Potential Impacts of 9-150 kHz Harmonic Emissions on Smart Grid Communications 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 between distributed smart meters and some central relay point. 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. Numerous smart meter products are designed to communicate in the 2-150 kHz frequency band range. 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 the International Electrotechnical Commission Technical Committee 77, Sub-Committee 77A, Working Group 8, which is presently tasked with developing compatibility levels for disturbances in this band. However, only limited (if any) work has been done in North America. It is unknown if compatibility levels developed based on the European low-voltage environment are applicable in North America where the environment is much different in several key aspects. Emission evaluation results from product testing in the 120 V three-wire low-voltage environment commonly found in North America are presented in this paper. Results of initial tests conducted to evaluate 9-150 kHz disturbance propagation through North American low-voltage systems are also presented.**

Keywords-smart grid, power line communication, high-frequency harmonics, electromagnetic compatibility.

I. INTRODUCTION

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 providing many other characterizations of 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.

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 over the range 2-150 kHz [1]. This frequency range includes the bands used by most smart meter manufacturers for communications via the power line (PLC). Lacking existing compatibility levels and limits in the 9-150 kHz range has resulted in smart meter development without regard to standardized background emission levels and problems are beginning to appear [2]. Other problems in addition to PLC failures have also been attributed to harmonics in this range [3]-[5]. All industry stakeholders recognize the need for rapid standardization and numerous activities are underway across Europe. Concerns related to PLC systems are most often the main focus [2][6-8].

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 compatibility levels in the 2-150 kHz frequency range [9]. 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 [6][10]. 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 alternative energy (e.g., photovoltaic system) interfaces with the public network. All of these emissions combine in the LV network serving the end-user facility and the cumulative disturbance 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 [11]-[13].

To date, all testing, research, and evaluation of high-frequency harmonic product emissions has been focused on products used in European LV networks [11][14]. While these networks are certainly important, smart meter manufacturers stand to benefit from a truly international specification that can be used on a global scale. To accomplish this, information on products used in North American LV networks is required. The testing and measurement approach used in this work to help provide

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information on North American LV networks is described in Section II. Emission testing results for some 120 V products in common use in North America are presented in this paper in Section III. Also in Section III, results of tests to assess high-frequency disturbance propagation in 120 V, three-wire LV systems are presented so that postulates can be developed regarding how multiple disturbance-producing (in the 9-150 kHz range) products might summate at the point of service where the smart meter is located.

II. TEST AND MEASUREMENT APPROACH

All measurements were carried out on 120 V equipment and systems using a 100 MHz Tektronix 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 (#12 AWG solid copper "romex" cable commonly used in North America) 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 and mimics a standard 120V service to end-use equipment. Note that the required filters, described later in this paper, are connected at the terminals of measurement points M_1 and M_2 prior to the connection of the measurement equipment.

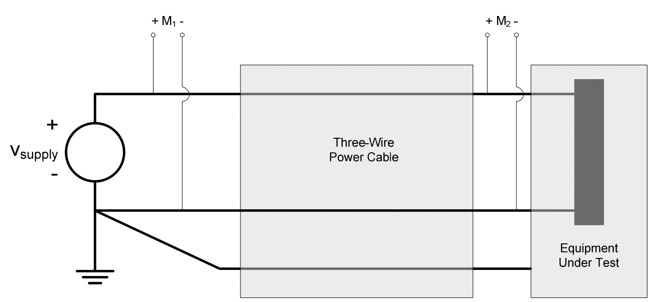


Figure 1. Test and Measurement Setup

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.

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 [11]-[13]. While theoretical models can be developed for simple cases, this task can be 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 disturbance levels in the range 9-150 kHz are on the order of a few millivolts (mV) and are commonly expressed in the units "decibel-microvolt" (dBμV) where 20 dBμV= 10*1 μV=10 μV, 40 dBμV=100*1 μV=100 μV, etc. Expressed in this common dBμV unit, typical disturbance levels in the frequency range of interest will be around 80-100 dBμV (10-100 mV). Of course, these disturbance 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 [14]. The analog filter design is shown schematically in Figure 2.

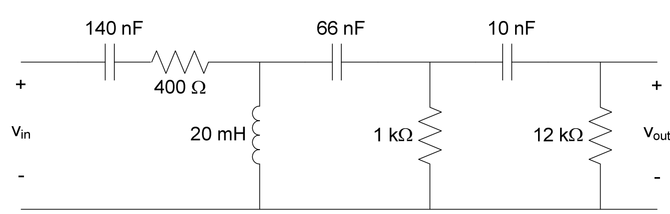


Figure 2. Filter Design and Parameters

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 frequency response characteristic of the filter is shown in Figure 3.

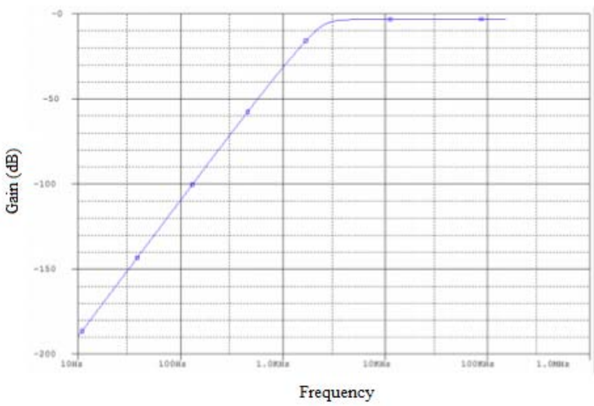


Figure 3. Simulated Frequency Response of Custom Filter

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).

III. Measurement Results

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 (Matlab) spectral analysis. All measurements were taken in a university office/laboratory environment. 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 disturbance 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 4 averaged over a period defined by a particular date and hour-of-day range as shown in the figure. It is clear from Figure 4 that the variations in background disturbance levels are not overly significant. It is equally clear that there are significant background disturbances in the frequency range 60-70 kHz.

The background disturbance levels in Figure 4 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. It is important to note that the particular background levels shown are relevant only to the particular measurement sets of this paper and should not be directly transferred or assumed applicable to another location or time period. An example of this time dependence can be seen in some of the measurement results that follow where "before" and "after" measurements are shown.

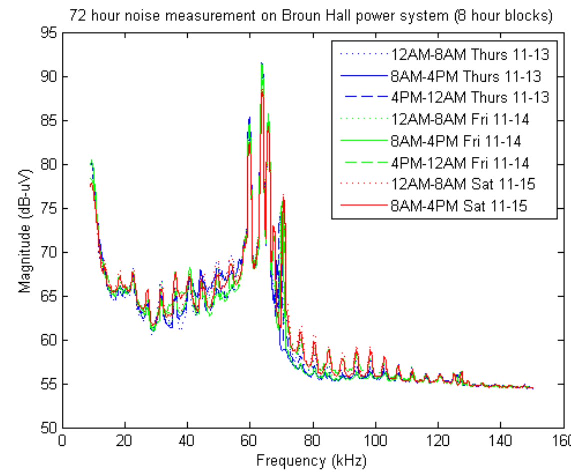
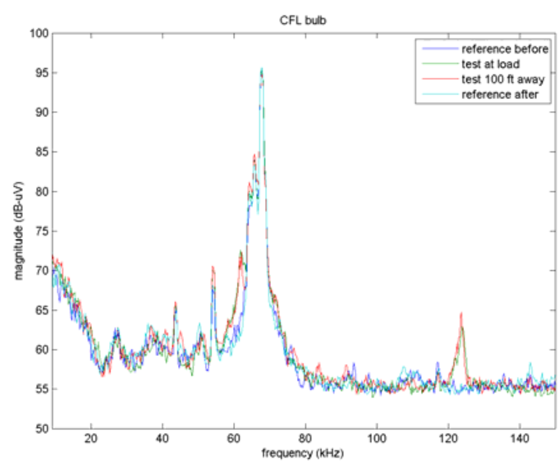


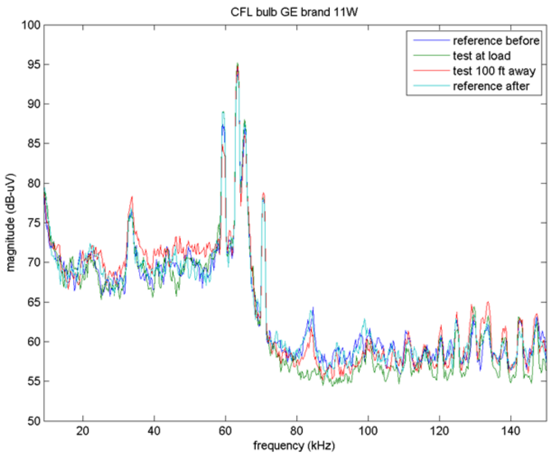
Figure 4. 72 hr Background Disturbance Levels

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) 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 4 as appropriate.

The results of two compact fluorescent lamp (CFL) tests are shown in Figure 5 (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 affect 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.



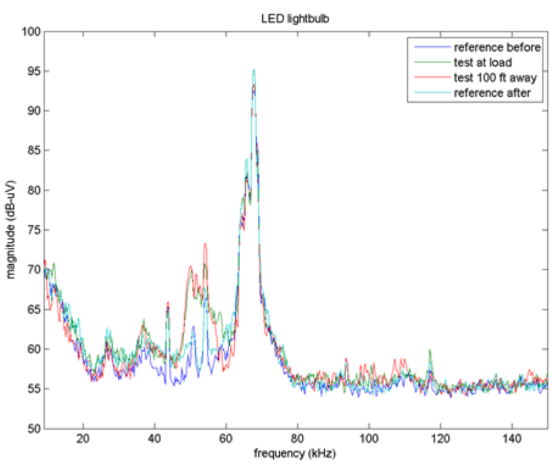
(a)



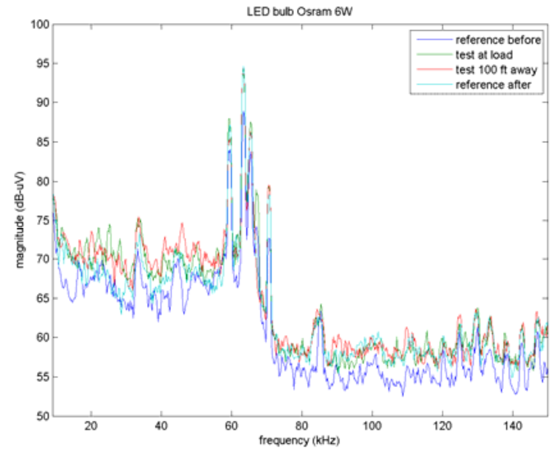
(b)

Figure 5. Emissions from Compact Fluorescent Lamps

The results of four LED lamp tests are shown in Figure 6 (a)-(d). These results show higher emissions around 50 kHz (a), the effects of an increasing change in background disturbancess (b), a general change with some increases and some decreases (c), and the effects of a decreasing change in background disturbances (d). For all the tested LED lamps, there does not appear to be a significant impact on disturbance levels relative to the background levels at either the source or load terminals.



(a)



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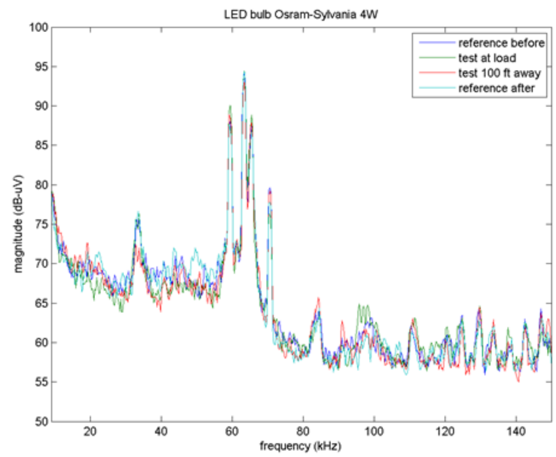
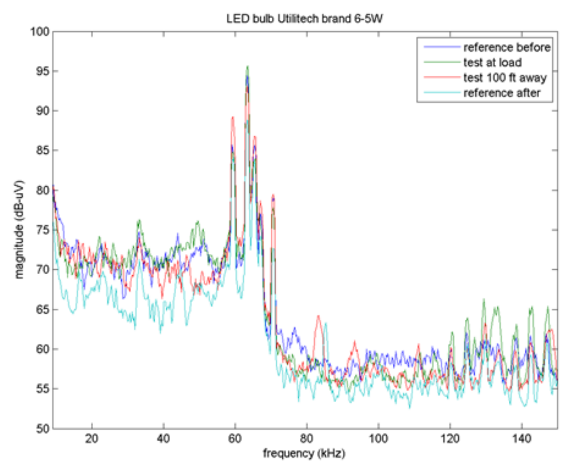
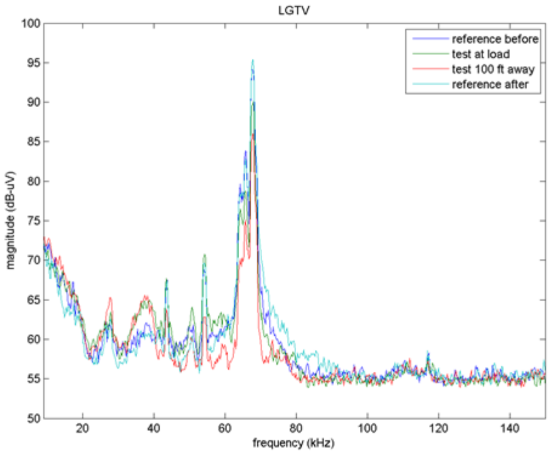


(c)

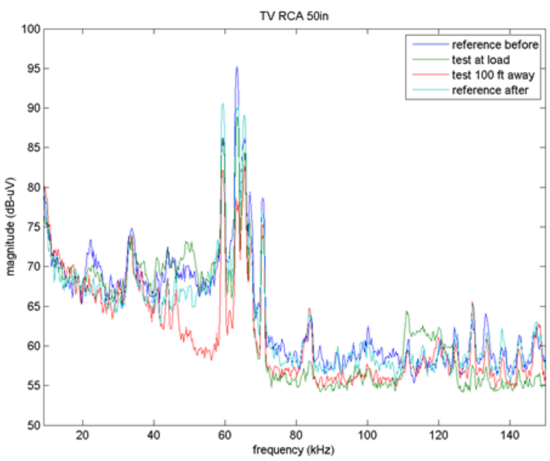


(d)

Figure 6. Results of LED Lamp Tests



(a)



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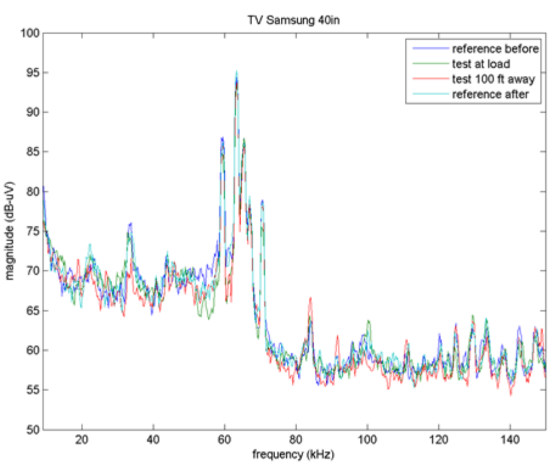
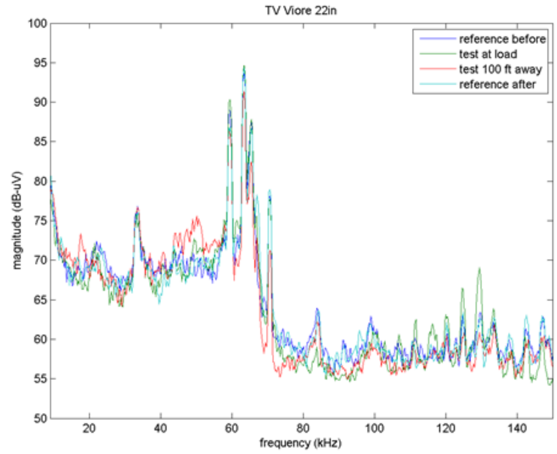


(c)



(d)

Figure 7. Results of Television/Monitor Tests

The results of four television/display tests are shown in Figure 7 (a)-(d). Tests (b) and (d) show some amplification and attenuation effects of the power cable, particularly around 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 disturbance levels change with and without the EUT in operation in all cases.

IV. CONCLUSIONS

Emission testing of 120 V consumer products that are in common use in the United States has shown that typical products do in fact present the potential to appreciably change the high-frequency harmonic disturbance levels in locations in close (electrical) proximity to the equipment under test. However, the measurement results reported in this paper are clearly different from one piece of (similar) equipment to the next and no obvious generalizations can be made. Furthermore, connecting a public-supply source to the tested equipment using standard power cable conductors has shown that the power cabling can have amplifying or attenuating effects depending on the specific situation.

All of the tests conducted as a part of this work support the general conclusion that typical consumer equipment can be expected to increase the disturbance level by 5-10 dBμV (more in some cases) over relatively narrow ranges of the general band of interest 9-150 kHz. Combined with the long-duration evaluation of the background disturbance levels present in the public supply source, these increases can help to establish a realistic compatibility level for harmonics in the 9-150 kHz band. Given these levels, smart meter manufacturers can offer improved communications hardware that can more effectively communicate using public power system conductors as the channel.

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