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ELECTROMAGNETIC COMPATIBILITY TESTING OF ELECTRIC VEHICLES AND THEIR CHARGERS

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Abstract. *The article presents the latest information about electromagnetic compatibility testing of electric vehicles, on-board chargers and electric vehicle charging stations with a consideration of current standards and Regulation No. 10 of the United Nations Economic Commission for Europe (UNECE). The aspects of immunity, conducted and radiated emissions were taken into account.*

Keywords: electromagnetic compatibility; electromobility; electric vehicle; EV charging

TESTOWANIE SAMOCHODÓW ELEKTRYCZNYCH ORAZ ICH ŁADOWAREK POD KĄTEM KOMPATYBILNOŚĆI ELEKTROMAGNETYCZNEJ

Streszczenie. *W artykule przedstawiono najnowsze informacje na temat badań samochodów elektrycznych oraz ładowarek pokładowych i zewnętrznych stacji ładowania pod kątem kompatybilności elektromagnetycznej z uwzględnieniem obowiązujących norm oraz Regulaminu nr 10 Komisji Gospodarczej Organizacji Narodów Zjednoczonych (EKG ONZ). Pod uwagę wzięto aspekty odporności i emisji zaburzeń przewodzonych oraz promieniowanych.*

Słowa kluczowe: kompatybilność elektromagnetyczna; elektromobilność; samochód elektryczny, ładowanie samochodów elektrycznych

Introduction

Electromagnetic compatibility (EMC) tests are carried out on almost every system intended for commercial use [10,11]. It is the same with electric vehicles (EVs) and electric vehicle (EV) chargers, also known as electric vehicle supply equipment (EVSE) due to the fact they are equipped with many high and low power electrical and electronic devices, for instance a large number of sensors, GPS navigators, controller units and equipment that enable the GSM connectivity. What is more, EVs use electric motors that are dynamically controlled with fast switching modules (Pulse-Width Modulation) and power converters. Moreover, EV charging can also pose a threat to the electromagnetic environment and affect the power system (Fig. 1) [3,16].

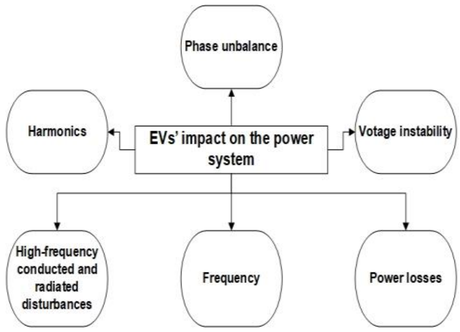

Fig.1. EVs' impact of EV charging on the power system [1,2]

Every manufacturer of EVs preparing to release a product in a given country must comply with and adhere to a list of relevant EMC guidelines, standards and legislation that aim to protect devices from electromagnetic interference (EMI). The aim of EMC for automobiles is to ensure that a vehicle does not produce unnecessary excessive EMI which could potentially disrupt or disable the operation of other electrical systems. It also guarantees that the performance of the tightly packed components within the vehicle will not decline due to the existence of EMI.

As the number of co-existing electrical systems is large, this poses a major challenge to designers of EVs and EV chargers. The application of EMC best practices from the concept to the prototyping and production phases of an EV, including its subassemblies and all electrical and electronic parts in the initial design phase of an EV charger prototype and the EV itself can minimise or even prevent any time-consuming and costly modifications of the final product before its release. Pre-normative research into measurement methods of EV chargers is justified, as electronic control systems are developing in electric vehicles, and any errors or failures due to electromagnetic disturbances can affect the EMC environment or even a human's life. A poor electromagnetic compatibility (EMC) design of the AC/DC and DC/DC converters of EV chargers can cause deterioration of the electromagnetic environment inside the vehicle, degradation of a user's experience, and even might endanger the reliability of the vehicle. Thus, providing safety with a consideration of EMC requirements is of paramount importance [17].

Electric vehicles are becoming more and more popular every year. As the number of EVs increases, so does the number of charging points. According to Global EV Outlook 2019 [27], in 2018, there were about 5.1 million electric cars and over 540,000 public charging points (of which 150,000 were fast charging points). Tab. 1. shows the countries with the highest number of slow and fast charging points that year.

Table 1. Chosen countries with the highest number of publicly accessible slow and fast chargers in 2018 [27]

Country	Number of chargers
South Korea	9,303
Norway	12,371
The United Kingdom	17,424
France	24,132
Germany	25,724
Japan	29,971
Netherlands	36,671
The United States	54,500
China	275,000

As far as Poland is concerned – according to the Polish Alternative Fuels Association (PSPA) [20], on April 5, 2020, there were:

- 1093 charging points in Poland, 760 of which were AC type and 333 DC type,
- 9803 electric vehicles (5700 battery EVs and 4103 plug-in hybrid EVs).

The scope of the article is to present the basics of electromagnetic compatibility (EMC) testing of electric vehicles and electric vehicle chargers in accordance to current EMC standards, for instance Regulation No. 10 of the United Nations Economic Commission for Europe (UNECE). The article provides information about the existing regulatory procedures for the EMC automotive industry and information about the chosen permissible limits. Aspects of radiated and conducted emissions and radiated immunity testing are addressed.

1. EMC standards for automobiles

There are a few organisations involved in writing and enforcing EMC regulations for electric vehicles and EV chargers, for example CISPR (International Special Committee on Radio Interference), IEC (International Electrotechnical Commission), ISO (International Organization for Standardization) and SAE (Society of Automotive Engineers) [5]. The standards set out in law in the European Union are the EMC standards in the EMC Directive of the European Union [23].

Currently, the most important paper on EMC requirements and EMC test methodologies for vehicle approval is Regulation No. 10 by the UNECE, which considers an EV and its electrical / electronic sub-assemblies as a whole.

The EMC aspect of EV charging infrastructure is regulated by the two following standards [4]:

- IEC 61851-21-1 [24] for on-board chargers,
- IEC 61851-21-2 [25] for off-board chargers, which considers EMC pre-compliance test methods for either the charging device or the vehicle alone, but not their combined setup.

2. EMC emission tests for EVs

2.1. Conducted emissions testing

In the case of conducted emission testing, a product is tested for the radio-frequency voltage noise which is generated by the product on a conductive medium, for instance multi-wire connectors (communication signals) or a power line cable (power supply). The source of this disturbance can be, for instance, a rectifier of an AC to DC power supply system. The disturbance might impact the operation of other components through the cabling system [13]. What is more, due to the presence of communication systems between the EV charger and the EV, measurements of conducted emission levels from the telecommunication ports of the EV and the EV charger are significant [6].

The conventional components of an EMC laboratory station for conducted emissions tests should include:

- Line Impedance Stabilisation Network (LISN), 1-phase + N and/or 3-phase+N,
- EMI (Electromagnetic Interference) Test Receiver,
- coaxial cables,
- ground reference plane.

Fig. 2. presents a laboratory setup for conducted emissions testing during charging of a vehicle in accordance with Regulation No 10. The EV must be connected to the Line Impedance Stabilisation Network (LISN) also called an Artificial Mains Network (AMN) that is connected to a charging station or directly to a power mains socket. The functions of the LISN are as follows [19]:

- provide supply voltage to the equipment under test (EUT),
- decouple the disturbances emitted by the EUT on a conductive path, and then allow them to be measured by connecting an EMI receiver to the radio frequency connector placed on the LISN network housing,
- stabilise the mains impedance,
- eliminate interference from the mains,
- disallow interference emitted by the EUT from entering the public power supply network.

The wire harness inductance for automotive applications is 5 μH. Methodologically, DC charging, and generally fast charging naturally requires a much more powerful LISN than is used for slow charging as there are currently a few 400 kW (1000 V; 400 A/DC) charging stations [13].

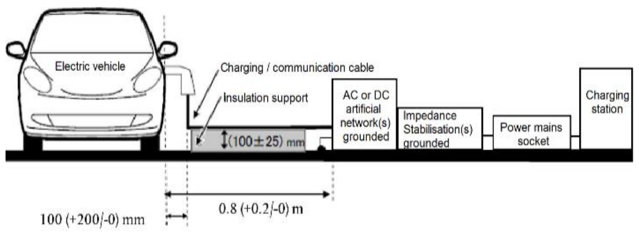

Fig. 2. Example of a laboratory setup for conducted emission testing during EV charging with communication (a charging plug located on the side of an EV) according to Regulation No 10 [6, 26]

According to Regulation No 10 [24], a quasi-peak or an average detectors must be employed on the EMI receiver and then compared with the limits. As a peak detector significantly reduces the duration of the test and provides quick insight into the measured results, it is advisable to use it when the chosen EMC standard allows it. During the emission testing, the engine of the vehicle must be off and the vehicle must be immobilised.

The state of charge (SoC) of the battery must be kept between 20 % and 80 % of the maximum SoC during the whole time of the measurement. When the output current can be adjusted, the current should be set to at least 80% of the nominal value. The conducted emissions should be assessed between the 150 kHz and 30 MHz frequency range [26].

Tab 2. presents limits for radio frequency conducted disturbances on 1-phase AC power lines for on board vehicle chargers according to IEC 61851-21-1 and limits for Class B equipment - radio frequency conducted disturbances on AC power lines for off-board vehicle chargers according to IEC 61851-21-2 (frequency range: 150 kHz – 30 MHz).

Tab. 2. Limits for radio frequency conducted disturbances on 1-phase AC power lines for on-board vehicle chargers according to IEC 61851-21-1 (Table 2) and limits for Class B equipment for off-board vehicle chargers according to IEC 61851-21-2 (Table 8) [22, 23]

Frequency range [MHz]	Average [dBμV]	Quasi-peak [dBμV]
0.15-0.5	56 Decreasing linearly with logarithm of frequency to 46	66 Decreasing linearly with logarithm of frequency to 56
0.5-5	46	56
5-30	50	60

According to Regulation No 10, EMC testing must also include a measurement of the harmonics emissions generated on the ac power lines from the vehicle so as to ensure that it is compatible with residential, commercial and light industrial environments. This type of test requires a power quality analyser that measures even and odd current harmonics up to the 40th harmonic. Regulation No 10 set the current harmonics emission levels in accordance with limits defined in IEC 61000-3-2 (input current ≤ 16 A per phase) and IEC 61000-3-4 (input current > 16 A and ≤ 75 A per phase). A typical EV charger comes with AC to DC converters that directly affect the parameters of power quality. The presence of high-speed fast-changing digital or pulse type signals that are present in the EV charging have the potential to generate harmonics, which can attribute to the generation of conducted and radiated emissions [7–9]. Measurements of the harmonics emissions from the on-board charger of a BMW i3 are presented in [3].

Regulation No 10 requires that voltage changes, voltage fluctuations and flicker on AC power lines from a vehicle are measured in order to ensure it is compatible with residential, commercial and light industrial environments. The measurements should be taken according to IEC 61000-3-3 or IEC 61000-3-11.

2.2. Radiated emissions testing

With regard to the issue of radiated emissions, the EV shall fulfill the criteria focused on the research methods being carried out in compliance with CISPR 12. This means the current edition of Regulation No 10 is based on a standard that is over a decade old (CISPR 12:2007+AMD1:2009 CSV) [15].

Generally speaking, the implementation of EMC tests under CISPR 12 takes into account the following specific guidelines when determining emission levels from the whole vehicle [21]:

- frequency range: 30 MHz – 1 GHz,
- a receiving antenna must be positioned on the right and left sides of the vehicle,
- two operating conditions of the vehicle must be considered (Key-On, Engine-Off mode, and tests when the vehicle is driven at a constant speed of 40 km/h).

However, Pliakostathis et al. [15], Visvikis et al. [18] and Paterson et al. [12] believe that the measurement conditions listed above do not reflect all driving scenarios. Nonetheless, the field of evaluation of these gaps is still limited and a systematic research approach is not easily traceable in the literature. Pliakostathis et al. [15] suggest new, more realistic methods of measuring radiated emissions beyond the requirements of Regulation No 10, which are as follows:

- a measurement of the peak level of electromagnetic field around the vehicle during driving and charging (360 degrees, with 1 degree resolution),
- an implementation of frequency domain and time domain techniques in order to link the nature of the vehicle's radiated electromagnetic emissions during the driving state of the vehicle (fixed at a critical EMI frequency),
- testing conducted at various constant speeds with a replication of possible real case scenarios, for instance acceleration, deceleration and gearbox effect,
- testing for EMI levels during slowing down with normal braking and freewheeling separately,
- frequency range extended below 30 MHz (150 kHz – 30MHz, resolution bandwidth – 9 kHz),

The conventional components of an EMC laboratory station for radiated emissions tests should include:

- various types of antennas suitable for a specific frequency bandwidth (Fig. 3.),
- EMI Test Receiver,
- coaxial cables,
- ground reference plane,
- semi-anechoic chamber / Open Area Test Site.

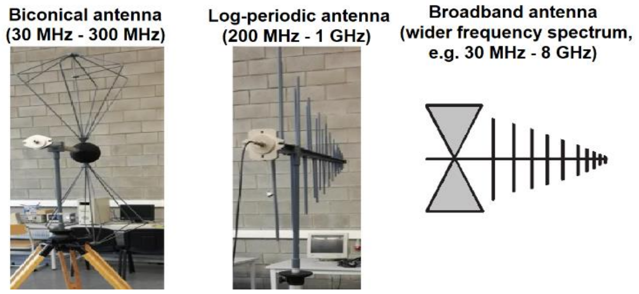

Fig. 3. Examples of antennas used for EMC testing

Fig. 4. presents the laboratory setup for radiated emission testing according to the requirements of Regulation No 10, which is based on CISPR 12. For the radiated emissions from EV chargers, the most commonly used distances are 10 m or 3 m, nevertheless other distances may be used given that the appropriate limits are modified according to CISPR 16-1-4:2019 [13,22].

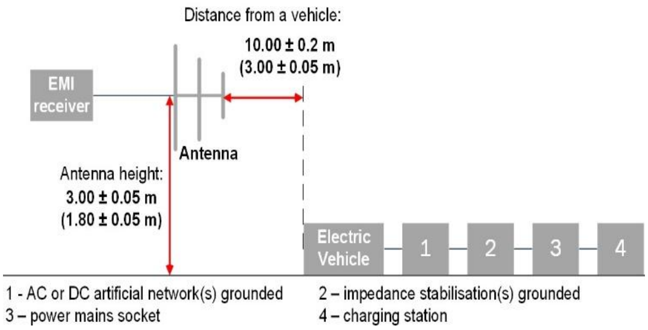

Fig. 4. Radiated emission test setup during EV charging [26]

Limits for the radiated emissions from vehicles (broadband type, 3 m antenna distance) are quoted in Tab. 3. in accordance with Regulation No 10 based on the CISPR 12 standard.

Tab. 4. presents the limits for radiated emissions from an EV and on-board charger according to IEC 61851-21-1.

Tab. 3. Limits for assessing the radiated emissions from a vehicle during driving according to CISPR 12 (broadband type, 3 m antenna distance) [21]

Frequency range [MHz]	Limit [dBμV/m]	Bandwidth resolution / detector type
30–75	42	120 kHz / Quasi-peak
75–400	42+15.13 log(f/75), f in MHz	
400–1000	53	

Tab. 4. Limits for high-frequency radiated emissions from an EV and on-board charger according to IEC 61851-21-1 (Table 3) [22]

Frequency range [MHz]	Peak detector [dBμV/m]
30–75	32
75–400	32–43 Increasing linearly with logarithm of frequency
400–1000	43

As far as the IEC 61851-21-2 standard is concerned, it allows both an antenna height scan and all sides of the EUT to be tested for the radiated emissions between 30 MHz and 6 GHz. Nevertheless, the use of the quasi-peak detector is only foreseen by IEC 61851-21-2 for frequency measurements below 1 GHz (though the peak detector is specified for radiated measurements between 1–6 GHz) [IEC 61851-21-2]. In [13] it was suggested that it would be rational to harmonise the type of detectors defined in the test protocol of the radiated emissions between the 30–1000 MHz and the 1–6 GHz bands due to the fact that a quasi-peak detector cannot always identify the disturbances that a peak detector can.

It is essential that EMC testing should always include consideration of correction factors, for example [14]:

- an attenuation factor for the LISN (conducted emissions),
- an antenna factor (radiated emissions),
- coaxial cable losses between the EMI receiver and the antenna or LISN.

3. EMC immunity tests for EVs

3.1. Conducted immunity testing

Conducted immunity testing includes the test equipment being exposed to currents injected into the conductors connected to it. According to Regulation No 10, the SoC during immunity tests should be between 20% and 80% and the vehicle shall be immobilised [24].

The laboratory equipment for surge immunity testing should consist of a reference ground plane, a surge generator and a Coupling/Decoupling Network (CDN) that shall meet the conditions of IEC 61000-4-5 (Fig. 5). The surge test levels for DC power lines and AC power lines (phases: 0°, 90°, 180°, 270°) are defined as ± 500 V and ± 1 kV (line to line); ± 2 kV (line to earth) respectively.

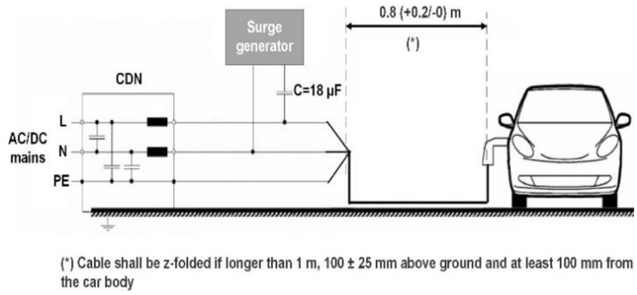

Fig. 5. Laboratory test setup for surge immunity testing (coupling between lines for DC or AC power lines, single phase) according to Regulation No 10 [26]

The laboratory equipment for fast transient/burst immunity testing of the whole system should include a CDN, a transient/burst generator, a capacitive coupling clamp and a reference ground plane. The measurements must be taken in accordance with IEC 61000-4-4. The burst levels are ± 2000 V for AC and DC power lines [6,26].

3.2. Radiated immunity testing

EVs and EV chargers should be immune to radiated electromagnetic fields. Radiated immunity testing enables the susceptibility of EVs and EV chargers to be tested with the emissions of surrounding devices, which can affect their operation. Considering today's large amount of electronic parts in the automotive industry, this type of EMC testing has become even more relevant. It requires an antenna, an EMI receiver, a shielded chamber or enclosure, a signal generator, an amplifier, a directional coupler and coaxial cables.

4. Conclusions

More new test methodologies under real drive conditions, beyond those recommended in the EMC standards are needed because they can show that results of conventional test methodologies may differ considerably.

In the opinion of the authors of the article, the [24,25] standards should extend towards EMC testing of a combined setup (an EV and an EV charger) as it happens in real situations.

It can be concluded that high-frequency conducted and radiated disturbances are significant threats that have not been sufficiently examined. Regulations, standards and directives on EMC help to control and solve the problems of electromagnetic interference.

More research into EMC testing of EV chargers is needed due to the fact that one of the main EMI sources are the DC/DC converters as they operate at a fast switching rate (dV/dt). As a result of the sophistication of EV chargers and EVs, EMC performance issues related to EV charging stations will receive more and more attention from researchers in the future.

Since the number of EVs is still increasing, the EMI footprint might become significant as a result of the cumulative effect of electromagnetic fields. Therefore, it should be important for the automotive industry and stakeholders to proactively research and analyse the EMC aspect of modern EVs and associated equipment, for instance, EV chargers, to prevent any technological and regulatory problems that could arise in the future from large-scale market deployments.

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