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EMI Pre-Compliance Measurements Reveal Sources of Interference

Bystrík Dolník

Abstract

The chapter focuses on the electromagnetic compatibility of a prototype of electrical equipment such as street lighting with various LED controllers, LED information boards, and audio equipment. The requirements for the harmonic content of the input currents of the conducted emission power lines are used as a basis for the analysis of compliance with the EMC standards. The results obtained from the experiments indicated that some commercially produced voltage drivers are not compatible with the requirements for the harmonic current content of the input line. The problem is caused by two factors: a bad design by the manufacturer or the wrong LED driver design concerning the rated load. EMI radiation measurements indicate the need to precisely design all functional blocks placed on a PCB with suitable grounding and shielding techniques. This chapter is intended for engineers and researchers working in the development of electrical equipment as well as the general public interested in EMC issues.

Keywords: EMI, coupling, LED driver, LED information board, audio device

1. Introduction

Today, no one doubts that the production and the use of large amounts of electrical equipment and electronics have brought an important requirement: electromagnetic compatibility (EMC). It turns out that the requirements for an electrical product to comply with EMC have two aspects. The first aspect follows naturally to ensure that the product complies with EMC regulations. The second aspect, still influenced by environmental experts whose efforts are to monitor the long-term effects of electromagnetic fields generated by technical devices in the environment on living organisms. It is likely that with the growing awareness of the population, in the future, more attention will pay to the effects of electromagnetic fields acting simultaneously from multiple electrical devices on the environment.

According to the International Electrotechnical Vocabulary (IEV) IEV 161-01- 07, EMC is the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment [1]. Electrical equipment and electrical systems are always exposed to internal and external electromagnetic disturbances. However, it should be noted that each electrical device is at the same time more or less a source of electromagnetic interference (EMI) [2–6].
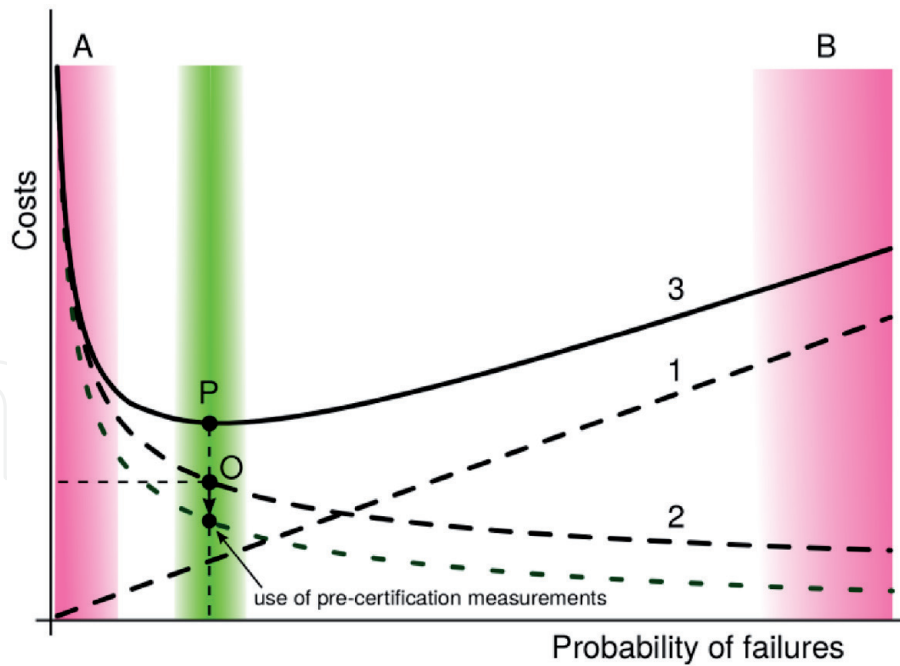
Figure 1.
Optimal financial costs for EMC provision: Point O; 1 – Operating costs, 2 – Costs of ensuring EMC compliance, 3 – Total costs; pre-compliance measurements shift the point O to lower values.

If the EMI level of the equipment under test[1] (EUT) is below the permitted EMC level of the standard, the EMC compatibility goal of the product is achieved. Otherwise, further measures are needed to reduce the EMI level from the EUT. The role of the engineers is to adjust the internal layout of the functional blocks in the EUT and connect (or disconnect) some components to the EUT to eliminate EMI, especially according to their professional experience. Subsequently, the results of the modifications are verified by re-sending the EUT to the EMC test facility. The process of making changes to reduce EMI and then repeat testing in the EMC test room can be time-consuming and costly until the EUT passes the EMC test. Every manufacturer of electrical equipment wants to gain a foothold in the market and sell the product. The necessary condition for selling products on the marketplace is to obtain an EMC certificate of conformity. The manufacturer must therefore take into account the costs to ensure the EMC conformity of the product.

In recent years much effort has been made to reduce the cost of EMC compliance and speed up the EMC compliance process. The EMC pre-compliance methodology in the test room or at the open site of the product manufacturer is proposed in the early 1990s. In the initial phase, EMC preliminary conformity measurements were performed in a product manufacturer's test facility with standard EMC test equipment and standard test methods. Later, more flexible EMC compliance measurements were developed and introduced an alternative test apparatus or test methodology to reduce compliance costs [7].

The selection of specific permissible levels and the related reserves for the devices are not prescribed. It is within the competence of the device manufacturer. If the manufacturer chooses too large EMC reserves, then unnecessarily high financial costs for interference are incurred. Conversely, if the EMC reserve is too small, there is a greater risk that the equipment will not pass EMC certification. Subsequent measures must take to achieve EMC.

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[1] In some professional and scientific sources such as journals, standards, and books, DUT (Device Under Test) is used instead of EUT.

The graph in **Figure 1** represents a typical course of financial costs for the production and operation of technical equipment depending on the probability of failures. It is clear from the graph that as the number of failures increases, additional operating costs increase. Conversely, the failure probability by failing to comply with EMC principles is inversely proportional to the amount of investment in providing EMC equipment.

Therefore, the total operating costs of the equipment are the sum of the two mentioned components, which have the minimum marked as point P in **Figure 1**. The part of the EMC compliance investment of the equipment must choose (point O) so that the total costs are equal to the minimum.

The optimal costs of providing EMC should be about 2–10% of the development and production costs. Under certain conditions, the total cost of providing EMC is less than 1%, which can be considered a success [8]. The area marked with the letter "A" corresponds to too high a cost of providing EMC at the planning stage. The area marked with the letter "B" corresponds to the conditions under which the costs of ensuring EMC are neglect at the planning stage of the equipment production, which results in a high rate of failures.

Pre-certification EMC pre-compliance measurements significantly reduce the cost of developing new electrical equipment and shorten the time to market. Thus, point O in the graph in **Figure 1** defining the optimal cost for EMC provision shifts towards lower values.

2. EMC pre-compliance measurements

Data from EMC testing laboratories report that 85% of products submitted for final EMC compliance testing fail for the first time. However, using pre-compliance EMC measurements, it is possible to reverse these statistics so that products pass EMC tests successfully [9].

Performing pre-compliance measurements significantly increases the probability of a successful first transition to complete EMI compliance testing, saves time and money. Large companies developing products for medical, automotive, military, and other industrial applications perform pre-compliance measurements as part of a standard procedure. Small companies and startups are starting to follow this way as well, as they can benefit from investing in setting up pre-compliance measurements.

Pre-compliance EMC measurements can define as the ability to perform internal testing of EMC products before going to the final certified testing laboratory. In doing so, pre-compliance measurements can be performed by the manufacturer either internally or in agreement with an experienced development laboratory.

Of course, there are even more reasons to do pre-compliance measurements, which are as follows:

1. Ensure that newly developed equipment has sufficient immunity to maintain the specified parameters in the presence of EMI.

2. Early identification of potential EMC issues. It allows detection problems with EMC of developing products before testing in a certified laboratory using custom testing.

3. Reduction of EMC related costs. Products are more likely to be certified for the first time, avoiding additional development time and costs.

4. Accelerates time to market by reducing delays.

5. Immediate feedback on the impact of design changes.

6. An immediate inspection of the modifications made to the product results in the acquisition of experience in the design of other products.

7. Better communication between test and development groups provides fast real-time feedback from internal sources.

Figure 2 shows very clearly an example of the process of product development using pre-compliance measurements. Whether the product passes the individual stages of development or not is determined by the results of not only pre-compliance measurements. Although pre-compliance tests may seem to have only advantages, they have a higher measurement uncertainty than compliance EMC tests due to their simplification. However, this disadvantage is many times compensated by savings not only in money but especially in time during product development.

More complex electrical equipment contains several functional blocks, such as power supply circuits, switching power supply, input/output (I/O) circuits, sensitive analog circuits, digital circuits, high-frequency (HF) circuits, converters, peripherals, control circuits, I/O connectors, and filters, reference ground plane. These circuits must arrange in such a way that they do not interfere with each other and that they are at the same time sufficiently immune to external electromagnetic fields. **Figure 3** shows an example of the optimal arrangement of circuits on a PCB in compliance with EMC principles.

The precise design of a printed circuit board (PCB), and the selection of quality components, play a significant role in the product prototype design. The PCB designer must have good experience to eliminate interference generation by precise PCB design. Currently, CAD software can use in PCB design, which provides the ability to select different tracing strategies. In the design of PCBs, the generation of Joule losses and methods of loss dissipation must also take into account.

Some researchers are working on methods for diagnosing and managing enhanced EMC for a specific area of EMC, such as mobile phones. The authors in [10] constructed a knowledge graph that presents interference and sensitive units based on mathematical rules. EMC diagnostic and management reports are generated by searching knowledge graphs with an extracted entity and parameter information. The authors performed an experiment and found that the proposed intelligent method of EMC diagnostics and control significantly increased the efficiency of the calculation, saved storage space, and increased the accuracy of identification.
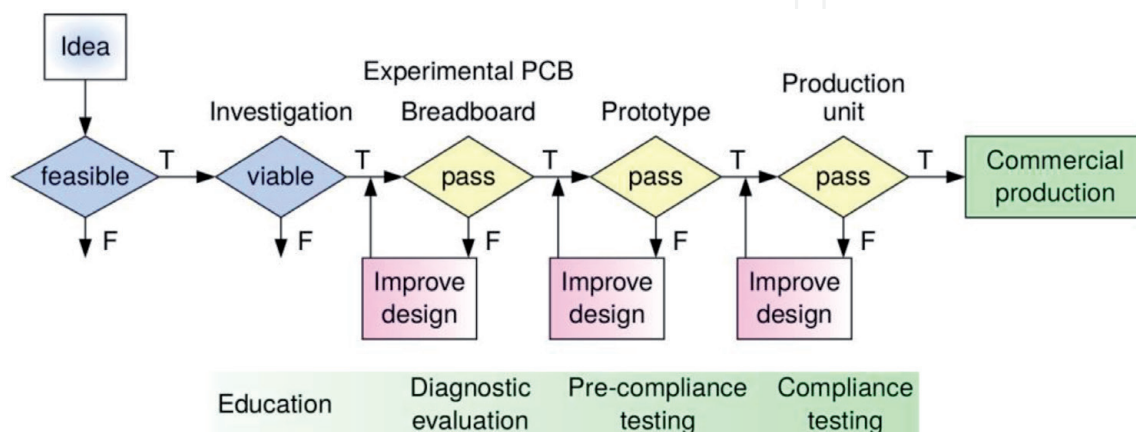

Figure 2.
Product development cycle; the meaning of capital letters is: T – true, F – false.
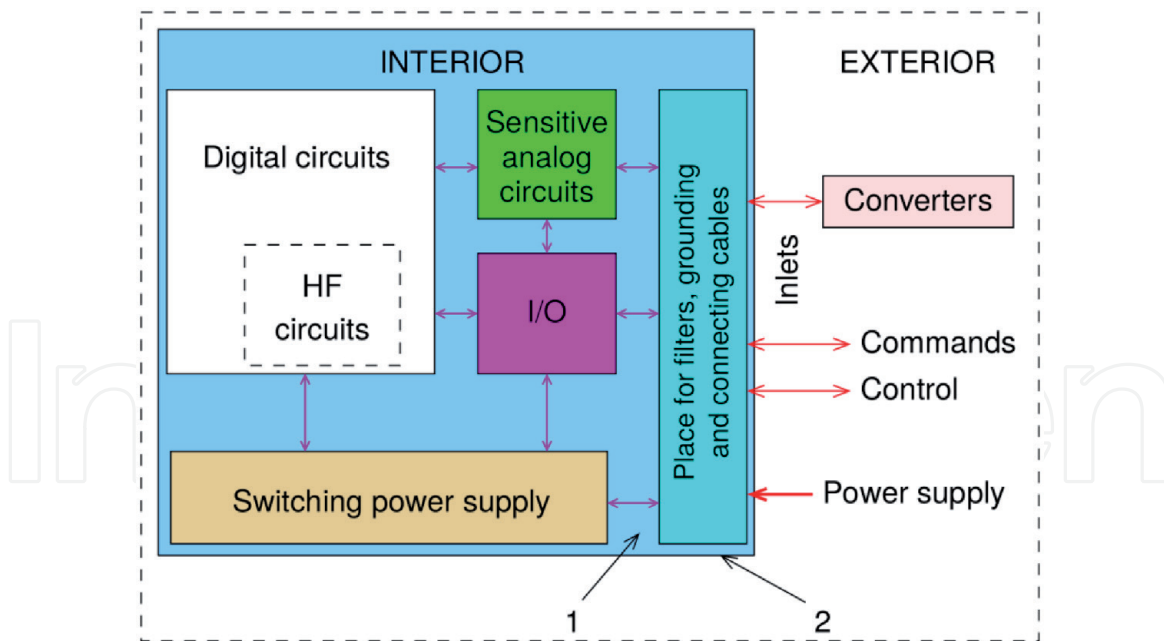
Figure 3.
Circuit layout on the PCB in compliance with EMC principles: 1 – The necessary connections must filter, 2 –
The reference ground plane located below all elements and conductive surfaces.

2.1 Solving EMI problems during pre-compliance measurements

When solving EMI problems during pre-compliance measurements, engineers face several challenges. Some EMI problems can be detected and eliminated relatively quickly and easily; some are more complicated and time-consuming. Therefore, engineers must address the technical side of the problem along with the requirement to minimize costs. Remember that each metal wire in an electrical circuit acts simultaneously as an EMI source and an EMI receiver. Thus, any interference can affect the electrical equipment either by metallic conductors or by electromagnetic waves. A distinction exists between EMI by conduction (conducted Interference) and EMI by radiation (radiated interference).

Radiated interference is due to radio noise or unwanted signals over the air, not through a physical medium. Conducted interference is due to conducted radio noise or unwanted signals entering a victim by direct coupling (via cables).

According to the IEV 161-03-28, a radiated disturbance is an electromagnetic disturbance for which the energy is transferred through space in the form of electromagnetic waves; IEV 161-03-27 conducted disturbance is an electromagnetic disturbance for which the energy is transferred via one or more conductors. IEV 161-01-05 defines electromagnetic disturbance as an electromagnetic phenomenon that can degrade the performance of a device, equipment or system, or adversely affect living or inert matter [1]. Strategies based on theoretical knowledge of circuit technology, micro-electronics, and professional experience are used to detect EMI sources. The EMI problems that need to address are closely related to the electromagnetic couplings between the source and the victim. The procedure can be as follows:

1. all EMI sources must detect on the PCB,

2. check interference levels in all metallic conductors,

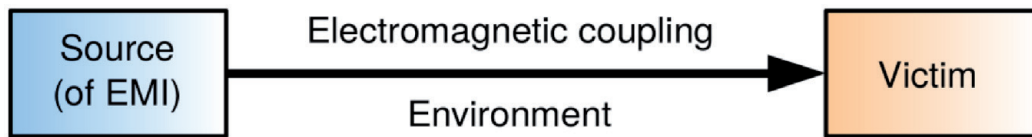3. short-distance EMI verification of the prototype (1 m or 3 m).

Figure 4.
EMC base chain.

2.1.1 Detect all EMI sources on the PCB

Use near-field probes (either E- or H-field). These small hand-held antennas are mainly used in the development and diagnostics of electronic devices, monitoring the radiation of components and blocks directly inside the developed device, for the most accurate search for the source of the interfering signal at the area of interest or for detecting electromagnetic leaks in shields.

Measurements using a near-field probe are not regulated by any standards. It is only a matter of determining the relative degree of interfering radiation in a given place or a given circuit. EMI sources generally include fast-edge digital signals. When the product contains a shielded enclosure, check the area around the joined parts and near the holes.

2.1.2 Check interference levels in all metallic conductors

Use a current probe to measure high-frequency currents flowing through a wire quickly. When the laboratory is better equipped, a line impedance stabilization network[2] (LISN) connection can use. Remember that cables are the most likely structure emitting radio-frequency (RF) energy. During the measurement, move the probe back and forth along the cable to maximize the highest currents. Be careful not to affect the measurements with the user's own body (hand movement).

2.1.3 Verify short-distance EMI

Use a short-distance antenna to find out which of the harmonic contents radiates. Then compare these harmonics with indoor measurements and EMI measurements in cables to determine the most likely energy sources that are coupling to and radiate through the wires or slots.

2.2 Measures used to eliminate EMI

The technical measures used to reduce EMI in any EMC chain are called interference suppressors. Interference suppressors include filters, surge protection devices (SPDs), shielding, and grounding. Through these measures, the electromagnetic coupling between the source and the victim is eliminated. **Figure 4** shows the relationship between the EMI source and the victim via coupling.

SPDs eliminate the destructive effect of current pulses and high-energy voltage pulses. EMC grounding diverts interfering signals from the victim, creates a reference ground plane on PCBs, grounds the cable shield and metal enclosures for safety purposes. The shielding attenuates EMI propagated by radiation.

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[2] The LISN is a low pass filter located between the AC or DC power source and the DUT to create a known impedance and provide a port for measuring HF noise. The main function of the LISN is to provide an accurate impedance to the EUT power port. It also isolates unwanted radio-frequency signals from a power source.

In EMC, the couplings are classified as follows:

- galvanic,

- inductive,

- capacitive,

- and electromagnetic coupling.

Knowing the principle of how coupling works using equivalent models, a procedure can make to reduce coupling [11]. **Figure 5** shows simplified equivalent circuits for galvanic and inductive coupling between the source and the victim. The magnitude of the interfering voltage on the series impedance according to **Figure 5a** can calculate as follows

$$u_{EMI}(t) = R \cdot i(t) + L \frac{di(t)}{dt} \tag{1}$$

where R is the resistance of the conductor, L is the self-inductance of the conductor, and $i(t)$ is the disturbing current. According to Eq. (1), several measures can perform to eliminate the interfering voltage. For example, reduce the voltage drop across resistor R and inductance L. The resistance R can reduce by shortening the length of the conductors, reducing the number of bends, or increasing the cross-section of the conductors. These resistivity reduction measures follow from Eq. (2)

$$R = \rho \cdot \frac{l}{S} \tag{2}$$

where l is the length of the conductor, S is the conductor cross-section, and ϱ is the specific resistivity of the conductor. The voltage drop across the reactance component is done by reducing the inductance L or reducing the time changes ($di(t)/dt$)

Figure 5.
Equivalent circuit: Galvanic coupling (a) and inductive coupling (b); R – Resistance, L – Self-inductance, M_{12} – Mutual inductance between wires, i – Disturbing current, u_{EMI} – Disturbing voltage, H – Magnetic field strength.

of the interfering current. The magnitude of the interfering voltage across the inductive coupling can calculate as follows

$$u_{\mathrm{EMI}}(t) = M_{12}\frac{\mathrm{d}i(t)}{\mathrm{d}t} \tag{3}$$

where $i(t)$ is the disturbing current and M_{12} is the mutual inductance between wires. The mutual inductance between the conductors is bound to the magnetic flux as follows

$$\Phi_{12} = B_1 \cdot S_2 \tag{4}$$

where S_2 is the area bounding the victim's circumference, and B_1 is the magnetic flux density generated by the EMI source. Based on (Eqs. (3) and (4)), the following measures can use to reduce the inductive coupling: reducing the mutual inductance by shortening the length of the parallel conductors, increasing the mutual distance between the circuits, orthogonal distribution of the circuits, and others. Similarly, an analysis of equivalent circuits for capacitive coupling and electromagnetic coupling can perform.

3. Precompliance measurements examples

In the following section, we will show three examples of pre-compliance measurements. The first case will concern the detection of EMI sources in a prototype of an LED street light. The second case will matter the detection of EMI sources from the LED information board. Finally, the third case points to unexpected changes in EMI radiation during the development of audio equipment.

3.1 Prototype of a LED street light

The best choice to achieve the highest system efficiency is a switched-mode power supply. Correcting the harmonic distortion of the input line current is one of the main goals in designing the street light power supply. For the LED street light EN 61000-3-2, Class C applies at full load [12, 13]. EN 55015 is a product family standard (largely based on CISPR 15). Key EMC standards include EN 61000-3-2 for limits on harmonic current emissions, EN 61000-3-3 for limits on voltage changes, voltage fluctuations, flicker, and EN 61547 for immunity requirements.

The pre-compliance measurements realized on the prototype of LED street light focus on the power line conducted emissions and harmonic current emissions. The power line conducted emissions measured on the first 60 W LED driver shows **Figure 6**. It is clear from **Figure 6** that the level of emission of the LED driver is below the limits specified in the standard EN 55015. Therefore, a peak detector in a frequency range from 9 kHz to 30 MHz is used.

Table 1 lists harmonic currents generated by the 60 W LED driver. The power factor (PF) is 0.444, and the corresponding limit for the 3rd harmonics is 13.32%. The third column of **Table 1** lists the multiples of limits. The corresponding average total harmonic distortion (THD) of the current generated by the 60 W LED driver is equal to 181.33% the maximal THD is 181.73%.
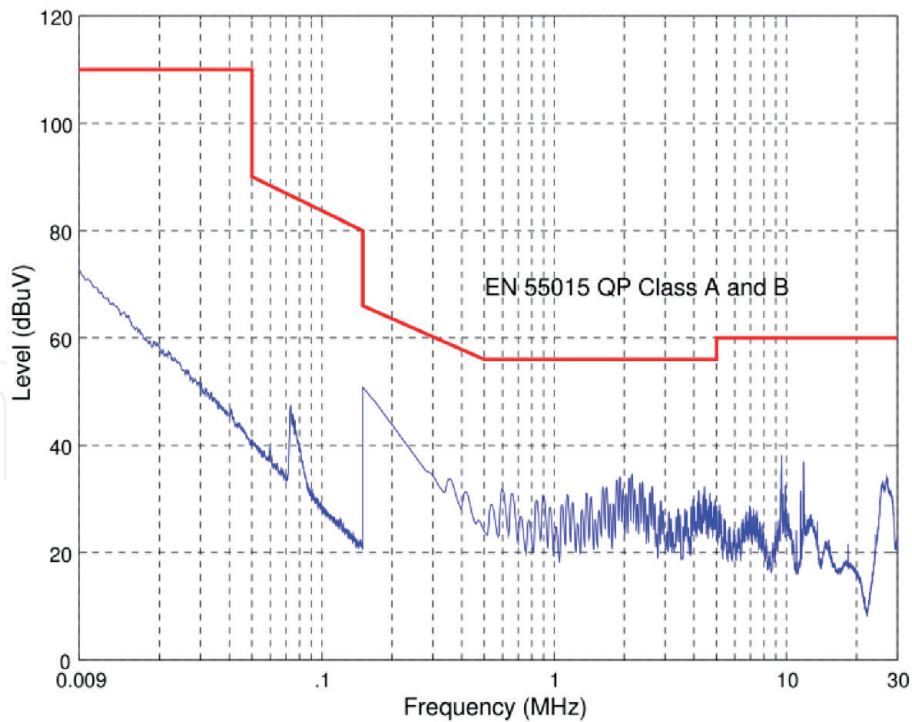
Figure 6.
Limits and measured EMI level of the conducted emissions on the first 60 W LED driver between the phase conductor and earth.

Harmonic order	Harmonic current	Multiple of limit[a]
n	**(%)**	
2	2.46	1.23
3	89.71	6.74
5	84.12	8.41
7	76.39	10.91
9	66.89	13.38
11	56.38	18.79

[a]*Calculated.*

Table 1.
Measured harmonic current emissions of the 60 W LED driver – Class C, power factor PF = 0.444.

It is clear from **Table 1** that the harmonic currents generated by the 60 W LED driver far exceed the limits set by the standard. This fact is confirmed by the time course of the terminal voltage and the current flowing into the first 60 W LED driver shown in **Figure 7**. Measured values of the odd harmonics extremely exceed the specified limits, thus resulting in the high value of THD of the supply current and low power factor.

Figure 7 shows the time course of the terminal voltage and current flowing into the 60 W LED driver and the THD of the current through the 60 W LED driver and corresponding PF measured for the first 2500 minutes of measurement. It is clear that the current time course in **Figure 7** is periodic but does not have a sinusoidal shape. The deformation of the current waveform is due to harmonic currents emission from the LED driver.

For comparison, **Table 2** lists the harmonic currents generated by the 50 W LED driver. Measured levels of the conducted emissions on the 50 W LED driver
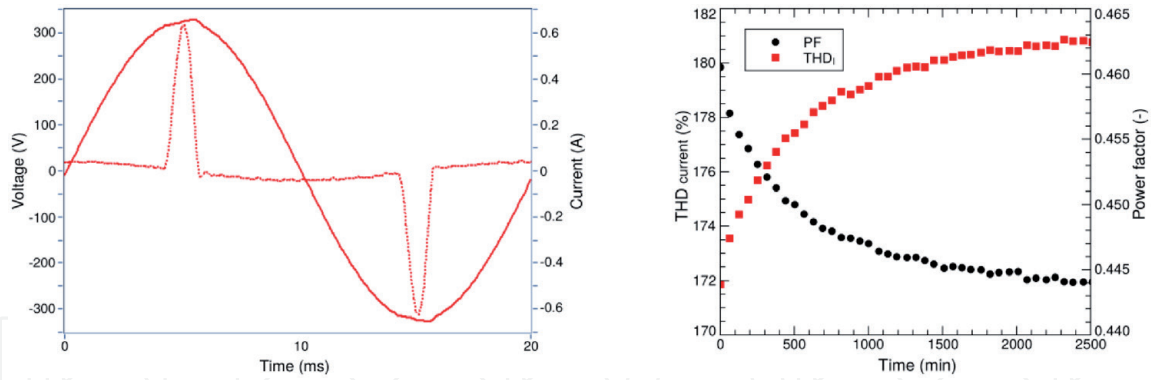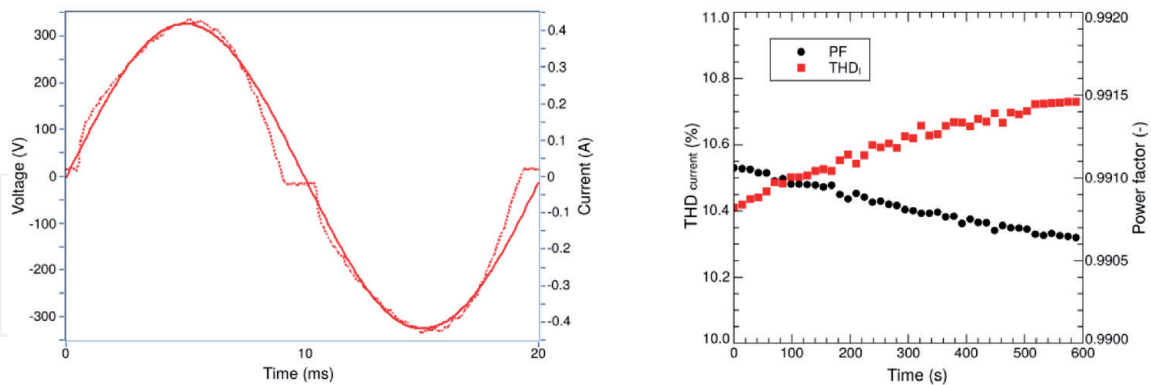
Figure 7.
Time course of the terminal voltage and current flowing into the 60 W LED driver during one period (left), and corresponding THD and PF measured in phase conductor during 2500 minutes (right).

Harmonic order	Harmonic current	Multiple of limit[a]
n	**(%)**	
2	0.13	0.065
3	7.30	0.246
5	4.83	0.483
7	4.13	0.590
9	3.13	0.626
11	2.35	0.783

[a]*Calculated.*

Table 2.
Measured harmonic current emissions of the 50 W LED driver – Class C, power factor PF = 0.991.

Figure 8.
Time course of the terminal voltage and current flowing into the 50 W LED driver during one period (left), and corresponding THD and PF measured in phase conductor during 600 seconds (right).

between the phase conductor and earth need not indicate as they are below the specified limits. It is clear from **Table 2** that the 50 W driver meets the requirements for harmonic current emissions with a sufficient margin. The corresponding average THD of the current generated by the 50 W LED driver is equal to 10.73%. The maximal THD is 10.77%.

Figure 8 shows the time course of the terminal voltage and current flowing into the 50 W LED driver and the trend over time of the THD of the current through the 50 W LED driver and corresponding PF measured for the first 600 seconds of measurement.

By comparing the measured data, it can conclude that all LED drivers comply with the standard EN 55015 with a sufficient margin and are not sources of EMI. However, as for the harmonic current emissions, the measurements have shown the lack of some drivers. The reason lies in permissible limits according to the standard EN 61000-3-2 were exceeded. Further, the THD of the supply current is high, and the measured PF is low. Therefore, harmonic current emissions are due to either improper circuit design of the LED driver or wrong LED driver design concerning the rated load of the LED street light.

3.2 LED information board

Measures to mitigate the galvanic coupling through AC mains wires and DC power supply of the LED modules to the LED information board are investigated. The LED information board enclosure is a galvanized steel with a protection rating of IP65 and anti-reflective protective glass. The LED information board supplies from a single-phase AC low-voltage network converted by DC-to-DC converters with a maximum current of 20 ampers. A total of three DC-to-DC converters are in the LED information board. For receiving and sending data in several ways, an optical converter, router, and ADSL modem are installed. A mini PC controls data processing and process control [14]. The results show that the EMI emissions in horizontal polarization are higher in comparison to vertical polarization. The following measures were sequentially used to reduce the EMI emissions:

- twisted power wires,

- chokes on wires (straight or twisted),

- suppression capacitors,

- impedance matching resistors,

- data wires on PCB with SMD LC filters,

- twisted data wires.

Figure 9 shows the interference level with three different EMI mitigation measures. Pre-compliance testing shows that the most critical frequency range is 30 to 130 MHz. From the initial measurements without EMI measures, the results
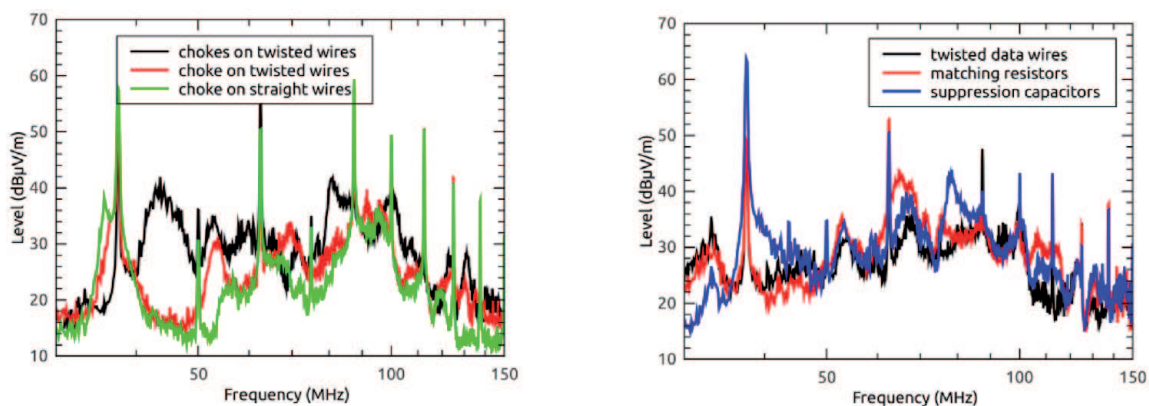

Figure 9.
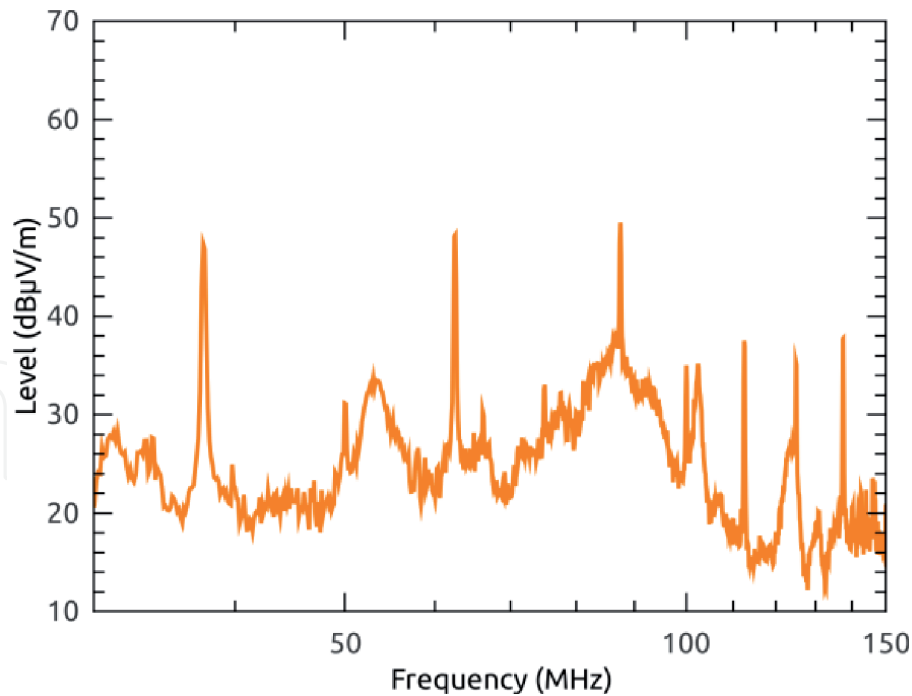*Frequency characteristic of EMI level for different EMI mitigation measures.*

Figure 10.
Frequency characteristic of EMI level for combined EMI mitigation measures.

show that the maximum EMI radiation is at 37.5 and 87.5 MHz. Other sources of EMI emissions are at 62.5, 100, 112.5, and 125 MHz. It is evident from the list that frequencies are multiples of 12.5 MHz.

The most optimal EMI reduction reach by the simultaneous use of several EMI reduction measures. An example of the measured EMI emissions levels for such a case shows **Figure 10**, where chokes on twisted pairs from AC-to-DC converters at both ends, impedance matching resistors, and data wires on PCB with SMD LC filters are used. Other variants used in testing had only a slight effect, a few tenths of dB. To compare the effects of EMI measures with each other, the vertical scales in **Figures 9** and **10** are the same.

3.3 Audio equipment

Sound equipment is still popular, and home theaters provide quality surround sound. Retro designs with small dimensions are popular. In the past, analog amplifiers have been used in high-performance audio devices to emphasize sound quality. In recent years, digital amplifiers have improved sound quality and become popular in home audio. Today, audio devices have implemented multiple communication and I/O technologies to provide comfort. This is associated with EMI problems in the development of new audio equipment.

The EMI sources are the display unit, switching power supply, Bluetooth, USB port, S/PDIF connection. Due to a large number of connections, the cabinet of the audio device contains many holes. Holes are places where the generated interfering electromagnetic fields radiate out into space. **Figure 11** shows a selection of pre-compliance measurements on audio devices in different operating conditions.

Figure 11a shows the EMI for an audio device (amplifier with compact disc (CD) drive) with a metal cover, Bluetooth active, CD playback on, the maximum power delivered to the rated load, and the connected S/PDIF cable. It is clear from the measured data that the device emits a discrete spectrum from 80 to 700 MHz, 930 to 1000 MHz, and a significant continuous spectrum between 220 and 300 MHz.
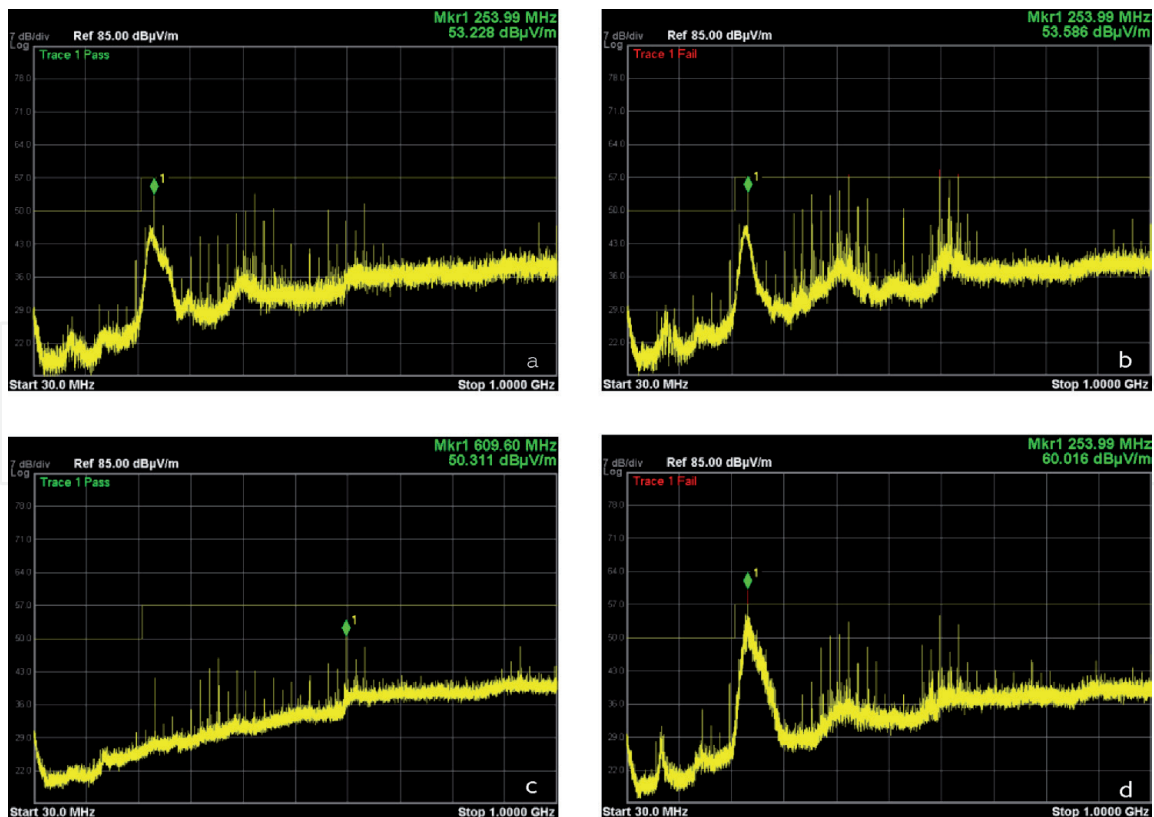
Figure 11.
EMI pre-compliance measurements on audio devices in different operating conditions.

Figure 11b shows the EMIs for the same audio device under the same conditions with a change in the use of the choke in the power conductors inside the cabinet of the audio device. Surprisingly, this measure has the opposite effect. Instead of the expected reduction of EMI field radiation, emissions are increased by 6 to 8 dB in the band 340 to 680 MHz. In addition, the use of a choke affected the width of the continuous spectrum. As a result, the continuous spectrum is narrower by shifting the upper limit from 300 to 270 MHz.

Figure 11c shows EMIs for an audio device (amplifier with CD drive) with a cabinet in which some parts are wood. In this case, the audio device is powered by a battery pack. The CD drive is empty without a CD inserted, and the audio cables are not connected. The aim is to determine the basic level of EMI radiation with the possibility of subsequently monitoring the effect of connecting cables to audio inputs and outputs and a CD drive with a CD inserted. The measured EMI in **Figure 11c** shows only the discrete spectrum of EMI field radiation. **Figure 11d** shows the EMIs for the same audio device with a CD inserted in the CD drive, and the device operates in "play" mode. S/PDIF cables are connected as well. The measured EMI emissions in **Figure 11d** show the continuous emission spectrum of EMI fields from 220 to 300 MHz. The same CD drive and CD drive control are used, as in the first measured audio device (see **Figure 11a** and **b**). Thus, a component generating continuous EMI emissions in an audio device is classified.

4. Summary and conclusions

Electromagnetic smog is a problem for technical equipment and living organisms. The manufacturer of electrical equipment wants to gain a foothold in the market and sell the product. The successful sales of the product on the market require an EMC certificate of conformity, which increases the development and production

costs of the product. To reduce equipment development costs, shorten time to market, and obtain a risk-free EMC certificate, pre-compliance measurements are needed. In addition, shortening the time to market accelerates the professional experience of engineers.

This chapter has provided three examples of EMI measurements using pre-compliance measurements. The first case concerns the generation of unwanted harmonic currents and the detection of EMI sources by conduction in a prototype of street LED lighting. The second case concerns EMI sources from the LED information board and how some measures reduce EMI interaction. Finally, the third case points to unexpected changes in EMI radiation during the development of audio equipment.

Acknowledgements

Conflict of interest

The author declares no conflict of interest.

Abbreviations

CAD	Computer aided design
CD	Compact Disc
DUT	Device Under Test
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EUT	Equipment under test
IEV	International Electrotechnical Vocabulary
HF	High-Frequency
I/O	Input/Output
LISN	Line Impedance Stabilization Network
PCB	Printed Circuit Board
PF	Power Factor
RF	Radio-Frequency
SPD	Surge Protection Device
THD	Total Harmonic Distorsion

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