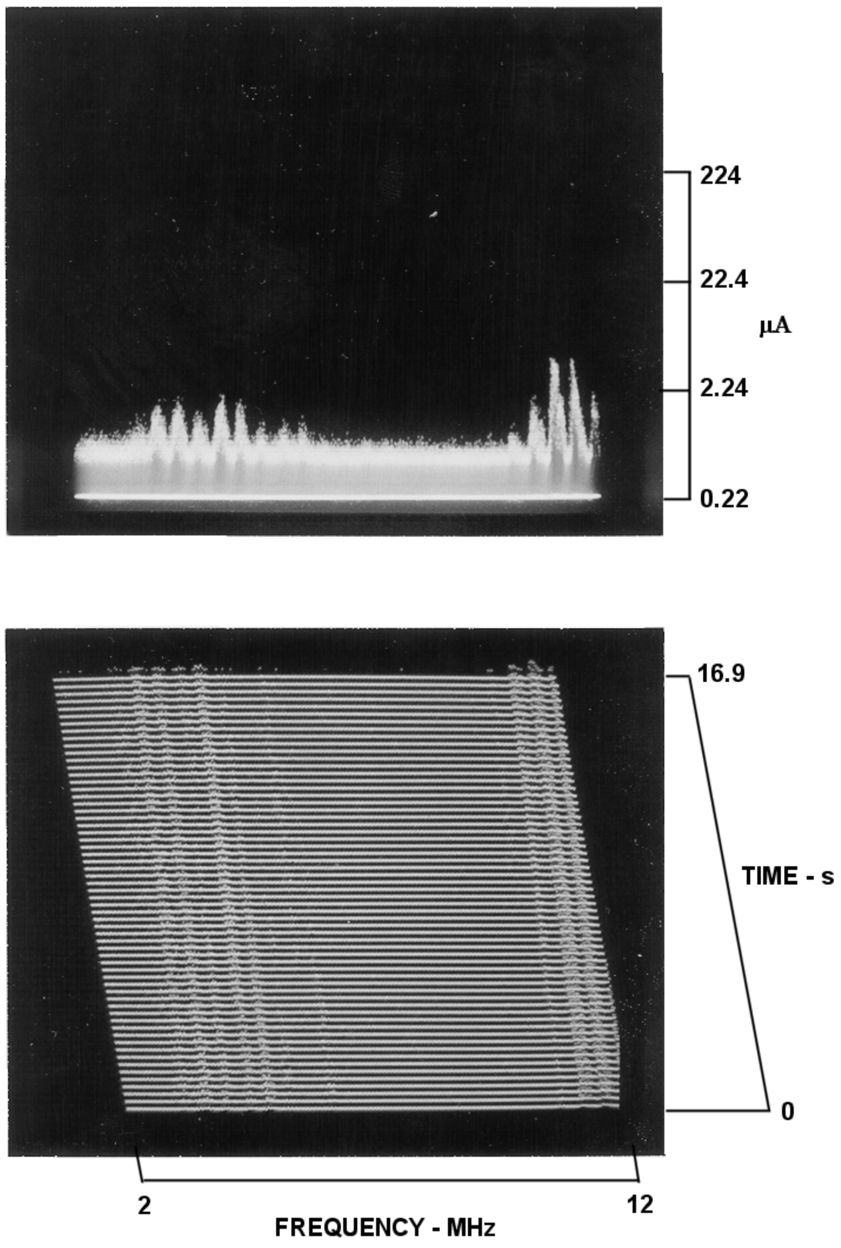
000818 1536
NPS, MODIFIED BEST UPS, ON CHARGING, LOAD
BLACK, INPUT PWR
7M, 10M, 100 k, 200 ms
F-70, +20, 0, -20

Figure 3.21: High-frequency EMI Current on the Black Input Conductor, Modified UPS



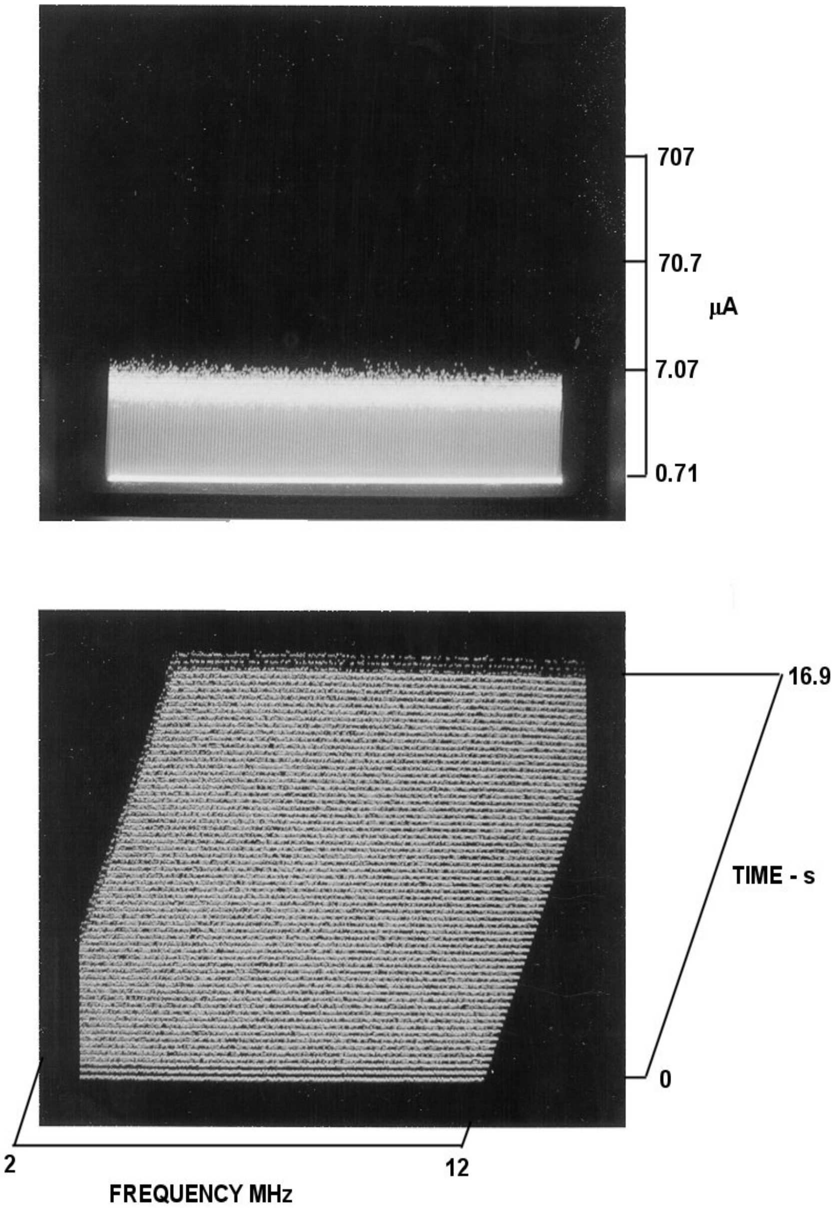
000818 1548
NPS, MODIFIED BEST UPS, ON, CHARGING, LOAD
WHITE, INPUT PWR
7M, 10M, 100 k, 200 ms
F-70, +20, 0, -20

Figure 3.22: High-frequency EMI Current on the White Input Conductor, Modified UPS



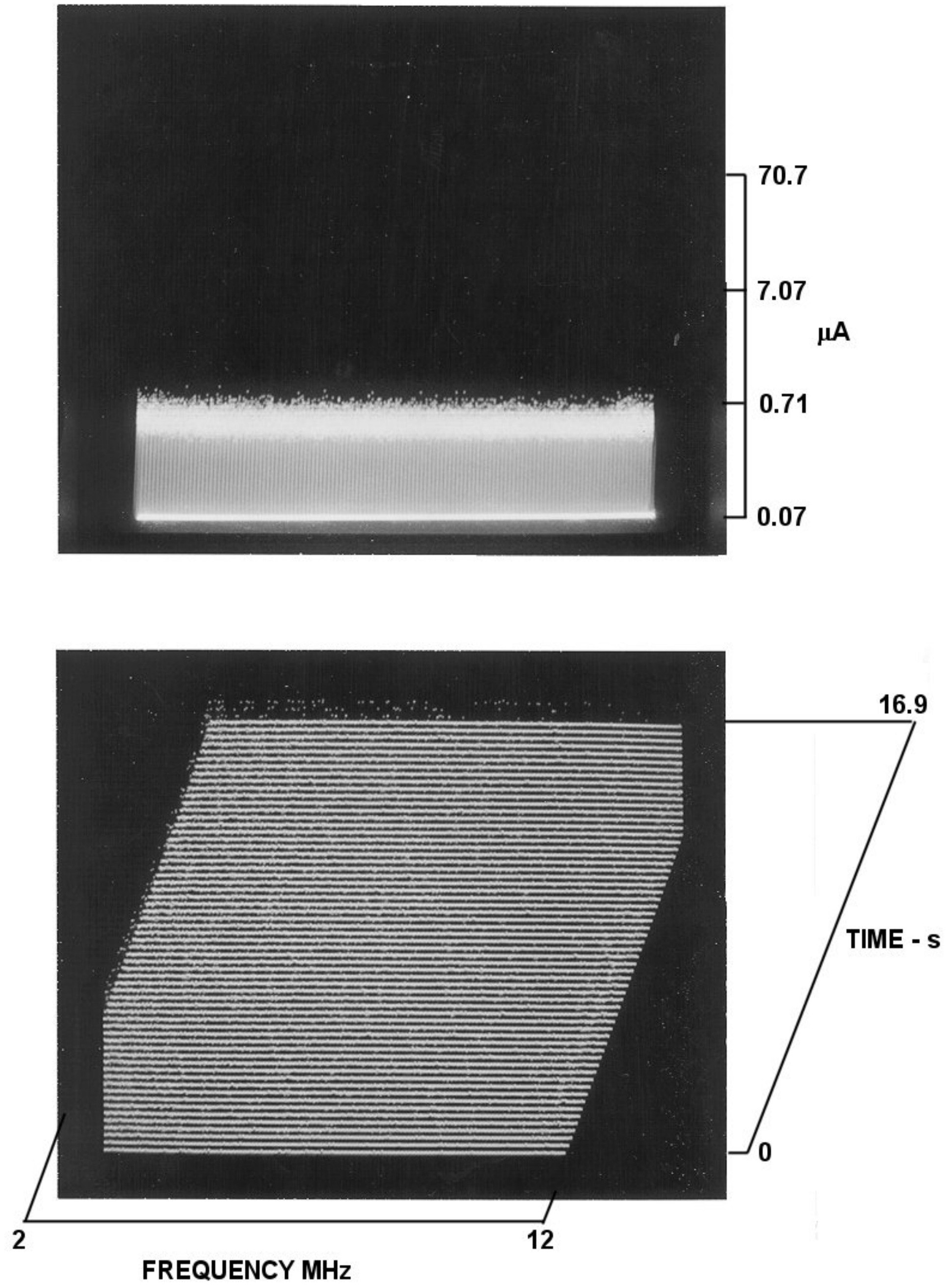
000818 1534
NPS, MODIFIED BEST UPS, ON, CHARGING, LOAD
GREEN, INPUT PWR
7M, 10M, 100 k, 200 ms
F-70, +20, 0, -20

Figure 3.23: High-frequency EMI Current on the Green Input Conductor, Modified UPS



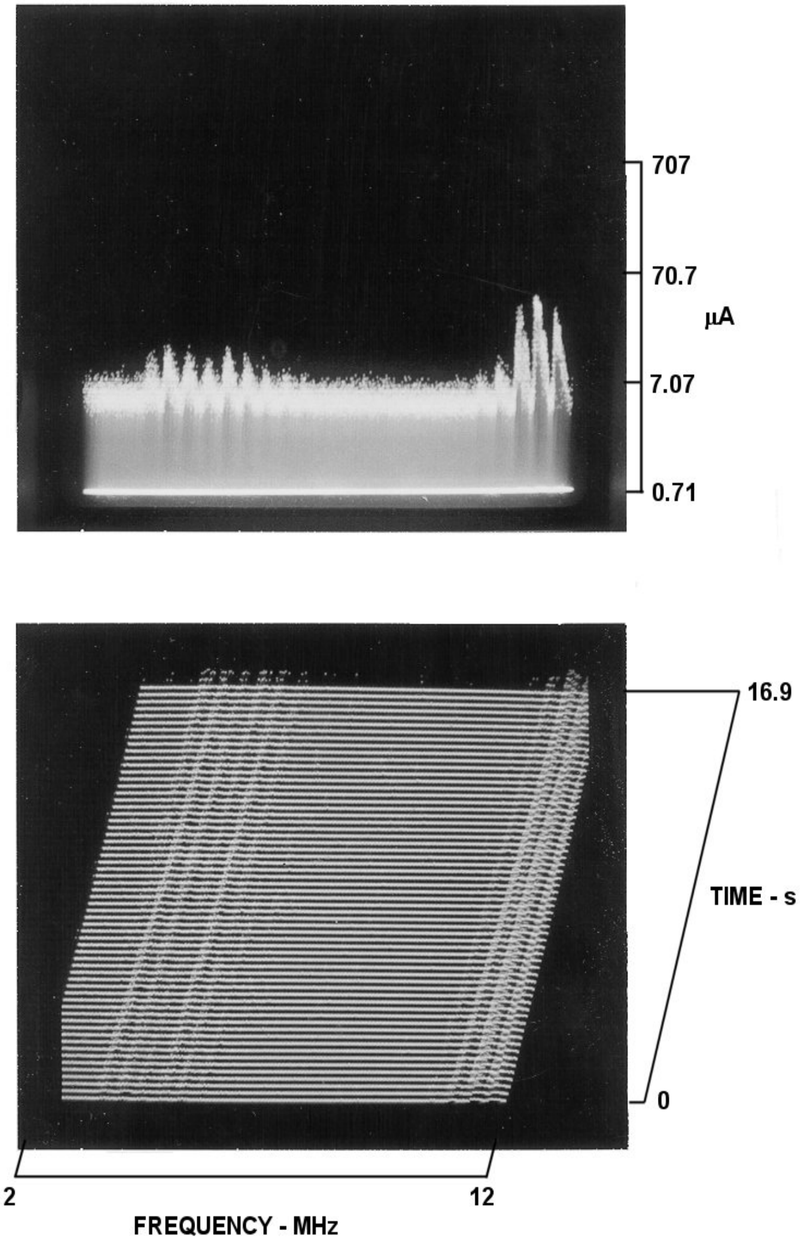
000818 1555
NPS, MODIFIED BEST UPS, ON, CHARGING, LOAD
BLACK, OUTPUT PWR
7M, 10M, 100 k, 200 ms
F-70, +20, 0, -30

Figure 3.24: High-frequency EMI Current on the Black Output Conductor, Modified UPS



000818 1557
NPS, MODIFIED BEST UPS, ON, CHARGING
WHITE, OUTPUT PWR
7M, 10M, 100 k, 200 ms
F-70, +20, 0, -30

Figure 3.25: High-frequency EMI Current on the White Output Conductor, Modified UPS



000818 1551
NPS, MODIFIED BEST UPS, ON, CHARGING, LOAD
GREEN, OUTPUT PWR
7M, 10M, 100 k, 200 ms
F-70, +20, 0, -30

Figure 3.26: High-frequency EMI Current on the Green Output Conductor, Modified UPS

black output conductor. The minimum detectable signal for the example shown is about 7 μA peak and 4 μA rms using a measurement bandwidth of 100 kHz. Additionally, a lower-level discrete-frequency signal and/or lower-level narrow band spectral components of noise can be detected with a narrower measurement bandwidth. This was attempted at measurement bandwidths down to 3 kHz and UPS-generated noise could not be detected.

Figure 3.25 shows a similar result for the white input power conductor. The modified UPS again lowered EMI current well below the detection level of the instrumentation.

Figure 3.26 shows the high-frequency EMI current flowing on the output green-wire ground conductor. In this case ambient current was found, but no UPS-generated component was detectable. The ambient current resulted from the conducting path provided by the input green-wire conductor, the external surface of the UPS case, and the green-wire output ground conductor.

While the configuration with the addition of modifications successfully prevented UPS-generated current from flowing on input and output conductors, the UPS modifications could not prevent ambient current generated by other sources from flowing on facility ground conductors. The ambient current from other sources must be controlled at each source and the modification of other devices will not correct other facility problems. This is also a clear indication that ambient current in a facility ground cannot be eliminated by ground-system modifications.

F. PROPOSED UPS EQUIPMENT SPECIFICATIONS

Although no manufacturers have EMI filters installed prior to purchase, it is suggested that engineers, users, or procurers of UPS systems edit UPS equipment specification (AIA Specification 16611, Appendix F of this thesis) to reflect EMI current concerns when installing an UPS into a facility containing receiving and sensitive data-processing equipment. It is noted that some manufacturers will agree to have EMI filters installed upon request. During the specification phase of procurement, the purchaser must specifically advise the manufacturer that filters be placed at the input and output of UPS systems. It is imperative that an investigation of the UPS equipment specification sheet be made prior to purchasing the unit in order to make certain these filters can be added by the manufacturer. Otherwise, satisfaction with the UPS will not be as desired since these filters obviously do make the product more reliable.

This technical equipment specification is from Section 16611 (Facilities, Electrical Components) from MASTERSPEC DRAWING COORDINATION, The American Institute of Architects (AIA), December 2000. A user of UPS equipment can modify this specification for their own uniquely personal situations. This particular specification is directed toward a single-phase, on-line, static-type, Uninterruptible Power Supply (UPS) system.

The data provided in the thesis shows conclusively that a small to mid-size UPS can be modified to prevent the occurrence of harmful electromagnetic interference at radio-receiving and sensitive data-processing facilities. Furthermore, this can be achieved by the use of inexpensive commercial components.

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IV. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

Electromagnetic interference (EMI) can degrade the operation and performance of many kinds of electronic devices and radio receiving systems. This is especially the case at Department of Defense radio-receiving sites and sensitive data-processing facilities. The increasing use of computers, digital-data-processing devices, and power-control devices in such facilities [including Uninterruptible Power Supplies (UPS), switching power supplies, and motor controllers based on solid-state switching techniques] has resulted in many cases of EMI problems. This thesis concentrated on EMI generated by UPS.

EMI is generated by the rectifier and inverter sections of UPS systems, which often produce noise up to and sometimes higher than 50 MHz. Also, another intermittent source of impulsive noise is load-current changes (load switching) that create voltage and current impulses and electrical noise.

The EMI generated by two unmodified commercial models of UPS was examined. The detailed results from one of the two systems are provided in this thesis. The second system provided almost identical results. The particular units available for testing were obtained for another task, and they were selected because of their low ambient levels of EMI compared to other available commercial units. Nevertheless, their conducted EMI levels were considered too high for use in HF and VHF radio-receiving sites and for some sensitive data-processing uses.

The units were modified in accordance with integrated Barrier, Filter, Ground techniques and again tested. Significant reductions in conducted EMI current was achieved on all conductors penetrating the UPS case including all power and ground conductors. The modifications resulted in the test units meeting all known conducted

EMI current limits including those of MIL-STD-461 and the suggested limits provided by the US Navy SNEP team.

The MASTER DRAWING COORDINATION document issued by the American Institute of Architects (AIA) dated December 2000 is often used as a guide for the procurement and installation of UPS systems. This document, in its original form, does not consider the impact of UPS-generated EMI on other systems. Based on the results of this investigation, suggested changes to the AIA document are provided in Appendix F.

B. RECOMMENDATIONS

The Naval Security Group (NSG) issued a recommendation in 1994 for the use of UPS, which is shown below. This recommendation is fully supported, and the DOD will be best served by following the NSG recommendation:

> "ONLY MISSION-ESSENTIAL EQUIPMENT NOT ABLE TO TOLERATE EVEN MOMENTARY POWER DISTURBANCES SHALL BE CONNECTED TO UPS POWER."
>
> [From NSGINT 113`0.1D G43 (CRITICAL LOAD), 27 Jan 1994

In addition, to the above general recommendation, additional precautions need to be taken to ensure that UPS-generated EMI does not degrade the operation of other radio and electronic systems. This is especially the case in HF, VHF, and UHF radio-receiving sites where UPS-generated EMI is often found at the input terminals of the radio receivers and in sensitive data-processing facilities where UPS-generated EMI is often found on data-cable shields and grounds.

When a determination is made that an UPS is required, or an UPS already exists, specific guidelines and critical aspects for consideration both prior to purchase and after the product has been obtained or installed should be followed. Following are precautionary measures and information designed to insure product satisfaction and to guide a purchaser through the ordering process:

- Upon determining the feasibility of purchasing an UPS, it must be remembered that the UPS will use energy in a rather inefficient manner, although at times (such as in a mission critical area) the benefit provided by an UPS far outweighs any detrimental aspect.
- Although the electronics, mechanical components, and battery portions are quite reliable, an UPS will require regular maintenance or repair. Because of this, an annual maintenance contract included with any order is desirable to insure reliable operation and optimum satisfaction.
- Prior to purchase, a determination should be made as to whether any location chosen for installation is a sensitive facility (i.e., data- processing or radio-receiving facility), due to the fact that these areas have the highest susceptibility to noise and interference.
- Care should be taken to review the equipment specification sheet, to ensure that EMI filters have been properly installed by the manufacturer.
- In most cases, the use of EMI filters on input and output power conductors will be an additional item to purchase; however, these filters are considered "off the shelf" and in actuality it will prove less costly to have them installed at the manufacturer's plant prior to shipment.
- Upon arrival of the order, and before acceptance of the UPS, carefully peruse the accompanying equipment specification sheet. This provides an opportunity for equipment modifications to be made in advance of acceptance.

Although an UPS provides excellent protection for sensitive equipment from many kinds of power faults, the generation of low- and high-frequency EMI must be considered. At times, interference may exist after the UPS has been installed. During these occasions, the procedure for identifying and documenting harmful levels of EMI becomes somewhat more complicated. The following recommendations or suggestions should be considered after installation has been accomplished and EMI is an identified problem:

- A study must be conducted by a team of EMI technical experts to investigate all sources of harmful levels of EMI.
- The team must narrow the cause of EMI from many potential sources to the UPS.

- Prior to taking any action to modify the UPS, all other sources of EMI must be considered. The time of day/week when the EMI occurs at the site should be identified to determine if a pattern of occurrence is repetitive, as this is a key in identifying the sources of EMI.
- Additionally, improper grounding or radiated EMI may also be a reason for interference problems.
- If an UPS is shown to be a source of EMI, it is recommended that wide-band current clamps and a spectrum analyzer be used to examine the level of the EMI over frequency ranges of interest.
- If EMI current exceeds the threshold of criteria provided by the SNEP teams or the limits in MIL STD 461, then filters should be added to all input and output conductors of the UPS system. Appendix E identifies several steps to determine the filter specification decision making process.

In cases where UPS noise may be a factor degrading the performance of electronic and radio devices and systems, it is recommended that UPS be procured and installed in accordance with the additions to *"The MASTER DRAWING COORDINATION document issued by the American Institute of Architects (AIA) dated December 2000*". These additions and changes are provided in Appendix F. These changes apply to small and medium power UPS systems (up to about 50 kVA) where standard filters are available as COTS items.

Finally, it is recommended that future projects be undertaken to better understand methods to control EMI caused by a medium-sized (i.e., 50 to 250 kVA) UPS and large sizes (i.e., 250 kVA and higher). The project is required to develop methods and filter configurations to lower conducted and radiated EMI from medium and high power UPS to acceptable limits.

APPENDIX A. SOURCES OF EMI AND NOISE

This Appendix provides a “Table of Noise Sources” obtained from United States Signals Intelligence Directive dated July 1998. The title of the directive was called “Electromagnetic Compatibility Technical Guidelines”.

The sources in Table A.1 are intended only for general guidance to planners and operational units since it is impossible to list all possible sources. While only a limited number of sources existed in past years, the recent introduction of new devices into Department of Defense facilities, especially digital power-control devices, has introduced many new kinds of sources. Each situation involving electrical and radio-noise problems must be evaluated on a case-by-case basis to identify and mitigate any adverse input on facility operations from each individual source.

Existing noise sources in Department of Defense facilities cannot always be summarily removed because of overall operational considerations, but each source can and should be modified or replaced to minimize the deleterious impact of noise on the operation of electrical and electronic systems. Every effort must be made to protect against ongoing mission performance degradation created by EMI. Such actions will improve the performance of radio and data-processing systems and usually result in the improved efficiency of the devices causing noise.

Of special concern is the recent introduction of COTS equipment into DOD facilities without full consideration of the possibility that some COTS devices are major sources of radio and electrical noise. Once such devices are introduced into a facility, a major effort is often required to reduce EMI from them to harmless levels.

Table A.1 includes many sources of EMI identified in past years. It includes sources producing both radiated and conducted EMI.

Table A.1: NOISE DESCRIPTIONS AND TYPICAL SOURCES

SOURCES	NOISE DESCRIPTIONS
Diesel engine generators	Rarely produce radio noise
Transformers	Rarely produce radio noise
Battery charger	More or less continuous frying noise hum; harmonics with power
Mercury arc rectifiers	More or less continuous frying noise hum; harmonics with power
Silicon-controlled rectifiers (SCRs)	More or less continuous frying noise hum; harmonics with power
Separate radio ground and power	More or less continuous frying noise hum; harmonics with power
Ground in dry weather	More or less continuous frying noise hum; harmonics with power
Hot or burned fuse holders	More or less continuous frying noise hum; harmonics with power
Hot or burned switch or circuit breaker contacts, wet insulation, wires on trees, etc.,in wet weather	More or less continuous frying noise hum; harmonics with power
Faulty heating devices	More or less continuous frying noise hum; harmonics with power
Incandescent lamps, with broken filament or loose in socket	More or less continuous frying noise hum; harmonics with power
Thermostats	Frying noise with power hum harmonics; cut off and on
Voltage regulators	Frying noise with power hum harmonics; cut off and on
Slowly opening switches or Controllers	Frying noise with power hum harmonics; cut off and on
Certain motors during starting Period	Frying noise with power hum harmonics; cut off and on
Faulty heating device	Frying noise with power hum harmonics; cut off and on
Fluorescent lamps	Frying noise with power hum harmonics; cut off and on

Table A.1 (Continued): NOISE DESCRIPTIONS AND TYPICAL SOURCES

Ultraviolet-ray machine	Frying noise with power hum harmonics; cut off and on
Diathermy machine	Frying noise with power hum harmonics; cut off and on
Small motors with commutator, such as electric razors, drills, vacuum cleaners, or mixers	Buzzing noise
Vehicle or variable speed commutator motor	Buzzing noise
Stationary gasoline engine	Erratic clicks of different intensities
Switches being turned off and on	Erratic clicks of different intensities
Appliances being plugged in or disconnected	Erratic clicks of different intensities
Thermostats	Erratic clicks of different intensities
Time clocks	Erratic clicks of different intensities
Telephone dialing	Erratic clicks of different intensities
Ungrounded wires or pieces of sheet metal blowing against other pieces of metal in windy weather	Erratic clicks of different intensities
Electric fence	Regular clicks (frequently at 1-second intervals)
In dry weather - "high-line noise", usually off site	Faint hiss with or without power frequency - hum modulation, punctuated by a "sleet on tin roof" effect
In dry weather - neon sign, usually off site	Faint hiss with or without power frequency - hum modulation, punctuated by a "sleet on tin roof" effect
During snow storm, or sand storm, sometimes with light rain, but always with wind-precipitation static corona effects from ungrounded guy wires, antennas, or insulated metal structures	Faint hiss with or without power frequency - hum modulation, punctuated by a "sleet on tin roof" effect

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APPENDIX B. EMI RELATED TECHNICAL STANDARDS

A. INTRODUCTION

Many organizations and agencies provide standards, handbooks, and other publications related to EMI. Following is a partial listing of such documents:

- FCC Part 15, “Radio Frequency Devices”, Federal Communications Commission, Washington D.C.
- FCC Part 18, “Industrial, Scientific, and Medical Equipment”, Federal Communications Commission, Washington D.C.
- ANSI/IEEE, “Radio Interference: Methods of Measurement of Conducted Interference Output to the Power Line from AM and Television Broadcast Receivers in the Range of 300 kHz to 25 MHz”, American National Standards Institute (ANSI) and Institute of Electrical and Electronic Engineers (IEEE).
- ANSI/IEEE 214, “Construction Drawings of Line Impedance Networks Required for Measurements of Conducted Interference to the Power Line from FM and Television Broadcast Receivers in the Range of 300 kHz to 25 MHz as Specified in ANSI/IEEE Standard 213”, American National Standards Institute (ANSI) and Institute of Electrical and Electronic Engineers (IEEE).
- ANSI/IEEE 518, “Guide for the Installation for Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources”, American National Standards Institute (ANSI) and Institute of Electrical and Electronic Engineers (IEEE).
- ANSI/IEEE C63.2, “ANSI Specification for Electromagnetic Noise and Field Instrumentation, 10 kHz to 40 GHz”, American National Standards Institute (ANSI) and Institute of Electrical and Electronic Engineers (IEEE).
- ANSI/IEEE C63.4, “ANSI Specification for Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 10 kHz to 1 GHz”, American National Standards Institute (ANSI) and Institute of Electrical and Electronic Engineers (IEEE).
- ANSI/IEEE C63.12, “Recommended Practice of Procedures for Control of System Electromagnetic Compatibility”, American National Standards Institute (ANSI) and Institute of Electrical and Electronic Engineers (IEEE).

- MDS-201-0004, “Electromagnetic Compatibility Standard for Medical Devices”, Federal Drug Agency (FDA) Regulations.
- NFPA 70, “National Electric Code”, National Fire Protection Association (NFPA).
- NFPA 70E, “Electrical Safety Requirements for Employee Workplace", National Fire Protection Association (NFPA).
- NESC Handbook, “National Electrical Safety Code Handbook”, Edition 4, Institute of Electrical and Electronic Engineers (IEEE).
- “United States Signals Intelligence Directive", July 1982.
- NSG Instruction (NSGINST) 2450.1, NAVSECGRU “Shore Electronics Criteria”, Naval Security Group, Fort Meade, MD.
- MIL-HDBK-1004, Military Handbook, “Preliminary Design Considerations”, U.S. Dept. of Defense
- MIL-HDBK-419A, Military Handbook, “Grounding, Bonding and Shielding for Electronic Equipment and Facilities”, U.S. Dept. of Defense, December 1987.
- MIL-STD-461E, Military Standard, “Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment”, (Replaces previous editions of 461 and 462), U.S. Dept. of Defense, August 1999.
- DOD C-3222.5, “Electromagnetic Compatibility (EMC) Program for SIGINT Sites”, U.S. Dept. of Defense, July 1988.
- IEEE Standard 1100-1999, “IEEE Recommended Practice for Powering and Grounding Electronic Equipment”, IEEE Emerald Book, 1999
- FIPS Publication 94-1983, “Guideline on Electric Power for ADP Installations”, NTIS, U.S. Department of Commerce.
- CISPR 22, “Limits and Methods of Measurement of Electromagnetic Disturbance Characteristics of Information Technology Equipment (ITE)”, 1985.
- IEC-61000-4-6, “Immunity to Conducted Disturbances”, International Engineering Consortium, 1995.

The large number of handbooks, standards, and documents related to EMC is an indication of the importance of the topic as well as the diverse nature EMC. No other topic related to the use of electricity has generated such a large list of such documents as well as a massive number of articles in the technical journals and other publications.

Many of the above publications are large and complex, and they require considerable technical expertise and costly equipment to comply with their requirements. In addition, it is not always clear which document applies to specific cases, how to handle situations introduced by new technology and how to resolve conflicts between the various publications.

Of special interest is the recent tendency to specify the purchase of electrical and electronic equipment and devices based on Commercial-Off-The-Shelf (COTS) requirements. In many cases this has resulted in the ability to quickly obtain new technology such as advanced computers and data-processing devices. In other cases, this process has resulted in the introduction of severe EMI problems into government and commercial facilities (for example, the use of variable-speed motor drives in and around radio receiving sites that are purchased to COTS requirements).

B. DISCUSSION

It is not feasible to provide a comprehensive review of each of the listed standards, handbooks, and documents in this Appendix. This is a formidable task that needs to be done to highlight the inconsistencies and even some errors that are buried in the available documents. Many of the listed documents are recent editions based on older versions that contain some information of little value and some that is quite misleading. Some of the documents even contain information that is technically incorrect.

To obtain a partial understanding of these matters, partial reviews of selected documents are provided. The reader must recognize that the reviews provided are very limited in scope and they do not provide a good overall evaluation of the applicability of the selected document to specific cases. Even though the author researched the above documents, only the most pertinent documents are described below.

C. DOCUMENTS

1. American National Standards Institute (ANSI) 63.12

ANSI 63.12 is titled the "American National Standard Recommended Practice on Procedures for Control of System Electromagnetic Compatibility". Figure B.1 shows the conducted emission guidelines.

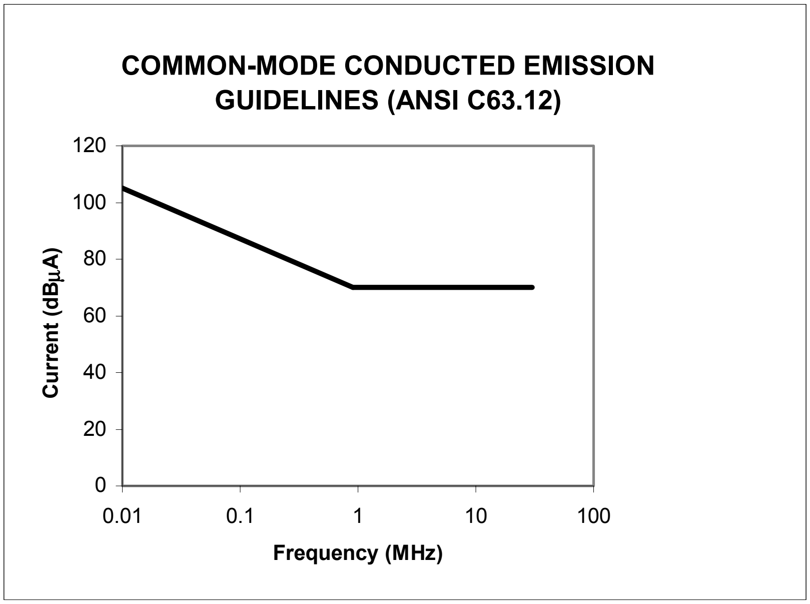

Figure B.1: ANSI C63.12 Conducted Emission Guidelines.

The reader should note that the vertical axis (or current) is in terms of dBμA. The decibel is used extensively in electromagnetic measurements. The "dB" is the logarithm of the ratio of two amplitudes. Examples of amplitudes are power, voltage, current, electric field units, and magnetic field units. The power ratio is:

$$\text{decibel} = \text{dB} = 10\log\left(P_2/P_1\right). \qquad \text{(B-1)}$$

Measurements can be expressed in terms of current ratios. In this case, replace P with I^2R. If the impedances (50 ohms) are equal, the ratio for current becomes:

$$\mathrm{dB} = 20\log\left(I_2/I_1\right) \quad \text{(B.2)}$$

Since the EMI current measured is in terms of dBmA and dBμA, the equation becomes:

$$\mathrm{dBmA} = 20\log\left(I_2/I_1\right) - 30 \quad \text{(B-3)}$$

$$\mathrm{dB}\mu\mathrm{A} = 20\log\left(I_2/I_1\right) - 60. \quad \text{(B-4)}$$

Included in this section is the power-to-current equation associated with this thesis. The power-to-current equation for 50 ohms is:

$$\mathrm{dB}\mu\mathrm{A} = \mathrm{dBm} + 107. \quad \text{(B-5)}$$

The acceptable guideline for the threshold of interference is to remain at approximately 3 mA or 69.5 dBmA. The guideline is cut off at 30 MHz since conducted emission is generally negligible above the 30 MHz, owing to line losses. The proposed guideline as shown in Figure B.1 is described by Table B.1.

Table B.1: Common-Mode Conducted Emission Guidelines

Frequency of Emissio	**Common-Mode Current**
Below 800 kHz	2400 / f (kHz) mA
Above 800 kHz	3 mA

2. FCC Regulations: Class B Conducted Limits

The FCC conducted limits for FCC Class B non-intentional emitters are specified in FCC Section 15.107 "Conducted Limits" Paragraph a. The limit for Class A devices is: “For equipment that is designed to be connected to the public utility (AC) power line, the radio frequency voltage that is conducted onto the AC power line on any frequency or frequencies within the band 450 kHz to 30 MHz shall not exceed 250 microvolts.”

Assuming measurement across a 50-ohm load, this is equivalent to 5 μA. This was based on 250 μV/50 Ω = 5 μA. This is equivalent to 14 dBμA (20 log (I)), where I is in terms of μA.

3. MIL-STD-461E (CE-102) Conducted Emissions

MIL-STD-461E (CE-102) conducted emissions specification specifies 60 dBμV or 20 μA (or 26 dBμA) for "28 VDC" power supply leads. The limit is reduced by 6 dB for 115 VAC power lines to 32 dBμA. However, MIL-STD-461E (CE-102) only specifies the current limit to 10 MHz.

MIL-STD-461E also gives the emission and susceptibility requirements for conducted type EMI. Figure B.2 shows its conducted current limits from 60 Hz to 100 kHz.

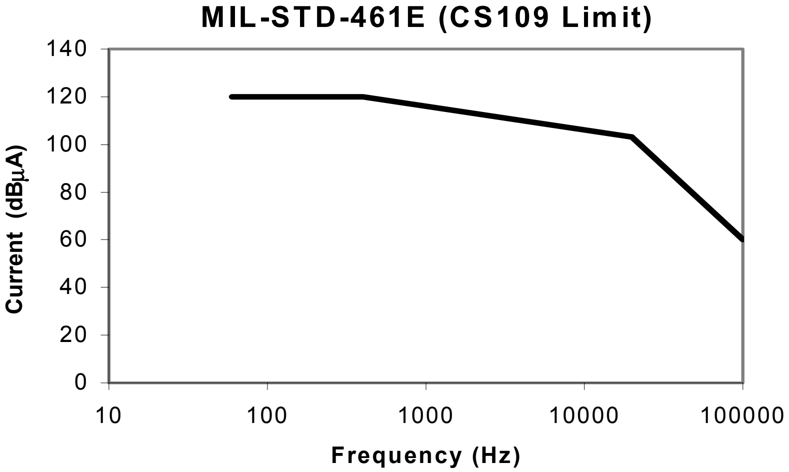

Figure B.2: MIL-STD-461E, CS109 Limit

4. US NAVY SNEP Documentation

An additional published source has been documented by the US Navy Signal-to-Noise Enhancement Program (SNEP). Suggested limits have been established for EMI current injected into ground conductors and all other related conductors of a receiving site. The SNEP teams have recommended various EMI standards for equipment installed in data-processing and signal-receiving sites [Reference 6]. These limits are provided in Tables B.2 and B.3.

Table B.2: Suggested Maximum Permissible Limits for Conducted EMI Current for Large Receiving Site.

Frequency Range	Maximum Current
0 to 10 kHz	2 mA
100 kHz to 100 MHz	10 μA

Table B.3: Suggested Maximum Permissible Limits for Conducted EMI Current for Small Receiving Site.

Frequency Range	Maximum Current
0 to 10 kHz	2 mA
100 kHz to 100 MHz	2 μA

These limits have been established from extensive field measurements of the susceptibility of HF, VHF, and UHF receiving sites to internal sources of EMI by US Navy Signal-to-Noise Enhancement teams. The maximum limit between 10 kHz and 100 kHz is established by linear extrapolation from the disparate limits. When these limits were met at radio receiving facilities, no interference from internal sources of EMI was encountered.

While suggested maximum levels of EMI current have been provided for receiving sites, similar levels for data-processing sites have not yet been established.

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APPENDIX C. DESCRIPTION OF UPS SYSTEMS

A. GENERAL

An Uninterruptible Power Supply (UPS) is used to provide electric power to critical loads when utility power is interrupted, removed, or fails. Figure C.1 shows a diagram of a typical single-module UPS system. A battery is trickle charged from the AC-to-DC converter, usually with a full-wave rectifier. The battery drives an inverter using transistors for lower-power units and thyristors or silicone-controlled rectifiers (SCRs) as solid-state switchers for higher-power units. The details and configurations of UPS systems, their performance and capacity, and their physical configuration vary somewhat from one manufacturer to another, but all provide electrical power to loads for a short period of time when their input power fails. UPS units also provide protection against a number of other power problems including surges, sags, transients, dropouts and brownouts as well as total power failures. The duration of this protection is dependent on a combination of battery capacity and load. For times exceeding the protection provided by an UPS, and where operation is critical, standby diesel engine-driven generators must be provided.

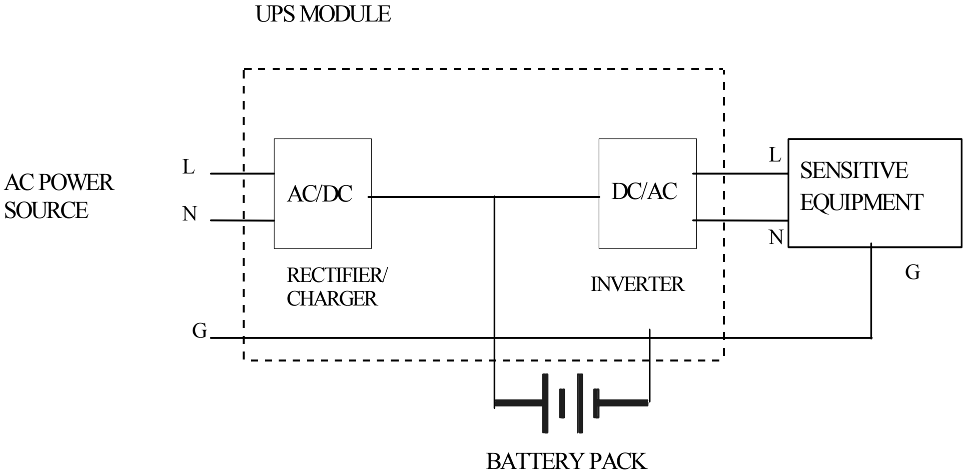

Figure C.1: Typical On-Line Single-Phase Single-Module UPS Diagram.

B. UPS COMPONENTS

An UPS is a device used to provide continuous, acceptable power to its load regardless of the input power supplied. UPS systems come in various types and sizes. An UPS is used to provide clean, conditioned, and continuous power to critical electronic equipment. It can protect electronic equipment from most detrimental conditions experienced on power systems. The UPS will provide power to the load including an event causing a total outage. The UPS supplied power will last only as long as the systems battery bank will permit, typically 10 minutes. These systems are commonly used to protect computer systems from short-term outages such as those experienced during stormy conditions or other inclement weather situations.

Figure C.1 depicts the major components of a typical single-phase single-module UPS system. The UPS systems tested for this thesis are of a type shown in Figure C.1. They had a single input with a maintenance bypass section. The components of this UPS system contained the following sections:

- Rectifier or Charging Unit - takes the utility AC power and converts it to DC and also charges the batteries.
- Inverter - takes the DC from the rectifier or batteries and converts it to AC for use in the computer system.
- Battery Bank - supplies DC power for the inverter in the event of unacceptable AC input.

C. UPS STANDARD

While no specific government or industry standard exists for the specification of an UPS system, two sources provide useful information to aid in their design, procurement and use.

Underwriters Laboratories (UL) Inc. publishes Standards for Safety documents. Their document UL 1778 titled "Uninterruptible Power Supply Equipment", provides recommendations about construction, performance, rating, marking, and testing of UPS systems. The following sections in UL 1776 have applicable references to this thesis:

- Section 42: The leakage current that is accessible to the user shall not be more than 0.75 milliampere.
- Section 42.1a: Leakage current shall not exceed 5.0 milliamperes.
- Section 48.2: Testing criteria on UPS systems that have EMI filter capacitors installed.
- Section 74.1.2.j: For an UPS to have circuit filtering to meet EMC/EMI regulations.

The Federal Communications Commission (FCC) specifies EMI limitations for electronic and electrical devices under Part 15 of their regulations. They provide maximum permissible levels of EMI voltage on the conductors supplying power to electronic devices intended for use in industrial and residential applications. The maximum permissible levels for industrial (Class A level) use are much higher than for residential (Class B level) use. The FCC specified limitations are often used for the procurement of COTS UPS systems by the government. No mention is made in the FCC documentation of the use of UPS systems at radio-receiving or data-processing facilities.

D. UPS INVERTER SECTION

Most inverters in UPS products employ solid-state switching techniques to convert the DC power to AC power. Some of the techniques employed in the conversion are square-wave, stepped-wave or pulse-width modulation. Each technique has beneficial qualities, but each has limitations. The detrimental aspects of the switching actions of an inverter are output distortion of the voltage waveform, limitations in transient response, efficiency, and the generation of EMI. This aspect of an UPS converter should be taken into account when selecting a unit for installation in a facility.

E. UPS HAZARDOUS WARNING LABELS

Figures C.2 and C.3 show EMI/RFI warning labels found on the external surface of the case of two UPS systems installed at two different receiving sites. These labels are also reproduced in the manuals of both systems. Such warnings are required in the United States on all commercial electronic and electrical equipment that generates EMI/RFI. Both of the UPS systems containing the warnings were purchased as COTS devices in accordance with FCC Class A requirements. This is a common procurement procedure since UPS systems meeting the stricter Class B requirements are seldom specified during procurement, and they are seldom available from manufacturers as COTS devices.

> ***WARNING:*** *This equipment generates, uses, and can radiate radio frequency and if not installed and used in accordance with instructions may cause interference to radio communications. It has been tested and found to comply with the limits for Class A computing devices pursuant to Subpart J or Part 15 of FCC Rules, which are designed to provide reasonable protection against such interference when operated in a commercial environment. Operation of this equipment in a residential area is likely to cause interference in which case the user at his own expense will be required to take whatever measures may be necessary to correct such interference.*
>
> ***CAUTION:***
>
> ***Always be aware that hazardous voltages may be present within the UPS even when the system is not operating.***

Figure C.2: LABEL ON AN UPS INSTALLED IN A RECEIVING SITE[1]

> *This equipment complies with the requirements in Part 15 of FCC Rules for a Class A computing device. Operation of this equipment in a residential area may cause unacceptable interference to radio and TV reception requiring the operator to take whatever steps are necessary to correct the interference.*

Figure C.3: Another UPS Warning Label[2]

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[1] This label was reproduced from a photograph taken from a UPS located at NSGA Northwest during a visit to the site in April 1997. The photograph is located in field notebooks for that visit.

[2] This label was reproduced from a photograph taken from an UPS located at Detachment L, Field Site Korea during a visit to that site in October 1999. The photograph is located in field notebooks for that visit.

The warning labels clearly indicate that EMI/RFI can be expected if a Class A UPS is located at a facility containing radio receivers. This should be sufficient warning; the additional steps will probably be required to ensure EMI/RFI problems are not encountered after a Class A UPS is installed and becomes operational. Unfortunately, very costly corrective actions to the UPS must be implemented to reduce EMI/RFI to harmless levels after the installation.

No mention is made in the warning labels of possible adverse affects of EMI generated by a Class A UPS system to data-processing devices, the possible contamination of signals carried by wired local area networks (LANs) or other adverse effects to electrical or electronic devices.

The procurement and installation of Class A UPS systems require attention during the design stages of a facility and prior to procurement. This is especially the case for UPS systems intended for use in or near facilities containing HF, VHF and UHF radio receivers. Class A devices of any kind should not be used at or near receiving facilities without first ensuring that problems will not be encountered or all Class A devices are modified to reduce RFI/EMI to harmless levels.

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APPENDIX D. CALIBRATION

A. GENERAL

Normal performance tests and system calibrations were made at the start of each set of measurements or at any time a significant change was made in the instrumentation. Of special concern was the transfer of amplitude calibration scales from the HP 141 Spectrum Analyzer to the ELF Model 7200B 3-Axis Display. In addition each current probe was calibrated with test fixtures specifically designed for that purpose.

B. TIME-AXIS CALIBRATION OF THE 3-AXIS DISPLAY

The duration of the time axis of the time-history views is dependent on the scan time of the spectrum analyzer and the blanking or dead time at the end of each scan. The time axis can be calculated from the following formula:

$$T_t = (t_s + t_b) \cdot 60 \tag{D-1}$$

where:

T_t is the duration of the time axis in seconds,

t_s is the total time of each scan of the spectrum analyzer in seconds, and

t_b is the blanking or dead time between each scan in seconds.

An initial value of t_s can be obtained from the scan-time control on the spectrum analyzer. Additionally, this can be measured with an oscilloscope or a counter to obtain more accurate values. The value of t_b is not provided by the manufacturer, and it must be measured with an oscilloscope or a counter. The value of t_b varies from analyzer to analyzer and with the setting of the scan-time control.

Table D-1 shows a typical calibration chart summarizing the parameters needed to establish the time-axis values when the scan-time of the spectrum analyzer is operated in the auto-sync mode.

Table D-2 shows a typical calibration chart summarizing the parameters needed to establish the time-axis values when the scan-time of the spectrum analyzer is operated in the line-sync mode.

Table D-1: Time Scale Calibration, Auto Sync

Scan Time (in ms)	Measured Scan Time (in ms)	Blanking Time (in ms)	Time Axis (in sec)
2	1.9	0.29	0.13
5	4.3	0.30	0.28
10	9.75	5.0	0.89
20	20	5.0	1.5
50	45	6.0	3.1
100	105	85	11.4
200	200	85	17.1
500	450	85	32.1
1000	1025	85	66.7
2000	2050	675	163
5000	4600	688	317

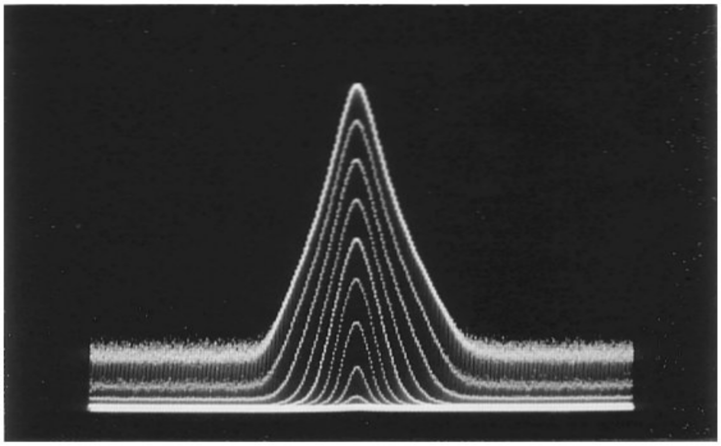
Table D-2: Time Scale Calibration, Line Sync

Scan Time (in ms)	Measured Scan Time (in ms)	Blanking Time (in ms)	Time Axis (in sec)
2	2.45	15	1.0
5	4.5	12.5	1.0
10	10	6.8	1.0
20	20	13	2.0
50	45	22	4.0
100	105	95	12
200	200	100	18
500	450	90	32.4
1000	1025	95	67
2000	2050	937	179
5000	4600	687	317

C. AMPLITUDE CALIBRATION

The amplitude calibration of the spectrum analyzer must be transferred to the time-history display. The amplitude calibration levels of the spectrum analyzer are recorded on the time-history display in 10-dB steps starting with the full trace setting on the analyzer and proceeding downward in steps. A photograph is then made of the amplitude traces on the time-history display. It is important that the same camera used to photograph the calibration traces is used for all subsequent data-recording work. This avoids camera-to-camera variations.

Figure D.1 shows an example of an amplitude-calibration photograph. The levels shown on the original photograph can be transferred to any example of measured data to obtain amplitude scales in mA or µA as needed. Since the dynamic range of the measured data was very large, it was necessary to use a logarithmic amplitude scale to portray the full range of EMI current.



000818 0733
NPS CALIBRATION
HP 141T, S/N MO51344, IF/RF 2
7200B, NPS 2

Figure D.1 Amplitude Calibration

D. BANDWIDTH CALIBRATION

EMI produced from the solid-state switches in an electronic UPS is highly impulsive, resulting in spectral components of EMI that are much wider than the bandwidth of the measurement process available from a spectrum analyzer. Because of this, the amplitude of impulsive noise is a function of the measurement bandwidth. A calibration curve permitting the conversion of impulse amplitude from the measured value to other bandwidth values is provided to aid in the analysis and application of the data. Figure D.2 provides the curve used to aid in the evaluation of the data obtained and shown in this document. A reference curve to scale changes in the amplitude of time-stable gaussian noise with bandwidth is also provided.

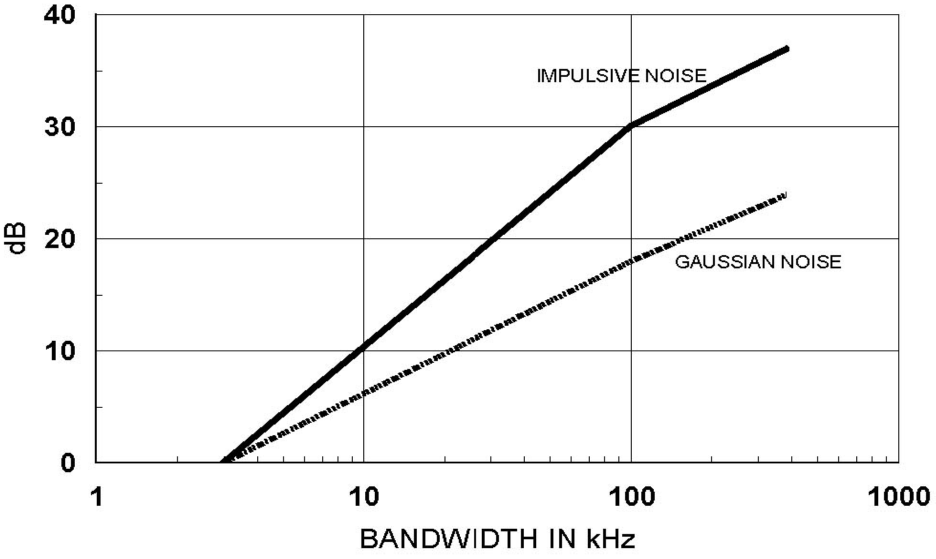


Figure D.2 Bandwidth Scaling Curve

E. PROBE CALIBRATION

The two current probes used to measure EMI current levels were flat in frequency response over their normal operating frequency range. A Tektronix Model 6021 Current Probe interfaced with a Tektronix Model CT-4 Current Probe was used to measure EMI current at frequencies below about 100 kHz. While the specified frequency range of this combination of probes extended to much higher frequencies (up to 50 MHz), the higher portion of its range could not be used. The limited dynamic range of the instrumentation (about 80 dB) prevented the measurement of low-level spectral components of current above a few tens of kHz. Nevertheless, the combination of the P6021/CT-4 probes provided a means to understand harmonic content of the input and output power of UPS systems and the spectral components of low-frequency EMI current. It was necessary to provide a means to convert the probe readings into amplitude scales in mA or µA on the recorded data. The next charts (Figures D.3 and D.4) are calibration curves associated with the current transformer (CT) used for the testing. The CT-4/P6021 current transformer was used for the low-frequency test setup and F-70 CT was used in a high-frequency test setup.

The response of the P6021/CT-4 combination of probes falls at frequencies below 200 Hz, and a calibration curve is required to obtain compensation values of current below this value. Figure D.3 shows the calibration curve used to understand low-frequency current levels.

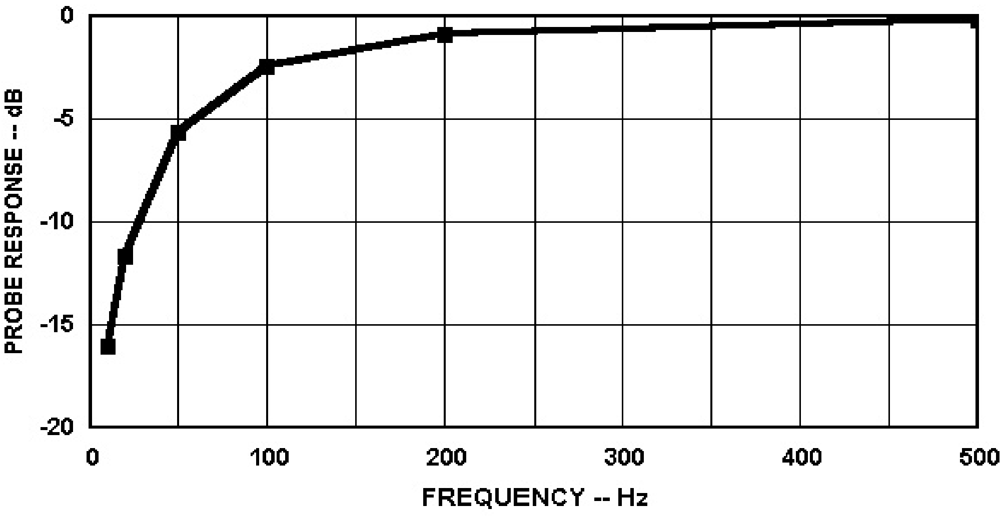


Figure D.3 CT-4/P6021 Probe Calibration

A Fischer Model F-70 Current probe was used to measure EMI current at frequencies above 100 kHz. Its low-frequency response diminishes below 100 kHz and allows the measurement of high EMI current levels at higher frequencies without concern for the high levels of low-frequency current flowing on conductors. The response of the probe was flat from 100 kHz up to 100 MHz. This permitted the use of a single amplitude scale on the data describing high-frequency EMI current levels.

A calibration curve was used to extend the amplitude response of the F-70 probe to frequencies below 100 kHz. This provided a means to extend the frequency range of the F-70 probe downward into the useful frequency range of the CT-4/P6021 probe for comparative measurements. Figure D.4 shows the calibration curve for the probe used during these measurements.

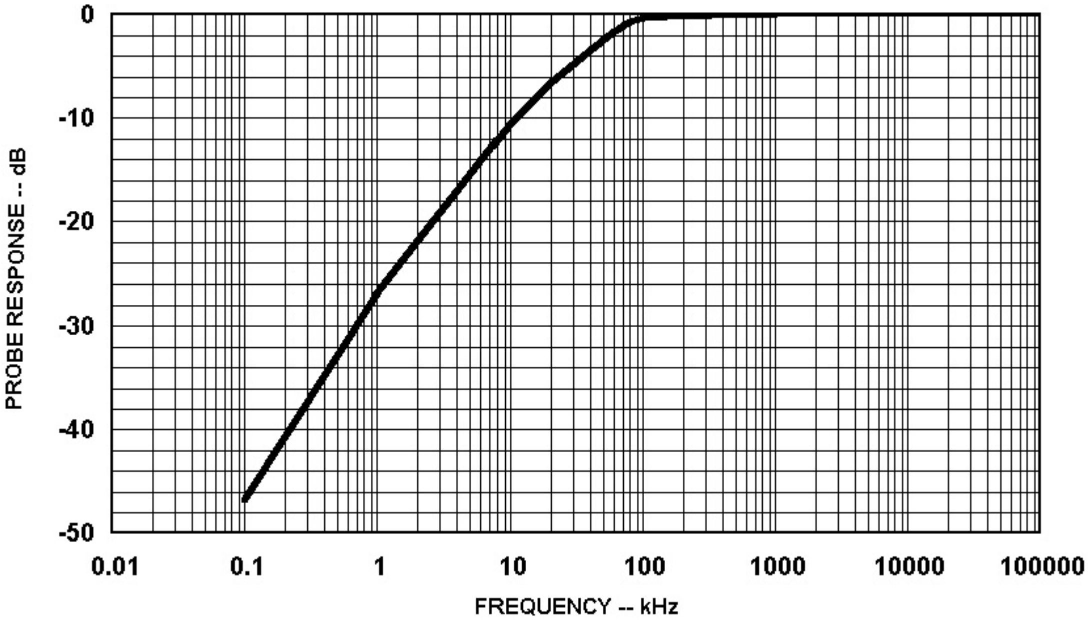


Figure D.4 F-70 Probe Calibration Curve

APPENDIX E. POWER LINE FILTERS

A. INTRODUCTION

The information in this section is limited to a description of filters composed of discrete components; usually capacitors, inductors, and resistors. This is the type normally used to correct EMI problems associated with the power conductors of electronic equipment. Four main types of such filters can be obtained which are low-pass, high-pass, band-pass, and band-trap. For the purposes of this thesis, the discussion will be limited to the low-pass type which allows alternating electrical power to be provided to an uninterruptible power supply (UPS) while attenuating higher-frequency EMI being conducted out of the UPS. Similarly, a second filter can be provided on the output conductors to attenuate high-frequency EMI while allowing low-frequency electrical power to be applied to a load. When properly installed at the surface of the conducting case of an UPS, low-pass filters can be highly effective in reducing conducted EMI current on entry and exit power conductors to harmless levels.

A number of references provide detailed information about the detailed design of filters, and this readily available information is not duplicated in this appendix. Fortunately, a variety of low-pass filters are available as standard catalog items up to modest power-handling ratings. Two types were considered for use in the tests of the UPS described in this thesis. The first was the standard "Pi" configuration shown in Figure E.1.

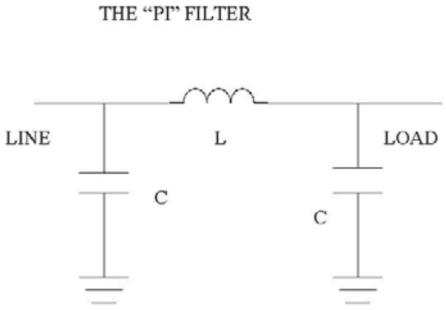


Figure E.1: "Pi" Configuration Filter

The "Pi" configuration provides low attenuation to all frequencies below its cut-off frequency and a high transfer impedance to all spectral components above the cutoff frequency. In addition, it provides a low input and output impedance to all spectral components above the cutoff frequency.

The second type considered was the standard "T" configuration shown in Figure E.2. This type also provides low loss to spectral components below its cutoff frequency, and it also provides high transfer impedance to all spectral components above its cutoff frequency. It differs from the "Pi" configuration in that it provides high input and output impedance to all spectral components above the cutoff frequency.

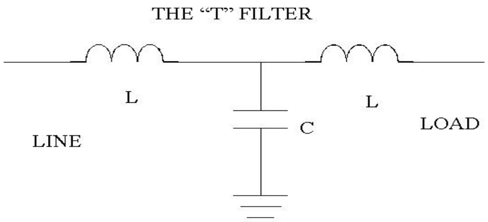


Figure E.2: "T" Configuration Filter

Transfer impedance, Z_t, is defined as:

$$Z_t = \frac{E_{\text{in}}}{I_{\text{out}}} \qquad \text{(E-1)}$$

where:

E_{in} is the voltage of a spectral component of EMI produced by the UPS, and

I_{out} is the current of the selected component of EMI on the outside conductors.

The reason both configurations of filters were considered is that some switching devices (especially motor controllers using similar switching techniques) used for the conversion of electric power are sensitive to the above-band impedance of filters on the input and/or output conductors. The type of UPS chosen for the work described in this thesis was insensitive to such impedance problems which allowed either type of low-pass filter to be used. The standard “Pi” configuration was chosen simply because it was readily available at low cost.

One additional consideration was used in the selection and use of filters. This is the physical configuration of the green-wire ground connection to the input and output sides of a filter. It is necessary to select a filter case configuration that provides a conducting path for EMI current flowing on the green-wire ground conductor to return to its source within the UPS case. This was accomplished by the selection of a standard and inexpensive COTS filter using a metal case that complied with the electrical configuration shown in Figure 3.19 of the main body of the thesis. This configuration provides low transfer impedance to low frequencies to meet the safety requirement of the NEC while providing high transfer impedance to high frequencies. The high transfer impedance at high frequencies is obtained from the shielding of the metal case housing the UPS.

Two additional terms are used to evaluate filter effectiveness. They are common-mode (CM) and differential mode (DM) EMI. CM EMI flows on both the white and black conductors of a 120-V power source, and CM EMI voltage is measured from either conductor to ground. DM EMI flows in one direction on the white wire and in the other direction on the black wire. DM voltage is measured between the black and white conductors. Both CM and DM modes are considered in this thesis.

B. FILTER CHARACTERISTICS

1. General

In order to select an appropriate EMI power-line filter, the following are some of the characteristics that a user must be concerned with: type, application, performance, agency approvals, insertion loss range, current ratings, temperature range and voltage range. The EMI power-line filter is of a low-pass type that is used on electronic equipment. The filter's function is to block the flow of EMI current while passing a desired 60-Hz current.

2. Insertion Loss

Insertion loss (IL) is a measure for effectiveness of a filter. It is defined as the ratio of voltage (*E1*) across the phase-to-ground, with a filter in the circuit at a given frequency, while voltage (*E2*) across the phase-to-ground contains no filter in the circuit at the same frequency. Since insertion loss is dependent on the source and load impedance in which a filter is to be used, IL measurements are defined for a matched 50-ohm system. The IL is measured in decibels (dB) and defined as:

$$\mathrm{IL}(\mathrm{dB}) = 20\log\left(\frac{E_1}{E_2}\right). \tag{E-2}$$

The insertion filter loss equation is also expressed in terms of number of poles or stages of filter:

$$\mathrm{IL}(\mathrm{dB}) = 10\log\left[1+\left(\frac{f_1}{f_2}\right)^{2N}\right] \tag{E-2}$$

where f_1 = interfering EMI frequency,

f_2 = cutoff frequency of filter, and

N = number of poles or stages of filter.

The number of stages determines the attenuation slope of the filter's characteristic curve. If the filter has 2 stages, then the slope of the curve is 40 dB per decade.

C. FILTER STANDARDS

The following military and commercial standards documents associated with filters and insertion loss measurements are:

- MIL-F-15733: Filters and Capacitors, Radio Frequency Interference
- MIL-F-28861: Filters and Capacitors, Radio Frequency Interference / Electromagnetic Interference Suppression
- MIL-STD-220: Method of Insertion Loss Measurement
- ANSI C63.13: American National Standard Guide on the Application and Evaluation of EMI Power-Line Filters for Commercial Use

When specifying in accordance with MIL-STD-220 the minimum insertion loss shall be accordance with Table E.1.

Table E.1: MIL-STD-220 Insertion Loss Filter Characteristic

Frequency	**15 kHz**	**100 kHz**	**500 kHz**	**1 MHz**	**100 MHz**	**1 GHz**
AC Insertion Loss (dB)	10	42	70	70	70	70

D. INPUT FILTER

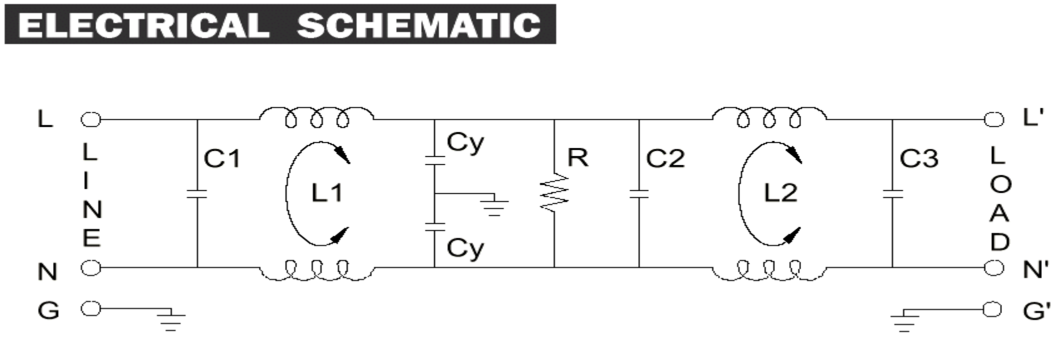
A Delta power-line EMI filter was used for purposes of this research, as the filter is a common "off-the-shelf" item and available from the SNEP laboratory. The schematic and characteristics are shown in Figure E.3. The insertion loss diagram (for a DELTA ELECTRONICS, 10DRDG3, EMI FILTER) was obtained from the manufacturer and is shown in Figure E.4.

E. OUTPUT FILTER

The output filter used for thesis research was a Corcom EMI filter Model 6VSK7. It is a 6-amp, 120-volt, 60-Hz, single stage filter.

F. INSTALLATION CRITERIA

The proper installation of a filter is critical to achieve successful filtering of EMI generated by an UPS or preventing EMI from external sources from affecting the operation of an UPS. The filter must provide an electrical barrier to prevent harmful spectral components of EMI from escaping or entering the UPS. To accomplish this, the filter must be installed on the metal case of an UPS and in accordance with the principles shown in Figure 3.19 of the main body of this thesis. Installation at other locations (i.e., in the interior of an UPS or externally on the power conductors of an UPS) will result in the significant loss of effectiveness and the use of filters at such locations is inadvisable and not recommended.



Manufacturer: Delta Electronics, Inc.
Model Number: 10DRCG3
DR Series, High Performance Filter

Two Stage Filter
Characteristics: 115v, 60 Hz, 40 degrees C, 10 amps
Filter is used in suppressing both line-to-line and line-to-ground noise.
All parts are UL recognized, CSA certified, and VDE approved

Specifications:
1) Maximum leakage current (line-to-ground) = 0.25 mA
2) Hipot rating (one minute):
    line-to-ground = 2250 VDC
    line-to-line = 1450 VDC
3) Operating frequency = 50/60 Hz
4) Rated voltage = 115/250 VAC

Where:
R= 2.2 MΩ
C1= .22 μF
C2= .22 μF
C3= .22 μF
Cy=3300 pF
L1, L2= 1 mH

Figure E.3: The Schematic and Characteristics of the Delta 10DRCG3 Filter
(Technical Product Catalog, Delta High Performance Filters, Delta Inc., Page 6-8, Reference 7)

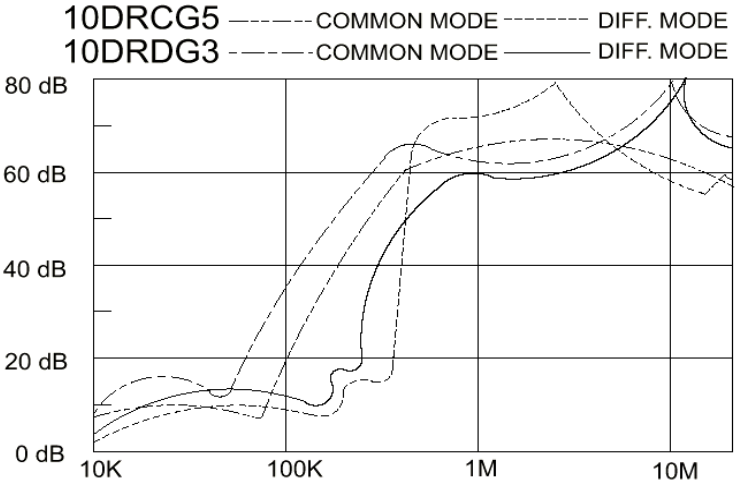


Figure E.4: Insertion Loss Diagram for the Input UPS Filter
(Technical Product Catalog, Delta High Performance Filters, Delta Inc., Page 6-8, Reference 7)

When selecting an EMI power-line filter, several steps are recommended. They are:

1. If a device is suspected of generating harmful levels of EMI, measure the EMI current on all conductors entering and exiting the device. Ascertain if any spectral component of current generated by the device appears to be abnormal.
2. Compare the measured levels of EMI current to emission limit criteria provided by government publications or other organizations.
3. Determine the attenuation required to reduce EMI current levels to acceptable limits.
4. Select a filter that provides sufficient attenuation and install it in accordance with the principles provided in this thesis.

G. FILTER MANUFACTURERS

Below in Table E.2 are several filter manufacturers from EEM 2001 (Reference 8). The EEM is well known electronic equipment source of technical information. Information is also available from the EEM 2001 (http://eemonline.com) on the World Wide Web.

Table E.2: Power Line Filter Manufacturers

AEROVOX
CORCOM, INC.
CURTIS INDUSTRIES
DEARBORN ELECTRONICS, INC.
DELTA ELECTRONICS, INC.
EMISSION CONTROL LTD.
FILTERS CONCEPTS, INC.
LINDGREN RF ENCLOSURES, INC.
MECHATRONICS, INC.
METUCHEN CAPACITORS, INC.
OKAYA ELECTRIC AMERICA
POWER DYNAMICS, INC.
RFI (DEL ELECTRONICS)
SAE POWER, INC.
SCHAFFNER EMC
SCHURTER, INC.
SPECTRUM CONTROL INC.
TAMURA CORP.
TEXAS SPRECTRUM ELECTRONICS, INC.
TRI-MAG INC.
WICKMANN USA

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APPENDIX F. PROPOSED SPECIFICATION

Section 16611 from the MASTERSPEC DRAWING COORDINATION document issued by the American Institute of Architects (AIA) and dated December 2000 provides an overall specification for an Uninterruptible Power Supply (UPS). The specification is directed toward the purchase and installation of a single-phase, on-line, static-type UPS.

This particular specification does not consider the possible impact of EMI generated by an UPS on other electronic systems and devices, but users of UPS systems in such facilities can modify this specification to meet their unique and special requirements. Suggested changes in this specification are listed in **bold**. These changes are directed at the use of UPS systems in radio-receiving and sensitive data-processing facilities. Of particular concern is the elimination of harmful levels of UPS generated EMI on radio signal reception and on the operation of sensitive data-processing systems.

SECTION 16611 - UNINTERRUPTIBLE POWER SUPPLY

PART 1 - GENERAL

1.1 RELATED DOCUMENTS

A. Drawings and general provisions of the Contract, including General and Supplementary Conditions and Division 1 Specification Sections, apply to this Section.

1.2 SUMMARY

A. This Section includes 1-phase, on-line, static-type, uninterruptible power supply (UPS) systems, complete with battery and battery circuit breaker.

1.3 DEFINITIONS

A. UPS: Uninterruptible power supplies that automatically provide power, without delay or transients, during any period when normal power supply is incapable of performing acceptably.

B. THD: Total harmonic distortion.

C. **EMI: Electromagnetic Interference. EMI is the impairment of a desired electromagnetic signal by an electromagnetic disturbance, i.e., electrical noise. This undesirable electromagnetic emission or any electrical disturbance, man-made or natural, which causes any undesirable response, malfunctioning or degradation in the performance of electrical equipment**

D. **EMI filter: An EMI filter is a passive electronic device used to suppress conducted interference present on any power or signal line. It may be used to suppress interferences generated by the device. Most EMI filters include electronic components to suppress both common- and differential-mode interference.**

1.4 SUBMITTALS

A. Product Data: Include data on features, components, ratings, and performance for each product specified in this Section.

B. Shop Drawings: Detail fabrication, internal and interconnecting wiring, and installation of UPS system. Include dimensioned plan, elevation views, and details of control panels. Show access and clearance requirements. Differentiate between field-installed and factory-installed wiring and components.

C. Product Certificates: Signed by manufacturers of UPS systems certifying that the products furnished comply with requirements.

D. Qualification Data: For firms and persons specified in the "Quality Assurance" Article.

E. Factory Test Reports: Comply with specified requirements. **Include conducted noise data over the frequency range of 1 kHz to 50 MHz.**

F. Field Test Reports: For tests specified in Part 3.

G. Maintenance Data: For system and products to include in the maintenance manuals specified in Division 1. Include the following:

1. Lists of spare parts and replacement components recommended to be stored at the project site for ready access.
2. Detailed operating instructions covering operation under both normal and abnormal conditions.

H. Warranties: Special warranties specified in this Section.

1.5 QUALITY ASSURANCE

A. Testing Agency Qualifications: An independent testing agency with the experience and capability to conduct the testing indicated without delaying the work, as documented according to OSHA criteria for accreditation of testing laboratories, Title 29, Part 1907; or a full member company of the International Electrical Testing Association.

1. Testing Agency's Field Supervisor: Person currently certified by the International Electrical Testing Association or the National Institute for Certification in Engineering Technologies, to supervise on-site testing specified in Part 3.

B. Comply with NFPA 70.

C. Source Limitations: Obtain UPS, including components, from a single manufacturer with responsibility for entire system.

D. Listing and Labeling: Provide UPS specified in this Section that are listed and labeled as a factory-assembled unit.

E. Listing and Labeling: Provide UPS specified in this Section that are listed and labeled for use in computer rooms. Comply with NFPA 75.

1. The Terms "Listed" and "Labeled": As defined in the National Electrical Code, Article 100.
2. Listing and Labeling Agency Qualifications: A "Nationally Recognized Testing Laboratory" as defined in OSHA Regulation 1910.7.

F. Comply with UL 1778.

1.6 DELIVERY, STORAGE, AND HANDLING

A. Deliver equipment in fully enclosed vehicles after specified environmental conditions have been permanently established in spaces where equipment is to be placed.

B. Store equipment in spaces with environments that are controlled within manufacturer's ambient temperature and humidity tolerances for nonoperating equipment.

1.7 WARRANTY

A. General Warranty: The special warranty specified in this Article shall not deprive the Government of other rights the Government may have under other provisions of the Contract Documents and shall be in addition to, and run concurrent with, other warranties made by the Contractor under requirements of the Contract Documents.

B. Special Warranty for Batteries: A written warranty, signed by manufacturer and principal Installer, agreeing to replace UPS system storage batteries that fail in materials or workmanship within the specified warranty period.
   1. Special Warranty Period for Batteries: 10 years from date of Substantial Completion. A full warranty applies to the first year of the period, and a prorated warranty applies to the last 9 years.

1.8 EXTRA MATERIALS

A. Furnish extra materials described below that match products installed, are packaged with protective covering for storage, and are identified with labels describing contents. Deliver extra materials to Government.

   1. Fuses: 1 for every 10 of each type and rating, but not less than 1 of each.
   2. Cabinet Ventilation Filters: One complete set.

PART 2 PRODUCTS

2.1 MANUFACTURERS

A. Available Manufacturers: Subject to compliance with requirements, manufacturers offering products that may be incorporated into the Work include, but are not limited to, the following:

1. Best Power Technology, Inc.
2. Computer Power, Inc.
3. Controlled Power Co.
4. Deltec Corp.
5. Exide Electronics.
6. HDR Power Systems, Inc.
7. International Computer Power.
8. International Power Machines Corp.
9. Liebert Corp.
10. Mitsubishi Electronics America, Inc.
11. Pacific Power Source Corp.
12. Square D Co.; EPE Technologies, Inc. Subsidiary.
13. Toshiba International Corp.

2.2 MANUFACTURED UNITS

A. Description: Electronic components and switching devices are housed in one or more metal cabinets, with batteries rack mounted separately. Automatic system operating functions include the following:

    1. Normal Conditions: Supply the load with power flowing from the normal AC power input terminals, through the rectifier/battery charger and inverter, with the battery connected in parallel with the rectifier output.
    2. Abnormal Supply Conditions: When the normal AC supply deviates from specified voltage, waveform, or frequency limits, the battery supplies energy to maintain constant inverter output to the load.
    3. When normal power fails, energy supplied by the battery through the inverter continues supply to the load without switching or disturbance.
    4. When power is restored at the normal supply terminals of the system, the rectifier/battery charger supplies power to the load through the inverter and simultaneously recharges the battery. Synchronize the inverter with the external source before transferring the load.
    5. When the battery becomes discharged and normal supply is available, charge the battery by the rectifier/battery charger. On reaching full charge, shift the rectifier/battery charger to a float-charge mode.
    6. When any element of the UPS system fails and power is available at the normal supply terminals of the system, the static bypass transfer switch switches the load to the normal source with less than one-quarter-cycle interruption of supply.
    7. If a fault occurs in the system supplied by the UPS and current flows in excess of the overload rating of the UPS system, the static bypass transfer switch operates to bypass the fault current to the normal supply circuit of the UPS system for fault clearing.

8. When the fault has cleared, the static bypass transfer switch returns the load to the UPS system.

B. Functional Description of Manual Operation: Manual operating functions include the following:
  1. Turning the inverter off causes the load to be transferred by the static bypass transfer switch directly to the normal AC input source without interruption.
  2. Turning the inverter on causes the static bypass transfer switch to transfer the load to the inverter.

C. Maintenance Bypass/Isolation Switch: Interlocked so UPS cannot be operated unless the static bypass transfer switch is in the bypass mode. The device has 3 settings that produce the following conditions without interrupting supply to the load during switching:

  1. Full Isolation: Load is supplied bypassing UPS. UPS AC supply input, static bypass transfer switch, and UPS load terminals are completely disconnected from external circuits.
  2. Maintenance Bypass: Load is supplied bypassing UPS. UPS AC supply terminals are energized to permit operational checking, but system load terminals are isolated from the load.
  3. Normal: UPS AC supply terminals are energized and the load is being supplied through either the static bypass transfer switch or the UPS rectifier and inverter.

2.3 SYSTEM SERVICE CONDITIONS

A. Environmental Conditions: Operate continuously in the following environmental conditions without mechanical or electrical damage or degradation of operating capability:

  1. Ambient Temperature: 0 to 40 deg C.
  2. Relative Humidity: 0 to 95 percent, noncondensing.
  3. Altitude: Sea level to 4000 feet (1220 m).

2.4 SYSTEM CHARACTERISTICS

A. Minimum Duration of Supply: 15 minutes, if rated full load is being supplied solely from the battery.

B. System Performance When Supplied from Battery: Performance under steady-state and transient-load conditions remains within specified tolerances throughout minimum duration of supply from battery specified.

C. Input Voltage and Frequency Tolerance: System steady-state and transient output performance remains within specified tolerances when steady-state AC input voltage varies plus or minus 10 percent from nominal voltage; when steady-state input frequency varies plus or minus 5 percent from nominal voltage; and when the THD of input voltage is 15 percent, and the largest single harmonic component is a minimum of 5 percent of the fundamental value.

2.5 COMPATIBILITY WITH LOAD

A. Operate within specified performance tolerances, supply type of distribution system indicated, and serve rated load comprised of various load elements. Load elements provide an overall load profile with the following characteristics:

1. Aggregate Load for Single-Phase Electronic Equipment with Switch-Mode Power Supplies, served at 120 or 208 V: 55 percent of UPS capacity.
2. Aggregate Load for Polyphase Electronic Equipment with Switch-Mode Power Supplies, served at 208 V: 5 percent of UPS capacity.
3. Aggregate Load for Fluorescent Lights with Electronic Ballasts having load-current rated at 15 Percent THD: 5 percent of UPS capacity.
4. Aggregate Load for Motors, 3-Phase-Induction Type, Random Across-the-Line Starting: 15 percent of UPS capacity. Largest individual motor full-load kVA is 10 percent of UPS capacity.
5. Aggregate Load for Motors, Single-Phase, Capacitor Start, Induction Run: 5 percent of UPS capacity. Motors operate continuously.
6. Aggregate Load for High-Intensity-Discharge Lighting (High-Pressure-Sodium Type, Photoelectrically Controlled): 5 percent of UPS capacity.
7. Miscellaneous Linear Loads: 10 percent of UPS capacity.

2.6 PERFORMANCE EFFICIENCIES

A. Overall system efficiency, when operated within indicated nominal input- and output-voltage and frequency limits, is within the following minimums **(choose the size for your application)**:

1. 30-kVA and Smaller Systems: 65 percent at 100 percent load, 60 percent at 75 percent load, and 55 percent at 50 percent load.
2. 37.5- to 74-kVA Systems: 78 percent at 100 percent load, 77 percent at 75 percent load, and 75 percent at 50 percent load.
3. 75- to 124-kVA Systems: 84 percent at 100 percent load, 83 percent at 75 percent load, and 82 percent at 50 percent load.
4. 125- to 224-kVA Systems: 88 percent at 100 percent load, 87 percent at 75 percent load, and 86 percent at 50 percent load.
5. 225-kVA and Larger Systems: 90 percent at 100 percent load, 89 percent at 75 percent load, and 88 percent at 50 percent load.

B. Maximum Acoustical Noise: 58 dB, "A" weighting, emanating from the system under any condition of normal operation, measured 36 inches (900 mm) from the nearest surface of the enclosure.

C. Maximum Energizing Inrush: 6 times the full-load current.

D. Maximum Output-Voltage Regulation for loads up to 50 percent unbalanced: plus or minus 2 percent of the full range of battery voltage.

E. Output Frequency: 60 Hz, plus or minus 0.5 percent of the full range of input voltage, load, and battery voltage.

F. Maximum Harmonic Content of Output-Voltage Waveform: 5 percent RMS total and 3 percent RMS for any single harmonic for rated full linear load more than the full range of battery condition and input voltage and frequency.

G. Overload Capacity of System at Rated Voltage: 125 percent of full-load rating for 10 minutes and 150 percent for 10 seconds.

H. Maximum Output-Voltage Transient Excursions from Rated Value: For the following instantaneous load changes, stated as percentages of rated full load, voltage shall remain within the stated percentages of rated value and recover to within plus or minus 2 percent of that value within 100 ms:

1. 50 Percent: Plus or minus 8 percent.
2. 100 Percent: Plus or minus 10 percent.
3. Loss of AC Input Power: Plus or minus 5 percent.
4. Restoration of Input Power: Plus or minus 5 percent.

I. Normal mode (Common mode) EMI noise attenuation range over 10 kHz to 50 MHz range: 60–80 dB. If this attenuation is not attainable, EMI filters at the input and output conductors shall be installed into the UPS equipment.

NOTE : When used in HF and VHF radio receiving sites and sensitive data-processing facilities, all conductors entering and exiting the UPS (including AC, DC, and ground conductors) must meet one of the following EMI requirements:

1. **FCC Class B requirements.**
2. **The conducted current limitations of Section of MIL-STD- 461.**
3. **The conducted current limitations provided by the SNEP program.**

If these limitations are not met by a standard model of an UPS, EMI filters must be added to the input and output power conductors to meet the stated conducted current limitations over the frequency range of 10 kHz to 50 MHz.

2.7 SYSTEM COMPONENTS, GENERAL

A. Description: Solid-state devices using hermetically sealed semiconductor elements. Devices include rectifier/battery charger, inverter, static bypass transfer switch, and system controls.

B. Enclosure: Provide separate cabinets or separate compartments of enclosures for major components such as static bypass transfer switch, rectifier, battery, inverter, and maintenance bypass.

C. Control Assemblies: Mount on modular plug-ins, arranged for easy maintenance.

D. Surge Suppression: Protect UPS system input elements, rectifier/battery charger, inverter, controls, and output components against voltage transients with surge suppressors listed in UL 1449, and tested according to IEEE C62.41, Category B.

E. Power Assemblies: Mount rectifier and inverter sections and static bypass transfer switch on modular plug-ins, arranged for easy maintenance.

F. Design and fabricate internal supports for assemblies, subassemblies, components, supports, and fastenings for batteries to withstand static and anticipated seismic forces in any direction, with the minimum force value used being equal to the equipment weight.

2.8 RECTIFIER/BATTERY CHARGER

A. Capacity: Adequate to supply the inverter during full output load conditions and simultaneously recharge the battery from fully discharged condition to 95 percent of full charge within 10 times the rated discharge time for duration of supply under battery power at full load.

B. Input Current Distortion: Harmonic suppression, either by input harmonic filters or inherent in the rectifier/battery charger design, reduces total harmonic content of the current drawn from the input power source by the system to less than 10 percent for sources with X/R ratios from 2 to 30. This applies for all UPS load currents from 0 to 100 percent of full load.

C. Input Current Distortion: Less than 32 percent THD at rated UPS load. **(change to 10 percent THD)**

D. Rectifier Control Circuits: Immune to frequency variations within the rated frequency range of the system. Response time can be field adjusted for maximum compatibility with local generator-set power source.

E. Battery float-charging conditions, in terms of voltage and charging current under normal operating conditions, are within battery manufacturer's written instructions for maximum battery life.

F. Input Power Factor: At least 0.85 lagging when supply voltage and current are at nominal rated values and UPS are supplying rated full load.

2.9 BATTERY (Choose one type depending on installation application)

A. Description: Valve-regulated, recombinant, lead-calcium units, factory assembled in an isolated compartment of UPS cabinet, and complete with battery disconnect switch.

B. Description: Valve-regulated, recombinant, lead-calcium units, factory assembled in a separate cabinet that matches UPS cabinet in appearance. Equip battery assembly with battery disconnect switch and arrange for drawout removal of the battery assembly from the cabinet for inspection and test.

C. Description: Lead-calcium, heavy-duty, industrial type in styrene acrylonitrile containers mounted on 3-tier, acid-resistant, painted steel racks arranged as indicated. Assembly includes a battery disconnect switch, intercell connectors, a hydrometer syringe, and a thermometer with specific gravity-correction scales.

2.10 BATTERY-MONITORING SYSTEM

A. Battery ground-fault detector initiates an alarm when resistance to ground of positive or negative bus of battery is less than 5000 ohms.

B. Battery compartment smoke/high-temperature detector initiates an alarm when smoke or a temperature greater than 75 deg C occurs within the compartment.

C. Automatically measure and electronically record individual cell voltage, impedance, and temperature, plus total battery voltage and ambient temperature. Measure parameters on a routine schedule selected by the operator. Measure battery and cell voltages and time to the nearest second during battery-discharging events such as utility outages. Monitoring system includes the following:

   1. Factory-wired sensing leads to cell and battery terminals and cell temperature sensors.
   2. Modem and connectors for data transmission via RS-232 link and external signal wiring to a computer. External signal wiring and computer are not specified in this Section.
   3. Software designed to store and analyze battery data using an IBM-compatible computer, which is not specified in this Section. Software reports individual cell and total battery performance trends and provides data for scheduling and prioritizing battery maintenance.

D. Automatically measure and electronically record individual cell voltage, impedance, temperature, and electrolyte level, plus total battery voltage and ambient temperature. Measure parameters on a routine schedule selected by the operator. Measure battery and cell voltages and time to the nearest second during battery-discharging events such as utility outages. Monitoring system includes the following:

   1. Modem for data transmission via RS-232 link and external signal wiring to a computer. External signal wiring and computer are not specified in this Section.

   2. Software designed to store and analyze battery data using an IBM-compatible computer, which is not specified in this Section. Software reports individual cell and total battery performance trends and provides data for scheduling and prioritizing battery maintenance.

2.11 INVERTER

A. Description: Pulse-width modulated, with sinusoidal output. Include a bypass phase synchronization window to optimize compatibility with local generator-set power source.

2.12 STATIC BYPASS TRANSFER SWITCH

A. Switch Rating: Continuous duty at rated full load. Switch provides make-before-break transfer. A contactor or electrically operated circuit breaker in the inverter output provides electrical isolation.

2.13 MAINTENANCE BYPASS/ISOLATION SWITCH

A. Comply with NEMA PB 2 and UL 891.

B. Switch Rating: Continuous duty at rated full load of system.

C. Mounting Provisions: Locate inside one of the modular system cabinets, behind a lockable door.

D. Mounting Provisions: Separate wall- or floor-mounted unit as indicated.

E. Key interlock requires unlocking maintenance bypass/isolation switch before switching from normal position with key that is released only when UPS are bypassed by static bypass transfer switch. Lock is designed specifically for electrical component interlocking.

2.14 OUTPUT DISTRIBUTION SECTION

A. Panelboard: Comply with Division 16 Section "Panelboards" for panelboards with circuit breakers and other features as indicated in a panelboard schedule. Match and align panelboard cabinet with other UPS cabinets.

2.15 INDICATION AND CONTROL

A. General: Group displays, indications, and basic system controls on a common control panel on the front of UPS enclosure.

B. Minimum displays, indicating devices, and controls include those in lists below. Provide sensors, transducers, terminals, relays, and wiring required to support listed items. An audible signal sounds for alarms as well as the visual indication.

C. Indications: Labeled LED display.

D. Indications: Plain-language messages on a liquid crystal or digital LED display.

  1. Quantitative Indications: Include the following:

     a. Input voltage, each phase, line to line.
     b. Input current, each phase.
     c. Bypass input voltage, each phase, line to line.
     d. Bypass input frequency.
     e. System output voltage, each phase, line to line.
     f. System output current, each phase.
     g. System output frequency.
     h. DC bus voltage.
     i. Battery current and direction (charge/discharge).
     j. Elapsed time-discharging battery.

  2. Status Indications: Include the following:

     a. Normal operation.
     b. Load on bypass.
     c. Load on battery.
     d. Inverter off.
     e. Alarm condition exists.

  3. Alarm Indications: Include the following:

     a. Bypass AC input overvoltage or undervoltage.
     b. Bypass AC input overfrequency or underfrequency.
     c. Bypass AC input and inverter out of synchronization.
     d. Bypass AC input wrong-phase rotation.
     e. Bypass AC input single-phase condition.
     f. Bypass AC input filter fuse blown.
     g. Internal frequency standard in use.
     h. Battery system alarm.
     i. Control power failure.
     j. Fan failure.
     k. UPS overload.
     l. Battery-charging control faulty.
     m. Input overvoltage or undervoltage.
     n. Input transformer over temperature.
     o. Input circuit breaker tripped.
     p. Input wrong-phase rotation.
     q. Input single-phase condition.

r. Approaching end of battery operation.
s. Battery undervoltage shutdown.
t. Maximum battery voltage.
u. Inverter fuse blown.
v. Inverter transformer over temperature.
w. Inverter over temperature.
x. Static bypass transfer switch over temperature.
y. Inverter power-supply fault.
z. Inverter transistors out of saturation.
aa. Identification of faulty inverter section/leg.
ab. Inverter output overvoltage or undervoltage.
ac. UPS overload shutdown.
ad. Inverter current sensor fault.
ae. Inverter output contactor open.
af. Inverter current limit.

4. Controls: Include the following:

   a. Inverter on-off.
   b. UPS start.
   c. Battery test.
   d. Alarm silence/reset.
   e. Output-voltage adjustment.

E. Analog Meters: Accurate within 2 percent.

F. Dry Form "C" Contacts: Available for remote indication of the following conditions:

1. UPS on battery.
2. UPS on-line.
3. UPS load on bypass.
4. UPS in alarm condition.

G. Remote Status and Alarm Panel: Labeled LEDs indicate conditions listed above. Audible signal indicates alarm conditions. Silencing switch in face of panel silences signal without altering visual indication.

1. Cabinet and Faceplate: Surface- or flush-mounted to suit mounting conditions indicated.

2.16 REMOTE UPS CONTROL AND MONITORING SYSTEM

A. Description: A remote microprocessor for the unit control panel to indicate alarms and to control as specified in "Indication and Control" Article above. Record power-line transients and provide analytical capability. Include the items described below, but do not include the remote computer or the connecting signal wiring. System includes the following:

1. Modem and connectors for data transmission via RS-232 link and external signal wiring to a computer. External signal wiring and computer are not specified in this Section.

2. Software designed to secure control and monitoring of UPS functions and to provide on-screen explanations, interpretations, and action guidance for monitoring indications. Include on-screen descriptions of control functions and instructions for their use. Permit storage and analysis of power-line transient records. Design for an IBM-compatible computer, which is not specified in this Section.

2.17 MECHANICAL FEATURES

A. Enclosures: NEMA 250, Type 1.

B. Ventilation: Redundant fans or blowers draw in ambient air near the bottom of the cabinet and discharge it near the top rear.

2.18 SOURCE QUALITY CONTROL

A. Factory test complete UPS, including battery, before shipment. Include the following tests:

1. Functional test and demonstration of all functions, controls, indicators, sensors, and protective devices.
2. Full-load test.
3. Transient-load response test.
4. Overload test.
5. Power failure test.
6. Efficiency test at 50, 75, and 100 percent loads.

B. Observation of Test: Give 14 days advance notice of tests and opportunity for Government's representative to observe tests.

C. Report test results. Include the following data:

1. Description of input source and output loads to be used. Describe actions required to simulate source load variation and various operating conditions and malfunctions.

   2. List of indications, parameter values, and system responses considered satisfactory for each test action. Include tabulation of actual observations during test.
   3. List of instruments and equipment required to duplicate factory tests in the field for those tests required to be repeated there.

PART 3 - EXECUTION

3.1 INSTALLATION

A. Install system components on 4-inch- (100-mm-) high concrete housekeeping bases. Cast-in-place concrete, reinforcing, and formwork are specified in Division 3.

B. Maintain minimum workspace at equipment according to manufacturer's written instructions and NFPA 70.

C. Connections: Interconnect system components. Make connections to supply and load circuits according to manufacturer's wiring diagrams, unless otherwise indicated.

3.2 IDENTIFICATION

A. Identify components according to Division 16 Section "Electrical Identification."

   1. Identify each battery cell individually.

3.3 FIELD QUALITY CONTROL

A. Manufacturer's Field Service: Supervision of unit installation, connections, tests, and adjustments by a factory-authorized service representative. Report results in writing.

B. Manufacturer's Field Service: Supervision of unit installation, connections, pretests, and adjustments by a factory-authorized service representative. Report results in writing.

C. Supervised Adjusting and Pretesting: Under supervision of a factory-authorized service representative, pretest system functions, operations, and protective features. Adjust to ensure operation complies with specifications. Load the system using a variable-load bank simulating kVA, kW, and power factor of loads for which unit is rated.

D. Tests: Perform tests listed below by an independent testing agency meeting the qualifications specified in the "Quality Assurance" Article. Perform tests according to the manufacturer's written instructions. Load the system using a variable-load bank to simulate kVA, kW, and power factor of loads for the unit's rating. Use instruments calibrated, within the previous 6 months, according to NIST standards.

1. Simulate malfunctions to verify protective device operation.
2. Test duration of supply on emergency, low-battery voltage shutdown, and transfers and restoration due to normal source failure.
3. Test harmonic content of input and output current less than 25, 50, and 100 percent of rated loads.
4. Test output voltage under specified transient-load conditions.
5. Test efficiency at 50, 75, and 100 percent rated loads.
6. Test remote status and alarm panel functions.
7. Test battery-monitoring system functions.

E. Retest: Correct deficiencies and retest until specified requirements are met.

3.4 CLEANING

A. On completion of installation, inspect system components. Remove paint splatters and other spots, dirt, and debris. Repair scratches and mars of finish to match original finish. Clean components internally using methods and materials recommended by manufacturer.

3.5 DEMONSTRATION

A. Engage a factory-authorized service representative to train Government's maintenance personnel as specified below:

1. Train Government's maintenance personnel on procedures and schedules related to startup and shutdown, troubleshooting, servicing, and preventive maintenance.
2. Review data in the operation and maintenance manuals. Refer to Division 1 Section "Contract Closeout."
3. Review data in the operation and maintenance manuals. Refer to Division 1 Section "Operation and Maintenance Data."
4. Schedule training with Government, through COR, with at least 7 days advance notice.

3.6 COMMISSIONING

A. Battery Equalization: Equalize charging of battery cells according to manufacturer's written instructions. Record individual cell voltages.

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   Naval Postgraduate School
   Monterey, CA

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