# Study of High-Frequency Spectrum for 120 V Household Appliances

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# Introduction

In recent years, increasing numbers of tripping incidents involving certain types of household appliances connected to a circuit protected by Class A Ground Fault Circuit Interrupters (GFCI) have been reported. In response to reported interoperability incidents, two task groups (TG) were formed to explore the root causes contributing to unwanted tripping and develop consensus standard proposals to mitigate these incidents.

The TGs are the UL 101 Leakage Current TG, and the UL 943 GFCI TG. UL 101 is the Standard for Leakage Current for Utilization Equipment; UL 943 is the Standard for Ground-Fault Circuit-Interrupters. Each TG is made up of members from the Association of Home Appliance Manufacturers (AHAM), the National Electrical Manufacturers Association (NEMA), UL Solutions and the relevant Standard Technical Panels (STP).

One hypothesis developed by the TG is that tripping the GFCI was caused by high-frequency leakage current flowing through the grounding conductor of the appliance's power supply cord and onto the premises wiring system. In this paper, "high-frequency" mainly refers to frequency harmonics in the spectrum of the ground or differential current, usually in the range of 1 kHz up to 150 kHz. Appliances are transitioning to power conversion technologies by use of high-frequency components in their design — e.g., electronic motor drives, switch-mode supplies, variable speed drives, inverter drives — to become more energy-efficient to meet U.S. Department of Energy (DOE) requirements. Designs incorporating these types of components can introduce high-frequency currents to the appliance grounding conductor and premises wiring system. Class A GFCIs are required to operate at 60 Hz when they sense a differential current between 4-6 mA to meet the requirements in UL 943. Some GFCIs may trip when they sense a current for frequencies above 60 Hz, but there are presently no defined performance requirements in UL 943 for frequencies other than 60 Hz (UL 943 scope per Clause 1.1). It is understood that there are other hypotheses of the root cause of the tripping, but this work focuses on the high-frequency components of the ground current.

To validate this hypothesis, the TGs decided to evaluate the spectral response of both GFCIs and household appliances for frequencies other than 60 Hz. In late 2019, 10 samples of 120 V Class A GFCIs from different manufacturers of various types — i.e., molded case circuit breaker type, receptacle type, panel-mount type — were studied. The high-frequency leakage current threshold was measured from 60 Hz to 50 kHz. This also included three types of field reported appliances reported to exhibit interoperability issues.

In this paper, ground current and the spectral response of three types of household appliances will be presented. The current passing through the grounding conductor is equal to the differential current between the line and neutral conductors, which is the current measured by the GFCI. The goal of this testing was to assess this as a root cause of GFCI tripping when used in combination with appliances generating high-frequency ground currents. The results of this testing were subsequently used in a proposal to add a GFCI interoperability test to UL 101. This interoperability test is intended to develop other than 60 Hz leakage current limits to evaluate an appliance's compatibility with a circuit protected by a Class A GFCI. This proposed test is also intended to mitigate unwanted ground currents and tripping of GFCIs. These results are anticipated to facilitate and complement the parallel development of new performance requirements to be proposed for UL 943 for frequencies other than 60 Hz.

The results are reproduced in this report for comparison and to validate the underlying theory discussed above.

# Frequency factor

Based on Dalziel's experiments [1], the "let-go" current increases as the frequency of signals increases; that is, the human body can tolerate higher current at higher frequency. In other words, more current at a higher frequency is needed to obtain similar physiological electrical shock effects at 60 Hz. For example, 5 mA at 60 Hz has similar shock effects of 7.2mA at 1 kHz, and 30 mA at 10 kHz, etc. IEC 60479-2 [2] defines the frequency factor as the ratio of the current limit for the relevant physiological effects at the frequency f to the current limit at 50/60 Hz. The relevant physiological effect in this context is called the "let-go" effect.

Figure 1 plots the "weighted" current limits over frequency using the frequency factor of "let-go" for 3.5 mA, 4 mA and 6 mA at 60Hz. The term "weighted" is intended to define the limit at other frequencies based on the limit at 60 Hz. It can be expressed in an equation as

$$\textit{Weighted limit } (f) = FF\ (f) \times \{\textit{Limit at 60 Hz}\}$$

where *FF (f)* represents the frequency factor at a specific frequency.

The 60 Hz limits for GFCI ground current are less than 4 mA as the non-tripping limit, and 6 mA as the must-trip limit. The 3.5 mA limit is used as the potential leakage current limit for certain appliances at 60 Hz. Present GFCI technologies assess RMS current values.

To be clear, compliance with the weighted current limits over the frequency spectrum has not been a performance requirement for past designs of the equipment based on existing standard requirements. Lack of conformance with the weighted current limits is not intended as any indication of a technical shortcoming for the equipment based on today's requirements. This study helps clarify the interoperability issues across the combinations of affected equipment with the intent of supporting continued progress across industry to optimize both safety and practical outcomes.

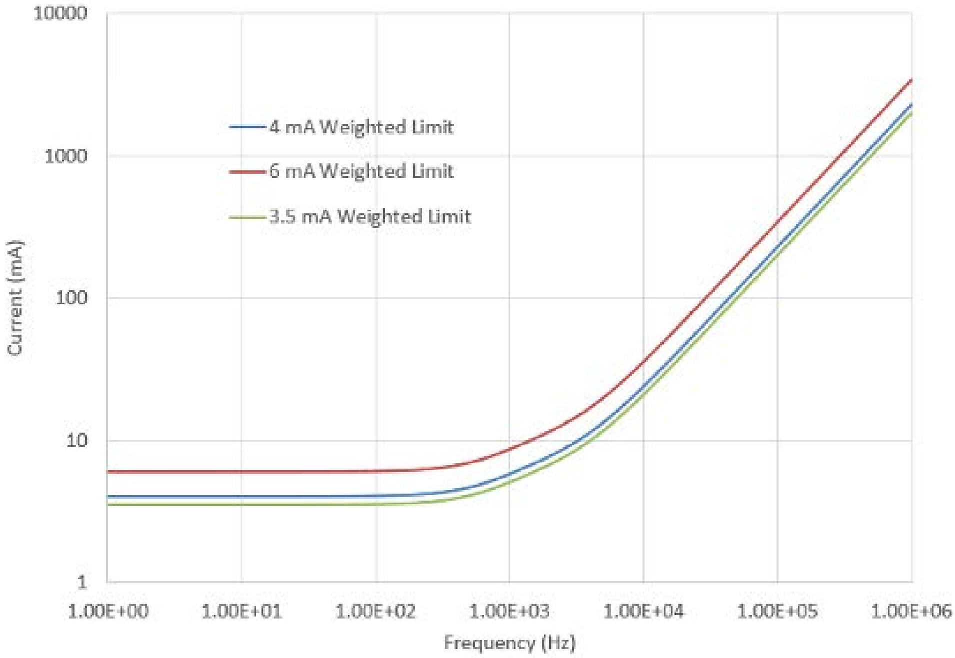


*Figure 1: Weighted current limits using frequency factor*

# Experimental setup

The Class A GFCI measures the differential current between the line and neutral wires, which is equivalent to the ground current for single-phase, three-wire grounded products. Figure 2 shows the experimental setup diagram. The differential current or ground current is measured with a broadband high-resolution current monitor. Spectral response of the differential current or ground current is measured without the human body network using the Fourier Transform Function on the oscilloscope.

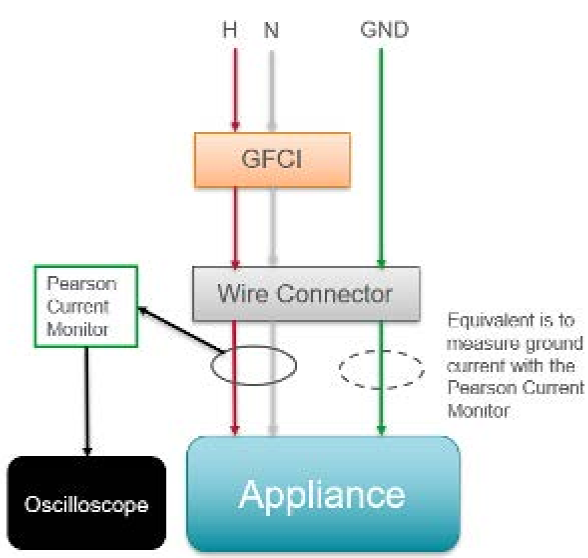


*Figure 2: Ground current measurement setup*

## Appliances under test

Three different cord-and-plug-connected household appliances were tested: clothes washing machine, refrigerator and portable air conditioner. Each of these appliances uses a variable speed drive and electronic circuits in their design. Each of these appliances has been identified due to the reported interoperability issues in combination with some GFCIs in the field.

The figures below show the ground current frequency spectrum of the appliances as compared to the high-frequency performance curves of 10 different models of GFCIs. Also shown in the figures are three limits that exist in UL 943 — 3.5 mA, 4 mA and 6 mA — weighted by Dalziel's "let-go" frequency factor (Dalziel, 1943). The term "weighted" is used to define the limit at other frequencies based on the limit at 60 Hz.

The limit at 4 mA is the non-tripping limit for Class A GFCIs — i.e., the GFCI shall not trip below 4 mA — and 6 mA is the tripping limit for GFCIs at 60 Hz. The 3.5 mA limit is the common leakage current limit for certain appliances at 60 Hz [3].

# Results

The tripping behavior of 10 different GFCIs from various manufacturers is measured between frequencies of 60 Hz and 50 kHz, with multiple discrete measurements at single frequencies. The frequency spectrum of ground (or differential) current for three different types of household appliances are presented. The results are plotted together for comparison and analysis.

For the appliances, leakage current and ground current are reported in Tables 1, 2 and 3. The first column provides the existing leakage current results. It is noted that the measurement indication unit (MIU) is a mathematical unit for leakage current measurement using the frequency-sensitive network about which more details can be found in UL 101.

. MIU measurement takes into consideration the fact that the human body can tolerate higher current as frequency increases. The relationship of the MIU and the leakage current at a specific frequency can be expressed as

*Leakage current at f Hz in mA= FF (f)×{MIU at f Hz}*

where ff represents the frequency factor. The second column is the raw ground current without any body impedance network in the current path, as would be assessed by a GFCI referenced as unweighted raw ground current. The "unweighted" term indicates that there is no frequency-sensitive network inserted in the measurement circuit. The third column is the ground current after passing through the "let-go" frequency network without the body impedance model. The unit would be the value used for the new characteristic of the interoperability indication unit (IIU), which was just recently proposed for UL 101 and consensus was achieved from the STP. IIU is equivalent to the MIU measurement, minus the body impedance model. Both the measurement and unit were developed to examine the interoperability of appliances with Class A GFCIs. It is observed that the raw ground or differential current of the tested household appliances is much higher than the IIU, which is filtered by the "let-go" network. This is because the ground currents from the appliances have significant high-frequency components due to the nonlinear motor drives, and those are significantly reduced after passing the "let-go" network, which is a low-pass filter.

## Sample I – 120 V clothes washing machine

Table 1 shows the current measurements. The IIU of ground current is significantly lower than the raw unweighted ground current. This indicates that the ground current for this appliance contains f high-frequency components. These high-frequency components are reduced significantly by the "let-go" frequency network, which is a low-pass filter.

*Table 1: Leakage and ground current from clothes washer (all in RMS)*

| Household appliance | Leakage current at 60 Hz (MIU) | Unweighted raw ground current | Ground current at 60 Hz (IIU) |
|---|---|---|---|
| Clothes washer | 0.2 MIU | 5.3 mA | 0.67 IIU |

Figure 3 shows the ground current having a significant current component at 16 kHz, with a peak value of 5.48 mA. It is also observed that the magnitude at 16 kHz intersects the tripping curve measured for one GFCI model (labeled "MF7" in the figure). The 0.67 IIU curve is also plotted and found intersecting with MF7. The interoperability was further examined by connecting each of the 10 GFCIs with the appliance and it was observed that the GFCI MF7 exhibited interoperability issues — e.g., the GFCI disconnected the supply circuit — with this washing machine. All other combinations of the washing machine and GFCIs did not exhibit interoperability issues, e.g., the GFCIs did not disconnect the supply circuit.

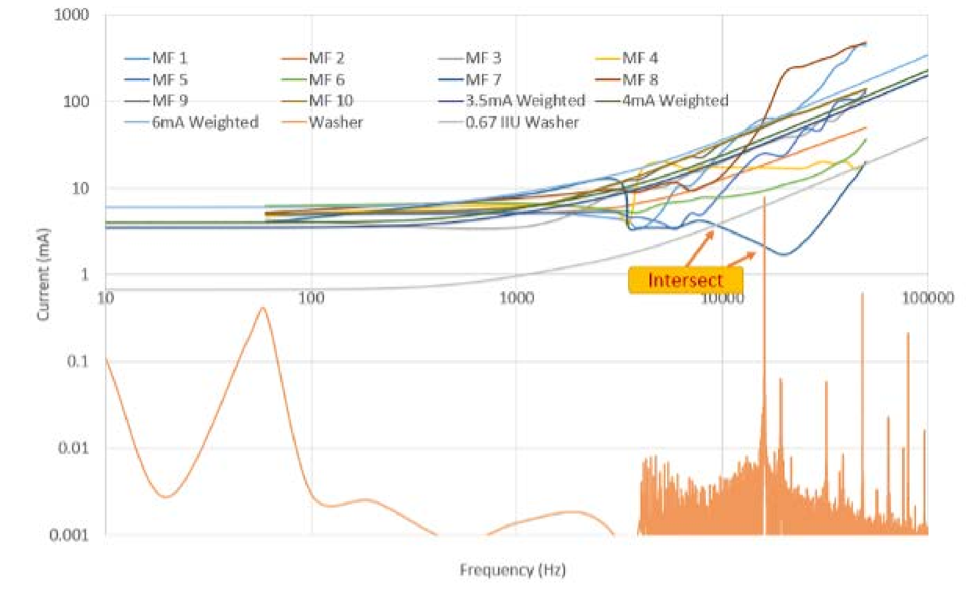


*Figure 3: Ground current frequency spectrum of the washer compared the spectral performance curve of 10 different models of GFCIs*

## Sample II – 120 V French door refrigerator

Table 2 shows the leakage and ground current measured for the French door refrigerator in RMS values. The traditional leakage current is measured at 0.28 MIU, which is within the 0.75 mA limit of UL 101. Again, the IIU of the ground current (third column of Table 2) is much lower than the raw ground current of 17.6 mA. The 1.32 IIU curve is plotted with the GFCI high-frequency performance curves. Figure 4 is plotted with the GFCIs, which demonstrate interoperability issues when combined with the refrigerator when tested in the laboratory. Figure 5 shows those GFCIs that do not demonstrate interoperability issues. The ground current frequency spectrum of the refrigerator is also included in the plots for reference.

*Table 2: Leakage and ground current from refrigerator (all in RMS)*

| Household appliance | Leakage current at 60 Hz (MIU) | Unweighted raw ground current | Ground current at 60 Hz (IIU) |
|---|---|---|---|
| Refrigerator | 0.28 MIU | 17.6 mA | 1.32 IIU |

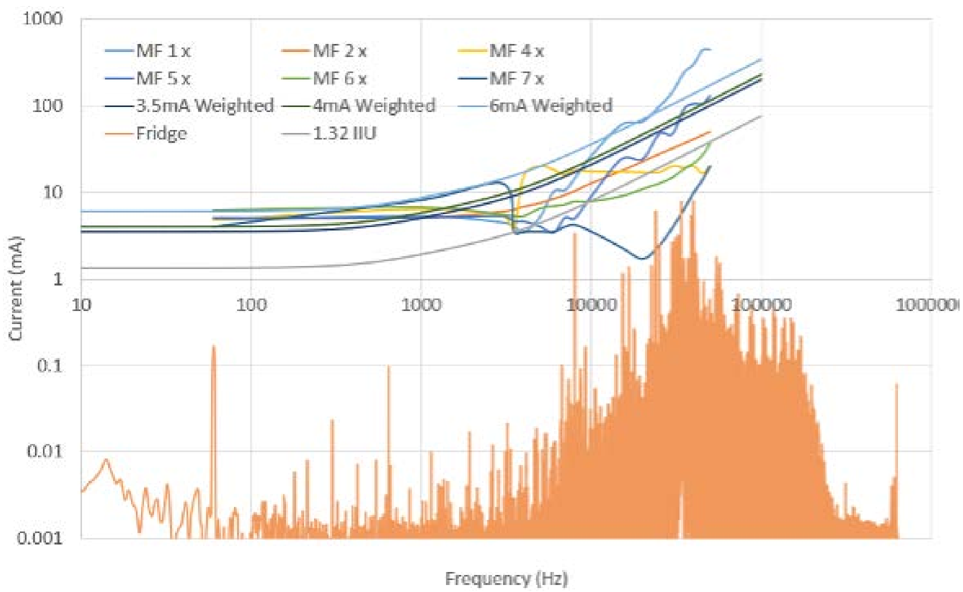


*Figure 4: Ground current frequency spectrum of the refrigerator and high-frequency performance curve of 6 GFCIs with interoperability*

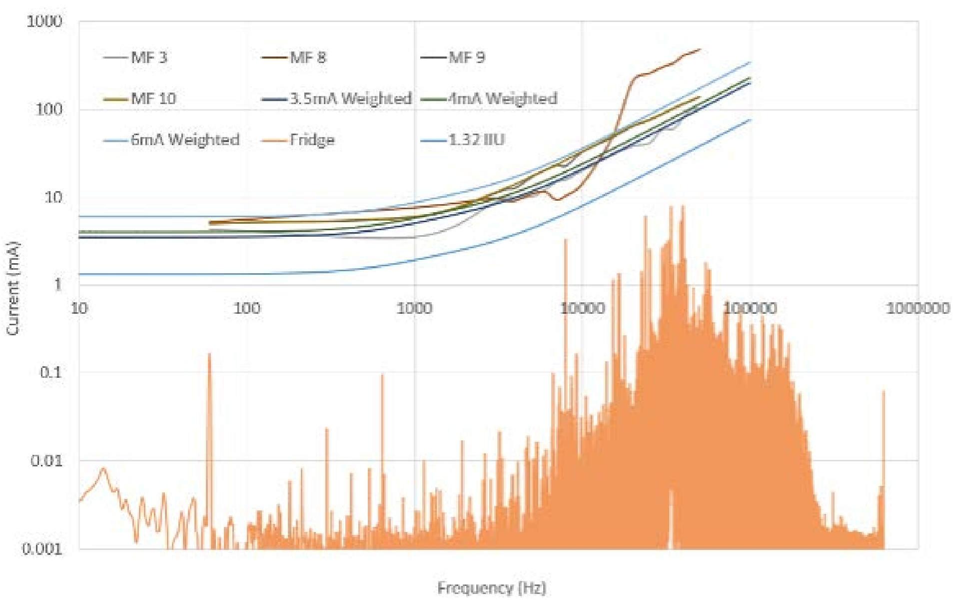


*Figure 5: Ground current frequency spectrum of the refrigerator and high-frequency performance curve of 4 GFCIs without interoperability*

There are six GFCIs that demonstrate interoperability issues with the refrigerator. In Figure 4, it is observed that the 1.32 IIU curve intersects with five GFCIs demonstrating interoperability issues, except for GFCI model MF2. The spectral performance curves of these GFCI models do not follow the weighted 4 and 6 mA limits above 1 kHz, and interoperability issues are exhibited. It is observed that between 3.5 kHz and 7 kHz, GFCI models MF1, MF4, MF5 and MF7 exhibit tripping current at 3.5 mA. This value is lower than the GFCI 60 Hz non-tripping limit of 4 mA, again noting that GFCI performance at frequencies other than 60 Hz is presently undefined. The spectrum of GFCI model MF7 intersects with the ground current spectrum of the refrigerator. GFCI technologies assess the overall RMS value of differential currents on the combined waveform, and do not assess current individual high frequencies. Therefore, a new methodology to examine the interoperability would need to be based on the IIU RMS current value of the combined complex waveform with all frequency components of the spectrum.

Figure 5 shows the ground current IIU and frequency spectrum from the refrigerator and spectral performance trip curve of four GFCIs that do not demonstrate interoperability issues when combined with the refrigerator as tested in the laboratory. As shown in Figure 5, the spectral performance of two GFCIs with no interoperability issues observed strictly stays between the 4 mA and 6 mA weighted curves. The other two GFCIs in Figure 5 almost reside in between the mA and 6 mA weighted curves but follow the trend of the weighted limits.

## Sample III – 120 V portable air conditioner

Table 3 shows the leakage and ground current measured for the portable room air conditioner (AC) in RMS values. The IIU measured for this appliance is 0.66 IIU, which is lower than the raw grounding current of 7.4 mA showed in the second column. Figure 6 shows the frequency spectrum of the raw ground current, which also contains high-magnitude components at higher frequency around 10 kHz.

*Table 3: Leakage and ground current from portable AC (all in RMS)*

| Household appliance | Leakage current at 60 Hz (MIU) | Unweighted raw ground current | Ground current at 60 Hz (IIU) |
|---|---|---|---|
| Room AC | 0.25 MIU | 7.4 mA | 0.66 IIU |

Figure 6 shows the IIU and spectrum of the net ground current plotted with the weighted 3.5 mA limit curve and all 10 GFCI performance curves. The combination of GFCI model MF 7 and the AC demonstrated interoperability issues. It is observed that GFCI model MF 7 intersects with both the 0.66 IIU and the frequency spectrum of the appliance. The combination of the AC with GFCI model MF 5 exhibits intermittent interoperability when there is a disturbance introduced on the ground wire using variable resistors.  For example, tripping may occur while changing the resistance from 5k Ohms all the way to 0 Ohms. No intersects are observed between the GFCI model MF 5 performance curve and the appliance IIU curve.

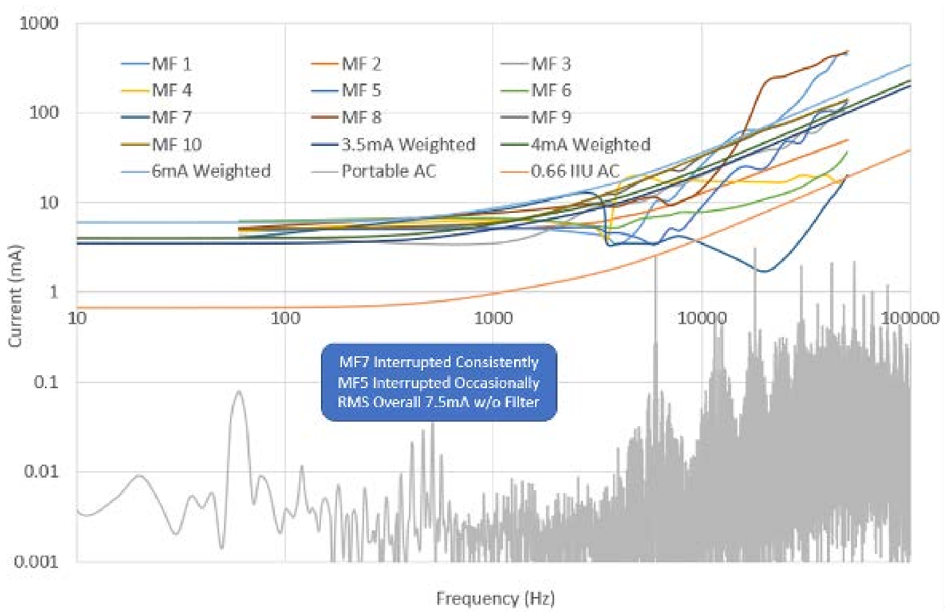


*Figure 6: Ground current frequency spectrum of portable AC unit and high-frequency performance curve of 10 GFCIs*

# Summary

The combination of three different types of household appliances and 10 Class A GFCIs were studied. The manufacturers had reported the selected appliances as exhibiting interoperability issues in the field when used in combination with some GFCIs. Various spectral-current components at frequencies higher than 1 kHz were found on the grounding conductor, which in totality across the spectrum exceeded the tripping limits for some of the tested GFCIs and were shown to induce tripping. It is also found that the spectrum at a single frequency may be insufficient for examining the interoperability of an appliance and GFCI, as the GFCI measures the true RMS value of the differential current including all frequency components. Therefore, the test methodology to measure the IIU of ground current in RMS value for appliances in the time domain is being developed and will combine all frequency components in the spectrum.

For the next steps, the UL 101 and UL 943 Working Groups are actively working together to develop coordinated testing methodology to mitigate interoperability. At the time when this paper was written, the UL 101 GFCI interoperability test proposal had been submitted to the 101 Technical Committee for review and ballot, and consensus was reached to include the GFCI interoperability test in UL 101. TGs continue to develop proposals for UL 943 to include requirements for GFCI performance for other than 60Hz.

Additionally, proposals will be made to include the UL 101 GFCI interoperability test in the relevant appliance and utilization equipment safety Standards. The objective of defining coordinated requirements across the appliance Standards and protective device Standards are intended to mitigate the present appliance/GFCI interoperability issues in the field.

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# Endnotes


1. Dalziel, C. (1943). Effect of Frequency on Let-go Current. IEEE Electrical Engineering, Vol. 62, Issue 12, 745-749.
2. IEC 60479-2, “Effects of current on human beings and livestock - Part 2: Special aspects,” Ed. 1, 2019
3. UL 101, the Standard for Leakage Current for Utilization Equipment, Ed. 6, 2017

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