Metrology for Electric Vehicle Charging Systems: an Overview of the European Research Project

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***Abstract*— The Electrical Vehicle (EV) is the core of the European Commission's transition plan for the transport sector towards zero emission mobility. The successful integration of EVs requires deploying an extensive EV Charging Station (EVCS) infrastructure covering the overall charging needs of the consumers. This project will tackle the challenges of power quality effects on and, as a result of EVCS, evaluate the associated losses and reliability of metering under actual on-site conditions. The project goals are aimed to cover several charging modes, such as direct DC charging at low and high power, smart charging and specialised bi-directional charging. The European research project "Metrology for Electric Vehicle Charging Systems", which will start in July 2024, will support the industry needs through the development of a pan-European infrastructure for traceable testing of EVCSs, which remains a major bottleneck at the moment. The project will also provide input to OIML/TC12, WELMEC/WG11 and the European Commission Working group WgMI E01349 for uptake in their guidelines and regulations, which will, in turn, support the EV charging industry through standardisation.**

Keywords—Automotive, Electric Vehicle, Metrology, Measurements, Charging Systems.

I. Introduction

Electrical Vehicle Charging Stations (EVCSs) are a key element in electromobility and in the European Union (EU) Alternative Fuels Infrastructure Directive 2014/94/EU [1]-[3], which has taken measures to increase the number of recharging points and to ensure that they have a standardised design and use. Though such a charging system may be considered simply as a feeding point and a meter, very similar to a utility meter, this is only partially true, and only when it comes to AC charging.

The EV charging industry is one of the fastest growing industries in Europe, with over 700k EVs registered in the EU in the last quarter of 2022 alone. The EU's EV charging landscape is expected to quadruple by 2025 to accommodate this growing pace [4]-[9]. The EVCS industry, however, is faced with some challenges that come with the nascent deployment of its technology. The lack of harmonised legislation that should cover the charging conditions concerning the correct, traceable and fair metering of electrical energy to ensure consumer protection and confidence has been a tough one to tackle. Several open research questions relating to the power quality due to EV and EVCS deployment and their actual efficiency have also been raised.

Standardisation in any field is a catalyst for open and responsible innovation. At the organisation level, product innovation in response to standards helps to create a competitive advantage. Standards can entail significant influence to the success of innovation by creating a shared framework for innovation and establishing common rules. This also includes the definition of common terminology, setting the essential characteristics of a product, service or technology, and detecting a best practice guide within their ecosystems to ensure successful results. Therefore, industries often welcome regulation through standardisation, since this gives them a level playing field to showcase their products. In the case of the European EV charging industry, the EVCS transfer of electrical energy to the vehicles must meet the European Directive 2014/32/EU (MID), but the specific DC commercial transfer of energy to the vehicles is not addressed in this directive. Moreover, there are no harmonised standards for AC. So, both DC and AC need the urgent development of relevant metrology requirements.

Concerning power quality and distortion, there are no specific EMC standards for EVCSs. The EMC standards that are currently applied are for low and medium power applications and are limited to the low-order harmonics [10]. There are also no requirements or standards/limits for the supraharmonic (SH) emissions. Harmonic and SH distortion is generally recognised as a stress factor for interfacing cables and transformers and a possible cause of grid oscillations (especially for modern grids with many deployed power converters and highly dynamic power flow). Besides, there is a general concern for disturbances from harmonics and SH to connected loads, particularly Power Line Communication (PLC) devices. Additionally, SHs are known to influence household devices in terms of reliability and can cause additional heating, malfunction or failure of equipment and audible noise. In newer charging modes, such as the V2G mode, requirements from grid codes should also be included.

For the 9-150 kHz frequency range, there is no normative framework for measurement methods; only 'informative' (not normative) methods are proposed in the IEC 61000-4-30 [10]-[16] which implies that PQ instrument manufacturers and utilities are not obliged to implement or use these methods. The IEC SC77A WG9 is currently working on a normative method for this band to update the IEC 61000-4-30 standard. There is a need for research on the definition of standardised methods and setups adapted to the particularities of this frequency range (broader frequency range of analysis, frequency-dependant impedance and wider dynamic range of amplitudes). Moreover, compatibility levels (CLs) up to 150 kHz are defined based on different types of detectors and measurement systems, which impedes the direct comparison of the results and complicates the analysis over the entire frequency range. Preliminary results of disturbance caused by EVCSs show high amplitude with significant variations over time. Such variations are not reflected by the current measurement methods, which focus instead on the spectral pattern of momentary emissions. Aggregation strategies of the measurement results for long-term analysis need to be defined as well. In summary, a new method capable of characterising complex time and frequency patterns of disturbances from EVCS is needed and sought for by the standardisation committees.

The proposed measurement methods must be validated to ensure and demonstrate the required level of accuracy. However, the test signals defined in some standards have very simple patterns. Therefore, a specific set of test signals, with complex time and frequency patterns, similar to the disturbances generated by EVCSs in different operation regimes, needs to be developed.

With newer charging scenarios, such as ultra-fast charging (reaching power levels higher than 300 kW), smart bi-directional chargers supplied by solar-powered micro DC grids, etc., special studies are required to understand the actual efficiency and power flows based on the grid and EVs changing impedances.

The paper is organised as follows. Section II discusses the needs for the project. Section III presents the specific objectives of the project. Section IV shows the expected progress beyond the state of the art and the results. Section V discusses the outcomes and the impact of the project. Finally, Section VI draws the conclusions.

II. Need for the Project

The first need is related to the determination of operating conditions concerning conducted grid emissions and dynamic grid impedance.

The on-site operating conditions of the EVCS may be various and variable:

- high frequency grid distortion is variable with time, depend on the loading conditions on the grid, and the charging configuration of the EV and may impact the metering and disrupt charging;
- the grid impedance and the dynamic impedance of the EV through its front-end converter and battery state of charge (SoC) may affect significantly distortion and its spectral characteristics.

Additionally, new charging modes have been introduced in recent times. These modes include direct DC charging at low power (typically below 20 kW), fast charging modes at high power (which can reach 350 kW and as of 2021 represent 32% of installations [8]), smart charging that regulates based on network loading conditions, and bi- directional charging. All these modes make the charging scenarios more intricate and can cause undisclosed issues that can further challenge the metering system within the EVCS. There is therefore an urgent need to address these issues related to metering in EVCS and to build a specialised European metrology infrastructure that accounts for uncertainties in charging/discharging modes in various scenarios. This project, therefore, aims to determine the real operating conditions of the EVCS during charging and discharging modes in a wide variety of scenarios ranging from different network conditions, cable connections and charging configurations in order to further study its influence on the metering performance.

The second need regards the laboratory characterisation of EVCS metering and losses.

Currently, the characterisation of the EVCS is limited to energy meter verification. This characterisation is insufficient as it neglects all the other factors of influence that occur during actual operation. Hence, a comprehensive laboratory characterisation/validation procedure needs to be implemented that can account for the varying degree of uncertainty occurring during operation. The lack of such a procedure will lead to incorrect metering, resulting in erroneous electricity billing. This can pose a considerable risk leading to a lack of confidence in the overall EV charging and billing process.

In addition, there is no investigation into the losses associated with the EV charging infrastructure. Though the losses are an integral part of any electricity transport system, there is a need to quantify and account for these losses. This will enable a more competitive environment for the manufacturers of EV chargers and promote charging stations with higher efficiency (in other terms, lower losses). It will also provide novel insights to the operators and users of the charging infrastructure to select more efficient systems and operate them in a way that optimizes efficiency.

The third need regards the on-site verification of EVCS metering. In order to establish a sustainable European metrology infrastructure, there is a need to follow a smart specialisation strategy when it comes to providing services. This is increasingly applicable to services that deal with newer technologies as it helps accelerate the pace of their release and uptake. Similarly, when it comes to the verification of EVCS metering, the need to have a versatile compliance procedure that can be easily implemented to address the metrology needs of different regions in Europe is crucial to avoid bottlenecks in its development and deployment. This project aims to partly focus on this pan-European need to develop a simplified validation procedure in addition to the previously discussed extensive plan to both help and assist in the smooth deployment of EVCS across Europe.

In recent times, several EU member states have introduced local-national regulations for EVCS metering to protect their citizens. However, the validity of such verification across EU countries is jeopardised. Without further adjustment of metrological guides and regulations to have a reliable but cost-effective tool for verifications of EVCS, which is acceptable at the EU level, the market will become more fragmented.

III. Objectives of the Project

The project focuses on the development of metrology capabilities for the traceable evaluation of EVCS under realistic operating conditions. The specific objectives of the research projects are listed below.

1. To define representative on-site operating conditions for EVCS in terms of local grid disturbances and local grid im-pedance under live grid operation. For this, dedicated equipment will be developed able to measure local grid dis-turbances and local grid impedances up to 150 kHz. With this equipment, measurements will be performed at, at least, 5 sites with DC chargers and 5 sites with AC chargers with a variety of (i) charger brands, (ii) operating modes, and (iii) charging power levels (WP1).

2. To develop traceable methods and test benches for the characterisation of EVCS under representative operating conditions for both AC and DC charging at low, medium, and high-power levels and in accordance with IEC 61851-1. This characterisation of EVCS will include the evaluation of (i) metering accuracy and energy transfer efficiency with a target uncertainty of 0.1 % (with respect to nominal power) and (ii) generated conducted emis-sions up to 150 kHz. For DC EVCS test benches will be developed. for voltages up to 800 V, currents up to 500 A and charging power levels up to 350 kW. For AC EVCS, test benches will be developed for 3-phase systems at 230 V up to 100 A and charging power levels up to 44 kW. Methods will also be applicable for a variety of test scenarios including smart charging, bidirectional transfer of energy (G2V and V2G), dynamic loading and dif-ferent levels of grid distortion and grid impedance. For the calibration of the test benches, measurement stand-ards will be developed suitable for covering the voltage, current and frequency ranges. (WP2, WP3).

3. To develop the required metrological infrastructure for on-site verification of EVCS energy metering, in support of le-gal metrology and acceptance testing, with a target uncertainty of 0.5 %. This will include the development of reliable methods for EVCS energy metering evaluation based on commercially available equipment, which have been validated under representative operation conditions, including smart charging and bidirectional ener-gy transfer.

4. To facilitate the uptake of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (IEC TC 69, WELMEC WG 11, OIML TC12/p3, EC WgMI E01349), and end users (e.g., EMN Smart Electricity Grids, EMN Clean Energy, EVCS operators, grid operators, EVCS manufacturers).

IV. Progress Beyond the State of the Art and Results

A. *EVCS regulation*

OIML TC12 P3 has recently produced a guide document, OIML G22 “Electric vehicle supply equipment”, to provide a blueprint of requirements and procedures for type testing to be used by national regulators and approval authorities to set up their own legislation. Practical technical experience in testing and approving is lacking in some respects, especially for DC charging applications.

The project will provide input to the OIML TC 12 P3 project group for improvements of the current guide on methods for verification of DC and AC EVCSs.

B. *Determination of conducted emissions and dynamic impedance*

In the project EMPIR 18NRM05 SupraEMI, ElaadNL, TU Eindhoven and TU Dresden performed indicative field measurements to collect data in the range between 2 kHz and 150 kHz for the SH distortion and grid impedance. From these measurements, it was concluded that there are SH disturbances present in the grid and there are significant differences in the grid impedance at various frequencies. It was also concluded that current standards overestimate the actual grid impedance for higher frequencies, hence a quantification of grid and device impedances for the 2-150 kHz range is essential.

The project will address both areas of research, providing a consistent and extended set of data with at least 5 measurement sites for each AC and DC EVCS. The project will be 3-4 times larger than in 18NRM05 SupraEMI, spanning different countries, grid topologies and types of connected devices [17].

Data regarding distortion, impedance, transient events and environmental conditions will be collected systematically and will undergo a specific analysis to spot relationships and correlations between parameters; such analysis is provided for the first time and is possible due to the large set of data the project will provide, and the care in planning and selection of test scenarios, based on a design-of-experiment approach.

C. *Electrical vehicle battery simulators as variable loads*

Currently, the most common way of modelling battery electric vehicles (BEVs) is by treating their loads as constant power elements without considering the voltage dependency of the EVCS during different SoCs. As the battery’s voltage increases with higher SoC, the EVCS must generate a higher voltage to fully charge the EV. This effectively means the charging power is reduced because the output current is reduced when the EVCS needs to generate a higher voltage, while the input power remains the same. Additionally, the impedance of the battery increases as its SoC rises, which generates more heat. Depending on the temperature and cooling capacity of the EV, this may result in a lower charging current to keep the battery temperature below the maximum rating.

So, EV load demand cannot be considered a constant power load, modelling as a constant power load will not provide accurate information about the behaviour of the charging system during the charging process. Several research projects on smart grids are now looking into models representing the realistic behaviour of an EV load in order to understand the impact of EV charging load.

The project will investigate typical EV voltage and impedance patterns as a function of time and SoC during the charging process and will employ an EV simulator (dummy load) that can simulate these voltage and impedance patterns. This simulator will be used to replace real EVs in the certification and testing activities of EV charging stations. Several conditions will be investigated, covering a representative set of most used EVs, energy transfer modes, environmental conditions and battery capacities. The EV simulator will be characterised and validated using reference equipment and climatic chambers. The disturbances from the EV simulator and its impact on the test bench will also be thoroughly investigated.

D. Laboratory characterisation of EVCS metering and losses

Currently, the characterisation of the EVCS is limited to energy meter, the requirement for DC is derived from domestic AC supply meter regulation, which does not fully cover DC meters. Large (Fast) charging stations are considerably more complex because they sometime have direct access to the MV grid and have to handle voltages and currents in the range of a few kV and up to a kA. Hence, established measurement methods need to be developed. The influence of the operating conditions, such as ripple from rectifying or grid quality, on the energy measurements should also be investigated. It is also necessary, for correct billing, to investigate methods to measure what part of the energy actually goes into the EV battery system.

The work in this project will develop the metrological infrastructure for laboratory characterisation of EVCS, including the definition of test methods, operating conditions and reference standards concerning the main energy transfer standards: total energy, charging power, losses, etc. EV simulators and dummy loads will be used instead of the whole real EV.

The infrastructure required for the laboratory characterisation of the EVCS operating under DC, especially high-power DC, is particularly scarce and requires, to a large extent, new development of reference standards. The current and voltage levels to be tackled are also much higher for DC charging scenarios. Hence, dedicated developments towards traceability at higher voltage and current levels at wide bandwidths are necessary.

E. On site verification testing of EVCS metering

The establishment of laboratory verification of EVCS metering is delayed with respect to EVCS market requirements due to the (up to now) missing legal metrology frame within the EU for DC metering with built-in meters. The newly published OIML Guide 22 gives the first guidance for EVCS metrological controls and performance tests. Its practical implementation is a challenge, and further investigation for reliable verification is needed. Several tests require expensive hardware and time-consuming measurements, especially when EVCS metrological properties under maximal current and voltage levels are of interest. The verification of smart and bidirectional charging (V2G) also needs to be investigated in further detail. Finding optimal necessary requirements based on a statistical appraisal of the behaviour of real EVCS distributed across the EU market is necessary for the establishment of an economically feasible metrological infrastructure for EVCS verification. Otherwise, further dissemination of new EVCS types will be decelerated due to the expensive realisation of legal metrology requirements.

An investigation will be done with a practical metrological point of view on the newly published OIML Guide 22. A practical proposal will be established for a minimum set of test requirements for both on-site and laboratory testing, where different tools will be applied. Based on newly developed test programs, measurement setups with adequate traceability chains will be realised. A feasibility study of future power scalability of the developed measurement setups will support further extension of measurement ranges. On-site tests performed with the simplified test setups will be compared with more accurate measurements to confirm their applicability in the realisation of a new metrological infrastructure for EVCSs at minimum cost. This will directly benefit the industry in implementing straightforward and reliable regulatory checks on EVCS.

During the last years, in the context of power and energy-related research and development, a great effort has been made to build infrastructure aimed towards sustainable metrology. By this means, the European metrology institutes are the obvious partners for all metrology-related answers that the industry seeks. The EMNs (European Metrology Networks) in the field will serve as a liaison towards this goal.

This project will build on the results of some of the previous EURMAET projects as follows.

This project will build on the results of the 16ENG04 MyRailS project on ‘Metrology for smart energy management in electric railway systems’ [18]. The 16ENG04 project aimed to develop the metrological framework and measurement infrastructure that underpin the adoption of energy-efficient technologies in European railway systems. 16ENG04 investigated distortion in a frequency bandwidth limited to 5 kHz. In this project the bandwidth will be expanded up to 150 kHz, and EVCS-specific distortion with their own dynamics will be identified. The work started in 16ENG04 was for initial railway-specific parameters with an intended 0.1 % uncertainty. However, this level is insufficient for application in ECVSs, and further work is needed.

This project will also build on the results of the 17NRM02 MeterEMI project on ‘Electromagnetic Interference on Static Electricity Meters.’ [19]. The 17NRM02 project performed normative research required to develop new IEC/CENELEC standards for testing electricity meters for the influence of specific distortions caused by electronic equipment for which the standardised test waveforms are not representative. EVCSs, for which the impedance of the EV is constantly changing based on the battery SoC, were not particularly considered in 17NRM02. This involves similar bandwidth, voltage and current levels, and accuracy, but the instantaneous non-constant impedance complicates the interpretation of the measurement data and requires different measurement approaches and laboratory test-beds.

Finally, this project will build on the results of the 18NRM05 SupraEMI project on 'Grid measurements of 2 kHz – 150 kHz harmonics to support normative emission limits for mass-market electrical goods.' The overall aim of the 18NRM05 project was to develop new normative measurement techniques to enable the regulation of interference. These techniques bridged the gap between traditional on-site PQ (up to 9 kHz) and laboratory emission measurements (9 kHz – 150 kHz) in the presence of a Line Impedance Stabilisation Network [17]. However, the dynamics of EVCSs were not considered in the 18NRM05 project and still need to be investigated.

The present proposal will build on these projects with a focus on the traceability and verification of the efficiency and metering in EVCS, which has not been considered. before.

V. OUTCOMES AND IMPACT

The project will provide a thorough quantification of high-frequency emissions and distortion caused in the supplying grid, together with feeding and EVCS impedance, improving the knowledge provided by the few existing standards (e.g. IEC 60725) and allowing manufacturers to simulate the emissions of their own equipment more accurately, improving margins to consider during design and production, but also being able to foresee resonance situations for specific grid topologies.

EVCS operators and DSOs can use the results of grid and EVCS interaction measurements and modelling to plan a high concentration of EVCS in the near future. The set of waveforms for distortion and emissions gathered in the project will be evaluated for the influence on metering and losses, providing an indication to many actors (manufacturers, grid operators, consumers) of the cost of distortion as affecting efficiency through losses directly or indirectly through disturbance to metering.

The test benches and test procedures developed in the project for EVCS metering and loss verification will contribute to the lasting metrology infrastructure in the field and provide the various NMIs with testing capabilities to fulfil their market needs. These measurements will help build trust and experience with the technology and further help the EVCS Industry, both manufacturers and Charge point operators (CPOs) in the widespread deployment of EVCS. This will also provide guidance as input to the new European legislation on EVCS testing, which will, in turn, lead to mass production of EVCS.

This project will provide new insights to the manufacturers and operators on ways to optimise the design of the charging station and emphasise the shortfalls in their current design by investigating the influence of external factors on metering and losses in EVCS. The outcomes of the project are set to benefit significantly the EV industry and the operators of EV charging stations. The development of a European metrology infrastructure for the verification of the metering and losses in the EV charging infrastructure will further propel the pace of development in the field of EV chargers by reducing waiting times in certification and testing. The European consumers will eventually benefit from a good EV charging infrastructure with the added traceability and fair metering of electrical energy. This will increase the level of confidence in the consumers and, as a result, support the transition to electromobility in Europe.

The developed test benches for the verification of the metering and losses in EVCS in the various charging modes and the setups and methods for the consistent on-site measurement of EVCS and EV emissions and distortion by different European institutes will lead to the establishment of an integrated European Metrology Infrastructure. This upholds the idea of smart specialisation, of an integrated metrology infrastructure of the European area. The devised procedures for the certification and verification are a key step towards the establishment of a common regulation. These methods will further become a part of the CMCs of the NMIs and calibration laboratories performing these measurements. Knowledge transfer to non-participating NMIs and test institutes will be performed via project workshops and presentations at scientific and industry workshops and conferences.

The project will establish a benchmark for disturbances and impedance measurements that will lead to defining a procedure to evaluate EVCS distortion. For that, comprehensive measurement methods will be defined and validated. Ad-hoc test waveforms, similar to the complex waveforms generated during the EVCS process, will be defined and used to optimise and validate the assessment methods.

The published results in terms of the test waveforms, impedance envelopes and procedures will serve as a starting point for new and improved research in the field. It is expected that the new measurement and analytical methods, as anticipated, can be reused for similar types of scientific research.

The knowledge of changes in the grid impedance during the EVCS charging will be fundamental for the grid operators to support the impact of EVCS deployment in the near future.

The increased distortion of distribution grids in the near future following the extensive increase of EVCSs and EVs requires revised standards related to PQ issues on public electricity networks. Completing previous results, including the 18NRM05 SupraEMI project, accurate measurement methods for EVCS disturbances will be proposed for the current standardisation work at IEC SC77A in relation to the IEC 61000 family standards.

This project will provide two guidelines for metering evaluation and on-site verification of EVCS to several national and international standard committees dealing with the legal regulation of electrical meters as IEC/CENELEC TC13.

Significant input is anticipated for the working groups of OIML TC 12 'Instruments for measuring electrical quantities ' for the next revision of the recently published EVSE guide G22; of WELMEC WG11 ' Utility meters' for the harmonised regulation for EVCS across Europe through the generated Practice Guides.

VI. Conclusions

This paper has given an overview of the European research project 'Metrology for Electric Vehicle Charging Systems ', which will start on July 2024. The project goals are aimed to cover several charging modes, such as direct DC charging at low and high power, smart charging and specialised bi-directional charging. It will support the industry needs by the development of a pan-European infrastructure for traceable testing of EV charging systems which remains a major bottleneck at the moment. The project will also provide input to OIML/TC12, WELMEC/WG11 and the European Commission Working group WgMI E01349 for uptake in their guidelines and regulations which will in turn support the EV charging industry through standardisation.

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