# Improving the way we measure insertion loss

## A proposed set of new test methods may provide more accurate attenuation data.

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MANY COMMERCIAL AND INDUSTRIAL ELECtrical environments contain equipment that is sensitive to radio-frequency (RF) interference. Theft detectors, digital sensors, and medical-telemetry systems have all been known to malfunction in the presence of RF interference. To prevent RF signals from entering a facility via the power lines, a power-line filter can be installed between sensitive loads and the power source. As shown in Figure 1, a power-line filter passes frequencies in its pass band (including the frequency of the power source, either 60 or 50 Hz) but blocks frequencies in its stop band (including the frequencies of RF interference).

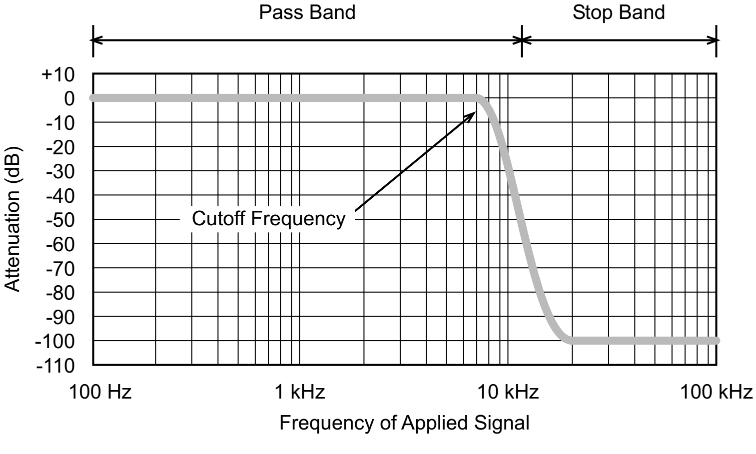

*Figure 1. Attenuation plot for an ideal power-line filter.*

The attenuation plot in Figure 1 is entirely conceptual; the *in situ* performance of a power-line filter will certainly fail to meet this ideal and may even fail to meet the performance predicted by the manufacturer's specifications. Therefore, power-line filters are routinely tested to determine their actual performance in the field. One of the parameters of filter performance is *insertion loss,* which is the difference between the level of an interference signal without and with a filter in the circuit.

The principal standard currently used to measure the insertion loss of a power-line filter is MIL-STD-220, *Method of Insertion Loss Measurement.* This standard is used to measure the attenuation performance of a filter that is connected to a 50-Ohm power source and a 50-Ohm load—a setup termed "matched impedance." This standard was originally developed in 1952 to measure the insertion loss of filters used to mitigate radio interference in mobile communication systems. Since 1952, MIL-STD-220 has been widely used to create general performance specifications for all types of filters. The problem arises from the application of MIL-STD-220 to determine the insertion loss of a power-line filter used with an unmatched source and load. In the real world, power-line filters must operate under a wide range of impedances (see Schlicke 1976), as well as a wide range of load types.

Unfortunately, MIL-STD-220A has become the industry norm, largely because of the lack of a viable alternative. The problems associated with the test methods defined in MIL-STD-220A have been known since it was first used. In fact, the standard itself admonishes users about its limitations. Nevertheless, this standard has been referenced in other standards and has been applied in thousands of applications throughout the military and in commercial industries to characterize power-line filters. An example of this trend in the military industry is found in the application of MIL-PRF-28861B-1994, *Filters and Capacitors, Radio Frequency/Electromagnetic Interference Suppression, General Specification for*. This MIL document calls for measurements of insertion loss to conform to MIL-STD-220.

In efforts to meet today's strict requirements for electromagnetic compatibility, many military standards such as MIL-STD-461E–2000, *Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*, have undergone significant change. Still, most of these standards assume the accuracy of MIL-STD-220. Although MIL-STD-220A was revised in 2000 to MIL-STD-220B (some describe this revision as a facelift), its test methods are virtually unchanged. MIL-STD-220B describes itself as a quality-control standard. The standard itself emphasizes that its test methods are not intended to predict the actual performance of filters that are used in mismatched-impedance situations. Yet, testers continue to use this standard to predict the behavior of filters in the field.

Many other standards have been developed since the creation of MIL-STD-220A. Two examples of standards used to measure power-line filters are SAE ARP 4244–1998, *Recommended Insertion Loss Test Methods for EMI Power Line Filters,* and CISPR 17 1981, *Methods of Measurement of the Suppression Characteristics of Passive Radio Interference Filters and Suppression Components*. The authors of these standards have attempted to correct the problems associated with using MIL-STD-220A. At best, these standards address the issues pertinent to the requirements for a particular organization or application but do not directly address the root of the problem—test methods incorrectly defined for real-world applications with mismatched-impedance conditions.

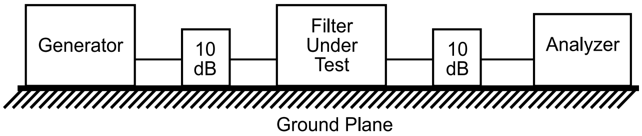

*Figure 2. Unloaded test setup according to MIL-STD-220B.*

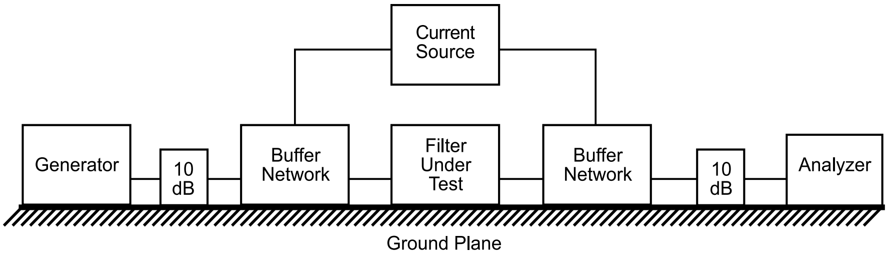

*Figure 3. Loaded test setup with buffer networks according to MIL-STD-220B.*

## MIL-STD-220B: TEST SETUPS

Figure 2 illustrates the typical test setup used for performing the matched-impedance testing described in MIL-STD-220B. Note that for this test, the filter is not powered or under load. The generator in the test setup injects an RF signal (in steps from 150 kHz to 1 GHz); the 10-dB attenuators provide matched impedances for the generator and analyzer; and the spectrum analyzer measures the RF signal. Measurements are made with the filter in the circuit and out of the circuit (by removing the filter and inserting a conductor). The difference between the two measurements is the insertion loss at a particular frequency, indicated as a single point in an attenuation plot such as the one shown in Figure 1.

Figure 3 illustrates another test method defined in MIL-STD-220B, in which a generic buffer network is used with a current source. As with the earlier unloaded test, this test method requires matched impedances, thus the 10-dB attenuators. Current is applied to each buffer network in a short-circuit configuration. The short circuit is created through the inductive components of the buffer networks and the filter under test. The magnitude of this current is adjusted so that the rating of the filter is not exceeded. Once the correct current through the filter has been established, RF signals are injected into the input of the buffer network; and the resulting attenuated signals are measured at the output of the buffer network, which is similar in design to the one used at the input.

The frequency range for testing filters under load using this method is

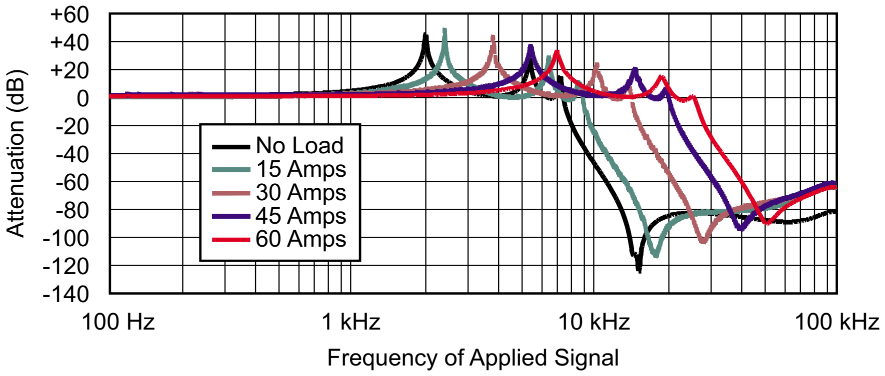

*Figure 4. Effect of inductor saturation under DC current loading.*

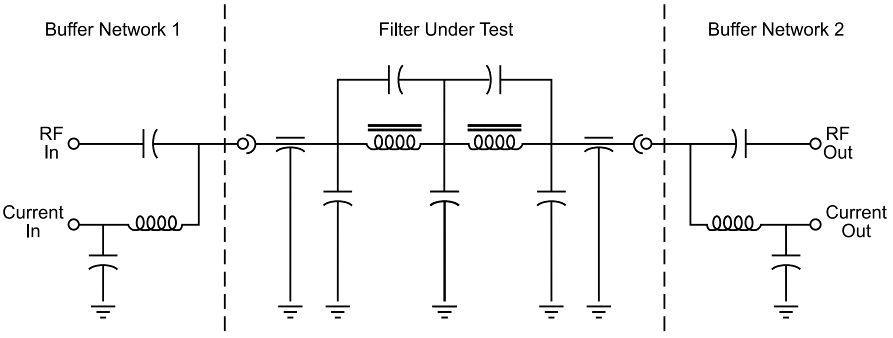

***Figure 5. Buffer network and filter arrangement demonstrating the adding effect of additional LC networks.***

from 100 kHz to 20 MHz. Most power-line filters are designed to reach 100-dB attenuation at about 14 kHz. If testing adheres to the 100-kHz minimum frequency of MIL-STD-220B, then some significant filter behaviors may be missed. For example, as shown in Figure 4, resonances may develop when a filter is loaded. Also, note that the cutoff frequency shifts to the right as the current through the filter increases as a result of inductor saturation. Testing at a minimum of 100 kHz would obscure this behavior.

Not only is the frequency range of a typical buffer network insufficient for accurate predictions of field performance, a buffer network poses yet another problem in measurement accuracy. As shown in Figure 5, a buffer network, when placed in a test circuit, adds additional LC elements to the already complicated network of the filter under test. This situation is analogous to Heizenburg's Uncertainty Principle, wherein the introduction of a measuring device itself introduces an uncertainty in the measured value. With the addition of these LC elements, it is difficult to ascertain their possible effects on the overall filter-attenuation measurement being performed—unless one compensates for the insertion loss of the buffer network within the filter parameters. This compensation would be necessary for each new filter design.

## INACCURACY OF UNLOADED 220B MEASUREMENTS

Matched-impedance testing under no-load conditions should not be used to predict the performance of filters used in an unmatched-impedance environment. An unmatched impedance results in an unbalanced filter network, which, in turn, results in less-than-expected attenuation in the stop band or, in some cases, random resonance or even an amplification in the pass band.

Evaluating filter performance under loaded conditions can cause other problems. For example, MIL-STD-220B is well suited to the evaluation of inductor saturation and uses DC current in this process. As the inductor becomes saturated, it loses most of its inductive properties. This effect varies according to core construction and the core material chosen. The loss of inductance caused by saturation alters the attenuation properties of the filter at frequencies below 100 kHz. As shown in Figure 4, the cutoff frequency increases as the core approaches saturation. In addition, the gains from 2 kHz to 7 kHz vary as a function of filter load. These filter characteristics may not be detected using MIL-STD-220B.

## INACCURACY OF LOADED 220B MEASUREMENTS

Although the application of current through buffer networks seems like a reasonable way to predict the attenuation performance of a powered filter, it still does not account for realistic source and load impedances. More often than not, when a filter is tested with a load, the load is usually resistive. Fifty years ago, using a purely resistive load in a filter test may have been an acceptable method because most building wiring systems powered linear (passive) loads, such as motors. Today, however, silicon technologies permeate the electrical environments where power-line filters are used. For example, motors are rarely connected directly to the power source. Instead, they are controlled by motor drives, which are power-electronic, nonlinear loads.

Millions of end-use devices now rely on nonlinear power supplies. According to Briggs (1994), problems with applying power-line filters to these nonlinear loads are often not fully realized until the filter has failed either in everyday performance or during a catastrophic event, such as the failure of capacitors inside the filter. Figure 6 illustrates the dynamic difference of filter performance under linear and nonlinear loading using a method called "RF current-injection," which can be found in MIL-STD-461. This standard is used to

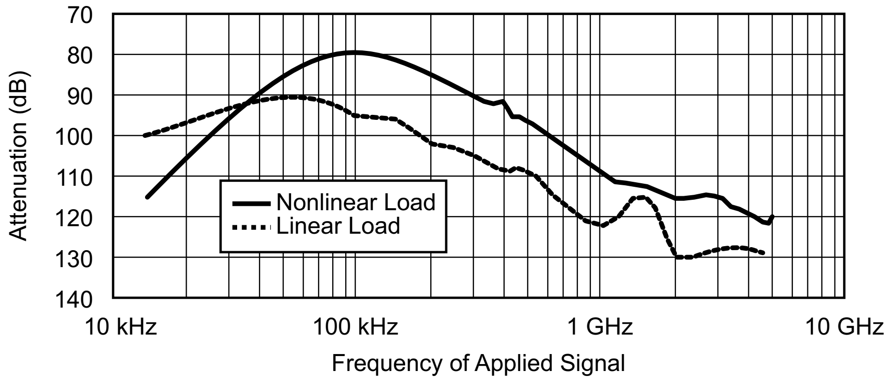

***Figure 6. Effect of inductor saturation of performance under DC current load using strictly RF current injection.***

determine the susceptibility of equipment to conducted RF interference by injecting RF currents into the cables and harnesses of the equipment.

## PROPOSED ALTERNATIVE METHOD FOR MEASURING INSERTION LOSS

To address the shortcomings of traditional insertion-loss testing methods, the IEEE P1560 Working Group is:

1. Evaluating traditional test methods for characterizing the performance of power-line filters.
2. Developing alternative methods that account for real-world conditions.
3. Assembling the accepted and proven test methods into a single standard for the frequency range of 100 Hz to 40 GHz.

Presently, the IEEE P1560 Working Group is preparing a draft standard intended for filters used in industrial and commercial facilities. Although the draft test methods described in this article are subject to change, the direction of the Working Group is promising and worthy of some discussion.

## LOADED AND UNLOADED TESTING

Currently, the draft IEEE P1560 standard specifies no-load and loaded test methods, which are extended down to 100 Hz, as opposed to MIL-STD-220B, which extends down to just 100 kHz for the loaded test method and 150 kHz for the loaded method using standardized buffer networks. IEEE P1560 discourages the use of buffer networks and line-impedance stabilization networks (LISNs) for measurements below 100 kHz and proposes techniques for using RF current injection probes to be utilized from 100 Hz to 100 kHz.

According to Nicholson (1972), LISNs have long been accepted as a standard source impedance for measuring power-line interference. Many specifications and procedures such as MIL-STD-461E, FCC part 15, and CISPR 22 specify the LISN as the source impedance to replicate the commercial power-line impedance in the RF region of the electromagnetic spectrum. However, the LISN is often misused in low-frequency RF measurements. Nicholson points out that the 5-mH LISN is a satisfactory representation of the power-line impedance from 150 kHz to 25 MHz, based on measurements performed at 36 unfiltered commercial power sources. Consequently, LISNs are encouraged as a source impedance only for RF current-injection techniques from 100 kHz to 10 MHz. However, matched-impedance no-load test methods such as MIL-STD-220B should be sufficient for determining performance from 10 MHz to 40 GHz.

Comparing the alternative method to MIL-STD-220B yields some interesting differences. Figure 7 shows the attenuation performance of a filter specified to have an attenuation of 100 dB at 14 kHz. The filter was tested using both the MIL-STD-220B (no load) method and the proposed alternative method. As shown in the figure, the MIL-STD-220B method results in a significantly different predicted attenuation than the alternative method, which uses RF current-injection techniques. The unloaded, MIL-STD 220B method reflects the manufacturer's specifications. However, are these specifications accurate when the filter is installed in a powered circuit?

Attenuation testing using the loaded, alternative method results in a more realistic attenuation plot. At 14 kHz, there is no attenuation. Moreover, the cutoff frequency specified by the manufacturer (6 kHz) has shifted to a higher frequency of about 14 kHz—the expected 100-dB attenuation point.

Also of interest is the fact that the measurement was performed using an extended low frequency of 100 Hz. The frequency range of MIL-STD-220B for no-load testing is 150 kHz to 1 GHz. Attenuation data below 150 kHz cannot be determined by strictly adhering to MIL-STD-220B. Also, the alternative method can reveal resonance conditions that may result in signal gains and, eventually, premature component failures. For example, the alternative method revealed a gain of about 25 dB at just over 4 kHz (in the specified pass band of 100 Hz to 6 kHz), which was not predicted by the 220B method. According to Schlicke (1976), the maximum insertion gain in the pass band should be less than 10 dB.

## WAVEFORM QUALITY TEST

In addition to linear loads, IEEE P1560 considers nonlinear loads and the effects of a filter on waveform quality when the filter is connected to a nonlinear load. The proposed *waveform quality test* requires a nonlinear load. The alternative method calls for a diode bridge rectifier as a standard nonlinear load, which is found in typical nonlinear power supplies.

Figure 8 illustrates the typical voltage distortion from a highly inductive filter. The flat-topping of the waveform may create problems for nonlinear power supplies because the DC-bus capacitors may fail to charge to their rated voltage. The result is a low bus voltage, which can, in turn, result in intermittent startups or nuisance resets of microprocessor-con-

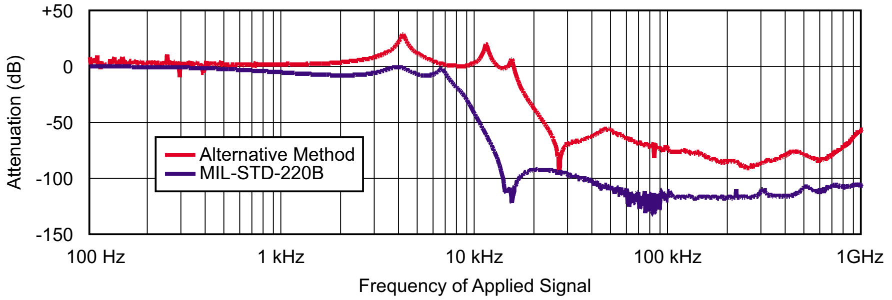

***Figure 7. insertion loss of a generic 50-amp filter measured using MIL-STD-220B (no load) and alternative method (30-amp load).***

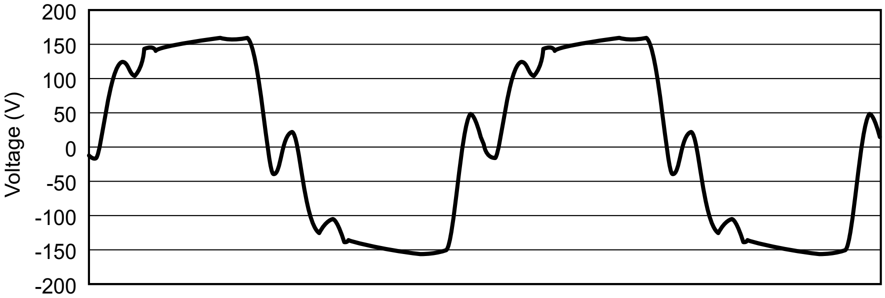

*Figure 8. Voltage flat-topping and ringing due to inline inductive impedance and resonance.*

trolled equipment.

Figure 9 illustrates the typical current drawn by a nonlinear load. Such current contributes to the saturation of inductors inside a connected power-line filter, resulting in a change in the cutoff frequency of the filter. As shown in Figure 8, the impedance added by the series inductance of the filter results in a flat-top waveform. The greater the crest factor for the nonlinear load current, the more prominent the flat-topping becomes. With the increase of the peak value of the nonlinear load current, the filter inductors will eventually saturate; and the low-frequency performance of the filter will be altered because of the "loss" of the inductance in the filter circuit.

According to Mansoor and Key (1998), the effects of nonlinear current on filter performance pose a considerable design problem. To reduce flat-topping, the impedance of the series inductor must be reduced, which in turn forces an overall reduction in the value of the inductors. However, with newer design techniques and core construction, as well as the availability of newer core materials, state-of-the-art power-line filters may perform as designed even when connected to nonlinear loads.

## CONCLUSION

Traditional methods for predicting the insertion loss of a power-line filter are simply not accurate. Often, filters are selected based upon specifications resulting from matched-impedance, no-load testing. The IEEE P1560 standard promises to provide a set of test methods to achieve more accurate attenuation data.

The proposed alternative method relies on techniques of RF current injection, which can determine filter load performance and waveform quality without the confounding effects of buffer networks. Test methods defined in IEEE P1560 will not only give a better indication of the expected performance of power-line filters, but they will also help to avoid many problems associated with testing under nonlinear load and mismatched-impedance conditions, which can affect the performance of power-line filters. Impedance characteristics of the source and load are frequently overlooked when filters are selected. However, when they can be determined, a filter can be designed to operate maximally in a specified environment, particularly where the source and load impedances are not matched. Application of improved test methods for a more accurate determination of the performance of power-line filters will also result in filter components that are less stressed in the field—as well as a reduction in component failures caused by overheating.

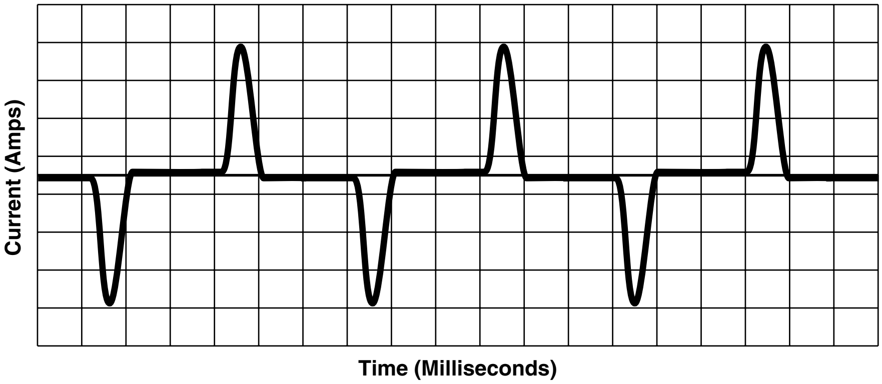

*Figure 9. Current waveform of a nonlinear load.*

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