Consideration of 2-150 kHz Disturbances in North American Power Systems

by

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Abstract

This is an evaluation of considerations for electromagnetic compatibility (EMC) limits for power line communication (PLC) based on North American standards. In the vast majority of cases, smart meters are located in the low voltage (LV) environment and must be designed to operate suitably in the presence of disturbances bounded by set compatibility levels (CLs). In Europe, without standardized limits for emissions in the frequency range allotted for smart meters (2-150 kHz), levels have reached the point where smart meter communication disturbances occur. In the United States, there are no defined CLs for 2-150 kHz, but there are limits for voltage notches in IEEE Standard 519. In this evaluation, compatibility level curves proposed by European utilities and end user equipment manufacturers are used to consider the emission limits set by North American commutation notch limits. The proposed CLs are also evaluated based on end user device measurements taken in North America. Further consideration is given to the propagation from the point of measurements to the point of common coupling (PCC). It is found that North American commutation notch limits may be considered for the purpose of setting emission limits.

Acknowledgments

To Demi, Jacob, Christian, and Tyler – thank you for making every day brighter. I love y'all to the moon and back.

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List of Abbreviations

CL	Compatibility Level
EHV	Extra High Voltage
EL	Emission Level
EMC	Electromagnetic Compatibility
HV	High Voltage
IL	Immunity Level
LV	Low Voltage
MV	Medium Voltage
PCC	Point of Common Coupling
PL	Planning Level
PLC	Power Line Communication

Chapter 1: Introduction

The smart grid offers a robust set of networks that facilitate bidirectional exchange of data for power supplies and electrical equipment connected to the power grid. The technologies that make up the smart grid enable effective monitoring of the operation and conditions of the grid, providing the benefits of a more efficient power system that can regulate and control the distribution of electricity based on consumption without failures or outages. Therefore, communication is a major advantage to having a smart grid. These smart grid technologies can provide system operators with near real-time information about the system and consumer usage that is obtainable remotely. A primary use of remote communication techniques involves smart meters.

Smart meters have rapidly become a dominant metering option for utilities in North America and abroad. Primarily, wireless radio is used by utilities to receive demand information for customer billing in North America. This option is attractive because it is wireless and does not require much additional infrastructure. However, there are some locations where wireless radio may not be reliable. In these locations, another technique, such as power line communication (PLC), is beneficial because very little additional infrastructure is needed to establish links for reliable, remote communication.

Using PLC relies on already established power lines and therefore is subject to the imperfect system conditions that result from electrical equipment connected to the grid.

Specifically, high frequency disturbances must be considered. Harmonics are the integer multiples of the fundamental frequency, which is 60 Hz in North America and most of South America, and 50 Hz in Europe and the majority of the rest of the world. Harmonics result from repeating signals, such as the sinusoidal voltage and current waveforms transmitted on the power grid and converted by end user devices such as cell phone chargers and stereos. The sum of harmonics produced by all end user devices seen at the meter, which often serves as the point of common coupling (PCC), must not exceed certain levels to prevent disturbances with communications technology. In order to combat disturbances for PLC, further study of the frequency range allotted to smart meters, 9-150 kHz, must be completed. These disturbances are referred to as high frequency disturbances. Manufacturers have not previously considered this frequency band when designing appliances, and utilities have not previously had issues with the lack of standards in this range. Setting standards for the allotted frequency range for smart meters requires testing to measure what is currently seen in the environment and analysis of related standards. Therefore, measurements and comparable standards must be considered.

Although smart meters are not exclusively used by all utilities in the United States, it is important to consider future use of this technology. Currently, in Europe, there are cited issues with retrieving reliable data for billing customers using PLC. These issues have brought attention to the need for setting electromagnetic compatibility (EMC) levels in the 2-150 kHz range. Established compatibility levels (CLs) could be modified to help prepare for any future roadblocks with implementing smart meters using PLC in North America. The Institute of Electrical and Electronics Engineers (IEEE) develops industry standards in North America, and the International Electrotechnical Commission (IEC) is responsible for creating standards internationally. Therefore, development of IEC standards in cooperation with IEEE standards could make for truly international disturbance level management procedures for high frequency disturbances that could impact PLC.

It is in the best interest of IEEE to follow and aid in work being done by IEC. Setting CLs based on international considerations will help to make future considerations by IEEE readily adopted. Although there are no standards in North America that are directly related to the CLs being planned by the IEC, there are recommended practices in IEEE Standard 519 that relate to disturbance limits that would be required to not exceed defined CLs when summed at the PCC. Consideration of these limits, measurements of the high frequency environment, and measurements of the propagation from the disturbance source to the PCC are relevant and could aid in the development of EMC standards worldwide. Each of these topics is considered in this thesis.

Chapter 2: Disturbance Limits and Levels

Harmonics are the sinusoidal waveforms at frequencies that are integer multiples of the fundamental frequency. Power system harmonics are a primary cause of distortion of mains voltage and load current waveforms. In order to combat these distortions, limits are set to handle interference with devices connected to the system, such as the equipment used for PLC systems. These disturbance or emission levels (ELs) account for varying levels of disturbances present at a location. The goal of setting disturbance limits is to safeguard a globally acceptable electromagnetic environment for all system elements to work normally. Disturbance or emission limits are set to deal with the normal and worst-case levels of allowable disturbances. The relationship between these limits and levels is shown in Fig. 1 [1].

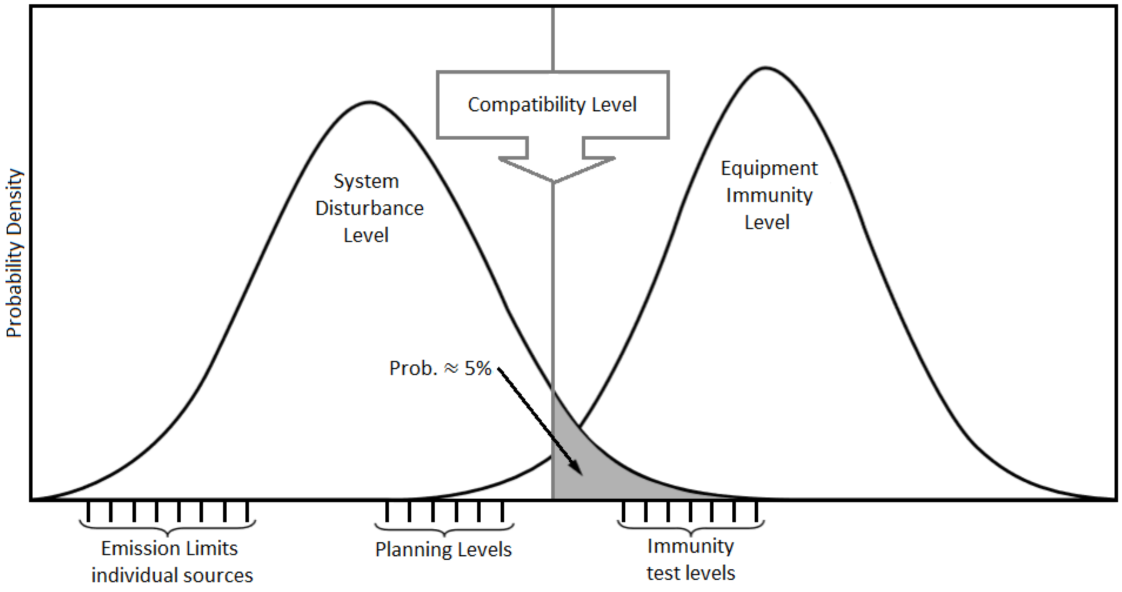


Fig. 1. Relationship Between Disturbance Limits and Levels

2.1 Compatibility Level

The maximum level that the sum of emission limits for a system cannot pass is referred to as the reference or compatibility level (CL) for a particular electromagnetic disturbance. By convention, the CL is chosen so that it will be exceeded by the actual EL only with a probability of no more than ~5 %. Since an immunity level (IL) represents the level equipment can tolerate and still function properly in a specific environment (such as the LV network), then all equipment intended to operate in that environment is required to have immunity at least at that level of disturbance. Therefore, a reasonable margin representative of the equipment operating in that environment is provided between the CLs and the ILs [1]. These CLs are specified for different frequency ranges and environments so that there is limited probability that they will be exceeded by the actual system ELs.

Power system EMC is a condition of the electromagnetic environment such that the EL is sufficiently low and the ILs are sufficiently high to assure that all devices and systems (such as the PLC system) operate as intended. This requires coordinated control of ELs and ILs in order to ensure that the ILs of the equipment and systems at any location are not exceeded by the EL at that location resulting from the cumulative emissions of all sources and equipment impedances. As a result, EMC is assumed to exist if the probability of the deviation from expected performance is negligible – less than 5 % [2].

2.1.1 Proposed CLs for 2-150 kHz

In order to combat the issues encountered by European utilities using PLC, emission limits are being set, beginning with considerations for CLs in the 2-150 kHz range. The International Electrotechnical Commission’s Technical Committee 77, Sub-

Committee 77A, Working Group 8 is working on a revision of IEC 61000-2-2 that will provide CLs for high frequency disturbances. More work, and possibly new documents, are needed to define limits that satisfy the utility's need for accurate billing information, while not requiring a lot of costly changes to manufactured devices. These proposed CLs for LV networks are shown in Fig. 2. The units dB-µV are used in order to represent the ratio between the measured or specified voltage emissions and 1 microvolt (µV). Referring to these limits in dB (decibels) rather than by absolute quantities allows for larger ranges (between µV and volts) in numbers to be represented on a relatable scale [3]. Emissions in the 2-150 kHz frequency range are usually on the order of millivolts (mV), around 10-100 mV or, 80-100 dB-µV. Therefore, choosing the units dB-µV for the purpose of analyzing all high frequency phenomena (levels and limits) allows for larger variation in mV to be represented on a smaller scale.

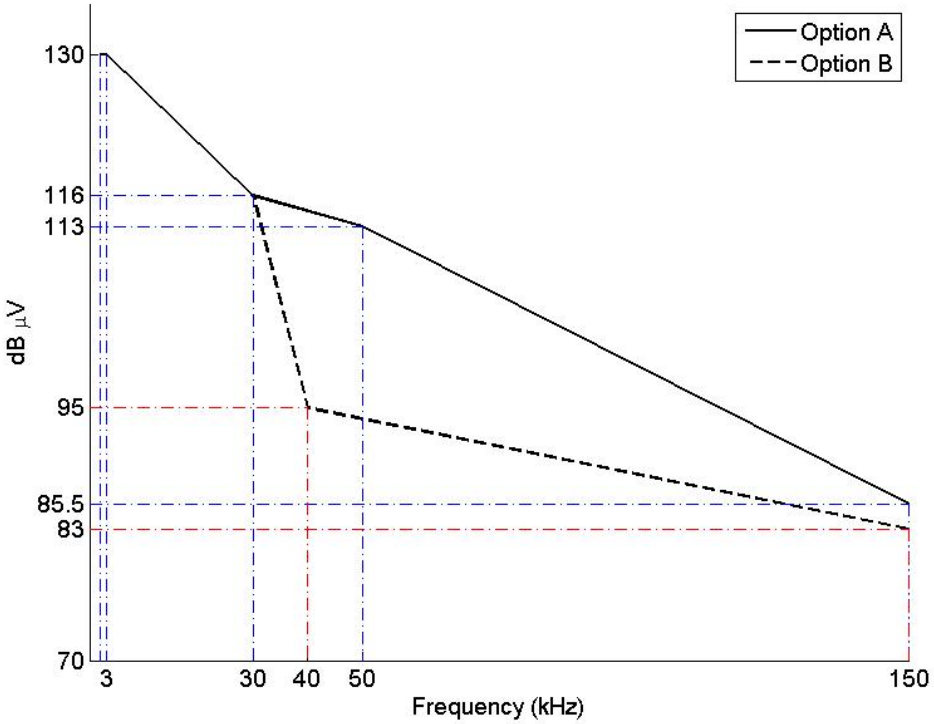


Fig. 2. IEC Proposed CLs

Working Group 8 manufacturing and utility experts have reached an agreement on the CLs between 2-30 kHz. There are two options, shown in Fig. 2, that are being considered for the 30-150 kHz range. Option A is supported by experts related to general industry manufacturing and usage equipment, not including communication systems. Experts recommending option A are in favor of this higher-level curve, arguing that initial estimates have shown the use of filters systematically in all equipment to reduce disturbance ELs is far more expensive than solving the electromagnetic interference to communication system issues on a case by case basis. Further, reports show that PLC technology is operating as intended in more than 97 % of the locations in Finland, with no emission limits existing in the 2-150 kHz range for most equipment [4]. Alternatively, supporters of option B, experts in electricity distribution and the communication systems industry, argue that the emission limits for non-intentional emissions provided in IEC 61000-3-8 have been assumed as reference for designing PLC technologies used for smart metering and other smart grid services in Europe and worldwide. The proposed option B curve is based on CLs derived from the IEC 61000-3-8 curve for non-intentional emissions. Therefore, option B would insure proper operation of technologies for smart grid communications. Additionally, based on data collected recently in Italy, it has been shown that the non-intentional emissions generated by several pieces of equipment (such as lighting equipment) were below this proposed CL curve, minus 3 dB, leaving room for deviation from estimates.

Further investigation of the benefits and concerns for both options for CLs in the 30-150 kHz range is required in order to come to a final consensus. It is assumed by all experts involved in the revision of IEC 61000-2-2 that the implementation of this standard for all equipment will assure that ELs in LV networks will be kept at the same level for the future. Also, new limits will certainly need to be defined with the intent to produce minimum costs to society.

2.2 Planning Level

Planning levels (PLs) are set based on the summation of individual emission limits for normal operation. These PLs are accepted as a reference to coordinate emission limits set for consumer load devices connected to the power system. Therefore, these levels are generally lower than the CL by a specific margin that takes into account the structure and electrical characteristics of the local supply network. This margin is necessary to make allowance for possible system resonance and for an upward drift in the levels on the network due to future loads that may be connected. Such loads include computers and other home and office electronic equipment that contain switched-mode power supplies. Additionally, there is uncertainty about the impedance of the supply systems and the customers' equipment at harmonic frequencies. As a result, PLs are determined after CLs are defined.

2.3 Emission Limits

Provided PLs, emission limits can be determined. Emission limits are limits set for individual end user devices [3]. Setting emission limits is necessary in order to limit the total disturbance at the meter and throughout the system as a whole. Determining emission limits requires the PL to be set so that emission limits for individual devices may be selected to reasonably account for the total sum of emissions system-wide.

Knowledge of the present harmonic environment in the 2-150 kHz range is necessary to assist the industry and utilities with specifying new emission limits. Information about high frequency disturbances is also useful in setting reasonable standards so that neither manufacturers nor utilities require major changes for appliances or communication methods, respectively. There has been some activity in Europe [5] and in North America [6] in investigating ELs of lamps, televisions, and common household appliances. Analysis of ELs at the power supply outlet may be used to preliminarily consider emissions produced by a distinct device. Nonetheless, a summation law for the 2-150 kHz range will be required to provide approximate emission limits for individual devices given the total EL at the PCC, or installation-level emission limits.

There are installation-level emission limits in IEC Standard 61000-3-6 [7] that have a designated summation law for harmonics up to 2 kHz for medium voltage (MV), high voltage (HV) and extra high voltage (EHV) systems (1). This summation law is defined by α, the summation law exponent chosen according to the harmonic order, defined in Table 1; U_{hi}, the hth harmonic for a single customer i; and U_h, the total hth harmonic voltage component produced collectively by all users. At this time, no summation law exists in the 2-150 kHz LV environment.

$$U_h = \sqrt[\alpha]{\sum_i {U_{hi}}^{\alpha}} \qquad (1)$$

Table 1. Summation Law Exponents (50 Hz system)

Harmonic Order	**Frequency Range**	α
$5 \leq h \leq 10$	250 – 500 Hz	1.4
$11 \leq h \leq 40$	550 – 2000 Hz	2

Consideration of a summation law in this environment, in the higher-order harmonic range, requires CLs and PLs to be defined. Therefore, determining CLs and PLs, and setting a summation law for the 2-150 kHz range may be aided by analyzing standards that are set for types of disturbances that may attribute to the high frequency disturbances that are of consequence to PLC systems. Analyzing current standards relevant to these disturbances caused by end user devices could assist in choosing different levels.

Chapter 3: Commutation Notches

End user devices, such as a computer or a television, contain AC to DC converters, known as rectifiers. The process of converting an alternating current to a direct current is known as rectification. An example of a rectifier is shown in Fig. 3. The bridge rectifier shown has two diode pairs. One diode pair is switched on while the other is switched off for each half-cycle of Vac. When current flow transitions from one diode pair to another, this is known as commutation. Ideally, AC voltages and currents are perfect sinusoids without distortion. In an actual power system, this is not the case due to harmonics resulting from non-linear loads. Harmonics are sinusoidal voltages and currents at integer multiples of the system's fundamental frequency, which is 60 Hz in North America and 50 Hz in Europe. There are standards that limit power system disturbances above 150 kHz (in IEC 61000-3) and below 3 kHz (in IEEE-519) and 2 kHz (in IEC 61000-2), but no standards are currently set for the range between 2-150 kHz used by wired smart meters. Higher integer (higher-order) voltage distortion can affect revenue billing due to communication failures, resulting in inaccurate discernment of kilowatt-hour consumption for billing.

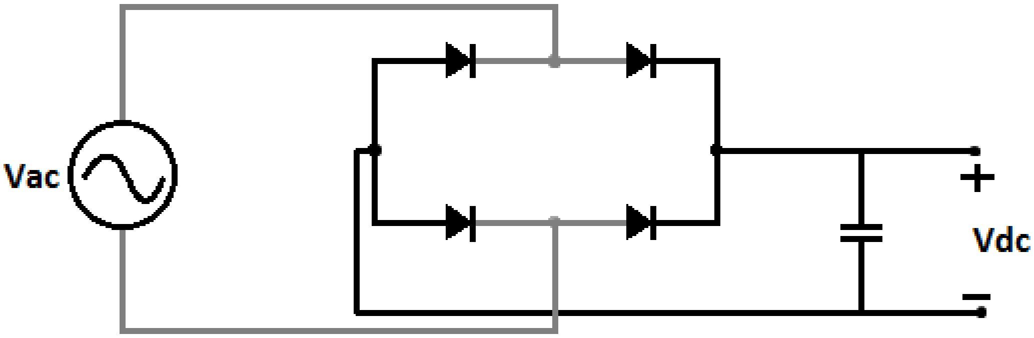


Fig. 3. Bridge Rectifier

An example of a recurring disturbance seen during the normal operation of an end user device that contains a rectifier is a commutation notch. Commutation notches occur as a result of current flow transitions from one diode pair to another, represented in Fig. 4. The resulting voltage notches can be characterized by harmonics because notching occurs in steady-state and can be distinguished by the harmonic spectrum of the voltage, and by transients because they are a repetitive event [8]. Voltage notches introduce harmonic frequencies in the radio frequency range, 3 kHz to 300 GHz, causing negative operational effects in communication circuits.

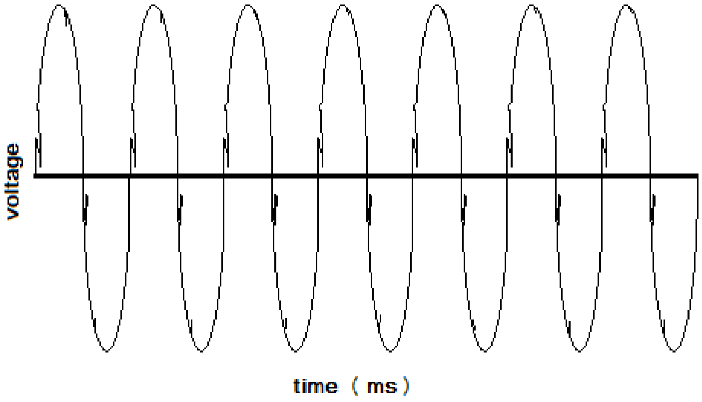


Fig. 4. Commutation Notch Example

3.1 IEEE Standard 519

The only standard in North America that contains limits for commutation notches is IEEE-519 [9]. The requirements for dedicated systems that supply a specific consumer or consumer load, general systems, and special applications such as airports are listed in Table 2. These limits are defined in Fig 5. The limits set for notch area represent the total area deviation from the normal sinusoidal waveform of a period of one half-cycle.

Table 2. IEEE Std. 519 Recommended Commutation Notch Limits

	Special applications	**General System**	**Dedicated system**
Notch depth (d)	10%	20%	50%
Notch area (A_N)[a, b]	16400	2280	36500
[a]In volt-microseconds at rated voltage and current. [b]The value for A_N have been developed for a 480 V system. It is necessary to multiply the values given by V/480 for application by all other voltages.			

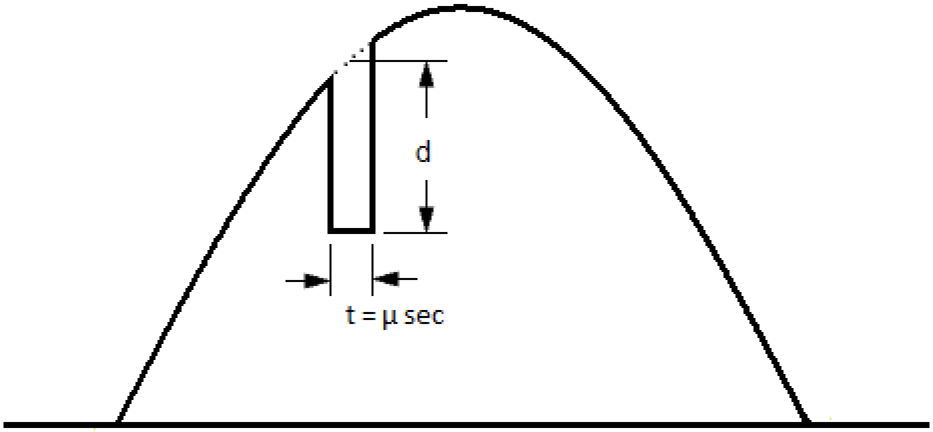


Fig 5. Definition of Notch Depth for Notch Area Calculation

These notch limits are not representative of the considerations used in deciding the proposed CLs discussed in Chapter 2. Notch limits are limits – they are not levels of any kind. First CLs must be defined, then PLs will be set, and finally, emission limits can be derived. For the purposes of this evaluation, the commutation notch limits defined for general systems are used to establish PLs for the 2-150 kHz band. Once the PL curve is defined, individual shares for users or equipment can be divided to establish ELs. These shares will likely be based on a summation law for the 2-150 kHz range. In order to consider these commutation notch limits for the development of PLs in the 2-150 kHz range, the notch limits detailed in IEEE-519 must be considered in the frequency domain over the specified range.

Chapter 4: Fourier Series of Commutation Notches

In order to compare the commutation notch limits to the CLs in Chapter 2, Fourier analysis is performed to transform the notch area limits defined in the time domain to the frequency domain. Again, the results based on commutation notch limits defined in IEEE Standard 519 are not used to compare to the CLs that will be set by IEC, but the results should provide an indication of what PLs must be set in order to consider emission limits allotted for individual end user devices and households. All of these considerations will also require a summation law for the 2-150 kHz range.

4.1 Trigonometric Fourier Series

In order to calculate the Fourier coefficient, c_n (2), the coefficients a_n (3) and b_n (4) were calculated for each integer harmonic in the 2-150 kHz range based on [10]. These calculations were performed for a 50 Hz system. The waveform f(t), shown in Fig. 6, was defined for a full cycle (20 ms) with a notch set at the maximum allowable area set for general systems in IEEE Standard 519. In order to normalize results of the notch limits over the range 2-150 kHz for a general system, the area was divided by 480 V. The angle at which the notch was centered was chosen at 60 degrees and 240 degrees for the positive and negative half cycle, respectively. It is important to note that this angle was varied and no change to the final results was observed.

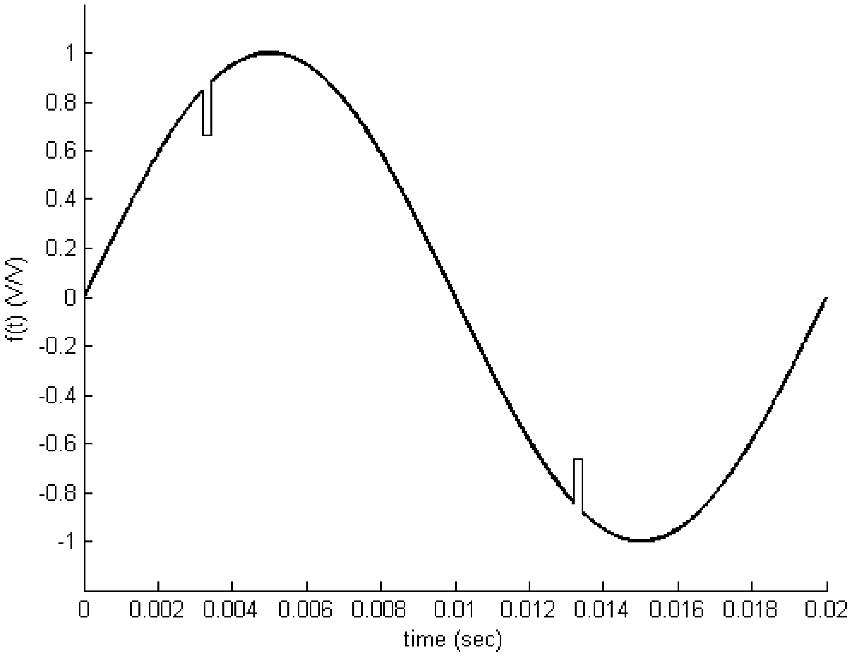


Fig. 6. Per- Unit f(t) for Fourier Analysis

$$c_n = \sqrt{{a_n}^2 + {b_n}^2} \tag{2}$$

$$a_n = \frac{2}{T}\int_0^T f(t) * \cos(n * \omega_o * t)\, dt \tag{3}$$

$$b_n = \frac{2}{T}\int_0^T f(t) * \sin(n * \omega_o * t)\, dt \tag{4}$$

MATLAB was used to calculate and plot the results of the Fourier coefficients. The best-fit line for the output c_n is shown in Fig. 7. The best-fit line is used to represent the maximum notch limits over the range. A selection of results at noted frequencies from the IEC utility proposed CLs are shown in Table 3. Based on the specifications of the notch limits in IEEE-519 and the characteristics of the summation of emissions for lower order disturbances, the notch limits are clearly representative of single disturbances and not the summation of disturbances represented by the proposed CL curve. Therefore, the commutation notch limits seem to reasonably represent future considerations for equipment limits.

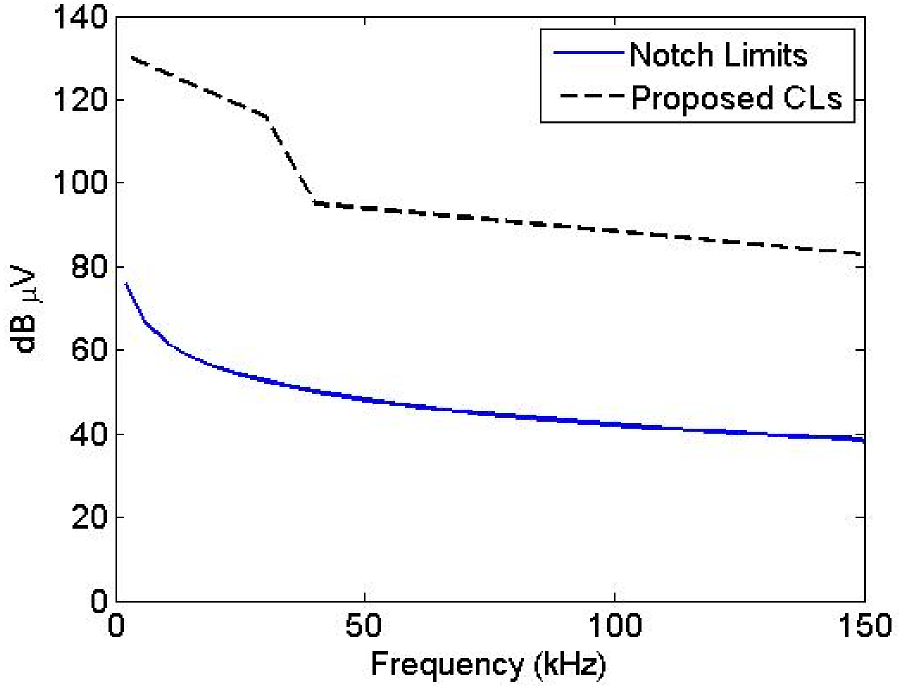


Fig. 7. Notch Limit Results Using Trigonometric Fourier Series

Table 3. Notch Limit Results at Select Frequencies

Frequency (kHz)	CLs (dB µV)	Notch Limits – 50 Hz (dB µV)
2	130	76.3
3	130	70.9
30	116	52.7
40	95	50.1
150	83	38

4.2 Exponential Fourier Series

Calculating the Fourier coefficient, c_k (5), for each integer harmonic in the 2-150 kHz range required fewer calculations using the exponential Fourier series [10] and serves as a validation of the results in Fig. 7. The results of the Fourier analysis are shown in Fig. 8. The results for the exponential Fourier analysis were the same as the results in Fig. 7. The results of the exponential Fourier analysis verify the results from the trigonometric Fourier analysis.

$$c_k = \frac{1}{T}\int_0^T f(t) * e^{-j*k*\omega_o*t}dt \qquad (5)$$

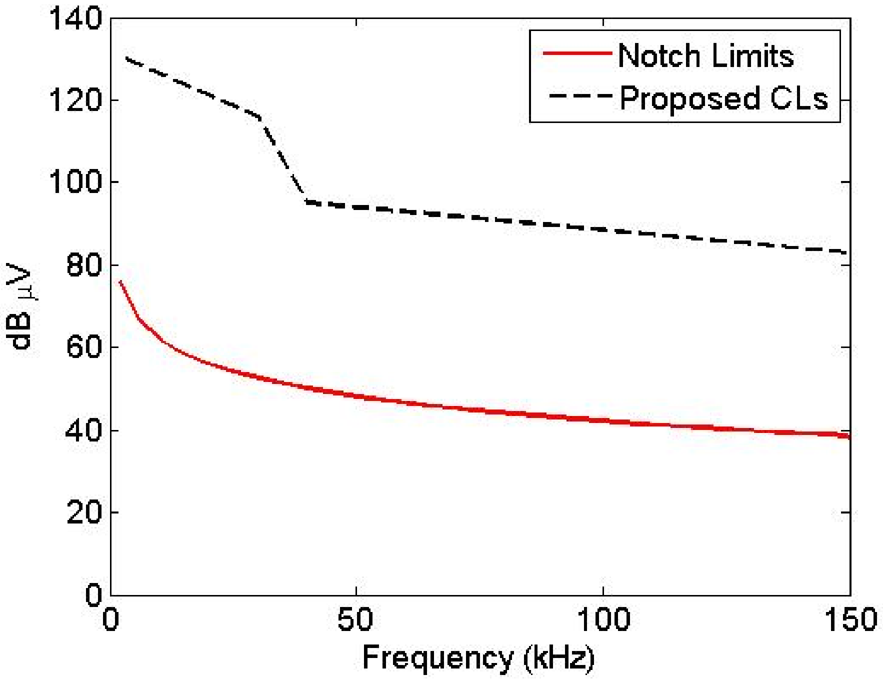


Fig. 8. Notch Limit Results Using Exponential Fourier Series

Evaluating IEEE-519 to assess the utility proposed CLs may not be directly useful in setting CLs, but it is useful in determining suitable PLs and ELs for individual end-user devices. An example of possible PLs, compared to the notch limit results and proposed CLs, is shown in Fig. 9. This illustrates the relationship between CLs, PLs, and individual device emission limits – where the sum of individual device limits will not exceed the PLs, and the PLs are roughly an order of magnitude less than CLs. Since CLs must be chosen first, other analyses are required before the actual PL curve can be identified. It is reasonable to use measurements of the present system environment in order to further consider the IEC proposed CLs.

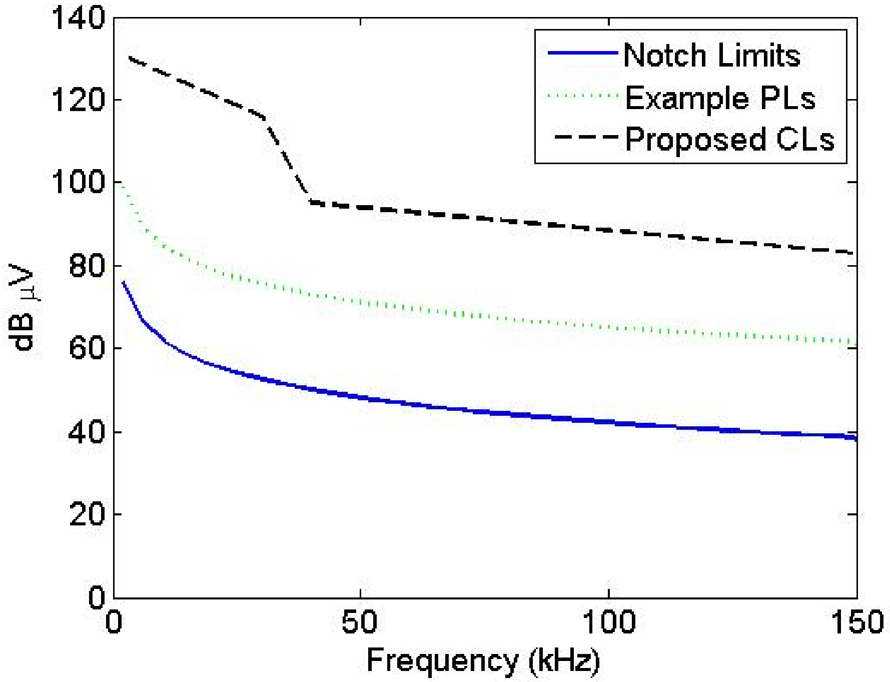


Fig. 9. Example PLs vs. Notch Limits and Proposed CLs

Chapter 5: Measurements

To better consider the proposed IEC levels, measurements of end-user devices are necessary to inspect the existing high frequency environment. Measurements of common end-user devices, such as lamps and kitchen appliances, have been conducted in Europe and reported in the literature [11, 12]. However, there is limited data available from North America. Again, it is beneficial to consider measurements and standards internationally in order to set reasonable ELs.

To obtain a reasonable representation of the 9-150 kHz environment (the band particularly critical for smart meters) based on current conditions, common household items such as lighting and televisions were tested in North America. A 100 MHz digitizing oscilloscope with built-in Fourier analysis tools was used to take voltage signal measurements directly from the local public network. Equipment was connected to the public supply source (wall outlet) using a standard three-wire cable. Measurements were taken at (1) the wall outlet, and (2) the load equipment connection at the other end of the three-wire cable, as represented in Fig. 10 [6].

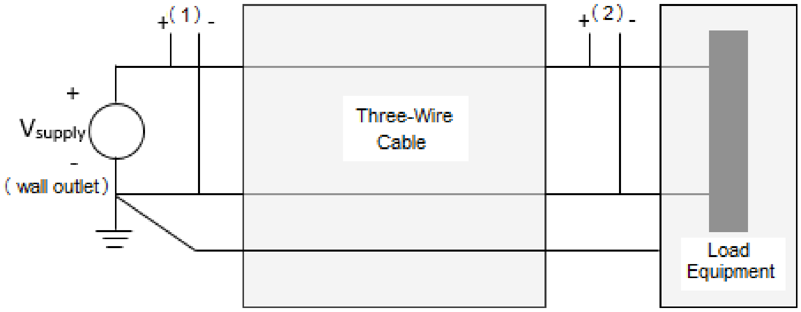


Fig. 10. Load Equipment Measurement Setup

Further, the fourth-order high-pass filter with an estimated cutoff frequency, f_c, of 1 kHz, shown in fig. 11, was added at the wall outlet. The purpose of the high-pass filter was to attenuate the 60 Hz power frequency to remove small spectral components that would otherwise be added over the 9-150 kHz range [6]. The transfer function, Vout/Vin, of the high-pass filter was analyzed using the Solartron SI 1260 Impedance/Gain-Phase Analyzer, and the results in Fig. 12 verify that the filter attenuates well above the power frequency, and offers minimal attenuation in the 9-150 kHz frequency range.

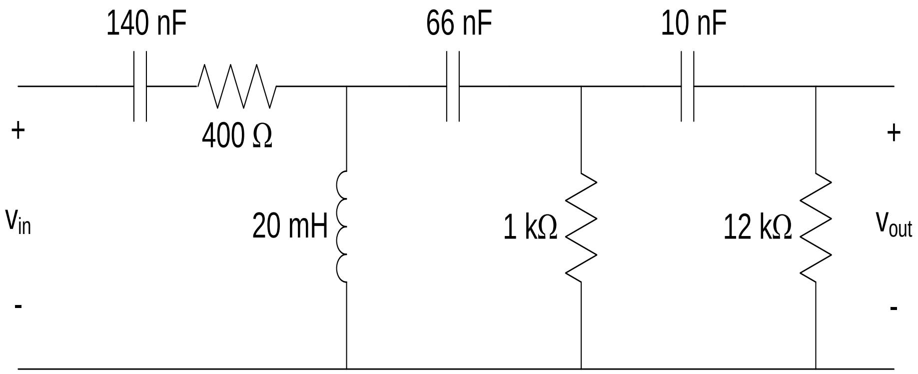


Fig. 11. High-Pass Filter Designed to Remove Power Frequency

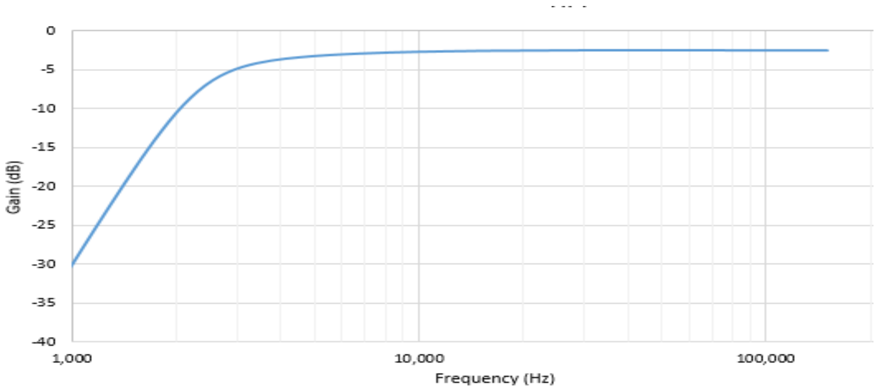


Fig. 12. High-Pass Filter Transfer Function

5.1 Measured End-Use Device Results

Measurements were initially performed at the wall outlet with no end-use devices operating to establish a baseline condition of the high frequency environment. The ability to recognize and analyze expected variations in background ELs over a long period of time was obtained by measuring over a 72-hour evaluation period including an ordinary workday, multiple nighttime periods, an end-of-week day, and a holiday. The results were averaged over a period defined by a date and hour-of-day range, and are shown in Fig. 13. The magnitudes of the recorded measurements were converted from RMS to peak values so that they may be considered on the same scale as the proposed CLs.

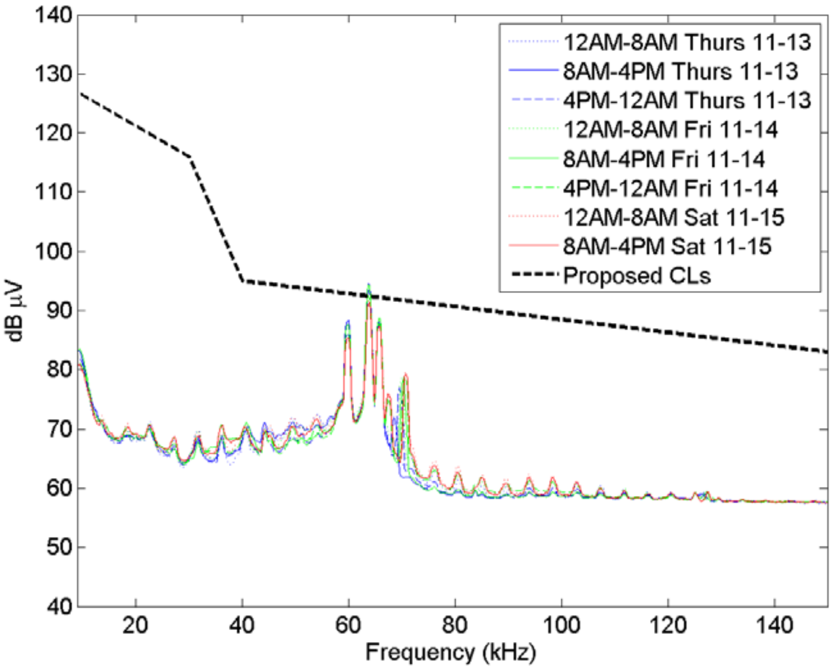
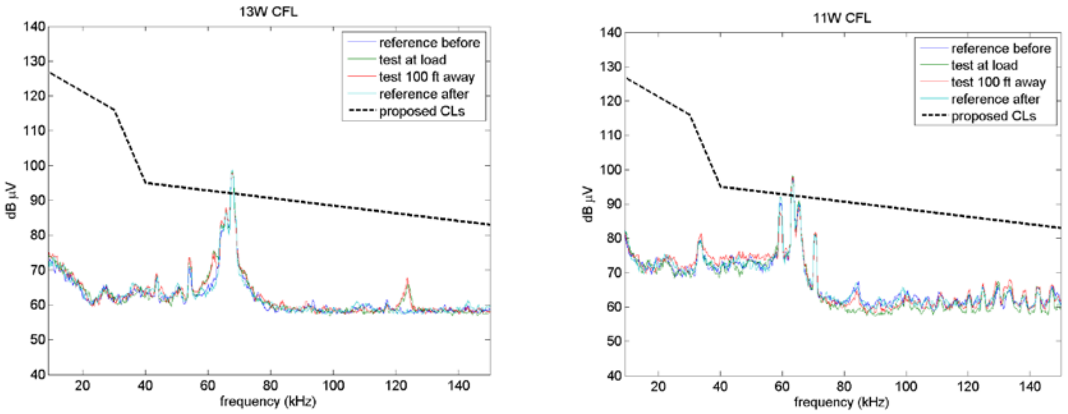


Fig. 13. 72-hour Background Emission Levels vs. Utility Proposed CLs

Variations in the background ELs are negligible over the 9-150 kHz range. The most significant note from these results is the background emissions in the 60-70 kHz range that exceed or nearly exceed the proposed CL curve. These longer period background levels will be useful for evaluating potential measurement errors, as erroneous measurements would likely deviate significantly from the established background levels shown in Fig. 13.

Provided the background EL results, specific end-use devices were measured on both ends of the supply cable (at the wall outlet and at the load) and with and without the end-use device in operation. For the cases with the end-use device disconnected, measurements were made both before and after the end-use device was connected and operating. This means the reference levels immediately before and after each test could be known and, for validation purposes, compared to the averaged time results of Fig. 13.

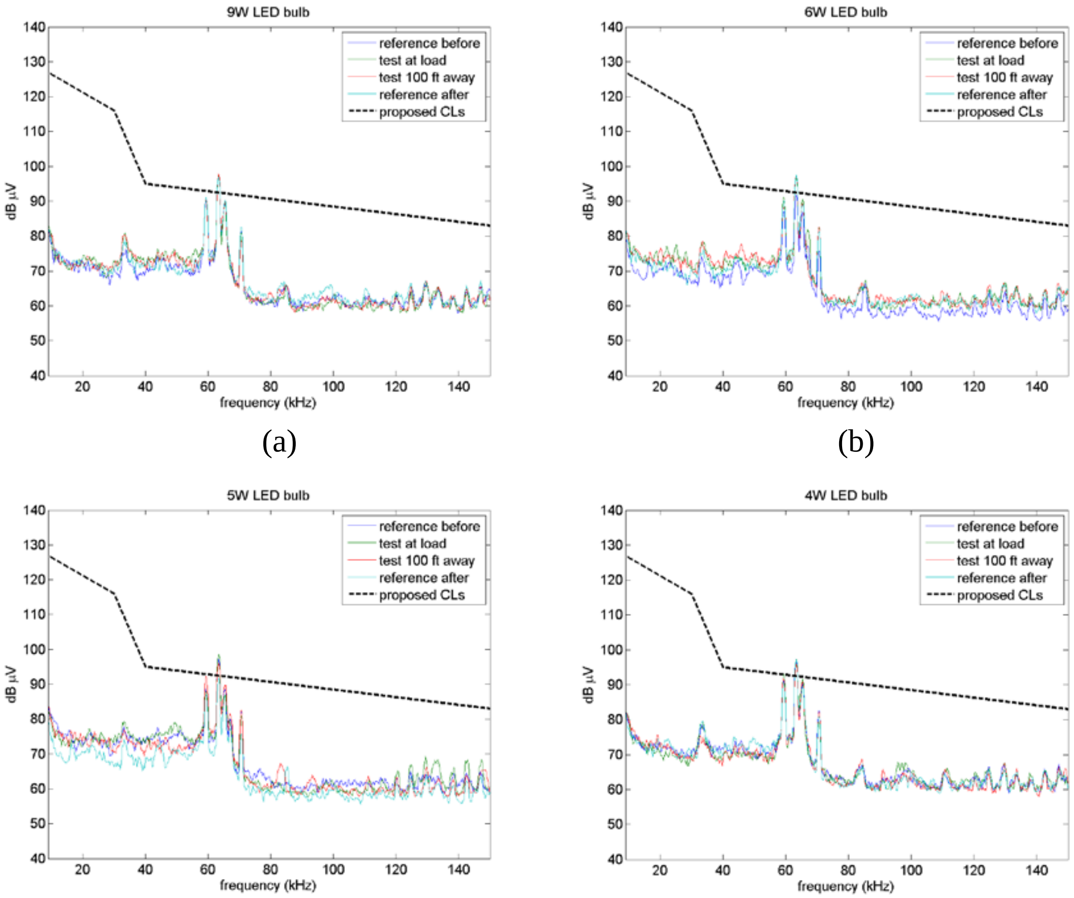
The results of two different compact fluorescent lamp (CFL) tests are shown in Fig. 14 (a) and (b). These results clearly show that one of the CFLs produces a noticeable emission around 120 kHz whereas the other tested lamp provides an attenuating effect around 80 kHz at the load terminals, but not at the supply terminals. From these two tested lamps, it does not appear reasonable to draw generalized conclusions. However, comparing the test results to the proposed CL curve, it is evident that ELs 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-use devices and is indicative of the EL of each of the tested CFLs.



(a) (b)

Fig. 14. CFL Measurements vs. Utility Proposed CLs

The results of four LED lamp tests are shown in Fig. 15 (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 is no significant impact on emissions relative to the background levels at either the wall outlet or load terminals. Again, all the tested LED lamps contribute to exceeding or nearly exceeding the proposed CL curve in the 60-70 kHz range for each of the tests conducted. In tests (b) and (c), before the reference and after, respectively, there is a lower EL than measurements taken while the end-use device was in service for the entire 9-150 kHz range.

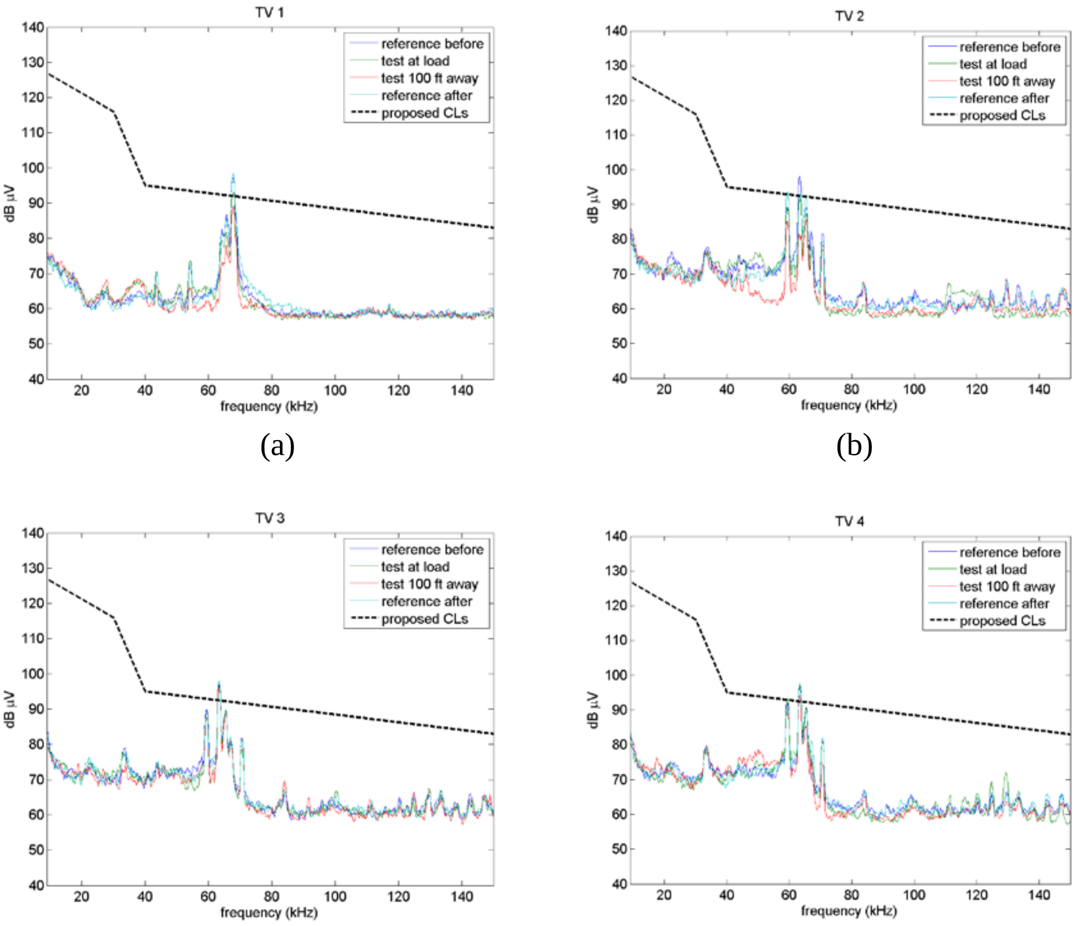


(a) (b)

(c) (d)

Fig. 15. LED Measurements vs. Utility Proposed CLs

The results of four television/display tests are shown in Fig. 16 (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 the ELs change with and without the end-use device in operation in all cases. Again, all tests show that ELs in the 60-70 kHz band exceed the utility proposed CL curve.



(a) (b)

(c) (d)

Fig. 16. Television Measurements vs. Utility Proposed CLs

5.2 Line Resonance Considerations

So that the measurements at the supply terminals (wall outlet) will represent the measurements at the PCC, measured data at the wall outlet must be multiplied by the transfer function of the line that connects between these two points. Therefore, the transfer function of a line connecting the wall outlet to the PCC was determined by measuring a 50ft (approximately 15.24m), Romex 12 gauge, 3 conductor indoor non-metallic sheathed cable using an impedance analyzer. Further, the line model was approximated based on the specifications of the Romex cable. 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.

5.2.1 Line Impedance Measurements

The Solartron Impedance/Gain-Phase Analyzer was set up once more so that a signal input and output were measured on opposite ends between two of the Romex cable conductors, as shown in Fig. 17. The input signal was set at 10V. The analyzer was set up to measure transfer function Vout/Vin (V2/V1) over the total frequency range 2-150 kHz. The results are shown in Fig. 18. The measurements were conducted over the 2 kHz-20 MHz frequency range to determine resonances that occur in the line, even beyond the range of interest. It is evident from the measurements shown that resonances in the wire do not occur until the MHz range, and the gain is approximately 1V/V in the 2-150 kHz range.

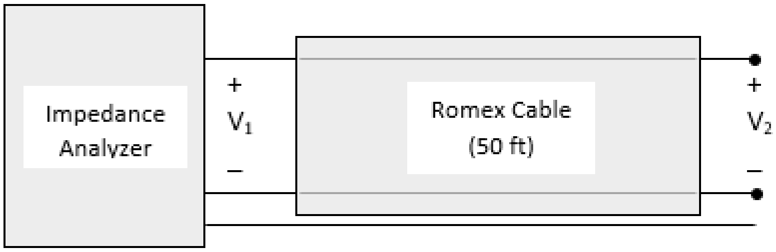


Fig. 17. Romex Cable Measurement Setup

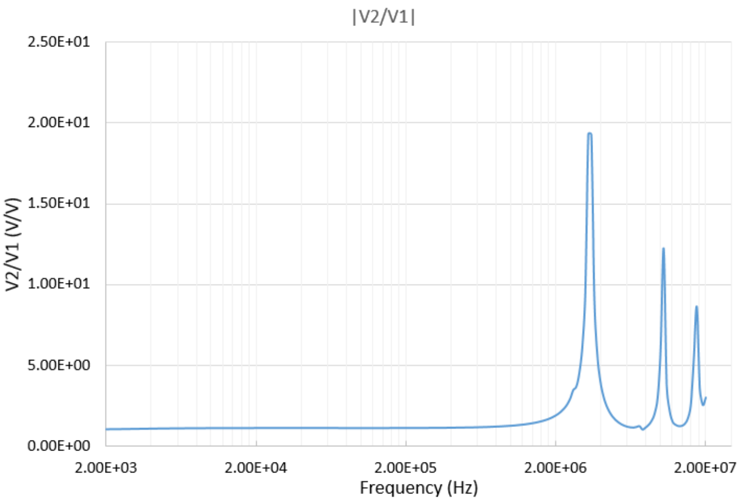


Fig. 18. Impedance Analyzer Measurements of 12-3 Romex Cable

5.2.2 Line Impedance Model

An equivalent, per-meter line model based on RLC parameters was calculated to determine the resonant frequency (f_0) of the Romex cable to verify the measured results. The series dc conductor resistance R, series inductance L, and shunt capacitance C parameters were calculated using (6), (7), and (8) based on single line calculations [13]. The per-meter line model design is shown in Fig. 19. It is important to note that resonances at high frequencies cause issues, however, the length of the line is important when considering line modeling [14]. The f_0 based on the calculated LC values (for the 15.24m line) is approximately 2.8 MHz according to (9). Recognizing the free space for conductors to move in the Romex cable, the measured distance between conductors (D) is not exact. Still, considering the measured transfer function in Fig. 18, the calculated value for f_0 is reasonable.

$$R_{dc} = \frac{\rho l}{A} \tag{6}$$

$$L = \frac{\mu}{2\pi} ln \frac{D}{r'} \tag{7}$$

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{D}{r}\right)} \tag{8}$$

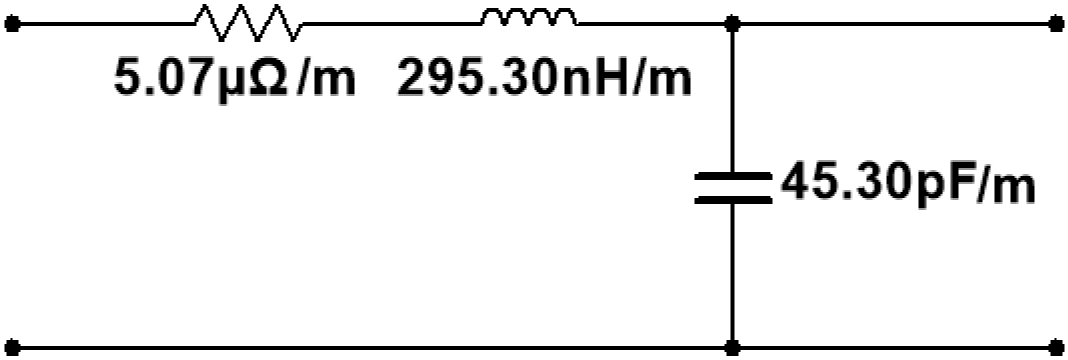


Fig. 19. Per-Meter Romex Cable Line Model

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{9}$$

Based on the calculations and measurements of the Romex cable, it is reasonable to state that for short lines used in residential homes in the United States (i.e. 100ft), a single equivalent RLC circuit is sufficient for modeling the line between the wall outlet and the meter. This claim is based on the electrical wavelength, λ, for this line. The wavelength (10) is approximately $1.5\text{x}10^5$ m – $2\text{x}10^3$ m from 2-150 kHz. Assuming an electrically short line is λ/4, the Romex cables 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 [14], such as the one in Fig. 19.

$$\lambda = \frac{v}{f} \tag{10}$$

Chapter 6: Summary

Although North America has not (yet) faced the same issues with PLC for smart meter communication, it is of interest for North America to follow and make recommendations for future proposals made by the IEC in order to prepare for implementation of alternative metering methods such as PLC that may be utilized in the future. Considering the CLs proposed in Europe, CLs based on established standards in North America should also be considered. Since the limits for specific disturbance sources exist only in IEEE Standard 519, there are no true CLs defined in the 2-150 kHz range that can be directly considered and compared to the maximum EL that is defined by CL curve proposed by the IEC. However, the analysis of limits based on IEEE Standard 519 commutation notches are reasonable to consider for development of PLs and a summation law for the higher-order harmonics in the 2-150 kHz range. These PLs and a summation law may only be considered once a CL curve is established. It is clear from the results of the Fourier Analysis of the 519 commutation notch limits for general systems that they are a reasonable representation of emission limits that may be set if the CLs proposed are chosen.

The ultimate objective of defining these different ELs is for the emission limits for individual disturbing sources to result in total summated PLs, considering all disturbance sources, which are below the established CLs. These PLs are based on a reasonable range so that they do not exceed the maximum permissible total ELs, the CLs. Both sets of the

IEC proposed CLs drop off as frequency increases, however, the IEEE limits are based solely on commutation notches, and therefore only represent a single type of disturbance. The CL curve is representative of the limit for the sum of all disturbances seen at the PCC.

Based on the results from the measurements taken at a wall outlet compared to the IEC proposed CLs, it is evident that the total level of disturbance, based on background ELs and the different end-user devices analyzed, exceeds the utility proposed CL curve when the tested equipment is in service. However, comparing the measurements to the manufacturer proposed CL curve shows that the curves are not exceeded, with or without the tested equipment in service, in the 60-70 kHz range. Therefore, based on the North American measurements conducted, the manufacturer proposed CLs in the 30-150 kHz are a better choice than the utility proposed CLs. If the utility proposed CL curves were to be adopted in the United States, filtering (added on devices or at the PCC) would be required to help reduce undesired harmonics to values below the defined CLs in the 60-70 kHz range.

It is important to note that the different end-user devices and the averaged background EL measurements were conducted at the wall outlet and not at the PCC. However, based on the measurements and calculations performed to analyze the propagation from the wall outlet to the probable smart meter location, it is reasonable to assume that there is no need to multiply measurements taken at a wall outlet by anything. Therefore, measurements taken at the wall outlet reasonably represent measurements seen at the meter PCC.

Chapter 7: Recommendations and Future Work

After CLs are standardized to reflect a compromise between utilities and manufacturers, considerations for an internationally accepted summation law must be established. This summation law should be based on combining multiple items of equipment, each complying with the notch limits in 519 or similar emission limits, that results in some reasonable number of items of equipment combining with a summated result equal to the PL. This summation law would define how many pieces of equipment, each complying with the notch or similar limits, can be in service at the same time before the total EL at the PCC reaches the PL. Such a summation law could alternatively be used to provide an approximate identification of emissions produced by individual end user devices from total measured levels.

Further, measurements of total emissions based on allotted established limits requires the development of testing and measurement specifications that are applicable to the general 2-150 kHz range similar to those which exist for products at frequencies below 2 kHz, as specified in the 61000-4 series IEC standards. Specifically, measurements at the PCC (the summation of connected devices) and at the public supply source (the individual devices) will provide insight for this summation law.

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Appendix 1

1.1 MATLAB Code for Initial Set-up of Fourier Series Calculations

```
V = 480;               % 480V sys used for An in Std.519
f = 50;                % fund. freq.
T = 1/f;               % period
n = 3000;              % 3k*50Hz = 150kHz
wo = 2*pi*f;           % rad/s freq.
An = 22800;            % notch area, 480V gen sys
Vs = 1;                % p.u. voltage
An1 = Vs*An/V;         % notch area, 1V gen sys
d = 0.2;               % notch depth limit, gen sys
dT = (An1/d)*e-6;      % since An = d*(T2-T1) in u-sec
Tc = 60/360/f;         % for 60deg
T1 = Tc - (dT/2);      % T2-T1 = dT
T2 = Tc + (dT/2);
```

1.2 MATLAB Code for Calculating the Fourier Series – Trigonometric

```
% Calculate Fourier Series – 2-150kHz
for k = 1:n
    fun1 = @(t) sin(wo*t).*cos(k*wo*t);
    fa1(k) = integral(fun1,0,T1);
    fun2 = @(t) (((sin(T1*wo)+sin(T2*wo))/2)-
d).*cos(k*wo*t);
    fa2(k) = integral(fun2,T1,T2);
    fun3 = @(t) sin(wo*t).*cos(k*wo*t);
    fa3(k) = integral(fun3,T2,T/2+T1);
    fun4 = @(t)
(((sin((T/2+T1)*wo)+sin((T/2+T2)*wo))/2)+d).*cos(k*wo*t);
    fa4(k) = integral(fun4,T/2+T1,T/2+T2);
    fun5 = @(t) sin(wo*t).*cos(k*wo*t);
    fa5(k) = integral(fun5,T/2+T2,T);
    Ak(k) = 2*f*(fa1(k)+fa2(k)+fa3(k)+fa4(k)+fa5(k));
    fun6 = @(t) sin(wo*t).*sin(k*wo*t);
    fb1(k) = integral(fun6,0,T1);
    fun7 = @(t) (((sin(T1*wo)+sin(T2*wo))/2)-
d).*sin(k*wo*t);
    fb2(k) = integral(fun7,T1,T2);
    fun8 = @(t) sin(wo*t).*sin(k*wo*t);
    fb3(k) = integral(fun8,T2,T/2+T1);
    fun9 = @(t)
(((sin((T/2+T1)*wo)+sin((T/2+T2)*wo))/2)+d).*sin(k*wo*t);
    fb4(k) = integral(fun9,T/2+T1,T/2+T2);
    fun10 = @(t) sin(wo*t).*sin(k*wo*t);
    fb5(k) = integral(fun10,T/2+T2,T);
    Bk(k) = 2*f*(fb1(k)+fb2(k)+fb3(k)+fb4(k)+fb5(k));
    fs(k) = (k*f);
    Ckn(k) = sqrt((Ak(k)^2)+(Bk(k)^2));
    Ck(k) = mag2db(Ckn(k))+120;  % +120 for dBuV,
end

plot((fs(39:2:n-1))/1000,Ck(39:2:n-1))
xlabel('Frequency (kHz)');
ylabel('dB \muV');
```

1.3 MATLAB Code for Calculating the Fourier Series – Exponential

```
% Calculate Fourier Series – 2-150kHz
for k = 1:n
    fun1 = @(t) sin(wo*t).*exp(-1j*k*wo*t);
    fc1(k) = integral(fun1,0,T1);
    fun2 = @(t) (((sin(T1*wo)+sin(T2*wo))/2)-d).*exp(-
1j*k*wo*t);
    fc2(k) = integral(fun2,T1,T2);
    fun3 = @(t) sin(wo*t).*exp(-1j*k*wo*t);
    fc3(k) = integral(fun3,T2,T/2+T1);
    fun4 = @(t)
(((sin((T/2+T1)*wo)+sin((T/2+T2)*wo))/2)+d).*exp(-
1j*k*wo*t);
    fc4(k) = integral(fun4,T/2+T1,T/2+T2);
    fun5 = @(t) sin(wo*t).*exp(-1j*k*wo*t);
    fc5(k) = integral(fun5,T/2+T2,T);
    C15(k) = fc1(k)+fc2(k)+fc3(k)+fc4(k)+fc5(k);
    Ckn(k) = 2*f*(abs(C15(k)));
    fs(k) = (k*f);
    Ck(k) = mag2db(Ckn(k))+120;  % +120 for dBuV,
end

plot((fcn(39:2:n-1))/1000,Cn(39:2:n-1))
xlabel('Frequency (kHz)');
ylabel('dB \muV');
```