energies

Article

Comparison of Two Measurement Methods for the Emission of Radiated Disturbances Generated by LED Drivers

Kazimierz Kuryło, Wiesław Sabat, Dariusz Klepacki * and Kazimierz Kamuda

Department of Electronic and Telecommunications Systems, Rzeszow University of Technology, W. Pola 2, 35-959 Rzeszow, Poland
* Correspondence: dklepa@prz.edu.pl

Abstract: The comparison of the results obtained using two methods for measuring the radio disturbance emissions produced by compact lighting drivers in the frequency range of 30 to 300 MHz has been presented in this paper. Any electrical and electronic equipment used within the EU must comply with Directive 2014/30/EC and harmonised standards. For lighting equipment, the dedicated standard is EN-IEC 55015:2019-11E. In this standard, for tests in the frequency range of 30 to 300 MHz, two equivalent test methods are allowed for lighting drivers, i.e., the traditional method in which disturbance emissions are measured in a semianechoic chamber SAC and the alternative CDNE (Coupling Decoupling Network Emission) method. Each method is characterised by a different measurement technique. For this reason, this paper aims to compare the results obtained by the two methods and to find out whether the CDNE and SAC methods, despite the difference in measurement technique, can be considered equivalent. The theoretical part of this study presents the results of an analysis of the literature on the subject and the technical aspects of measuring disturbance emission using both measurement methods. The practical part describes the construction of measurement stands for selected LED lamps and presents the measurement results and their statistical analysis.

Keywords: LED lamp; electromagnetic compatibility; statistical analysis

check for updates

Citation: Kuryło, K.; Sabat, W.; Klepacki, D.; Kamuda, K. Comparison of Two Measurement Methods for the Emission of Radiated Disturbances Generated by LED Drivers. *Energies* **2022**, *15*, 9372. https://doi.org/10.3390/en15249372

Academic Editors: Lubomir Bena, Damian Mazur and Bogdan Kwiatkowski

Received: 11 November 2022
Accepted: 8 December 2022
Published: 11 December 2022

1. Introduction

Nowadays, apart from traditional bulb lamps, all lighting technology equipment and accessories are subject to the EMC Directive 2014/30/EC [1]. Going back two decades, the primary light sources of the time were gassed, halogen, and incandescent light sources. The second group consisted of discharge (luminescent) lamps, i.e., fluorescent lamps—fluorescent tubes, high-pressure mercury vapour lamps, and high-pressure and low-pressure sodium lamps. The third group of sources are incandescent–luminescent lamps, i.e., mercury vapour, xenon, and arc lamps. Today, significant technological advances in the production of semiconductor light sources have led to LEDs being used as full-fledged light sources. The increasing emission powers of these sources have allowed LEDs to be used in both outdoor and indoor general lighting, the automotive industry, large LCDs, decorative and architectural lighting, and traffic signalling.

The significant advantages of LED lamps are their exceptional durability of up to 100,000 h of reliable operation and energy efficiency resulting from the use of modern SMD-type, light-emitting diode LEDs.

The widespread use of LEDs in lighting technology is made possible by the high luminous efficacy of white LEDs. Currently, LEDs with efficiencies in excess of 200 lm/W are commercially available. LED lamps based on them have efficiencies in excess of 100 lm/W [2].

They are usually powered by direct current, so there is no flickering or pulsating effect, and they do not emit ultraviolet radiation. They do not contain mercury in their construction. LED drivers have high efficiency ($\eta > 0.95$ and even 0.98), and overload and thermal protection are included. The modern modules are compatible with intelligent lighting systems in buildings.

Among the number of the abovementioned advantages, modern LED lamps also have disadvantages. From the point of view of electromagnetic compatibility, a significant problem with LED lamps is their generation of electromagnetic disturbances. This problem was not present in the case of classic incandescent lamps. The generation of disturbance is a consequence of DC/DC converter circuits. Electronic power supplies, which are an integral part of an LED lamp, are used for this purpose. They range from simple converters without a transformer through power supplies containing specialised current stabilisers to more advanced constructions with AC/DC and DC/DC converter circuits [3]. Each LED requires a stable constant value of voltage and a DC to operate properly regardless of whether the LED and its circuits are powered from a DC voltage source or the 110 or 230 V mains. In order to ensure a stable value of the current flowing through the LEDs in modern LED lamps, current stabilisers of the direct AC driver type are commonly used as well as AC/DC and DC/DC converters in various configurations depending on the power source and the layout of the LEDs being powered. In the case of a power supply circuit with a direct AC driver stabiliser, the mains voltage is rectified by a Greatz bridge and smoothed by an electrolytic capacitor connected to the bridge output. At the output of the rectifier, a DC voltage is obtained which directly supplies the LEDs, usually connected in one or two branches in series (applying to the lamp power). The role of the direct AC driver current stabiliser is to maintain a constant value of the current supplying the LEDs irrespective of fluctuations in the mains voltage. In the case of AC/DC converters, the mains voltage is converted to DC voltage in the first phase and then converted to a voltage with a value adapted to the layout of the LEDs being powered in the second phase. In the case of LED lamps powered from a DC source, the supply voltage is converted in the DC/DC converter from the value of the supply source to the voltage required to power the LEDs. Each converter, whether AC/DC or DC/DC, must ensure that the LED supply current is stable regardless of fluctuations and variations in AC or DC voltage [4].

If the manufacturer has not introduced appropriate EMC solutions into these power supply systems of LED lamps, they may be a source of electromagnetic disturbance emissions EMI, which may adversely affect the operation of other equipment. Given that LED lamps and other light sources play a significant role in people's lives, as they are used to illuminate open spaces, thoroughfares, architectural structures, and room interiors, they form, together with their accessories, a significant group of devices. It is estimated that global energy consumption for lighting in 2005 was 2650 TWh, representing 19% of global electricity consumption [5]. Compatibility requirements and the significant contribution of lighting fixtures to electricity consumption result in this group having its own dedicated standard: EN IEC 55015:2019-11 [6].

An analysis of the publications indicated that the problem of conducted and radiated disturbance generation by LED lamps is significant [7–22]. As indicated by the results of studies contained in publications [7–18], LED lamps can have a negative impact on the operation of sensitive electronic devices: consumer, medical, IT, military, etc. In critical cases, they can cause a sensitive device or system to lose its function or even be damaged. The cases analysed in the publications [7–18] show how LED lamps can cause falsification of the information transmitted in medical or IT systems. It is therefore very important that any sensitive equipment should have an adequate level of immunity to any possible disturbance that may occur in its operating environment and that potential sources of disturbance located in the vicinity of such equipment should have the emission levels specified in the adequate EMC standards.

In the search for an answer to the nagging problem regarding the equivalence of results obtained using the SAC and CDNE methods, a number of thematic publications on the phenomenon of radio disturbance generation by LED lamps were analysed. As shown by the analysis of publications from the last decade [10–18,23], with the widespread introduction of LED lamps into lighting technology, the problem of disturbance generation with a sufficiently broad harmonic spectrum exceeding 300 MHz was recognised. This is reflected in the increase of the current EN IEC 55015:2019-11 [6] standard in question, which extends the range of disturbance analysis to 1 GHz.

The analysis carried out showed that the problem regarding the compatibility of the radio disturbance emission measurements generated by LED lamps using the SAC and CDNE methods have described in a small number of publications [13,14]. In article [13], the authors presented the results of the research carried out, among others, in terms of comparing the SAC and CDNE methods. They showed that measurements obtained with the CDNE method can give results that are discrepant with the SAC method. In the case of publication [14], the authors compared the results obtained with the GTEM comeasurement method with those obtained with the CDNE method, also finding significant discrepancies between the results of one method and the other.

2. Methods of Measurement

According to the current EN IEC 55015:2019-11 standard, the analysis of radiated disturbances generated by lighting technology components is carried out in the frequency range of 9 kHz to 1 GHz. In the frequency band from 9 kHz to 30 MHz, the magnetic field component generated by the test object is analysed while from 30 MHz to 1 GHz, the electric field component is analysed. In addition, if the lamp is powered from the mains power supply in the band from 9 kHz to 30 MHz, the level of conducted disturbances propagated through the power supply circuits of the lamp is measured. According to the provisions of the standard, the measurement of the radio emission of the test object can be carried out on an open OATS (Open Test Area Site) testbed, in a semianechoic chamber SAC, in a fully anechoic chamber FAR, a TEM chamber, or by an indirect method using a coupling and decoupling network referred to in the standard [6] as the 'CDNE method. While the OATS/SAC, FAR, and TEM methods are similar to some extent, the CDNE method does not measure the value of the electric field strength but measures the equivalent value of the induced disturbance voltage at the terminals of the coupling/decoupling network. According to a note in the standard [6], the CDNE method can be used in the frequency range of 30 to 300 MHz alternatively to the previously used methods (SAC, FAR, and TEM). This means that if the lamp under the test obtains a positive result using the CDNE method, it can be concluded on this basis that it meets the requirements of the standard [2] in the frequency range of 30 to 300 MHz. The limitation is that this method can be used for lamps that have components in their circuits that generate clock signals of up to 30 MHz. Modern LED lamps meet this criterion, as the frequencies of the DC/DC and AC/DC converters used in LED lamps range from tens to hundreds of kilohertz.

The results obtained for a selected number of LED lamps which were obtained by measuring each lamp first with the SAC method and then with the CDNE method have been compared in this paper. As previously mentioned, the CDNE method was introduced as an alternative method for testing lighting technology objects in the version of the EN 55015 standard issued in 2013. In this method, the level of the disturbance voltage generated in total on all the power supply lines of the object under test is measured during testing at the signal port of the CDN. The measured value of the disturbance signal is expressed in dBμV and is related to the limit curve defined in the standard [6]. The peculiarity of this method is that the measurement can be made in an unshielded room (which means that the measurement does not have to be conducted in an anechoic chamber), provided that during the tests, the level of external disturbance does not affect the measurement result. To confirm this, a disturbance measurement should be carried out before the test in the target configuration with the test object switched off. It is recommended that the level of a disturbance generated by external sources should be at least 6 dB below the permissible value. Another advantage of the CDNE method is that the test duration is considerably shorter than that of the SAC method. In the SAC method, the electrical component of the electric field strength, which is expressed in dBμV/m, is measured. Because the two methods measure different types of disturbance signals, they also have different permissible disturbance limits. The permissible disturbance limits measured by the SAC and CDNE methods are described in Tables 1 and 2.

Table 1. Radiated disturbance limits in the frequency range 30 to 300 MHz for a measurement distance of 3 m for the SAC method.

Frequency Range MHz	Limits, Quasi—Peak dBμV/m
30 to 230	40
230 to 300	47

Table 2. Disturbance voltage emission limits at the power supply terminals for the frequency range 30 to 300 MHz for CDNE method.

Frequency Range MHz	Limits, Quasi—Peak dBμV
30 to 100	64 do 54 [x]
100 to 230	54
230 to 300	61

[x]—The limit decreases linearly with the logarithm of the frequency.

The permissible disturbance levels in Tables 1 and 2 represent a reference limit that cannot be exceeded by the measured values of the analysed disturbances. For both the SAC and CDNE methods, the final disturbance level is determined using a quasipeak detector. The characteristic features by which the two methods differ have been shown in Table 3.

Table 3. Comparison of the SAC and CDNE methods.

SAC Method	CDNE Method
The electrical component of the disturbance field strength, expressed in dBμV/m, is measured.	The disturbance voltage is measured at the supply terminals, which is expressed in dBμV.
Measurements are made in an anechoic chamber.	An anechoic chamber is not required.
It is time-consuming. The measurement takes several tens of minutes.	It is a fast method. The measurement takes several minutes.

The main advantage of the CDNE method is the relatively low cost of the test stand. It can be used in unshielded rooms with moderate levels of RF disturbance. There is a provision in EN-55015 that states that if a lighting device under test complies with the requirements of the CDNE method (emission limits), that device is deemed to comply with EN IEC—55015:2019 in the range 30 to 300 MHz. Due to the specific properties of the CDNE method, it is important to ask whether the two methods give equal, unambiguous results. As part of the research work, a comparative analysis was carried out for four selected LED lamps.

3. Description of the Test Stands

3.1. SAC Method

The rules for the measurement of electromagnetic emissions are subject to strict guidelines as laid out in EN 55016-2-3 [21]. These are a consequence of the need to obtain representative, repeatable measurement results. Measurements to determine the level of disturbance emissions require the use of a certified set of apparatuses. The requirements are specified in EN 55016-1-1 [24] and EN 55016-1-4 [25]. For the measurement of conducted and radiated disturbance emissions, the minimum laboratory equipment required is an anechoic chamber equipped with appropriate technical infrastructure, a measurement receiver, a set of antennas, artificial networks, and structured cabling. In order to obtain meaningful, reliable measurement results, all test bench equipment must have appropriate calibration certificates issued by independent, notified bodies. This makes it possible to isolate the test object and test setup from the influence of the external electromagnetic environment.

Tests using the SAC method were carried out in a 3M anechoic chamber from TDK, a certified Seibersdorf laboratory from Austria. The chamber was equipped with a DS2000S1t-H300 rotary table and an MA 4000-NS mast from INNCO. A setup consisting of an HK116 antenna and an ESU26 measuring receiver from Rohde & Schwarz controlled by the EMC32 software package was used to measure the disturbance emissions. The EMC32 package enables automation of the measurement process and allows all nonlinearities and attenuations in the measurement path, i.e., from the antenna to the input of the measurement receiver, to be taken into account.

The LED lamp under test was placed on a table 0.8 m high and powered, as recommended in the standard [6], via Ericka Fiedler's CDN M2 artificial network. During the measurements, the RF measuring circuit of the network was shunted with an impedance of 50 Ω. The LED lamp under test and the CDN artificial network were supplied with 230 V AC via high-efficiency interference suppression filters (Figure 1). The socket in which the test lamp was fitted was connected to the CDN with a 1.5 m twin-core cable. The LED lamp under test was placed at a distance of 3 m from the HK116 measurement antenna. During testing, the LED lamp table was rotated in 45° increments for a full 360° rotation around its vertical axis. For each table position, emission levels were measured for the vertical and horizontal positions of the antenna. During the measurements, the antenna position changed from 1 to 4 m with a step of 0.5 m.

Figure 1. Test stand for measuring the radiated disturbance emissions generated by the LED lamp under test in the frequency range of 30 to 300 MHz using the SAC method.

3.2. CDNE Method

The required (according to [6]) test setup configuration for measuring the conducted disturbance emission of lighting lamps in the range of 30 to 300 MHz using the CDNE method is presented in Figure 2. The LED lamp under test was placed in a socket on an insulating sub-base 0.1 m high and supplied with 230 V AC (PS) via the CDN-M2 artificial network. The disturbance signal via a 6 dB attenuator (T) was measured by an ESU-26 receiver (R). The components of the test setup, such as the LED lamp under test, the artificial network, the attenuator, and the required isolation pads, were placed on a metal plane (MP) connected to the reference ground of the 3 M TDK anechoic chamber. In accordance with the requirements of the standard [2], the socket in which the LED lamp under test was placed was connected to the CDNE network with a 0.2 m long two-wire cable. To ensure its required distance to the metal plane, it was placed on an insulated spacer 0.04 m high.

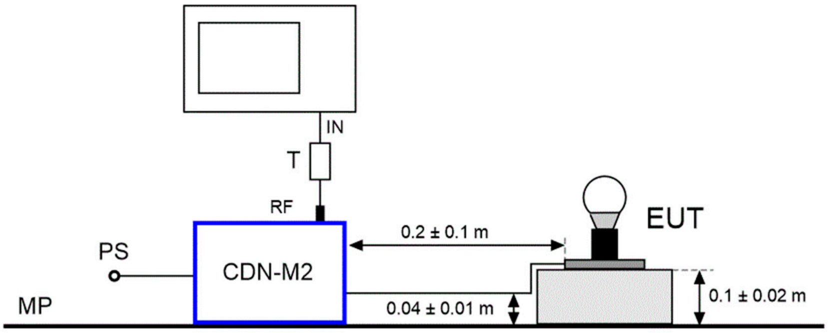


Figure 2. Test setup for testing lighting devices using the CDME method in accordance with EN 55015:2013: PS—power supply, R– measuring receiver ESU-26, CDN-M2—coupling and decoupling network, T—attenuator 6 dB, EUT—tested LED lamp, MP—grounded metal plate.

Although tests using the CDNE method do not require an anechoic chamber, the measurements also were made in a 3 M TDK chamber (Figure 3).

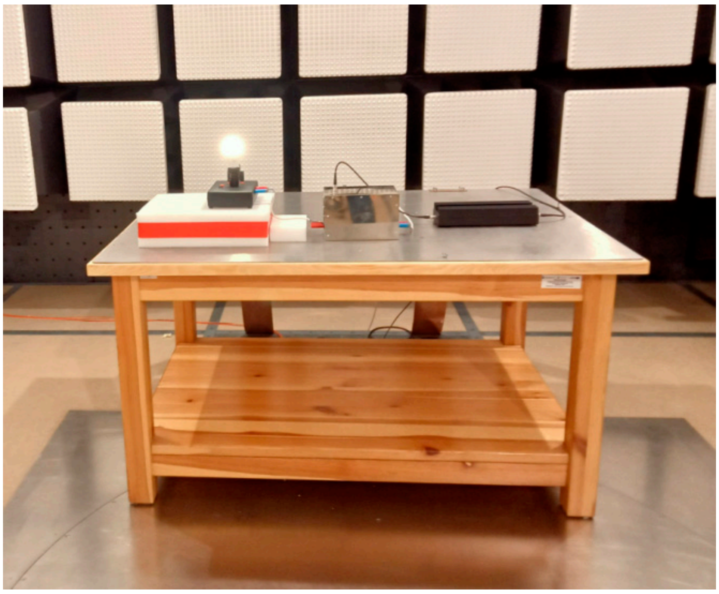
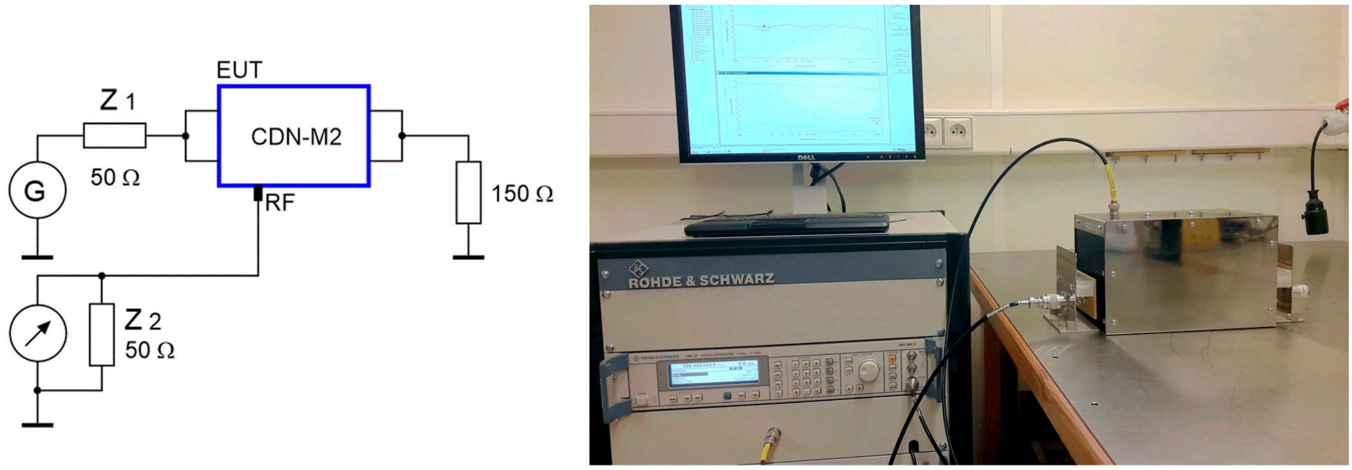


Figure 3. Measuring stand for determination of conducted disturbance emissions generated by the LED lamp under test in the range of 30 to 300 MHz using the CDNE method.

As previously mentioned, the signal output of the CDN network was connected to the ESU-26 measurement receiver by means of a 6 dB attenuator and RF cable system. The attenuation characteristics of the filter, the attenuation of the RF cables, and the voltage division factor of the CDN-M2 network were included in the total signal balance of the measurement path. The voltage division factor was measured according to the guidelines in the standard. A test stand was designed for this purpose. The SML100A signal generator, Rohde & Schwarz power probe NRP-Z21, was used to measure the division factor (Figure 4). The measured value of the voltage division factor for the network used for the measurements is presented in Figure 5.



(**a**) (**b**)

Figure 4. CDN-M2 network voltage division ratio measurement stand. (**a**) Electrical diagram and (**b**) photograph of the stand.

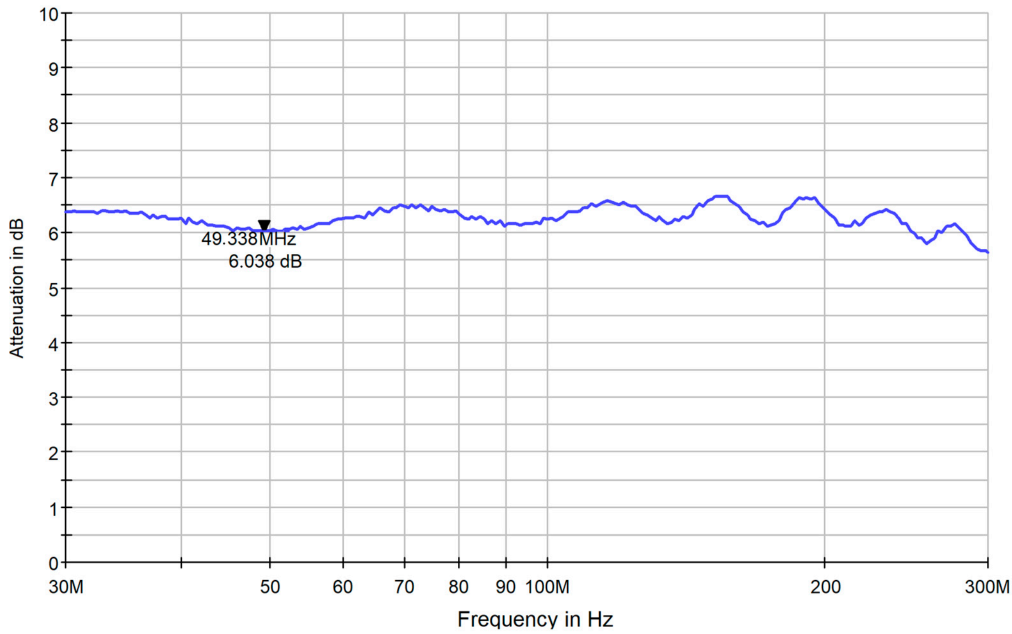


Figure 5. Frequency characteristics of the voltage division factor for Ericka Fiedler's CDN-M2 network.

As in the SAC method, in the CDNE method, the measuring system was also controlled by specialised software EMC32.

4. Experimental Section

4.1. Test Methodology

Four types of LED lamps were used to verify the SAC and CDNE methods. Their selection was guided by the level of the electromagnetic disturbance they generated. The parameters of the selected lamps for testing are summarised in Table 4. Lamps 5 W, 9 W, 15 W, and 18 W were selected for testing, respectively. The lamps selected for testing allowed to test three scenarios. The first was when the lamp under test was characterised by emission levels far removed from the limit values specified in the standard [6] for the SAC and CDNE methods. The second was when the emission values of the lamp under test were close to the limit values, and the third was when the lamp under test had emission levels well above the limit values.

Table 4. Basic parameters of the tested lamps.

	Parameter	Unit	Lamp A	Lamp B	Lamp C	Lamp D
1.	Power	W	9	5	15	18
2.	Counterpart	W	52	33	100	85
3.	Luminance	lm	680	360	1520	1220
4.	Supply	V	230 V/50 Hz	230 V/50 Hz	230 V/50 Hz	230 V/50 Hz
5.	Colour	K	3000	3000	4000	3000
6.	Reliability	h	40,000	50,000	20,000	50,000
7.	No. of cycles	Cycles	10,000	18,000	15,000	15,000
8.	Class	-	A++	A+	A+	A

The following test chronology was adopted in this study: Firstly, the dispersion of the disturbance signal values emitted by LED lamps of the same nominal power and manufacturer was checked. For this purpose, three 18 W lamps were tested sequentially once with the SAC method and then with the CDNE method. Then three 5 W lamps were tested using both methods. These tests showed that there were no significant differences in the achieved values of emitted disturbances between the groups for each method separately. This made it possible to carry out further tests in such a way that each of the four LED lamps from different manufacturers with powers of 5, 9, 15, and 18 W were first tested using the SAC method and then using the CDNE method. For the SAC method, the required frequency range of 30 to 300 MHz was divided into 60 intervals. In each interval, one frequency value corresponding to the maximum emission level was obtained after measurement with the peak detector. Then, for this frequency value, the emission level was measured with a quasipeak QP detector. In this way, 60 QP values were obtained for each of the tested lamps. It should be noted that the frequency values for which QP values were obtained were different for each tested lamp. This is because each LED lamp has its own characteristic spectrum of disturbance emission. Subsequently, each LED lamp was tested using the CDNE method for the frequency values that the individual lamp had previously obtained using the SAC method. Thus, a given lamp was tested first with SAC and then with CDNE for the same frequency values. The recorded QP values obtained using the SAC and CDNE methods for each tested lamp, together with the corresponding limits (Limit) and margins (Margin), were then compared using the statistical tools available in Statistica software v13. An analysis of the results showed different performance scenarios for a given tested LED lamp once with the SAC method and then with the CDNE method. The obtained results and their analysis are presented in the next subsections.

4.2. Test Results for LED Lamp A

The partial results obtained for the analysed LED lamp A are presented in Figure 6.

In Figure 6, from the left: the frequency values determined according to the adopted methodology then the QP values expressed in dBμV, which were measured using the CDNE method; the allowable limit values (Limit dB V) for this method and the calculated margin values (Margin dB) as the difference between the allowable limit and the corresponding measured QP value. Columns 5 to 7 show the values obtained for the same LED lamp when tested using the SAC method. Already at this stage, the results show differences. For example, for the frequency of 99.27 MHz, it can be seen that using the CDNE method, the 9 W LED lamp tested obtained a not-insignificant margin value of 2.39 dB (Figure 6, column 4). In contrast, the same lamp tested using the SAC method obtained a margin of 11 dB at this frequency (99.27 MHz). A graphical representation of the relationship between the QP values and the acceptable limits obtained using the SAC and CDNE methods is shown in Figure 7, where the differences between the values obtained with the two methods at 99.27 MHz are highlighted.

1 Frequency, MHz	2 QP, CDNE, dBµV	3 Limit, CDNE, dBµV	4 Margin, CDNE, dB	5 QP, SAC, dBµV/m	6 Limit, SAC, dBµV/m	7 Margin, SAC, dB
60.06	49.09	58.24	9.14	28.14	40.00	11.86
64.02	50.58	57.70	7.13	29.07	40.00	10.93
64.74	50.72	57.61	6.89	29.35	40.00	10.65
67.35	51.24	57.28	6.05	28.21	40.00	11.79
72.33	50.96	56.69	5.73	28.72	40.00	11.28
72.78	50.90	56.64	5.74	28.73	40.00	11.27
78.30	50.25	56.03	5.78	27.97	40.00	12.03
80.31	50.46	55.82	5.36	28.99	40.00	11.01
84.48	51.01	55.40	4.39	28.93	40.00	11.07
87.12	51.29	55.15	3.86	29.71	40.00	10.29
88.05	51.41	55.06	3.65	29.50	40.00	10.50
93.33	51.91	54.57	2.67	29.73	40.00	10.27
94.98	51.93	54.43	2.50	29.35	40.00	10.65
99.27	51.67	54.06	**2.39**	28.28	40.00	**11.72**
103.02	50.53	54.00	3.47	28.14	40.00	11.86
106.56	48.71	54.00	5.29	27.50	40.00	12.50
110.73	46.21	54.00	7.79	26.08	40.00	13.92
115.02	44.31	54.00	9.69	22.95	40.00	17.05

Figure 6. Selected SAC and CDNE measurement results for LED lamp A.

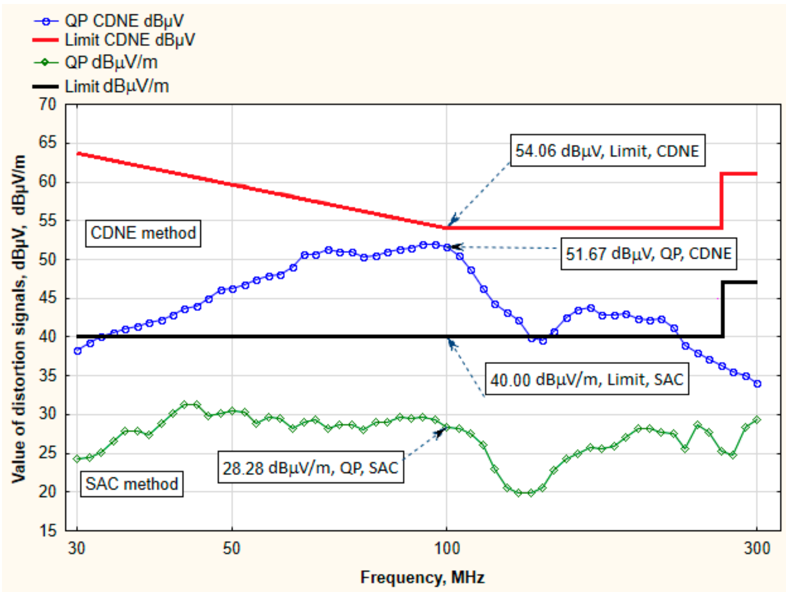


Figure 7. Recorded QP values using CDNE and SAC methods against the allowable limits for the tested LED lamp A.

Statistical tools were used to compare the results obtained with the two methods. When comparing the mean QP values calculated for the recorded QP values over the entire frequency range (from 30 to 300 MHz), they were 44.35 dBµV for the CDNE method and 27.27 dBµV/m for the SAC method, respectively. When the CDNE method was used, the recorded QP values showed a greater scatter around the mean value (44.35 dBµV) of 4.98 dB (S-stat. deviation). The significant S-stat. deviation obtained is the result of changes in the QP values, which increased in the frequency range from 30 to 100 MHz with a decrease thereafter. Looking further at the value of the third quartile Q3, it can be seen that 75% of the recorded QP values did not exceed 49.09 dBµV while the remaining 25% of the values had higher values reaching up to the recorded maximum QP value of 51.93 dBµV. In comparison, the value of the third quartile Q3 calculated for the QP values obtained using the SAC method was 29.30 dBµV/m and is comparable to the mean and median (Me) values. This means that 75% of all recorded values had values no greater than 29.30 dBµV/m while the remaining 25% of recorded values had values greater than that, reaching up to the recorded maximum QP value of 31.32 dBµV/m. One and the other values (i.e., 29.30 and 31.32 dBµV/m) show a large margin of over 8 dB with respect to the applicable limit for the SAC method.

Based on the value of the first quartile, Q1 = 25.59 dBµV/m, it can be concluded that 25% of the recorded values had a margin of over 14 dB in relation to the limit. On this basis, it can be noticed that the disturbance signal emitted by the 9 W LED lamp A had a considerable margin of overlap with the limit value of the SAC method. Next, it can be seen (Figure 7) that the recorded QP values with the SAC method are characterised, in the case of this lamp, by a stable pattern of values over a wide frequency range, i.e., from 43.44 to 94.98 MHz, which is confirmed by analysis of the calculated values of the range (R) and standard deviation (S). The range value is the difference between the highest recorded value (max.) of 31.32 dBµV/m and the lowest recorded value (min.) of 19.83 dBµV/m, giving R = 11.49 dBµV/m. The standard deviation calculated for the recorded QP values has a small value of 2.75 dBµV/m (Figure 8).

Lamp A									
SAC method									
Parameter	L	Av.	Me	Min.	Max	Q1	Q2	R	S
Frequency, MHz	60	112.20	90.69	31.02	298.29	51.36	161.64	267.27	71.63
QP, dBµV/m	60	27.27	28.13	19.83	31.32	25.59	29.30	11.49	2.78
Limit, dBµV/m	60	40.48	40.00	40.00	47.00	40.00	40.00	7.00	1.79
Margin, dB	60	13.21	12.07	8.68	22.16	10.93	14.96	13.48	3.35
CDNE method									
Parameter	L	Av.	Me	Min.	Max	Q1	Q2	R	S
QP, CDNE, dBµV	60	44.35	43.36	34.03	51.93	41.07	49.09	17.90	4.98
Limit, CDNE, dBµV	60	57.17	55.93	54.00	63.72	54.00	60.78	9.72	3.36
Margin, CDNE, dB	60	12.82	11.70	2.39	26.97	7.13	16.87	24.58	6.76

Figure 8. Recorded QP values using the new and traditional method against the allowable limits for LED lamp A under test, where: L—number of analysed values; AV—calculated average value; Min, Max—minimum and maximum values; Q1, Me(Q2), Q3—first, second and third quartile; R—range; and S—standard deviation.

The stock values can also be read from the margin values (Margin dB, Figure 8). In the case under consideration, for the SAC method, the minimum margin value was 8.68 dB. This is the value calculated as the difference between the 40 dBµV/m limit and the maximum value of the measured signal. The result obtained is very important because its value indicates that the tested lamp had a considerable margin to the admissible limit, so it passes the test. In contrast, the same lamp tested with the CDNE method obtained a margin of 2.39 dB. In order to make a proper decision as to whether the tested 9 W LED lamp A meets the requirements of the standard [6], the value of the margin (Figure 8, Margin CDNE dB) defines the relation between the QP value, and the permissible limit (Limit) is important. It is a very small margin value, which resulted in a negative decision that the tested lamp does not meet the requirements of the standard [6] in the range of 30 to 300 MHz. This could be because the manufacturer or importer should make changes to the electronic circuit to reduce the disturbance generated by the LED lamp.

On the other hand, the same LED lamp A tested using the SAC method obtained a high margin, which allows us to conclude that this lamp meets the requirements of the standard, i.e., the test result is positive. This example allows for the conclusion that the use of the SAC method and the CDNE method for the same LED driver can give different results, which will influence different decisions.

4.3. Test Results for LED Lamp B

When testing the 5 W LED lamp B, the opposite result scenario was obtained compared to the 9 W LED lamp discussed earlier. The results obtained from testing the LED lamp B with the CDNE and SAC methods show that the lamp meets the requirements of the EN IEC 55015:2019 standard if the CDNE method is used while it does not meet the requirements of the standard if tested with the traditional SAC method. The results of the QP value obtained for this lamp are shown in Figure 9. The lamp tested with the SAC method exceeded the limit value by 0.3 dB. (The EMC 32 programme calculates the margin value as the difference between the allowable limit value and the recorded QP value, which gives a negative value when exceeded. Therefore, the 5 W LED lamp B tested obtained a value equal to −0.3 dB—Figure 10.) In contrast, the same lamp tested using the CDNE method obtained a large stock margin value of 7.39 dB.

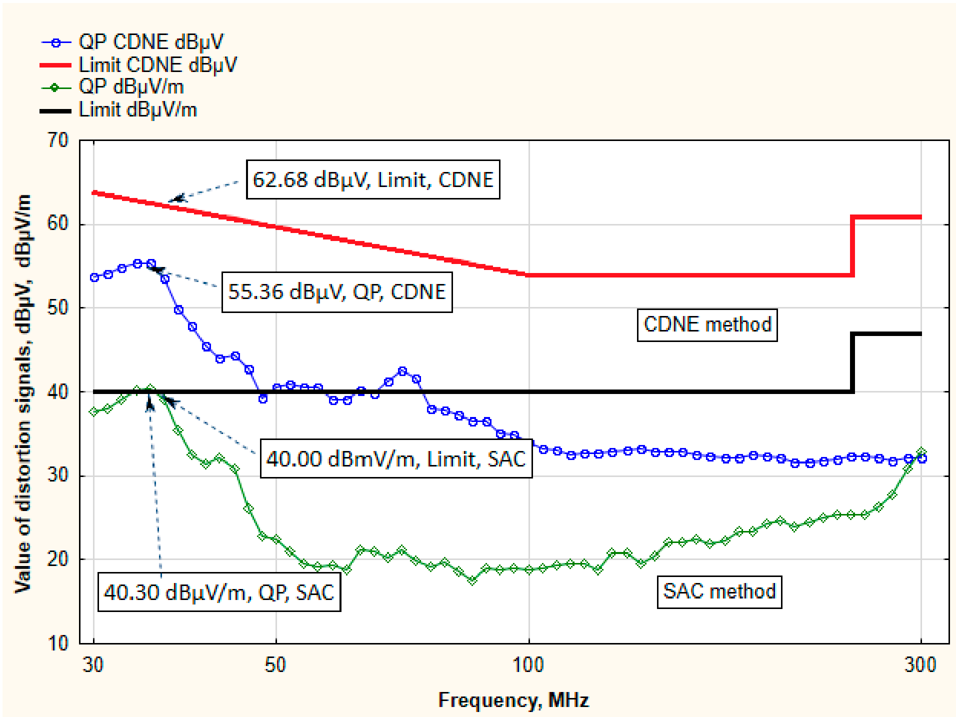


Figure 9. Recorded QP values using the new and traditional method against the allowable limits for the tested LED lamp B.

Lamp B									
SAC method									
Parameter	L	Av.	Me	Min.	Max	Q1	Q2	R	S
Frequency, MHz	60	117.60	94.56	31.05	297.50	53.34	169.60	266.40	76.20
QP, dBµV/m	60	24.50	22.19	17.55	40.30	19.58	26.20	22.80	6.43
Limit, dBµV/m	60	40.70	40.00	40.00	47.00	40.00	40.00	7.00	2.12
Margin, dB	60	16.70	18.82	-0.30	22.50	15.17	20.60	22.80	6.38
CDNE method									
Parameter	L	Av.	Me	Min.	Max	Q1	Q2	R	S
QP, CDNE, dBµV	60	38.10	35.00	31.65	55.36	32.36	41.10	23.70	7.17
Limit, CDNE, dBµV	60	57.30	56.39	54.00	63.70	54.00	61.00	9.70	3.40
Margin, CDNE, dB	60	19.30	19.76	7.39	29.30	17.53	21.70	21.90	5.12

Figure 10. Recorded QP values using the new and traditional method against the allowable limits for the LED lamp B under test, where: L—number of analysed values; AV—calculated average value; Min, Max—minimum and maximum values; Q1, Me(Q2), Q3—first, second and third quartile; R—range; and S—standard deviation.

The recorded QP values shown in Figure 9 have a decreasing trend and obtain large marginal values of the allowable limits starting at about 40 MHz. Only in the initial measurement frequency range, i.e., from 30 to 35.19 MHz, the analysed QP values had an increasing trend. At 34.65 MHz and 35.19 MHz, the QP values reached a maximum of 55.36 dBµV and 40.30 dBµV/m for the CDNE method and the SAC method, respectively. As can be seen from the statistical values shown in Figure 10, the values of the R range and the statistical deviation S have similar values obtained in each measurement method. The decreasing trend of the analysed QP waveforms resulted in 75% of the recorded QP values not exceeding 41.10 dBµV and 26.20 dBµV/m for the CDNE method and the SAC method, respectively. It can be concluded that a significant proportion of the recorded QP values had a large margin to the limit values. However, in EMC tests, the recorded QP values of the disturbance signal emitted by the devices under test must not exceed the permissible limit set normatively for the entire measurement frequency range. It is desirable that the values of the disturbance signal have an adequate margin of the reserve to the limit value. In the case in question, the QP values for LED lamp B tested with the SAC method were exceeded by 0.3 dB, which results in a negative decision on the test result. In contrast, the same lamp tested using the CDNE method achieved a large margin of the reserve, i.e., passes the test.

4.4. Test Results for LED Lamp C

LED lamp C with a nominal power of 15 W obtained positive test results with both methods, i.e., it complies with the requirements of EN IEC 55015:2019. The waveforms of the recorded QP values are shown in Figure 11, and the statistical results obtained are shown in Figure 12. In the case of this LED lamp, very high margin values were obtained. From the values of the third quartile Q3, it can be read that 75% of the recorded QP values did not exceed the values of 39.51 dBµV and 24.12 dBµV/m for the CDNE method and the SAC method, respectively. The highest recorded value obtained from the set of QP values analysed was 44.50 dBµV when tested with the CDNE method and 28.57 dBµV/m with the SAC method. Relating these values to the permissible limits for both methods results in significant margin values (Margin dB, Figure 11) of 16.66 dB and 11.97 dB for the CDNE and SAC methods, respectively. By analysing the calculated statistical measures (Figure 11), it can be concluded that the recorded QP values by both methods are characterised by similar values of standard deviation and range. Based on the values of the Q3 quartiles, it can be concluded that 75% of the recorded QP values had a margin of up to 20.93 dB for both methods while the remaining 25% had an even greater margin reaching 28.08 dB for the CDNE method and 23.26 dB for the SAC method.

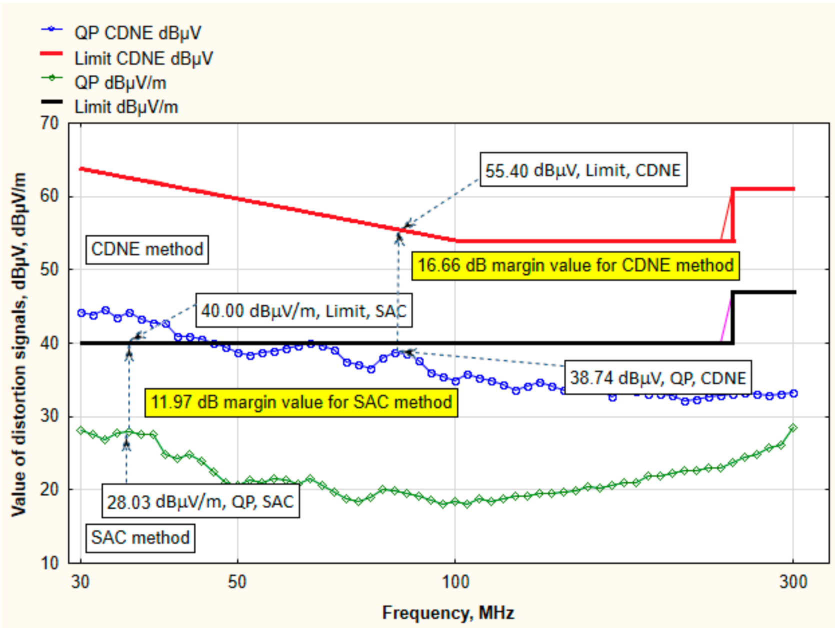


Figure 11. Recorded QP values using the new and traditional method against the allowable limits for the tested LED lamp C.

Lamp C									
SAC method									
Parameter	L	Av.	Me	Min.	Max	Q1	Q2	R	S
Frequency, MHz	60	117.40	94.31	30.39	299.19	53.12	171.24	268.80	76.03
QP, dBµV/m	60	21.97	21.05	18.09	28.57	19.58	24.12	10.48	3.04
Limit, dBµV/m	60	40.70	40.00	40.00	47.00	40.00	40.00	7.00	2.12
Margin, dB	60	18.73	19.31	11.97	23.26	17.50	20.93	11.46	2.94
CDNE method									
Parameter	L	Av.	Me	Min.	Max	Q1	Q2	R	S
QP, CDNE, dBµV	60	36.90	35.88	32.20	44.50	33.55	39.51	12.30	3.73
Limit, CDNE, dBµV	60	57.34	56.37	54.00	63.89	54.00	61.00	9.89	3.41
Margin, CDNE, dB	60	20.44	19.83	16.66	28.08	19.01	20.93	11.42	2.74

Figure 12. Recorded QP values using the new and traditional method against the allowable limits for the 15 W LED lamp C under test, where: L—number of analysed values; AV—calculated average value; Min, Max—minimum and maximum values; Q1, Me(Q2), Q3—first, second and third quartile; R—range; and S—standard deviation.

4.5. Test Results for LED Lamp D

Another tested LED lamp D had a nominal power of 18 W. This lamp was negative in both test methods. The recorded QP values presented against the permissible limits are shown in Figure 13. As can be seen from Figure 13 and analysis of the data in Figure 14, the recorded QP values exceed the permissible limits over a wide frequency range, i.e., from 31 MHz to about 230 MHz, when the CDNE method was used and from 31 MHz to about 115 MHz when the traditional SAC method was used. Analysing the quartile values when the CDNE method was used, it can be seen that 75% of the recorded QP values had exceedances greater than −5.14 dB, of which, 25% of the recorded QP values had exceedances greater than −16.02 dB. The maximum exceedance was −21.19 dB at 81.71 MHz for the CDNE method. In contrast, using the traditional SAC method, 75% of the recorded QP values had exceedances greater than −0.15 dB, including 25% of the values that exceeded the acceptable limit by −14.52 dB (this is the absolute value of −14.52 for the Q1 quartile, Figure 14). It can further be concluded that the exceedances occurring above the permissible limits have significant values. The largest exceedance values are indicated in Figure 13, i.e., −24.17 dB (the absolute value was 24.17 dB) at 37.74 MHz for the SAC method.

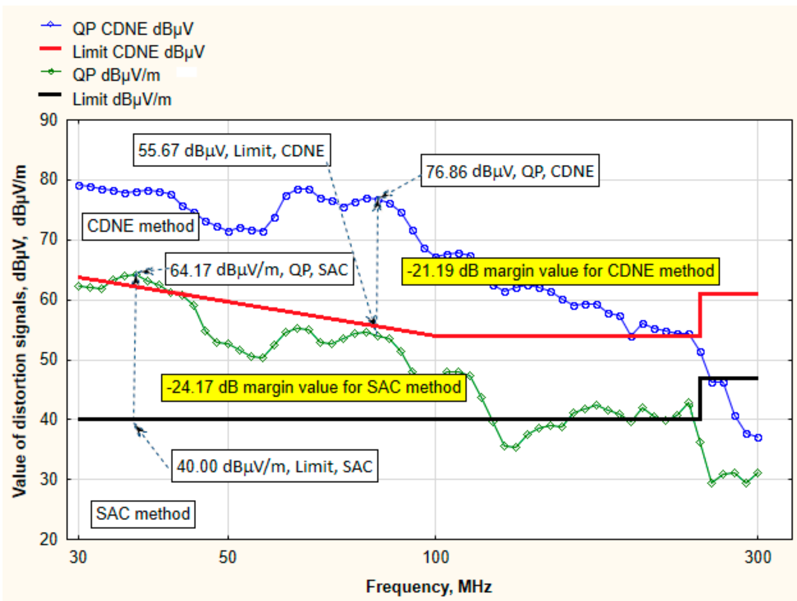


Figure 13. Recorded QP values using the new and traditional method against the allowable limits for the tested 18 W LED lamp D.

Lamp D									
SAC method									
Parameter	L	Av.	Me	Min.	Max	Q1	Q2	R	S
Frequency, MHz	60	117.17	93.14	31.11	298.89	53.61	169.79	267.78	75.53
QP, dBμV/m	60	47.91	47.92	29.38	64.17	40.15	54.52	34.79	9.87
Limit, dBμV/m	60	40.70	40.00	40.00	47.00	40.00	40.00	7.00	2.12
Margin, dB	60	-7.21	-7.92	-24.17	17.62	-14.52	-0.15	41.79	11.20
CDNE method									
Parameter	L	Av.	Me	Min.	Max	Q1	Q2	R	S
QP, CDNE, dBμV	60	66.56	70.02	36.98	79.02	59.14	76.68	42.04	11.33
Limit, CDNE, dBμV	60	57.33	56.36	54.00	63.70	54.00	61.00	9.70	3.39
Margin, CDNE, dB	60	-9.23	-12.65	-21.19	24.02	-16.02	-5.14	45.21	11.00

Figure 14. Recorded QP values using the new and traditional method against the allowable limits for the 18 W LED lamp D under test, where: L—number of analysed values, AV—calculated average value, Min, Max—minimum and maximum values, Q1, Me(Q2), Q3—first, second and third quartile, R—range, S—standard deviation.

4.6. Summary of Selected Analysis Results for Tested Lamps

From the analyses presented in the earlier chapters, it can be concluded that out of the four LED lamps tested with the two equivalent methods CDNE and SAC, only two LED lamps obtained unambiguous test results. Figure 15 presents a summary of the most important analysed values. The information on the value of the obtained margin was decisive for whether the LED lamp under test achieved a positive result in the tests carried out with the CDNE method and the SAC method. For the two LED lamps with 9 and 5 W power, alternating results were obtained. The 9 W LED lamp obtained a positive test result with the SAC method and a negative result when the CDNE method was used. The opposite results were obtained for the 5 W LED lamp B. The lamp obtained a positive test result when tested using the CDNE method while it obtained a negative result when tested using the SAC method. In contrast, the other LED lamps tested with 15 W and 18 W obtained unambiguous results with both methods. The 15 W LED lamp C passed the test using both the CDNE and SAC methods. This lamp achieved very high margin values in relation to the applicable limits. A negative test result using both the CDNE and SAC methods was achieved by the 18 W LED lamp. The recorded QP values showed significant exceedances above the applicable limits for both methods.

Designation of the tested LED lamps	Parameter	CDNE method			Parameter	SAC method			Decision
		Av.	Min.	Max.		Av.	Min.	Max.	
LED A	QP, CDNE, dBμV	44.35	34.03	51.93	QP, dBμV/m	27.27	19.83	31.32	Negative result - CDNE method Positive result - SAC method
	Limit, CDNE, dBμV	57.17	54.00	63.72	Limit, dBμV/m	40.48	40.00	47.00	
	Margin, CDNE, dB	12.82	**2.39**	26.97	Margin, dB	13.21	**8.68**	22.16	
LED B	QP, CDNE, dBμV	38.10	31.65	55.36	QP, dBμV/m	24.50	17.55	40.30	Positive result - CDNE method Negative result - SAC method
	Limit, CDNE, dBμV	57.30	54.00	63.70	Limit, dBμV/m	40.70	40.00	47.00	
	Margin, CDNE, dB	19.30	**7.39**	29.30	Margin, dB	16.70	**-0.30**	22.50	
LED C	QP, CDNE, dBμV	36.90	32.20	44.50	QP, dBμV/m	21.97	18.09	28.57	Positive results of the tests
	Limit, CDNE, dBμV	57.34	54.00	63.89	Limit, dBμV/m	40.70	40.00	47.00	
	Margin, CDNE, dB	20.44	**16.66**	28.08	Margin, dB	18.73	**11.97**	23.26	
LED D	QP, CDNE, dBμV	66.56	36.98	79.02	QP, dBμV/m	47.91	29.38	64.17	Negative results of the tests
	Limit, CDNE, dBμV	57.33	54.00	63.70	Limit, dBμV/m	40.70	40.00	47.00	
	Margin, CDNE, dB	-9.23	**-21.19**	24.02	Margin, dB	-7.21	**-24.17**	17.62	

Figure 15. Summary of test results obtained using the new and traditional test methods for the tested LED lamps A ÷ D.

This study concluded that the SAC method and the equivalent CDNE method can, in some cases, lead to ambiguous differing decisions, which can have negative consequences not only legally but also economically.

5. Conclusions

The objective of this study was to compare two methods for measuring electromagnetic disturbance emissions generated by light sources. The current EN 55015:2019-11 standard allows two equivalent methods to measure the radiated disturbance emissions of LED lamps in the frequency range of 30 to 300 MHz. However, the SAC method requires a large investment to build a test stand. Measurements must be carried out in a semianechoic chamber. To reduce the cost of building a test stand, the CDNE method was introduced in the previous edition of EN 55015:2013. With certain restrictions, this technique can be used to measure electromagnetic disturbance, and the test result obtained should be equivalent to that obtained using the SAC method. In particular, there is a provision in the aforementioned standard that if the lighting device under test meets the requirements set out for one of these methods, the device under test is considered to comply with EN55015. However, can the CDNE method always be used equivalently and interchangeably with the first traditional SAC method? The results obtained make it possible to state that the SAC and CDNE methods are not equivalent test methods because they give different test results, leading to ambiguity in deciding whether a given LED lamp tested meets or fails to meet the requirements of the standard.

In a situation where the result is inconclusive, the question arises as to whether or not the tested lamp meets the requirements of the standard and the basis that decides which method is superior. In such disputable cases, in the opinion of the authors, the SAC method should be used to solve the problem, which performs tests with the use of more advanced techniques and measurement tools (in this method, tests are performed in an anechoic chamber, the tested object is placed on a rotating measurement table, and the measurement antenna on a special mast scans the values of disturbances in the horizontal and vertical axis and changes its height in the range of 1 to 4 m). However, an unquestionable advantage of the CDNE method is that the duration of the test is considerably shorter compared to that of the SAC method. The abovementioned advantages of the CDNE method make it suitable for use in quality control departments for EMC testing on production lines in industrial plants. Of course, the previously obtained results for a given product in production must be correlated with the results obtained using the SAC method. In further studies, the authors intend to identify factors that, when eliminated, will enable both methods to be used equally.

Author Contributions: Writing—original draft preparation, conceptualization, methodology, W.S.; writing—review and editing, D.K.; resources, validation, formal analysis, investigation, data creation, visualization, W.S., D.K., K.K. (Kazimierz Kuryło) and K.K. (Kazimierz Kamuda). All authors have read and agreed to the published version of the manuscript.

Funding: This research paper was developed under the project financed by the Minister of Education and Science of the Republic of Poland within the "Regional Initiative of Excellence" program for years2019–2023. Project number 027/RID/2018/19, amount granted PLN 11,999,900. The work was developed by using equipment purchased in the programs EU: POPW.01.03.00-18-012/09-00; UDA-RPPK.01.03.00-18-003/10-00.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of this study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the Harmonisation of the Laws of the Member States Relating to Electromagnetic Compatibility, European Parliament and the Council of the European Union. 2014. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0030 (accessed on 1 September 2020).
2. U.S. Department of Energy. 2022 Solid-State Lighting R&D Opportunities. Available online: https://www.energy.gov/sites/default/files/2022-02/2022-ssl-rd-opportunities (accessed on 1 November 2022).
3. Yu, L.; Yang, J. The Topologies of White LED Lamps′ Power Drivers. In Proceedings of the 2009 3rd International Conference on Power Electronics Systems and Applications (PESA), Hong Kong, China, 20–22 May 2009; pp. 1–6.
4. Winder, S. *Power Supplies for LED Driving*; Newnes: London, UK, 2008; ISBN 10 0750683414.
5. Arie, S.; Ishida, K.; Wu, I.; Gotoh, K.; Matsumoto, Y.; Hirose, M. Statistical Characteristics of Radiation Noise from LED Lamps and its Effect on Wireless Medical Telemeters. In Proceedings of the International Symposium on Electromagnetic Compatibility (EMC EUROPE), Amsterdam, The Netherlands, 27–30 August 2018; pp. 408–412. [CrossRef]

6. *EN IEC 55015:2019*; Limits and Methods of Measurement of Radio Disturbance Characteristics of Electrical Lighting and Similar Equipment. European Standard: Brussels, Belgium, 30 August 2019.
7. Ishida, K.; Suzuki, K.; Hanada, E.; Hirose, M. EMC of Wireless Medical Telemeters and Noise Radiated from Light Emitting Diode Lamps. In Proceedings of the 2017 International Symposium on Electromagnetic Compatibility-EMC EUROPE, Angers, France, 4–7 September 2017; pp. 1–4. [CrossRef]
8. Wibisono, M.A.; Moonen, N.; Leferink, F. Interference of LED Lamps on Narrowband Power Line Communication. In Proceedings of the 2020 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI), Reno, NV, USA, 28 July 2020–28 August 2020; pp. 219–221. [CrossRef]
9. Wu, I.; Ohta, H.; Gotoh, K.; Ishigami, S.; Matsumoto, Y. Relation between electromagnetic noise from LED light bulb and its impact on bit error rate performance of DTTB. *IEICE Electron. Express* **2012**, *9*, 666–672. [CrossRef]
10. Sabat, W.; Kamuda, K.; Klepacki, D.; Kuryło, K. Measuring Methodology of Conducted Disturbances Generated by Avionic Systems in Aircrafts. In *Methods and Techniques of Signal Processing in Physical Measurements*; Hanus, R., Mazur, D., Kreischer, C., Eds.; MSM 2018, Lecture Notes in Electrical Engineering; Springer: Cham, Switzerland, 2019; pp. 1–12. [CrossRef]
11. Putz, Ł.; Bednarek, K.; Nawrowski, R. Disturbances Generated by Lighting Systems with LED Lamps and the Reduction in Their Impacts. *Appl. Sci.* **2019**, *9*, 4894. [CrossRef]
12. Kamuda, K.; Klepacki, D.; Kuryło, K.; Sabat, W. Comparison of Emission Measurement Methods for Electromagnetic Disturbances in the Frequency Range from 30 MHz to 300 MHz for LED Lamps According to EN 55015. *Period. Polytech. Electr. Eng. Comput. Sci.* **2019**, *63*, 106–111. [CrossRef]
13. Džeriņš, G.; Asmanis, A.; Asmanis, G.; Dzenis, A. LED lighting Equipment Electromagnetic Compatibility. In Proceedings of the 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 12–13 October 2017; pp. 1–6. [CrossRef]
14. Brodecki, D. Problemy Pomiaru Zaburzeń Radioelektrycznych Wytwarzanych Przez Źródła Światła LED, Przegląd Elektrotechniczny—Electrical Review; ISSN 0033-2097, R. 95 No. 3/2019. Available online: https://sigma-not.pl/publikacja-118950-2019-3.html (accessed on 1 November 2022). (In Polish)
15. Bednarek, K.; Typańska, D.; Misiorny, J.; Pietkiewicz, A. Reduction of Electromagnetic Disturbances Emission Generated by LED Lighting Fixture. In Proceedings of the Applications of Electromagnetics in Modern Techniques and Medicine (PTZE), Racławice, Poland, 9–12 September 2018; pp. 13–16. [CrossRef]
16. Bugaj, M.; Przesmycki, R.; Bugaj, J. Electromagnetic Compatibility of LED Lamps. In Proceedings of the 2019 PhotonIcs & Electromagnetics Research Symposium-Spring (PIERS-Spring), Rome, Italy, 17–20 June 2019; pp. 3147–3152. [CrossRef]
17. Matsumoto, Y.; Wu, I.; Gotoh, K.; Ishigami, S. Measurement and modeling of electromagnetic noise from LED light bulbs. *IEEE Electromagn. Compat. Mag.* **2013**, *2*, 58–66. [CrossRef]
18. Oganezova, I.; Kado, R.; Khvitia, B.; Gheonjian, A.; Jobava, R. Simulation of LED Lighting System Under BCI Test Setup. In Proceedings of the 2016 IEEE International Symposium on Electromagnetic Compatibility (EMC), Ottawa, ON, Canada, 25–29 July 2016; pp. 110–115. [CrossRef]
19. Pop, F.; Munteanu, C.; Răcăşan, A.; Păcurar, C.; Pruşu, S.; Mihai, G. Evaluation of conducted disturbances from LED lamps according to EN 55015. In Proceedings of the 2016 International Conference on Communications (COMM), Bucharest, Romania, 9–10 June 2016; pp. 509–512. [CrossRef]
20. Ishida, K.; Oshida, T.Y.; Arie, S.; Matsuzuki, M.; Hanada, E.; Hirose, M. Study of Electromagnetic Noise Radiated from LED Shadowless Lighting and Its Effect on Surgical Navigation System. In Proceedings of the 2018 International Symposium on Electromagnetic Compatibility (EMC EUROPE), Amsterdam, The Netherlands, 27–30 August 2018; pp. 866–869. [CrossRef]
21. *EN 55016-2-3:2017*; Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods-Part 2-3: Methods of Measurement of Disturbances and Immunity-Radiated Disturbance Measurements. European Standard: Brussels, Belgium, 2017.
22. Letha, S.S.; Bollen, M.H.J.; Rönnberg, S.K. Analysis and Recommendations for LED Catastrophic Failure Due to Voltage Stress. *Energies* **2022**, *15*, 540. [CrossRef]
23. Otomański, P.; Pawłowski, E.; Szlachta, A. The Evaluation of Expanded Uncertainty of DC Voltages in the Presence of Electromagnetic Interferences using the LabVIEW Environment. *Meas. Sci. Rev.* **2021**, *21*, 136–141. [CrossRef]
24. *EN 55016-1-1:2019*; Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods-Part 1-1: Radio Disturbance and Immunity Measuring Apparatus-Measuring Apparatus. European Standard: Brussels, Belgium, 2019.
25. *EN 55016-1-4:2019*; Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods-Part 1-4: Radio Disturbance and Immunity Measuring Apparatus-Antennas and Test Sites for Radiated Disturbance Measurements. European Standard: Brussels, Belgium, 2019.