



IEEE Standard for Methods of Measurement of Radio-Frequency Power-Line Interference Filter in the Range of 100 Hz to 10 GHz

IEEE Electromagnetic Compatibility Society

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Abstract: Uniform methods of measurements of radio-frequency power-line interference filter attenuation performance in the range of 100 Hz to 10 GHz are set forth. Nonloaded and loaded attenuation measurements are presented with varying source impedance, including radio-frequency current injection with linear and nonlinear load impedances. H- and S-parameter measurements are introduced for modeling results. New methods for placing filter performance criteria on a filter label are also included.

Keywords: attenuation measurements, crest factor, dB, electromagnetic interference power-line filters, EMI/RFI filters, insertion loss, LISN, no-load insertion loss, nonlinear load, radio-frequency current injection, S-parameters

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Introduction

This introduction is not part of IEEE Std 1560-2005, IEEE Standard for Methods of Measurement of Radio-Frequency Power-Line Interference Filter in the Range of 100 Hz to 10 GHz.

The interest in low-voltage ac/dc radio interference filters has grown due to strict conducted emissions requirements of many end-use equipment, appliances, and medical equipment standards. However, tests that predict the performance of these filters in realistic situations have not been forthcoming. Until recently, general design considerations were based on filter performance as a result of matched-impedance test methods. The popular test specification for the measurement of electrical filter insertion loss is MIL-STD-220A-1978 [B14],^a now MIL-STD-220B,^b which also uses the matched-impedance method. The test methods found in MIL-STD-220B are best suited for quality control during quantity production of power-line filters. The specified matched-impedance test conditions are satisfactory for quality-control purposes but do not represent conditions that exist in actual circuits or installations. The power source impedances in actual installations are typically much lower than 50 ohms at frequencies in the filter stop band. These methods should be the last step in the filter design and specification process. All too often, matched-impedance method specifications are improperly used as the initial and primary design specification. The insertion loss measurement results may bear little or no resemblance to the actual performance of the filter as installed.

Because the nature of end-use loads and conducted emissions has changed significantly since the concept of interference filters was developed, manufacturers of filters have put forth many efforts in the past few years to enhance filter design and performance. Characterization of filters from the field and on-site investigations indicated that many filters were operating in electrical environments where filter performance was substantially degraded because of very low source and load impedances. Laboratory tests and research to understand fully the performance of power-line filters in these realistic environments were conducted with the cooperation of the respective manufacturers. As a part of the research, existing filter standards were reviewed and studied in a laboratory environment. These studies indicated that improved standardized test methods were needed to permit the manufacturer to describe, and the end user to understand and predict, how a given filter would perform in the user's environment. With participation from filter manufacturers and a need to develop a new filter standard to support the filter industry, efforts were initiated by the individuals in the Working Group to develop a new standard.

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Current interpretations can be accessed at the following URL: <http://standards.ieee.org/reading/ieee/interp/index.html>.

^aThe numbers in brackets correspond to those of the bibliography in Annex A.

^bInformation on references can be found in Clause 2.

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Contents

1.	Overview.....	1
1.1	Scope.....	1
1.2	Purpose.....	1
1.3	Application of test methods and use of this document	1
2.	Normative references	4
3.	Definitions.....	5
4.	Safety	8
4.1	Stored capacitor energy.....	8
4.2	RF hazards	8
4.3	Voltages and currents.....	8
5.	Measurement instrumentation.....	9
5.1	General.....	9
5.2	Calibration of measuring equipment.....	9
5.3	Measurement tolerances.....	9
6.	Measurement uncertainty.....	9
6.1	General.....	9
6.2	Calculation of measurement uncertainty	9
7.	Test equipment and minimum specifications	10
7.1	AC power source.....	10
7.2	Alternating current source.....	10
7.3	DC power source.....	10
7.4	Direct current source.....	10
7.5	Ammeter	10
7.6	Buffer networks	10
7.7	Differential voltage probes	11
7.8	Dynamic range	11
7.9	Ground plane.....	11
7.10	Impedance-transforming networks	11
7.11	Line-impedance stabilization network.....	11
7.12	Linear load	12
7.13	Nonlinear load.....	12
7.14	Oscilloscope.....	12
7.15	Power amplifier.....	13
7.16	Power analyzer.....	13
7.17	Attenuators, 100 dB	13
7.18	RF matching network.....	13
7.19	RF bulk current injection probe	13
7.20	RF current transformers	13
7.21	RF injector	13
7.22	Shielded enclosure	13

7.23	Spectrum analyzer or network analyzer.....	14
7.24	S-parameter test set.....	14
7.25	Tracking generator.....	14
8.	Test facilities.....	14
8.1	Standard testing conditions.....	14
8.2	General operating conditions.....	14
8.3	Grounding.....	15
8.4	Regulatory agency restrictions.....	15
8.5	Screened equipment and shielding requirements.....	15
8.6	RF test fixture and mounting requirements.....	15
8.7	Source impedance.....	15
8.8	Test equipment noise floor level.....	15
8.9	Attenuators, phase splitters, power splitters, and network matching pads.....	16
8.10	Lead dress.....	16
9.	Divisions of frequency ranges and recommended sensitivity.....	16
10.	Required measurement methods.....	17
10.1	Quality assurance testing—No load (10 kHz to 1 GHz).....	18
10.2	Quality assurance test—Loaded (10 kHz to 20 MHz).....	20
10.3	RF characteristic test, mismatched impedance—No load (100 kHz to 30 MHz).....	23
10.4	Variable source impedance attenuation measurement (100 Hz to 100 kHz).....	25
10.5	Attenuation measurement (100 kHz to 30 MHz).....	28
10.6	Aperture leak testing by electric fields (1 GHz to 10 GHz).....	31
10.7	Voltage drop and waveform quality test (linear/nonlinear loading).....	33
10.8	S-parameter measurement (100 Hz to 30 MHz).....	35
11.	Record keeping and data handling.....	39
	Annex A (informative) Bibliography.....	40
	Annex B (normative) Filter labeling.....	42
	Annex C (informative) Waveform quality and harmonic loading-related performance of power-line filters.....	44
	Annex D (informative) S-Parameters.....	54
	Annex E (informative) Line-impedance stabilization networks.....	62
	Annex F (informative) Frequency response curves.....	66
	Annex G (informative) Designing RFI filters for their worst-case behavior.....	70
	Annex H (informative) Estimating measurement uncertainty.....	78
	Annex I (informative) Glossary.....	82

IEEE Standard for Methods of Measurement of Radio-Frequency Power-Line Interference Filter in the Range of 100 Hz to 10 GHz

1. Overview

1.1 Scope

The scope of this standard is to develop a standard method of measurement for evaluating the electromagnetic and radio frequency suppression capability of power-line filters in the frequency range of 100 Hz to 10 GHz. This will apply to electromagnetic interference/radio-frequency interference (EMI/RFI) filters in general, i.e., dc, single-phase or polyphase systems rated for 600 V and below 1000 A. The method of measurement will describe general considerations, such as the method of standardizing source impedance for nonlinear loads, temperature rise, attenuation measurement, components, and or derating requirements when supplying nonsinusoidal load currents and operating in matched- or mismatched-impedance environments.

1.2 Purpose

The purpose of this standard is to provide measurements that evaluate the performance of power-line interference filters in practical installations involving varying load and source impedances. These factors are not usually considered in design and performance verification testing of EMI/RFI filters. Both manufacturers and end users should benefit from this standard that defines the ranges and environment, expected effects, and test methods to verify filter attributes.

1.3 Application of test methods and use of this document

Clause 10 describes filter performance measuring techniques. Although it might be desirable to characterize each production filter in accordance with all the measurement methods described, it is generally not economically feasible to do so. Usually, only first-design filters will be analyzed through multiple performance tests. These tests establish a performance baseline for that filter design. Subsequent production units of the same design may be tested using matched-impedance techniques to ensure that there is no significant deviation from the original due to component or assembly changes.

Case design and assembly testing may be required on a need basis to ensure control of radiated emissions from the filter at frequencies above 1 GHz. There are several methods for observing case integrity that do not employ RF testing to ensure proper case construction. These include the die penetration method. However, it is recommended that radiated field testing be performed at the installation site with the filter in its final configuration on a shielded enclosure for best results at frequencies above 1 GHz. Refer to IEEE Std 299™.¹ Where it is not possible to perform the test with the filter in its final configuration, then reasonable screening or enclosures may be used.

Clause 10 is divided into eight test methods (see 10.1–10.8), alphabetically coded in Table B.1. It is desirable to label all power-line filters in a similar manner in accordance with Annex B. The nameplate data may be derived from the different tests outlined in Clause 10. Annex F illustrates generic filter curves and points of interest such as the 3 dB point, 20 dB point, and the ratio calculations of the shape factor, which may be requested to be printed with the filter curves in the original baseline data.

1.3.1 Use of test methods

1.3.1.1 Quality assurance tests

- Quality assurance—No load (10 kHz to 1 GHz) (see 10.1)
- Quality assurance—Loaded (10 kHz to 20 MHz) (see 10.2)

The quality assurance (QA) test follows traditional matched-impedance testing methods currently in practice by most manufacturers. The frequency ranges are selected based on reproducibility, QA control indicators, and reasonable performance frequencies where the filter might be operating under varying loads.

1.3.1.2 Mismatched-impedance tests

- RF characteristics mismatched impedance—No load (100 kHz to 30 MHz) (see 10.3)

The mismatched-impedance subclause finds its origins in the tradition of CISPR 17. Using a set of mismatched source and load impedance, this low-cost performance indicator may be used when current injection techniques are not practical or cost-effective. For example, the 0.1 ohm and 100 ohm impedances used in the no-load test setup result in an apparent insertion loss without the filter of approximately 50 dB, limiting filter dynamic range testing to approximately 60 dB. It may be necessary to use pre- or post-amplifiers if a larger dynamic range is desired.

Other impedances may be used when the source and load impedances are known. Further details may be found in CISPR 17 regarding the construction of the impedance networks.

1.3.1.3 RF current injection tests

- Variable source impedance attenuation measurement (100 Hz to 100 kHz) (see 10.4)
- Attenuation measurement (100 kHz to 30 MHz) (see 10.5)

The current injection method has been described in documents such as MIL-STD-461E-1999 [B15]² for conducted susceptibility testing. This method is becoming more popular in the user community. The intent of these tests is to provide meaningful source impedance and realistic load testing. The data from these tests will more accurately predict the performance of a filter when installed on a typical power conductor. The following selection of source impedance and load characteristics should be followed:

¹Information on references can be found in Clause 2.

²The numbers in brackets correspond to those of the bibliography in Annex A.

At low frequencies (below 100 kHz), power-line source impedance characteristics are primarily related to the source's ability to deliver the current with minimum voltage distortion. Hence, it is important to characterize the load for these frequencies without the filter in the circuit. The desired parameters to be reached are a nonlinear load whose current crest factor is approximately 2.2 and a voltage distortion below 2%. This would be qualified as a "stiff" source. Once the load crest factor has been determined, then a variable or fixed reactor may be introduced to provide a voltage drop of 3% to 9% at the current rating of load used for the test without the filter in place, thus providing a "soft" source. For further information regarding nonlinear loading and source information, refer to Annex C.

For frequencies above 100 kHz, the typical power-line characteristic impedance is observed to be approximately 50 ohms. Line-impedance stabilization network (LISN) or artificial mains network (AMN) is used to provide this standardized source impedance during testing. The popular 50 μ H LISN has been determined to be best suited for this application and has its origin in such test practices as MIL-STD-461E-1999 [B15], and CISPR 16-2: 2003 [B4], or IEC 61000-4-3:2002 [B5]. For further details regarding the use and selection of the 5 μ H LISN, refer to Annex E.

1.3.1.4 Aperture leak tests

- Aperture leak test selection (see 10.6)

To determine realistic filter performance above 1 GHz, it is necessary to perform radiated electric field tests to determine aperture leaks and mounting issues. For typical power-line filters, IEEE Std 299 should be referenced. Mode stirred chamber setups are not required. Basic radiated emission test setups found in MIL-STD-461E-1999 [B15] may be employed for the filter aperture testing and are illustrated in the test setup. Measurements are taken in three dimensions at about 2 m separation of the chosen antenna set. Either matched bow ties, dipoles, or microwave horns may be used.

1.3.1.5 Voltage drop and waveform quality tests

- Voltage drop and waveform quality test (linear/nonlinear loading) (see 10.7)

Equipment operating within a shielded enclosure often presents a nonlinear load to the ac power supply. The nonlinearity arises from bridge rectifiers within the equipment charging a filter capacitor at each peak of the ac voltage. The pulses of current drawn by the equipment, combined with the inductance presented by the power-line filters, can cause serious distortion (flat-topping) of the ac voltage following the filter. If the voltage distortion is sufficiently serious, equipment malfunctions can result. Refer to Annex C for further details.

1.3.1.6 S- and Z-parameter measurement set

- S-parameter measurement (100 Hz to 30 MHz) (see 10.8)

In today's electromagnetic compatibility (EMC) environment, it is crucial to gain an understanding of the effects and parameters of filters, sources, and loads. Annex G provides information on designing filters for worst-case behavior and understanding the impedance domain for the networks. From Annex G we can see that a filter is a complex network that can be broken down into H- and S-parameters. Also sources and loads may be described accordingly. Annex D describes the measurement techniques and use of such parameters and how to model the data provided to choose a filter best matched for the intended installation. These methods are best used but not limited to when designing systems for fuel cells, mission-critical loads, and various distributed generation sources.

1.3.2 Use of test methods

In some cases, various types of standards have been used for specifications. In the case of applying these test methods, it should be noted that this standard is not a filter specification but rather a standard method of test for filter performance. In order to assist in selecting appropriate tests that may be used to ensure that a given specification may be met, Table 1 is provided as a suggested guidance. However, testing should not be limited to the selection menu, but should be based on available information and specification. For instance, if a specification states a method (e.g., MIL-STD-220B), then it would only qualify as a QA test and would not necessarily meet the intended specification.

2. Normative references

The following referenced documents are indispensable for the application of this standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI/IEEE Std C63.2TM, American National Standard for Electromagnetic Noise and Field Strength Instrumentation, 10 Hz to 40 GHz—Specifications.³

ANSI Z540.1, Calibration Laboratories and Measuring and Test Equipment General Requirements.

ANSI Z540.2, U.S. Guide to the Expression of Uncertainty in Measurement.

CISPR 17, Methods of Measurement of the Suppression Characteristics of Passive Radio Interference Filters and Suppression Components.⁴

IEEE Std 299TM, IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures.^{5, 6}

IEEE Std C95.1TM, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.

IEEE/ASTM SI 10TM, IEEE/ASTM Standard for Use of the International System of Units (SI): The Modern Metric System.

ISO/IEC 17025, General Requirements for the Competence of Testing and Calibration Laboratories.⁷

MIL-STD-220B, Method of Insertion Loss Measurement.⁸

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⁴CISPR documents are available from the International Electrotechnical Commission, 3, rue de Varembe, Case Postale 131, CH 1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch/>). They are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

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⁸MIL publications are available from Customer Service, Defense Printing Service, 700 Robbins Ave., Bldg. 4D, Philadelphia, PA 19111-5094.

NIST Special Publication 330, The International System of Units (SI), Barry N. Taylor, ed.⁹

NIST TN 1297, Guidelines for Evaluating and Expressing Uncertainty of NIST Measurement Results, Barry N. Taylor and Chris E. Kuyatt.

3. Definitions

For the purposes of this standard, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B6] or Annex I should be referenced for terms not defined in this clause.

3.1 buffer networks: A multiport network used for inductor saturation tests. They are acceptable as quality control/quality assurance (QC/QA) tools for production testing. (CISPR 17 and MIL-STD-220B).

3.2 decibel (dB): A unit of measure for the ratio of two amounts of voltage, current, and power. With E_1 and E_2 designating the two amounts of voltage, and n the number of decibels denoting their ratio as follows:

For voltage, the ratio is computed:

$$n(\text{dB}) = 20 \log \left(\frac{E_1}{E_2} \right)$$

where

- n is the number of decibels
- E_1 is the measured load voltage with the filter in the circuit
- E_2 is the measured load voltage with the filter out of the circuit

For current, the ratio is computed:

$$n(\text{dB}) = 20 \log \left(\frac{I_1}{I_2} \right)$$

where

- n is the number of decibels
- I_1 is the measured load current with the filter in the circuit
- I_2 is the measured load current with the filter out of the circuit

For power, the ratio is computed:

$$n(\text{dB}) = 10 \log \left(\frac{P_1}{P_2} \right)$$

where

- n is the number of decibels
- P_1 is the measured load power with the filter in the circuit
- P_2 is the measured load power with the filter out of the circuit

⁹ NIST publications are available from www.nist.gov/.

3.3 displacement power factor: The ratio of the active power of the fundamental wave, in watts, to the apparent power of the fundamental wave, in volt-amperes. This is the cosine of the phase angle by which the fundamental current lags the fundamental voltage. This is the power factor as seen in utility metering by watt-hour and var-hour meters, assuming that the ac voltages are sinusoidal.

3.4 distortion factor (harmonic factor): The ratio of the rms of the harmonic content to the rms value of the fundamental quantity, expressed as a percent of the fundamental, as shown in the following equation:

$$df = \left[\sum_{k=2}^n \frac{A_k^2}{A_1^2} \right]^{1/2}$$

where

- A_1 is the rms value of the fundamental component
- k is a number from 2 to n
- A_k is the rms values of the k th harmonic components

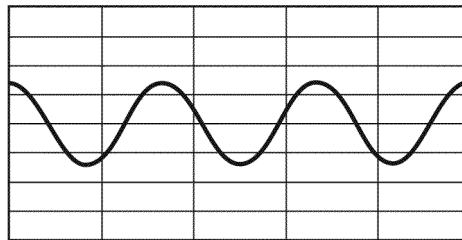
3.5 error (relative): The ratio of an error to the correct value.

3.6 insertion loss: The ratio of voltages, current, or power, at a given frequency, appearing across the line immediately beyond the point of insertion, before and after insertion of the filter under test. (CISPR 17)

3.7 isolation attenuators: An isolation attenuator should be a resistive T network having a 50-ohm input impedance and a 50-ohm output impedance. The attenuator shall have a minimum insertion loss of 6 dB to 10 dB measured in a 50-ohm system. Looking into either end of each attenuator with the other end terminated into 50 ohms, the voltage standing-wave ratio (VSWR) shall be a maximum of 1.25 to 1 from dc to 10 GHz. The power rating of the attenuator should be such that when the system is subjected to the maximum signal power, it does not degrade from heating. These attenuators are for the purpose of obtaining a standard 50-ohm termination for all attenuation measurements. (MIL-STD-220B).

3.8 linear load: A load that draws a sinusoidal current wave when supplied by a sinusoidal voltage source.

NOTE—A typical current waveform for a linear load is shown in the following figure.¹⁰



Example of current drawn by linear load

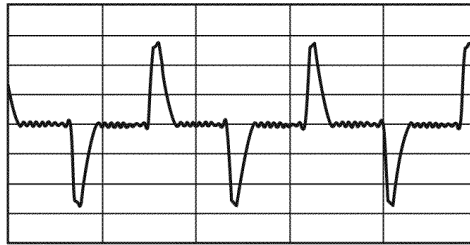
3.9 metric units: A system of basic measures that are defined by the International System of Units based on “Le Système International d’Unités (SI),” of the National Institute of Standards and Technology. (NIST Special Publication 330).

3.10 nonlinear load: A load that draws a nonsinusoidal current even when supplied by a sinusoidal voltage source. An electrical device that in steady-state operation has impedance that varies during the cycle of the input voltage waveform.

NOTE 1—See IEEE Std 1250™-1995 [B7].

¹⁰Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

NOTE 2—A typical current waveform for a nonlinear load is shown in the following figure.



Example of current drawn by nonlinear load

3.11 rating: The designation of an operating limit for a device.

NOTE—Such operating characteristics as current, voltage, frequency, etc., may be given in the rating.

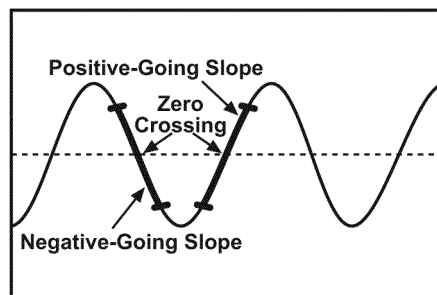
3.12 total harmonic distortion (THD): *See:* **distortion factor.**

3.13 true power factor: *See:* **displacement power factor.**

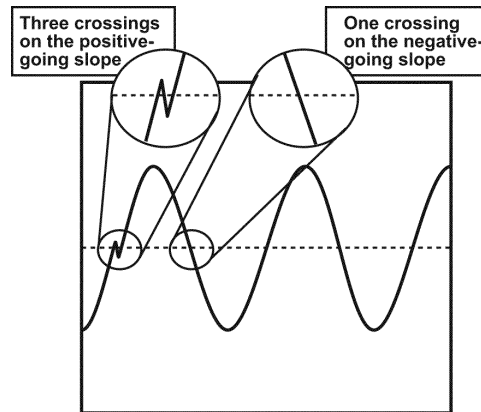
3.14 true rms: Refers to the use of a meter that displays an rms value calculated from the average of instantaneous readings rather than an rms value that is calculated from an average reading. The difference is that the instantaneous method allows the meter to display the correct rms value for waveforms that are not sinusoidal shaped while the other does not. The square root of the mean value of the square of the voltage values during a complete cycle.

3.15 zero-crossing: A waveform that is graphed on a rectangular-coordinate system is said to have a zero-crossing when it passes through a horizontal line drawn through the origin (x-axis). A sinusoidal-shaped, 60 Hz waveform has two zero-crossings per period, one per slope.

NOTE—See the following figures.



Sinusoidal-shaped waveform showing location of zero-crossings



Sinusoidal-shaped waveform showing details of zero-crossings

4. Safety

Many of the tests described in this standard are inherently hazardous. The safeguards for personnel and property described in this clause are essential. All testing shall be conducted by technically qualified personnel who are knowledgeable about the test and measurement equipment, and filters under test, and aware of the hazards of such testing.

4.1 Stored capacitor energy

Capacitors in a test circuit or a device under test might retain stored energy in the form of electric charge. If a filter is required to have bleeder resistors as part of its design, those resistors shall be installed and functional when testing the filter in accordance with this document. Suitable bleeders or short-circuiting devices should be used to ensure operator safety against any such trapped charge after a filter is de-energized.

4.2 RF hazards

Some tests in this standard will result in electromagnetic fields that are potentially dangerous to personnel. The permissible exposure levels of IEEE Std C95.1 shall not be exceeded in areas where personnel are present. Safety procedures and devices shall be used to prevent accidental exposure of personnel to RF hazards. During these tests, precautions must be implemented to avoid inadvertent exposure of personnel to fields.

4.3 Voltages and currents

The voltage and current levels generally associated with testing radio interference filter, especially the power-line type filters, may be lethal and are well above those considered safe. Precautions should be taken when connecting or disconnecting equipment, filters, and power sources to avoid the potential for electric shock.

5. Measurement instrumentation

5.1 General

The use of proper measurement instrumentation is critical to obtaining accurate and reproducible test results. Various measuring accessories may be needed during a test depending upon the particular measurements to be performed. RF sweep methods are preferred, and point-to-point measurement methods are discouraged.

5.2 Calibration of measuring equipment

A calibration system in accordance with ANSI Z540.1 or other equivalent organizations shall be used and maintained. The calibration of the instrumentation shall be verified frequently to ensure its accuracy. Adjustments may be made and correction factors applied where applicable as long as they are documented.

In addition to the measuring instrumentation, cables, LISNs, voltage and current probes, test facility, etc., are to be checked and verified as necessary on a regular basis to ensure accuracy of the test results and checked frequently for deterioration. Shielded cables used for testing must exhibit a shielding effectiveness that is at least 10 dB greater than the expected filter performance over the frequency range of interest. This will help to ensure that measurements less than 100 dB may be performed accurately (e.g., double-shielded cables providing 99% shielding coverage such as a RG-223/U cable equivalent or better).

5.3 Measurement tolerances

During electrical measurement processes, tolerances will vary with the device under test and what parameter is being measured. Unless otherwise stated for a particular measurement, the tolerance of the following parameters (items a through d) shall be as follows:

- a) Frequency: $\pm 2\%$

NOTE—Accuracies of $\pm 0.1\%$ may be obtained if desired based on bandwidth resolution and sweep rate.

- b) Amplitude (at a measurement receiver): ± 2 dB
- c) Amplitude (of a measurement system that includes measurement receivers, transducers, cables, etc.): ± 3 dB
- d) Time (waveforms): $\pm 5\%$

6. Measurement uncertainty

6.1 General

Measurement uncertainty can be caused by many factors. The total uncertainty may have several contributors, including (but not limited to) the test equipment used and its calibration accuracy, signal loss of test interconnection cables (which varies on a per-unit length basis by frequency), type and number of connectors in the signal path, and the quality of the interface connection between the filter under test and the measurement setup. Cable resonances may also cause uncertainty.

6.2 Calculation of measurement uncertainty

Annex H discusses how uncertainty may be estimated using an example for the test method described in 10.1. Standard uncertainty, combined standard uncertainty, and expanded uncertainty are discussed.

7. Test equipment and minimum specifications

Test equipment and minimum specifications for performing tests are discussed in this clause. Measurement equipment shall be as specified in the individual test procedures of this standard. EMI measuring instrumentation characteristics may be found in ANSI/IEEE C63.2.

7.1 AC power source

An ac power source is required to supply power to linear and nonlinear loads, whose characteristics shall be a voltage equal to or less than the filter voltage rating. The power source shall be tested and supporting documentation attached to verify that the true-rms voltage of the power source does not change by more than 5% as the load (linear and nonlinear) is varied from 0% to 100%. The waveform of the power source voltage shall not have more than two zero-crossings per period as the load is varied from 0% to 100%. The use of 50 Hz or 60 Hz is satisfactory for filters rated at 50/60 Hz. For filters rated at other ac line frequencies, the ac power source shall provide power to the filter on at least one of the rated working frequencies.

7.2 Alternating current source

An alternating current source is required to supply an ac current whose characteristics shall be equal to 1.4 times the filter full rms current rating or equal to the full dc current rating if the filter is dc-rated only. The current source shall be tested and supporting documentation attached to verify that the regulation of the alternating current source is less than 2% for 1.4 times the full-rated load current. The alternating current source shall be floating and not connected to ground.

7.3 DC power source

A dc power source is required to supply power to linear and nonlinear loads, whose characteristics shall be a voltage equal to the filter dc voltage rating. The power source shall be tested and supporting documentation attached to verify that the dc power source voltage ripple factor is less than 2% for 1.4 times the full-rated load current. The dc power source shall be floating and not connected to ground.

7.4 Direct current source

A direct current source is required to supply a dc current whose characteristics shall be equal to 1.4 times the filter full rms current rating or equal to the full dc current rating for dc rated filter only. The power source shall be tested and supporting documentation attached to verify that the direct current source regulation is less than 2% for 1.4 times the full-rated load current. The direct current source shall be floating and not connected to ground.

7.5 Ammeter

An ammeter is required to measure and display the amount of current through the load. It must have the ability to measure true-rms current at three times the filter's rated current.

7.6 Buffer networks

Buffer networks are used for inductor saturation tests. The use of buffer networks is discouraged for design testing and verification of the inductor performance below frequencies of 100 kHz, where RF current injection techniques are preferred for filter evaluation. Buffer networks are acceptable as QC/QA tools for production testing and may come in many variations to accommodate the specified frequency band. Figure 1

illustrates a generic example of a buffer network, which should extend to 10 kHz for QC/QA purposes to better evaluate inductor saturation.

7.7 Differential voltage probes

Differential voltage probes are required to safely measure the line voltage and must be able to withstand the filter's rated voltages.

7.8 Dynamic range

The dynamic range is the amplitude difference between the maximum input level allowing linear operation of an instrument (or a test system) and the minimum signal that can be discerned by the instrument (or the test system). The range can be demonstrated by comparing the reference level to the measuring equipment noise floor. The reference level shall be observed to be a minimum 6 dB above the noise floor.

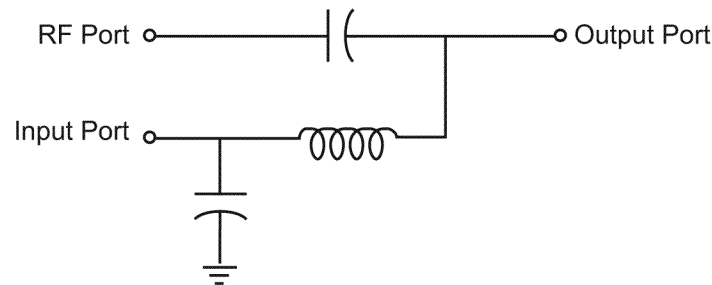


Figure 1—Generic example of a buffer network

7.9 Ground plane

The filter shall be installed on a ground plane that simulates the actual installation. If the actual installation is unknown or multiple installations are expected, then a metallic ground plane shall be used. When a ground plane is not present in the filter installation, the filter shall be placed on a nonconductive surface.

7.10 Impedance-transforming networks

Impedance-transforming networks are typically comprised of a set of wideband transformers whose turns ratio is 1.41:1 and 22:1. These networks are used to establish 50 ohms/0.1 ohms and 50 ohms/100 ohms impedance transfers. Refer to Schlicke [B17] and CISPR 17 for design guidance.

7.11 Line-impedance stabilization network

A LISN is a standard load impedance used to ensure repeatability and comparability of EMI measurements. It is an interface inserted at the measurement point between the EMI source and the power source (i.e., mains). It is sometimes referred to as an *artificial mains network* and may be used as a buffer network for ac/dc voltage sources and QA testing as a semi-realistic matched source impedance. Figure 2 illustrates the schematic for a typical 50 μ H LISN.

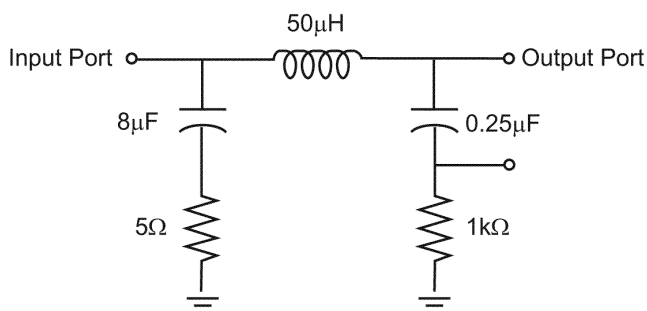


Figure 2—Specified typical LISN for realistic impedance testing from 100 kHz to 30 MHz

7.12 Linear load

Examples of linear loads are tungsten heaters, wire-wound ceramic resistors, or equivalent. They are to be used to draw sinusoidal-shaped current through the filter under test. The linear load shall be sized to draw the load current called for and shall exhibit a power factor between 0.95 lagging and 0.95 leading.

7.13 Nonlinear load

An example of a nonlinear load is a full-wave bridge-rectifier type, followed by a capacitor, as illustrated in Figure 3. This load shall be used to draw a nonlinear current through the filter under test. The capacitor and resistor shall be sized to draw current with a crest factor of 2.2 ± 0.2 (refer to Annex C) at the full-load rms rating of the filter when connected to the standard source (filter not connected). The crest factor is defined as the peak amplitude of the current divided by the rms value of the current, as show in Equation (1):

$$cf = \frac{I_{pk}}{I_{rms}} \quad (1)$$

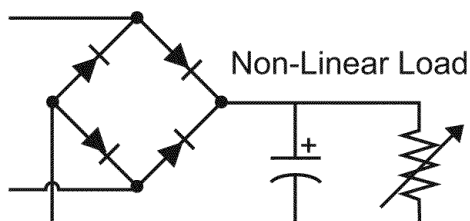


Figure 3—Simplified schematic of a nonlinear load

7.14 Oscilloscope

An oscilloscope is required to measure, display, and plot the recorded voltage waveforms. The oscilloscope should be dual channel with reading capability and include a minimum 1 MHz bandwidth.

7.15 Power amplifier

A power amplifier is a device used to amplify a signal to a level representative of a power signal. Several amplifiers may be required to amplify a signal from the signal generator. The amplifier must be able to amplify the signal to a level large enough to be injected on one side of the filter and measured on the other.

7.16 Power analyzer

A power analyzer is required to measure true-rms voltage, crest factor (peak voltage), and total harmonic distortion (THD). The analyzer must be able to measure up to the 13th harmonic.

7.17 Attenuators, 100 dB

An attenuation pad is used to provide the desired attenuation reference line, with respect to the filter, on the spectrum. As a minimum, the attenuator should have the following characteristics: a 1 W minimum power rating and calibrated to 100 dB over the specified frequency range. Attenuators may be fixed (i.e., an attenuation pad) or selectable (i.e., programmable attenuators).

7.18 RF matching network

An RF matching network may be required to improve the power transfer between the RF amplifier and RF current injection probe.

7.19 RF bulk current injection probe

An RF bulk current injection probe (BCIP) is used to inject large amounts of RF current onto the power conductor. Operating characteristics shall be as a minimum over the specified frequency range and a power-handling capability of 100 W (minimum).

7.20 RF current transformers

An RF current transformer (CT) is a high-frequency current probe that fits around a power conductor and is used to measure RF currents. As a minimum operating characteristic, the CT shall have a measurement range to accommodate the specified frequency range and a current rating of three times the filter rating.

7.21 RF injector

An RF current injector can be defined as any device such as a current injection probe, capacitive injector, and/or an RF switching current source.

7.22 Shielded enclosure

A shielded enclosure is required to shield the measurement side of the test setup from external radiated and conducted noise. An enclosure should be tested and approved per IEEE Std 299 to 10 dB below the lowest desired attenuation measurement and the specified frequency range, and at least 6 dB above the displayed noise floor.

7.23 Spectrum analyzer or network analyzer

A spectrum analyzer or network analyzer is recommended to measure and display the effective attenuation of a filter. The measuring instrument should be operational over at least the required frequency test range of the filter and have a dynamic range at least 6 dB greater than the expected insertion loss. Depending upon the test, two or more analyzers may be required.

7.24 S-parameter test set

S-parameters are called *scattering parameters*. They are a set of parameters describing the transmission, scattering, and reflection of traveling waves when a network is inserted into a transmission line. S-parameters are normally used to characterize N-port networks at higher frequencies, where simple models valid at high frequencies cannot be applied. S-parameters are normally measured as a function of frequency, so when looking at the formulae for S-parameters, it is important to note that frequency is implied and that the complex gain (i.e., magnitude and phase) is also assumed. For this reason, S-parameters are often called *complex scattering parameters*. They can be measured directly with network analyzer systems, which include S-parameter test sets. For information on S-parameter measurement test sets, refer to Annex D and Kraemer [B10].

7.25 Tracking generator

In conjunction with a spectrum analyzer, a tracking generator produces a signal whose frequency precisely tracks the tuning frequency of the spectrum analyzer. The tracking generator should have the following minimum specifications: a minimum tuning range from 9 kHz to 1 GHz and a 0 dBm source output level.

8. Test facilities

8.1 Standard testing conditions

Any comparison of the test results between two or more individual filters, or between results obtained in different laboratories, will be valid only if the tests have been performed under identical test conditions. If the tests are conducted primarily for exploratory purposes, consistency in environmental test conditions is not as important. The following test conditions are typical of accepted laboratory environments for conducted disturbances:

- a) Temperature: $25 \pm 5^{\circ}\text{C}$
- b) Relative humidity: less than 85%
- c) Sinusoidal test voltage: sinusoidal waveform, less than 5% THD
- d) Voltage: 120 V (rms), unless otherwise required, tolerance: $\pm 1\%$
- e) Frequency: 60/50 Hz, unless otherwise required, tolerance: ± 2 Hz (This tolerance allows for the use of generators.)

8.2 General operating conditions

All test areas shall be clean and free from clutter. The test setup shall be arranged in such a way that activities can be viewed and equipment connections clearly traceable by a visual inspection.

8.3 Grounding

The signal grounding connections must be made at each end of a filter and not through a common point on a conductor extending from a filter. As with many filters, the attenuation characteristics require that reproducible high-attenuation measurements be made on the surface of the filter enclosure. Grounding of the test equipment and the filter to a ground reference plane is very important for the accuracy of measurements of the low- and high-end frequency bands to eliminate spurious background noise and to ensure proper RF return paths. When external terminals, connector pins, or equipment grounding conductors are available for safety ground connections and are used in the actual installation, they shall be connected to the ground plane. Refer to MIL-STD-461E-1999 [B15], subclause 4.3.8.6.1, for arrangement and length.

8.4 Regulatory agency restrictions

Some of the tests require high-level signals to be generated that could interfere with normal frequency assignments granted by the local regulatory agencies such as the Federal Communications Commission (FCC) and other agencies. All such testing should be conducted within a shielded enclosure.

8.5 Screened equipment and shielding requirements

It is recommended that the test be performed in a screen room. The filter and test equipment should be secured and tested on a ground reference plane as a minimum requirement. If it is found that the ambient background noise is high, then it may become necessary to construct a Faraday cage for the filter under test and the measuring equipment, whichever is easier. For example, if it is found that the signal generator generates excessive interference, the offending equipment should be screened within a Faraday-shielded enclosure or Faraday cage. If noise still continues to be a problem, then the filter and measuring equipment should be placed inside a screen room. If the problem continues, place the filter and measuring equipment on the inside of the screen room and the generator source on the outside.

8.6 RF test fixture and mounting requirements

The main purpose of the RF test fixture is to ensure that the RF connector is maintained in a stable and RF tight-sealed position throughout the test. Depending on the design of the filter, custom connectors and fixtures may be constructed and used. The filter and test equipment should be secured and tested on a ground reference plane. If the filter's intended installation does not support a ground plane, the filter shall be tested on an insulated surface.

8.7 Source impedance

Impedance (Z) is the resistance of a circuit to alternating current. Technically, impedance is the total opposition (including resistance and reactance) that a circuit has to passing alternating current. A high-impedance circuit tends to have low current. A low-impedance circuit tends to relatively have high current. The impedance of a voltage or current source is the impedance as seen from its terminals or from the load terminals of a branch circuit. If the source impedance equals the load impedance, this is called *matching impedances*. It results in maximum power transfer from the source to the load. The source shall be capable of delivering inrush current of at least eight times the rated current.

8.8 Test equipment noise floor level

During testing, the noise floor level should be measured with the filter removed, and the test fixture should be in the bypass mode. All auxiliary equipment should be turned on. The noise floor shall be at least 6 dB below the allowable specified limits for the filter under test. When measurements are made outside a

shielded enclosure, the tests shall be performed during times and conditions when the noise floor is at its lowest level. The noise floor level at the time of this measurement shall be recorded.

It is recommended that the isolation transformer meeting the requirements of the listed power source description in Clause 7 of this standard be used for powered testing. The use of isolation transformers may be necessary to reduce line noise and to ensure that accurate measurements are performed when using RF current injection techniques, particularly in the frequency band of 100 Hz to 100 kHz. The isolation transformer shall be sized to provide at least eight times the inrush current of the highest current rating.

8.9 Attenuators, phase splitters, power splitters, and network matching pads

Attenuators that provide isolation are typically specified as having a 50-ohm impedance and a 10 dB loss. The 50-ohm input requirements should be maintained to match the 50-ohm outputs of signal generators and standard instrument that measure RF signals. Fifty-ohm matching pads and the 10 dB requirement should be used for non 50-ohm impedance test equipment to ensure that the voltage levels are maintained and a balanced measuring bridge is established. For other test methods and/or requirements, the input and output of the measuring bridge should match the equipment impedance to prevent overloading of the generator and provide correct signal measurements. The 10 dB requirement may be lifted and other values may be used if reasonable accuracy is maintained within the test setup.

Phase and power splitters and other specialized RF components may be required for network analyzers and custom test fixtures. Refer to CISPR 17 regarding the specification and construction of the mismatched-impedance networks. These networks may be of the resistive type, high-frequency toroid transformer type, or a combination network type, which will yield the desired impedance and pass-band ratio. For balanced systems, a transforming network may be used. An example of this would be a matching transformer with the desired impedance and relatively flat pass band, such as 600 ohms. These devices must meet the power and frequency requirements, and their losses must be recorded and compensated for in the reported data.

8.10 Lead dress

In all test fixtures, input and output leads should always be separated. All coaxial cables and power leads shall be spaced at least 5 cm above the ground plane when it is practical. All cables should be doubly shielded and as short as practical. Cables used to connect a tracking signal generator to the input of a filter and the output of a filter to a spectrum analyzer should be of equal lengths. In addition, cables used in the calibration process when using attenuation pads should be of equal lengths.

9. Divisions of frequency ranges and recommended sensitivity

The frequency range of 100 Hz to 10 GHz shall be divided up into multiple bands to ensure that no poles or zeroes are missed in the filter-measurement process due to the resolution of the measurement. The frequency bands selected may depend on equipment specification/ability and/or specified from predetermined requirements. Calibration of each band and bandwidth used during testing must be verified and documented. If the measurement range is broken into several bands, then a minimum frequency overlap of 2% is recommended. The recommended minimum sensitivity is 6 dB below the lowest specified and demonstrated attenuation requirement. A minimum number of 400 points per scan is allowed for each bandwidth only if accuracy is demonstrated and if the resolution determined is sufficient for the specified requirements. If frequency stepping is used, the minimum number of steps shall be as specified in the test method.

The sweep rate, start frequencies, and stop frequencies will be such that the equipment will be able to perform with accuracy and have the dynamic range of the specification. The resolution bandwidth should be set to the lowest possible setting, and the sweep time extended to the maximum setting for accuracy.

Using swept frequency methods is encouraged. The equipment used to perform a sweep should have tracking ability to ensure that the bandwidth and amplitude scaling is maintained and artificial attenuation is not introduced by the instrument as a result of a non-tracking bandwidth. The recommended equipment to perform this test is a spectrum analyzer and tracking generator whose bandwidth is set adequately for the test frequency range specified. Use of network analyzers or similar equipment is acceptable, including calibrated receivers.

10. Required measurement methods

On occurrences, standards have been used for specifications. It should be noted that this standard is not a specification but rather a standard method of test. In order to assist in selecting appropriate tests that may be used to ensure that a given specification may be met, Table 1 is provided as a suggested guidance, but testing should not be limited to the selection menu but should be based on available information and specification. For instance, if a specification states a method (e.g., MIL-STD-220B), then the test would only qualify as a QA test and would not necessarily meet the intended specification.

Table 1—Test applicability matrix

Purpose of test	Test subclause							
	10.1	10.2	10.3	10.4	10.5	10.6	10.7	10.8
First article	X	X	X	X	X		X	
QA	X	X						
Matched-impedance and balanced networks	X		X					
Generic filter comparison	X		X					
Low-frequency performance (below 100 kHz)	X			X			X	
High-frequency performance (above 100 kHz)	X	X			X	X		
Simulation and design	X		X					X

The following test methods are required for testing the suppression capability of RFI filters in the frequency range from 100 Hz to 10 GHz. Some of the methods are based on 50-ohm matched-impedance tests found in many different standards and requirements. Revising these methods increases the efficiency for QA and estimated performance evaluations for both common- and differential-mode filter circuits with the addition of incorporating waveform quality into filter performance. The following descriptions explain test setups, rationale, applicability, and basic procedures. The RF test methods are broken into the following categories:

- Quality assurance—No load (10 kHz to 1 GHz) (see 10.1)
- Quality assurance—Loaded (10 kHz to 20 MHz) (see 10.2)
- RF characteristics mismatched impedance—No load (100 kHz to 30 MHz) (see 10.3)
- Variable source impedance attenuation measurement (100 Hz to 100 kHz) (see 10.4)
- Attenuation measurement (100 kHz to 30 MHz) (see 10.5)
- Aperture leak test by electric fields (1 GHz to 10 GHz) (see 10.6)
- Voltage drop and waveform quality test (linear/nonlinear loading) (see 10.7)

- h) S-parameter measurement (100 Hz to 30 MHz) (see 10.8)

10.1 Quality assurance testing—No load (10 kHz to 1 GHz)

10.1.1 Purpose

The no-load 50-ohm matched-impedance method will be used for QA filter testing to verify the insertion loss characteristics from 10 kHz to 1 GHz under 50-ohm impedance conditions. The purpose of this test is to determine component malfunctions or assembly error. This is extendable in frequency range, if so desired. This test uses typical 50-ohm impedance methods for common-mode measurements with the exception of the differential mode where unbalanced-to-balanced networks may be used. For differential-mode measurements, Figure 4 illustrates the typical approach.

10.1.2 Rationale

To ensure that the workmanship and the specific components of a production filter will meet the same specifications from the first article design, a QA test is needed. This test may be used as a production test once the first article sample has met its performance requirements. Samples received from the field may have this test performed and the results compared against factory data to determine the integrity of the filter.

10.1.3 Materials/equipment

The recommended equipment to perform this test is a spectrum analyzer and a tracking generator set whose frequency coverage extends from 10 kHz to 1 GHz. The use of network analyzers or similar equipment is acceptable including calibrated receivers. An RF test fixture constructed for the filter under test is also needed. Materials/equipment include the following:

- a) Spectrum analyzer (operating in the specified frequency band)
- b) Tracking generator (operating in the specified frequency band)
- c) Variable attenuator up to 100 dB
- d) Two 10 dB pads
- e) Two each unbalanced-to-balanced networks (either resistor or transformer or hybrid configuration may be used)

10.1.4 Test setup/circuits

Figure 4 shows the typical test setup for a common-mode filter to measure common-mode insertion loss. The test setup is generic in nature, but caution and care are required to ensure that there are no undesired ground return paths or RF leakage in the RF test fixture during the test.

Figure 5 shows the typical test setup for a common/differential (mixed mode) mode two-line filter to measure common-mode insertion loss. The test setup is generic in nature, but caution and care are required to ensure that there are no unnecessary ground return paths or RF leakage in the RF test fixture during the test.

Figure 6 shows the typical test setup for a common/differential (mixed mode) mode two-line filter to measure differential-mode insertion loss. The test setup is generic in nature, but caution and care are required to ensure that there are no unnecessary ground return paths or RF leakage in the RF test fixture during the test.