AD-787 482

EMP (ELECTROMAGNETIC PULSE) PREFERRED TEST PROCEDURES

SELECTED ELECTRONIC PARTS

IIT RESEARCH INSTITUTE

PREPARED FOR

DEFENSE NUCLEAR AGENCY

29 AUGUST 1974

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AD 787 482

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DNA 3286H	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EMP PREFERRED TEST PROCEDURES (Selected Electronic Parts)		5. TYPE OF REPORT & PERIOD COVERED Handbook
		6. PERFORMING ORG. REPORT NUMBER IITRI Project E6230
7. AUTHOR(s) J. E. Bridges, W. C. Emberson		8. CONTRACT OR GRANT NUMBER(s) DNA 001-72-C-0089
9. PERFORMING ORGANIZATION NAME AND ADDRESS IIT Research Institute, 10 West 35th Street, Chicago, Illinois 60616		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NWED Subtask K99QAXEB097-07
11. CONTROLLING OFFICE NAME AND ADDRESS Director, Defense Nuclear Agency, Washington, D.C. 20305		12. REPORT DATE 29 August 1974
		13. NUMBER OF PAGES 182
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

DDC
OCT 19
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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

EMP Hardening
EMP Tests
EMP Hardening Component
EMP Surge Arrestors
EMP Filters
EMP Specifications

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Recommended EMP Test Procedures are provided to evaluate or characterize the performance of filters or surge arrestors. Areas covered in detail are experiment design, documentation, representative EMP induced transients, and test procedures to evaluate the EMP behavior of surge arrestors and filters.

182

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19. KEY WORDS (Continued)

Surge Arrestor Characterization
Filter Characterization
Surge Arrestor Damage
Filter Damage

SUMMARY

IIT Research Institute, under contract to the Defense Nuclear Agency (DNA001-72-C-0084), has developed EMP PREFERRED TEST PROCEDURES for surge arrestors and filters. This is part of a continuing program to formulate and recommend procedures by which EMP test data on selected hardening components may be obtained and reported.

In this connection, it is important to realize what these preferred procedures are and what they are not. They are a formal recognition of good practices and methods based on sound physical principles which can lead to useful EMP data. They provide a means of communicating useful information among workers in a large multidisciplined technology.

These preferred procedures are not necessarily cook-book simplifications and are not intended to be a "MIL-SPEC" or a panacea for designers of hardened systems. The EMP PREFERRED TEST PROCEDURES require some experience and intelligence on the part of the experimenter. These are somewhat different than "MIL-SPEC" testing which can usually be implemented by a responsible technician. The procedures emphasize the electrical test aspects. Some general guidance as to limits and other environmental aspects is provided; however, these last aspects are more properly considered in terms of the requirements for a specific system, such as design specifications. The procedures are designed to employ readily available or easily constructed laboratory equipment -- generally operating below 100,000 volts and 100 MHz -- and to be conducted in ordinary room-size laboratory space.

The material contained in this document is considered the best available and, where possible, it represents a concensus of recognized practices. Based on discussions with prominent members of the EMP community as well as other experts, a preliminary outline of the procedures was devised and actual

tests conducted to validate the procedures. A draft of the procedures was developed and then circulated among cognizant professionals in a number of organizations, and revised as needed to harmonize various viewpoints. While the results in this document are based on the experience of a number of active recognized professionals, it must be noted that all possible situations could not be considered. Clearly, it is not the intent of this document to impose "National EMP Standards and Limits." Even if these were desirable, it would not be appropriate to do so today because of the rapid changes taking place in the state-of-the-art. In this regard, it is important that others take an active part in supplying additional information to effect improvements.

PREFACE

Much of the work presented in the first three sections in this edition of the EMP Preferred Test Procedures was summarized directly from DNA Document 2028H, entitled "TREE Preferred Procedures." IIT Research Institute, therefore, gratefully acknowledges the efforts of Mr. Richard H. Thatcher and Mr. Michael L. Green at the Battelle-Columbus Laboratories for their efforts on DNA 2028H.

Discussions were also held with staff members of a number of organizations in EMP hardening. All organizations cannot be acknowledged, but include U.S. Army Electronics Command, Picatinny Arsenal, Naval Ordnance Laboratory, Harry Diamond Laboratories, Defense Communications Agency, Air Force Weapons Laboratory, Defense Civil Protection Agency, Boeing Aircraft Corporation, Rockwell Industries, General Semiconductor Industries, Siemens Corporation/Signalite, Joslyn Electronic Systems, Sandia Laboratory, and Stanford Research Institute.

The principle contributors to this document are Mr. W. C. Emberson and Mr. J. E. Bridges. Much of the laboratory work was conducted by Mr. S. Smandra and the technical management was provided by Mr. I. N. Mindel.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

1. GENERAL INFORMATION

TABLE OF CONTENTS

1. GENERAL INFORMATION

1.1 Background

The electromagnetic pulse (EMP) technology covers a wide range of scientific and engineering disciplines. In the past, the EMP community comprised a relatively small group of researchers and experimenters who could easily communicate and exchange information. However, now that many systems must meet EMP specifications, the community is expanding and reorienting itself toward more systems applications. Hence, a primary goal of much of the experimental work pertaining to EMP is gathering information needed to fill the gap between state-of-the-art information already available and the requirements of a specific system. Obviously, it is neither desirable nor efficient to unnecessarily duplicate experimental work. On the other hand, it is usually not economically possible to acquire experimentally all the data in a particular region of interest that might be desirable from the viewpoint of a regular scientific research study. The Defense Nuclear Agency (DNA) has recognized the need to exert a unifying influence on the EMP community to achieve a more efficient utilization of experimental and financial resources.

In pursuit of this task, DNA has undertaken a program to bring to the attention of those involved in planning, design, manufacturing, quality control and maintenance those procedures in testing and experimentation which experience has shown to be most likely to yield useful results that can be correlated with other work in the same area. To this end, this document is meant to provide persons conducting EMP tests with recommended procedures for evaluating the performance of selected hardening components.

1.2 Philosophy

Wherever possible, the recommendations in this document are a consensus of current good practice. Many people in the EMP field, in electronics-system design and in protection-device manufacturing were contacted. Their opinions and methods were evaluated and judiciously merged to form the basis for this work.

The results presented are considered neither controversial nor "far out". Many of the procedures recommended here are already followed by various competent groups involved with EMP. In other cases, new procedures had to be developed. If one procedure is obviously best, it is recommended; if several procedures are equally acceptable, all are presented for the user's choice. The object has been to formulate and recommend procedures by which EMP test data on selected hardening components may be obtained and reported.

In this connection it is important to realize what these preferred procedures are, and what they are not. They are a formal recognition of good practices and methods based on sound physical principles which can lead to useful EMP data. They provide a means of communicating useful information among workers in a large multidisciplined technology, so that people in different subspecialties will be able to use one term in place of various specialty terms to better understand one another.

These preferred procedures are not necessarily simplifications. They are not the formulation of recipes by which a person unfamiliar with EMP can become an expert chef by "cooking" up new data. They are not a panacea for hardened-system designers, electronic engineers who do not want to understand physics, or physicists who do not want to bother with applications. Sound scientific judgement and a basic understanding of the problems still are necessary attributes for the EMP experimenter.

This document is prepared as an integral part of a series of documents sponsored by DNA to assist and guide the EMP community. Other documents in this series are the EMP Awareness Course Notes, and volumes 1 through 4 of the EMP Handbook.

It is assumed that the users of this document will have access to the other documents in this series. The intelligent use of these preferred procedures relies on the user being familiar with the information contained in the other documents. Therefore, a thorough review of the pertinent subjects in the EMP Handbook is strongly recommended as a first step in planning any EMP experiment

1.3 Use of This Document

1.3.1 Who Should Use this Document

The procedures developed in this document should provide valuable assistance to those involved in a number of EMP areas. These include: (1) System and circuit designers in need of quantitative data on hardening components; (2) System engineers and project officers who perform trade-offs to formulate acceptance criteria and performance specifications; (3) Systems analysts in need of empirically characterized response models of hardening components; (4) Component manufacturers who can provide response data of EMP significance; and (5) Experimenters in EMP who perform or define tests. In addition, those responsible for manufacturing quality control systems, subsystem acceptance, and system maintenance will also find the preferred procedures a useful guide.

The procedures have been evolved such that the tests can be conducted on a laboratory basis using equipment that is generally available. Specifically, the procedures are designed to be conducted in room sized laboratory space using equipment whose output voltage does not exceed 100,000 volts or has a frequency response above 100 MHz. In some cases, this has resulted in departing somewhat from the ideal electrodynamic or circuit theory aspects. An attempt has also been made to satisfy a wide spectrum of user's interests ranging from the need for quick-look comparative performance data to development of empirical models of hardening components for sophisticated analyses.

1.3.2 User Responsibility

It should be realized that the material contained in this document is considered the best available at the present time; however, as the state-of-the-art advances, so will test and experimental procedures. As a result, this document will evolve as improvements are realized and a broader need for component-part testing is recognized. It is important that the experimenter realize this and (1) use only the most recent edition of the

Preferred Test Procedures, and (2) take an active part in supplying new information to effect improvements. Only in this way can this document grow in sophistication and utility.

The user should also realize that he bears the burden when simplifying or deviating from the suggested procedures. That is, he must justify any deviations from the suggested procedures and report his work in sufficient details to explain the deviations completely.

1.4 Limitations

This document covers only those effects of EMP induced transients which pertain to electrical behavior and not the chemical or physical changes that may occur. Further, the electrical behavior may well be a strong function of some features of the non-electromagnetic environment such as vibration, dust, corrosion, wear, packaging, or misuse. These non-electromagnetic environments are generally unique to a specific system, and it is impractical to consider these aspects on a general basis. The procedures can, however, be used to investigate the sensitivity of hardening components to the non-electromagnetic environments.

Further, large-scale or high-volume testing was not considered in the description of the test procedures. The principles presented in this document are applicable to high-volume testing. However, instrumentation for this type of testing probably will have to be specially designed, unless the laboratory facility to be used already has such equipment and it is applicable to the test program.

It should be understood that these component part measurement procedures were established to apply principally to design data acquisition and reporting and, where appropriate, to the development of empirically developed response models of components. The uniform procedures are not designed for full scale EMP simulation tests. For some theoretical studies the experimenter may want to investigate new phenomena or methods which would require use of different procedures or would study other parameters than those discussed here. In any case, the detailed experimental procedures actually used must be reported completely enough for another person to understand and repeat the experiment.

It must also be recognized that the preferred test procedures are not mil-spec or a cookbook standard of acceptance procedures, No limits are specified although ranges of likely values are noted. It is therefore up to the system, subsystem, or component designer to identify suitable test parameters. The procedure can be used as the basis for the electrical aspects of "MIL-SPECS" provided that limits are identified and all non-electrical environment conditions are noted.

2. EXPERIMENTAL DESIGN

TABLE OF CONTENTS

2. EXPERIMENTAL DESIGN

2.1 Introduction

It should be recognized that the preferred test procedures are only a portion of larger scale efforts. These efforts may range from simply designing new EMP hardening components to assessing the response of some portion of an EMP hardened system. Prior to conducting specific tests on components by employing the preferred test procedures, it is often desirable to identify the role and use of the preferred test procedures leading to the desired objectives. In a large organization it is often wise to identify this role by documentation.

This kind of documentation specifies experimental work to be accomplished and the results to be expected. It also provides a basis for integrating the experimental work into a development program in an efficient and effective manner.

In such a document it may be desirable to identify the protection levels required for various hardening components. In addition, the reliability of the test results should also be specified to be consistent with the available funding and time limitations.

2.2 Experimental Design Principles

Whether a small component or a very large system is involved, the role of the preferred test procedures in the overall EMP hardening must be considered. While these are self-evident, the following categories of questions may be useful to review:

1. Experimental purpose: What is the problem?
2. Experimental objectives: What information is needed to solve the problem?
3. Pretest analysis procedures: What analysis or prediction methods can be used to produce this information? How valid is the theory?

4. Requirements for experimental data: What experimental data are needed to solve the problem or some aspect of it?

5. Experimental procedures: What must be done experimentally to obtain these data?

6. Post test analysis: How are the data best analyzed in the required terms for this problem?

The role of analysis to support various experimental procedures has often been emphasized. Although uniform procedures have been identified, it does not mean that analyses can be neglected. To be meaningful the preferred test procedures must be utilized at some specified level of fields, currents, or voltages. These are clearly a function of the type of system or subsystem under consideration and cannot be uniquely identified in a general purpose document. Section 4 of this document presents some guidance in this particular area. The use of more applicable analytical results or use of analyses directly for this purpose are strongly recommended.

Study and analyses are also required such that a thorough understanding of the hardening component is realized. This is necessary such that meaningful evaluations of the performance of the hardening component can be made during the test. Some guidance is given in this particular area in each of the subsequent preferred test procedures. However, all aspects of the particular component or protective subsystem cannot be identified and therefore careful review prior to conducting the test in this area is necessary.

As a result of such studies, experimental data requirements can be identified. This specifically identifies the types and quantities of the samples, accuracies, operating conditions, environments, and other parameters relating to the test. Also the analyses will set forth the format, the list of required parameters and their dependencies, the accuracies, the number of test items, environmental ranges, and possibly any contractual requirements such as traceability to calibration standards.

One of the major problems in evaluating subsystems or components is the fact that the critical parameters vary within each component or subsystem. Therefore. statistical design considerations should be considered. These will identify the proper controls, the number of test groups sample lot sizes to meet the system confidence requirements. In critical systems the assignment of test sample sizes is not a trivial problem, nor can statistical methods be blindly applied to the EMP experimental design. One reason for this is that the distributions of the device parameters are likely not to be normal but rather truncated by manufacturers process control and screening tests. Another reason is that many of the tests envisioned will be designed to elicit device parameters as function of operating conditions and environments, rather than in terms of failure level or go-no-go criteria.

The general aspects of experimental procedures are undoubtedly well recognized. Specific details of the test procedure are function of variables, but several factors should should be considered and these are: (1) specific means for eliminating or controlling sources of systematic errors; (2) descriptions of the experimental subtasks and how these tasks integrate into the whole test to produce the desired result; (3) precision or calibration requirements.

These and other factors are self-evident, however, some thought should be given in detail in two major areas and these are: (1) statistical design of the experiment to account for individual parameter variations and (2) experimental technique consideration.

2.3 Experimental Design

The selection and specification of analysis procedures for an experimental design is primarily an engineering responsibility. The engineer should consult appropriate references in the speciality with which the experiment is concerned as well as more general references concerned with experimental design, data analysis, and statistics as appropriate.

For the preferred measurement procedures given in this document, the data reduction and analysis techniques usually are defined inherently by the experiment. In this process of data reduction, it is important to track the sources of uncertainty and error. Then the results and probable errors are quoted. This data reduction process is clear for the problem of determining response of one or a few devices.

The experimental design should also include sample size considerations. This is a subject in itself and has been thoroughly treated in the area of quality control. Several references in this area should be consulted, such as MIL-STD 19500 or 38510 for sampling plans and acceptance criteria.

The quest might have been, however, not simply to determine the response of one device, but rather to determine what is the expected response distribution of a population of devices of which a sample was selected for test? This question involves the entire test design to ensure proper sampling of the population, proper measures to control errors, etc., as well as the analysis of the response data of the subjected group(s) of devices. In this case, some statistical interpretations will have to be made.

One desired engineering result for EMP test data is often curves of failure level versus a factor such as pulse width. This involves fitting a curve to the measured (and reduced) data. It is convenient to express the data in terms that theoretically could be plotted linearly. Then, least squares and regression analysis can be used to determine how well the data fit, what slopes and intercepts are given with confidence, etc. More simply, such curves can be "eyeballed" if the statistical detail is not needed.

When the curves are not linear and/or the functional relations are not analytical, the purpose of the experiment will usually determine what effort is worthwhile in performing more complex statistical analyses.

For "go-no-go" tests, such as acceptance screening of parts by testing for certain parameter (or a few such parameters), the statistical design of the test is generally easier to establish. Here, the distribution of data is binomial and the techniques are well established. The part either passes or fails a test, depending on the response. But the parts-response distribution itself is not the entity in view; the data are the "passes" or "fails", a "go" or a "no go" for a given test item, or a fraction passing, p, and failing, q = 1-p in the population. Based on the number of failures in a sample drawn from the parts lot being accepted and on the system requirements, determination of the probability that the population failure rate will be within specified limits, using binomial distribution statistics, is straightforward.

For system assessment work, it is more likely that only a few parts can be found for tests, and the analysis technique must glean the most information from the test. This calls for careful test design and, perhaps, the use of "small sample" statistics and tolerance factors - an area for a specialist.

As stated previously, the experimental design should include a detailed specification of the methods to be used to evaluate measurement errors and experimental accuracy. For further guidance in the development of this section of the experimental design, the engineer is referred to the discussions of the nature of error and sources of experimental error by J. W. Richards in Interpretation of Technical Data.

2.4 Experimental Technique Considerations

In the normal process, the experimenter must first consider how to characterize the electronic device to be tested. Then he must measure the selected response of the device. In making this measurement there are several important points to be considered. These include choosing the proper operational mode for the device while it is being tested although this is generally not possible between pre and post vs. in situ measurements which are added considerations.

The measurements to be performed on the test device before subjecting it to a transient are generally of two types. Mandatory are those measurements in which the important transient-induced changes are expected to occur. For example, the change in the d.c. breakdown voltage is almost always a part of the EMP evaluation tests of a surge protective device. In addition to these measurements, it is desirable to perform other measurements by which the particular test device can be characterized. It is known that even within a particular device type number there are large variations of individual device characteristics. These are usually within the parameter specifications, but occasionally one finds devices whose characteristics fall outside of the specifications under which the devices were supposedly manufactured. Since it is desirable to be able to associate the pulse response with prepulse measurements, it is good practice to include in the parts characterizations those parameters which are likely to be correlated with the pulse response.

Depending upon data requirements, it may be necessary to exercise some control over the samples obtained from the device manufacturer. Samples with identical construction but with tighter initial-parameter spreads may be required to satisfy system specifications for the intended application and to obtain greater internal consistency in the test results. If controlled samples are used, it is important to identify them as accurately as possible when reporting test results.

There are several ways in which permanent-damage tests can be conducted. Tests in which parameter measurements are made only before and after the samples are pulse tested are called "pre/post tests". They serve to establish the damage incurred at a single pulse level. Since the samples are normally not energized during pulsing, these tests are the most convenient, least complex, and least expensive tests to perform. Such pre/post tests are useful as proof tests to establish adequate device performance at a given pulse level, as long as time dependence and bias dependence are not important.

Data may be obtained at several pulse levels by simply repeating a pre/post test as many times as desired, or by exposing different groups of samples to various pulse levels. The first procedure is more time-consuming and, since it involves repeated pulsing, may result in a different failure level. Due to differences in the pulse response of different experimental samples, certain parameter data obtained by exposing different samples to increasing pulse levels may exhibit a lack of internal consistency (i.e., there may not be a smooth pattern of parameter change with increasing pulse exposure.) Also, it has been observed that when extended periods without pulsing are present during a test, the sample parameter values sometimes change (due to defect annealing) so that data taken before and after the cessation do not correlate well. Therefore, measurements should be made at the beginning and end of such periods, if possible.

Tests in which the experimental samples are instrumented so that parameter measurements can be made without removing the samples from pulse test set-up are called "in-place tests". They serve to characterize the pulse response at various pulse levels and/or at specific time intervals during and after pulse exposure. The test equipment requirements make in-place testing more complicated and more expensive than pre/post tests.

While for permanent damage measurements, the choice of pre/post vs. in situ experiments is optional, it is obvious that with transient effect data the measurements have to be performed during and immediately after the pulse. The test circuit can affect the observed response by intentional or inadvertent loading of the terminals of the device. For this reason, it is necessary to accurately report the electrical loading of the device under test.

A very critical step in the process of EMP testing is determining what constitutes significant response and failure of a device. The system requirements obviously must be used to define component failure. Usually these failure criteria are much lower than would be normally expected because of circuit tolerances which are used to establish a "worst-case" failure criterion. The failure criteria for the components of a given system must be carefully determined by considering all electrical parameters of a device in its system application. The necessity of each specification limit must be carefully considered, because if the required specification is too strict, a heavy cost may result when devices are selected which are hard to the required level.

Conducting transient response experiments presents some severe problems to the experimenter. Generally, these experiments require transmitting small signals in the vicinity of a powerful pulse source. Careless handling of the signals can result in the loss of data, or in questionable data. Therefore, it is mandatory that the experimenter maintain as high a signal-to-noise ratio as possible.

Techniques used to minimize noise in electronic systems are fairly well understood, although often disregarded. General methods of realizing good experimental practices are described in the EMP Awareness Course Notes, Section VII. Specific experimental practices critical to a particular procedure are presented with the procedure. A few general comments are given in the following paragraph.

As few ground points as possible should be used, preferably only one. To be effective, this connection must have a very low inductance; otherwise, there will be a significant voltage buildup during the pulse which can then be coupled to the measuring circuit. High-frequency signals should be handled in a coaxial configuration with the shield being continuous. Transmitting high frequency pulse signals over coaxial cable runs requires that the cables be properly terminated in their characteristic impedances to insure that they faithfully reproduce the desired signal. In extreme electromagnetic fields, the experimental equipment should be enclosed in shielded boxes, with the interconnecting cables between equipments enclosed in a continuous shield, again grounded at only one point. Where it is necessary to provide 60-Hz power to some portion of the experiment, the low side of the 60-Hz power should not be connected to or used as the signal return line. If noise is being injected into the system through the 60-Hz line, a well designed filter or an isolation transformer may be sufficient to suppress the noise. In cases where these solutions fail, a battery pack and inverter should be used.

The EMP test measurement results can be very sensitive to lead length or terminal fattering (i.e., excess inductance or capacitance). For example, an excess of one inch length of number 20 lead wire can completely perturb the result of an EMP bench test on a surge arrestor. Extension of the measurment techniques normally employed at UHF or microwave down into the EMP spectral region will yield better and more consistent measurement results. A good rule-of-thumb is to design all elements of the test fixture as transmission lines with very nearly the same characteristic impedance. Also, ideal "short circuits" or "open circuits" do not exist. These aspects are often difficult for personnel whose experience has been limited to CW or the lower frequency regions to grasp.

Additional obvious precautions require such things as allowing sufficient warm up time to avoid drift, or proper calibration of instruments. If large amplitude pulses are employed, safety precautions are necessary. As noted earlier, the preferred test procedures require some expertise and intelligence on the part of the experimenter. Later on, these procedures may evolve into "MIL-SPECS" which can be implemented by technicians.

3. DOCUMENTATION REQUIREMENTS

TABLE OF CONTENTS

3. DOCUMENTATION REQUIREMENTS

3.1 Introduction

The inherent, unstated objective of any report should be to make clear to the reader the value and accuracy of the information contained in it. The entire effort of an expertly conducted experiment can be nullified if time and space is not taken to report the experiment in a manner that can be critically evaluated - by indicating the way in which the experiment was planned and performed, how the data were analyzed, and establishing a basis for the conclusions reached.

This section covers the general information normally required in an EMP effects experimental report. No attempt is made to detail all the specific information that may be required; certainly a good deal of judgment in this regard is required of the report writer as he assesses his particular test circumstances. However, some of the following sections do point out many minimum specific details that normally should be reported.

It is assumed that the experimentalist preparing the report is familiar with technical writing and the typical structure of a technical report. Occasionally the sponsoring agency will have a standard report format that must be followed. In all cases, however, the report should contain clear statements of the experimental purpose(s) and experimental objectives, a description of what was done and how it was done, and a concise but complete presentation of the test results and conclusions. Adequate information is particularly important in areas discussed below.

3.2 Plans and Procedures

The objectives of the experiment and the planned method of obtaining these objectives should be briefly but completely described. Items to be included are:

(1) A brief statement - with references if necessary - of any theory pertinent to the experimental design, including any assumptions made and their justification.

(2) A description of the experimental technique and apparatus. This may be simplified by referencing the preferred test procedure. Other aspects may include special equipment fabricated for the experiment, and the accuracy and date of calibration of all test equipment.

(3) Any precautions taken to assure the accuracy and precision of measurements, including precautions taken to exclude or limit extraneous variables.

(4) A description and justification of any deviations from the experimental design, the causes thereof and remedial measures taken.

(5) A description, with an example if necessary, of how the raw data were converted to the form used for analysis.

3.3 Experimental Samples

All basic types of samples should be described. A good technique to follow is to prepare a distinct report section that, for the various types of samples, presents the manufacturer, type or specification number, lot number, origin (factory, distributor, etc.), the number of samples in each category, and method of selection and validation. The importance of this information cannot be overemphasized. Include as an appendix any specification by which parts were selected or have a reference to where such data are available. In addition, any pertinent information about the history of the sample before testing it, such as previous exposure to transients, must be noted.

3.4 Sample Conditions During Measurements

The operational state of the samples and the environmental conditions that the samples were exposed to from the time the samples entered the program until the last measurement was made should be defined in the report. Specifically, this includes such items as electrical operating point; temperature during measurement; mounting configuration, a description of any potting used; etc. Photographs of special purpose equipment setups, mounting fixtures, etc., are recommended.

3.5 Test Results

General Requirements

The test results are the most important part of a report. They are the reason the experiment was performed. It is essential that they be reported as clearly and explicitly as possible. To make the report more comprehensible the results are usually presented in a condensed tabular or graphical form in the main part of the report. Even so, all of the basic (raw) data should be documented either as an appendix to the main report or in a separate report. Suggested formats for recording data are given for each procedure. Use of these formats will assist the experimenter in remembering to take all the necessary information and will put the data in a standardized form more readily usable by others. Charts, curves, and graphs are normally very helpful and desirable, but they should only supplement, not replace, basic data tabulations.

In planning an experiment, a theoretical model is usually selected to predict the effect to be expected. The reduced form of the data should then be chosen on the basis of the theoretical model, to reflect the expected dependence upon the relevant parameters.

A measurement set is defined as the data taken on a group of samples of the same type in a given combination of test conditions. It is essential that, when the data for a measurement set are presented, all qualifying test conditions be given specifically. If a reported quantity was not being measured directly, the method of analysis or evaluation should be given.

3.6 Analysis

A statement should be given as to the constancy of any control samples used. The estimated uncertainty in all important results should be quoted. In specifying errors, the value of one standard deviation is the quantity preferred, although other methods may be used if they are more suitable and are unambiguous. When statistical characterizations are given, at least a reference should be cited which explains the techniques involved.

4. REPRESENTATIVE EMP INDUCED TRANSIENTS

TABLE OF CONTENTS

4. REPRESENTATIVE EMP INDUCED TRANSIENTS

4.1 Introduction

In order to intelligently evaluate the effects of EMP on various system components and the effectiveness of hardening techniques or protective devices, one must be familiar with representative EMP induced transient and collector or source impedances. The actual EMP threats are classified; therefore, any calculations performed with these actual EMP threats would also be classified. It should be noted that such calculations are presented in the DNA EMP Handbook and should be used as additional guidance in the evaluation of EMP effects.

Although the actual EMP threats are classified, some of the basic characteristics of a representative EMP from a high altitude burst have been published in unclassified literature;

"A representative electromagnetic pulse from a high altitude burst will typically have maximum field strengths near the ground on the order of 50 KV/meter, time duration on the order of a microsecond and rise times on the order of 10 nanoseconds, resulting in broad frequency effects to systems and equipments and dampened exponential ringing of circuits at their fundamental and harmonic frequencies."(1)

In order to keep this document unclassified, the representative EMP transients presented in this document were calculated using this unclassified waveform. Further, the calculations were performed for the idealized case of a vertical monopole antenna with an infinite, perfectly conducting ground plane. Therefore, the representative EMP induced transients presented in this document should only be used as general guidance in cases where more realistic or appropriate information is not available.

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(1) Department of Defense/Office of Civil Defense, TR-61-B, EMP Protective Systems, November, 1971.

4.2 Specific Calculations

A limited analysis was performed using the fourier transform method* to develop representative EMP induced transients for the EMP waveform discussed above. The specific calculations that have been performed are as follows:

(1) For the idealized case of vertical monopole antennas, assuming broadside incidence and the EMP polarized parallel to the antenna with resonant frequencies of:

f_o = 100, 250, 500 KHz

f_o = 1, 2.5, 5, 10, 25, 50, 100 MHz

The following items were calculated and plotted for the 250 KHz, 2.5 MHz, and 25 MHz monopoles:

- Time history of the open circuit voltage (Figures 4-1 through 4-3)
- Time history of the short circuit current (Figures 4-4 through 4-6)
- Time history of the load voltage for a 50 Ω load (Figures 4-7 through 4-9)
- Energy dissipated in the 50 Ω load (Values given on Figures 4-7 through 4-9)

(2) From the calculations, the following parameters were determined and plotted:

- Peak open circuit voltage versus resonant frequency (Figure 4-10)
- Rise time of the open circuit voltage versus resonant frequency (Figure 4-11)
- Rate of rise of the open circuit voltage versus resonant frequency (Figure 4-12)
- Decay time of the open circuit voltage versus resonant frequency (Figure 4-13)
- Peak short circuit current versus resonant frequency (Figure 4-14)

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*IITRI Final Report, Project E6114, "Effects of EMP Environment on Military Systems", Contract No. DAAK02-68-C-0377, U.S. Army Mobility Equipment Research and Development Ctr., Ft. Belvoir, Va.

- Rise time of the short circuit current versus resonant frequency (Figure 4-15)
- Rate of rise of the short circuit current versus resonant frequency (Figure 4-16)
- Decay time of the short circuit current versus resonant frequency (Figure 4-17)
- Peak 50Ω load voltage versus resonant frequency (Figure 4-18)
- Rise time of the 50Ω load voltage versus resonant frequency (Figure 4-19)
- Rate of rise of the 50Ω load voltage versus resonant frequency (Figure 4-20)
- Decay time of the 50Ω load voltage versus resonant frequency (Figure 4-21)
- Energy dissipated in a 50Ω load versus resonant frequency (Figures 4-22 and 4-23)
- Collector or source impedance versus normalized frequency (Figure 4-24)

4.3 Discussion of Results

In cases where more realistic or appropriate data is not available, the representative EMP induced transients presented in this section should be used as general guidance for establishing rise times, rate of rise, pulse amplitudes, decay times and source impedance to be employed in the preferred test procedures. Obviously, a great deal of engineering judgement is required for the appropriate use of these calculations. Further, these calculations by no means represent the entire range of transients that would result in actual systems. For example, the induced transients for power distribution system or broadband antenna could easily be much more severe than those presented in this section. Whereas, typical shielded cable configurations could result in transient which are 10-60 dB below those presented in this section with different waveforms.

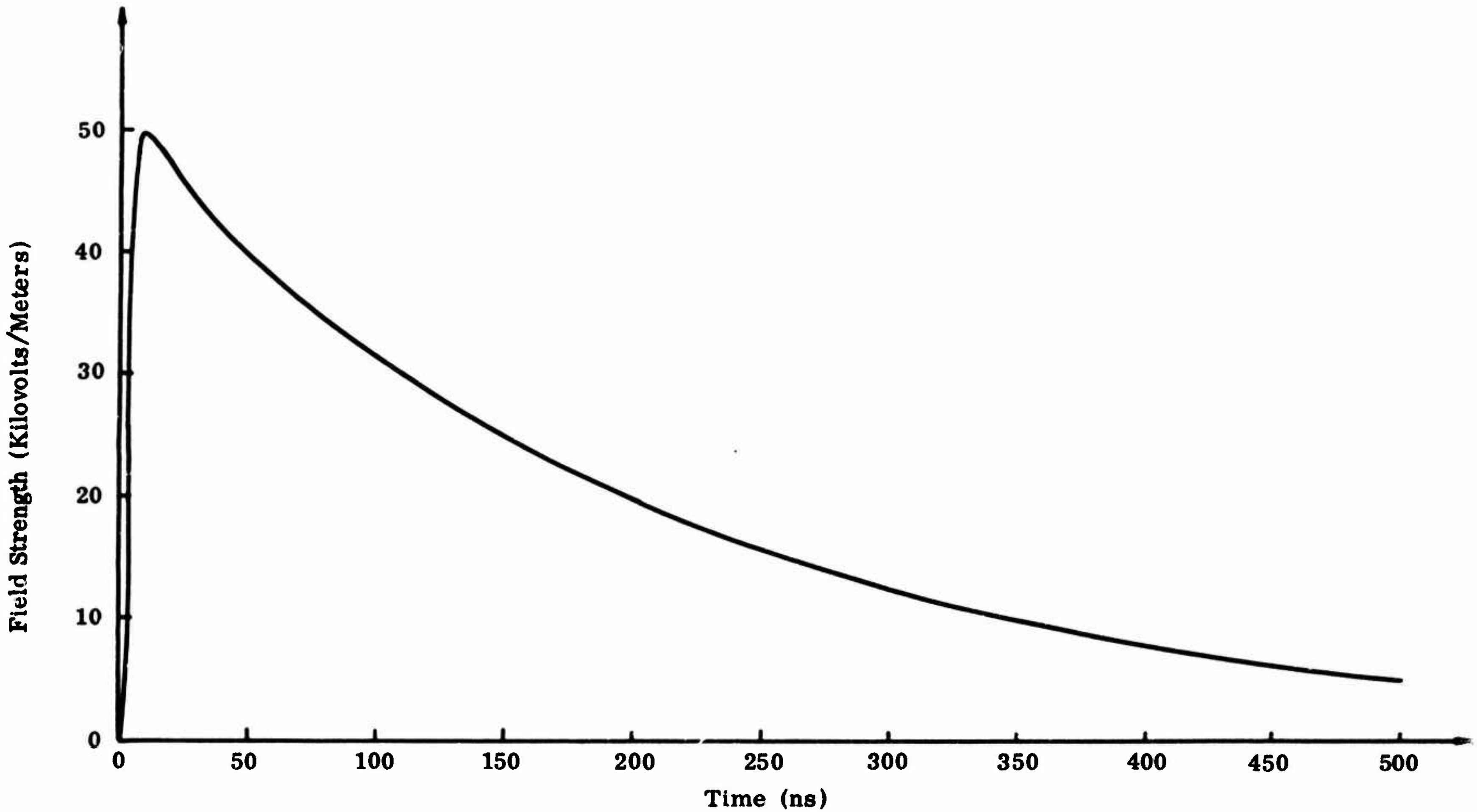

Figure 4-0. Representative EMP from a High Altitude Burst

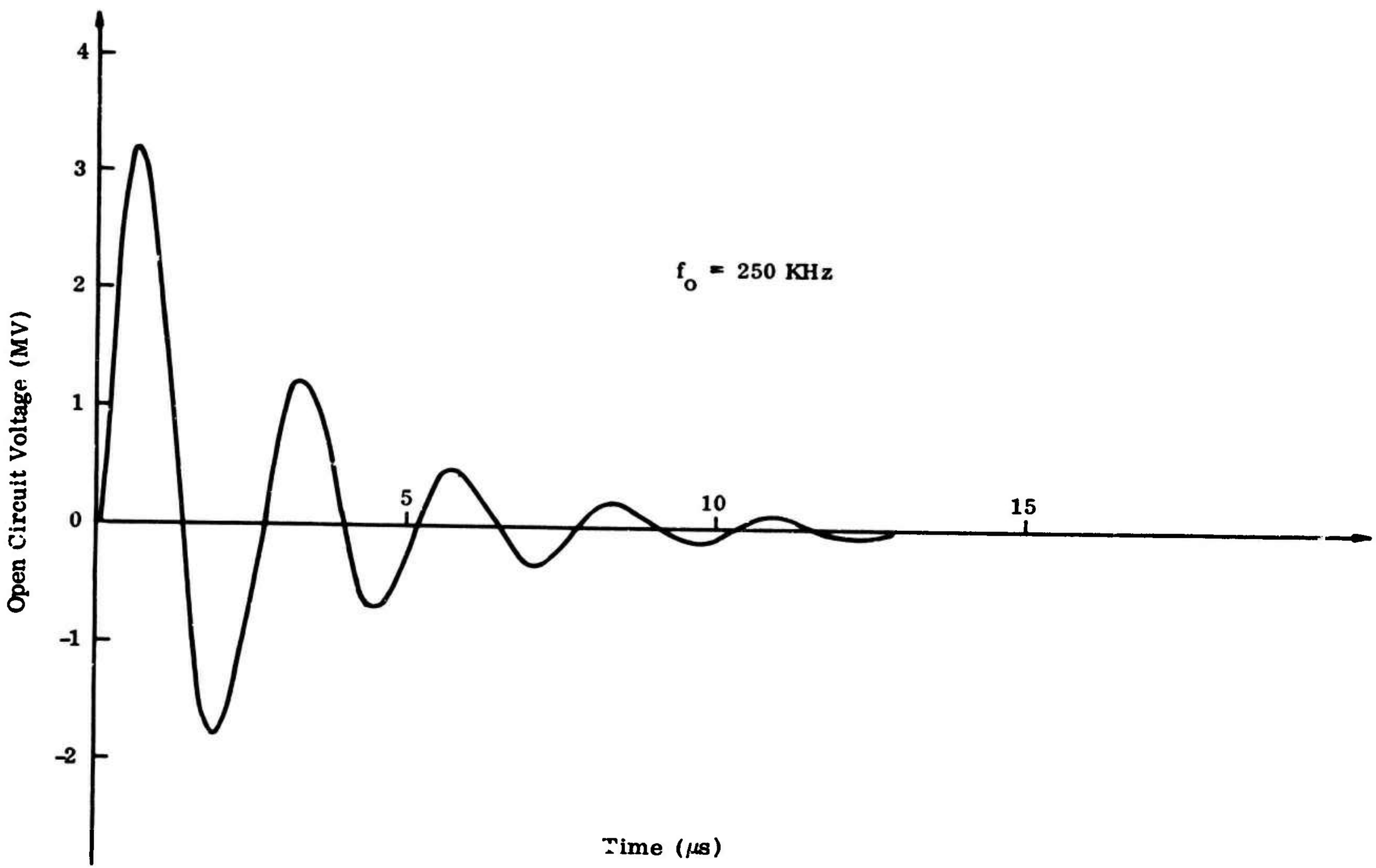

Figure 4-1. Open Circuit Voltage for a 300 Meter Monopole

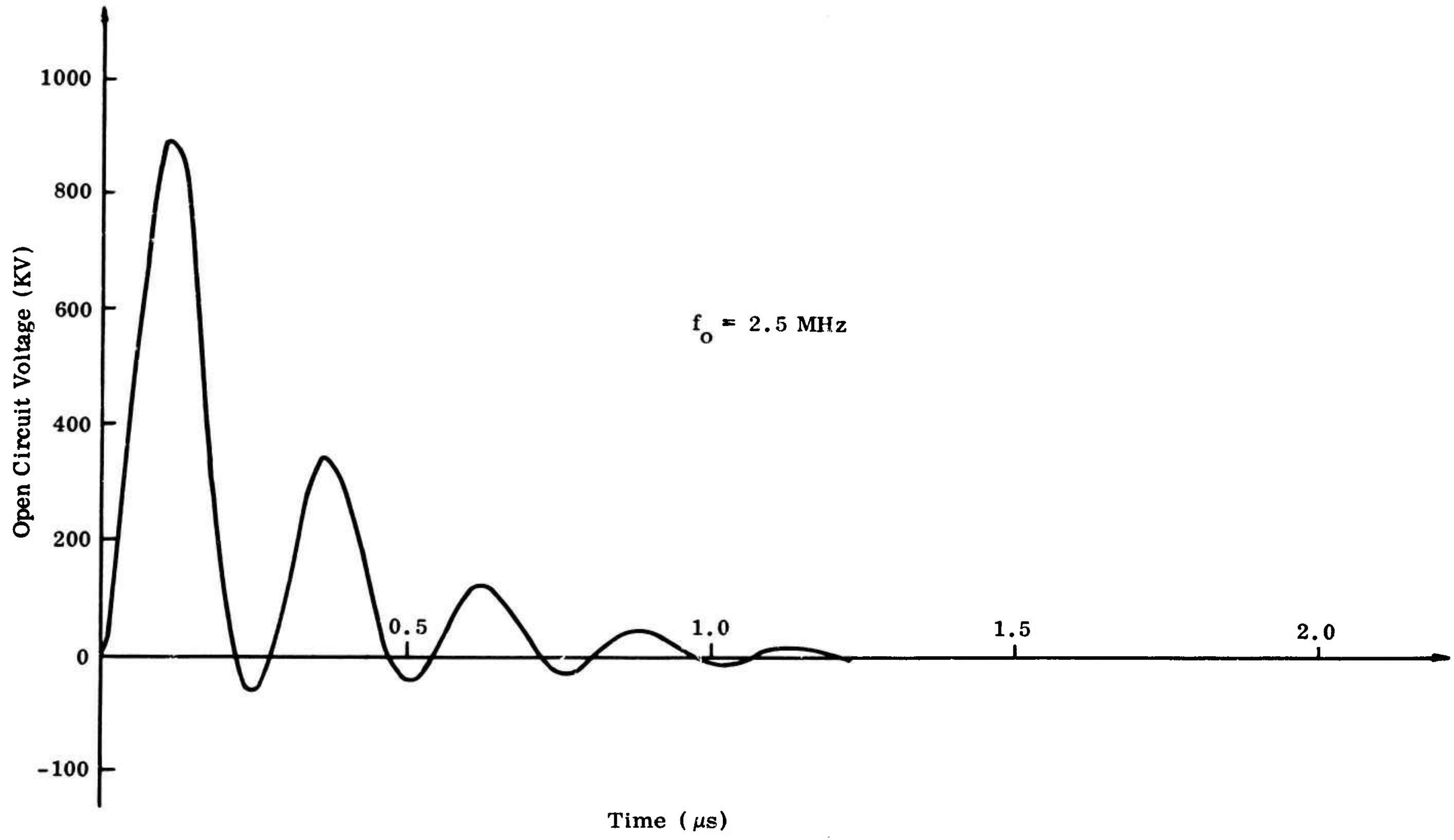

Figure 4-2. Open Circuit Voltage for a 30 Meter Monopole.

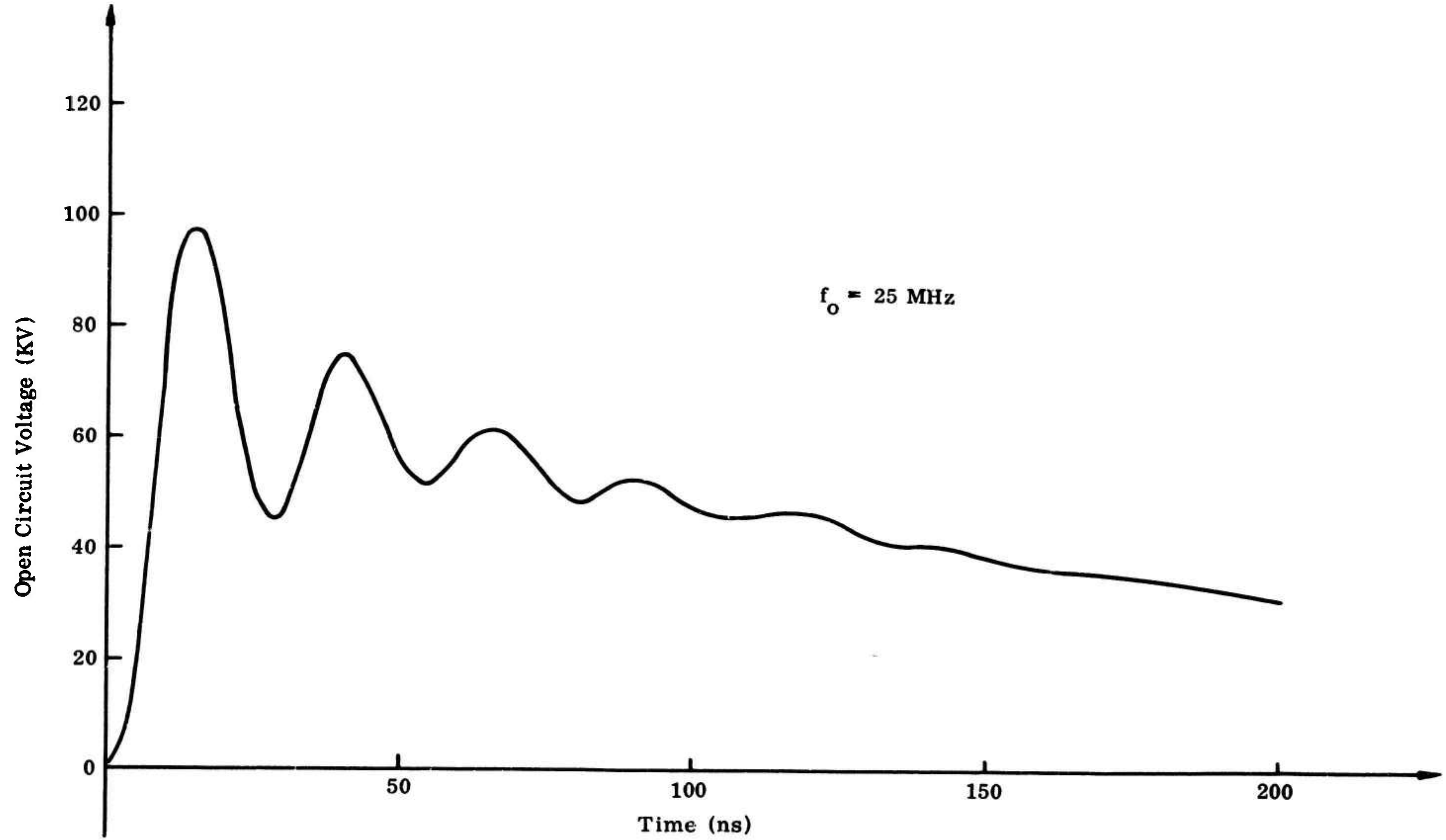

Figure 4-3. Open Circuit Voltage for a 3 Meter Monopole

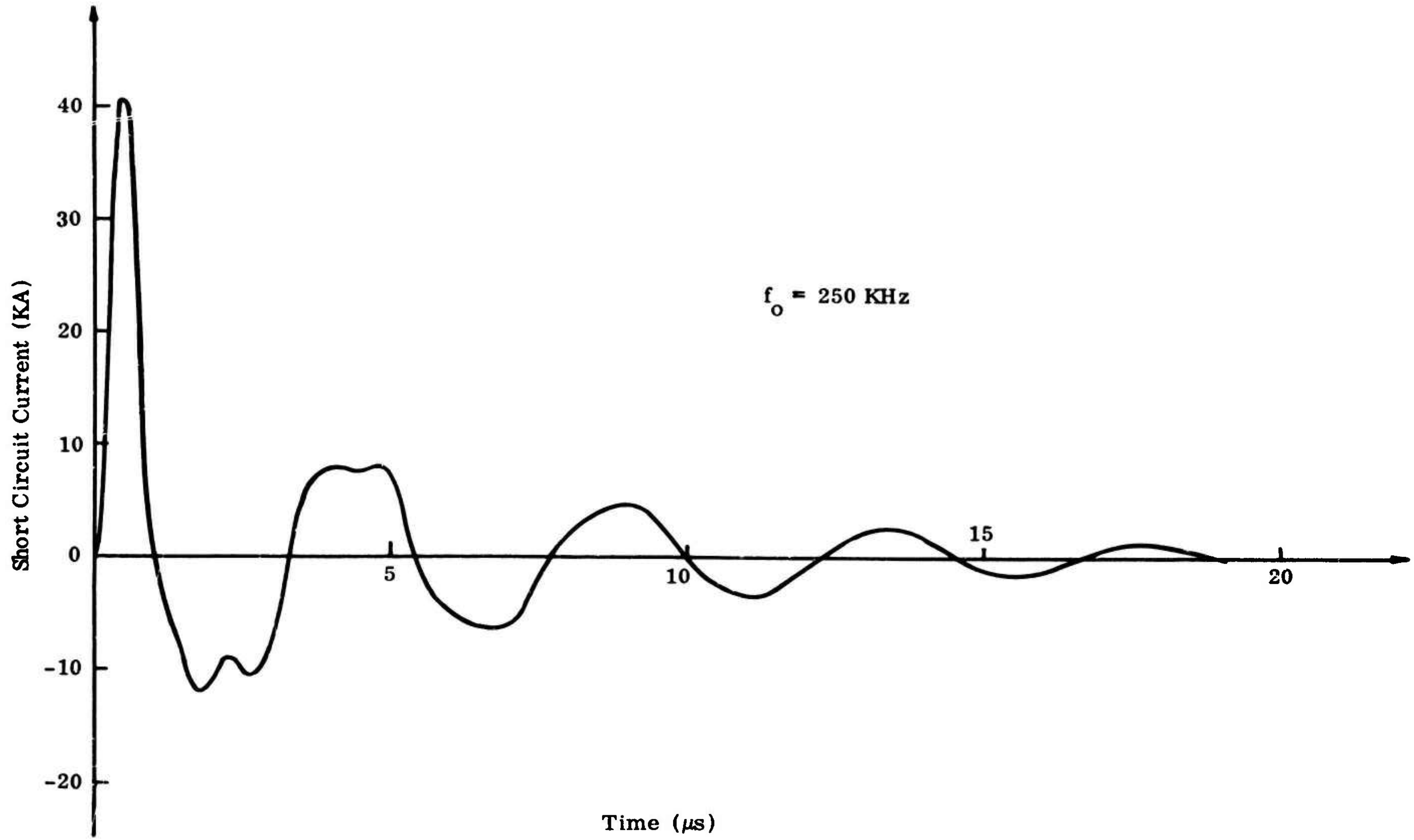

Figure 4-4. Short Circuit Current for a 300 Meter Monopole

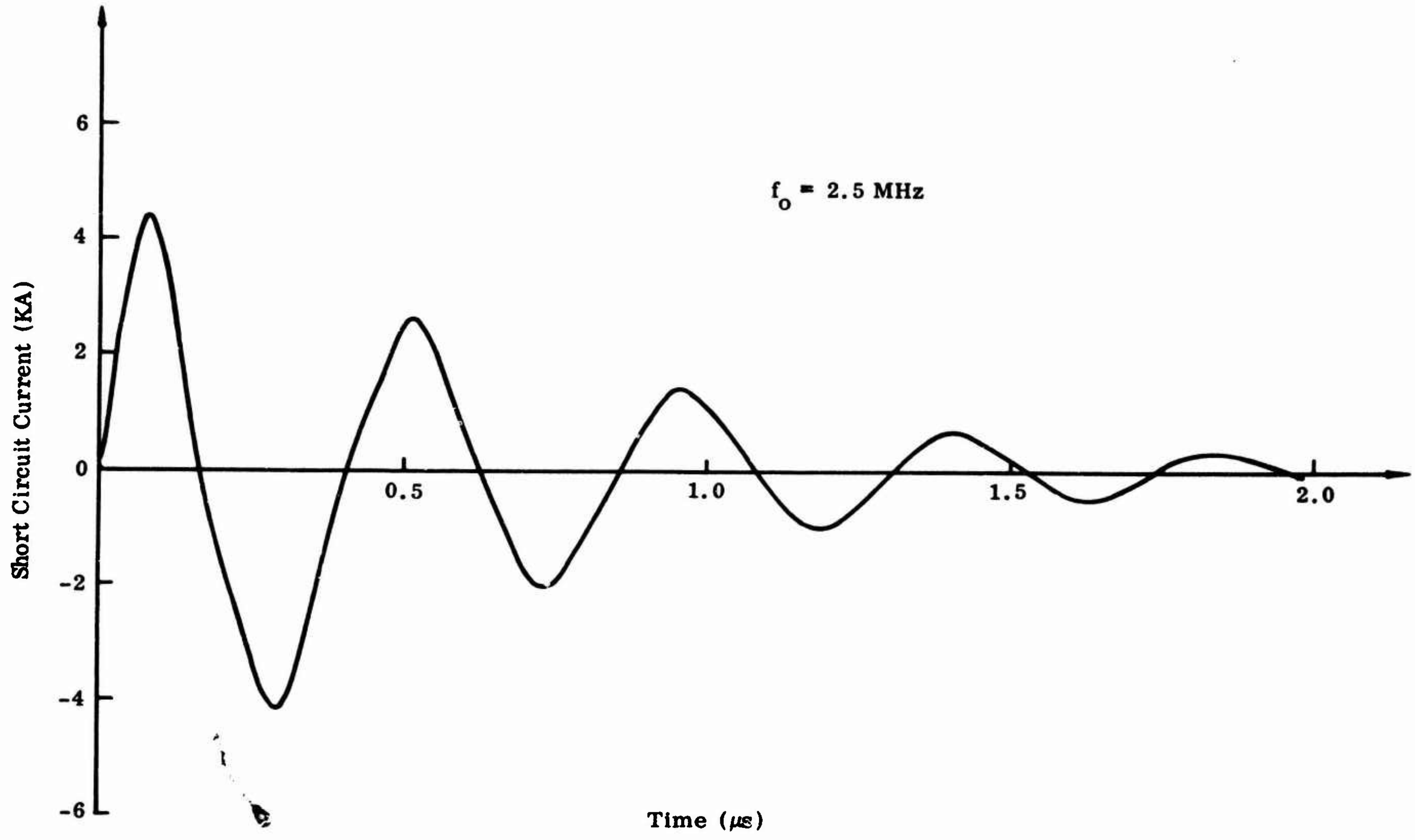

Figure 4-5. Short Circuit Current for a 30 Meter Monopole

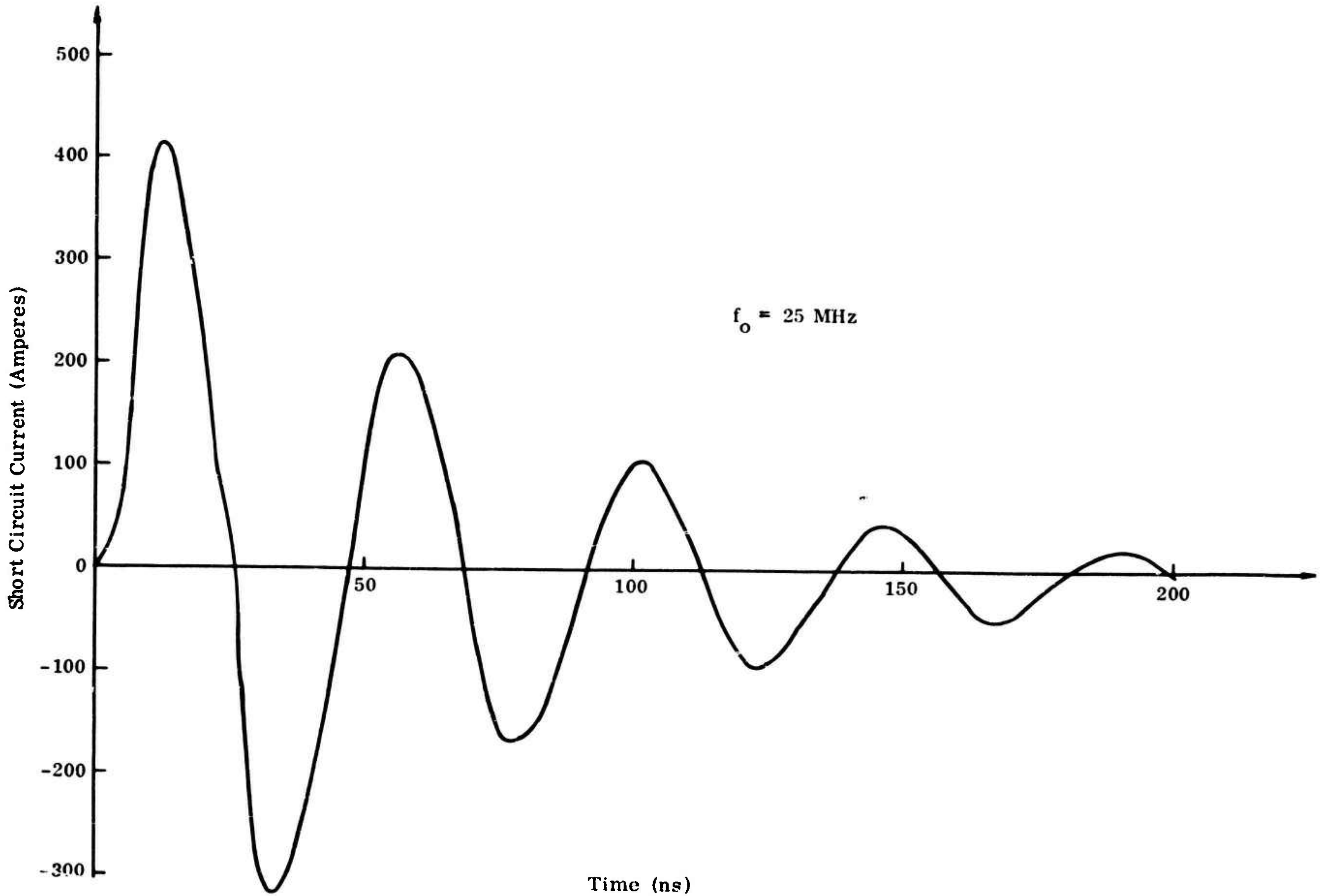

Figure 4-6. Short Circuit Current for a 3 Meter Monopole

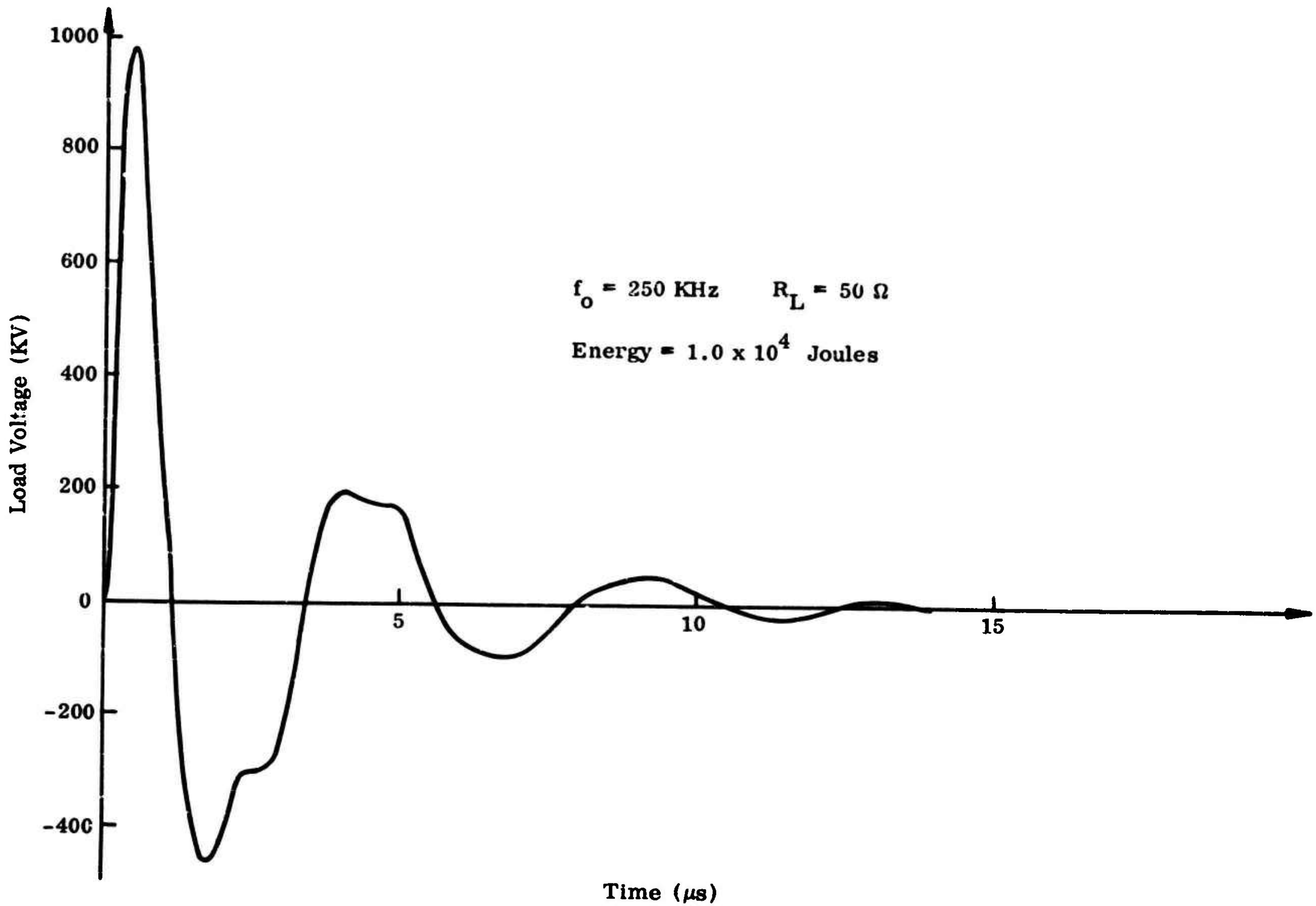

Figure 4-7. Load Voltage for a 300 Meter Monopole

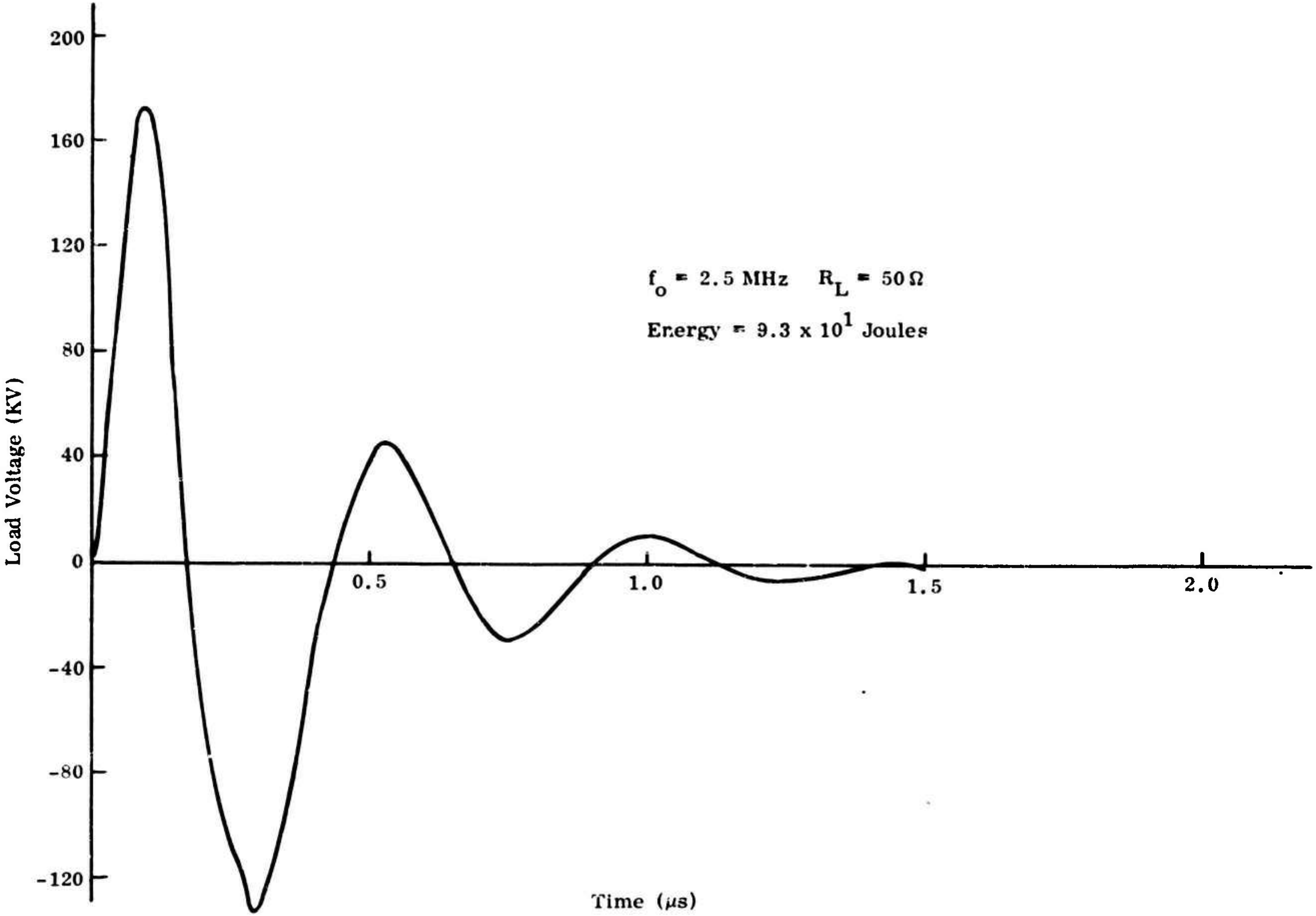

Figure 4-8. Load Voltage for a 30 Meter Monopole

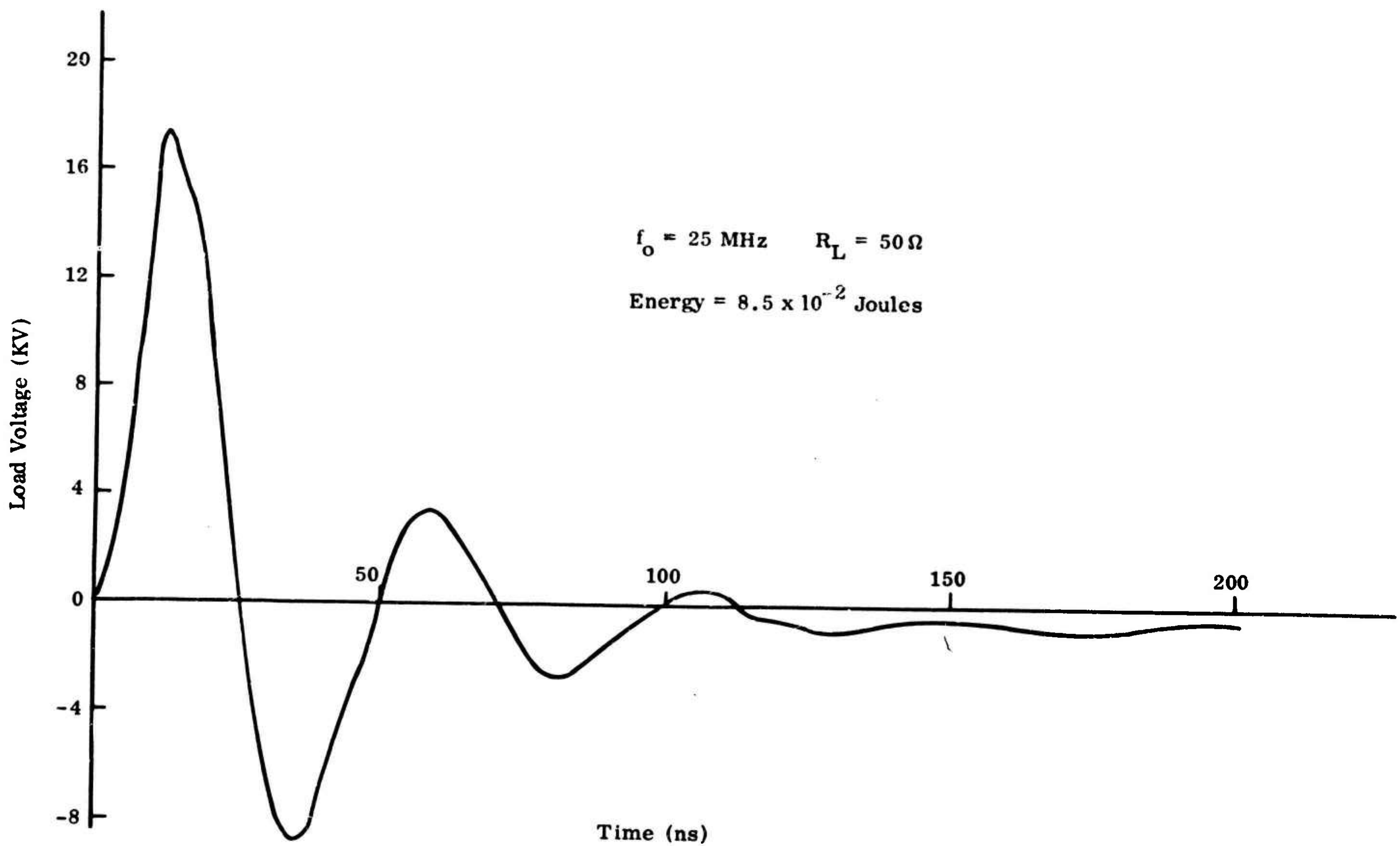

Figure 4-9. Load Voltage for a 3 Meter Monopole

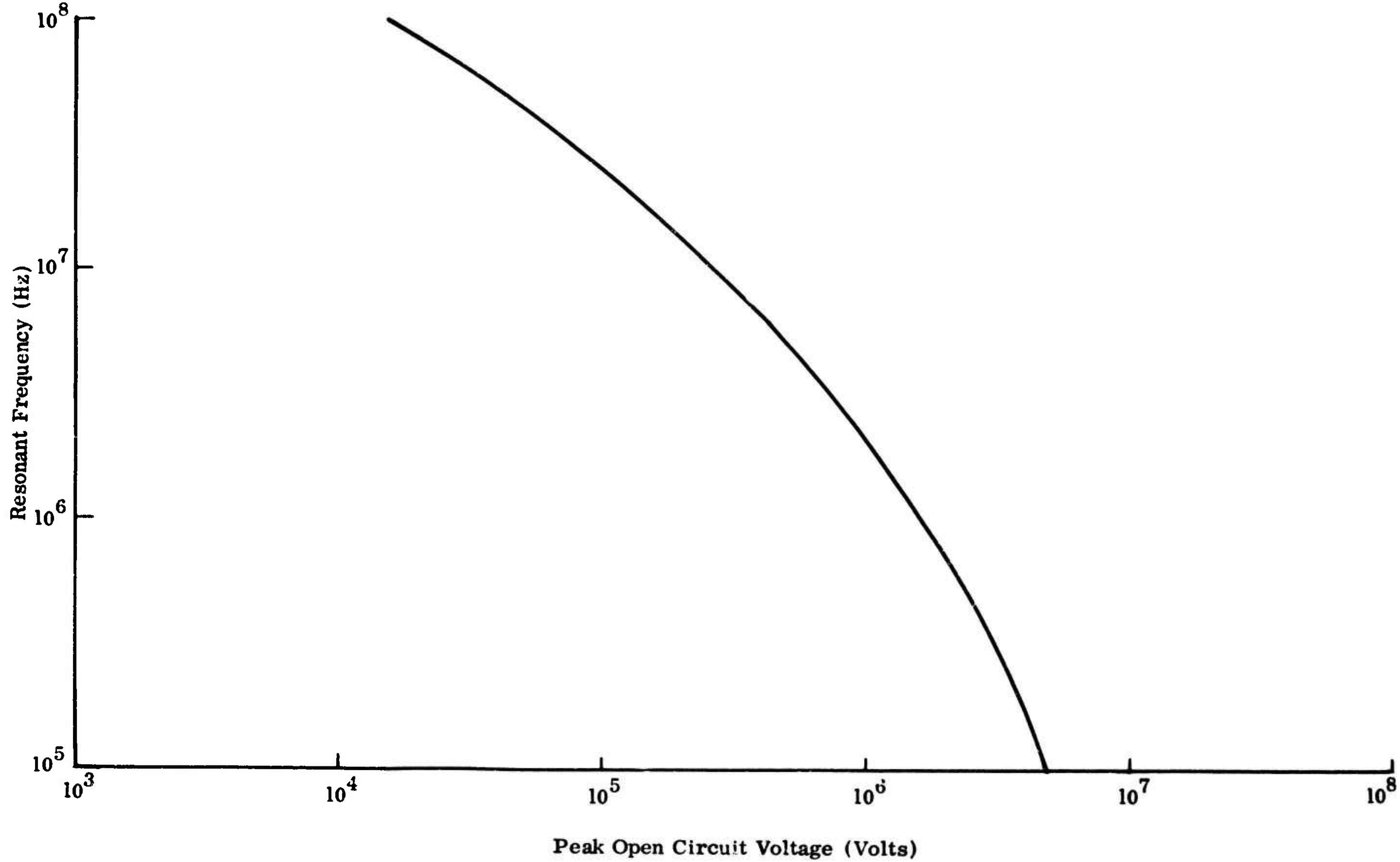

Figure 4-10. Peak Open Circuit Voltage Versus Resonant Frequency

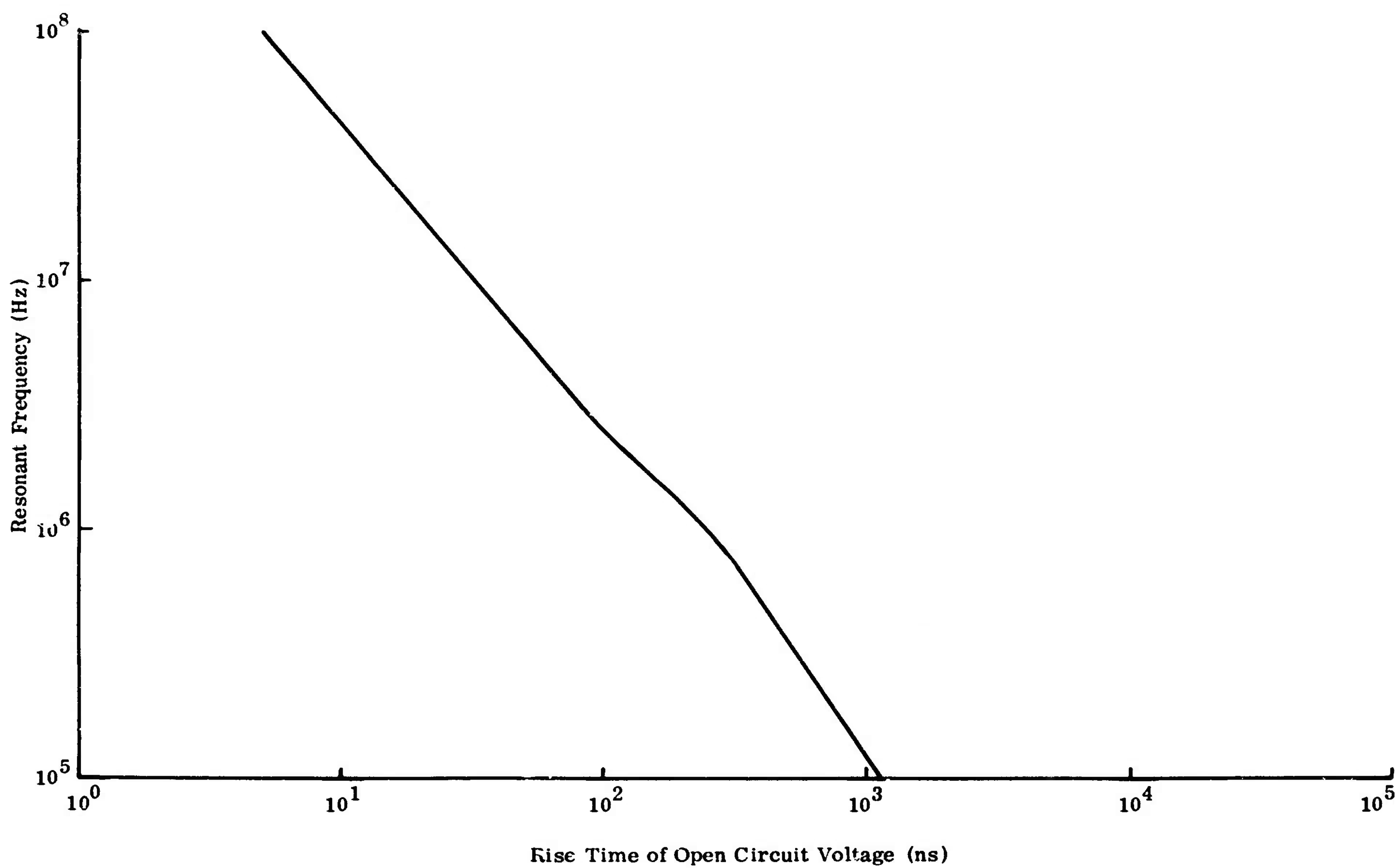

Figure 4-11. Rise Time of the Open Circuit Voltage Versus Resonant Frequency

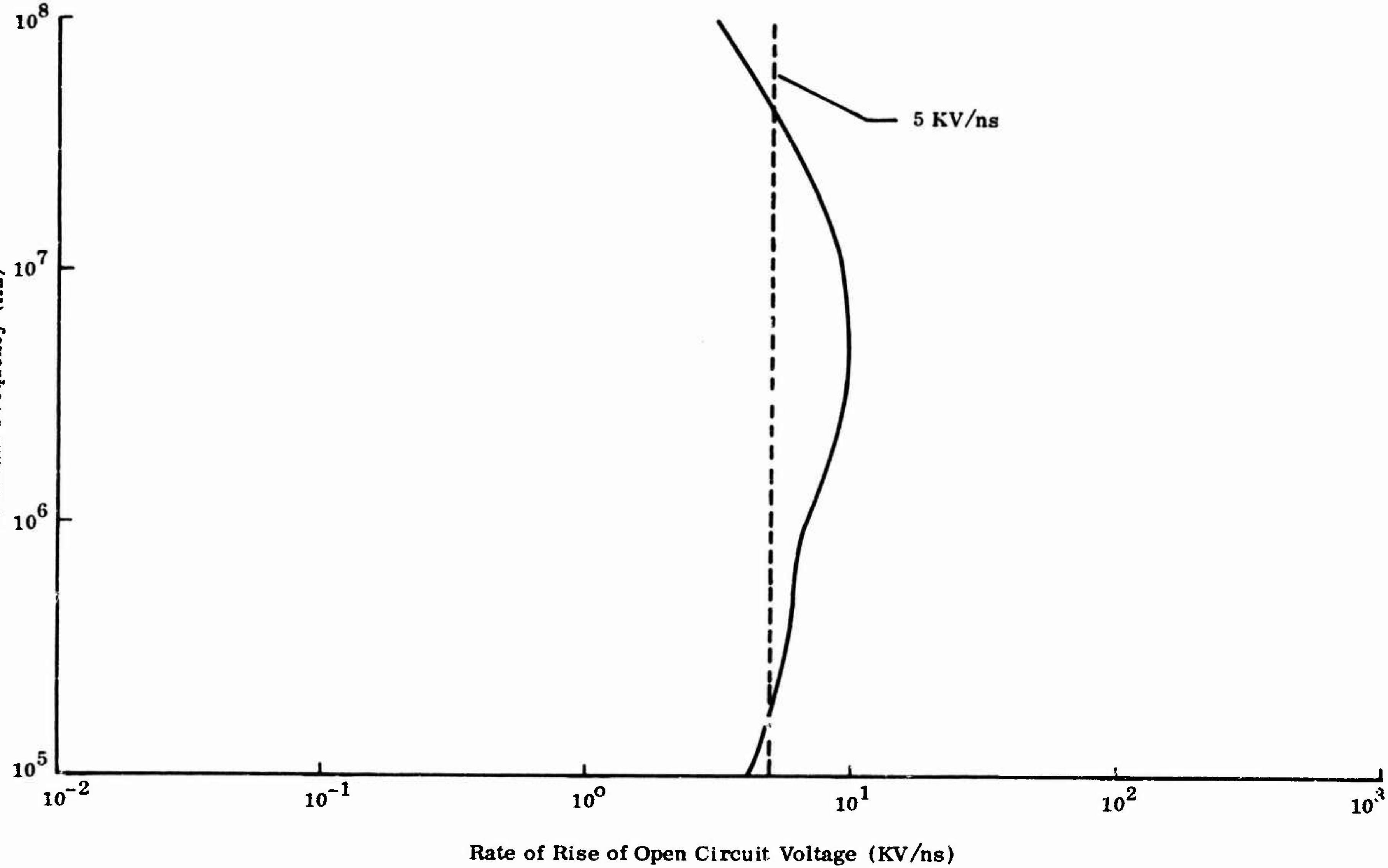

Figure 4-12. Rate of Rise of the Open Circuit Voltage Versus Resonant Frequency

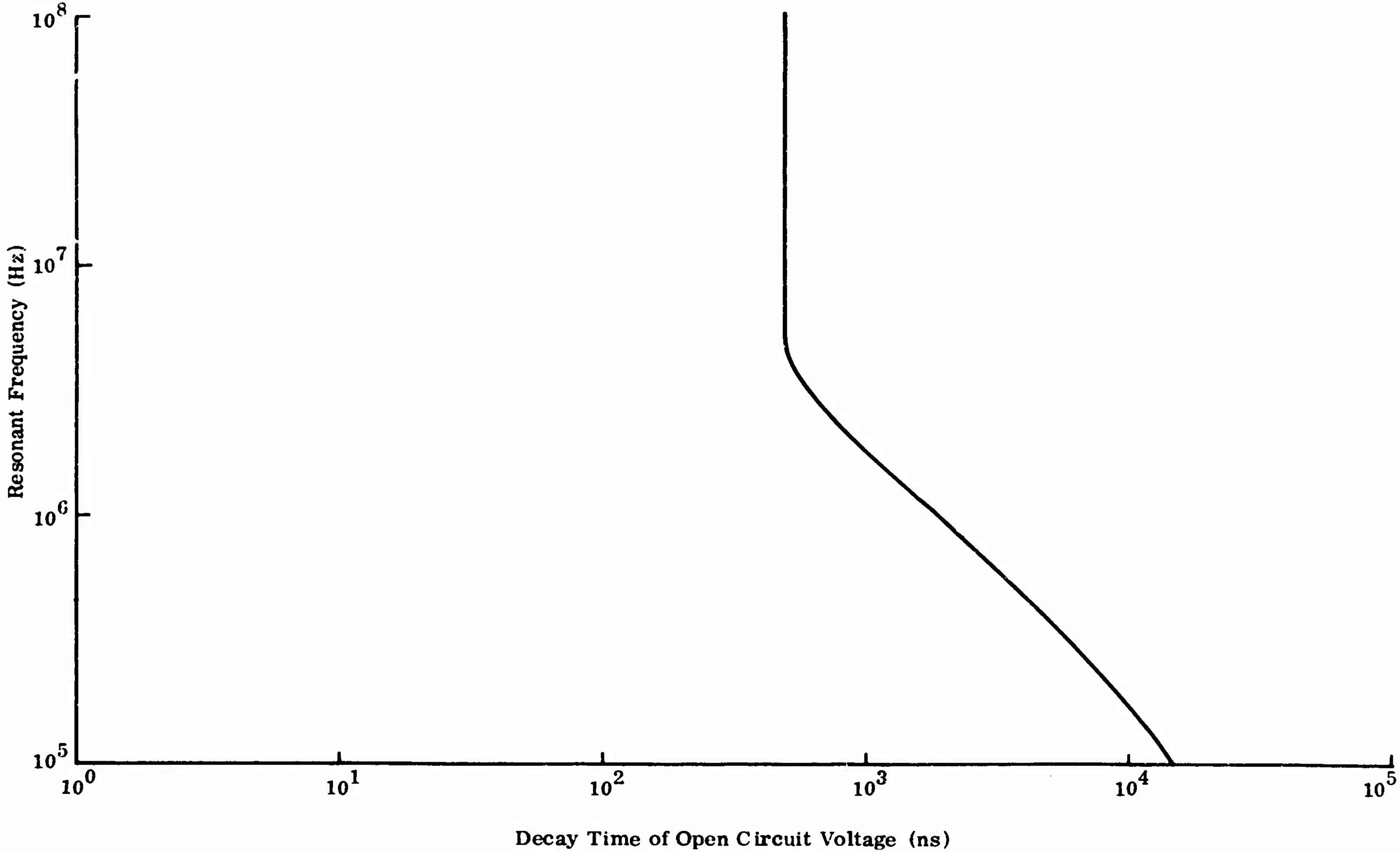

Figure 4-13. Decay Time of the Open Circuit Voltage Versus Resonant Frequency

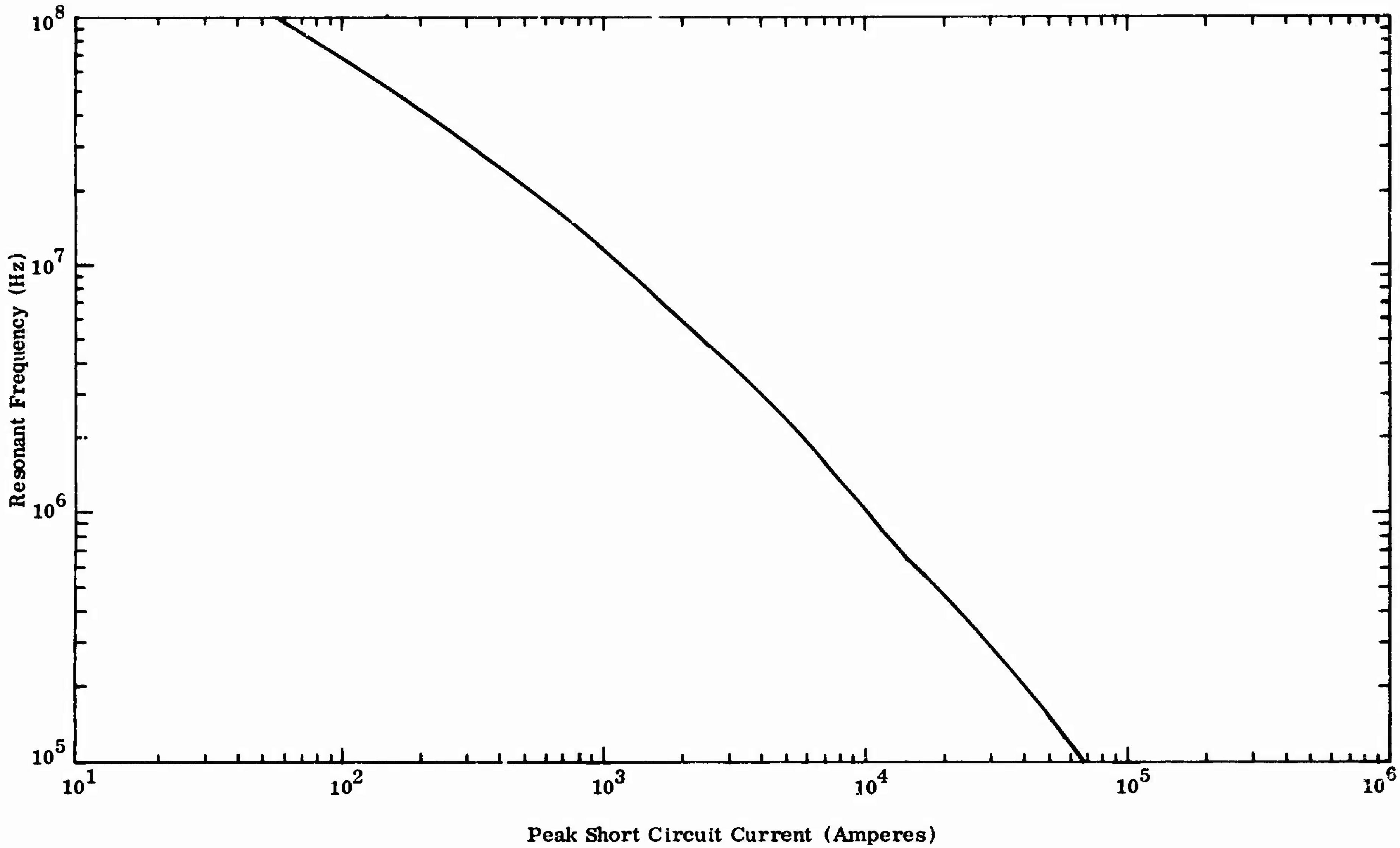

Figure 4-14. Peak Short Circuit Current Versus Resonant Frequency

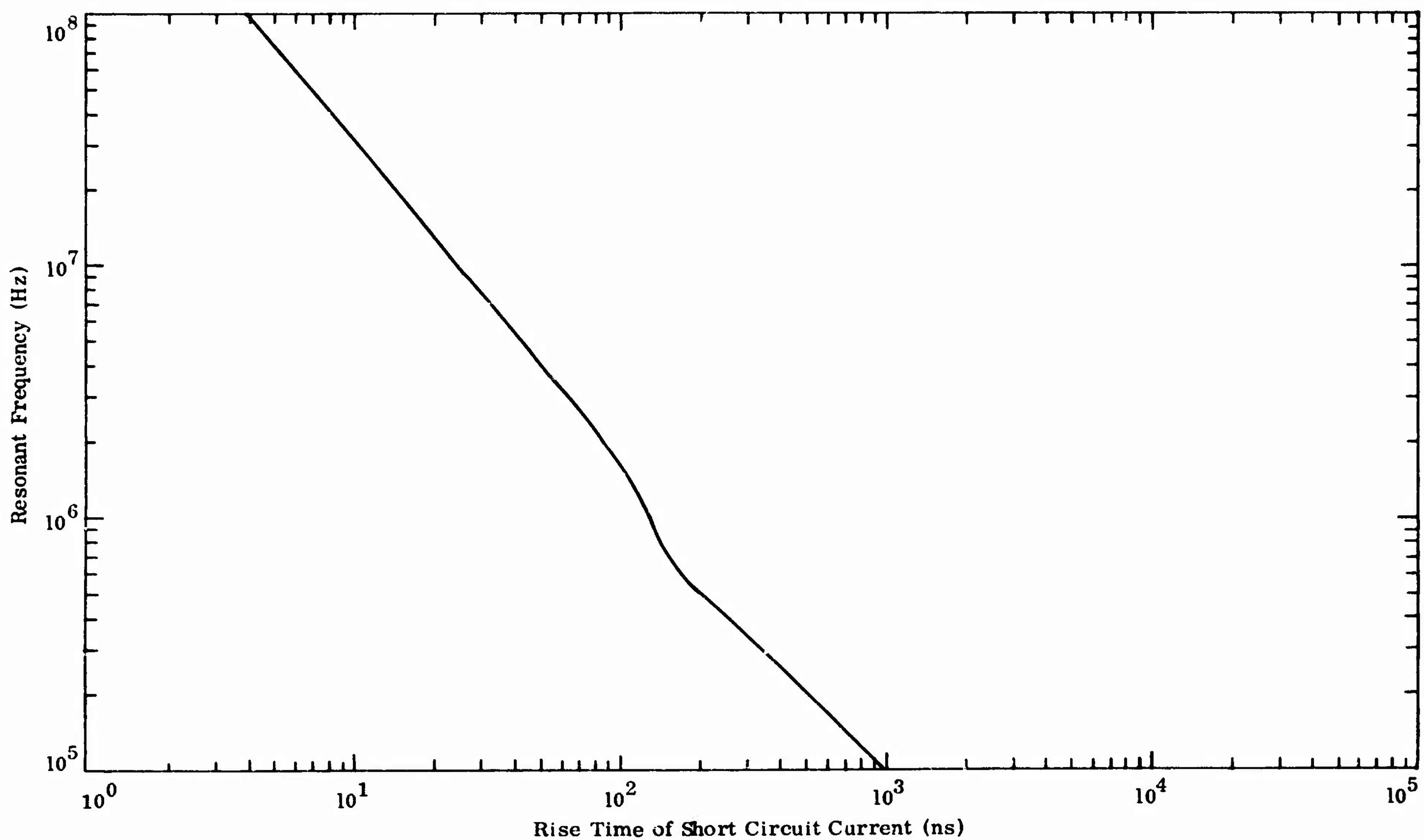

Figure 4-15. Rise Time of Short Circuit Voltage Versus Resonant Frequency

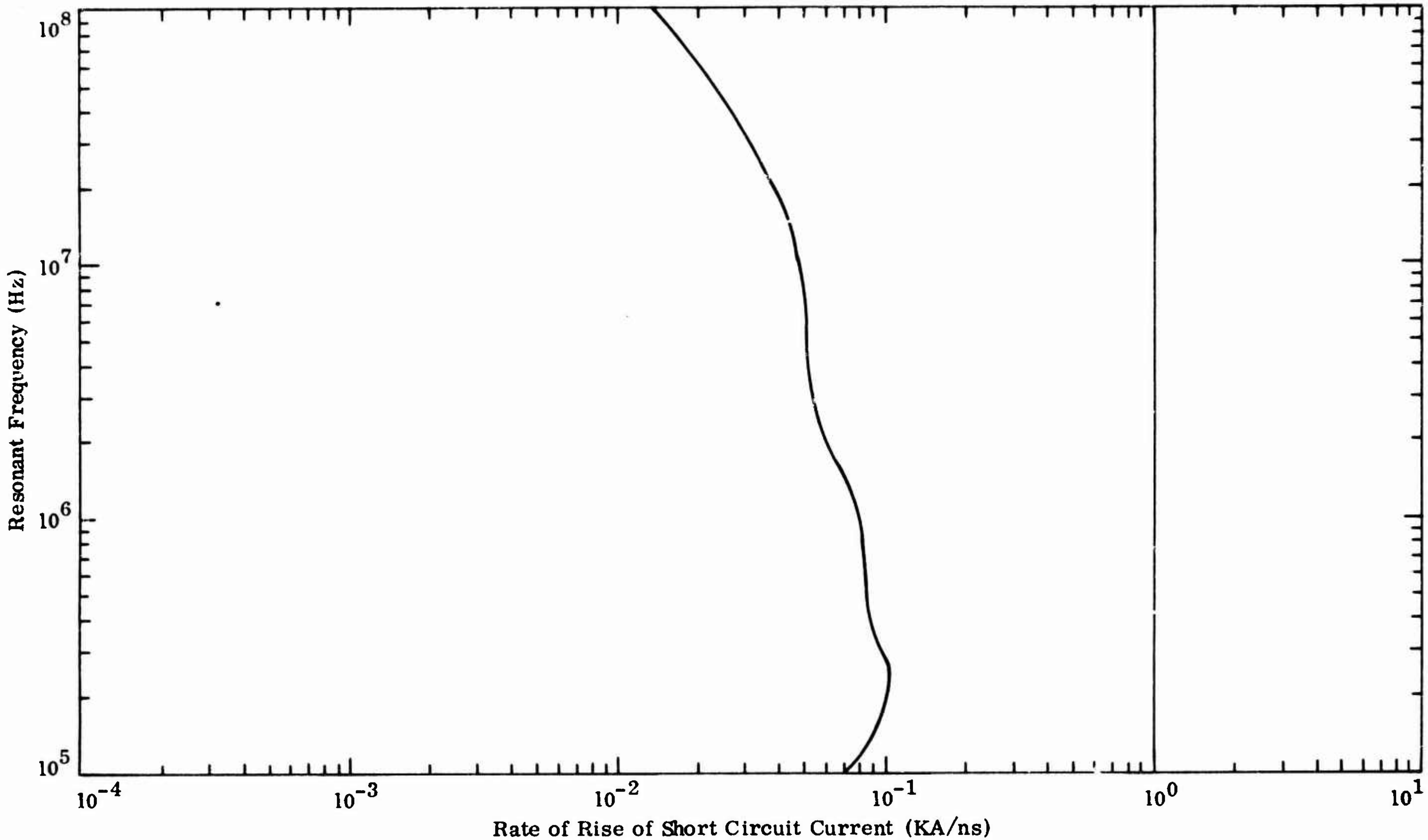

Figure 4-16. Rate of Rise of the Short Circuit Current Versus Resonant Frequency

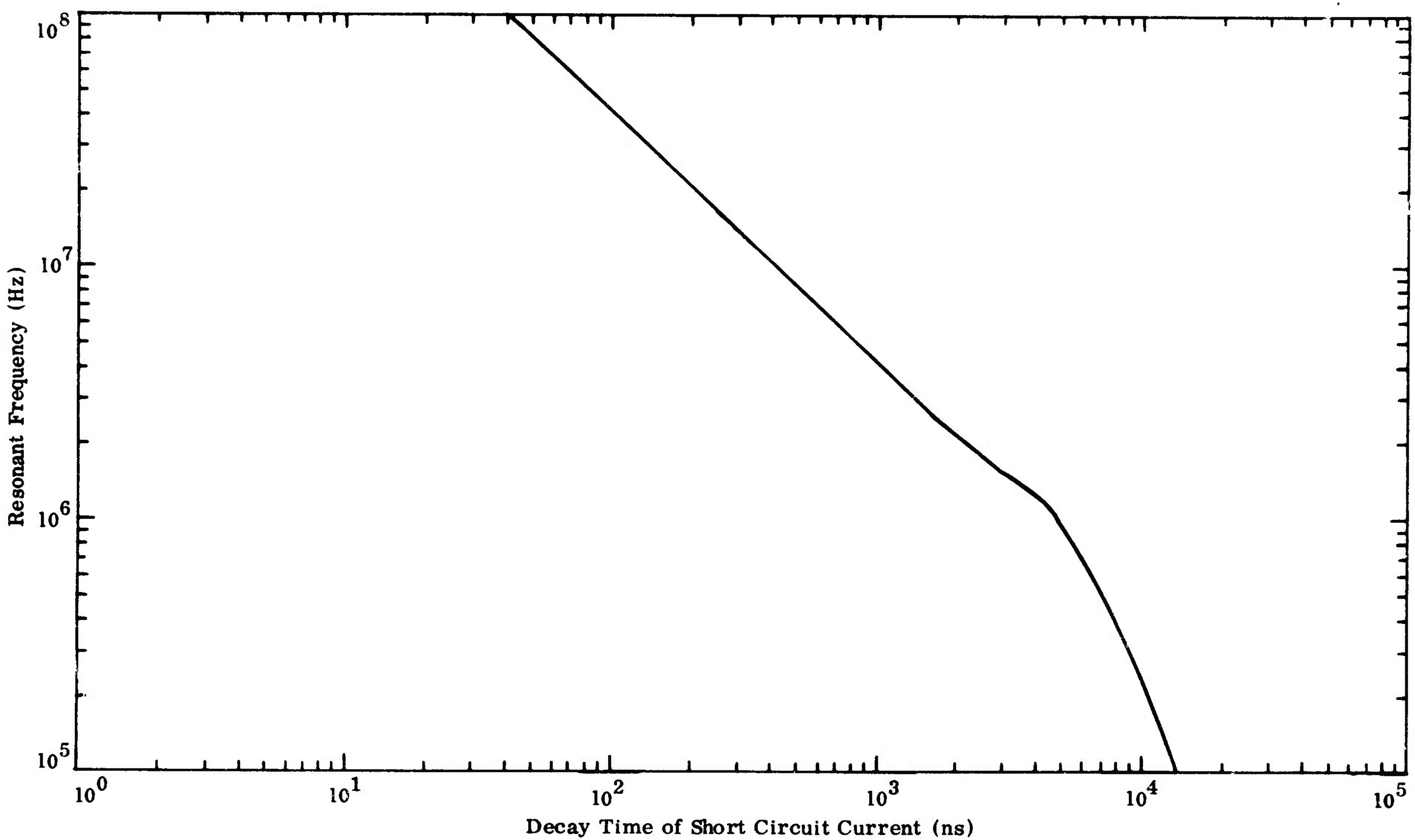

Figure 4-17. Decay Time of the Short Circuit Current Versus Resonant Frequency

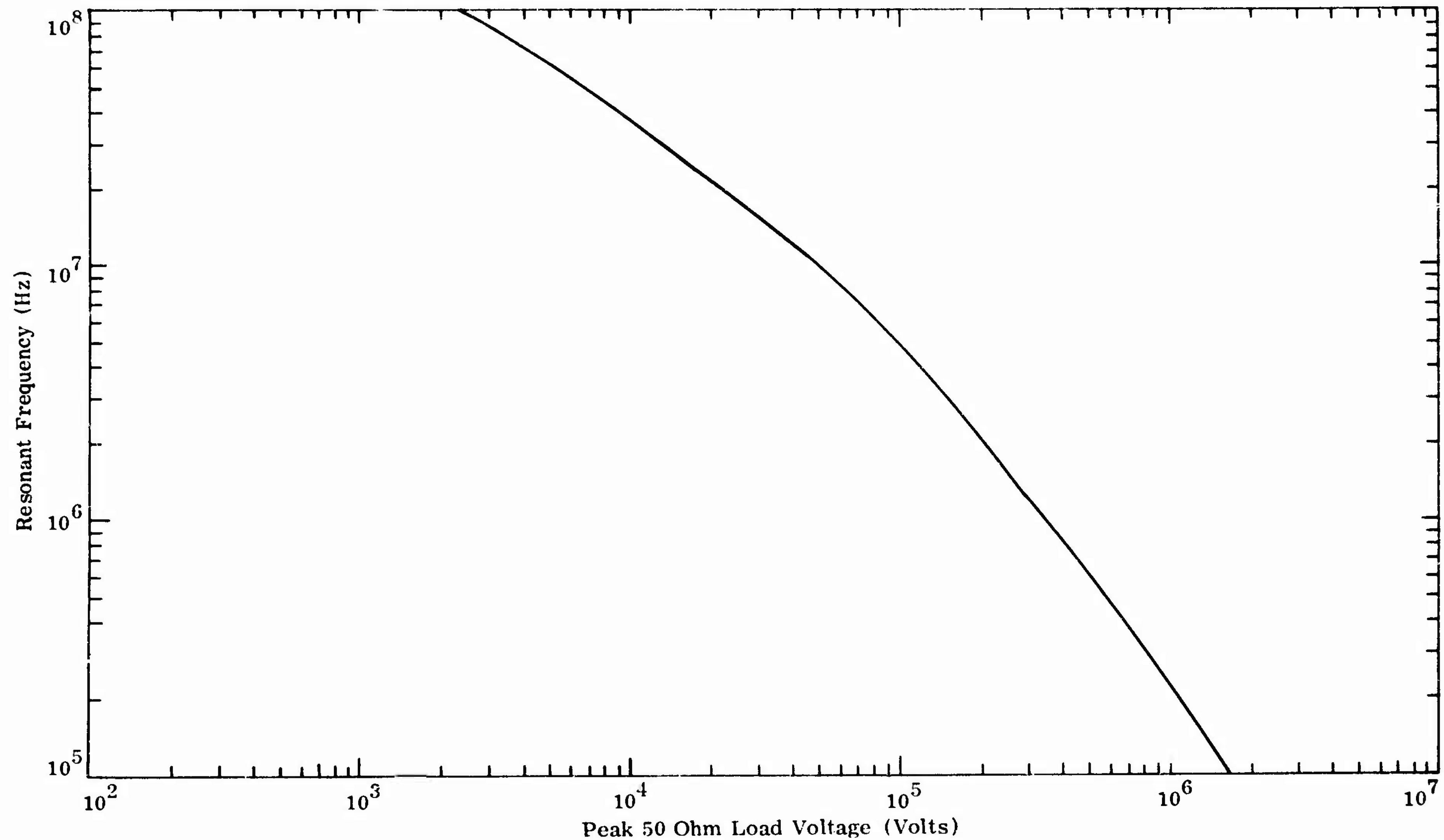

Figure 4-18. Peak 50Ω Load Voltage Versus Resonant Frequency

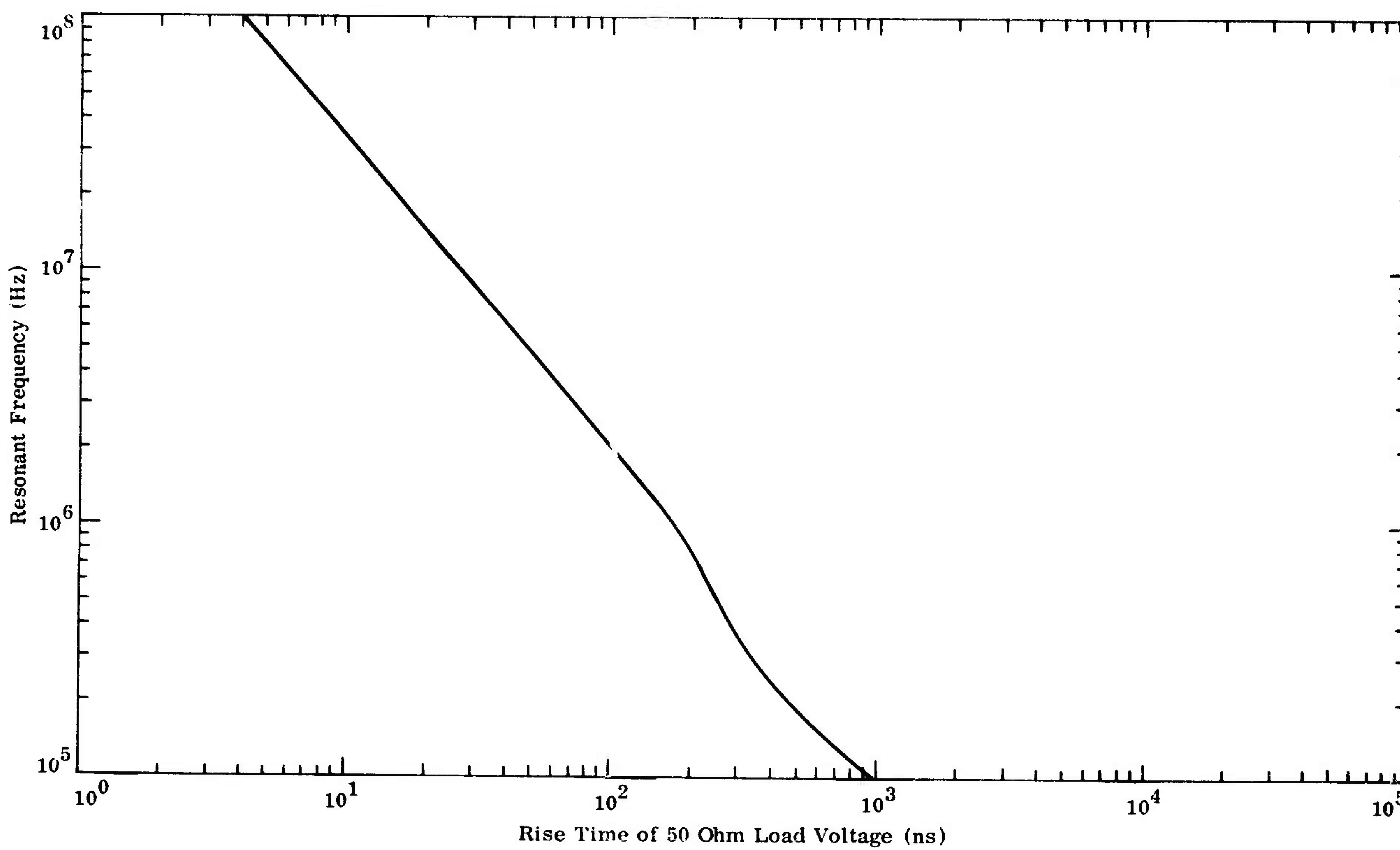

Figure 4-19. Rise Time of the 50Ω Load Voltage Versus Resonant Frequency

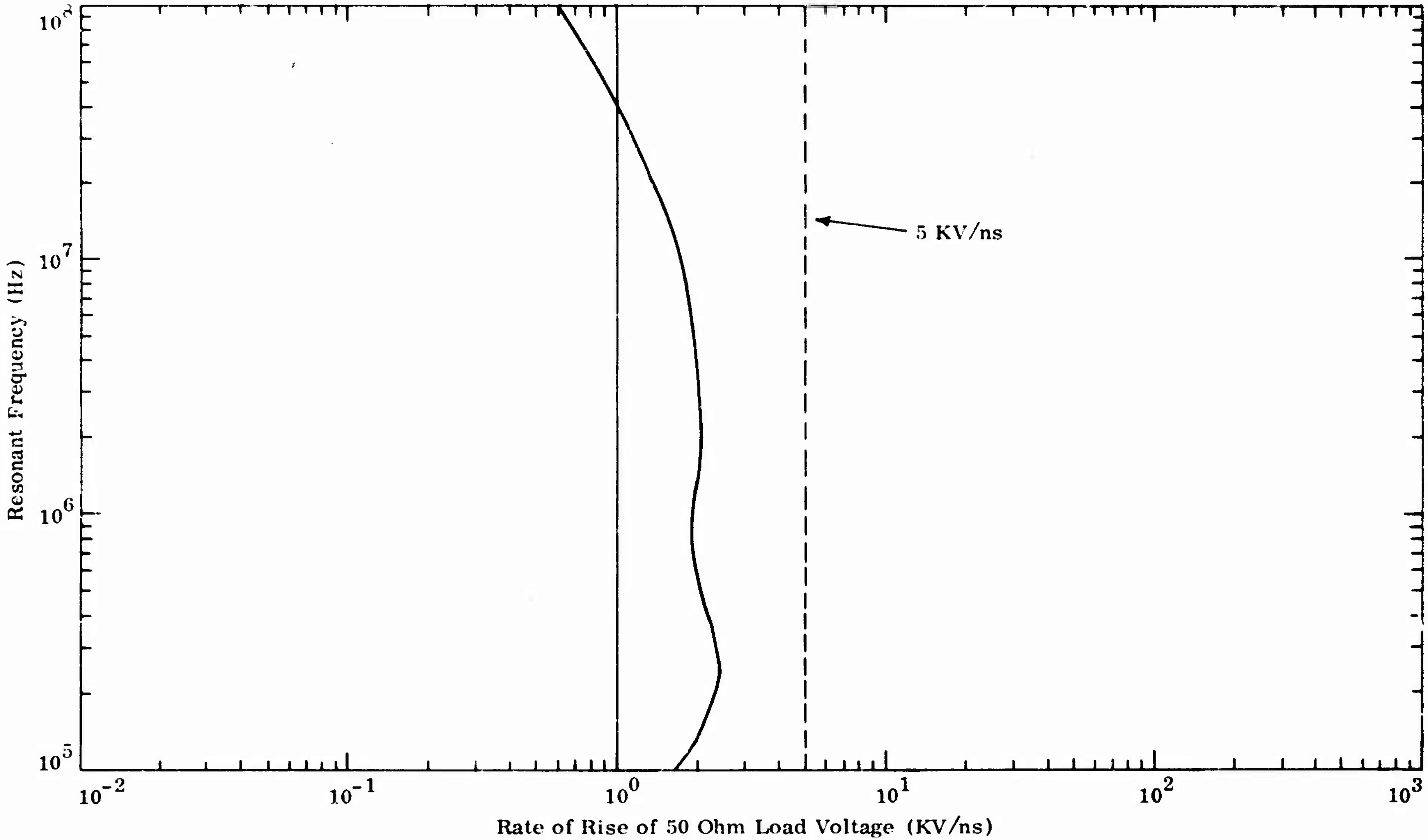

Figure 4-20. Rate of Rise of the 50Ω Load Voltage Versus Resonant Frequency

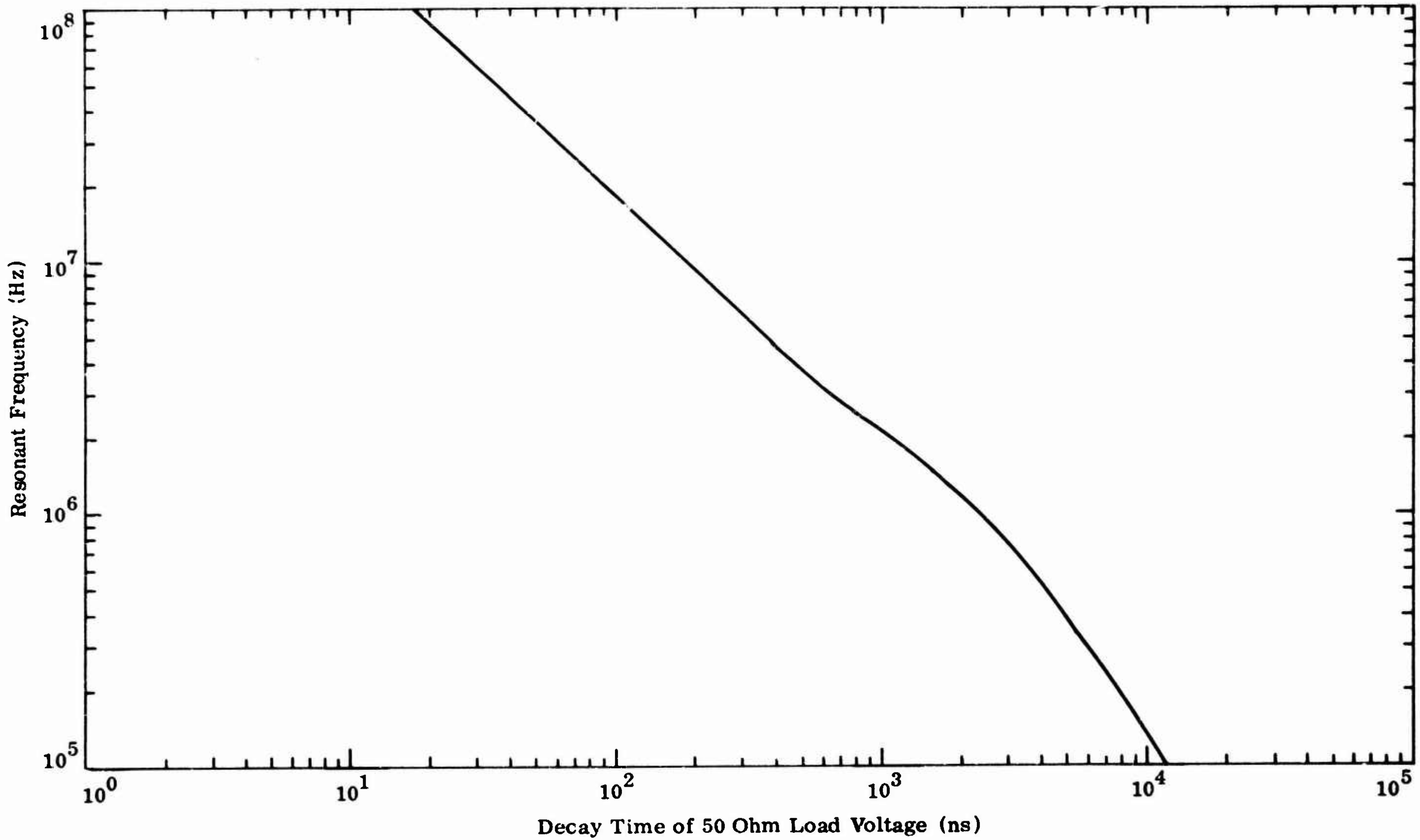

Figure 4-21. Decay Time of the 50Ω Load Voltage Versus Resonant Frequency

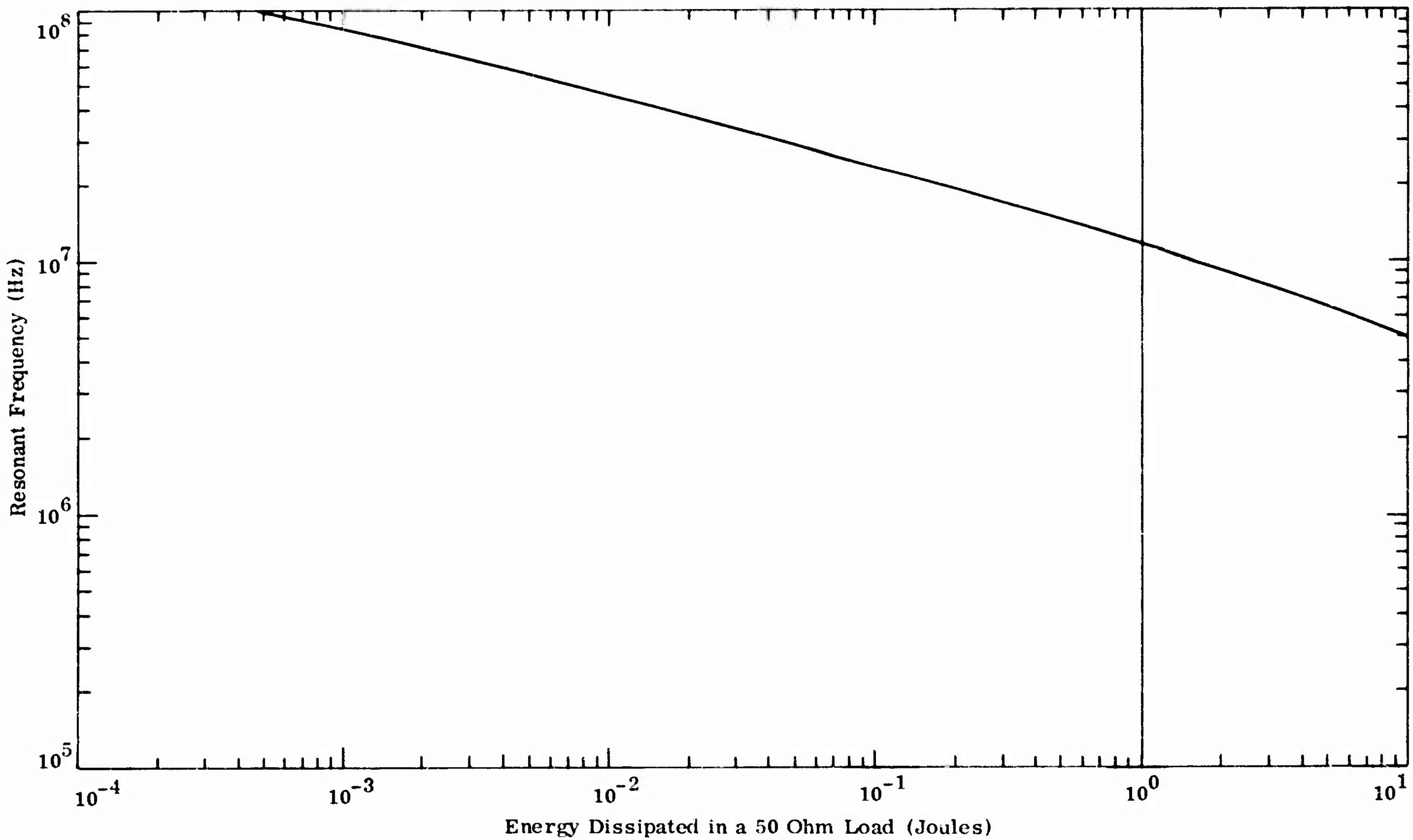

Figure 4-22. Energy Dissipated in a 50Ω Load Versus Resonant Frequency

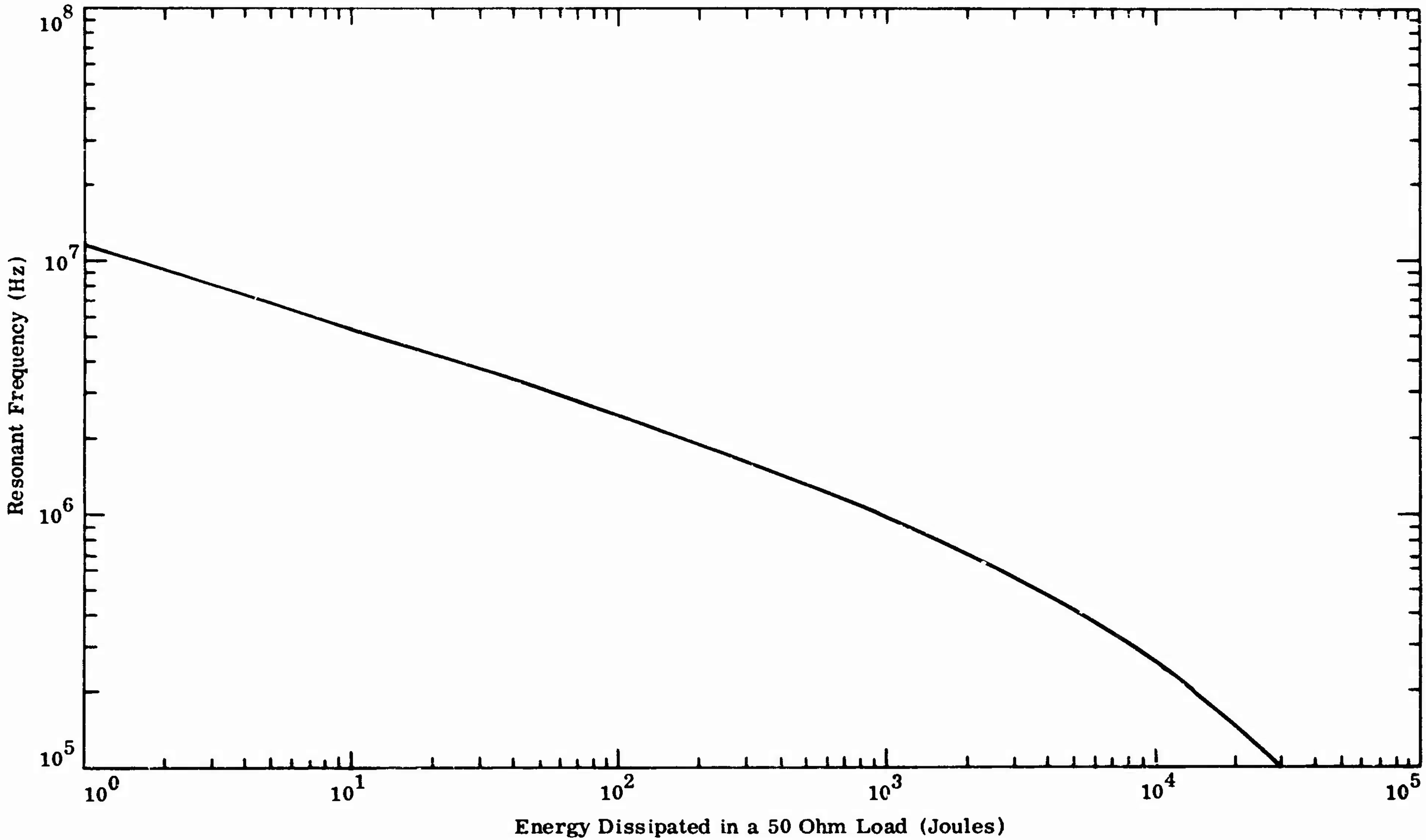

Figure 4-23. Energy Dissipated in a 50Ω Load Versus Resonant Frequency

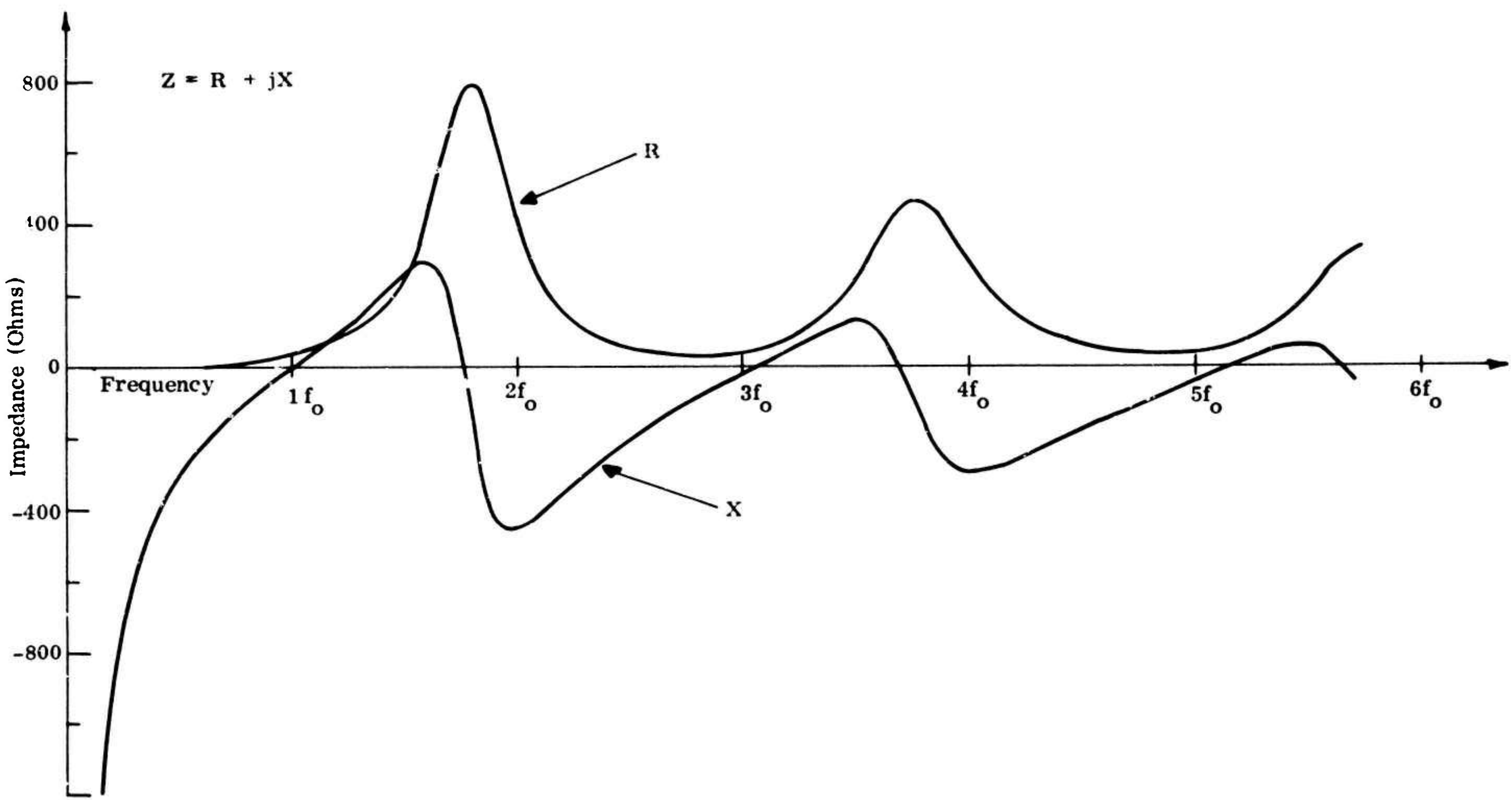

Figure 4-24. Collector or Source Impedance Versus Normalized Frequency

It is worthwhile to note the good agreement between the calculated (using the fourier transform method previously discussed) and measured transient response of simple monopoles for the output voltage into a 50 ohm load. The transient response of a 10.75 meter monopole was both measured and calculated.* The results are compared in Figure 4-25. This analysis did not include the effect of the base capacitance of the antenna; and, when this is considered, even better agreement between measured and calculated responses has been demonstrated.

More complex antenna arrangements have comparable responses. Figure 4-26 shows the measured short circuit current at the base of a 16-foot whip antenna mounted on a corner of a 6-foot conducting cubical hut in response to a typical EMP field.** Note that the resonant frequency departs significantly from that calculated for an ideal 16-foot monopole over a conducting infinite-sheet ground. Better agreement in resonant frequency values is obtained by adding the height of the cubical hut to give an effective monopole height of 22 feet. More sophisticated analyses have been employed to predict the response of complex antennas to obtain better agreement with experimental results. The user of the preferred test procedures should consider possible differences between the responses of idealized antennas employed here and those actually encountered.

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* Preliminary Study of the Time-Domain Measurement of Antenna Parameters, Final Report, IIT Research Institute Project No. E6148, Contract No. No. N00228-69-C-1494

** Effects of EMP Environment on Military Systems, Final Report, Contract No. DAAK02-68-C-0371 Mod III, U.S. Army Mobility Equipment and Research Center. More extensive data appears in the Antenna Users Manual, to be published by DNA.

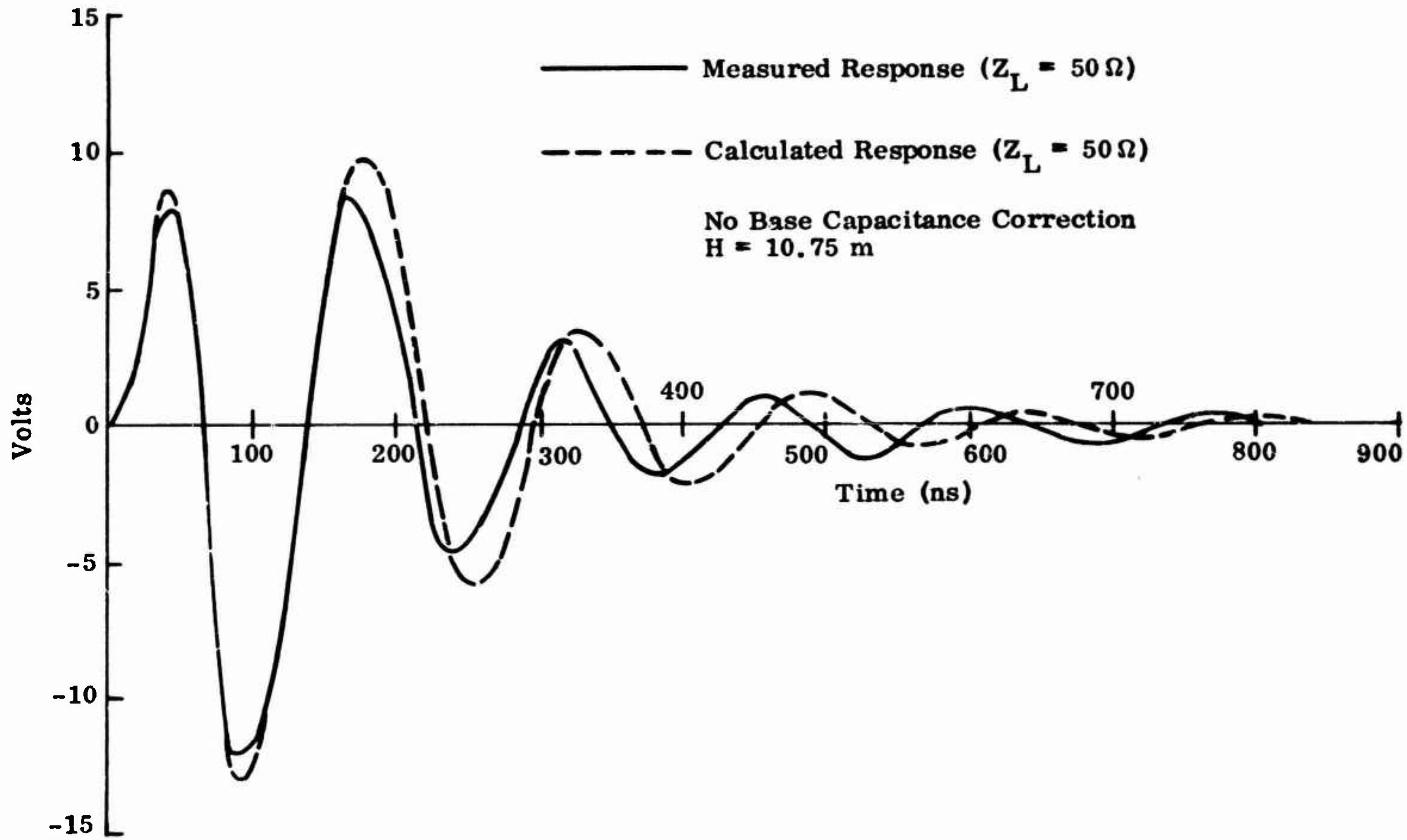


Figure 4-25. Comparison of Theoretical and Measured Transient Response of the HF Monopole Antenna

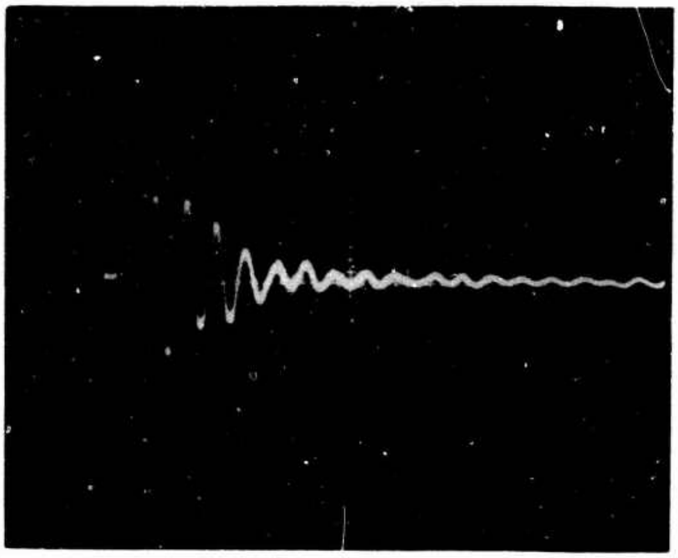


Figure 4-26 SHORT-CIRCUIT CURRENT OF A 16-FOOT MONOPOLE ANTENNA MOUNTED ON A CONDUCTING 6-FOOT CUBICAL HUT. VERTICAL 100 MILLIAMPERES/DIVISION, HORIZONTAL 200 NANOSECONDS/DIVISION. EXCITING FIELD - 15 NANOSECOND USE TIME, 150 NANOSECOND FALL TIME, 20 VOLT/METER PEAK FIELD, VERTICAL POLARIZATION

5. TEST PROCEDURES FOR SURGE PROTECTIVE DEVICES

TABLE OF CONTENTS

5. TEST PROCEDURES FOR SURGE PROTECTIVE DEVICES

5.1 Introduction

Voltage transients are common phenomena in communications systems and power transmission lines and are frequently generated internally in related equipment. Causes of transients are EMP, lightning strikes, static discharges, internal switching of inductive components, short circuits, etc.

The frequency with which transients occur and their size are subject to a statistical distribution. It is very difficult to arrive at a usable figure to predict the frequency of occurrence, but in the past this figure was underestimated by many engineers and may still be to a great extent. This is understandable since voltage transients in general did not present a serious problem as long as semiconductors or other similarly delicate components were not used. However, solid state circuitry demands from the design engineer his utmost attention with regard to protection against excessive voltages in order to provide the circuits with a high reliability factor, a long life expectancy and an assured level of EMP hardness.

To achieve these goals the selection of the best protection method is important. Therefore, this section deals with experimental procedures for evaluating the performance of surge protective devices. A surge protective device must protect the equipment without adversely affecting its performance and must be capable of withstanding the effects of both EMP induced transients and other transients in the system.

Three general categories of measurements are discussed in this section. The Quasi-Static Response Measurements are basically concerned with the parameters that determine how the device affects the performance of the equipment or how the equipment affects the performance of the protective device. The Transient Response Measurements are basically concerned with the parameters that determine the effectiveness of the protective device. Finally, the Permanent Degradation Measurements are concerned with the capability of the protective device to withstand the effects of both EMP induced transients and other transients in the system. These procedures are designed to evaluate the EMP performance of surge protection devices, especially devices designed to protect communication or low-power equipments where combined requirements must be met, such as operation in high-power circuit, or survival during lightning, these may be used as a guide.

5.2 Quasi-Static Response Measurements

5.2.1 Scope

This section deals with the measurement of the device parameters that determine how the device affects the system performance or how the system affects the device performance. Because of the variety and complexity of the possible system applications and the variety of surge protective devices, it is not possible to cover every facet of this problem in detail. In general, this document only covers the basic electrical parameters and the primary effects. It is the system designer or specifier's responsibility to be aware of and determine the more subtle effects for particular applications or system performance criterion. For example, if a silicon carbide varistor was used to protect the front end of a receiver, it could produce harmonic frequency components due to its nonlinear characteristics. The extend of this harmonic generation and its possible effects on system performance are not discussed in this document.

Throughout this document surge protective devices are divided into two general categories according to their basic operational characteristics. The two classes of surge protective devices are generally termed "Soft Limiters" and "Hard Limiters". In general, the "Soft Limiters" include both capacitors and varistors; varistors are voltage dependent nonlinear resistors. At the present time these procedures are limited to varistors; however, preferred test procedures for capacitors may be developed at a later date. The "Hard Limiters" include the various breakdown type devices such as gas gap, carbon blocks, zener diode, controlled avalanche rectifiers, etc. With regard to gas gap devices, electrical parameters are dependent upon physical parameters associated with the electrodes and the gas medium between the electrodes. The electrode parameters involve spacing and shape while the medium parameters encompass gas composition (impurities, ionization, etc.) and pressure. With a fixed gas composition and electrode geometry, increases in breakdown voltages for specific design requirements may be accomplished by adjustment of the gas medium pressure (typically in the range of a few atmospheres to hundreds of atmospheres). However, gas spark gaps commonly employed to protect communication, data processing, control and power systems are normally designed at a medium operating pressure in the order of one atmosphere. Therefore, subsequent discussions which involve gas gap arrestors primarily address performance characteristics associated with low pressure gas mediums. These devices present a near infinite impedance to a circuit while unfired and a near short when fired. The "Hard Limiters" could be further divided into two categories according to whether they are uni-polar or bi-polar devices. Although their intended application differ, the required measurements are very similar; hence, these two types of devices are considered in one class.

The various system applications can be divided into three general family groups according to the basic requirements they place upon the surge protective device. The three general family groups are as follows:

(1) AC Power

(2) DC Power

(3) Signal, Control, Communication and Data Links

Each of these presents a different set of requirements or problems for the surge protective devices. As an illustration of this point, consider the basic performance of a precision low-pressure spark gap. Figure 5-1 illustrates the basic performance curve that precision spark gaps follow at low arc currents, and in the quasi-glow region.

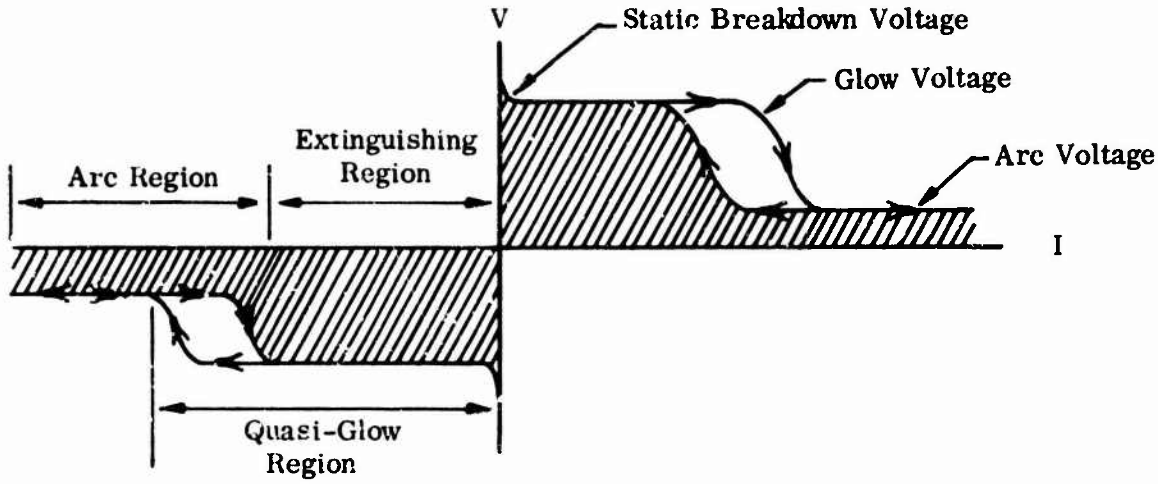


Figure 5-1. Typical Spark Gap Performance

Low-pressure gaps have two different conducting conditions: the quasi-glow region and the arc region. If the current through the gap after ignition does not reach sufficient values the gas tube will conduct only in the glow stage. At high currents the tube is forced into the arc region with a very low voltage across the gap. It should be noted that the initial point of arcing is not the same for increasing and decreasing currents. Upon decreasing current after arc initiation, the spark gap may flutter between the arc and quasi-glow modes. This does not appear important for single transient point at which the quasi-glow discharge becomes an arc discharge, and vice-versa, will vary greatly between samples of a given type of gap as well as on the same sample. This transitional point depends on the design of the gap and on the operating conditions. Even when operating conditions are kept constant, as is the case in plotting the V-I curve, a tolerance range of $\pm$ 25% can still be anticipated.

Obviously, the first consideration when applying a spark gap to a DC power circuit is that the circuit voltage must be less than the static (DC) breakdown voltage of the gap. The curve in Figure 5-1 illustrates the second consideration in applying a spark gap to a DC circuit, that of ability to extinguish the follow current of the electrical range.

A spark gap whose current is limited below the transition region by a limiting impedance in series with the gap, for instance a high DC system source impedance, and across whose terminals the DC system voltage is less than the glow voltage, will extinguish following initiation of an arc by an electrical surge. If the DC system voltage is greater than the glow voltage, even though the gap current is below the transition region the spark gap will fail to extinguish and continue to draw current from the system source until it overheats and eventually destroys itself.

If the gap current is not limited below the transition region, the DC system voltage must be less than the arc voltage for the gap to extinguish following initiation of an arc. Again, if the gap does not extinguish, it will continue to draw current from the system source until it overheats and eventually destroys itself.

In an AC power circuit this extinguishing problem does not occur since the system voltage returns to zero with each half cycle. Therefore, the gap voltage is brought to a point below both the glow voltage and arc voltage and the gap extinguishes. However, an AC power circuit presents the alternate problem of follow current. More specifically, in AC applications the fired spark gap will conduct during the remainder of the half cycle or until the voltage across the gap in combination with the current through the gap brings it into the region which permits extinction. Any statement regarding the extinguishing behavior of a protector should take into consideration that overheated electrodes (caused either by high surge currents or follow current) or other factors may prevent extinguishing and can cause repeated firing in following half cycles.

This follow current, because of its possible long duration, even if limited can cause deterioration of the spark gap electrodes resulting in erratic breakdown performance. Further, through deposition of the sputtered electrode material on the interior insulating walls of the device, can cause a lowering of insulation resistance and a rise in electrode to electrode capacitance.

In AC circuit applications where voltage transients routinely fire a protective gap, the degradations due to follow current could alter or destroy the protection after some period of time. This is one of the more subtle aspects involved in EMP hardness assurance and illustrates the need for periodic checks and maintenance of EMP protective measures.

In signal, control, communication and data link circuits the extinguishing voltage and follow current are generally not a problem. In such applications, the pulse response characteristics and the insertion loss due to shunt resistance and capacitance are generally the primary considerations.

5.2.2 Specific Test Procedures

5.2.2.1 Hard Limiters

Static Breakdown Voltage (V_{SB})

Breakdown voltage, firing voltage, trip voltage and striking voltage are synonymous terms referring to the point at which the protector begins to conduct and are used interchangeably throughout the protector industry. Throughout this document the term breakdown voltage will be employed. In general, the breakdown voltage depends on the rate of rise of the applied voltage transient. The Static Breakdown Voltage (V_{SB}) is the voltage at which a protector begins to conduct if subjected to a very slowly rising DC voltage. The generally accepted rate of rise for the measurement of the Static Breakdown Voltage is a frontal slope equal to or less than 100 V/sec.

Static Breakdown Voltage (V_{SB}) can easily be measured using a typical circuit as shown in Figure 5-2. The voltage across the protector is increased at a rate less than 100 V/sec; immediately after breakdown the power supply is turned down to

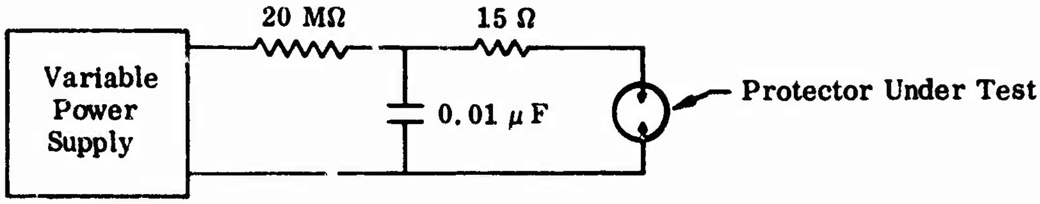


Figure 5-2. Typical Circuit for Measurement of V_{SB}

zero volts. A suitable voltmeter is used to measure V_{SB} across the protector. For bi-polar devices the Static Breakdown Voltage should be measured for both polarities; whereas, it should only be measured for the appropriate polarity for uni-polar devices.

The Static Breakdown Voltage of a protector is of minor importance under surge or pulse conditions. Consideration of Static Breakdown Voltage alone can lead to serious errors in predicting performance during its intended use as a surge protector. A low Static Breakdown Voltage does not necessarily guarantee a low Pulse Breakdown Voltage. The preferred test procedure for measuring the Pulse Breakdown Voltage is presented in the next section.

The principal value of the Static Breakdown Voltage is to indicate the relationship of the minimum protector breakdown voltage and the circuit steady-state voltage. The normal circuit voltage must be safely below the protector's Static Breakdown Voltage. Further, changes in the Static Breakdown Voltage are generally used as a failure criterion for Permanent Degradation Measurements or the effects of follow current.

Extinguishing Voltage (V_E)

Extinguishing Voltage, holdover voltage and sustaining voltage are synonymous terms, referring to the point at which the protector's self quench or self extinguish occur, are used interchangeably throughout the protector industry. Throughout this document, the term Extinguishing Voltage will be employed. The Extinguishing Voltage is the DC circuit voltage that would allow the protector to self quench or extinguish after surge firing. If the V-I (voltage versus current) curve of the device has a positive or zero voltage gradient over the entire range of interest, then the Extinguishing Voltage is equal to the Static Breakdown Voltage. However, if the V-I curve of the device has a negative voltage gradient (e.g., gas gaps) then the Extinguishing Voltage depends upon the current and could be significantly less than the Static Breakdown Voltage for some applications.

Since the Extinguishing Voltage can be a function of the current, it depends upon the current of the initiating transient and also on the current capability of any associated power supply. Therefore, for a particular system application the Extinguishing Voltage should be measured at the maximum short circuit current of the particular circuit. When measuring the Extinguishing Voltage with no particular circuit application in mind, the range of short circuit currents employed should be specified.

The Extinguishing Voltage, V_E, can be measured using the typical circuit shown in Fig. 5-3.

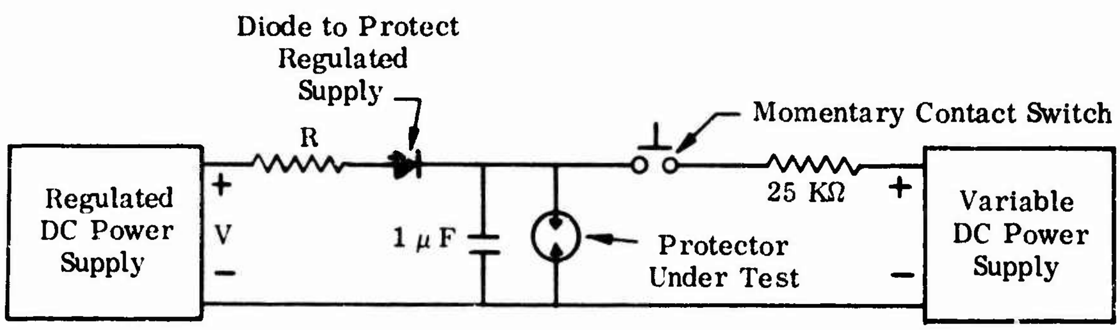


Figure 5-3. Typical Circuit for Measuring V_E

The regulated DC power supply, which must have the required current capability, is set at "V" volts and the resistance R is chosen to obtain the specified short circuit current. Then the variable DC power supply is adjusted to slightly above the protector Static Breakdown Voltage and the momentary switch is depressed to fire the protector. If the protector extinguishes in less than one second following the opening of the momentary switch, the Extinguishing Voltage is equal to or greater than "V" for that particular short circuit current. Obviously, one merely repeats the procedure increasing V and R (always keeping the short circuit current constant) until the protector does not extinguish within one second. Again, this measurement should be performed for both polarities for bi-polar devices and the appropriate polarity for uni-polar devices.

It should be noted that some manufacturers recommmend using a resistor in series with the arrestor since this will greatly assist its ability to extinguish without tripping the normal overload circuit breaker associated with the circuit to be protected, if provided. If such an approach is employed for a particular application, it should be emphasized that the resistor is essentially part of the overall protective device and must be included during the other evaluation tests.

Maximum Follow Current (I_{MF})

Follow current is the current from the connected power source which flows through the protector during and following the passage of current from an initiating transient. If the V-I curve of the device has a positive or zero voltage gradient over the entire range of interest, then the follow current is very small and this test is not applicable. As discussed previously, high follow current can overheat the electrodes and cause repeated firing in following half cycles. The Maximum Flow Current, I_{MF}, is the peak 60 Hz follow current that allows the protector to extinguish at the next zero crossing after ignition.

The Maximum Follow Current, I_{MF}, can be measured using the typical circuit shown in Fig. 5-4. The variable DC power supply is adjusted so that the initiating transient will have sufficient current to force the protector into the arc region. Unless the Static Breakdown Voltage is too low, a 120V - 60 Hz power source should be used and the value of R is chosen to

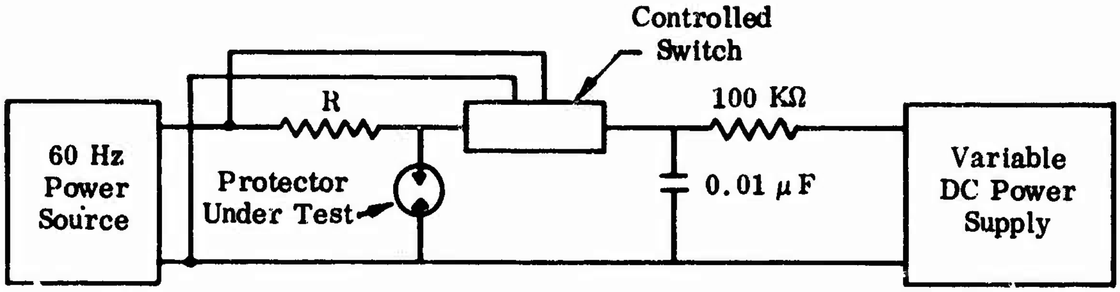


Figure 5-4. Typical Circuit for Measuring I_{MF}

obtain the desired follow current. If the Static Breakdown Voltage is too low for 120V application, a lower voltage 60 Hz power source should be used. The controlled switch is set such that the initiating transient occurs at approximately the 50% point on the rising portion of the first half cycle used for the test. Obviously, if the protector extinguishes at the first zero crossing after the initiating transient, the follow current should be increased by decreasing the value of R until the protector does not extinguish at the zero crossing. A pause of 30 seconds should be allowed between each test cycle.

Where the impressed AC voltage is different that 60 Hz, different extinguishing behavior may occur. Where this may be important, these procedures can be used as a guide to conduct tests at other frequencies.

Rated Follow Current (I_{RF})

The Rated Follow Current, I_{RF}, is the peak 60 Hz follow current that the protector can withstand for 3000 consecutive surges separated by 30 seconds without the original value of the Static Breakdown Voltage changing by more than $\pm$ 10%. The Rated Follow Current can be measured using the same typical circuit that is employed to measure the Maximum Follow Current (Fig. 5-4). The only difference is that the controlled switch is designed to provide the required surge every 30 seconds for 25 hours, rather than a single pulse. Again, if the V-I curve of the device has a positive or zero voltage gradient over the entire range of interest, then the follow current is very small and this test is not applicable.

Rated AC Discharge Current (I_{RA})

The Rated AC Discharge Current, I_{RA}, is the RMS value of the 60 Hz current applied in five consecutive cycles, each cycle consisting of two one second surges five seconds apart, after which a pause of five minutes shall be provided. The Rated AC Discharge Current can be measured using the same typical circuit that is employed to measure the Maximum Follow Current (Figure 5-4). The only difference is that the controlled switch is designed to provide the required one second surges rather than a single pulse.

Following this test, the Static Breakdown Voltage, V_{SB}, of the protector shall not differ from its original value by more than $\pm$ 10%. If a more liberal or conservative failure criterion is warranted for a particular application, then it should be employed. Again, if the V-I curve of the device has a positive or Zero voltage gradient over the entire range of interest, then the follow current is very small and this test is not applicable.

Shunt Resistance (R_S)

The Shunt Resistance, R_S, of a protector is the DC insulation resistance at a particular test voltage. The Shunt Resistance can easily be measured using a resistance meter, such as the Hewlett Packard Model 4329A. However, because of the extremely high resistance value usually involved, it is very difficult to obtain an accurate measurement. In general, it is sufficient to merely specify the order of magnitude of the Shunt Resistance, such as $R_S > 10^{10}\Omega$. When specifying the Shunt Resistance, the test voltage employed should be stated. Generally, the test voltage employed is the highest convenient test voltage that does not exceed the Static Breakdown Voltage.

It should be noted that changes in the Shunt Resistance could be and are sometimes used as a failure criteria for

Permanent Degradation Measurements. However, because of the extremely high resistance values usually involved, it is generally difficult to define what constitutes a significant change with respect to system performance degradation.

Shunt Capacitance (C_s)

The Shunt Capacitance, C_s , of a protector is the electrode to electrode capacitance and is usually measured at a convenient test frequency (1-100 KHz). The Shunt Capacitance can easily be measured using a L-C meter or an impedance bridge, such as the Tektronix Type 130 L-C meter, the General Radio 1650B Impedance Bridge or the 1615-A Capacitance Bridge. Because of the extremely small Shunt Capacitance in many devices, it may be very difficult to obtain an accurate measurement. In such cases it is sufficient to merely specify the order of magnitude, such as $C_s < 2$ pf. Further, the Shunt Capacitance of some devices depends upon the DC bias voltage and should thus be measured for the appropriate bias voltage. Therefore, it should be noted that the General Radio 1650B Impedance Bridge has the capability of measuring capacitance with up to 600 volts bias.

Since the Shunt Capacitance can have a significant effect on the transient response and may limit the possible applications of the protective device, it should be measured for all types of devices even though the shunt capacitance may not be an important factor for the intended application. Further, the effective Shunt Capacitance of uni-polar devices should also be measured using either back-to-back or front-to-front combinations to form a bi-polar configuration.

Voltage - Current Characteristics (V-I Curve)

Even though the Shunt Resistance is usually very high and the Shunt Capacitance is small, the resulting leakage current may be significant for some system applications. In such cases, the Voltage-Current Characteristics (V-I Curve) of the device should be measured. Use of a Tektronix Model 575 or 576 curve tracer is recommended for this measurement.

5.2.2.2 Soft Limiters

Voltage - Current Characteristics (V-I Curve)

In general, the "Soft Limiters" include both capacitors and varistors; however, these procedures are presently limited to varistors. A varistor is a nonlinear voltage dependent resistor for which the current varies as a power of the applied voltage. The most common present-day expression which approximates the Voltage-Current Characteristics is :

$$I = KV^{\alpha}$$

where

I = instantaneous current
K = device constant
V = instantaneous voltage
α = device exponential

The constants K and α depend upon the resistivity of the material, the geometry and various factors in the manufacturing process (i.e., variation of both size and composition of both the crystals and grain boundary).

The nonlinear voltage-current characteristics of a varistor extends over an extremely wide current range and the above equation approximates these characteristics. The higher the exponential, the more nonlinear the electrical characteristics; hence, alpha (α) is a measure of how well a suppressor approaches the ideal. In general, the exponential is somewhat dependent on the applied voltage. A reduction in voltage gradient is usually accompanied by a reduction in exponent. At voltages less than one volt it is generally impractical to supply material having an exponent greater than 2.

Because of the possible variation of the exponential (α) with applied voltage, especially at low voltage, the effective α of varistors should be measured by means of high current pulse testing. These techniques are discussed in the Transient Response Measurement section. Further, the low level characterization for determining how the device affects the system performance or how the system affects the device performance should include the measurement of the voltage-current characteristics (V-I curve) over the range of interest. Use of a Tektronix 575 or 576 curve tracer or equivalent type test equipment is recommended for this low current range measurement.

In many test programs it may only be necessary to perform calibration checks of the devices. Incoming calibration checks cannot be made by ohmmeter or by bridge resistance circuits, since varistors are voltage sensitive. The standard steady-state calibration circuit is shown in Figure 5-5.

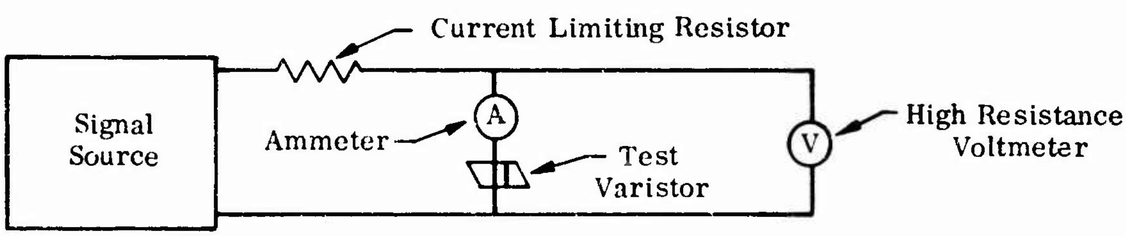


Figure 5-5. Standard Steady State Calibration Circuit for Varistors

The primary purpose for these calibration checks is that changes in the Voltage-Current Characteristics are generally used as a failure criterion for Permanent Degradation Measurements. Therefore, for a particular system application the calibration check should be performed for the appropriate operating conditions (i.e., frequency and signal level). When performing tests with no particular circuit application in mind, the calibration checks should be performed at either the DC or 60 Hz voltage rating of the device.

If these calibration checks are performed at 60 Hz or any other frequency, it should be noted that because of the variable resistance of the device, the wave shape of the current is quite different from the wave shape of the voltage producing it. For example, if a sinewave of voltage is applied, a typical waveform of current is shown in Figure 5-6.

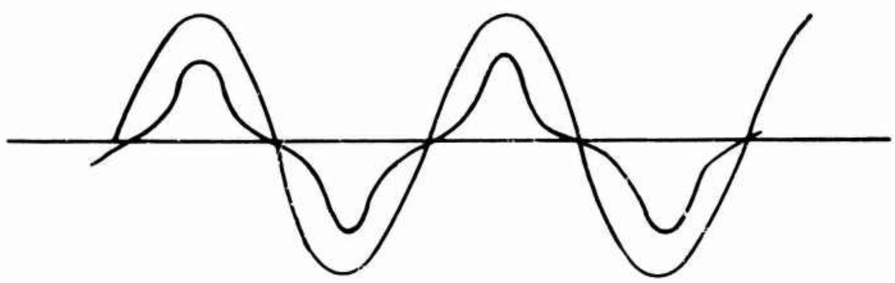


Figure 5-6. Representative 60 Hz Voltage and Current of a Varistor

Because of this change in waveform the ratio of the rms voltage to the rms current will not be the same as the ratio of the instantaneous voltage to the instantaneous current. This fact must be kept in mind if calibration checks performed with a rms voltmeter and a rms ammeter are to be correlated with V-I measurements performed with a curve tracer.

Further, it should be noted that the average power loss in a varistor for an applied AC voltage is given by:

$$P = V_{rms} \times I_{rms} \times (pf)$$

where the power factor depends on the exponential, α, and is somewhat less than unity. Since device failure is usually a result of overheating due to excessive power dissipation, calibration checks in terms of rms voltages and currents are definitely appropriate.

Steady State Voltage Rating

The Steady State Voltage Rating is determined by the average power dissipation capability of the varistor. The rating depends upon the permissible temperature rise of the varistor and provision made for heat dissipation. In general, the Steady State Voltage Rating should be specified as the maximum permissible 60-Hz rms voltage for still air cooling at a specified ambient temperature. Further, for many applications, it is desirable to know the rating as a function of ambient temperature.

When performing these measurements, the surface temperature of the varistor should be measured, using a thermocouple* epoxied to the body of the varistor. Further, some care is required so that the thermocouple leads and junction do not cause localized cooling and result in an erroneous reading. A 10 or 12 mil copper-constantan thermocouple junction is suggested.

Shunt Capacitance (C_S)

Again, as in the case of the "hard limiters", the shunt capacitance can have a significant effect on the transient response and may limit the possible applications of the device. Therefore, it should be measured for all types of devices, even though the shunt capacitance may not be an important factor for the intended application.

The Shunt Capacitance, C_S, of a varistor is the electrode-to-electrode capacitance and is usually measured at a convenient test frequency (1-100 kHz). However, because of the voltage dependent nonlinear resistance, it is not possible to accurately measure the shunt capacitance with some types of capacitance bridges. More specifically, the type of capacitance bridge employed should balance the real and imaginary parts of the unknown independently. In order to do this, both the real and reactive components in the complex balancing arm must be adjustable. The General Radio Type 1615-A Capacitance Bridge is of this type and would be acceptable for measuring the shunt capacitance of varistors. Further, for some types of varistors, the dielectric

*Aeropak Miniature Mineral Insulated

constant and resulting shunt capacitance is a function of the applied voltage. In such cases, the shunt capacitance should be measured at the particular signal level of interest or over an appropriate range of signal levels.

If only one component in the complex balancing arm is adjustable, the balancing depends upon the resistance of the varistor and, hence, on the amplitude of the test signal. In general, capacitance bridges, such as the General Radio 1650-B, which have a switch for high and low dissipation factor, D, are of this latter type and are generally not acceptable for accurate measurement. It should be noted, however, that this later type can give accurate measurements in cases where the varistor and test conditions result in a low dissipation factor.

5.2.2.3 Data Reporting

If the test was conducted as a complete quasi-static characterization, all of the pertinent parameters discussed in the preceding paragraphs should have been measured. Tables and figures on the following pages show the suggested formats for presenting these data for both hard limiters and soft limiters. Actual test circuits, test equipments, and detailed procedures should be specified in sufficient detail so that another experimenter could repeat the tests.

If the test was conducted as a partial characterization or as a simple proof test, not all of the parameters were necessarily measured. Nevertheless, the test data and detailed procedures should be reported. It is recognized that proof-test data are generally of little value to anyone other than the user, but by reporting the data, their usefulness and validity can be better assessed.

HARD LIMITER DATA

Device Type ______________________ Date ______________

Sample Number									
Static Breakdown Voltage									
Extinguishing Voltage									
Maximum Follow Current									
Rated Follow Current									
Rated AC Discharge Current									
Shunt Resistance									
Shunt Capacitance									

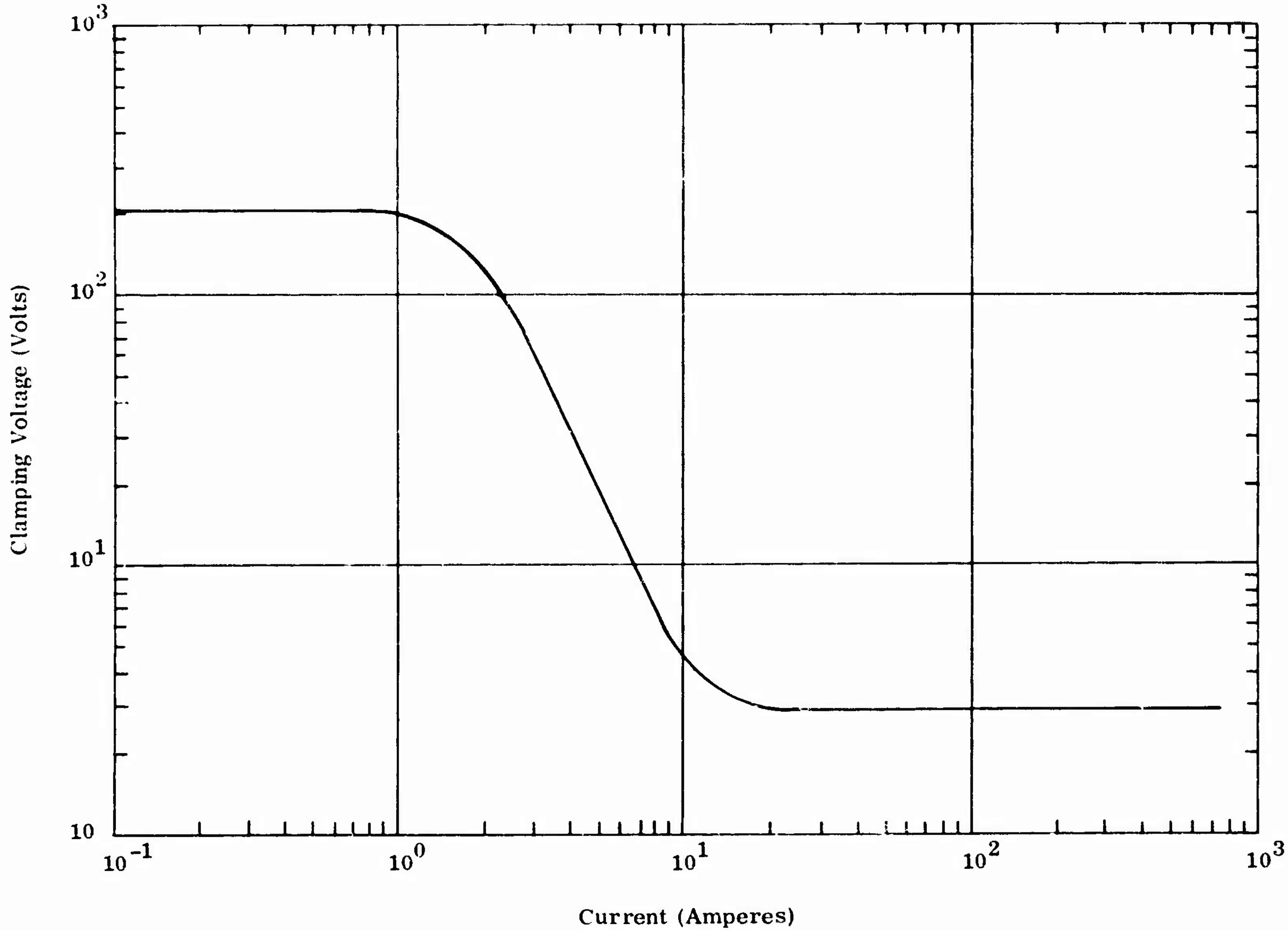
SOFT LIMITER DATA

Device Type ______________________________ Date ______________

Sample Number									
Steady State Voltage Rating									
Current @ Steady State Voltage Rating									
Shunt Capacitance									

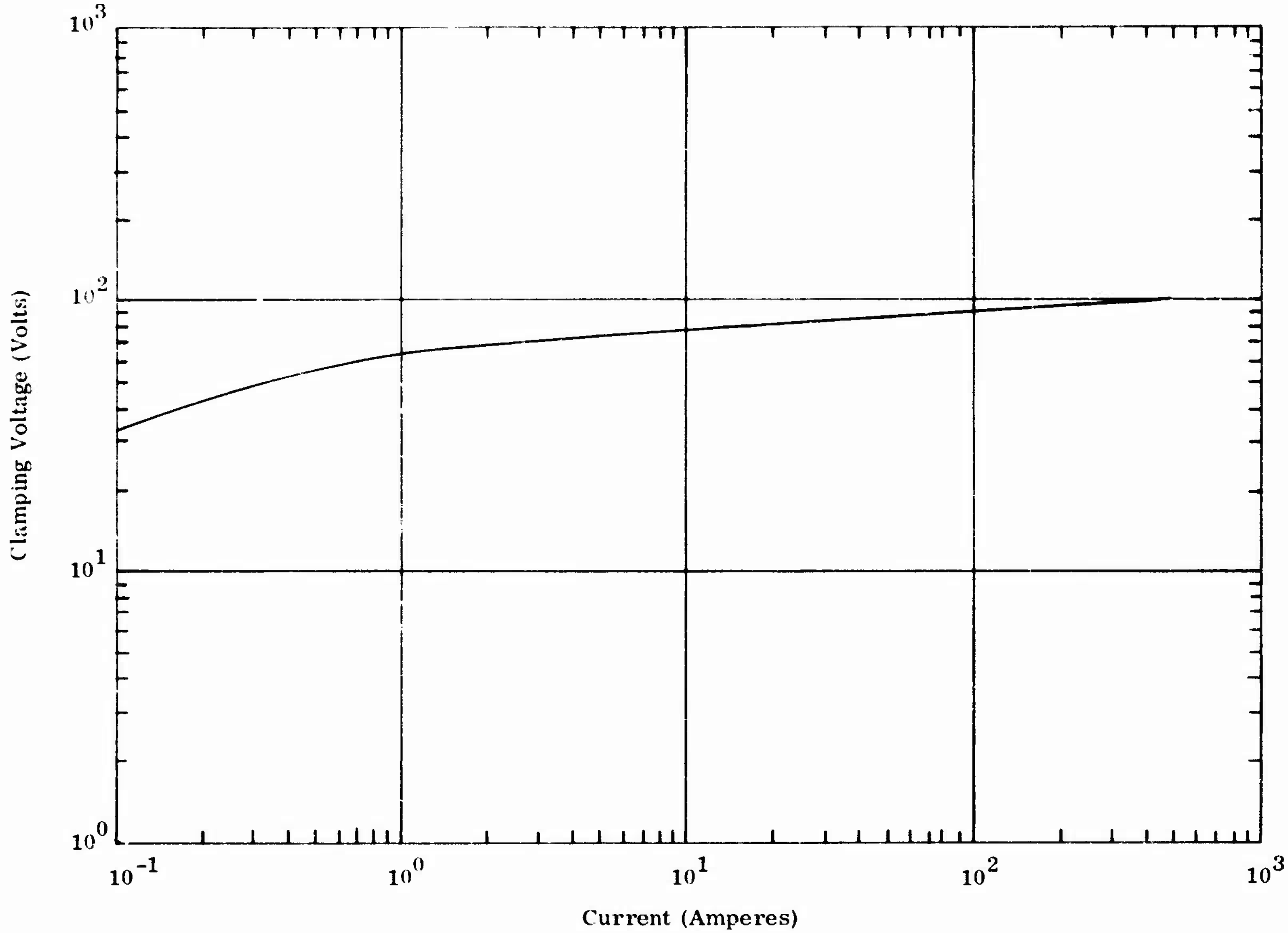
HARD LIMITER DATA

Device Type ______ Sample Number ______ Date ______



SOFT LIMITER DATA

Device Type ____________ Sample Number ____________ Date ____________



5.3 Transient Response Measurements

5.3.1 Scope

This section deals with the measurement of the parameters that determine the performance of the protective devices for various surge conditions. The main purpose of a protector is to detect the surge conditions and dissipate or shunt it before damage can occur to the equipment being protected. Therefore, in order to intelligently evaluate various protective devices, one must be familiar with representative EMP induced transients and typical damage mechanisms and levels for circuit components.

The discussion here will consider the failure mechanisms associated with a single pn junction since (1) such a junction is found in all semiconductor devices, and (2) extension of the results presented to multi-junction devices is relatively straight forward.

The power required for junction failure is a function of the applied pulse width (for single pulse excitation) as shown in Figure 5-7.

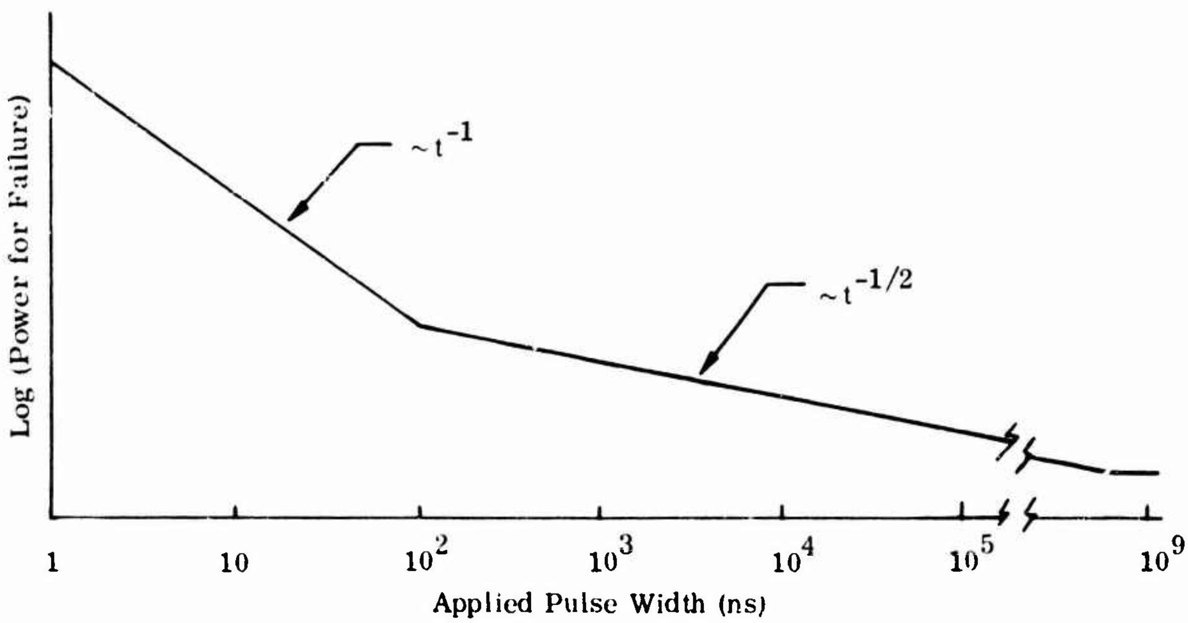


Figure 5-7. Typical Failure Level Versus Pulse Width

The same general relationship between the power level for failure and pulse width is found for both reverse and forward polarity excitation on the junction. However, in general, an increased power level of from 5 to 15 dB is required to achieve junction failure for voltage pulse across the pn junction diode in the forward direction.

The general shape of the curve may be explained as follows:

(a) for pulse widths on the order of 1 msec or longer, the continuous power ratings of the device applies with regard to failure.

(b) in the time domain of from 100 nsec to 1000 μsec, the pulse power level required for junction failure follows a $t^{-1/2}$ relationship. This result is obtained both experimentally and theoretically where a boundary value heat equation problem is solved under the assumption that all the energy expended in the device is converted to a plane heat source at the junction face.

(c) In the less than about 10 to 100 nsec time regime, the required power level to failure follows a t^{-1} relationship with respect to incident pulse width. This relationship holds due to the fact that at such short pulse widths, relatively large power levels and conversely large currents are required to generate enough heat in the device to cause failure. These large currents generate significant amounts of I^2R losses in the bulk semiconductor material, thus overshadowing the heat generated at the junction. Hence, for this case an extended heat source must be assumed as contributing to the junction failure. In theory and also experimentally, such a condition results in a t^{-1} time dependence.

(d) In the regime below about 10 nsec, one of two possible conditions may predominantly exist. A t^{-1} dependence signifying a uniform heat source throughout the body of the device, or a time independence implying a dielectric breakdown failure due to arcing or other surface effects. For a given device, whether one or the other trend is observed, is dependent upon its surface characteristics such as impurities, surface imperfections, geometry, etc.

Except for possible surface effects at extremely short pulse durations, the device damage mechanism is essentially the same for both the t^{-1} and $t^{-1/2}$ slope regimes and also for forward and reverse biased polarities. The basic effect is a local thermal runaway condition at the junction induced by severe current concentrations within the device which are a function of the biasing conditions, excessive junction fields and material defects. That is device degradation is a direct result of melting and re-alloying reactions at various current construction sites along the junction face.

These sites effectively form low resistive paths commonly called filaments which bridge across the junction at one or more sites. From an equivalent circuit point of view, the effect is to bridge the junction with a low value resistance which tends to nullify the junction action.

The same amount of energy is required at the junction to initiate damage independent of pulse polarity. For forward biased pulses, the voltage drop across the junction is very small, thus resulting in a high junction current. This high current causes high I^2R losses in the bulk semiconductor and hence, it requires more power at the device terminals to fail the junction in the forward direction.

As discussed in Section 4., typical EMP induced transients are generally of the form of an exponentially decaying sinusoidal (Figure 5-8) with various peak amplitudes, resonant frequencies and decay times. Further, the collector or source impedances are generally complicated complex functions.

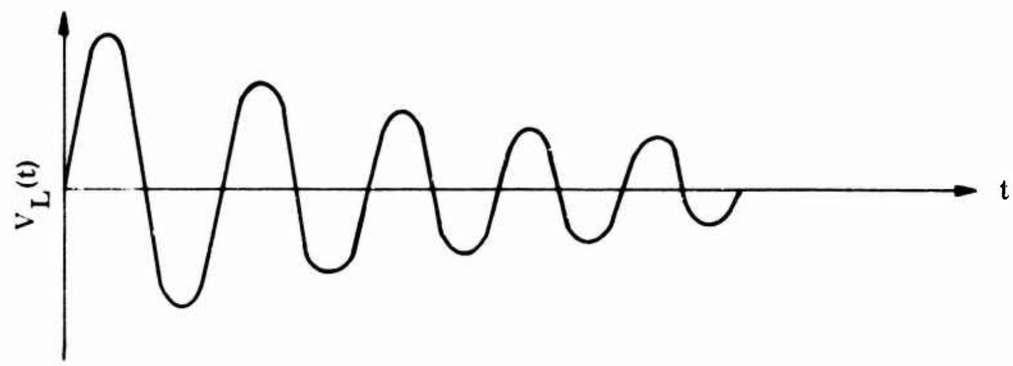


Figure 5-8. General Form of Typical EMP Induced Transient

Ideally, one would measure the response of the various surge protective devices for a broad range of exponential decaying sinsusoidal waveforms (such as shown in Section 4.) using a pulse injection source with the appropriate output impedance for each waveform. However, such injection sources are not presently available and would require significant development cost. Further, even if the required sources were available, such a procedure would be time consuming and expensive because of the wide variety of possible transients. Therefore, these preferred test procedures are based on the measurement of the parameters that are required to characterize the device in such a manner that one can calculate the response of the device for various surge conditions. Such an approach is possible because of the fact that surge protective devices generally have very little frequency selectivity and present very low impedances (almost a short circuit) under surge conditions.

Based on the above facts and the general nature of the transient response for surge protective devices, it is only necessary to measure two basic parameters to characterize the device. First, one must measure the early time overshoot characteristics for a rapidly rising transient. In general, the amount of overshoot is a function of the rate of rise and is controlled by the inherent inductance, shunt capacitance and response time of the device. For the soft limiters this parameter is termed the Peak Pulse Voltage and for the hard limiters it is termed the Pulse Breakdown Voltage. In both cases it is measured for both polarities and various rates of rise up to at least 5 KV/ns. Second, one must measure the intermediate time nonlinear voltage-current characteristics for various surge conditions. For both the soft limiters and hard limiters this parameter is termed the Clamping Voltage and is in general a function of the current. Again this parameter is measured for both polarities and for an appropriate current range.

Once these two sets of parameters are known, one can obtain a nonlinear circuit model for the protective device and calculate the overall response for various collectors and loading conditions. Further, if the load voltage without the protective device and the short circuit current are known, it is sometimes possible to easily estimate the response with the protective device in the system. More specifically, the rate of rise and peak amplitude of the load voltage is used in conjunction with the Pulse Breakdown Voltage or Peak Pulse Voltage to estimate the overshoot. Further, the short circuit current and the Clamping Voltage are used to estimate the voltage across the protected load for intermediate times. For example, if we consider the general form shown in Figure 5-8, the general form of the load voltage with the protective device in the circuit is illustrated in Figure 5-9.

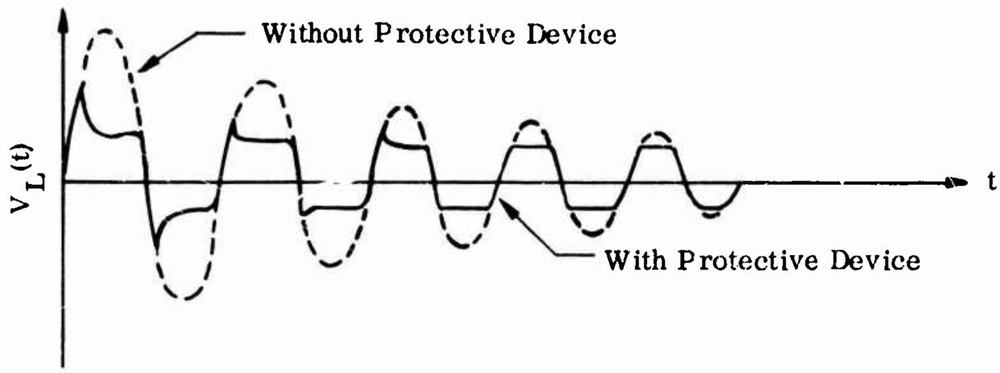


Figure 5-9. Representative Response for an EMP Induced Transient

From this response it is possible to determine the basic parameters generally used to specify failure levels of semiconductor devices (peak voltage, energy and power in various time domains).

It should be noted that these preferred test procedures are based on measuring or determining the overshoot characteristics with essentially zero initial conditions. Therefore, response calculations for oscillatory type transients may overestimate the spiking for all but the first half cycle. More specifically, because of the finite recombination rate a gas gap will be partially ionized at the start of the second and each subsequent half cycle; therefore, the actual Pulse Breakdown Voltage and resulting overshoot could be less than the calculated values, which is based on zero initial conditions.

5.3.2 Specific Test Procedures

5.3.2.1 Hard Limiters

Pulse Breakdown Voltage (V_{PB})

Impulse breakdown voltage, dynamic breakdown voltage, surge sparkover voltage and surge striking voltage are synonymous terms referring to the point at which the protector begins to conduct for various rates of rise of the initiating transient and are used interchangeably throughout the protector inductory. Throughout this document, the term Pulse Breakdown Voltage will be employed. The Pulse Breakdown Voltage is one of the most important characteristics of the protector and is determined by the minimum response time of the device and the effective inductance of the insertion technique.

The Pulse Breakdown Voltage, V_{PB}, is the peak voltage attained before the protector begins to conduct for a specific rate of rise of the applied transient. Therefore, the Pulse Breakdown Voltage, V_{PB}, is measured by observing breakdown on the front of the wave, using a suitable oscilloscope and a variable rate of rise pulse source, as indicated in Fig. 5-11. Measurements are taken using voltage pulses of a sufficiently high peak value ($V_P \leq 10$ KV, Fig. 5-10), so that the protector will breakdown on the rising or frontal portion of the pulse.

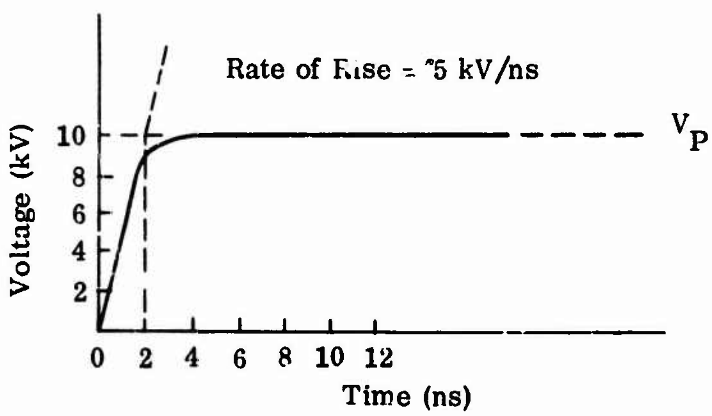


Figure 5-10. Typical Test Waveform

In general, the Pulse Breakdown Voltage increases with increasing rates of rise of the applied pulse. Based on this fact and the represented EMP transients discussed in Section 4, the Pulse Breakdown Voltage should be measured at various rates of rise up to at least 5 KV/ns. It should be noted that this rate of rise is a factor of 1000 greater than the maximum rate of rise generally employed (5 KV/μs) for other type transient evaluations of protective devices.

This required high rate of rise (5 KV/ns) results in some severe problems to the experimenter. These experiments require fast rise time (about 10 ns), high voltage pulse sources (about 30 KV), and broadband oscilloscopes (150 MHz bandwidth). Careless handling of the signals or test fixtures can easily result in loss of data, or in questionable data. In fact, in some cases the Pulse Breakdown Voltage for this high rate of rise will be controlled by the insertion technique rather than by the device itself. Therefore, it is mandatory that the experimenter maintain as high a signal-to-noise* ratio as possible and measure the inherent inductive voltage (noise level) of the test fixture for each of the test waveforms employed. The test pulses must be handled in coaxial configurations with the shield being continuous and the cables must be terminated in their characteristic impedances to insure that they faithfully reproduce the desired signal. In some cases it may be necessary to employ a filter on the 60 Hz power of the oscilloscope and enclose the scope in a shielded box.

The Pulse Breakdown Voltage, V_{PB}, should be measured using the typical circuit configuration shown in Figure 5-11.

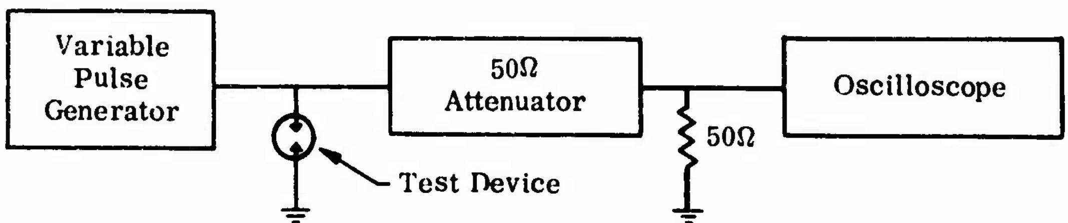


Figure 5-11. Typical Circuit Configuration for Measuring V_{PB}

* All extraneous voltages.

The first step in the preferred test procedure is to measure and record the test waveform. With the test device removed from the circuit, the pulse generator is adjusted to provide the required rate of rise and peak amplitude across the 50Ω termination. This waveform is then measured and recorded using a suitable oscilloscope and camera. Next, the test device is inserted in the circuit and again the voltage across the 50Ω termination is measured and photographed. The basic response characteristics and the Pulse Breakdown Voltage for this particular rate of rise is determined from this measurement and photo. Finally, the test device is replaced by a short circuit and the voltage across the 50Ω termination is again measured and photographed. This last measurement is basically a measurement of the noise level or inherent inductance of the test fixture. Since the Pulse Breakdown Voltage can sometimes be controlled by this inherent inductance, it is mandatory that this measurement be performed for each of the test waveforms employed.

Obviously, to obtain the Pulse Breakdown Voltage for other rates of rise the pulse generator is adjusted to provide the required rate of rise and the above procedure is repeated. Although the basic procedure is straightforward, setting up and performing the actual experiments is not always an easy task because of the high voltages and high rates of rise or bandwidth required. Therefore, the primary test considerations and some suggested experimental techniques and equipments are discussed below.

The first consideration is that the test pulse (i.e., peak voltage, peak current, pulse width and repetition rate) must be such that it does not damage or destroy the device. The general rule of thumb is that the pulse width and pulse amplitude employed are just large enough to insure frontal breakdown. Further, for the slower rates of rise it may be necessary in some cases to use a resistor in series with the source to limit the peak current. Finally, these measurements are generally performed on a single shot basis.

Because of the required broad bandwidth and single shot measurements, the monitoring oscilloscope must be a broadband real time oscilloscope. The actual bandwidth requirements depend upon the response characteristics of the device and the rate of rise being employed. When performing measurements at 5KV/ns, a 150 MHz bandwidth will suffice for some types of protective devices. In such cases, a Tektronix 454 or a HP1710A oscilloscope would be acceptable. In general, however, an even wider bandwidth is required and use of a HP183, a Tektronix 485 or a Tektronix 519 oscilloscope is recommended. Further, the combination of broad bandwidth (fast sweep speeds) and single shot measurements results in very high writing speed photography requirements. Therefore, the experimenter should be familiar with the present state-of-the-art in oscilloscope photography and writing rates for oscilloscopes. Either the Hewlett Packard or the Tektronix instrumentation catalogs present sufficient information in the area and are excellent starting points. The "Testing Section" in the EMP Course Notes might also be consulted.

The next primary consideration is the required variable rate of rise pulse source. At the present time there is no commerically available source that satisfies all the requirements. However, charged line sources are available or can be constructed to obtain peak voltages greater than 10 KV with rise times on the order of 1 nanosecond or less. Therefore, one suggested approach to obtain a 5 KV/ns test waveform is to employ such a charged line source in conjunction with a low pass filter, a series inductor or a section of lossy transmission line (i.e., RG-222) to slow the resulting rate of rise to 5 KV/ns. It would also be possible to construct a capacitor discharge source with the required 5 KV/ns rate of rise; however, it would probably be more expensive because of the low inductance, high voltage capacitor required. Further, the capacitor discharge source would result in significantly higher short circuit current than the charged line source and could result in device damage. At the slower rates of rise a capacitor discharge source may be more appropriate and because of the reduced bandwidth it would be much simpler to incorporate a series resistor in the source to limit the short circuit current.

Another of the primary considerations is the test fixture or device insertion technique. As mentioned previously, the Pulse Breakdown Voltage may be primarily controlled by the inductance of the insertion techniques. Numerous techniques are acceptable provided the experimenter measures the open-circuit and short-circuit response of the insertion fixture and describes it in sufficient detail that someone else can repeat the experiment. Some suggested approaches are to use a General Radio type 874-X insertion unit or use a coaxial tee (GR type 874-T tee) and a GR type 874-ML component mount. Another approach would be to use a coaxial tee and construct a shielded enclosure component mount similar to the GR unit. Shown in Figure 5-12 in some detail is an easily fabricated tee type mount arranged in a 50Ω test jig. The limiter is housed in the body of a coaxial cable plug whose cable retaining nut is modified to provide a shielded enclosure. Coaxial positioning of the limiter is achieved by soldering its terminals to the modified retaining nut and to the plug's center pin. Where limiters are not readily adaptable to coaxial components, a 50Ω strip transmission line mount, shown in Figure 5-12, can be employed with minimum inductive reactance affects. Since the Pulse Breakdown Voltage may be primarily determined by the insertion technique, a general rule of thumb is that the insertion unit should not be so sophisticated or expensive that it is not practical for system applications. Further, when testing protective devices with leads, the lead length employed during the test should be specified.

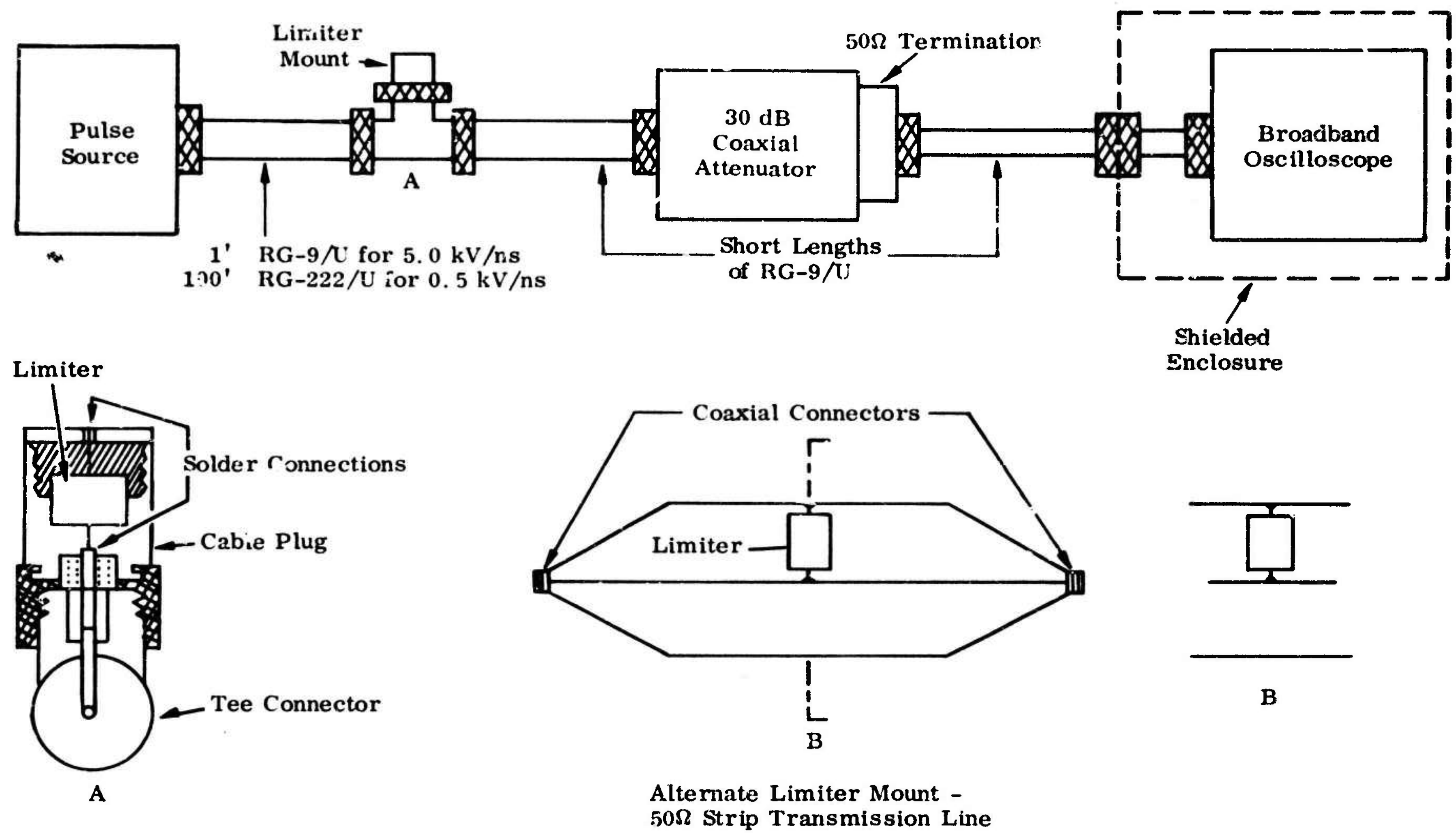


Figure 5-12. Limiter Mount in a Typical 50Ω Test Jig

The remaining element of the test circuit is the 50Ω attenuator. This could either be a specially constructed broad-band attenuator or an acceptable commercially available attenuator. One type of commercially available attenuator that can be used up to peak amplitudes of 11-12kV is the Bird Model 8325 30 dB coaxial attenuator with a type "HN" input connector. It should be noted that type "N" connectors will generally only withstand 8-9kV on a pulse basis.

Clamping Voltage (V_c)

The Clamping Voltage, (V_c), is the voltage across the protective device during surge conditions after any overshoot or spiking has decayed down. In general, the clamping voltage depends upon the current; therefore, it could also be termed the intermediate time voltage-current characteristics. Since the Clamping Voltage, V_c, depends upon the current, it should be measured over an appropriate current range. Further, it should be measured for both polarities for both unipolar and bipolar devices.

In order to avoid device damage, the Clamping Voltage should be measured on a pulse basis using a typical circuit as shown in Fig. 5-13.

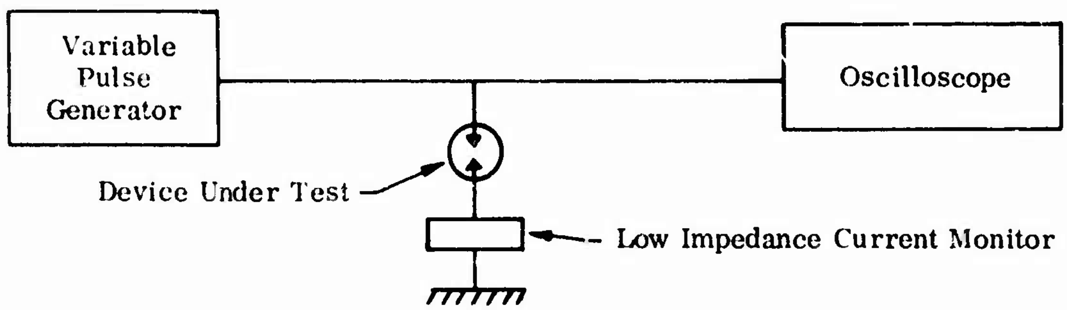


Figure 5-13. Typical Circuit for Measuring V_c

These measurements are usually performed using a rectangular pulse with a pulse width between 500 ns and 1 ms. The actual peak amplitude, pulse width and repetition rates employed are controlled either by the available source or the device peak current or energy capability. Various pulse generators are acceptable provided they have the required current capability. For example, a Velonex Pulse Generator Model No. 350 could be used for the low current range and a charged line source could be used for the higher current ranges. If even higher currents are required, a capacitor discharge source could be employed. In this case the waveform would not be rectangular; however, such an approach is acceptable provided the rate of change of the test waveform is sufficiently slow that the inductive effects of the circuit are negligible.

The impedance of the required current monitor must be small compared to the effective impedance of the protective device. A general rule is that it must be at least a factor of 10 less than the effective impedance of the device. The current monitor could be a commercially available current probe; (i.e., Tektronix CT-1 or CT-2, Genisco GCP-5110 or 5130, etc.), or merely consist of measuring the voltage across a low resistance current shunt. Care should be taken to use a non-inductive current shunt for narrow pulse work.

The voltage across the test device is monitored using a high impedance oscilloscope. Since the bandwidth or peak voltages are not generally very high, the voltage monitoring is not especially difficult and is, therefore, not discussed in detail. However, it should be noted that significant voltages could be applied to the oscilloscope if the device did not fire or failed to open.

5.3.2.2 Soft Limiters

Peak Pulse Voltage (V_{pp})

The Peak Pulse Voltage is defined as the peak voltage across the varistor for a specific rate of rise and peak amplitude of the test pulse. The Peak Pulse Voltage is very similar to the Pulse Breakdown Voltage of hard limiters in that it is a measure of the inductive overshoot or spiking. However, it is different than the Pulse Breakdown Voltage in that it also depends upon the peak amplitude of the test pulse. More specifically, if the applied voltage increased indefinitely at a constant rate of rise, then the voltage across the varistor would continue to rise until the device failed.

The test circuit and procedure for measuring the Peak Pulse Voltage, V_{pp}, for a soft limiter is exactly the same as that for measuring the Pulse Breakdown Voltage of a hard limiter. Again, the open circuit and short circuit (i.e., the device removed and the device replaced by a short circuit, respectively) response of the test circuit should be measured. It is particularly important that one measure the peak test voltage with the device out of the circuit (open circuit). Again, these measurements should be performed up to at least 5 kV/ns for both polarities and the basic test considerations discussed previously apply to this case also.

Clamping Voltage (V_c)

The Clamping Voltage, V_c, for soft limiters is defined and measured in exactly the same manner as indicated for hard limiters, Paragraph 5.3.2. Therefore, the preferred test procedure will not be repeated here.

As discussed previously, the exponential (α) is a measure of the effectiveness of the varistor. It should be noted that a plot of Clamping Voltage versus current could be used to determine the effective α of the device.

Rated Pulse Current (I_{RP})

The Rated Pulse Current, I_{RP}, for a particular fall time is defined as the peak current that the protector can withstand for 100 successive pulses separated by at least 30 seconds each without exceeding the failure criterion. The failure criterion, test circuit, test procedure or sequence and the range of decay times discussed for the Maximum Pulse Current apply to this measurement also.

5.3.2.3 Data Reporting

If the test was conducted as a complete transient characterization, all of the pertinent parameters discussed in the preceding paragraphs should have been measured. The tables and figures on the following pages show the suggested formats for presenting these data for both hard limiters and soft limiters. Actual oscilloscope photographs of the open circuit, short circuit, and device response for the fastest rate of rise employed is very desirable and should compliment the tabulated and graphical data. Sample time domain oscilloscope photographs of hard and soft limiter responses are also included as a suggested reference. The format of the photographs are such that for ease of comparison, the responses of the subject limiter (in a 50Ω jig) to two voltage waveforms of different rates of rise are exposed on the same print. Further, the actual test circuits, test equipments, and detailed procedures should be specified in sufficient detail so that another experimenter could repeat the tests.

If the test was conducted as a partial characterization or as a simple proof test, not all of the parameters were necessarily measured. Nevertheless, the test data and detailed procedures should be reported. It is recognized that proof-test data are generally of little value to anyone other than the user, but by reporting the data, their usefulness and validity can be better assessed.

HARD LIMITER DATA

Device Type ______________________________ Date ______________

Sample Number									
Pulse Breakdown Voltage @ 5 kV/ns									
Clamping Voltage ($I = I_{RP}$ @ $t_f = 1\ \mu s$)									

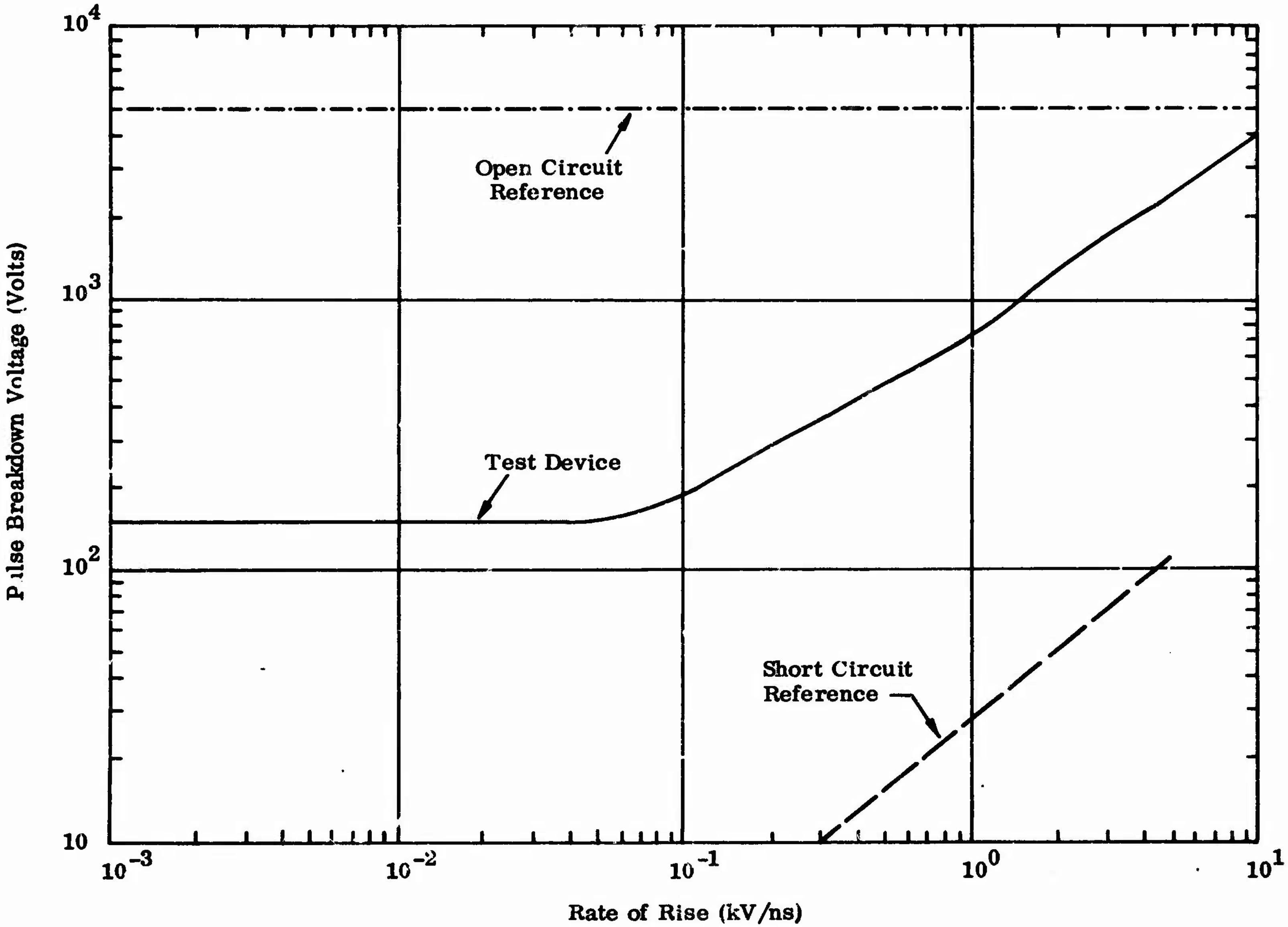
SOFT LIMITER DATA

Device Type ______________________ Date ______________

Sample Number									
Peak Pulse Voltage @ 5 kV/ns									
Clamping Voltage ($I = I_{pp}$ @ $t_f = 1\ \mu s$)									

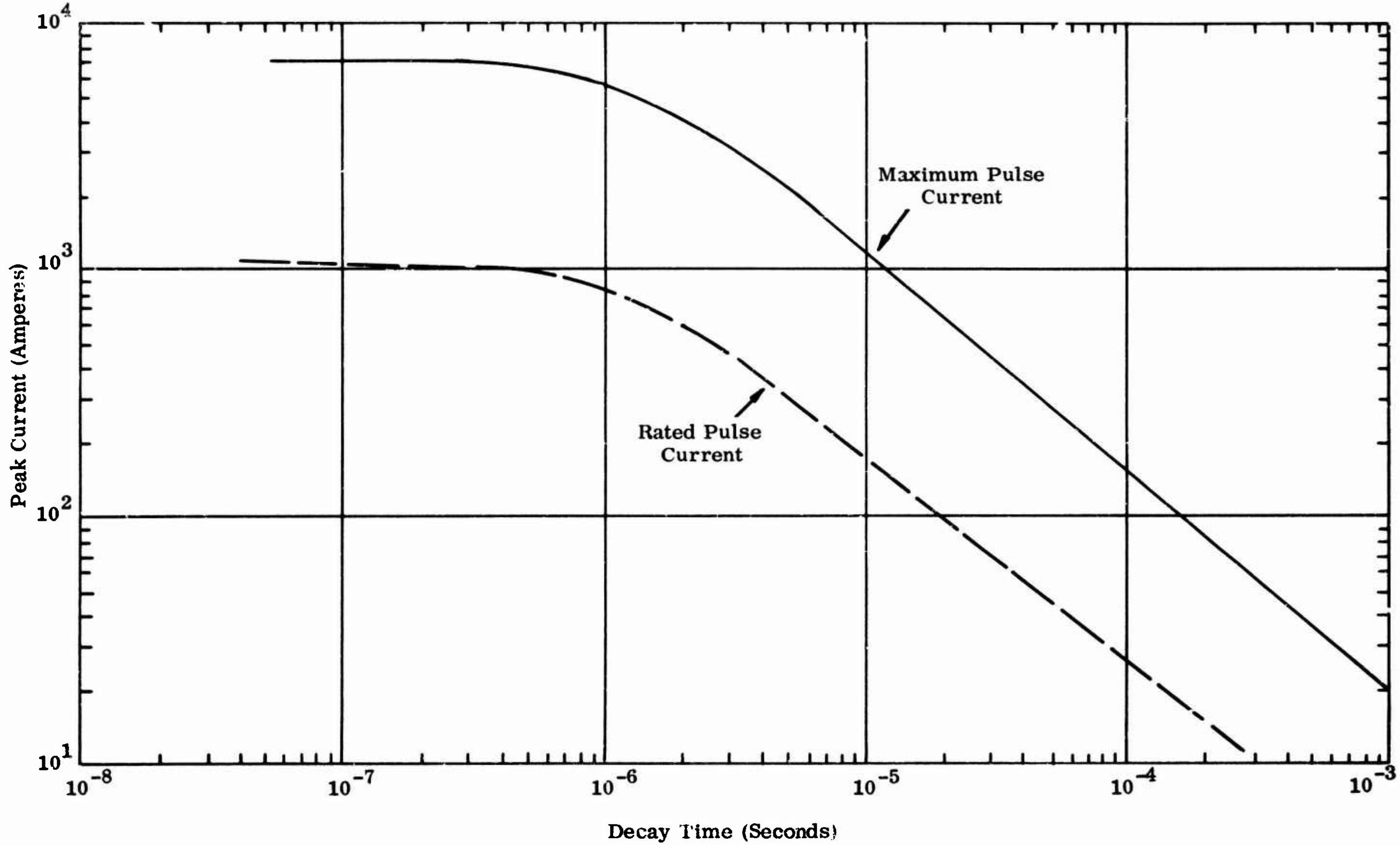
HARD LIMITER RESPONSE DATA

Device Type ____________ Sample Number ____________ Date ____________



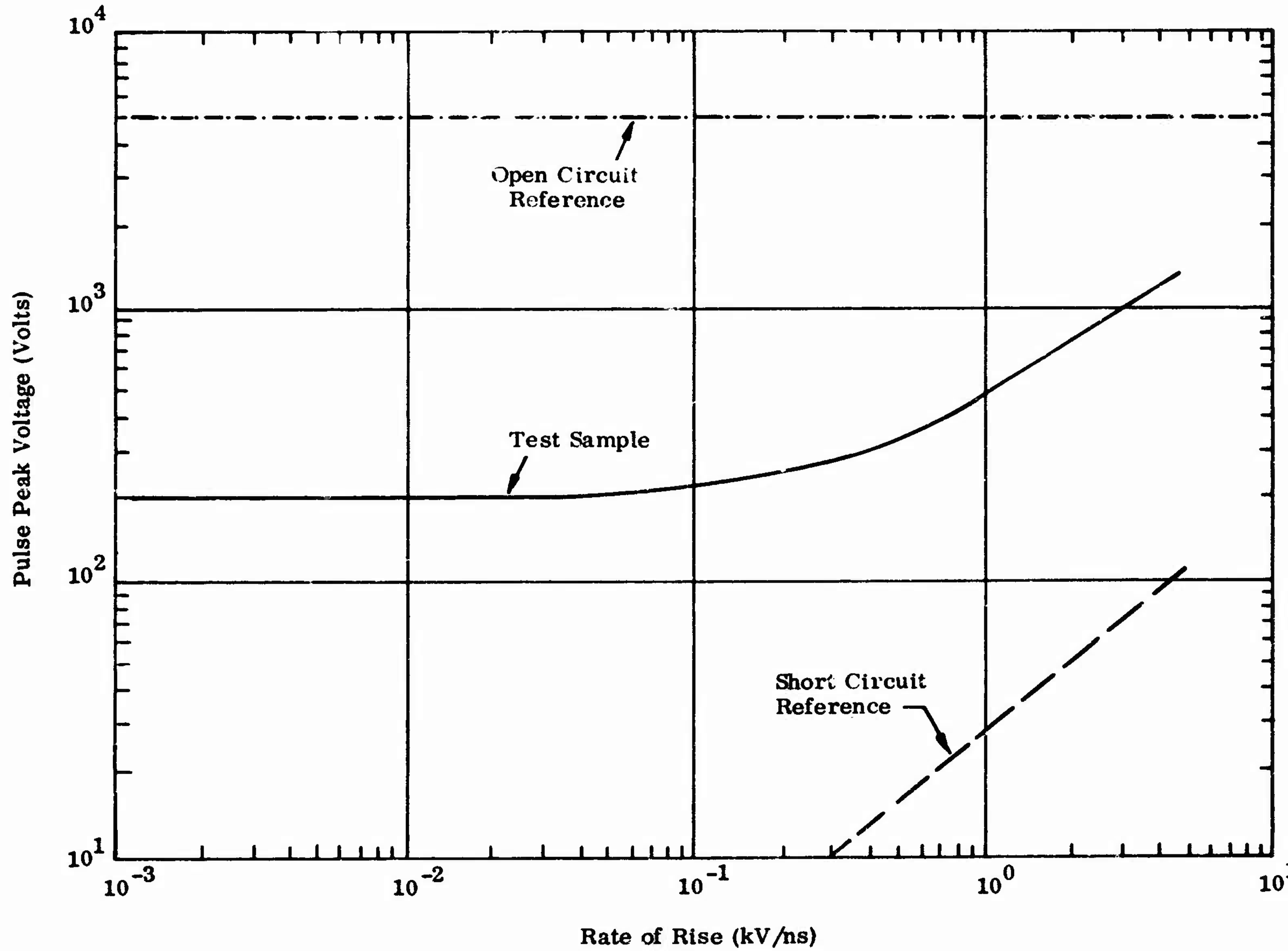
HARD LIMITER DATA

Device Type ______________ Sample Number ______________ Date ______________



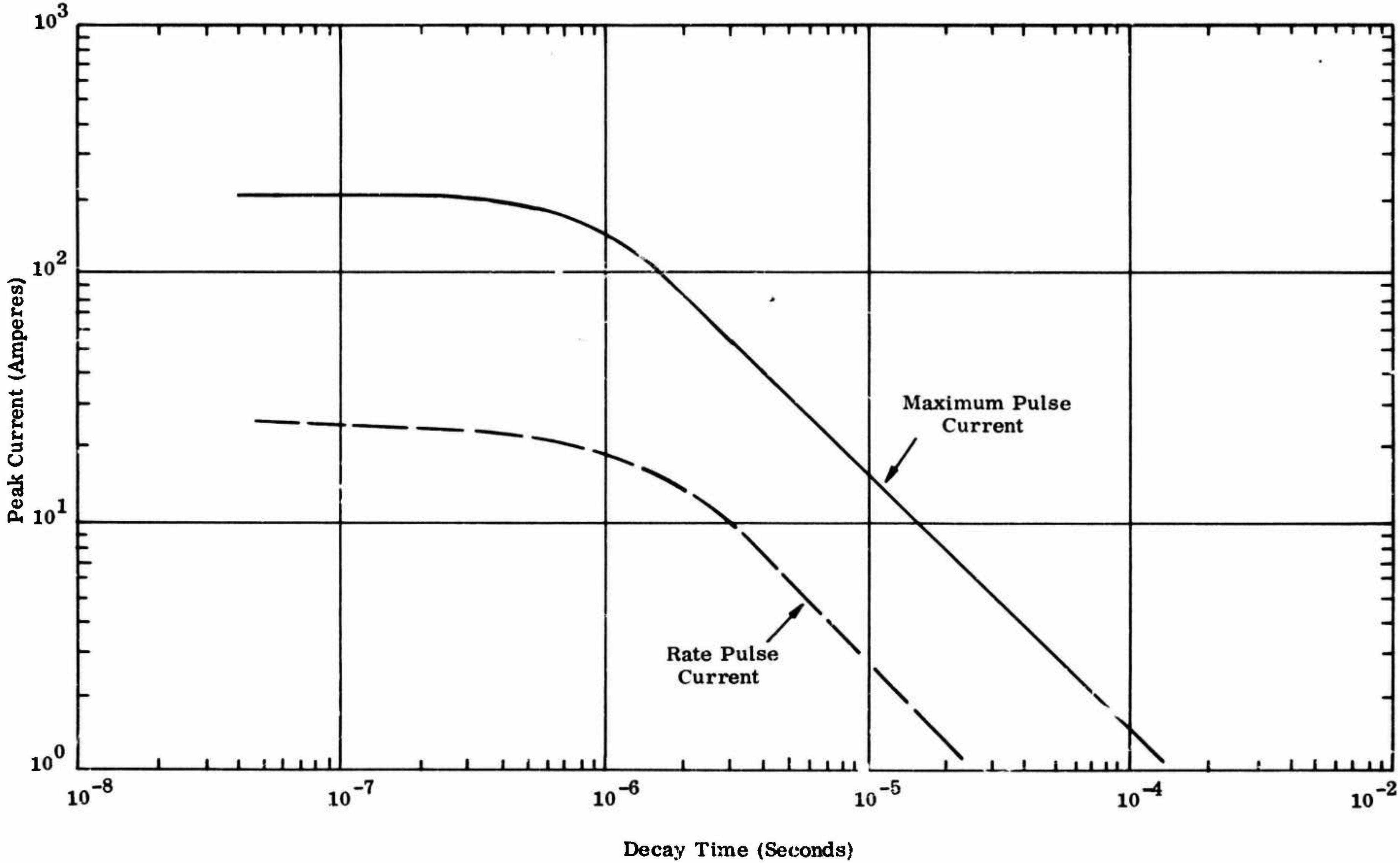
SOFT LIMITER RESPONSE CURVE

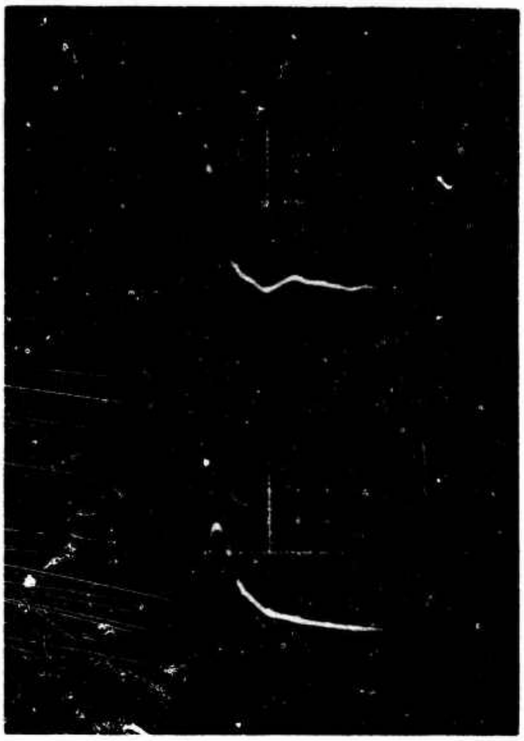
Device Type ____________ Sample Number ____________ Date ____________



SOFT LIMITER DATA

Device Type ______________ Sample Number ______________ Date ______________





Test Pulse 1 (5.0 kV/ns)

Device Response

Vertical	1000 V/Div
Horizontal	5 ns/Div

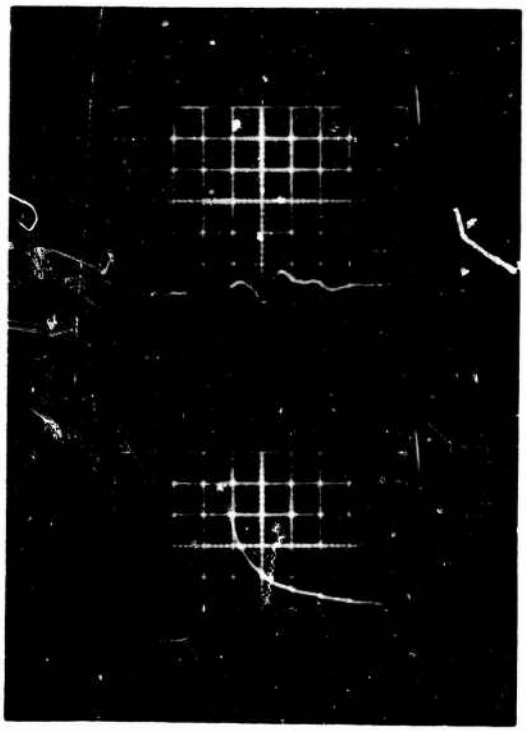
Test Pulse 2 (0.5 kV/ns)

Device Response

Vertical	500 V/Div
Horizontal	5 ns/Div

Signalite

Uni Imp Series UBD-550



Test Pulse 1 (5.0 kV/ns)

Device Response

Vertical 500 V/Div

Horizontal 5 ns/Div

Test Pulse 2 (0.5 kV/ns)

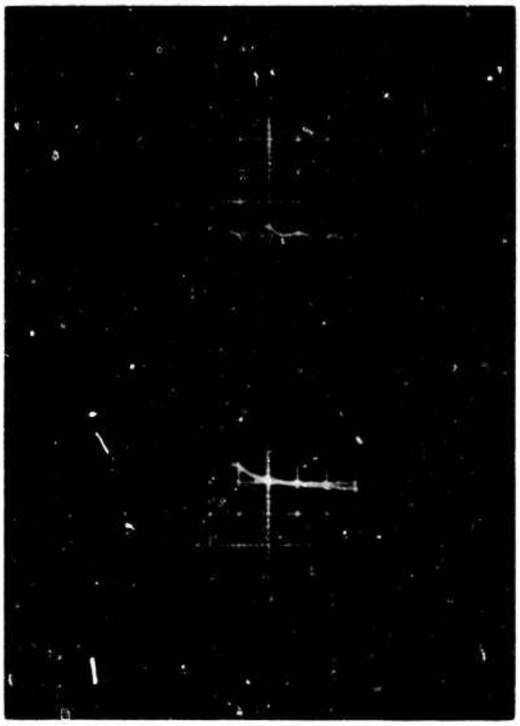
Device Response

Vertical 100 V/Div

Horizontal 5 ns/Div

Unitrode Corporation

Zener IN5612



Test Pulse 1 (5.0 kV/ns)

Device Response

Vertical 500 V/Div

Horizontal 5 ns/Div

Test Pulse 2 (0.5 kV/ns)

Device Response

Vertical 200 V/Div

Horizontal 5 ns/Div

General Electric

Metal Oxide Varistor VP130A10

5.4 Permanent Degradation Measurements

5.4.1 Scope

This section deals with the measurement of the device parameters that determine the capability of the protective device to withstand the effects of both EMP-induced transients and other transients in the system. Obviously, the primary emphasis in this document is on the effects of EMP-induced transients; however, other transients can not be ignored because they could degrade or destroy the EMP protection. Again, in order to intelligently evaluate various protective devices, one must be familiar with representative EMP-induced transients and collector impedances.

As discussed previously, typical EMP-induced transients are generally of the form of an exponentially decaying sinusoidal (Fig. 5-8), with various peak amplitudes, resonant frequencies, and decay times. Further, the collector or source impedances are generally complicated complex functions. Again, the ideal approach would be to subject the various surge protective devices to a broad range of exponential decaying sinusoidal waveforms (such as shown in Section 4) using a pulse injection source with the appropriate output impedance for each waveform. However, such injection sources are not presently available and would require significant development cost. Therefore, the preferred test procedures for Permanent Degradation Measurements are based on subjecting the protective device to two exponential current pulses with various rise times, peak amplitudes, and fall times.

Such an approach is realistic and provides meaningful test data because of the fact that surge protective devices generally have very little frequency selectivity and present very low impedance (almost a short circuit) under surge conditions. More specifically, because of this very low impedance under surge conditions, the protective device would typically be subjected to the EMP-induced short circuit current. As illustrated in Section 4, representative EMP-induced short circuit currents are generally of the form of exponentially decaying sinusoidals with various peak

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amplitudes, resonant frequencies, and decay times. Since surge protective devices generally have very little frequency selectivity, they generally will be capable of withstanding the various exponentially decaying sinusoidals provided they can withstand a two-exponential pulse of either polarity equal to or greater than the envelope of the decaying waveform (Fig. 5-14).

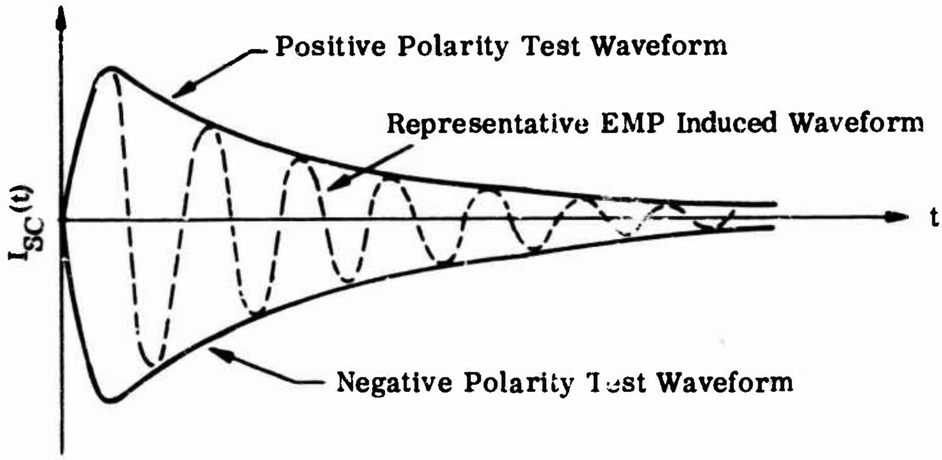

Figure 5-14. Comparison of Test Waveform and Representative EMP Induced Waveform

It should be noted that such an approach is generally not realistic and may not provide meaningful failure data for components or devices which have significant frequency selectivity. Further, although a rectangular test waveform could provide useful failure data, a two-exponential waveform is more appropriate since typical EMP transients are generally not rectangular pulses nor do they have rectangular envelopes.

One of the most difficult aspects of Permanent Degradation Measurements is determining realistic failure criteria. In general, the actual failure criteria or what constitutes a significant change in a particular parameter depends upon the system application and the required system performance criteria. Therefore, for particular system applications, it may be appropriate to select different criteria or more conservative or liberal limits than those suggested in this document. In all cases, the failure criteria employed in the Permanent Degradation Measurements should be explicitly stated. With no particular system application in mind, the suggested failure criterion for hard limiters is a change of more than ± 10% in the original Static Breakdown Voltage. In the case of soft limiters, the suggested failure criterion is a change of more than ± 10% in the effective resistance (V-I characteristics) at the Steady State Voltage Rating of the device.

5.4.2 Specific Test Procedures

5.4.2.1 Hard and Soft Limiters

The preferred Permanent Degradation Measurements for both soft limiters and hard limiters are exactly the same; except as discussed above, a different suggested failure criterion is employed. Therefore, the two basic types of surge protective devices can be considered as one class for these measurements.

Maximum Pulse Current (I_{MP})

The Maximum Pulse Current, I_{MP}, capability of a surge protective device is generally a function of the decay time of the current pulse and the history of the device (i.e., previous discharges). The Maximum Pulse Current, I_{MP}, should be determined using a typical circuit such as shown in Fig. 5-15.

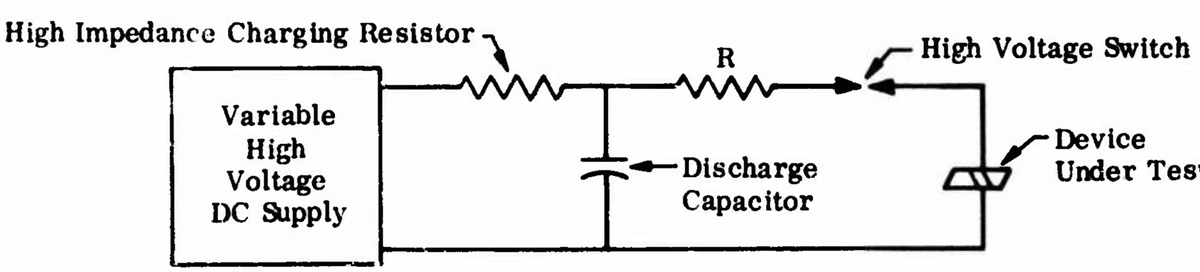

Figure 5-15. Typical Circuit for Determining I_{MP}

The value of the discharge capacitor and series resistor, R, are chosen to provide a two-exponential pulse with the desired decay time and a rise time at least of a factor of 10 less than the decay time. In general, the value of the series resistor should be large compared to the effective surge resistance of the test device and the total inductance of the discharge capacitor and the test circuit must be small enough to obtain the desired rise time. The variable DC supply is adjusted to provide the desired peak current for the particular RC combination being employed.

When performing these tests, the Maximum Pulse Current, I_{MP}, for a particular fall time is defined as the peak current that the protector can withstand for five successive pulses separated by at least 30 seconds each without exceeding the failure criterion. As stated previously, the suggested failure criterion for hard limiters is a change of more than $\pm$ 10% in the original Static Breakdown Voltage. In the case of soft limiters, the suggested failure criterion is a change of more than $\pm$ 10% in the effective resistance (V-I characteristics) at the Steady State Voltage Rating of the device. Since device failure can be a cumulative effect (depends on previous pulse exposure), each test sample should only be subjected to a sequence of five pulses. Nevertheless, the test procedure of subjecting the same sample to sequences of five pulses at increasing peak currents until failure occurs, can and should be used to obtain estimates of I_{MP}. Further, in test programs where device cost or other constraints limit the number of devices, this latter procedure is acceptable. However, if such an approach is employed, the actual test sequence should be explicitly stated.

Since the Maximum Pulse Current, I_{MP}, capability is a function of the decay time, it should be measured for an appropriate range of decay times. Based on the peak to 10% decay times of representative EMP-induced short circuit currents (Fig. 4-17), the range of decay times of particular interest is from 50 ns to 15 μs. Further, if the test program includes the effects of other transients (such as EMP-induced or lightning-induced transients on a power distribution system), much longer duration transients should also be considered.

Rated Pulse Current (I_{RP})

The Rated Pulse Current, I_{RP}, for a particular fall time is defined as the peak current that the protector can withstand for 100 successive pulses separated by at least 30 seconds each without exceeding the failure criterion. The failure criterion, test circuit, test procedure or sequence and the range of decay times discussed for the Maximum Pulse Current, ± 10% in the effective resistance (V-I characteristics) at the Steady State Voltage, apply to this measurement also.

5.4.2.2 Data Reporting

Tables on the following pages show the suggested formats for presenting degradation data for both hard limiters and soft limiters. Actual test circuits, test equipments, and detailed procedures should be specified in sufficient detail so that another experimenter could repeat the tests.

HARD LIMITER DATA

Device Type ______________________________ Date ______________

Sample Number									
Maximum Pulse Current @ $t_f = 1\ \mu s$									
Rated Pulse Current @ $t_f = 1 \mu s$									

SOFT LIMITER DATA

Device Type ______________________________ Date ______________

Sample Number									
Maximum Pulse Current @ $t_f = 1\ \mu s$									
Rated Pulse Current @ $t_f = 1\ \mu s$									

6. TEST PROCEDURES FOR FILTERS

TABLE OF CONTENTS

6. TEST PROCEDURES FOR FILTERS

6.1 Introduction

6.1.1 General

It should be remembered that voltage transients are not the only common interference phenomena in communications systems and power transmission or distribution circuits. More specifically, radio frequency interference (RFI) is also a common phenomenon in such systems. One of the standard techniques for reducing or eliminating RFI is to employ filtering or spectral limiting so as to pass only the desired frequency components. These filters can have a significant effect on the characteristics of any transients in the system and may dissipate or shunt them without damage to the equipment. Therefore, existing filters or additional filtering could also possibly provide EMP protection for the system.

To achieve this goal, it is important to select the best filter or filtering techniques consistent with other system performance criteria. Therefore, this section deals with experimental procedures for evaluating the performance of filters with respect to EMP-induced transients. In this regard, the filter must protect the equipment without adversely affecting its performance, and must be capable of withstanding the effects of both EMP-induced transients and other transients in the system. Examples of EMP induced transients appear in Section 4. Filters attached to very long or large collectors such as power lines may experience transients even larger than those presented in Section 4.

6.1.2 Classes of Filters

Filters can be categorized in a variety of ways depending on how they are designed, the type of elements used, or in terms of specified uses. From an EMP viewpoint, it probably is appropriate to classify the filters in terms of their filtering function at the interface between shielded zones.

Power lines can pick up very large amounts of EMP energies. As a consequence, power-line filters are of great significance from an EMP hardening viewpoint. Power line filters are generally formed by low pass networks which are capable of passing the 60 Hz with relatively small attenuation but yet provide significant attenuation for frequencies above a few kilohertz. In the case of filters leading into shielded room areas, the power-carrying capabilities of these filters is usually in the order of a few tens of kilowatts. Power-line filters attached to small equipments might be expected to carry approximately a few hundred watts.

Another category of filters might be classified as signal-line filters. These signal line filters carry either audio or video signals. The required filtering function is to eliminate the higher frequency non-signal components by low-pass designs. Typical signal line filters are not expected to carry significant amounts of power and as such these can be made with rather small components. Typical filtering characteristics associated with these filters are those related to a "pi" (such as shown in Fig. 6-3) or "T" networks. A simple filter for signal lines often uses only a shunt capacitor (as shown in Fig. 6-1), and less frequently, a series inductance. The shunt capacitor is often in the form of a feed through capacitor, and its performance is a strong function of the source and load impedance associated with related circuits.

A third general category of filters might be classified as radio-frequency filters. These are most frequently bandpass filters such as might be employed for preselectors for HF band receivers or special multicouplers associated with transmitting equipment. The basic filter configuration for RF filters generally is in the simple form of "pi" or "T" networks or simple parallel or series resonant configurations. In some cases, however, sophisticated networks are employed.

6.1.3 Filter Failure Modes

An important mode of failure insofar as filters are concerned for EMP purposes might be called a partial fortuitous match. Fortuitous match in the case of EMP is always likely since the EMP waveform has spectral components in nearly all frequency ranges of interest. The partial fortuitous match phenomena occurs because the data sheet filtering characteristics are never realized in the actual filter installation. The data sheet information is based on a 50 ohm insertion loss test, generally as specified by MIL-STD 220. In this procedure the filter performance is evaluated on the basis of the ratio of the output voltage with a filter in a 50 ohm reference jig versus with the filter removed from the test jig. Such an insertion loss test is defined in Fig. 6-1, where the filter is a simple type feed through capacitor.

Again referring to Fig. 6-1 it may be possible, that in an actual installation, the source impedance for the filter would not be a resistive 50 ohms but could be a series inductance. This series inductance can resonate with a shunt capacitor to form a "L" matching impedance transformation where the voltage of the source, such as shown on Fig. 6-2, is in effect stepped up at resonant frequencies where the capacitor reactance is considerably less than the load impedance.

This can have important EMP significance. Consider the effect of the near fields associated with a short circuit current for a three-meter 25 MHz resonant monopole as illustrated in Fig. 4-6. Assume that there is equipment in the vicinity of this monopole which has an exposed conductor forming a loop type pick-up. Assume this loop picks up a maximum peak voltage at the start of the transient of approximately 400 volts. Data sheet test results using this 50 ohm insertion loss test (MIL-STD 220) for a 0.0015 μfd. feed through capacitor shows an insertion loss of approximately 20 dB at 25 MHz. This would, if realized, reduce the pick-up voltage from approximately 400 volts to 40 volts which, in the case of many equipments, is an acceptable level. In actual practice, however, this filtering will not be realized because the inductive reactance of the loop is resonating with the filter feed through capacitance. Assume the fortuitous condition where this resonance is near 25 MHz. In this case the voltage step up will occur which roughly enhances the pick-up voltage by a factor of about 10. Thus instead of realizing

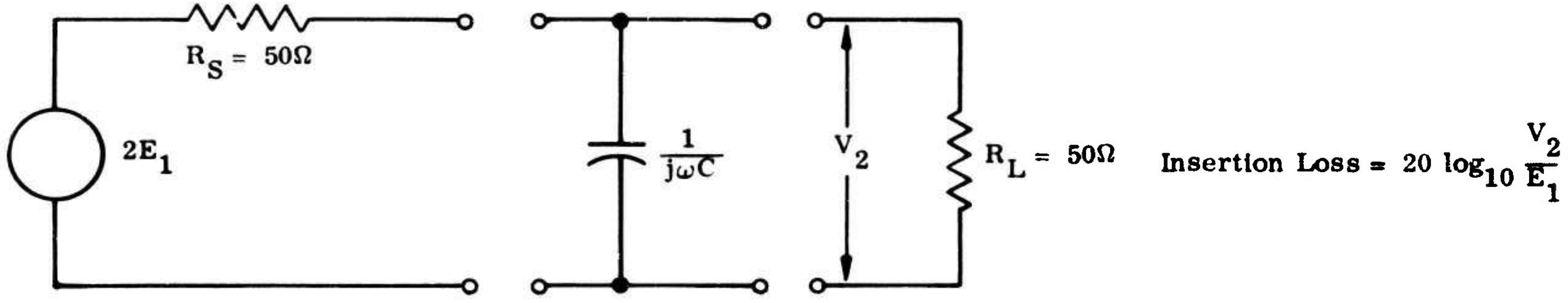

Figure 6-1. MIL-STD 220 Insertion Loss Test Where $V_2 << E_1$

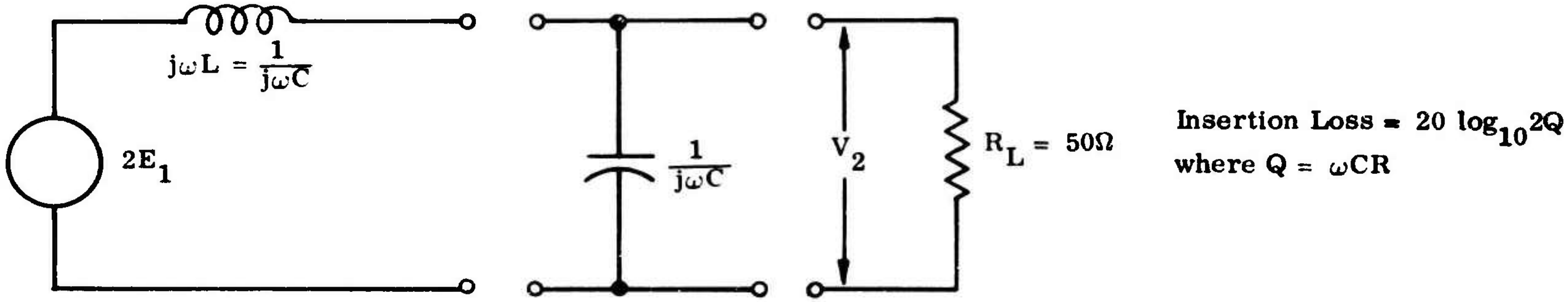

Figure 6-2. Insertion Loss Test with Reactive Source Where $V_2 = >> E_1$

the 40 volts as might be expected by the data sheet, a voltage in the order of a few thousand volts can be observed on the load input resistor.

The effect of the fortuitous match is also important in the case of cable driving tests. Consider the "pi" network type filter depicted in Fig. 6-3. If the cable driver for this network is a 50 ohm pulse type source, Fig. 6-3(A), the "pi" network type filter can provide very efficient filtering. The filter, being comprised of a large **essentially reactive** elements, in essence reflects the power back into the generator. This energy is dissipated in the 50 ohm source impedance in the generator. On the other hand if a capacitor discharge source is employed (which gives a similar waveform into a 50 ohm load) an entirely different result can occur. In this case there is no way that the energy reflected from the filter can be dissipated in the source. As a result, oscillating currents are set up within the three-loop network upon closure of the switch with essentially the bulk of the energy being dissipated in the load resistor. This and related phenomena could have extremely serious consequences in the case of hardening systems. Either extreme over-hardening or under-hardening can occur depending on the choices of filter types and cable driving sources.

Not all of the filters employed in current practice are comprised of largely reactive elements which are presented in the foregoing examples. However, many of the filters do rely to a great extent upon the mismatching or the reflection of power. Therefore a knowledge of the behavior of various filter types is required. This is not evident from the data sheets, since commonly available data sheet information is based on the 50 ohm insertion loss tests. Therefore, additional tests are required which will permit the design engineer, on a quick look basis or detailed quantitative basis, to evaluate the performance of a filter over a large selection of possible source and load impedances.

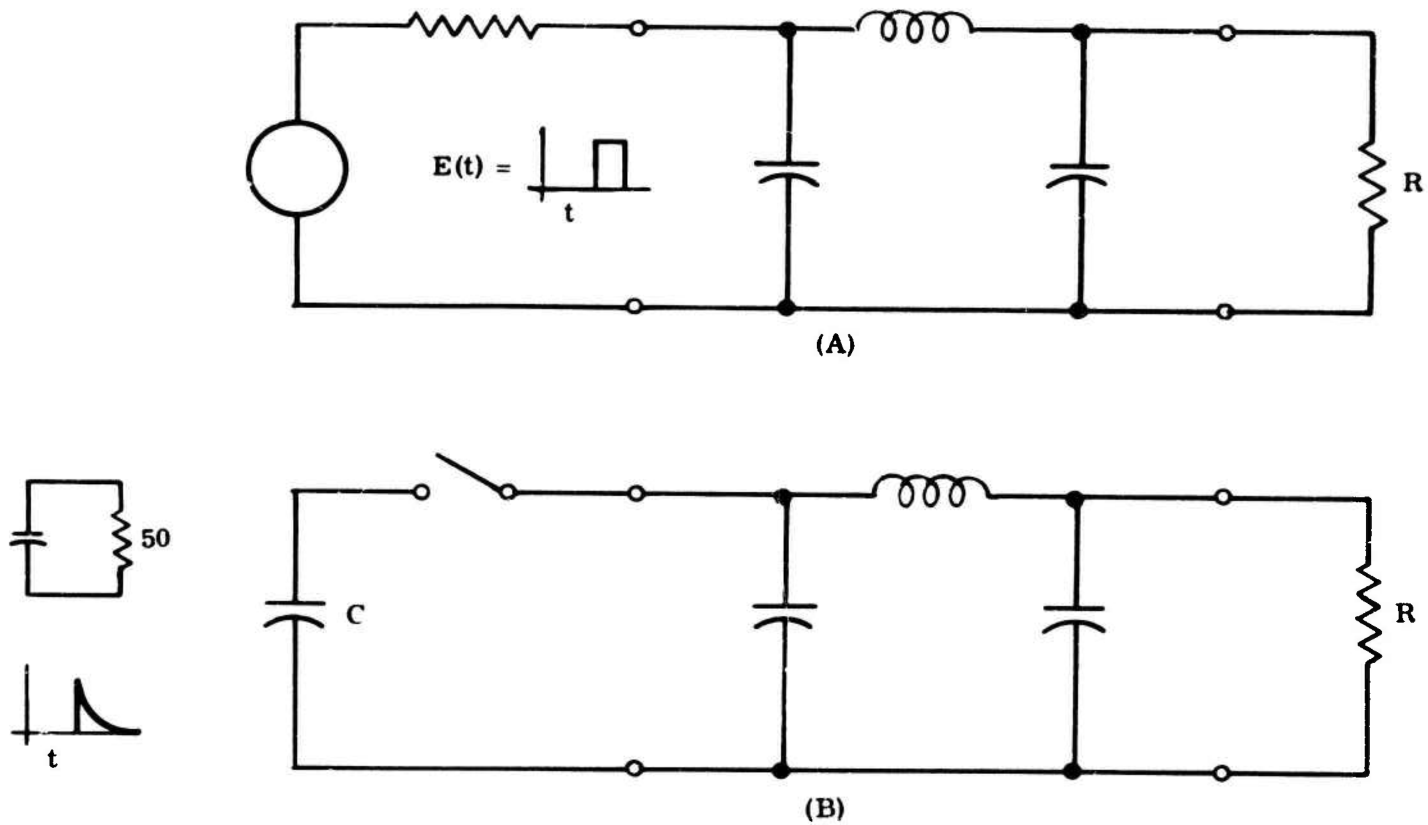

Figure 6-3. Example of Sensitivity of Response of PI Filter to Source Z
(A) Short Duration Pulse is Adequately Filtered
(B) Almost all Energy in Source Capacitor is Transferred to R

This mismatch problem is not only serious in the case of EMP, but in other areas as well. For example, power-line filters have exhibited significant resonant step up as illustrated by Fig. 6-2 (except that a multi-pi section filter was used). The conditions were such that these filters only provided design performance values for full load. A resonant step-up occurred for lighter loads which seriously overvolted the load side equipments.

A second mode of filter degradation can be catastrophic breakdown. Partial breakdown leading to eventual failure can also be serious, especially in the case of power-line filters which have sealed or capsulated components. By way of an actual case-history, a non EMP induced transient caused a partial failure of the one or more of the various shunt capacitors appearing on the line side of the filter. A capacitor failure in the form of excessive heating occurred which caused a build up of gases and a subsequent explosion. Also, gases can be emitted and ignited by similar processes. The ignition of the volatile vapors associated with this kind of filter degradation has been found to completely destroy buildings. A less dramatic filter impairment but still associated with the catastrophic breakdown of a filter component is simply a shorting of a series coil or a series capacitor. If this occurs the filtering performance is impaired and may or may not be of significance depending on the filtering requirements and needs at the particular time.

The mechanisms which lead to insulation breakdown are often complex and not well understood. In many cases it has been observed that a number of high level transients must be applied to a transformer or insulator before the insulation degrades sufficiently to exhibit a catastrophic failure. Thus the failure level for filters is often a strong function of the number of pulses applied to the filter. Related aspects deal with other environmental considerations. The catastrophic threshold for insulation is also a function of the past history, manufacturing techniques and operating temperature of the insulation. These factors must also be considered in the test procedures associated with the filters.

A third failure mode associated with the filters is associated with the nonlinear behavior. Two kinds of nonlinear behavior have been observed in the case of filters. One is simply arc over. If the arc jumps over between the input and output terminals of the filter, obviously the complete filtering characteristics will be negated. Another characteristic of an arc is "point rectification". Referring to the previous example of a small loop located near the base of a 25 MHz monopole, the average value of this induced voltage will be zero -- no DC component. Thus if a low pass filter is employed to eliminate a high-frequency tone burst, appropriate filtering can be realized particularly if a lossy type "pi" section network is employed. However, the ideal filtering performance can be negated if arc-type rectification occurs*. For example, a point (such as a terminal in the filter) over a conducting ground plane can exhibit a conduction polarity preference. Under the proper circumstances, the phenomena can rectify a portion of the tone-burst. Thus by means of the nonlinear behavior, a portion of the energy appearing around 20 MHz is converted into the audio and DC portion of the spectrum. This rectified energy is passed by the filter. This phenomena is considered important in protecting detonators against premature ignition by radar r-f pulses. It may also have EMP significance.

Another important source of problems is associated with a nonlinear collapse of the filtering characteristics. This occurs because some of the filtering elements are comprised of ferromagnetic materials. As the load current of the filter increases, the ferrous cores will tend to saturate. This is an important consideration under normal operations of the filter and is presently being considered in modifications of MIL-STD 220. It may also be of importance in the case of EMP.

*"Pseudo-Rectification and Detection by Simple Bi-Lateral Nonlinear Resistors," Proc. IRE, Vol. 49, Feb. 1961.

The breakdown characteristics of filters as a function of different source and load impedances must also be mentioned. The filtering characteristics of the filter are very sensitive to the source and load impedances. The breakdown characteristics of the filter, particularly in the case of CW or tone burst evaluation, is similarly sensitive. This is particularly true in the case of complex networks having at least two or more internal loops. These internal loops will exhibit different voltage or current buildups as a function of frequency. Should the generator be fortuitously matched into these loops but not necessarily into the load, breakdown or heating degradation can be induced within the filter beyond what might be indicated by input-output port analyses. Thus the breakdown characteristics of the filter can be quite complex and may not always be adequately studied on the basis of simple studies involving the two-port network characterization. The two-port analyses can determine the spectral ranges where the filter is strongly absorbing energy. Where this occurs the energy and power capability of the internal components of the filter should be considered.

6.1.4 Categories of Measurement and Uses

Three general categories of measurements are discussed in this section. The Low-Level Characterization Measurements are basically concerned with the parameters required to determine the effectiveness of the filter as a protective device and how the device affects the performance of the equipment. The Rated Load Current Measurements are basically concerned with whether the magnitude of the load current significantly affects the parameters of interest. Finally, the Permanent Degradation Measurements are concerned with the capability of the filter to withstand the effects of both EMP-induced transients and other transients in the system.

Filters by themselves are not always chosen for EMP hardening purposes. This has arisen partly because off-the-shelf filters designed to withstand a known surge have not been generally available. Also, means of establishing filter performance based upon simple tests have not been available. The peculiar nonlinear behavior of the filters is seldom well identified. As a result, unless one is somewhat of a filter design specialist there is often a tendency to avoid the use of filters, except possibly in conjunction with surge arrestors or shielding.

The filter problem is further complicated because filters are sold as "proprietary" products (a small "black box" with magic properties ill defined by a 50Ω insertion loss test). The only way a designer can intelligently employ such filters is by means of pragmatic tests, such as by inserting the filter into a circuit under design and, if it happens to work, accepting it. Generally no assessment is made of the sensitivity of the filter to likely changes, such as different cable lengths, or evaluating the response to a range of broadband waveforms.

One solution is for the circuit designer to build his own filters having the desired performance characteristics with reasonably good insensitivity to both expected and unpredicted changes in external operating conditions. The other solution is to employ uniform test procedures such that the performance of the filter is adequately defined for a group of engineers. It is this latter solution which is set forth in the succeeding sections.

Several words of caution are necessary. First, the performance of the filter is frequently determined by external circuit conditions, that is, the source and load impedances. The test procedures, if used for rigorous in depth performance calculations require knowledge of source and load impedances, either measured or assumed over plausible ranges. The state-of-the-art is such that, in some cases, the actual source and load impedance data is not easily developed, as may be the case for certain multiconductor cables, such as those employing balanced twisted pairs. Thus additional procedures may be needed to characterize these balanced mode external impedances.

Second, it should be recognized that a wide variety of filters exist, and it is not possible to devise relevant procedures for all conceivable filter types. Most filters have three terminals -- an input terminal, an output terminal, and a common ground terminal. Another class of filter may have the input and output terminal pairs isolated, such as by an internal transformer or may require balanced input and output circuits. The following procedures are applicable to both classes of filters, wherein the measurements can be made on a three terminal basis. Where the performance of the four-terminal filter is dependent on the common mode isolation afforded by internal transformers or by related external circuits, these procedures can serve as an useful guide.

Third, high power sources are not generally available having the necessary ranges of source impedances to test ideally the breakdown or nonlinear performance of filters. Thus, test procedures which ideally and completely define the performance of several classes of filters, such as an absorbtion filter employing ferrites prone to saturation, are held in abeyance pending availability of suitable high-power pulse sources with a wide range of source impedances. Procedures are set forth, however, which provide for assessing the breakdown (Section 6.6) or nonlinear behavior (Section 6.6) and for ideally measuring the linear time invariant characteristics (Section 6.2), either to analyze rigorously the performance of the filter or to evaluate quickly the gross performance characteristics.

The three procedures presented in the succeeding sections are best used as a unit for EMP hardening purposes. The procedures described in Section 6.2 completely measures the parameters necessary to characterize the linear behavior of the filter. The procedures described in Sections 6.3 and 6.4 provide the engineer with several techniques to evaluate the nonlinear and catastrophic behavior.

As a unit, the procedures provide the system or circuit designer with a number of options for EMP hardening or assessment purposes. Specifically these are:

- Identifying on a relative basis the potentially better performing filters
- Specifying filter performance requirements independent of a specific and often proprietary filter design
- Calculating the filter performance for known external circuits
- Estimating the sensitivity of the filter performance to variations in external circuits
- Calculating the worst-case performance
- Detecting changes in filter characteristics for quality control or acceptance purposes
- Assessing the nonlinear behavior of the filter in terms of either load current or EMP exposure
- Evaluating some of the catastrophic failure properties of the filter.

Using the 50 ohm insertion loss test (MIL-STD 220) as a point of departure may be of interest to those not familiar with this test procedure. This procedure defines the performance of filters by means of a 50 ohm insertion loss test previously described. The original interest of this test procedure was for manufacturing quality control purposes. Owing to the lack of other suitable test methods, filter manufacturers selling packaged filter designs gradually used this test method to describe filter performance, which can be misleading, in sales literature. However, relating the EMP filter test procedures to the widely used but often inadequate MIL-STD 220 is necessary because the bulk of filter manufacturers are familiar with this test method. With this background in mind, the EMP specialists who use these preferred test procedures will be able to communicate his requirements to the filter manufacturer.

6.1.5 Other Tests

Other test procedures may also be of interest but at the moment do not yet appear to be of general interest or are not practical to conduct on a laboratory basis with readily available equipments. Such other tests may include the non-linear behavior of band pass or high pass filters as a function of load current, the nonlinear "rectification-phenomena" of filters, and the saturation characteristics as a function of EMP currents. If such tests are necessary, these procedures can serve as a useful guide.

6.2 Low-Level Characterization Considerations

6.2.1 Scope

This section deals with the measurement of the parameters that determine the performance of the filter as an EMP protective device and how the filter affects the performance of the equipment. In order to intelligently evaluate the effectiveness of various filters as EMP protective devices, one must be familiar with representative EMP induced transients, source or collector impedances, load impedances, and typical damage mechanisms and levels for circuit components. In cases where more realistic or appropriate data are not available, the information presented in Sections 4 and 5.3.1 should be used as general guidance.

As discussed in Section 4, typical EMP induced transients are generally of the form of exponentially decaying sinusoids (see Fig. 4-8) with various peak amplitudes, resonant frequencies and decay times. Power-line and buried cables may exhibit non-sinusoidal waveforms of greater magnitudes than presented in Section 4. Further, collector and load impedances are generally complicated complex functions.

Ideally, one would measure the response of the various filters under the actual loading conditions for a broad range of exponential decaying sinusoidal waveforms (such as shown in Section 4), using a pulse injection source with the appropriate output impedance for each waveform. However, such injection sources are not presently available and would require significant development cost. Further, even if the required source were available, such a procedure would be time consuming and expensive because of the wide variety of possible transients. Therefore, this portion of the preferred test procedures is based on the measurement of the parameters that are required for the low-level characterization of filters.

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Linear time-invariant networks, or nonlinear time-invariant networks operating with sufficiently small signals so that they respond in a linear manner, can be completely characterized by parameters measured at the ports (network terminals). If sufficient measurements are performed for one set of source and loading conditions, the results can be extended to any other source and loading conditions. Further, since the time-domain and the frequency-domain responses are related by the Fourier transform pair for a linear system, the required measurements can be performed either in the time domain or the frequency domain. The pulse or time-domain measurements provide a better qualitative view of the transient behavior of the filter; however, the frequency-domain measurements provide greater dynamic range.

6.2.2 Rationale

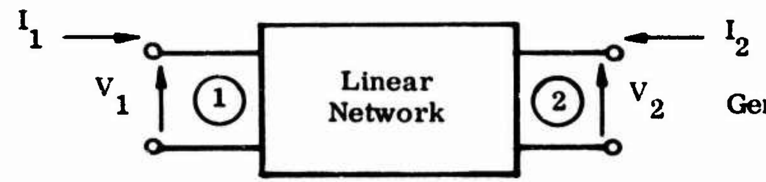
Existing test procedures based on 50 ohm insertion loss while yielding useful data, do not provide sufficient information to completely characterize performance of a filter over a wide variety of source and load impedance conditions. This can result, especially in the case of EMP, in unanticipated responses which can lead to underhardening or overhardening a system. To remedy this, a complex network characterization can be employed. If properly executed, such measurements can be used to predict the performance of conventional filters for all possible source and load impedance conditions. Moreover, these measurement results can be used to identify on a quick look basis the better filters or the problem areas.

These complex network techniques have been available for some time. The most common ones are entitled, "Z parameter", "Y parameter", "ABCD chain parameters", and "S parameter". These will be described in detail in ensuing paragraphs. The choice the selected network characterization was influenced by:
(1) whether or not existing test jigs would be available,
(2) whether or not the characterization method essentially extended the present technology, (3) whether or not it was consistent with other network measurement methods, and (4) whether it was capable of remote measurement and pulse or swept-frequency techniques.

The S parameter method of network characterization best met these requirements. A summary of the other types of network characterizations are summarized in Chart I. Details regarding the S parameters are summarized in Chart II and also appear in subsequent sections. The S parameter technique is based on measurements in a standard impedance test jig. The high frequency characteristics of transistors are often characterized by S parameter methods, and the impedance level employed for this is 50 ohms. If the reference impedance is chosen to be 50 ohms, the MIL-STD 220 test jigs as well as the equipment employed for transistor measurements can therefore be employed. Thus techniques and fixtures which many engineers understand can be employed to develop complex scattering parameters. The measurement of the S scattering parameters can be used to calculate the performance for any arbitrary source or load terminations or to identify on a quick-look basis the better filters or significant problem areas.

The insertion loss as developed by MIL-STD 220 is related to the scattering parameter S_{21} as indicated in the following equation where S_{21} is the filter forward transmission gain with a 50 ohm load and source impedance.

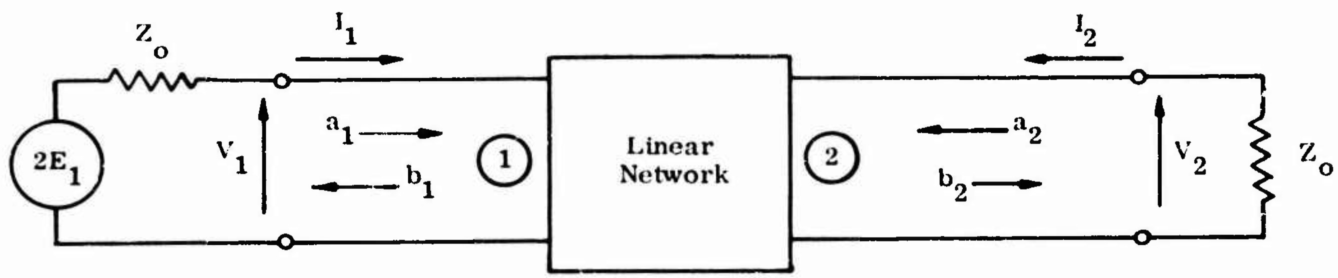
$$\text{MIL-STD 220 Insertion Loss} = -20 \log_{10} |S_{21}| \qquad (1)$$



General Two-Port Network

Z PARAMETER	Y PARAMETER	ABCD PARAMETER
$V_1 = z_{11}I_1 + z_{12}I_2$	$I_1 = y_{11}V_1 + y_{12}V_2$	$V_1 = AV_2 - BI_2$
$V_2 = z_{21}I_1 + z_{22}I_2$	$I_2 = y_{21}V_1 + y_{22}V_2$	$I_1 = CV_2 - DI_2$
where	where	where
$z_{11} = \left.\frac{V_1}{I_1}\right\vert_{I_2 = 0}$	$y_{11} = \left.\frac{I_1}{V_1}\right\vert_{V_2 = 0}$	$A = \left.\frac{V_1}{V_2}\right\vert_{I_2 = 0}$
$z_{12} = \left.\frac{V_1}{I_2}\right\vert_{I_1 = 0}$	$y_{12} = \left.\frac{I_1}{V_2}\right\vert_{V_1 = 0}$	$B = -\left.\frac{V_1}{I_2}\right\vert_{V_2 = 0}$
$z_{21} = \left.\frac{V_2}{I_1}\right\vert_{I_2 = 0}$	$y_{21} = \left.\frac{I_2}{V_1}\right\vert_{V_2 = 0}$	$C = \left.\frac{I_1}{V_2}\right\vert_{I_2 = 0}$
$z_{22} = \left.\frac{V_2}{I_2}\right\vert_{I_1 = 0}$	$y_{22} = \left.\frac{I_2}{V_2}\right\vert_{V_1 = 0}$	$D = -\left.\frac{I_1}{I_2}\right\vert_{V_2 = 0}$

Chart I -- SUMMARY OF Z, Y, AND ABCD NETWORK CHARACTERIZATION PARAMETERS



INDEPENDENT PARAMETERS

$$a_1 = \frac{V_1 + Z_o I_1}{2\sqrt{Z_o}}$$

$$a_2 = \frac{V_2 + Z_o I_2}{2\sqrt{Z_o}}$$

DEPENDENT PARAMETERS

$$b_1 = \frac{V_1 - Z_o I_1}{2\sqrt{Z_1}}$$

$$b_2 = \frac{V_2 - Z_o I_2}{2\sqrt{Z_o}}$$

BASIC EQUATIONS

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

where

$$S_{11} = \frac{b_1}{a_1}\Big|_{a_2 = 0}$$

$$S_{12} = \frac{b_1}{a_2}\Big|_{a_2 = 0}$$

$$S_{21} = \frac{b_2}{a_1}\Big|_{a_2 = 0}$$

$$S_{22} = \frac{b_2}{a_2}\Big|_{a_1 = 0}$$

50 Ω TEST RELATIONSHIPS

$$S_{11} = \frac{Z_1 - Z_o}{Z_1 + Z_o}\Big|_{a_2 = o} \quad (\text{Load } R_L = 50\ \Omega)$$

$$S_{21} = \frac{V_2}{E_1}$$

where $2E_1$ is source voltage and source and load R = 50 Ω

$$S_{22} = \frac{Z_2 - Z_o}{Z_2 + Z_o}\Big|_{a_1 = o} \quad (\text{Source } R_g = 50\Omega)$$

$$Z_1 = \frac{V_1}{I_1} \quad (\text{Load } R_L = 50\ \Omega)$$

$$Z_2 = \frac{V_2}{I_2} \quad (\text{Source } R_g = 50\ \Omega)$$

Chart II -- SCATTERING PARAMETER RELATIONSHIPS

The other two S parameters are S_{11} and S_{22}. S_{11} is simply the reflection coefficient of the input port of the filter with the filter terminated in a 50 ohm load. This is given in Equation (2) where Γ_s is the reflection coefficient on the source side of the filter.

$$S_{11} = \Gamma_s = \frac{Z_1 - Z_0}{Z_1 + Z_0} \qquad (2)$$

$$S_{22} = \Gamma_e = \frac{Z_2 - Z_0}{Z_2 + Z_0} \qquad (3)$$

The input reflection coefficient, S_{11}, may also be developed by measuring the input impedance of the filter in the MIL-STD 220A test jig when the output port of the filter is terminated in 50 ohms. This measured value is the value Z_1 appearing in Equation (2) where Z_0 takes on the value of 50 ohms. In a similar manner the output reflection coefficient can be measured either by reflection techniques or by impedance techniques as previously discussed. The relationship for this is presented in Chart III.

Only three additional measurements over that previously conducted for MIL-STD 220 tests are required. These are: (1) measurement of the phase of the output voltage during the usual MIL-STD 220 tests, (2) the measurement of the input port complex reflection coefficient or complex input impedance with the output of the filter terminated in 50 ohms, and (3) the measurement of the complex output reflection coefficient or complex impedance with the input of the filter terminated in 50 ohms. It should be noted that other reference impedance levels can be employed. However, the 50 ohm is chosen because this is the standard impedance level for the MIL-STD 220A and is the reference level for commercial test equipment which can be employed to make scattering parameter measurements.

Once the measurements have been made, these measurement results can be used in several areas: (1) a quick look assessment of the filter performance, (2) back-of-the envelope analysis of the performance of the filter in detail using several representative spot frequencies to resolve problem areas, and (3) detailed calculation of the filter responses employing digital computer techniques.

In the area of qualitative quick look evaluations, the additional information provided by the scattering measurement technique is worthwhile and can be used to categorize filters as either reflective or absorptive. In actual practice most commercial filters employ a combination of reflective and absorbtive filtering mechanisms. It is important that the design engineer understand how the particular filter provides this attenuation in the stop band. If the filtering is a reactive filter such as presented in Figs. 6-1, 6-2, and 6-3 then the possibility of fortuitous matches must be considered. On the other hand if the filter largely relies on power dissipation within the filter stop band, the behavior of this filter is largely independent of the source and terminating impedances. However, the joule energy or power absorption characteristics of the filters may severely restrict the application of this class of filter. Therefore it is necessary to understand the nature of the filtering mechanism, either absorption or reflection, and to test the impact of this mechanism in a specific situation as required.

In general, absorptive type filters can be identified where the input impedance of the filter in the 50 ohm test jig has a significant real component, phase angle less than 80°, while at the same time exhibiting a large 50 ohm insertion loss (MIL-STD 220) or a very small forward transmission gain, S_{21}, in the order of 10^{-4} or less. Values of S_{11} and S_{22} equal to or less than 0.9 when also coupled with S_{21} being on the order of 10^{-4} or less is also indicative of a dominant absorption mechanism in the stop band.

Filters which depend largely on reflection can be identified by noting the values of the reflection coefficients or input impedances in the stop band. This class of filter can be identified by noting that the input or output impedances, Z_1 and Z_2 as measured in 50 ohm jig, are either very small or large compared with the reference impedance, and have a phase angle which is close to 90°, while at the same time exhibiting a very small value of S_{21}.

Thus the S parameters provide useful additional guidance not currently available if only MIL-STD 220 data is employed. Additional rules-of-thumb can be evolved in terms of specific filter types and filtering situations and can be used to identify potential problem areas. Figures 6-8 and 6-10 illustrate the results of S and S related Z parameter measurements for several classes of filters.

Some potential problem areas can be resolved by simple calculation by calculating the worst-case performance of the filter or the performance of a filter over a wide variety of loads using the relationships presented in Charts II and III. This can be done using either vector slide rules or preferably some of the more modern desk top calculators which are designed to handle complex numbers and store intermediate results of a computation. The quick look assessment rules-of-thumb plus the spot type analyses employing slide rules-or-desk top calculators should provide the design engineer with sufficient information to select intelligently filters for initial design purposes.

Complete exploration of the response of a given filter to a wide spectrum of source and loading conditions for both CW and transient conditions is best accomplished by means of a high speed digital computer. In this case the S parameter measurements are entered as tabulated functions over the frequency band of interest. A number of computer service organizations are currently offering on a proprietary basis network analysis programs which can accept and utilize such tabulated data. No one program is recommended except that the services offered by the various computer service organizations should be reviewed prior to selection. Two of the programs of current interest are MATCH by AL/COM or MAJIC by UCC.

6.2.3 S Parameter Network Characterization

Before describing in detail the S parameters, it is useful to review some of the other characterizations. Although a network may have any number of ports, filters usually only have two ports and the network parameters can be explained most easily by considering a two-port network such as shown in Chart I. Such a network can be characterized by two linear equations relating a set of four variables associated with the two-port model. The two independent variables represent the excitation of the network and the two dependent variables represent the response of the network to the excitation. Depending upon which variables are selected as the independent and dependent variables, the resulting equations and the network parameters describing the variable relationships are different. Any of several parameter sets can be used, each of which has certain advantages and disadvantages, depending upon the intended application. However, each parameter set completely characterizes the network, and it is always possible to calculate any set in terms of any other set.

Some of the more commonly used parameter sets are the open-circuit impedance parameters (z-parameters), the short-circuit admittance parameters (y-parameters), and the transmission or chain parameters (ABCD-parameters). These three sets of parameters are defined by the relationships shown in Chart I.

The open-circuit impedance and the short-circuit admittance parameters are probably the most familiar and would be the most desirable from an analytical standpoint, if the objective was the synthesis of a lumped parameter equivalent circuit for the filter. Although the transmission parameters are probably the least familiar, they are the most desirable from an analytical for a frequency domain analysis of the system response since the transmission parameters simplify the analysis of cascaded networks. However, each of these sets of parameters presents some measurement problems in terms of obtaining well defined open and/or short circuits over an extended frequency range. Therefore, a preferred test procedure based on any of these sets of parameters would not facilitate swept frequency or pulse measurement techniques. Hence, this portion of the preferred test procedures is based on the measurement of the scattering parameters (S-parameters).

The S-parameters are reflection and transmission coefficients, familiar concepts to rf designers. Conceptually they are like the z, y, or ABCD parameters because they describe a network by its terminal relations; however, the S-parameters are defined in terms of the square root of power rather than in terms of voltages and currents. Chart II will help to explain the S-parameters.

In Chart II, "a" and "b" are the square roots of power and the standard convention that "a" is a signal into a port and "b" is a signal out of a port is employed. In the S-parameter representation of a network, the signals into the ports are used as the independent variables and the signals out of the ports are used as the dependent variables. More specifically, the independent variables are defined as a_1 and a_2 and the dependent variables are defined as b_1 and b_2 where Z_o is the characteristic impedance of the measurement system. Since 50 ohm coaxial transmission line components and equipments are readily available, Z_o is generally taken to be 50 ohms. Therefore, Z_o will be assumed to be 50 ohms through this document.

Using the above definitions of the independent and dependent variables, the resulting linear equations describing the network in terms of the S-parameters are shown in the center column of Chart II. From these equations it follows that S_{11} is the input reflection coefficient, S_{12} is the reverse transmission coefficient, S_{21} is the forward transmission coefficient, and S_{22} is the output reflection coefficient.

If a voltage source $2E_1$ with a source impedance of Z_o is connected to port-1 and port-2 is terminated with Z_o, it follows that

$$a_1 = \frac{E_1}{\sqrt{Z_o}} \tag{4}$$

and

$$a_2 = 0 \tag{5}$$

Therefore,

$$S_{11} = \frac{V_1 - Z_o I_1}{V_1 + Z_o I_1} \tag{6}$$

and remembering that the driving point impedance is

$$Z_1 = \frac{V_1}{I_1}, \quad Z_2 = \frac{V_2}{I_2} \tag{7}$$

it follows that the input reflection coefficient is

$$S_{11} = \frac{Z_1 - Z_o}{Z_1 + Z_o} \tag{8}$$

Finally, using Equations in Chart II the forward transmission is given by

$$S_{21} = \frac{V_2}{E_1} \tag{9}$$

Similarly, if a voltage source $2E_2$ with a source impedance of Z_o is connected to port-2 and port-1 is terminated with Z_o, it follows that

$$S_{22} = \frac{Z_2 - Z_o}{Z_2 + Z_o} \tag{10}$$

and $$S_{12} = \frac{V_1}{E_2} \tag{11}$$

Therefore, although the scattering parameters are defined in terms of the square root of power, the use of characteristic impedance terminations and source impedances reduces the scattering parameters to voltage reflection and transmission coefficients. Both the magnitude and phase of these voltage reflection coefficients can be measured directly with available test equipment.

Chart III summarizes some of the additional "s" parameter relationships. These equations relate the performance of the filter for any arbitrary source and load to scattering parameters measured in the 50 ohm test jig. Additional relationships are presented in the reference material. For example, the conversion of "s" parameter into impedances can be readily accomplished by means of a "Smith Chart" when $|S_{11}|$ and $|S_{22}|$ are less than 0.98.

Chart IV presents the interrelationships between the various other network parameters and the s parameters. These may be of interest where detailed network responses are required, since the scattering parameters are more oriented toward convenience of measurement rather than network analyses.

6.2.4 <u>Measurement Precautions</u>

The S parameter measurement technique recommended is based on tests in a 50 ohm test jig. This test jig may be similar to that employed for making MIL-STD 220 measurements. One of the more critical parameters is the measurement of S_{21} (this is the insertion loss as indicated by MIL-STD 220). For very large attenuations or very small values of S_{21}, significant isolation between signal source and the voltage measurement equipment at the output of the filter is required. Thus it is desirable to provide adequate shielding for both the source, interconnecting cabling, and the output voltage measurement equipment. In

Load reflection coefficient, arbitrary Z_ℓ

$$\Gamma_\ell = \frac{Z_\ell - Z_o}{Z_\ell + Z_o}$$

where Z_o is the reference impedance, 50 ohms, Z_ℓ is any load impedance.

Source reflection coefficient, arbitrary, Z_S

$$\Gamma_S = \frac{Z_S - Z_o}{Z_S + Z_o}$$

where Z_S is any source impedance.

Input reflection coefficient with arbitrary Z_L

$$S'_{11} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}$$

Output reflection coefficient with arbitrary Z_S

$$S'_{22} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S}$$

Voltage gain with arbitrary Z_L and Z_S

$$A_V = \frac{V_2}{V_1} = \frac{S_{21}(1 + \Gamma_L)}{(1 - S_{22}\Gamma_L)(1 + S'_{11})}$$

Power Gain = $\frac{\text{Power delivered to load}}{\text{Power input to network}}$

$$G = \frac{|S_{21}|^2 (1 - |\Gamma_L|^2)}{(1 - |S_{11}|^2) + |\Gamma_L|^2 (|S_{22}|^2 - |\Delta_S|^2) - 2 \text{ Re } (\Gamma_L N)}$$

Available Power Gain = $\frac{\text{Power available from network}}{\text{Power available from source}}$

$$G_A = \frac{|S_{21}|^2 (1 - |\Gamma_S|^2)}{(1 - |S_{22}|^2) + |\Gamma_S|^2 (|S_{11}|^2 - |\Delta_S|^2) - 2 \text{ Re } (\Gamma_S M)}$$

Network Power Gain = $\frac{\text{Power delivered to load}}{\text{Power available from source}}$

$$G_T = \frac{|S_{21}|^2 (1 - |\Gamma_S|^2)(1 - |\Gamma_L|^2)}{|(1 - S_{11}\Gamma_S)(1 - S_{22}\Gamma_L) - S_{12}S_{21}\Gamma_L\Gamma_S|^2}$$

The worst-case filter performance is with the maximum available power gain, G_{max}. This occurs when the source and load are complex conjugate matched to the input and output ports such that

$$\Gamma_S = (S'_{11})^* \text{ and } \Gamma_\ell = (S'_{22})^*$$

$$G_{max} = \left|\frac{S_{21}}{S_{12}}\right| (K + (K^2 - 1)^{1/2})$$

where

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta_S|^2}{2(S_{12}S_{21})}$$

and

$$\Delta_S = S_{11}S_{22} - S_{12}S_{21}$$

Chart III -- USEFUL SCATTERING RELATIONSHIPS

s-parameters in terms of h-, y-, and z-parameters	h-, y-, and z-parameters in terms of s-parameters
$S_{11} = \frac{(Z_{11} - 1)(Z_{22} + 1) - Z_{12}Z_{21}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12}Z_{21}}$	$Z_{11} = \frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}$
$S_{12} = \frac{2Z_{12}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12}Z_{21}}$	$Z_{12} = \frac{2S_{12}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}$
$S_{21} = \frac{2Z_{21}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12}Z_{21}}$	$Z_{21} = \frac{2S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}$
$S_{22} = \frac{(Z_{11} + 1)(Z_{22} - 1) - Z_{12}Z_{21}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12}Z_{21}}$	$Z_{22} = \frac{(1 + S_{22})(1 - S_{11}) + S_{12}S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}$
$S_{11} = \frac{(1 - y_{11})(1 + y_{22}) + y_{12}y_{21}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$	$y_{11} = \frac{(1 + S_{22})(1 - S_{11}) + S_{12}S_{21}}{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}$
$S_{12} = \frac{-2y_{12}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$	$y_{12} = \frac{-2S_{12}}{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}$
$S_{21} = \frac{-2y_{21}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$	$y_{21} = \frac{-2S_{21}}{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}$
$S_{22} = \frac{(1 + y_{11})(1 - y_{22}) + y_{12}y_{21}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$	$y_{22} = \frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{(1 + S_{22})(1 + S_{11}) - S_{12}S_{21}}$
$S_{11} = \frac{(h_{11} - 1)(h_{22} + 1) - h_{12}h_{21}}{(h_{11} + 1)(h_{22} + 1) - h_{12}h_{21}}$	$h_{11} = \frac{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}$
$S_{12} = \frac{2h_{12}}{(h_{11} + 1)(h_{22} + 1) - h_{12}h_{21}}$	$h_{12} = \frac{2S_{12}}{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}$
$S_{21} = \frac{-2h_{21}}{(h_{11} + 1)(h_{22} + 1) - h_{12}h_{21}}$	$h_{21} = \frac{-2S_{21}}{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}$
$S_{22} = \frac{(1 + h_{11})(1 - h_{22}) + h_{12}h_{21}}{(h_{11} + 1)(h_{22} + 1) - h_{12}h_{21}}$	$h_{22} = \frac{(1 - S_{22})(1 - S_{11}) - S_{12}S_{21}}{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}$

The h-, y-, and z-parameters listed above are all normalized to Z_0. If h', y', and z' are the actual parameters, then		
$z_{11}' = z_{11}Z_0$	$y_{11}' = \frac{y_{11}}{Z_0}$	$h_{11}' = h_{11}Z_0$
$z_{12}' = z_{12}Z_0$	$y_{12}' = \frac{y_{12}}{Z_0}$	$h_{12}' = h_{12}$
$z_{21}' = z_{21}Z_0$	$y_{21}' = \frac{y_{21}}{Z_0}$	$h_{21}' = h_{21}$
$z_{22}' = z_{22}Z_0$	$y_{22}' = \frac{y_{22}}{Z_0}$	$h_{22}' = \frac{h_{22}}{Z_0}$

Chart IV -- RELATIONSHIPS BETWEEN NETWORK CHARACTERIZATIONS some cases locating part of the test equipment outside of the shielded room and the remainder inside often provides additional beneficial isolation.

While the S parameters measurement technique can be conducted at some distance away from the filter under consideration, it is desirable to minimize data reduction by locating the signal generator and load termination as closely as possible to the filter. The time delay and/or phase shifts introduced by added cable length must be accounted for in the data reduction process. Even if this is done, the physical length of the filter may be such that it will introduce significant phase shifts or time delays at the higher frequencies. The phrase reference voltage is E_1. E_1 is defined as the voltage appearing across the 50 ohm termination in the absence of the filter. This voltage E_1 can be measured experimentally by removing the filter and attaching the port 1 connector directly to the termination.

If current or voltage probes are employed these may introduce fixed time delays, and exhibit a frequency dependent amplitude and phase shift near the upper and lower portion of the design frequency response. In some cases where the time delay is relatively constant, this can be compensated by the introduction of line stretchers. Where the response of the current and voltage sensors are frequency dependent, a correction factor should be applied or frequency independent sensor substituted.

To further minimize interactions between the various input and output readings it may also be desirable and even preferable to locate the test equipment and filter under measurement on a bench with a conductive copper sheet. The use of high performance cabling is recommended such as solid wall coaxial cable for the more permanent interconnections. Where flexible connections are required, the use of RG9 is preferable over single braided cable types.

If automatic equipment is employed, the sweep rates should be adjusted so the data recording equipment adequately tracks the responses. In some cases the automatic equipment will tend to limit the dynamic range of the measurement to something in the order of 80 to 100 dB.

The measurement procedure calls for the use of 50 ohm terminations; it should be remembered that an ordinary half-watt or quarter-watt resistor will not exhibit a 50 ohm termination at the higher frequencies. Therefore special termination devices will be required, such as 50 ohm dummy loads. In addition to selecting the coaxial cables and connectors to exhibit a high shielding characteristic, they also should be selected such that a minimum of mismatch to the 50 ohm reference is realized.

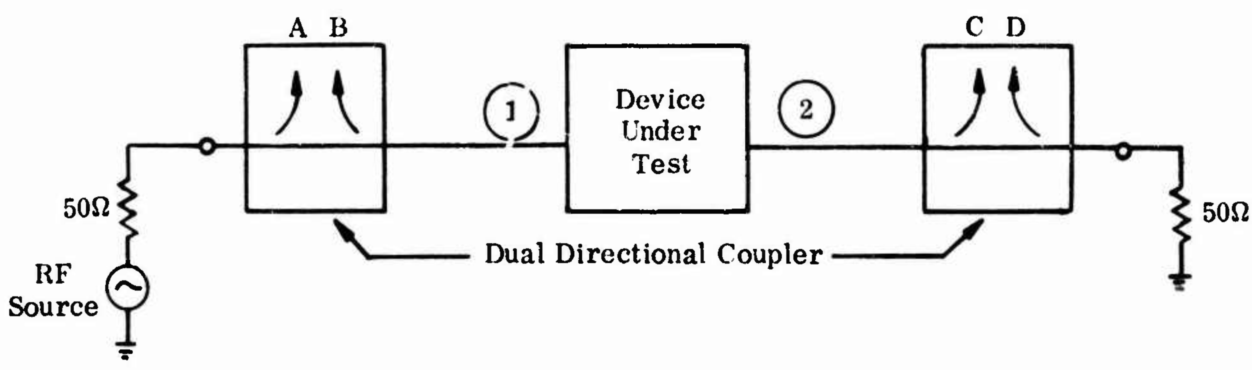
The procedure is essentially developed for two port filters which can, under test, be reduced to a three terminal network. This arises because the test equipment is essentially unbalanced, that is, one side requires a ground. The procedures can be extended to test filters requiring balanced inputs or outputs. However, commercial equipment which provides balanced input and balanced output over a broad band is generally not available. The test procedures can be used as a useful guide in designing special purpose test equipment for this class of filters.

6.3 Low-Level Frequency Domain Measurements by Reflectivity Techniques

The preferred test procedures for the low-level frequency domain characterization of filters is the measurement of the S parameters. Based on the typical EMP-induced transients, these measurements should be performed at least over a very wide frequency range. This procedure considers development of scattering parameters by reflectivity measurements. An alternate procedure, described in Section 6.2.6, considers development of scattering parameters by impedance measurement techniques. Both procedures are applicable over the frequency range of interest, generally from 1 KHz to 100 MHz. However, the reflectivity measurements are appropriate for frequencies above 100 KHz, partly because of equipment availability. Above 10 MHz, the reflectivity measurements can be more accurate and simpler than impedance measurements.

As discussed in the previous section, the S parameters reduce to voltage reflection and transmission coefficients when characteristic impedance terminations and source impedances are employed. Therefore, the S-parameters can be easily measured with commercially available test equipment. Some of the possible test set ups and equipments are presented below.

One of the standard circuits for measuring S-parameters is shown in Fig. 6-4. The RF source sends a signal down the 50 Ω



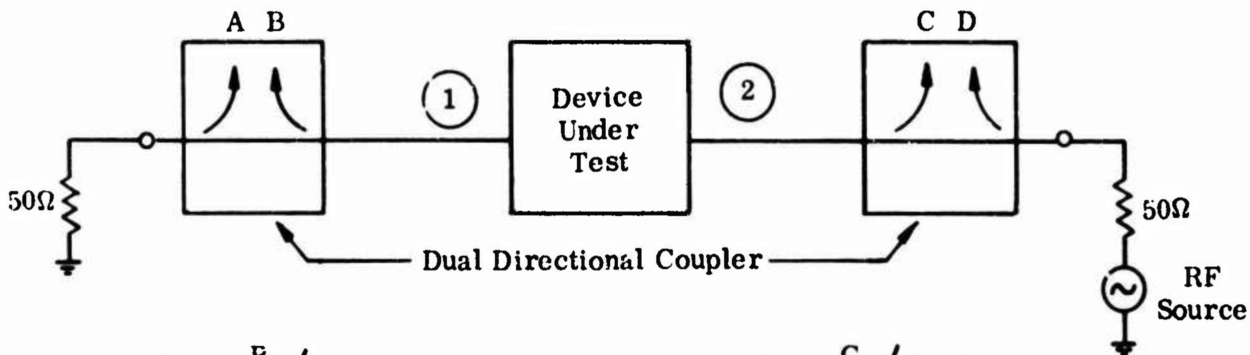
$$S_{11} = \frac{B}{A} \angle \phi_B - \phi_A \qquad S_{21} = \frac{C}{A} \angle \phi_C - \phi_A$$

Figure 6-4 Standard Circuit for Measuring S-Parameters

system toward the test device. The signal out of A is proportional to the signal incident on port 1 of the test device. The signal out of B is proportional to the signal reflected from port 1, and the signal at C is proportional to the signal transmitted through the test device and out of port 2. The 50 Ω system on the port-2 side is terminated in the 50 Ω load. As a result, the signal at D is zero because none of the signal out of port 2 is.

The ratio B/A is the magnitude of S_{11}, and the phase difference between B and A is the phase shift of S_{11} provided the phase shift between the directional coupler and device terminals is negligible. If this phase shift is not negligible, then a zero phase reference must be established by sending A through a 50-Ω delay line. Likewise, C and A determine S_{21}. Either the HP 8405A Vector Voltmeter, the HP 8407 Network Analyzer, or equivalent equipments could be used to detect and display these coupler outputs. A system for making swept-frequency measurements from 100 kHz to 110 MHz using an HP 8407 Network Analyzer is presented later in this section.

Similarly, the set-up shown in Fig. 6-5 measures S_{12} and S_{22}. The only difference between these two set-ups is that the 50-Ω load and the RF source have been interchanged.



$$S_{12} = \frac{B}{D} \angle \phi_B - \phi_D \qquad S_{22} = \frac{C}{D} \angle \phi_C - \phi_D$$

Figure 6-5. Standard Circuit for Measuring S-Parameters

One possible system for swept-frequency measurement of the S-parameters from 100 kHz to 100 MHz is presented below. This system employs the HP 8601A Generator/Sweeper, the HP 8407A Network Analyzer, the HP 8412A Phase-Magnitude Display and the HP 11652A Reflection/Transmission Kit. Further, if a HP 85404B S-Parameter Test Set were included in the system, the tedious job of connecting coaxial circuitry disappears and the S-parameter measurements can be made by pushing a button. Although this example employs Hewlett-Packard test equipment, other types of equivalent test equipment could be employed.

The following figures and discussion were taken directly from the Operating Manual for the HP 8407A Network Analyzer. A more detailed description of the measurement procedure and error analysis is also contained in the Operating Manual.

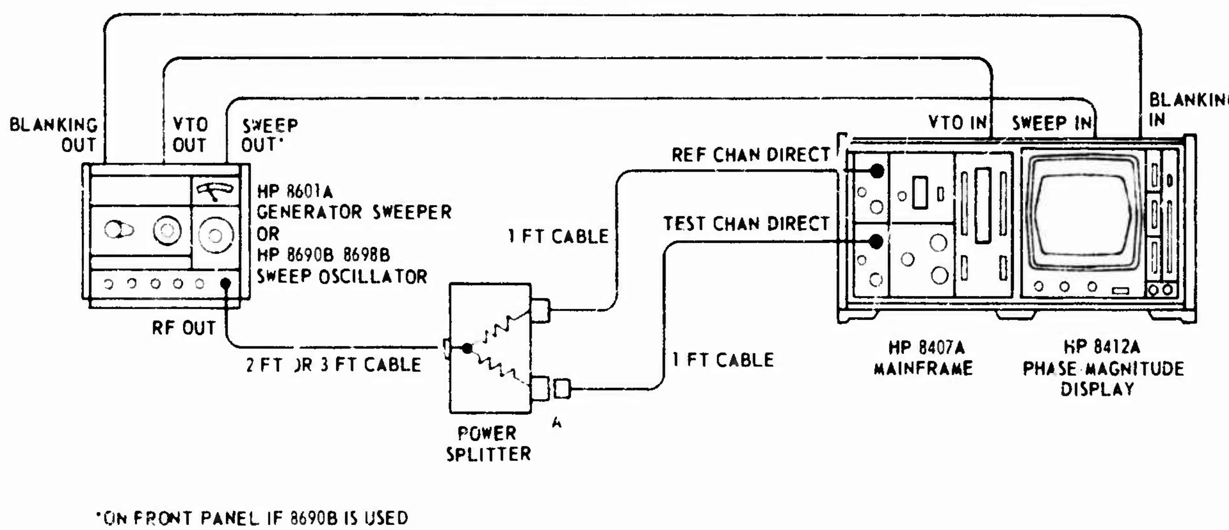


Figure 6-6. Basic Setup for Transmission Measurements

Measurement Process

The power from a sweeper (either the HP8601A Generator-Sweeper or the 8690B/8698B Sweep Oscillator) is divided by a power splitter into two different channels. A unity gain (0 dB) and zero degree phase condition is established in the 8407A. A test device is then inserted at Point A and the resulting display is a measure of the gain or loss and phase shift of the device under test.

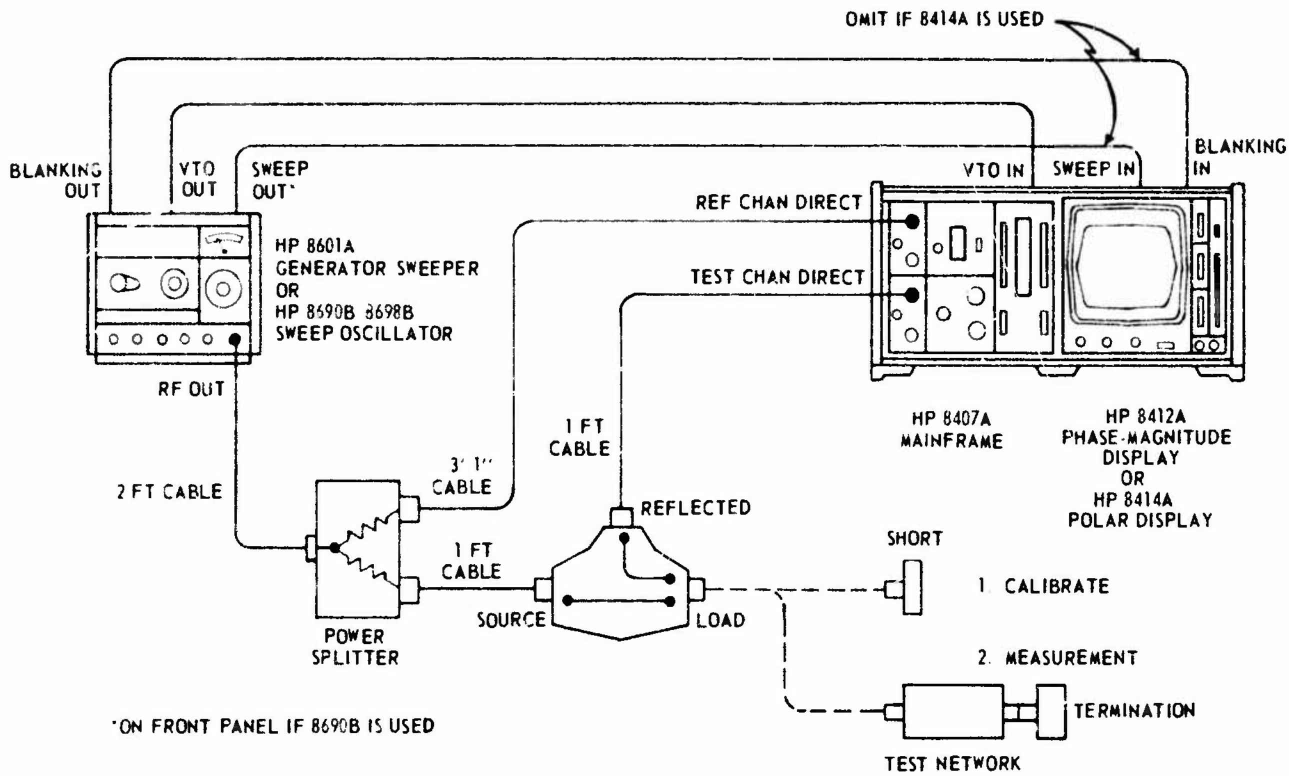


Figure 6-7. Basic Setup for Reflection Measurements

Measurement Process

Notice that the power from the signal generator is once again split into two channels; a reference channel and a test channel. This time, however, the signal entering the test channel of the 8407A is the reflected signal from the input of a network rather than the transmitted signal through a network. The directional bridge separates the incident signal from the reflected signal.

The 8407A again measures the ratio between the test channel and the reference channel signals. If you use the 8412A plug-in, the CRT trace displays return loss, the ratio of reflected signal to incident signal expressed in dB. It also displays the phase shift of the reflected signal.

No data format is suggested as was the case for surge arrestors. The characteristics of the different categories of filters and specific environmental requirements will be the determining factor. However, several general factors should be considered.

The relevant past history of the filter, such as manufacturing lot number or sample number, and whether or not the filter had been or is being subjected to environmental tests (such as temperature and humidity) should be noted. The data format should be consistent with the measurement accuracy.

In the case where scattering parameters are developed from reflectivity measurements, the data format should require the alternate procedure where S_{11} and S_{22} begin to approach either -1.00 or + 1.00. In this case, the direct measurement of Z_1 and Z_2 in the 50 Ω scattering parameter jig will lead to more accurate results.

The data format and reporting should consider the needs of the users. If the automatic test equipment is available, such as previously described, then a set of photographs of the oscilloscope displays of the scattering parameters as a function of frequency should be sufficient for either quick-look or detailed analysis purposes. An example of this is illustrated in Fig. 6-8. The data reporting format should require expanded frequency displays where a series of abrupt changes in the scattering parameters occur, such as near cut-off or roll-off points of either low pass or band pass filters.

The detail employed in the reporting format can be reduced if only quick-look comparative data is required. Possibly, the parameter values at selected frequencies need be reported. In some cases, presenting only the magnitude of parameters will suffice. As seen from the data in Fig. 6-8, the scattering parameters in the stop band are generally "well-behaved" and therefore detailed reporting of stop band parameters may not be needed. In and near the pass band, detailed information is often required.

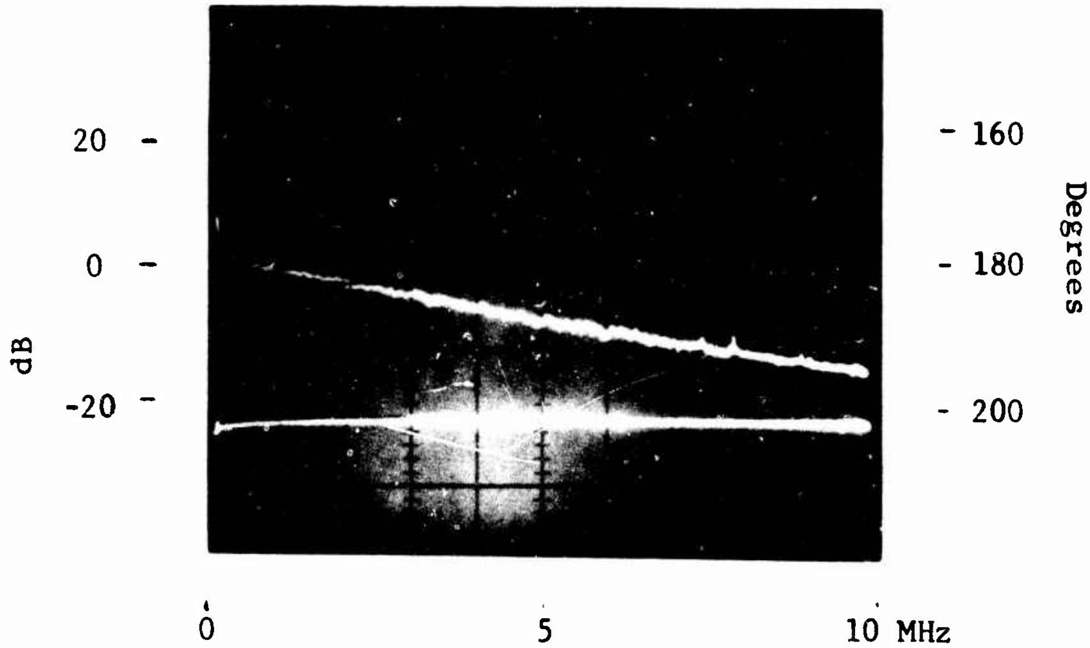


Fig. 6-8(A) S_{11}

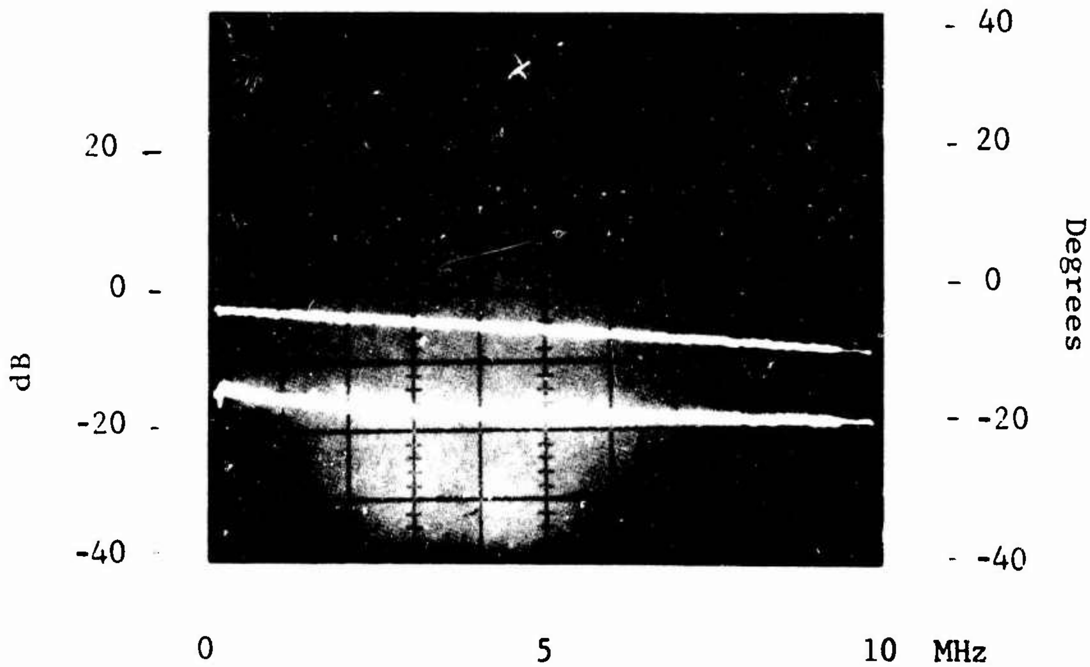


Fig. 6-8(B) S_{21}

One Foot Section of Lossy Cable Filter

Upper Curve Phase -- Right Scale

Lower Curve Amplitude -- Left Scale

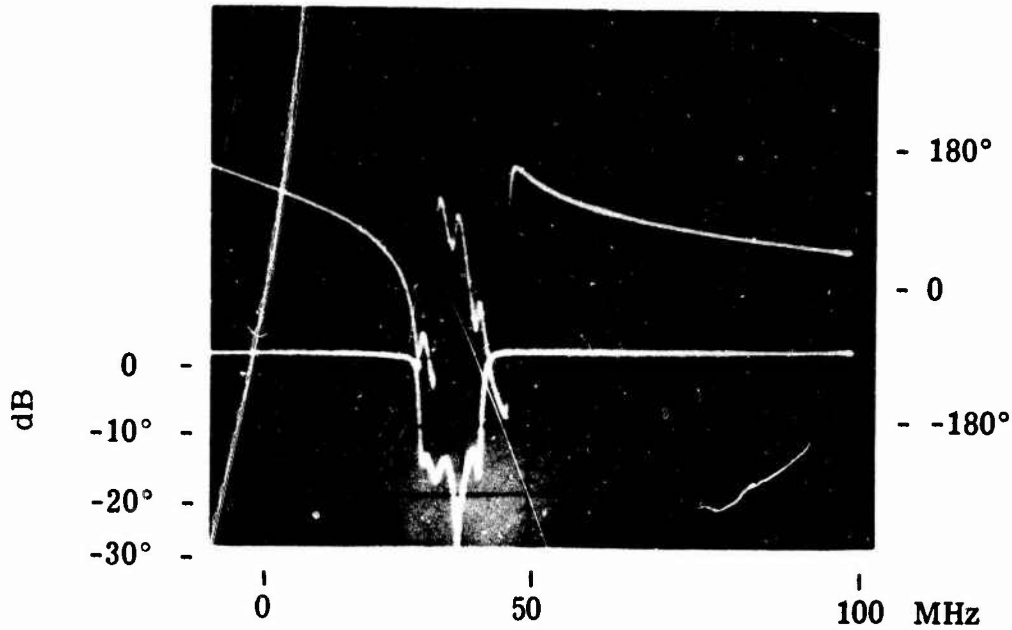


Fig. 6-8(C) S_{11}

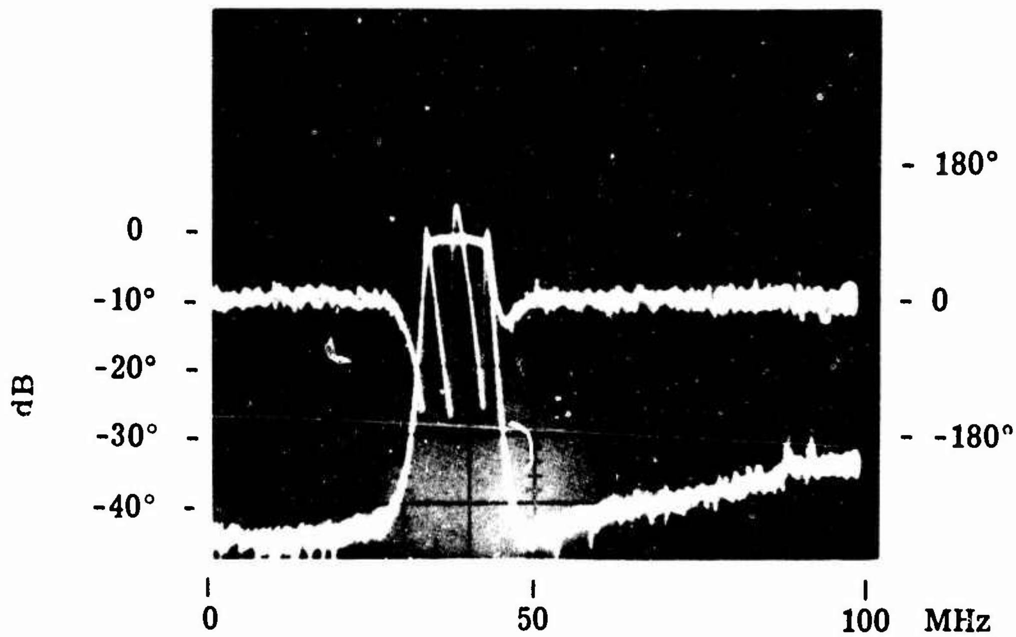


Fig. 6-8(D) S_{21}

38 MHz Bandpass Filter (Scattering Parameters)
Upper Curve Phase -- Right Scale
Lower Curve Amplitude -- Left Scale

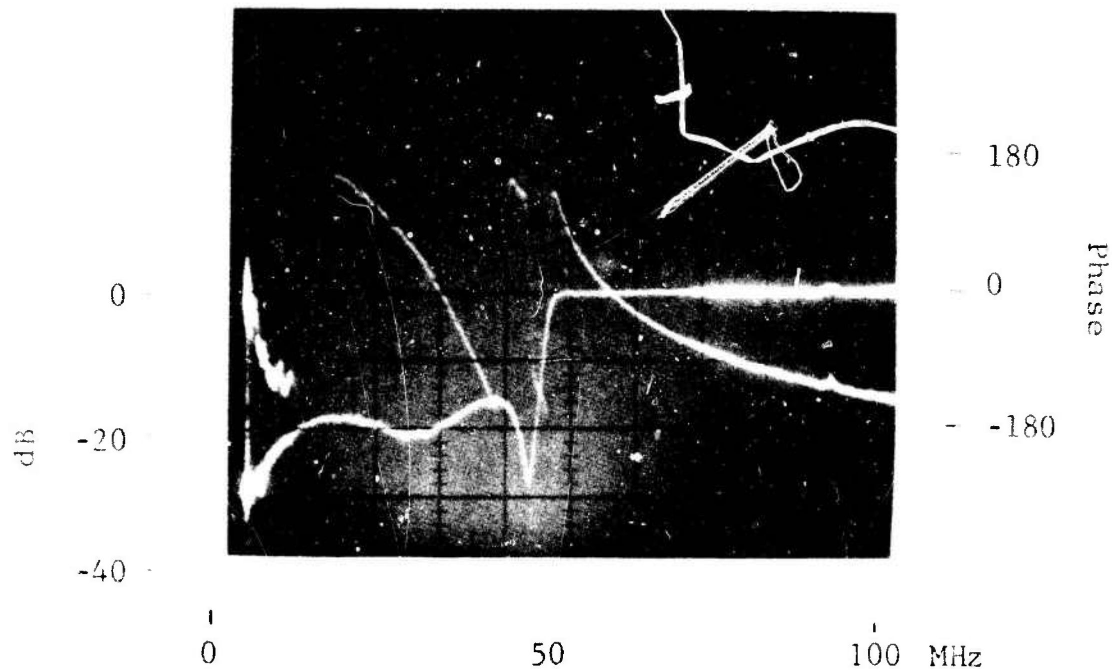


Fig. 6-8(E) S_{11}

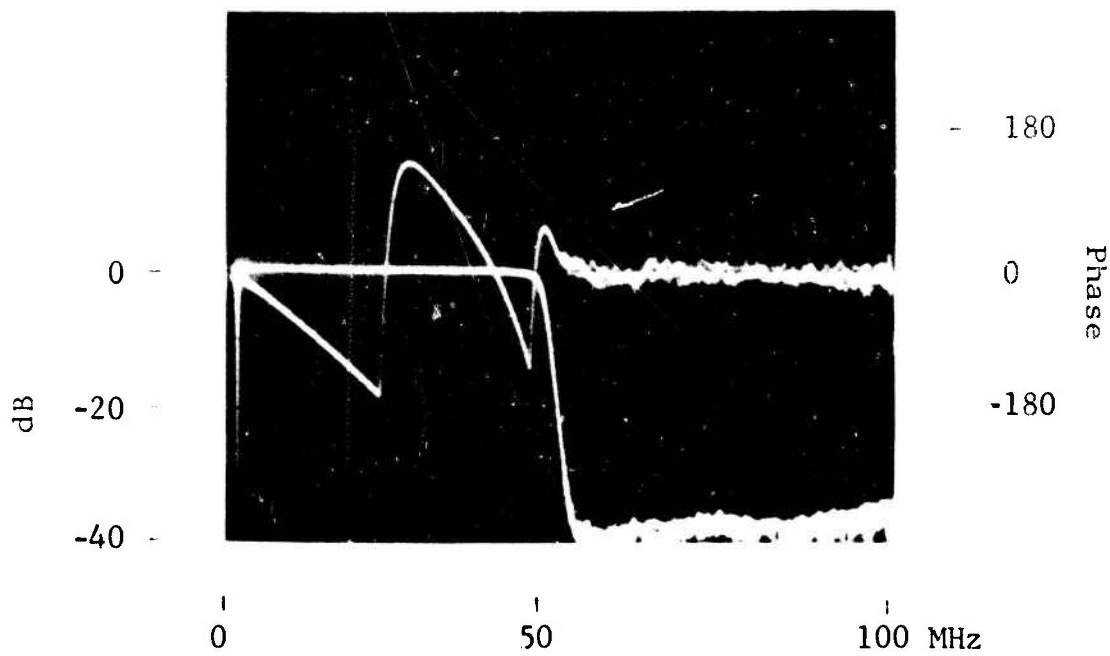


Fig. 6-8(F) S_{21}

50 MHz Low-Pass Filter

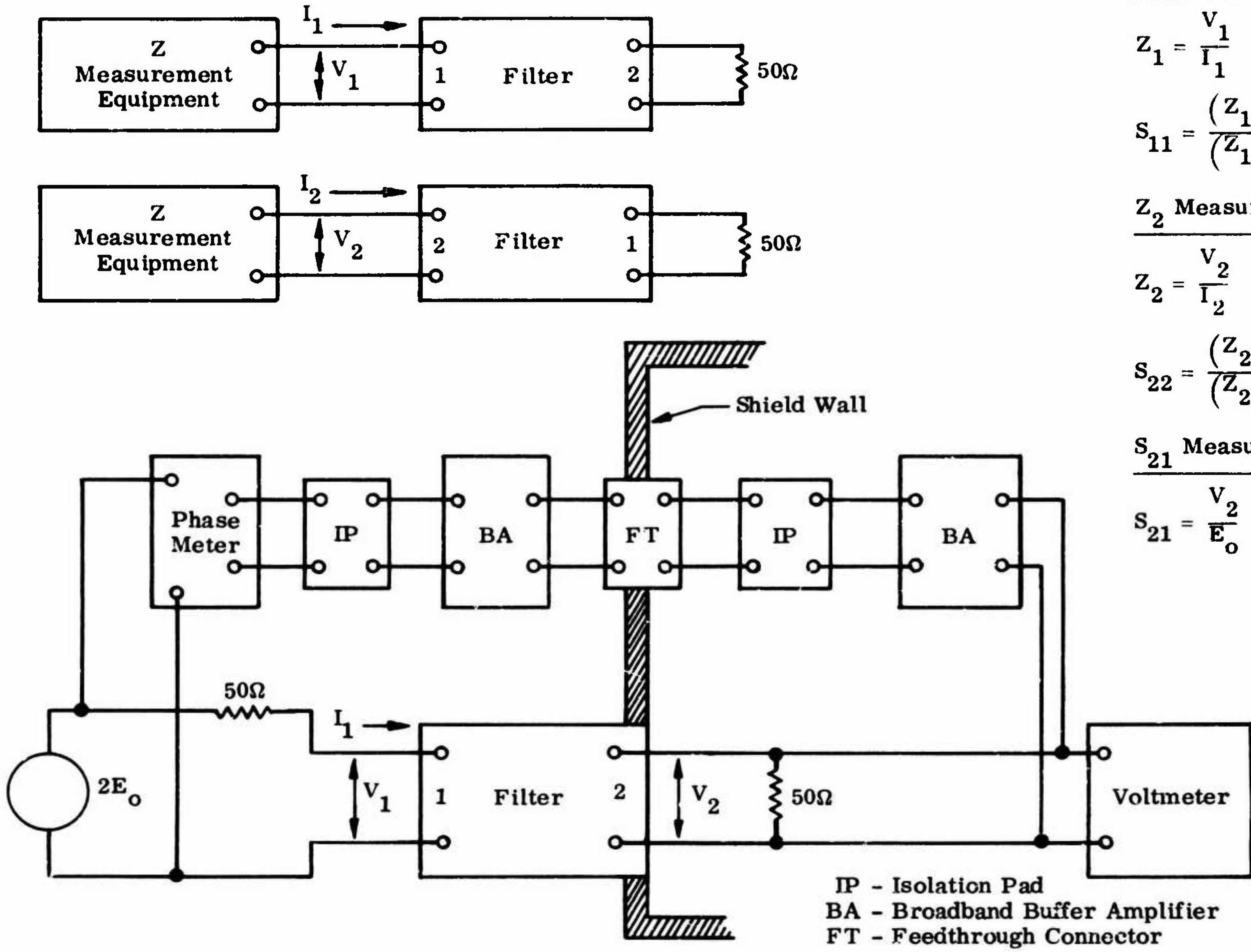
Upper Curve Phase -- Right Scale

Lower Curve Amplitude -- Left Scale

6.4 Low Level Frequency Domain Measurements by Impedance Measurement Techniques

This procedure considers the development of the scattering parameter, S_{11} and S_{22} by impedance measurement methods. An alternate procedure described in Section 6.2.5 considered development of these parameters by reflectivity measurement techniques. Both procedures are applicable over the frequency range of interest generally from 1 kHz to 100 MHz. The impedance measurement technique is more appropriate below 10 MHz, partly because of equipment availability and also because of difficulty in making impedance measurements above 10 MHz. With care, however, the impedance method may be used across the entire frequency range of interest although automatic equipment for tnis purpose may not be available.

The basic measurement procedure is illustrated in Fig. 6-9. The scattering parameters S_{11} and S_{22} are developed from impedance measurements. These impedance measurements are made when the filter terminated in 50 Ω as appropriate. The S_{21} measurement is made by noting the ratio of the output voltage to the voltage which would be present if the filter were removed and the terminal connected to port 1 connected to the 50 Ω termination. The phase angle of this ratio, V_2/E_1, must also be measured. This may prove difficult in the event that dynamic ranges of much more than 70 dB are required. The principle difficulty is that for the higher dynamic ranges, some of the signals from the signal generator may leak through the phase meter and produce higher readings at the output of the filter than would be under ideal measurement conditions. This can be avoided by the use of a series of buffered amplifiers and attenuators and locating the more sensitive measurement equipment within a shielded enclosure. The buffered amplifier not only provides added gain to insure proper operation of the vector voltmeter, but also can be used to provide additional gain to overcome series attenuators or pads. The purpose of



Z_1 Measurement

$$Z_1 = \frac{V_1}{I_1}$$

$$S_{11} = \frac{(Z_1 - Z_o)}{(Z_1 + Z_1)}$$

Z_2 Measurement

$$Z_2 = \frac{V_2}{I_2}$$

$$S_{22} = \frac{(Z_2 - Z_o)}{(Z_2 + Z_o)}$$

S_{21} Measurement

$$S_{21} = \frac{V_2}{E_o}$$

Figure 6-9. Development of S-Parameters by Impedance Measurements the series attenuators or pads is to provide additional attenuation to signals which might originate from the source generator and progress through the phase meter and through the buffers and thence into the shielded room and on to the output terminals of the filter. In general, typical buffer amplifiers can provide anywhere from 30 to 80 dB of isolation. However, typical amplifiers such as may be purchased cannot be relied upon to provide much more than 30 or 40 dB of isolation. Hence it is desirable to supplement this isolation by the use of increased gain and attenuation. Depending on the characteristics of the phase meter it may also be desirable to use two buffer amplifiers and sets of pads -- one set within the shielded room, and the other set external to the shielded room.

A wide variety of equipment exists to accomplish these measurements on a single frequency basis. The test equipment and test jig used for MIL-STD 220 tests can be modified also for this purpose. The principle addition in equipment to the MIL-STD 220 measurement is the phase meter and the impedance measurement equipment. Standard impedance measurement equipment is available for these measurements. The capability of this equipment should range from preferably milli-ohms to thousands of ohms. The range may be even more or less than this depending on the class of filter under consideration. Vector voltmeters or phasemeters are available on the market capable of making measurements in this particular range. Several vector voltmeters or phasemeters are suggested; such as Ad-Yu Model 408 Phasemeter, frequency range 1 Hz to 100 kHz; Dranetz Model Series 305 with plug in units ranging from 2 Hz to 10 MHz; Hewlett Packard 8405A Vector Voltmeter ranging from 1 to 1000 MHz in frequency.

Semi-automatic equipment may also be purchased for the measurement of the S related input impedance measurements and the transfer function. One such equipment is the HP 3575A determining factor. These general aspects were considered in Section 6.2.5, however, some of the factors unique to the impedance method are worth noting. The most desirable presentation would be the presentation of the S parameters and/or related input impedances (for the 50 Ω terminations) as a function of frequency. The use of the S parameter related input impedances is preferable where the values of S_{11} and S_{22} are close to one. This occurs when the input impedance to the filter is either less than one ohm or greater than a few thousand ohms.

If continuous displays of the pertinent parameters are employed, care should be taken such that sufficient detail is embodied in these displays around critical frequencies, such as near cut-off or roll-off points of either low pass or band pass filters.

The details employed in the reporting format can be reduced where only quick look comparative information is required. If the filter is well behaved, parameters need be measured at every octave, except at critical points such as the roll-off or passband areas. Again, depending on the situation, presenting only the magnitude of the parameters may suffice for many quick look comparison applications. These are specific to each user's need, and therefore recommendations are not given. As a guide, Fig. 6-10 illustrates how the scattering parameter impedance transfer function data can be presented for a typical power-line filter.

Phase Amplitude and Gain Meter, ranging in frequency from 1 Hz to 13 MHz. This equipment coupled with the appropriate signal generators supplementary current probe and amplifiers (such as Tektronix Current Probe and Amplifier Systems Model No. 134) can measure the S parameter input impedances and the transfer functions on a spot or swept frequency basis. Essentially the same arrangement of equipment illustrated in Figure 6-9 may be employed. To measure the S parameter input impedances (Z_1 and Z_2) the vector voltmeter will require the input current and input voltage to the filter when it is terminated by 50 Ω. The input impedance under these conditions can be developed on a continuous basis although the scanning time for the lower frequencies can be quite long. The measurement of S_{21} is accomplished,as indicated in the lower portion of Fig. 6-9, by the elimination of the voltmeter within the shielded room and replacing the phasemeter by the gain-phase equipment. A number of options also exist with this particular equipment, either in terms of the types of sources to supply the different frequencies or automatic recording and reduction data.

Totally automatic systems are becoming available which are currently being used to measure the characteristics of precision filter by major equipment manufacturers. This equipment can be readily programmed and perhaps modified by suitable test fixtures to accomplish the impedance measurements illustrated in Fig. 6-9. Such fully automatic equipment is being offered by at least one manufacture such as the Hewlett-Packard 3040 series and is capable of making precision filter measurements ranging from 50 Hz to 14 MHz. In addition to developing the Z related impedance, related S parameter measurements, and the S parameter transfer function, such equipment can also develop other parameters of significance necessary for proper filter performance.

No data reporting format is suggested as was the case for surge arrestors. The characteristics of the different categories of filters and specific environmental requirements will be the

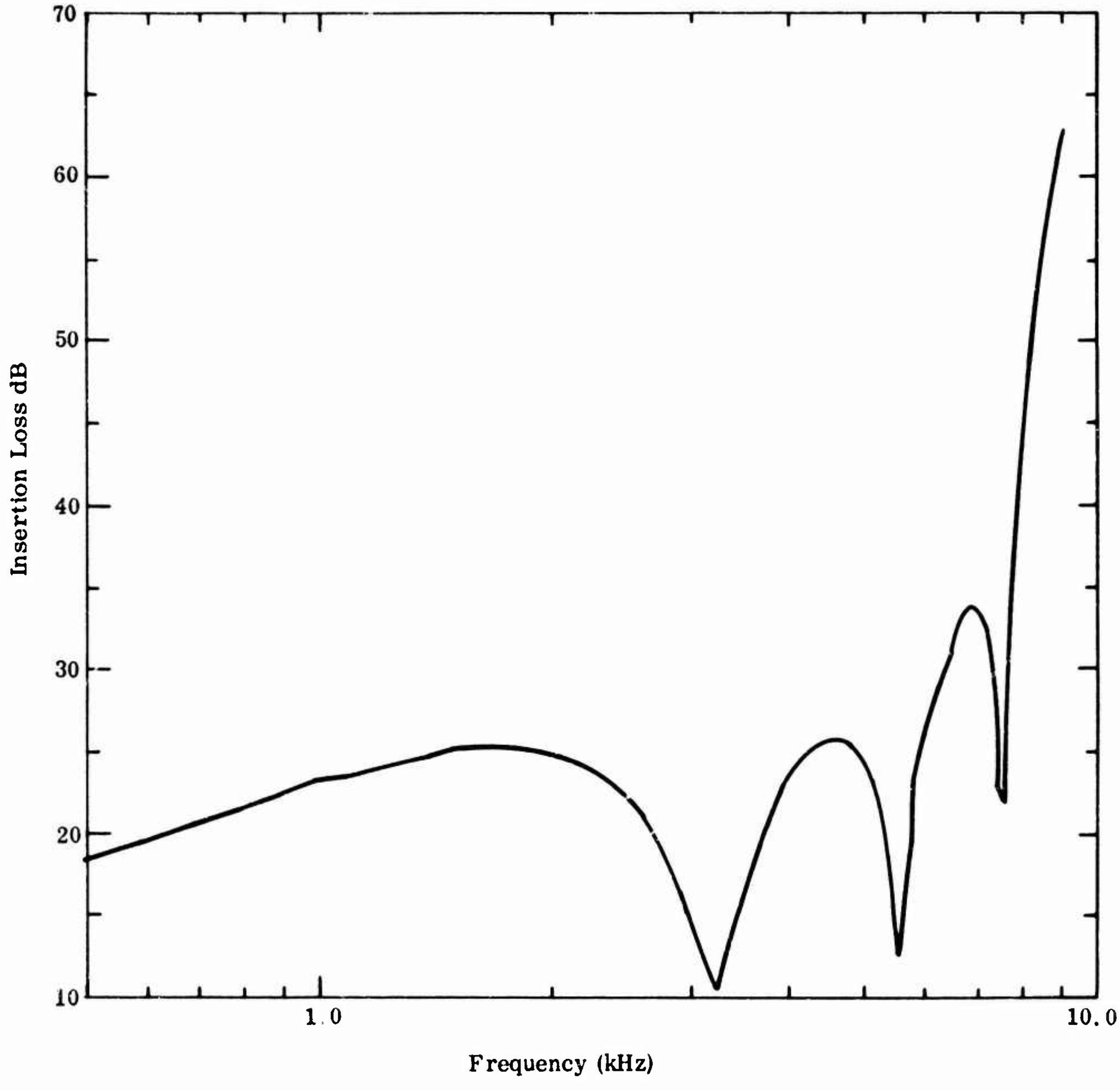


Figure 6-10(A). Insertion Loss in 50Ω Jig -20 Log$|S_{21}|$
50 Amp Power Line Filter FSR-1202E

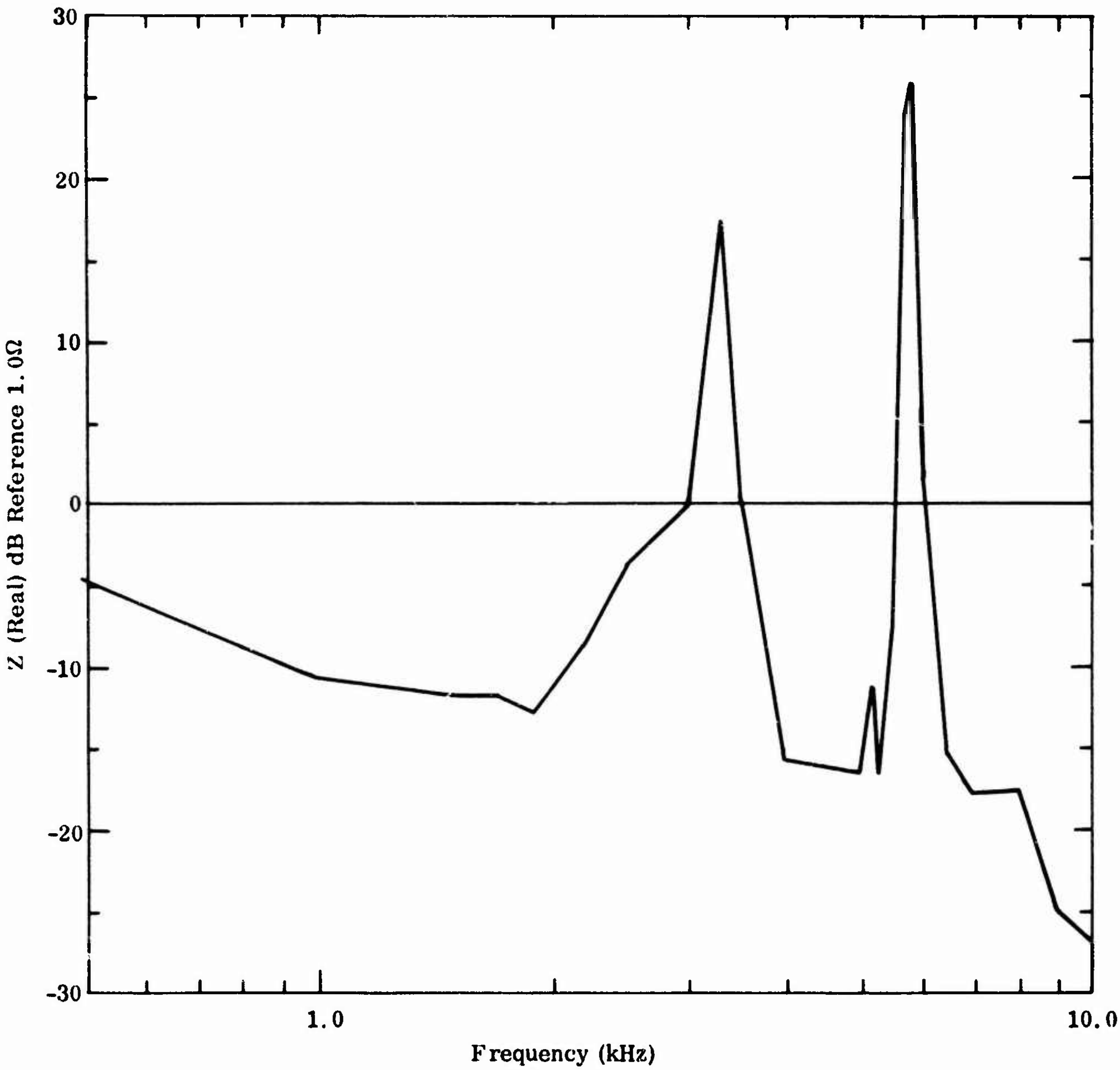


Figure 6-10(B). Real Z_1 Input Impedance in 50Ω Jig 50 Amp Power Line Filter FSR-1202E

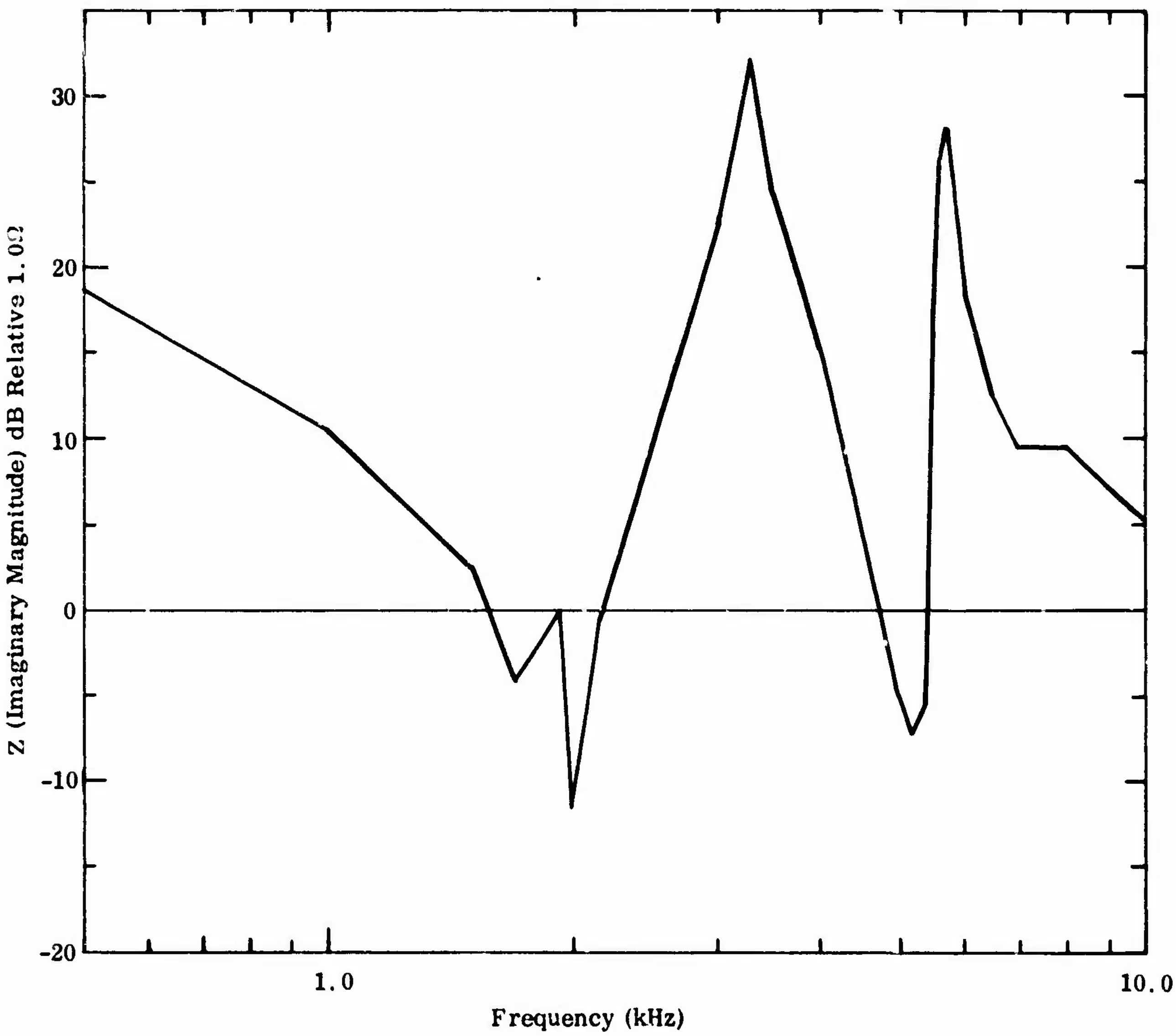


Figure 6-10(C). Imaginary Z_1 Input Impedance in 50Ω Jig
50 Amp Power Line Filter FSR-1202E

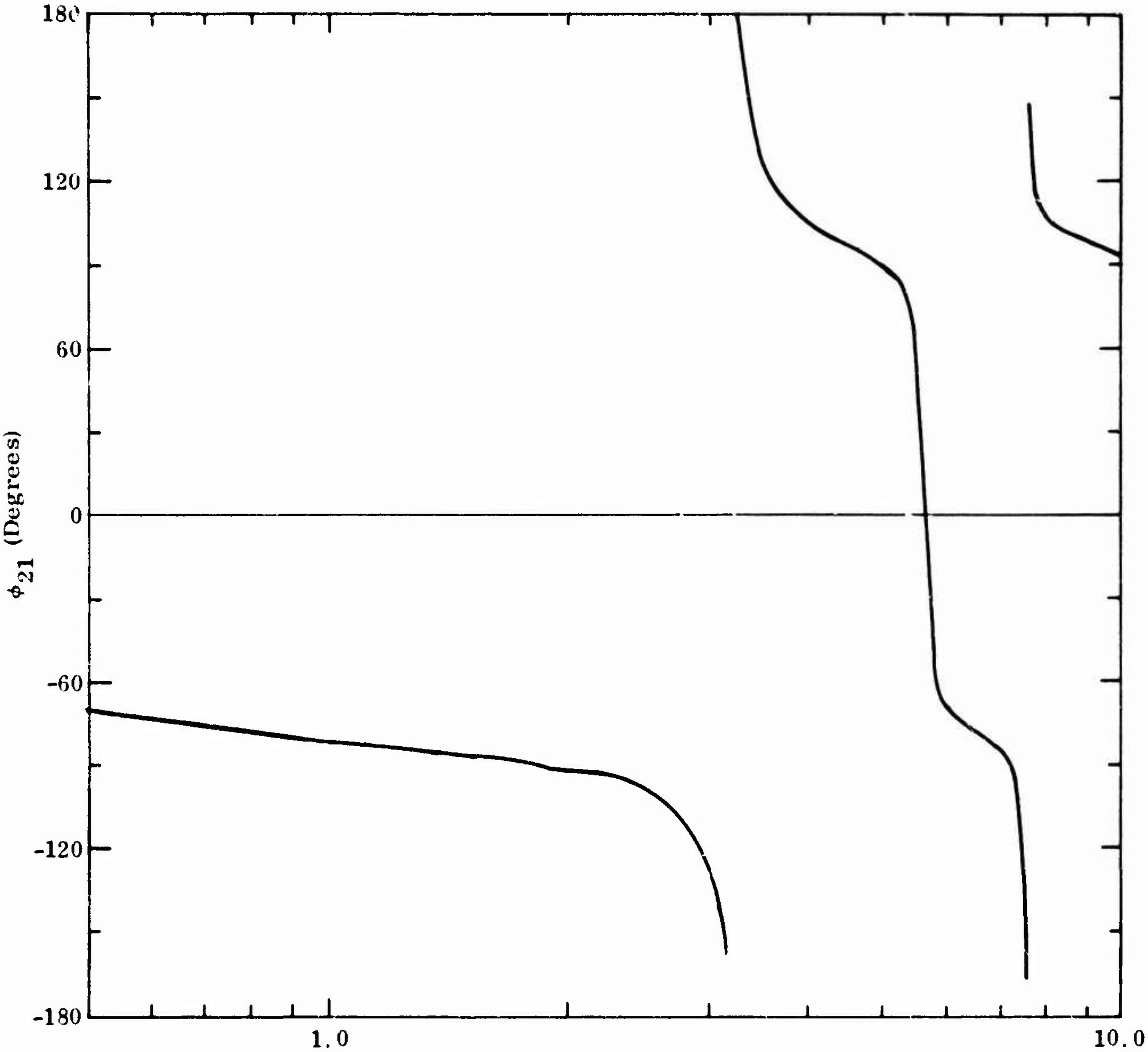


Figure 6-10(D). Insertion Loss Phase in 50Ω Jig 50 Amp Power Line Filter FSR-1202E

6.5 Time Domain Measurements

As stated previously, the frequency domain and the time domain are related by the Fourier transform pair for linear systems; therefore, the required measurements can be performed either in the time domain or the frequency domain. Although the frequency domain measurements provide greater dynamic range, the time domain or pulse measurements are very useful, since they provide a better qualitative view of the transient behavior of the filter.

One possible pulse test procedure is exactly the same as illustrated in Figs. 6-4 and 6-5, except the 50-Ω RF source is replaced by a 50-Ω pulse generator and the coupler outputs are detected and displayed with a wide band oscilloscope rather than a vector voltmeter or network analyzer. In this case, the measured quantities are transient responses or time domain quantities. Therefore, in order to obtain the frequency domain S-parameters, it is necessary to digitize the measured transient responses, perform the required numerical Fourier transforms with a digital computer, and then perform the required complex divisions to obtain the various S-parameters. Obviously, this overall procedure is more time-consuming than the swept frequency measurements discussed in the preceding section, unless an automated measurement and analysis system is employed. Such systems are very expensive; therefore, although this procedure is acceptable, it is not recommended as the preferred procedure. Further, this particular procedure is limited in dynamic range, unless a series of different pulses are employed. The selection of the pulse waveform is dependent on the filtering characteristic unique to a particular filter.

The preferred time domain or pulse test procedure for a filter is illustrated in Figs. 6-11 and 6-12. As shown, the input or output port is driven by a 50-Ω pulse generator, the other port is terminated by a 50-Ω termination, and the indicated voltages and currents are monitored using a suitable voltage

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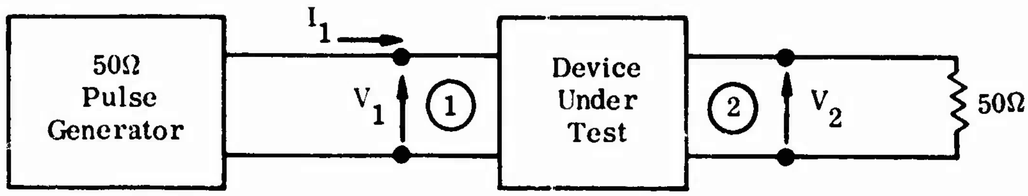

Figure 6-11. Preferred Pulse Test Procedure for Filters

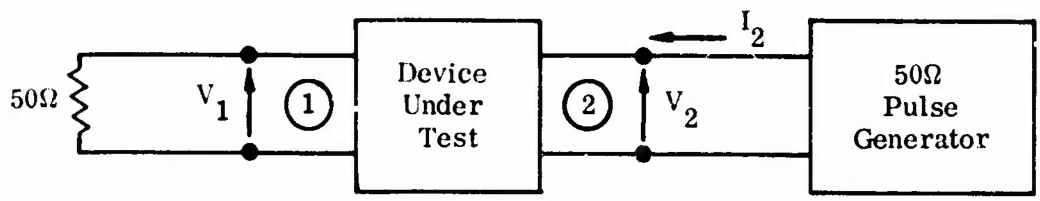

Figure 6-12. Preferred Pulse Test Procedure for Filters

probe, current probe, and oscilloscope. As in the case of the frequency domain measurements, the measurement system should have an overall bandwidth of at least 1 kHz to 100 MHz. Further, the voltages and currents should be measured at the device terminals.

It is recommended that these measurements should be performed for both a narrow rectangular pulse and a wide rectangular pulse. The narrow pulse should have a pulse width less than 50 ns so that it approximates an impulse or the spike that passes through some surge protectors. The wide pulse should be sufficiently wide so that it represents a step function for the filter. For example, in the case of a low pass filter, the pulse width should be considerably longer than $(\text{cut-off frequency})^{-1}$ These transient measurements should provide a good qualitative view of the transient behavior of the filter.

Again, it is theoretically possible to determine the frequency domain S-parameters from these measurements. However, the overall procedure is more time-consuming than the swept frequency measurements and is not recommended unless an automated measurement and analysis system is available.

6.6 Rated Load Current Measurements, Low Pass Filters

6.6.1 Scope

This section deals with the measurement of the parameters that determine whether the magnitude of the load current significantly affects the performance of the low pass filter. More specifically, it is primarily concerned with whether the inductors saturate at or below the rated DC load current of the filter. The DC equivalent of the peak rated AC current or EMP induced current may also be used to assess other saturation effects. These procedures may be used as a guide for tests to evaluate the possible saturating effects of EMP transients.

The nonlinear behavior of a filter is a function of the source and load impedances as well as the level and waveform of the applied transients. Complete procedures which consider these factors must await availability of pulse and tone burst sources having a wide range of source impedances. On an interim basis, the DC load current tests can be used to assess the nonlinear behavior of the filter.

The required parameters and measurements are exactly the same as those for the Low Level Characterization Measurements, except that the measurements are performed with the rated DC load current or DC equivalent flowing through the filter. Therefore, this section merely presents the preferred procedure for injecting the required DC current. As such, it is a modification of the procedures set forth in MIL-STD 220.

6.6.2 Measurement Procedure

The preferred procedure for injecting the required DC load current is illustrated in Fig. 6-13. It should be noted that the DC source should be a floating source and should not be connected to ground. The nominal DC rated load current should be applied during these tests and the measurement procedure is the same as discussed in Section 6.2, based on either reflectivity as shown in Fig. 6-13, or based on S-parameter related Z_1, Z_2 measurements.

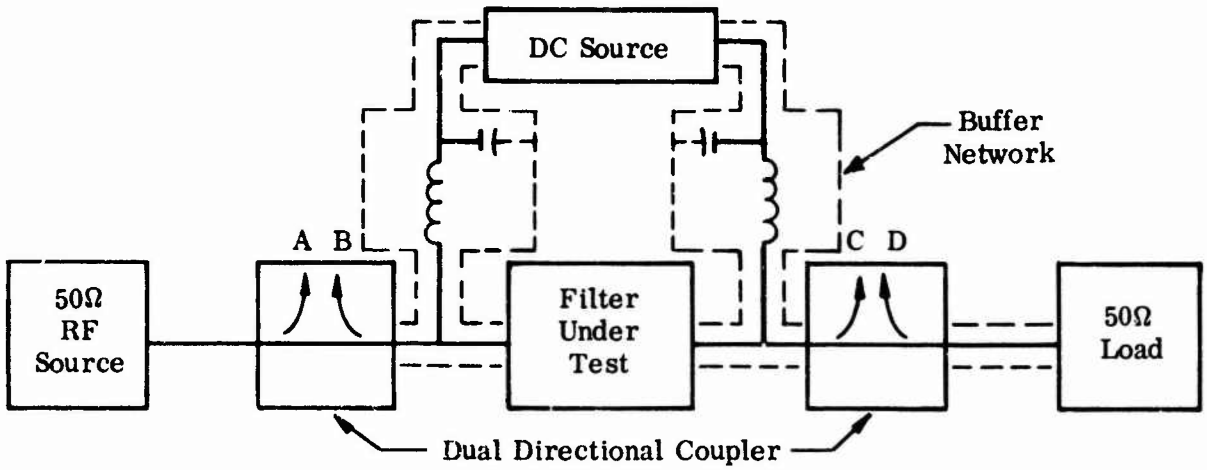

Figure 6-13. Basic Test Circuit for Rated Load Current Measurements

The buffer network should have sufficient inductance so that it does not significantly affect the measurements over the desired frequency range. As a check on the effect of the buffer networks, the DC source should be replaced by a short circuit and the desired filter parameters should be measured with and without the buffer networks connected. If these two measurements are significantly different, the buffer network is loading the measurement system and should be modified. The buffer network specified in MIL-STD-220A should be acceptable for most filters.

6.7 Permanent Degradation Measurements

6.7.1 Scope

This section deals with the measurement of the filter parameters that determine the capability of the filter to withstand the effects of both EMP-induced transients and other transients in the system. Obviously, the primary emphasis in this document is on the effects of EMP-induced transients; however, other transients can not be ignored because they could degrade or destroy the filter. Again, in order to intelligently evaluate various protective devices, one must be familiar with representative EMP-induced transients, collector impedances, and load impedances.

Except for very long buried or above ground cables, typical EMP-induced transients are generally of the form of an exponentially decaying sinusoidal with various peak amplitudes, resonant frequencies, and decay times. Further, the collector or source impedance are generally complicated complex functions. The ideal approach for obtaining meaningful failure data would be to subject the various filters, terminated with the actual load impedance, to a broad range of exponential decaying sinusoidal waveforms (such as shown in Section 4), using a pulse injection source with the appropriate output impedance for each waveform. However, as discussed previously, such injection sources are not presently available and would require significant development cost. Therefore, the preferred procedures for Permanent Degradation Measurements are based on subjecting the filters to various capacitor discharges.

It should be noted that such an approach may not provide meaningful failure data in all cases. More specifically, capacitors and inductors fail due to excessive voltages or currents and these test voltages and currents depend on the source impedance and applied waveform; therefore, the failure level will depend upon the source impedance and applied waveform. Further, because of the nonlinear effects, such as connector breakdown, it may be very difficult or impossible to extend the results from one set of source and load conditions to other source and loading conditions. Based on these considerations, the preferred procedure for Permanent Degradation Measurements has been entitled Interim Measurement Procedure. However, this procedure should be employed until the required pulse injection source with the appropriate output impedance and waveform are available or until a more appropriate procedure is developed.

One of the most difficult aspects of Permanent Degradation Measurements is determining realistic failure criteria. In general, the actual failure criteria, or what constitutes a significant change in a particular parameter, depends upon the system application and the required system performance criteria. Therefore, for particular system applications, it may be appropriate to select different criteria or more conservative or liberal limits than those suggested in this document. In all cases, the failure criteria employed in the Permanent Degradation Measurements should be explicitly stated. With no particular system application in mind, the suggested failure criteria for filters is either a change of 10 percent in the original in-band transmission coefficient or a change of 20 dB in the out-of-band transmission coefficient.

6.7.2 Interim Measurement Procedure

The pulse capability of filters should be determined using a typical capacitor discharge circuit such as shown in Fig. 6-14. The value of the discharge capacitor and series resistor, R, are chosen so that the short circuit source current (i.e., replacing the filter and 50-ohm load by a short circuit) is a two-exponential pulse with the desired decay time and a rise time at least a factor of 10 less than the decay time. The variable DC supply is adjusted to provide the desired peak short circuit current for the particular RC combination being employed.

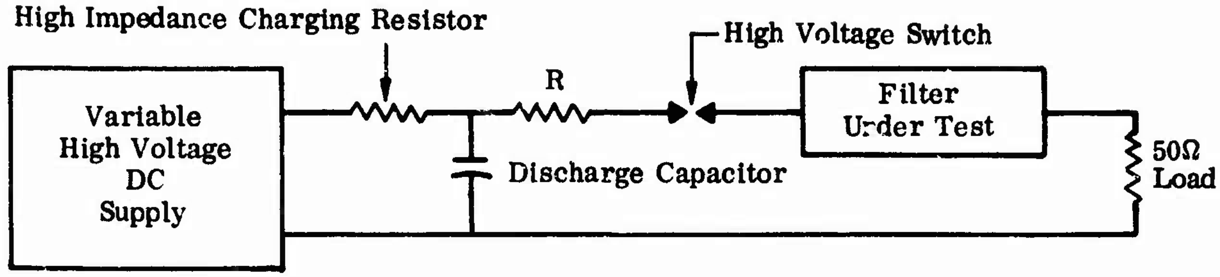

Figure 6-14. Typical Circuit for Determining Pulse Capability of Filters

decay time; therefore, it should be measured for an appropriate range of decay times. Based on the peak to 10 percent decay times of representative EMP-short circuit currents, a representative range of decay times of particular interest for the short circuit source current is 50 ns to 15 μs. Further, if the test program includes the effects of other transients (such as EMP-induced or lightning-induced transients on power distribution systems), much longer duration transients should also be considered.

The actual applied voltage and current waveforms will depend upon the source impedance and the input impedance of the filter; hence, it will depend upon the type of filter being tested. Therefore, when reporting failure data for filters, the charge voltage, capacitance and the value of the series resistance should be explicitly stated. For a complete characterization, the failure level should be plotted as the peak short circuit current versus decay time.

Maximum Pulse Capability

When performing these tests, the maximum pulse capability for a particular fall time is defined as the peak short circuit source current that the filter can withstand for five successive pulses separated by at least 30 seconds each without exceeding the failure criterion. Since device failure can be a cumulative effect (depends on previous pulse exposure), each test sample should only be subjected to a sequence of five pulses. Nevertheless, the test procedure of subjecting the same sample to sequences of five pulses at increasing amplitudes until failure occurs, can and should be used to obtain estimates of the maximum pulse capability. Further, in test programs where device cost or other constraints limit the number of test samples, this latter procedure is acceptable. However, if such an approach is employed, the actual test sequence should be explicitly stated.

Since the failure level is often a function of the decay time, the maximum pulse capability should be measured for an appropriate range of decay times. As stated previously, the decay times of particular interest are from 50 ns to 15 μs, but other values can occur.

Rated Pulse Capability

The rated pulse capability for a particular decay time is defined as the peak short circuit source current that the filter can withstand for 100 successive pulses separated by at least 30 seconds each without exceeding the failure criterion. The failure criterion, test circuit, test procedure or sequence, and the range of decay times discussed for the maximum pulse capability apply to this measurement also.

6.8 References

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