Considerations for Proposed Compatibility Levels for 9-150 kHz Harmonic Emissions Based on Conducted Measurements and Limits in the United States

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Abstract— **A key enabling component of the Smart Grid is communications. Of particular interest is power line communications where very little additional infrastructure is needed to establish communication links. In the very vast majority of cases, smart meters will be located in the low voltage environment and therefore must be designed to operate properly in the presence of disturbance levels bounded by established compatibility levels. Without standardized limits for emissions in this frequency range, levels can and have reached the point where smart meter communication disturbances have been reported. The International Electrotechnical Commission's Technical Committee 77, Sub-Committee 77A, Working Group 8 is presently tasked with developing compatibility levels for disturbances in the frequency range 2-150 kHz. This range is particularly important given that numerous smart meter products are designed to communicate in this band. Communication failures, thought to be due to higher-frequency harmonics, have been reported in the literature and demonstrated in tests conducted in Europe. All of this information is being considered by Working Group 8 and is reflected in a proposed compatibility level curve for this higher frequency range. However, only limited (if any) work has been done in North America. In the United States, there are no defined compatibility levels for 2-150 kHz, but there are limits for voltage notches in IEEE Standard 519. In this paper, compatibility level curves proposed by European utilities and end-user equipment manufacturers are used to evaluate the results of initial product testing in the 120 V three-wire low-voltage environment commonly found in North America. Further consideration is given to the measurement, propagation, and summation of disturbances at higher frequencies based on a model developed for the line(s) between in-service equipment and the service point where smart meters are connected. The results of the analysis show that the total level of disturbance further exceeds the proposed CL curve when the tested equipment is in service and that measurements taken at the public supply terminals represent measurements taken at the service point.**

Keywords – smart meters; power line communication; high-frequency harmonics; EMC standardization; commutation notches.

I. INTRODUCTION

In this paper previous work on the possible impacts of high-frequency harmonic emissions on smart meter communications [1] is extended. Smart meters are typically connected directly at the low-voltage (LV) point of service for an end user. These meters make the traditional direct measurements of voltages and currents and compute power and energy consumption for billing purposes. Of course, smart meters are also capable of characterizing the quantities measured such as harmonic content and voltage excursions. All of these evaluations/calculations are done locally at the meter point. When these meters and their enhanced capabilities are integrated into a coordinated communication and control system, the smart grid is born. Without data sharing and communications, there would be no smart grid. Therefore, disturbances in meter communications must be considered.

Smart meter communication approaches can be broadly divided into two categories: wired and wireless. Recognition and tolerance of the background environment and disturbances for wireless systems are covered by numerous applicable standards for wireless communications. Similar standards for wired systems exist for higher frequencies (generally above 150 kHz) and lower frequencies (generally below 2 or 3 kHz), but no consensus presently exists in the range 2-150 kHz [2]. This frequency range includes the bands used by most smart meter manufacturers for communications via the power line (PLC). Nonexistent compatibility levels (CLs) and limits in the 2-150 kHz range have resulted in smart meter development without regard to standardized background emission levels and problems are beginning to appear [3]. Other problems in addition to PLC failures have also been attributed to harmonics in this range [4]–[6]. All industry stakeholders have recognized the need for rapid standardization, and numerous activities across Europe have resulted in proposed standards. Concerns related to PLC systems are most often the main focus for wired systems [3], [7]–[9].

Working Group (WG) 8 of the International Electrotechnical Commission (IEC) Technical Committee (TC) 77, Sub-Committee (SC) 77A is specifically charged with reviewing and evaluating the results of these ongoing activities and developing consensus CLs in the 2-150 kHz frequency range [10]. This task is complicated by the fact that numerous end-use products produce emissions in this frequency range, usually due to the common use of various high switching frequency power converter designs required to meet energy efficiency requirements [7], [11]. These high-frequency emissions are produced by end-use equipment categories ranging from entertainment (e.g., televisions and displays) to lighting (compact fluorescent and LED ballasts and controls). Other sources of high-frequency emissions include voltage-source inverters used in motor drives and a number of distributed generation sources that are or could be interfaced with the public network. Active infeed converters (AICs), normally using high switching frequencies, are used to integrate energy from these sources (e.g., solar panels, fuel cells, or wind turbines) to the power supply system to be made available for other consumers. Distributed energy sources use AICs to synchronize voltages and currents to the power system or to exchange electrical energy between energy storage devices (e.g., batteries) and the system or end-use equipment. AICs also provide the possibility of adjusting the fundamental and controllable harmonic components that feed into or are taken from the power line, which in effect generates high frequency distortion. It is possible for AICs to be used to mitigate pre-existing harmonics in the power system [12] if they are controlled as an active filter. All of these emissions combine in the LV network serving the end-user facility and the cumulative emission levels could reach values such that interference with smart meter communications occurs. Alternatively, these high-frequency emissions could essentially circulate between local-area direct-connected devices, resulting in very little impact on the supply system [13]–[15].

In the United States, the only standard that pertains to disturbances in the 2-150 kHz range is IEEE Standard 519-2014 [16]. According to Standard 519, a notch is the result of disturbances in the normal voltage waveform that lasts less than 0.5 cycles, and is initially of opposite polarity than the waveform. Therefore, the area of this notch is subtracted from the normal waveform. These notches are often caused by rectifiers and other nonlinear devices, resulting in higher order harmonics. In order to avoid issues related to these notches, a total allowable notch area for LV systems is set. IEEE Standard 519 only contributes to limits regarding a single disturbance source, while the goal of WG8 is to set maximum acceptable levels for the sum of all disturbances at the point of common coupling (PCC), located between the smart meter and the LV system. There are no standards in the United States that deal with the cumulative sum of disturbances from all high frequency disturbing sources.

In this paper, proposed CLs are compared to emission testing results for some 120 V products in common use in North America so that postulates can be developed regarding how multiple disturbance-producing products in the 9-150 kHz range might summate at the point of service where the smart meter is located. In order to obtain reliable information from smart meters, high frequency disturbances must be managed. Therefore, the aim of this work is to present disturbance measurements that must be considered for the design and operation of smart meters using PLC. For measurements, focus is given to the 9-150 kHz frequency range because it has been recommended that different effects and limiting factors may be present for the frequency ranges 2-9 kHz and 9-150 kHz [17]. Related works are disclosed in Section II. The set-up used for measuring emissions levels is explained in Section III. In Section IV, proposed CLs are introduced. Further, in Section V, limits based on maximum notch area and notch depth set in IEEE Standard 519 for voltage notches are used to consider individual disturbance sources with regard to the proposed CLs. In Section VI, results of tests to assess high-frequency disturbance propagation in 120 V, three-wire LV systems are presented and compared to proposed CLs. In Section VII, a model for the line between the public supply terminals (where emissions were measured) and the PCC is considered in order to posit how the disturbances from multiple end-user pieces of equipment sum at each location. Finally, conclusions and future work are provided in Section VIII.

II. RELATED WORKS

To date, all testing, research, and evaluation of high-frequency harmonic product emissions has been focused on products used in European LV networks. This may primarily be a result of the common use of PLC for smart meter communication in European countries [3]. Published results of the similarities and differences of multiple product tests investigating voltage emissions have not been found in these works. Instead, previous testing has been focused on specific equipment, namely lighting, such as touch dimmer lamps [4] and fluorescent lamps [13], or on current distortion of various appliances [19].

Further, none of these works provide a solution to the problem, rather the data is used to assist in creating standards.

Smart meter manufacturers stand to benefit from truly international specified standards that can be used on a global scale. In order to accomplish this, information on products and standards used in North American LV networks is required. The work presented in the following sections is intended to contribute to the European works and aid in the development and acceptance of international standards for high frequency harmonic disturbances for PLC.

III. TEST AND MEASUREMENT APPROACH

All measurements were carried out on 120 V equipment and systems using a 100 MHz digitizing oscilloscope with built-in signal processing functions including Fourier analysis. Spectral analysis was also conducted off-line using digitized data transferred from the oscilloscope to a local computer. The tests were carried out using a 120 V supply taken directly from the local public network. Equipment was connected to the 120 V public supply source using a standard three-wire cable rated for continuous operation at 120 V, 15 A. Measurements are taken at two locations: (1) the supply terminals, M_1, and (2) the load equipment connection point, M_2. Voltage signals were the only quantities that were measured; current emissions were not considered in this work. The setup is shown in Figure 1.

As required by electrical codes in the United States, the public supply point is grounded at the point of service only. The equipment under test (EUT) is grounded by connection back to the single ground point at the service; this ground conductor is specifically required to be isolated from the normal current-carrying conductors. Because smart meters will communicate using the power conductors and not the ground, the emission levels produced at the EUT terminals and the supply voltage terminals are measured between the two power conductors rather than from either conductor to the ground.

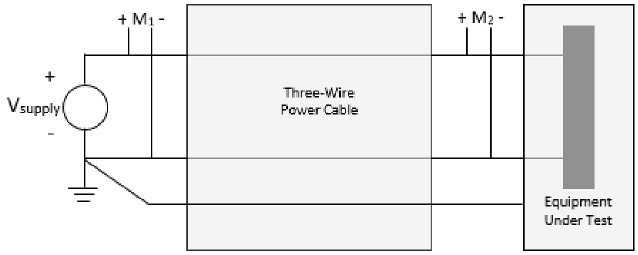


Figure 1. Test and Measurement Setup

Measurements are made at the points M_1 and M_2 as shown in Figure 1. The measured emission levels at M_2 with and without the EUT in operation can be used to evaluate the emissions due solely to the operation of the EUT. The measured levels at M_1 with and without the EUT in operation can be used to evaluate the propagation of emissions from the EUT to the supply point. Of course this propagation is a direct function of the frequency response of the power cable and the impedance of the supply system along with any other connected equipment [13]–[15]. While theoretical models can be developed for simple cases, this task can become difficult and inaccurate for realistically complex systems and is best assessed via direct measurement of input and output characteristics (e.g., at M_2 and M_1).

Typical emission levels in the range 9-150 kHz are on the order of a few millivolts (mV) and are commonly expressed in the unit "decibel-microvolt" (dBμV) where 20 dBμV= 10*1 μV=10 μV, 40 dBμV=100*1 μV=100 μV, etc. A decibel (dB) is the logarithmic unit representing the ratio between two quantities, and dBμV represents the ratio between the measured voltage emissions and 1μV. Expressed in this common dBμV unit, typical emission levels in the frequency range of interest will be around 80-100 dBμV (10-100 mV). Plotting the magnitude in dBμV allows possibly large variations in ratios to be plotted on a common scale. Of course, these emission levels will only be encountered at the specific frequencies at which they are produced; much lower levels, typically 40-60 dBμV, will be present over the majority of the frequency range of interest. In order to resolve these small spectral components with sufficient accuracy using a typical oscilloscope/spectrum analyzer, it is necessary to remove the power frequency component from the measured signal before it is processed by the spectrum analyzer. This removal process requires an analog filter of band-stop or high-pass design to eliminate the power frequency signal or pass without attenuation the higher frequencies of interest, respectively.

A high-pass design was chosen for the measurements reported in this work and a custom design was conceived and implemented to avoid any over-dependence on commercial products. In addition, it is difficult to select any particular commercially-available product based on accuracy, performance, or other criteria because no standardized interface coupling exists [18]. The analog filter design is shown schematically in Figure 2.

Because the filter is a custom design, it is necessary to validate the expected high-pass frequency characteristics and verify that the power frequency component, in this case at 60 Hz, will be sufficiently attenuated. The simulated frequency response characteristic of the filter is shown in Figure 3. It is clear from Figure 3 that the filter delivers a significant attenuation at the power frequency and corresponding low-frequency harmonics whereas the response is essentially flat with minimal attenuation in the frequency range of interest (9-150 kHz). The frequency response was further verified by measurement of the frequency response of the constructed filter. The result is shown in Figure 4 and verifies the essentially flat characteristic and minimal attenuation in the 9-150 kHz range.

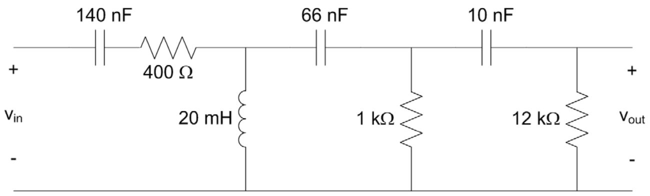


Figure 2. Filter Design and Parameters

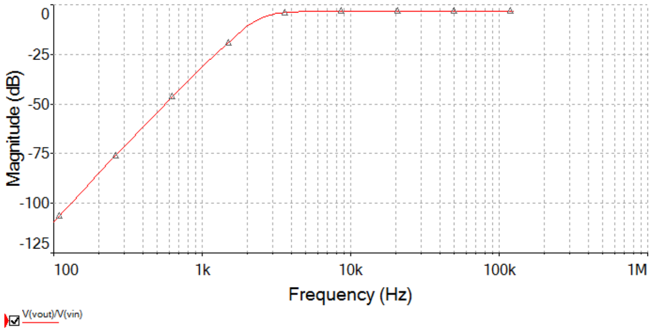


Figure 3. Simulated Frequency Response of Custom Filter

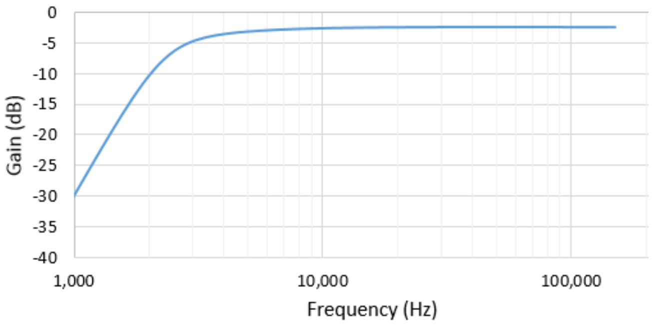


Figure 4. Measured Frequency Response of Custom Filter

IV. COMPATIBILITY LEVELS

A CL is the level of disturbance above which problems (e.g., communication interference) are expected to occur. Two CL curves have been proposed in Europe. One of the proposed CL curves made by European utilities is shown in Figure 5. Shown in the plot are the proposed maximum allowable peak levels in dBµV for the 3-150 kHz frequency range. The CL curve proposed by European manufacturers is given in Figure 6. The maximum allowable emissions are again given in dBµV, based on peak values, for the 9-150 kHz frequency range.

Considering both figures, the primary discrepancy between the proposed curves lies in the 9-50 kHz range. The communication issues sited by European utilities have played a major role in the development of CLs. As a result, the utilities' CL curve will be used as the primary reference for evaluation of the measurements discussed in this paper.

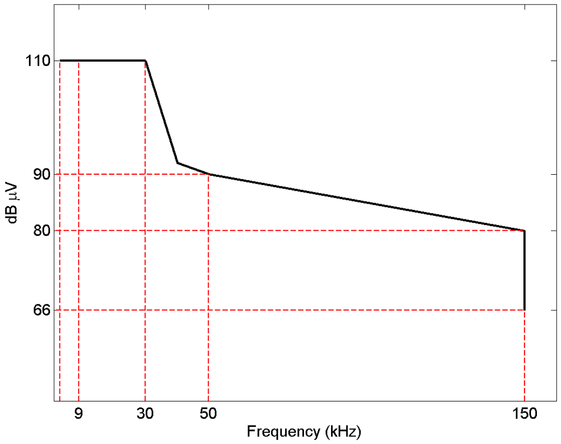


Figure 5. Utility Proposed Compatibility Levels

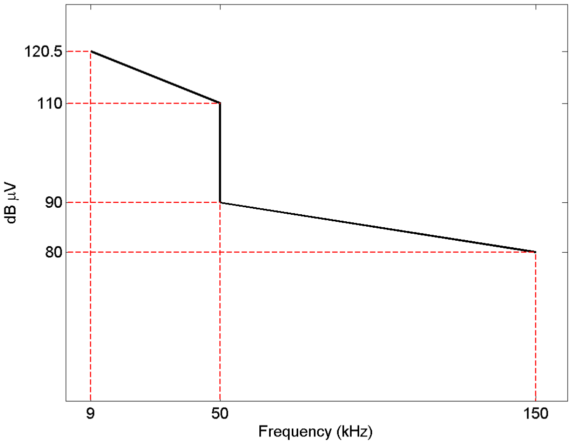


Figure 6. Manufacturer Proposed Compatibility Levels

V. COMMUTATION NOTCH LIMITS

In order to consider the CLs proposed in Europe, CLs based on established standards in North America should be considered if they exist. Unfortunately, only limits for specific disturbance sources exist in IEEE Standard 519 and these do not represent the total, maximum disturbance level that is defined by CLs. The ultimate objective, of course, is for the limits for individual disturbing sources to result in a total summated disturbance level, considering all disturbance sources, which does not exceed the maximum permissible total disturbance levels, which define the CLs.

The limits for commutation notches provided in IEEE Standard 519-2014 are shown in Table I and are based on the variables defined in Figure 7. Based on Figure 7, f(t) was written for a 50 Hz sinusoidal waveform, considering the general system notch area and depth from Table I. The notch area was normalized as a 1V system by dividing by 480V. In order to plot the magnitude, f(ω), for the frequency range 2-150 kHz, the Fourier series was calculated. Figure 8 is the plot of the results for the Fourier series and the European utility proposed CLs, both given in dBµV based on peak values. Both the CLs and the notch limits drop off as frequency increases. However, the IEEE limits are based solely on commutation notches, and are intended to be applied to a specific disturbance. The CL curve is representative of the maximum permissible value for the sum of all disturbances seen at the PCC.

TABLE I. RECOMMENDED LIMITS ON COMMUTATION NOTCHES[16]

	Special applications[a]	*General system*	*Dedicated system*[b]
Notch depth	10%	20%	50%
Notch area (A_N)[c,d]	16400	22800	36500

a. Special applications include hospitals and airports.
b. A dedicated system exclusively supplies a specific user or user load.
c. In volt-microseconds at rated voltage and current.
d. The values for A_N have been developed for 480 V systems.
It is necessary to multiply the values given by V/480 for application at all other voltages.

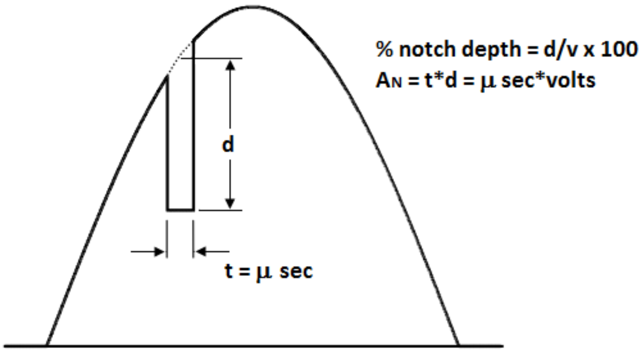


Figure 7. Definition of Notch Depth and Notch Area [16]

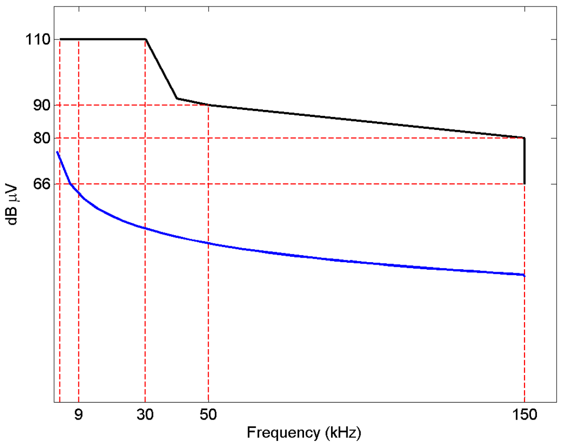


Figure 8. Utility Proposed CL vs. Commutation Notch Limits

VI. MEASUREMENT RESULTS COMPARED TO PROPOSED COMPATIBILITY LEVELS

Measurements were conducted at M_1 and M_2 in Figure 1 using the high-pass filter of Figure 2, the digitizing oscilloscope, and off-line computer-based spectral analysis. Measurements were initially performed at M_1 with no EUT operating in order to establish a baseline condition. To recognize and evaluate expected variations in background emission levels over time, the baseline evaluations were conducted over a 72 hr period including a normal workday, multiple nighttime periods, an end-of-week day, and a holiday. These results are shown in Figure 9, averaged over a period defined by a particular date and hour-of-day range as shown in the figure. The magnitude of the recorded measurements were RMS values, with units dBμV$_{\mathrm{RMS}}$. In order to compare the proposed CLs on the same scale, the RMS values were converted to peak values by dBμVpeak = (1.414)*dBμV$_{\mathrm{RMS}}$. The task of multiplying peak values by 1.414 was achieved by adding 3dB to the measurements.

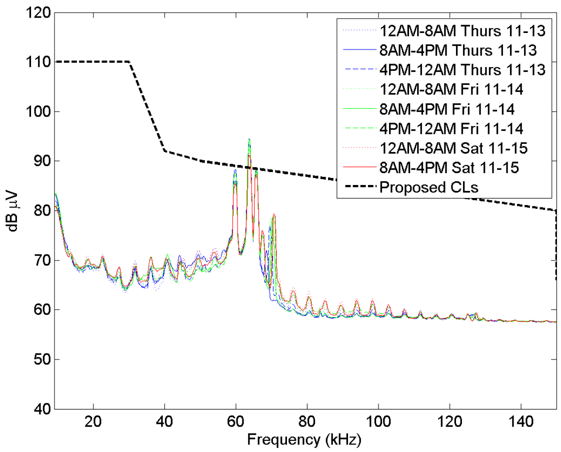


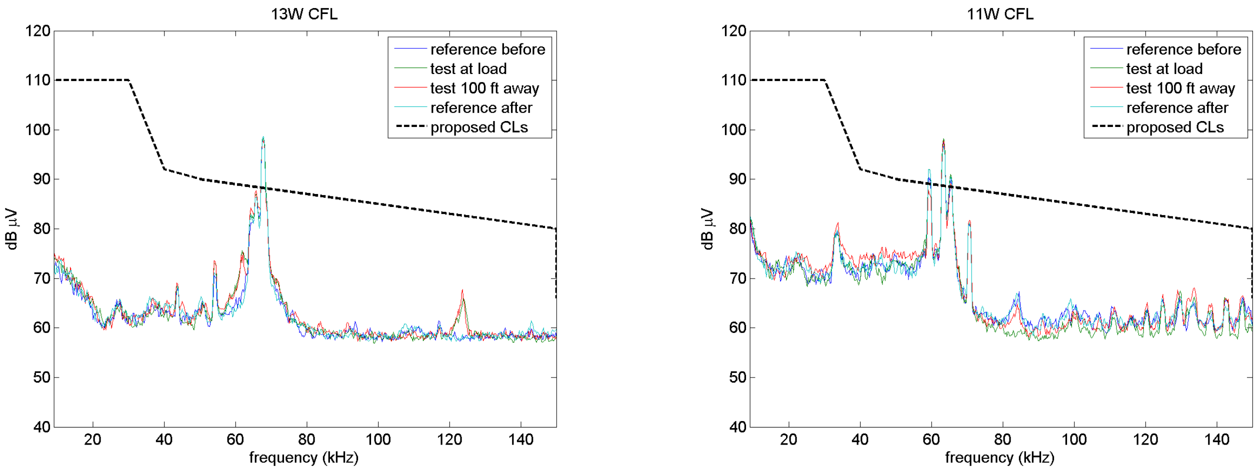
Figure 9. 72 hr Background Emission Levels

It is clear from Figure 9 that the variations in background emission levels are not overly significant. It is equally clear that there are significant background emissions in the frequency range 60-70 kHz that either exceed or nearly exceed the utility's proposed CL curve. The background emission levels in Figure 9 can be used during the emission assessment of various operating EUTs. These longer-time background levels are also useful for evaluating potential measurement errors; erroneous measurements would likely deviate significantly from the established background levels.

Two major categories of consumer products were tested in this work: lighting and televisions (displays). Measurements were taken on both ends of the supply cable impedance (approximately 30.5m long power cable as previously described) and with and without the EUT in operation. For the cases with the EUT disconnected, measurements were made both before and after the EUT connection and operation so that the reference levels immediately before and after each test could be known and, for validation purposes, compared to the longer-time results of Figure 9 as appropriate.

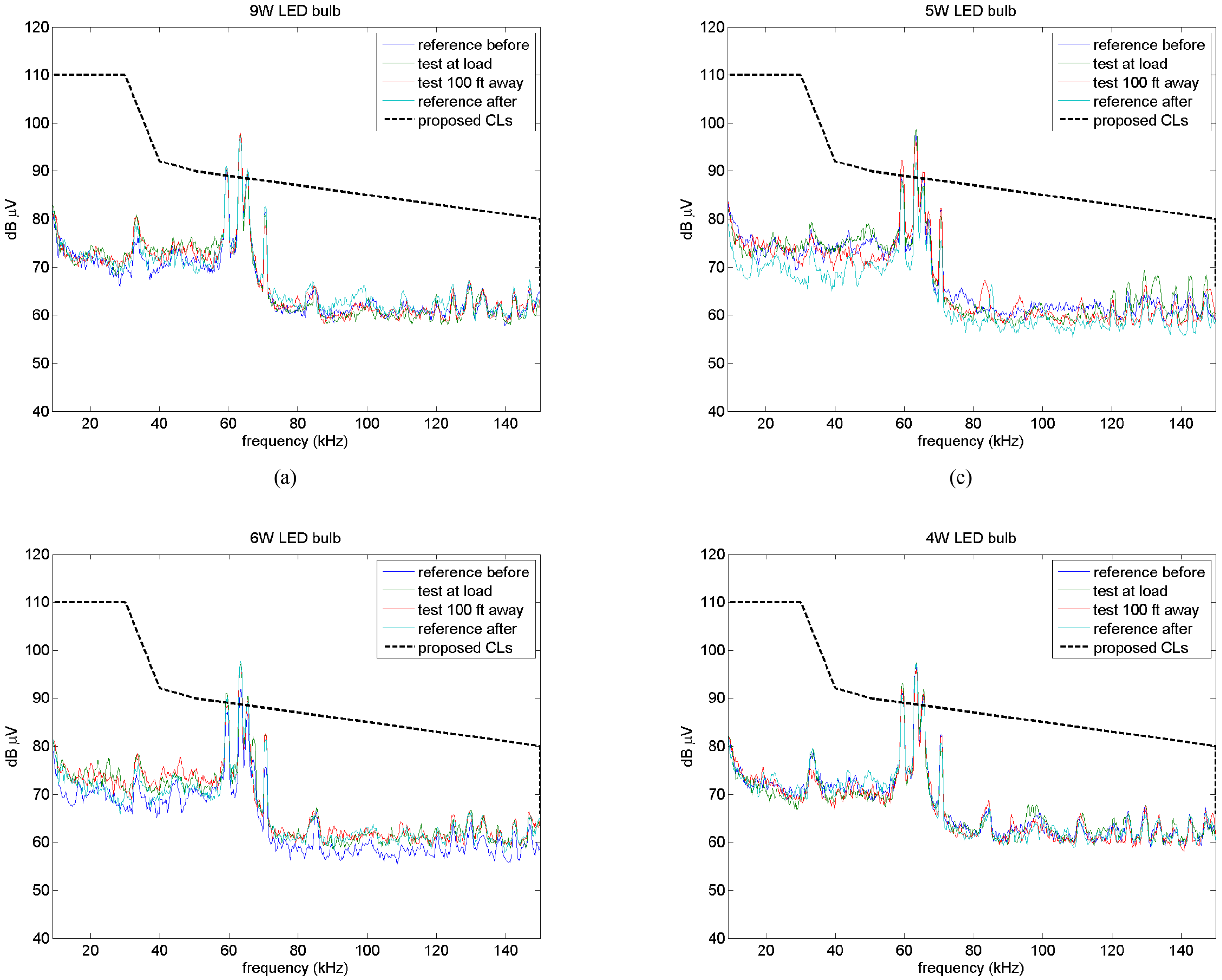
The results of two compact fluorescent lamp (CFL) tests are shown in Figure 10 (a) and (b). These results clearly show that one of the CFLs produces a noticeable emission around 120 kHz whereas the other tested lamp provides an attenuating effect around 80 kHz at the EUT terminals but not at the supply terminals. From these two tested lamps, it does not appear reasonable to make generalizations. However, comparing the test results to the proposed CL curve, it is clear that disturbance levels still exceed the proposed CL between 60-70 kHz. In this case, the 3-5 dBμV increase in magnitude in the 60-70 kHz range represents the additive effects of end-user devices and is indicative of the emission level of the EUT.

The results of four LED lamp tests are shown in Figure 11 (a)-(d). These results show the effects of a general change with some increases and some decreases (a) and (d), an increasing change in background emissions (b), and the effects of a decreasing change in background emissions (c). For all the tested LED lamps, there does not appear to be a significant impact on emissions relative to the background levels at either the source or load terminals. Again, all of the tested LED lamps contribute to exceeding or nearly exceeding the proposed CL curve in the 60-70 kHz frequency range for each of the tests conducted. In tests (b) and (c), before the reference and after, respectively, have a lower emission level than measurements taken while the EUT was in service for the entire band of interest.



(a) (b)

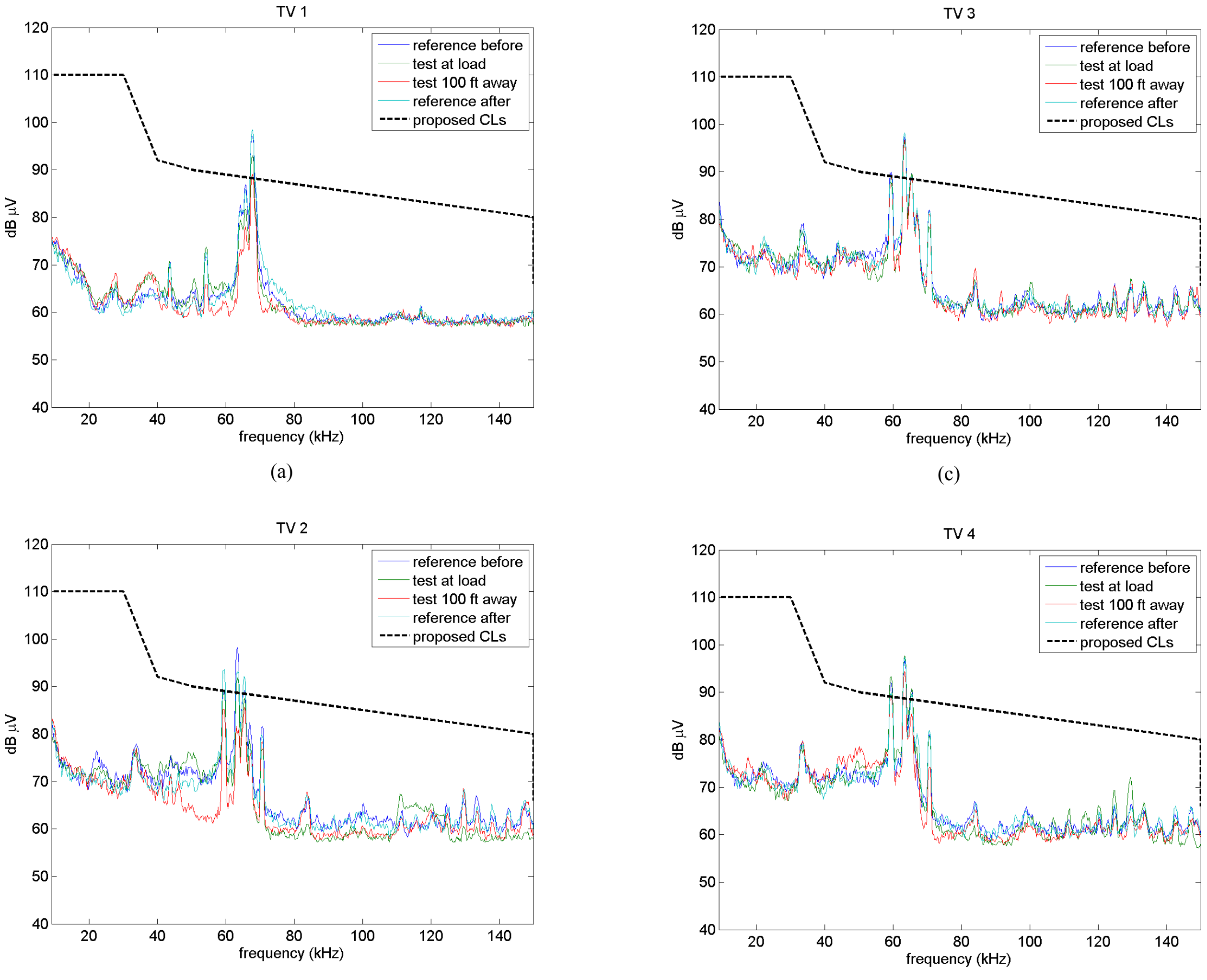
Figure 10. CFL Test Results vs. Utility Proposed CL



(a) (c)

(b) (d)

Figure 11. LED Test Results vs. Utility Proposed CL



(a) (c)

(b) (d)

Figure 12. Television/Monitor Test Results vs. Utility Proposed CL

The results of four television/display tests are shown in Figure 12 (a)-(d). Tests (b) and (d) show some amplification and attenuation effects of the power cable, particularly around 40-60 kHz and 110-120 kHz (b), and 120-130 kHz (d). The other two tests do not appear to have any single dominant features but it is clear that the emission levels change with and without the EUT in operation in all cases. Again, all tests show that disturbance levels in the 60-70 kHz band exceed the utility proposed CL curve.

It should be clearly noted that the results shown in Figures 10-12 show the total emission levels with and without the EUT in service. While a comparison of the "with" and "without" results gives some indication of the emissions produced by a particular EUT, this type of general observation is not sufficient in many areas, particularly in standardization related to equipment emission limits and possibly installation-level emission limits. With regard to installation-level emission limits, such as those in in IEC Standard 61000-3-6, it will be necessary to develop applicable summation laws that can be used as a first approximation to separate individual emission contributions from a measured total emission level. Such a summation law could, for example, be used to identify (approximately) the emissions produced by the EUTs in Figures 10-12 from the total measured levels.

At this time, no summation law exists in the 2-150 kHz band and general comparisons with and without the EUT in service are the only things possible. However, the commutation notch limits shown in Figure 8, based on IEEE Standard 519, can be used to consider the maximum limits allowed for specific equipment. The allotted limits for individual equipment can then be used to define a summation law for this higher frequency range. None of this work can be completed until CLs for the 2-150 kHz range are defined.

Further, in order to measure total disturbances based on allotted established limits, it is necessary to develop testing and measurement specifications that are applicable to the general 2-150 kHz band similar to those which exist for products for frequencies below 2-3 kHz as specified in IEC Standards 61000-3-2 and 61000-3-12. The measurements shown in Figures 9-12 were taken at the user supply terminals, not at the PCC. In order to establish proper measurement specifications at the PCC, the lines between the PCC and the user supply terminals (where these measurements were taken) must be characterized.

VII. LINE MODELING

In order for the values measured at the supply terminals to reflect the values measured at the PCC, it is necessary to multiply measured data at the public supply point by the transfer function of the line. The transfer function was determined by measuring a 50ft (approximately 15.24m), Romex 12-3 (12 gauge, 3 conductor) indoor non-metallic wire using an impedance analyzer. This wire was chosen because it is commonly used in the United States to wire residential indoor branch circuits for outlets, switches, and other loads.

The analyzer was set up so that a signal input and output were measured on opposite ends between two of the Romex wire conductors. The analyzer was set to measure V_{out}/V_{in} (V_2/V_1) over the frequency range 2-150 kHz. The results are shown in Figure 13. In order to determine resonances that occur in the line, the measurements were conducted in the 2 kHz-20 MHz frequency range. Inspection of the measurements shows that resonance does not occur, and the gain is approximately 1V/V, in the 2-150 kHz range.

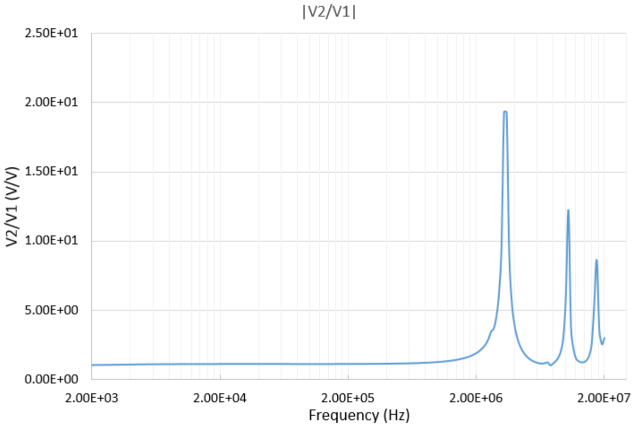


Figure 13. Measured Transfer Function for 12-3 Romex Wire

In order to verify these measurements, equivalent, per-meter, RLC parameters were calculated to determine the resonant frequency. The series dc conductor resistance R, series inductance L, and shunt capacitance C parameters were calculated using (1), (2), and (3) based on single line calculations [20]. According to [21], it is important to note that resonances at high frequencies cause issues. However, the length of the line is important when considering line modeling. The resonant frequency (f_0) based on the calculated LC values (for the entire 15.24m line) is approximately 2.8 MHz. Recognizing the free space for conductors to move in the Romex wire, the measured distance between conductors (D) is not exact. Considering the measured transfer function in Figure 13, the calculated value for f_0 is reasonable.

$$R_{dc} = \frac{\rho l}{A} \tag{1}$$

$$L = \frac{\mu}{2\pi} ln \frac{D}{r'} \tag{2}$$

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{D}{r}\right)} \tag{3}$$

Also, based on the calculations and measurements, it is reasonable to assert that for short lines such as those used in residential homes in the United States (for example, 100ft or 30.5m), a single, equivalent RLC circuit is sufficient for modeling the line between the supply terminals and the PCC. This assertion is based on the electrical wavelength, λ, for this line. The wavelength (4) is approximately $1.5x10^5$m–$2x10^3$m from 2-150 kHz for velocity (v) equal to the speed of light. Assuming an electrically short line is λ/4, wiring used in residential buildings can be assumed to be electrically short and modeled using a single RLC line model rather than a distributed parameter line model. This assumption is true even for velocity (v) much less than the speed of light.

$$\lambda = \frac{v}{f} \tag{4}$$

It is clear from these results that the measurements taken at the public supply terminals represent measurements taken at the service point where any smart meter would likely be located. This is true because the characteristics of the line between the two points is essentially flat for the 2-150 kHz range of interest. As a result, development of standardized measuring techniques for high-frequency harmonics can be considered at the public supply terminals.

VIII. CONCLUSIONS

The emission levels for some consumer equipment typically used in North America were compared to proposed CLs for high-frequency emissions. The results of the analysis show that the total level of disturbance further exceeds the proposed CL curve when the tested equipment is in service. Although there are variations in the recommendations made by European manufacturers, the existing difference in proposed CLs in the 9-50 kHz range between the utilities and manufacturers is not significant because neither level is exceeded with or without the tested equipment in service. For both the manufacturer and utility proposed CL, disturbance levels with and without tested equipment in service exceed the limits in the 60-70 kHz range.

If either of the European proposed CL curves were to be adopted in the United States, filtering would be required in order to reduce the harmonic levels that surpass the defined CLs in the 60-70 kHz range. Specifically, filters added on equipment or at the PCC can help reduce undesired harmonics to a value below the chosen CL curve. Although PLC is not (currently) the dominant communication technique used for smart meter communication in North America, it is still of interest for North America to follow future proposals made by the IEC and European utilities and manufacturers in order to prepare for alternative metering methods that may be used in the future. Further, the limits based on IEEE Standard 519 notch commutations is important to consider regarding a developed summation law for lower frequency harmonics once a CL curve is established. The summation law from IEC Standard 61000-3-6 should be evaluated for 2-150 kHz in order to determine if the same law may be applied to harmonics above the 50th order.

The evaluation of individual EUTs and the averaged day/time background disturbance levels measured confirm that individual products can add to background emission levels. Although, based on measurements and calculations performed, it is reasonable to assume that the measurements taken at the supply terminals are the same as measurements taken at the meter, further tests examining multiple products and additional measurements made at the PCC will be necessary for future consideration of CLs in the 9-150 kHz range.

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