Why Frequency Domain Tests Like IEC 61000-4-19 Are Not Valid; a Call for Time Domain Testing

Bas ten Have¹, Tom Hartman¹, Niek Moonen¹, Frank Leferink^{1,2}
¹University of Twente, Enschede, The Netherlands, bas.tenhave@utwente.nl
²THALES Nederland B.V., Hengelo, The Netherlands

Abstract—Testing of electrical and electronic equipment is generally performed using frequency domain tests like the IEC 61000-4-19. This standard covers the immunity to conducted, differential mode disturbances and signaling in the frequency range from 2 kHz to 150 kHz. Previous research describes several electromagnetic interference (EMI) cases in this frequency range, which cover pulsed, fast changing, current waveforms. For example cases are described where static energy meters can give misreadings when loaded with pulsed currents. Fast changing time domain signals are not covered by the standards. In this paper it is shown that the current frequency domain tests are not sufficient to determine the equipment's immunity, because of for instance non-linear effects, including saturation, digital sampling error effects and other non linear time invariant (LTI) effects.

I. INTRODUCTION

Traditionally electromagnetic interference (EMI) problems are described by a noise source, victim and a coupling path between them, Fig. 1. Both the source and victim are electronic products, where the noise source creates interference, that propagates via a coupling path to the victim. A main part of EMI is conducted interference, where several conducted EMI cases have been described in [1]. It shows that approximately 60% of the reported issues are in the frequency range from dc to 150 kHz, and these include: electric heater, DVD recorder, lightning, water pump and electric vehicle (EV). The switching of non-linear equipment generates noise that can cause conductive emissions through the mains [2]. Electronic devices used by consumers in a low-voltage distribution network behave non-linear. The use of these devices is increasing, while the use of conventional linear (resistive) equipment is decreasing. Electronic devices involved in EMI as a victim, with degraded performance or malfunctioning, are for example, but not limited to: static energy meters, communication systems (Ethernet-systems or asymmetric digital subscriber line (ADSL)-modems), alarm systems, electronic controls or household appliances [3].

A couple of conducted EMI cases are described hereafter. In [1] a case study is shown where ADSL service trouble was caused by an EV battery charger. When the charger operated, conducted emission levels had increased, causing bit errors at the ADSL modem disabling the network connection. Other cases reported misreadings of static energy meters due to conducted EMI. In [4] and [5], active infeed converters connected to photo voltaic (PV) systems caused lower energy readings. Controlled experiments in [6] showed deviations when static meters were loaded with a dimmer and a series

Fig. 1: Traditionally overview of EMI problems.

of compact fluorescent lightning (CFL) and light emitting diode (LED) lamps. In this case deviations between -32% and +582% were shown. When a commercially available water pump was used as a noise source static meter deviations between -61% and +2675% were shown experimentally in [7] and [8]. Many other EMI problems in the frequency range from 2 kHz to 150 kHz have been reported in CENELEC SC205A report [9]. These include: self-restart after end of operation phase of washing machines, malfunctioning of traffic lights, audible noise of TV and radio receivers and incorrect control lamp function of coffee cooker, among others.

The IEC 61000-4-19 standard, is used to test electrical and electronic equipment for immunity against conducted differential mode disturbances and signaling in the frequency range from 2 kHz to 150 kHz. The standard uses frequency domain, i.e. single tone testing, which is common among electromagnetic compatibility (EMC) compliance testing. However, this standard does not cover fast changing current pulses, with high peak amplitudes in time domain, which typically occur when using non-linear equipment.

In this paper it is shown that the conventional test standard for the immunity of electrical devices based on frequency scanning is not sufficient to determine its immunity. This is shown using a case study in which the victim, static energy meters, caused misreadings due to a noise source, a series of CFL and LED lamps in combination with a dimmer. In this case the time domain emission shows a non-linear signal that

has a high crest factor and peak amplitude. Comparing this to continuous wave (CW) type testing methods, in which case the peak and rms values (thus crest factor) are very low. Unless it is a linear time invariant (LTI) system, the test method does not accurately represent the noise source (anymore). This is a very specific case, but similar cases exist involving other noise sources and victims, as described before. Furthermore, it is shown that the conversion from time domain to frequency domain cannot be done as explained in the immunity standard, because the systems are not LTI.

The rest of this paper is organized as follows: Section II describes the IEC 61000-4-19 standard. Section III shows a case study, involving a series of CFL and LED lamps as the noise source and static energy meters as the victims. In Section IV it is shown that the used systems are not LTI and that therefore the time to frequency conversion is not valid. Finally, in Section V it is concluded that frequency domain tests are not sufficient to determine equipment's immunity, based on the shown case study.

II. IMMUNITY STANDARD

The IEC 61000-4-19 [3] is the current standard to test electrical and electronic equipment for immunity to conducted, differential mode disturbances and signaling in the frequency range from 2 kHz to 150 kHz. The equipment is classified in different test classes based on the environment it is used in. Class 1 is the well protected environment, Class 2 is the protected environment, Class 3 is the typical residential, commercial and light industrial environment and Class 4 is the severe industrial environment. The test levels for current testing for these different classes is shown in Fig. 2. Two different tests are defined for both differential voltage and current testing.

Fig. 2: Test levels for current testing.

A. Continuous wave pulses with pause

The first test defined is the continuous wave pulse with pauses. A continuous wave is applied to the equipment under

test (EUT) and the frequency, f_i , is increased from 2 kHz to 150 kHz. The test cycle consists of a duration in which a continuous wave of frequency f_i is applied and a pause where the signal is zero, after this the frequency is increased by a factor 1.02. This time domain behavior is visualized in Fig. 3.

Fig. 3: Test wave profile with continuous wave pulses with pause [3].

B. Rectangular modulated pulses

The second test described is performed by applying a sequence of rectangular modulated continuous wave pulses, with an increasing frequency from 2 kHz to 150 kHz, to the EUT. The frequency is increased by a factor of 1.02 every step. This behavior is visualized in Fig. 4.

Fig. 4: Test wave profile with rectangular modulated pulses [3].

Now the testing methods that have been applied have been discussed, there is continued with a case study that shows faulty measurements and the observation related to this study. This shows that no interference issues occur when these frequency domain type of test are being performed, but in time domain the signal differs from the test method.

III. CASE STUDY

In this section a conducted EMI case is described in which static energy meters, the victim, are not immune against emissions on the mains line, the coupling path. These emissions are created by the source, a string of CFL and LED lamps controlled by a dimmer. The purpose of static energy meters is to monitor the energy consumption in a low-voltage distribution network, but misreadings between -32% and +582% due to the conductive emissions of the source were reported, based on lab experiments in [6] as shown in Table I. Next to these lab experiments higher static meter readings have been observed on-site by a consumer when using a commercially available water pump [7]. In IEC 62053-21 [10] phase fired

and burst fired waveforms have been listed. These are however limited in frequency content, and in amplitude, so not creating a non-LTI situation when testing meters.

Some of the meters included in these tests are manufactured before 2014, and never tested according to the 61000-4-19 immunity standard, which holds from 2014 onwards. The meters tested according to the standard are static meter 4 and 10, for both meters errors are measured in the described tests, which are described in Table I. Furthermore, all the meters included in the setup show no deviations beyond the specification stated in the 61000-4-19 tests, as these tests were replicated in [11]. This means that all of the included meters comply with the 61000-4-19 standard, but still deviations are found as shown in Table I. These interference issues were later verified by [12] and these misreadings could result in higher energy bills (and also lower) for consumers. The test setup is shown in Fig. 5. The tested static meters are representative for the installed base of energy meters in the Netherlands. In the next sections the emissions generated are compared to the immunity standard 61000-4-19 in frequency as well as in time-domain.

Fig. 5: Test setup containing static energy meters (left) and string of CFL and LED lamps (right) [6].

TABLE I: Deviation of static meters (SM) as measured in [6].

Meter	Year of production	Dimmer 90°	Dimmer 135°	Dimmer 135° repeated
SM1	2013	60%	559%	566%
SM2	2007	64%	574%	581%
SM4	2014	-28%	-32%	-32%
SM5	2004	0%	-5%	-6%
SM6	2007	60%	563%	569%
SM7	2009	61%	575%	582%
SM8	2011	1%	0%	0%
SM9	2013	28%	480%	475%
SM10	2014	-25%	-31%	-31%

A. Frequency domain

The conductive emission generated by the noise source when connected to the mains line, is visualized in frequency domain in Fig. 6. Three different situations of the noise source operating are plotted: CFL and LED with phase dimmer at 0, 90 and 135 degrees phase shift. The situation with no phase shift was the only situation that did not interfere with the static meters, in the other cases the energy registration of the meters was incorrect. The emissions generated shows

mainly frequency harmonics in the lower frequencies. From around 2 kHz the emission generated with the dimmer on 90 and 135 degrees is higher compared with the situation the dimmer is at zero degrees. However, these current emissions are way below the test limits as indicated in Fig. 2. So from the frequency point of view these created emissions are covered by the immunity standard, and should not result in interference problems of the victim.

Fig. 6: Conductive emission generated by noise source in frequency domain [6].

B. Time domain

The time domain representation of the signal generated by the noise source can be seen in Fig. 7. This shows a pulsed fast changing current waveform in time domain, with a slope up to $1.1 \text{ A}/\mu\text{s}$ when the dimmer is at 135 degrees [6]. The rms value of the created emission is not that high, because it is zero for most of the period, but the peak value is approximately 20 times higher than the levels tested in the standard, resulting in a high crest value. Compared to the pulsed fire waveforms described in IEC 62053-21 [10], the observed rise times in this case are at least 10 times lower, and hence rise faster. These high peak currents can create an overshoot or overestimation by the static meter's transducers. These kind of fast changing signals with high peak currents are not covered in the immunity standard. So although the victim is immune according to the related test standard, these kind of signals in time domain are not covered by the standard, and might result in conducted EMI issues.

In CISPR 35 [13] surge testing is used for immunity testing of multimedia equipment. For compliance testing of ADSL networks the surge testing describes current test pulses that are placed at 90 and 270 degrees phase shift with respect to the voltage waveform, with a rise time of $8 \mu\text{s}$ and peak current of 25 A. These pulses have comparable characteristics as the interfering signal in Fig. 7, as these have rise times around $20 \mu\text{s}$ and peak values up to 60 A. Also the IEC 62053-21 [10] contains so-called phase fired waveforms.

Fig. 7: Conductive emission generated by noise source in time domain [6].

Fig. 8: System with static meter (SM) connected to the power distribution line, and non-linear and time variant loads.

IV. CONSIDERATIONS

The immunity test signals described in Fig. 3 and 4, consist of a sinusoidal signal, with frequency f_i , which is only on turned on for a certain period of time, meaning that it is multiplied by a rectangular function. In the frequency domain the Fourier transform shows a convolution of a Dirac delta function with a sinc function, which results in a frequency shifted sinc function. This sinc function is a function of frequency f_i , which increases from 2 kHz to 150 kHz. This means that at any moment in time only one frequency is tested. This sweeping of frequencies is done to determine the system's transfer function, to determine how the system reacts to each frequency individually. From LTI theory it is known that $H(s)$ is related to the impulse response $h(t)$ through the Laplace transform. Determining the impulse response is thus equivalent to the system transfer function under the assumption one is characterizing an LTI system. This means that the frequency domain tests would hold in the situation of an LTI system. However, the problem is that the combination of all the systems within a household cannot be considered LTI anymore. This is amongst others due to the non-linear elements within such a household. In Fig. 8 an example is given where the already non-linear static meter is connected

to several loads. The mentioned loads can be non-linear and time varying, which results in $H(s) \approx h(t)$. As the currents drawn are impulsive in nature, the system's response is more realistically described with its impulse response. These non-linear and time varying elements within the entire system result in the fact that the frequency domain tests do not hold anymore, which are based on the LTI assumption.

V. CONCLUSION

In this paper it is shown that non-linear, fast changing time domain signals with high peak and crest values could cause malfunctioning of electrical equipment. A case study is described that shows fast changing currents generated by a string of CFL and LED lamps combined with a dimmer. The emissions created misreadings of static energy meters. The fast changing signals with high peak currents could also be generated by other non-linear electrical equipment, like a speed-controlled water pump. Earlier observations in the field showed that a pulsed current from active infeed converters in photo-voltaic installations resulted in damped sinusoidal currents and voltages in the power supply systems. The frequency of the damped wave is determined by the size of the conducted power supply system and its connected equipment. This has led to the frequency-scanning immunity standards. This approach is valid for LTI (only). As in many cases we are not aware if a device is LTI, this paper calls for time domain testing. The rise-time and amplitude (crest factor) of the test equipment are then the most crucial parameters.

ACKNOWLEDGMENT

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. The results found reflect the author's view only. EURAMET is not responsible for any use that may be made of the information it contains.

REFERENCES

- [1] K. Murakawa, N. Hirasawa, H. Ito, and Y. Ogura, "Electromagnetic interference examples of telecommunications system in the frequency range from 2kHz to 150kHz," pp. 581–584, 2014.
- [2] F. Leferink, "Conducted interference, challenges and interference cases," *IEEE Electromagnetic Compatibility Magazine*, vol. 4, no. 1, pp. 78–85, 2015.
- [3] "IEC 61000-4-19: Testing and measurement techniques - Test for immunity to conducted, differential mode disturbances and signalling in the frequency range 2 kHz to 150 kHz at a.c. power ports," 2014.
- [4] J. Kirchhof and G. Klein, "EMV - Grenzwertlücke Wechselrichter stört Zähler," 24. *Symposium Photovoltaische Solarenergie, Bad Staffelstein*, 2009.
- [5] J. Kirchhof, "Grenzwertlücke - Wechselrichter stört Elektrizitätszähler," *EMV, Düsseldorf*, 2010.
- [6] C. Keyer and F. Leferink, "Conducted interference on smart meters," *IEEE International Symposium on Electromagnetic Compatibility*, pp. 608–611, 2017.
- [7] B. Have, T. Hartman, N. Moonen, C. Keyer, and F. Leferink, "Faulty Readings of Static Energy Meters Caused by Conducted Electromagnetic Interference from a Water Pump," *Renewable Energy and Power Quality Journal (RE&PQJ)*, 2019.

- [8] B. Have, T. Hartman, N. Moonen, and F. Leferink, "Misreadings of Static Energy Meters due to Conducted EMI caused by Fast Changing Current," *Submitted to 2019 Joint International Symposium on Electromagnetic Compatibility and Asia-Pacific International Symposium on Electromagnetic Compatibility*, 2019.
- [9] "CENELEC SC 205A Study Report on Electromagnetic Interference between Electrical Equipment/Systems in the Frequency Range below 150 kHz," no. SC205A/Sec0329/DC, 2013.
- [10] "IEC 62053-21: Electricity metering equipment (a.c.) - Particular requirements - Static meters for active energy (classes 1 and 2)," 2003.
- [11] F. Leferink, C. Keyer, and A. Melentjev, "Static energy meter errors caused by conducted electromagnetic interference," *IEEE Electromagnetic Compatibility Magazine*, vol. 5, no. 4, pp. 49–55, 2016.
- [12] G. Rietveld, D. Hooogenboom, and M. Acanski, "Conducted EMI Causing Error Readings of Static Electricity Meters," *CPEM 2018 - Conference on Precision Electromagnetic Measurements*, pp. 1–2, 2018.
- [13] "CISPR 35: Electromagnetic compatibility of multimedia equipment - Immunity Requirements," 2014.