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Overview of EV charging stations impact on harmonic distortion in power distribution grid

Željko Hederić, Marinko Barukčić, Toni Varga and Nenad Cvetković

Abstract - In this paper, an overview of the impact of electric vehicle (EV) charging stations on harmonic distortions in the distribution grid are given. Problems that are recognized as a result of the impact of the rapid rise of EV technology and their implementation in modern urban transport are presented through an overview of relevant research primarily related to the EU region and the concentration of EVs and EV charging stations in only a few countries. The effects of harmonics produced by EV chargers are not properly limited by adequate protection causing malfunctions at the facilities and equipment of the residential facilities. The paper emphasizes the need to match the speed of growth of EV technology with the speed of changes in the accompanying standards and the improvement of designers' education.

Keywords - electric vehicles, charging infrastructure, harmonic distortion, power quality.

I. INTRODUCTION

The modern trend of the rapid development of electric vehicle technologies into everyday life brings many changes. The outlines of cities are changing, and there is an urgent effort to adapt city spaces to new trends of the use of electric vehicles that introduce a whole new culture of behaviour. It also requires a change in the system that supplied the energy needed for transportation, changing the fossil fuel delivery system with the power delivery systems. We all around us are accustomed to the power grid systems that bring us all the joys of light, the work of machines, household appliances, and television into our daily lives. It is a general misconception that such a grid system can serve to supply energy to new electric vehicle technology. This system is changing too slowly and is not adapted to new problems [1].

The idea of a smart city environment, energy transfers in all directions, two-way systems for charging vehicles from the grid and supplying power to the grid from vehicles, issues of interconnection of electric vehicles of different power at different points in the distribution grid, as well as generally problems of availability of charging stations for the number of electric vehicles are all this is only part of the problems that are just being recognized. But as no one can stop the development of electric vehicle technology, so we helter-skelter are trying to reshape and adapt power grid systems. This approach has opened the door to many problems.

One such problem that is not clear is the problem of harmonic distortion in distribution grids. In the paper are reviewed some solutions presented through research in various fields as an effort to point out the need to change the paradigms of design and control in distribution grids to ensure the quality of electricity supply to existing consumers.

EV battery chargers have evolved primarily as vehicles, but with increasing demand for energy and current levels, charging stations are nowadays emerging as stand-alone units that convert AC to DC (fast charging). Also, through the development of services, there was a need for two-way energy flow [2].

Vehicle charger connection systems can be conductive or inductive. Conductive charging systems are the most common because they have evolved as a logical sequence of a plug connector in daily use and use direct contact between the plug and the charging port [2]. Inductive chargers use resonance and magnetic coupling technology to ensure energy transfer. This type of EV charger is a novelty that provides charging capability on the moving and has evolved from magnetic levitating train technology [2]. The detailed predictions of harmonic distortions in existing distribution grids are complex because many different categories of portholes appear in both amounts and nonlinearities. Many nonlinear loads have very low power consumption, and although they are relatively more and more present in the distribution grid, the regulatory systems for standards for very low levels of consumer power do not prescribe high quality requirements.

II. THE IMPACT OF EV CHARGERS ON THE DISTRIBUTION GRIDS

Numerous studies addressing the impact of the rapid development of EV technology point out that over the last 10 years, there has been a 200-1000 increase in the Western EU (Fig. 1).

This rapidly grow brings problems affecting everyone in contact with EV technology, and especially distribution grids as a place for EV connectivity to the power source. In [1] are presented an overview of charging infrastructure for the road vehicles using data from EU parliament researches. The study [1] analyses the various challenges posed by implementations of EV systems and their technologies that enable the penetration of energy flow collection infrastructures within the EU.

These include existing technologies and standardization

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issues that must accompany the accelerated growth of EV technology, measurement systems and business models, as well as connectivity to smart city systems with the implementation of renewables and Electricity Suitability technologies, all correlated with the public policies of individual EU member states.

Fig. 1. The representation of EV distribution in EU with red marked area with 90% of total EV and blue are marked Croatia with less than 0,1% of total EV [1]

When we talk about electric vehicles and their charging points (influenced by marketing) we usually imagine them as shown in Fig. 2.

Fig. 2. The representation of marketing of top EV technologies, beautiful EV sports car by Rimac and fancy city small car on charging station (source: The Financial Times web newspaper)

Problem is that few are mention problems shown on Fig. 3. We should now that EV are not toys; they demand a huge density of energy in new storage compartment with not so tested technology of connection, control and use. In [1] are mentioned that 85% of the Fire departments are not familiar to procedures for safe extinguishing the fire of a burning electric vehicle containing an electrical outlet and possible high-current circuits.

Fig. 3. The firefighters need to train new ways and approaches to dealing with battery-powered vehicle fires
(source: The Sun web newspaper)

If we apply the rules of analogy thinking, then consider linking familiar things like fossil fuel vehicles to new EV problems. Why not have a fuel pump in every garage? What are the standards for a gas station? What can go wrong when connecting an EV to a charging station? How to respond preventively and predictively, and how to design them? Why was it not important to emphasize protection? Is it installed in an electric vehicle charging station?

The components of the electric vehicle power drive, as well as the charging station, are shown in Fig. 4. The EV drive itself is realized by an electric motor that controls the frequency converter; the DC bus system connects the subsystems inside the vehicle; the board battery charge input system and the battery itself with the battery management system. Then, different forms of EV charger stations that connect EVs to the distribution grid are shown.

Charging time (as well as battery life) are related to the charger's characteristics. The battery charger must be efficient and reliable, with high power density, low cost and low power consumption.

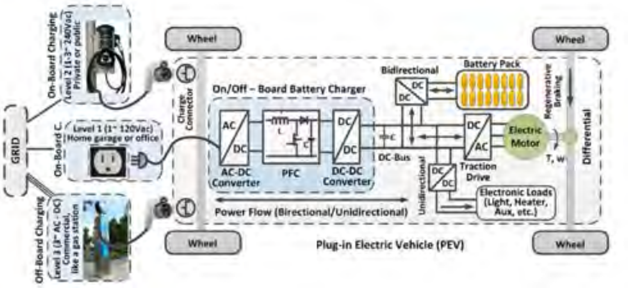

Fig. 4. On/off board charging system and power levels for EV different connections on charger [2]

The EV and charger subsystem shown in Fig. 4 is highly represented in the literature but it actually hides the error. What is missing in the picture? Why was it not important to emphasize protection? Is it irrelevant or is it integrated into the charger itself? Does safety devices by default need to be in the charging station? These are questions that are making a lot of confusion today.

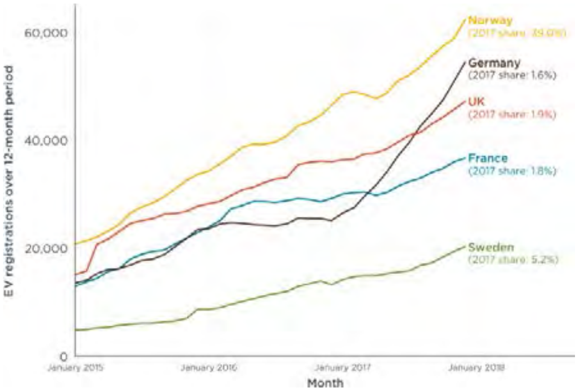

Fig. 5. Electric passenger car registrations numbers per years in

some EU countries who are leaders in EV technology implementation [1]

As standards are not changed quickly enough, the problem of accountability is emerging in many countries. If the standard is not set correctly, then wrong projects, which are not legally limited, are allowed to arise. Fig. 5 present rise of EV registration in the EU for the last 5 years what means developed EV technology and studies [1] show that EU countries standards are practically nonchanged in that period.

A. Battery pack design and modelling problems

The battery is an essential part of electric vehicles (EVs), so its design significantly affects the vehicle's drive characteristics, but also the vehicle's parameters as a dynamic load when charging vehicles at the charging station. In addition to the battery, in EV are several electronic converters that control the way they use the switch technology or the system that generates unwanted harmonics.

The method of connecting cells to the total package depends on a large number of design requirements (availability of energy, temperature protection, ...). Most often, they are connected in parallel blocks to provide capacity, and then the blocks are connected in series to the battery to ensure an adequate voltage level. What is often forgotten is that the battery does not store electricity. The battery is a reservoir of chemicals that produce electricity and store energy by a chemical reaction [3,4].

Because of this, the battery is a system that is continuously switched on, regardless of the total battery circuit being open inside the battery cells and the battery blocks, equalization currents are present. The Battery Management System (BMS) is designed to constantly monitor and optimize such a complex battery system, which has major problems with dynamic mode. Then cells are irregularly emptied, asymmetries are created and this can potentially break down.

A poorly defined material fatigue condition will cause the BMS, as a multiplicated switch system, to start to make irregular switching states and thus become a source of unwanted harmonics. This is especially true when charging quickly by connecting the vehicle to a charging station, in situations where the battery pack is below 50% of capacity level (this is by far the most common case when EVs are being charged to a charging station).

The battery pack design, as well as the BMS design, should be aligned. However, this is only fulfilled in initial states, and any intensive use promotes fatigue of the material and creates conditions for defective states. An example of this is the potential equalization currents inside a battery block, which in the long run leads to irreversible electrolyte degradation (battery potential).

Essentially, the stored chemicals within the cells are not capable of responding normally to electricity generation, by disintegrating and/or dissolving the structure of the active material bringing the cell to life [2]. There is numerous literature in which authors explain the problems that lead to battery failure. [5,6].

The fatigue of the materials that the electrodes are made of results in various side effects of Solid Electrolyte Interphase (SEI) [7], collectively referred to as ageing effects on the negative electrode and positive electrode (Fig. 6).

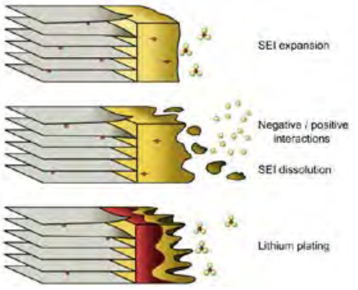

Fig. 6. Illustration of the ageing effect on battery negative electrode [7]

As can be seen in the block diagram (Fig. 7), numerous internal mechanisms of the battery and the environment affect the health of the battery. Most of them cause thermal decay of the chemical process, but these are already extreme situations that modern BMS systems are relatively successful at solving.

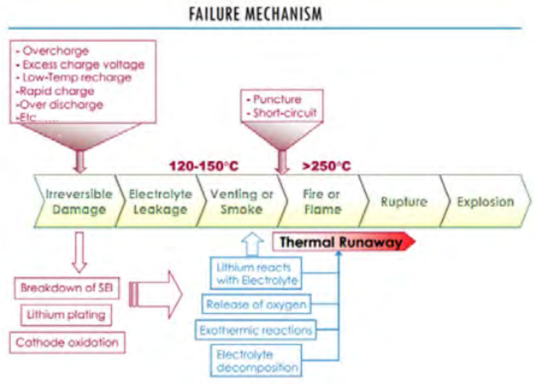

Fig. 7. Block diagram of failures event in Li-Ion batteries [1]

The problem arises when BMS fails as a control of the chemical process. As usual, man and negligence, that is, unprofessional work, play a major role.

Today, we have many vehicles that have come from workshops, garages and that have been successfully certified by the owners, although they have not passed even the most basic tests performed in the factories of the largest manufacturers. However, such vehicles also have access to public EV charger stations, with all the problems they can cause.

In [9], a modelling procedure is presented that gives rise to entirely new elements in battery circuits that are not provided by conventional designs. That is why most BMS systems today have deviations in EV battery management, that is, they have the wrong model by which they try to control the system of cells and blocks inside the battery, which then leads to uncontrolled switching states - the cause of unwanted harmonics. If we pay attention to the battery block (shown in Fig 8a), we can see that in the structure there is a current loop, which is exposed by its cross-section to magnetic fields generated in dynamic modes of operation. [6, 8, 9].

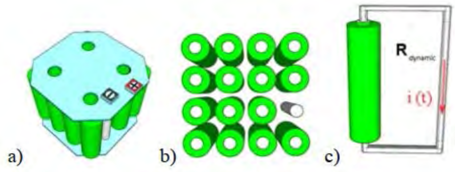

Fig. 8. Battery block design example and lumped model:
a) Battery block built by 15 parallel cells and interconnection bar. The contacts are on the same side on the upper plate,
b) Cross-section of the block with shown interconnection bar,
c) Lumped model of the electric circuit consists of one cell and interconnection bar [5]

The load, presented as a dynamic resistor, is a function of time (EV drive demand for energy from the battery as a function of time). Finally, the loop surface used to calculate the induced voltage source as a function of cell current (for the given geometry presented in Fig. 8.c) corresponds to the yellow marked area on Fig. 9.

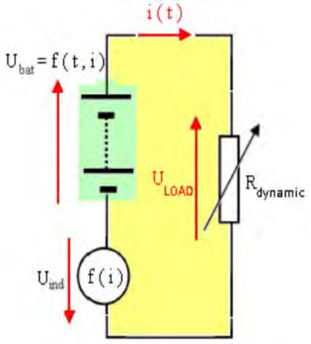

Fig. 9. Lumped model of an electric circuit for one battery cell as part of the battery parallel block [9]

B. The impact of harmonics on the distribution grid

To study what happens when we connect EVs to the distribution grid, it is necessary to define a well-known consumer model [10], for which there are well-developed and verified models as shown in Fig. 10.

Assuming that all consumers are within the IEC standard, no undesirable harmonic or THD levels should occur in the distribution grid. By entering EV charger in such topology and assuming that the charger itself meets the criteria of IEC standards by measurements and simulations, it is confirmed that distortions over the prescribed levels still occur in such altered topology [10].

Modelling of harmonic distortion, especially current waveforms in phases comparing with to without EV connected states, is presented in [10]. By plugging the EV into the charging station (location red in Fig. 10), only one phase current remains in the limits, while in the remaining phases and in the neutral conductor the current level rises as much as 6 times, and with it a significant increase in undesirable current harmonics.

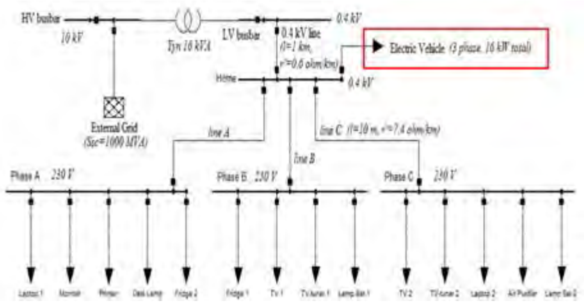

Fig. 10. Scheme of the composed model in DigSilent Power Factory for harmonic levels in the distribution grid simulation [10]

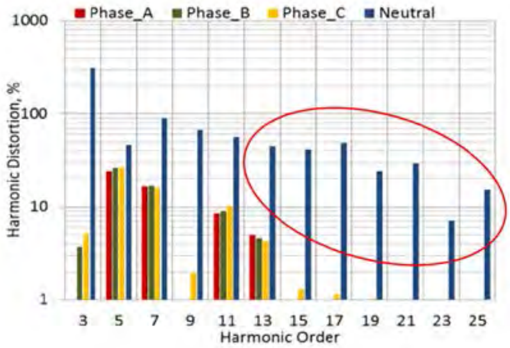

Fig. 11. Current harmonic distortion with EV connected in the distribution grid through charger [10]

In Fig. 11 showing current harmonic distortions with EV, it is evident that asymmetry and distortion occur, which consequently represents suitable conditions for resonant current harmonics, which are extremely dangerous for the highly sensitive and present ubiquitous computer, communication, monitoring technique.

C. BMS malfunction during EV charging

In the previous sections, we presented the problems of connecting EVs through charger units to the distribution grid, modelling batteries as part of an EV system. Another issue to consider is the battery management electronics system, which consists of numerous blocks. Battery management system (BMS) is to manage the output, charging and discharging and provide notifications on the status of the battery pack. They also provide critical safeguards to protect the batteries from damage. In all previous cases we present problems that occur with BMS normal function. What happens when a BMS malfunction occurs? Is it happen often?

A small 0.2ms decay or impulse jump causes 3-5kHz harmonics to "pass" through the transducer because they fit as a subharmonic of the switching frequency, and if no filters pass into the grid and look for a resonant pair.

Normal overcurrent protection does not respond. And now we have a wandering impulse in an unsecured distribution grid. Its power is enough to burn the Client–server systems power supply or air conditioning control.

This failure can result from a faulty battery pack model that cumulatively alters the charging process by the time the BMS does not recognize the "wrong" state relative to the estimated state. Then the BMS tends to reprogram and, due to the speed of operation of the switching part of the BMS, causes the appearance of an unwanted pulse that can be extended beyond the EV.

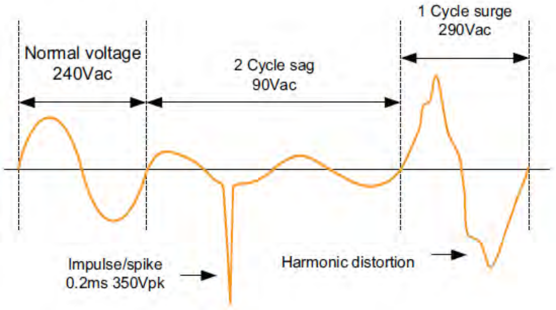

Fig. 12. Impulse present in the output from BMS during charging EV as an malfunction problem [11]

A further problem that arises is the case that there are multiple EV charger sites at the charger station at the same time [11]. When EVs of different manufacturers come on the distribution grid at the same time, we have a situation where undesirable harmonics of a much wider spectrum appear as in Fig. 12.

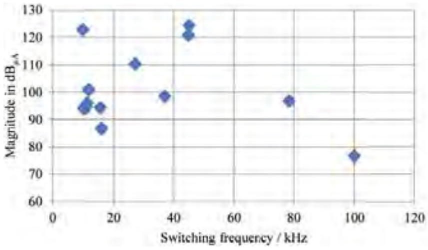

Fig. 13. Switching frequencies and magnitudes of different EV connected to EV charging group at same time [11]

Particularly prominent are distortions at frequencies below 2kHz (harmonics) and above 2kHz to 150kHz (supra-harmonics). Although the harmonic emission of EVs is strongly dependent on the grid voltage distortion, the supra-harmonic emission at the switching frequency of the inverter and its multiples is mainly determined by the design of the EV filter circuits.

The results of the harmonic and subharmonic distortion analysis of 19 different EVs connected via charging stations to the same distribution grid bus are presented in [11]. Note that different charge stations have approximately similar harmonic distributions but different harmonic spectra because they have different switching frequencies (Fig. 13). These are all kHz and are not multiples of the main harmonic of the distribution grid. The result is a partial resonance with a resonant pair within the distribution grid, a frequent supply of sensitive electronics that do not have the standard protection against such an attack.

What the authors point out in [12] is the fact that the classic standard safety devices are observing the distribution grid with substandard sampling, which does not seem to be a problematic harmonic image. Fig. 14 shows one such case in a 5EV chargers in the distribution grid. Significant differences exist in the harmonic performance between different EV types, which is majorly a result of different designs by the manufacturers.

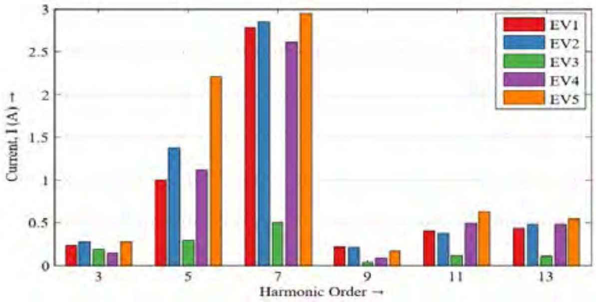

Fig. 14. The spectrum of current harmonic of the five EVs connected instantaneously on central charging infrastructure [13]

It is pointed out in [13] that in addition to the harmonic current emission, it is important to study the effect of the EV impedance on the distribution grid harmonic impedance. This is determined by the distribution grid side filter, which behaves often capacitively as it is required to reduce the high-frequency EV emission. Particularly if many EVs are connected to the same connection point, the risk of parallel resonances at low harmonics can be increased [13].

III. IMPACTS OF HARMONIC DISTORTION AND PROTECTION DEVICES

Current harmonics mainly affect the power distribution system from the bus to the inverter:

- Additional losses in wires and cables
- Additional heating of distribution grid transformers
- switch failures
- Third harmonics increase the zero component of the current and the voltage

Voltage harmonics affect mainly other devices connected to the bus (secondary of the distribution grid transformer):

- malfunctioning of telecommunication systems, computers, audio video equipment, monitors,

electronic control equipment. Etc.
- Resonance with capacitors for power factor correction
- Executive engine failures shortening the service life

How to reduce harmonic distortion? We need to be able to calculate - evaluate the harmonic distortion of the distribution grid and the impact of individual actors. This aspect is well reflected in practice by the standards defined for Structured Cabling and proper and high-quality grounding. Many IEC standards that have been defined for industrial plants where filter installation technology, especially external active filters, is normally present.

Very often we forget when observing the spectrum of currents that the time response is not a mean value but a "comb" [14] (Fig. 15).

The increase of harmonics at switching on and off of individual actors in a distribution grid that has combined connected consumers, an injected energy from a solar power plant and EV charger units can lead to the activation of protective devices (if installed) or to the swing of the distribution grid voltage.

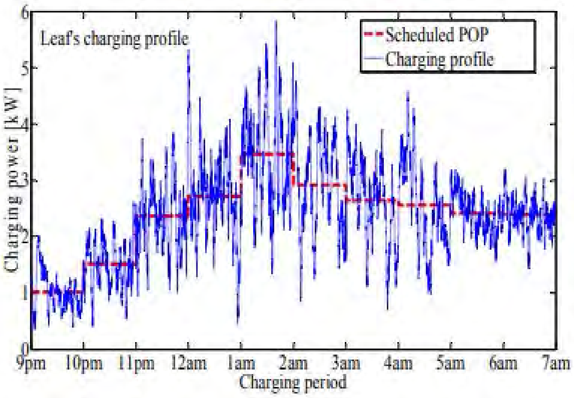

Fig. 15. Nissan leaf charging profile – the real measurement of power toward predicted profile [14]

There is a great danger of resonant harmonics - the harmonics of a particular EV charge can be in the rank of a single consumer opposite in phase - the resonance will capacitively burden the consumer and lead to possible adverse effects.

Current harmonics mainly affect the power distribution system from the bus to the inverter [15]:
- additional losses in wires and cables
- additional heating of distribution grid transformers
- switch failures (Fig. 16)
- third harmonics increase the zero component of current and voltage

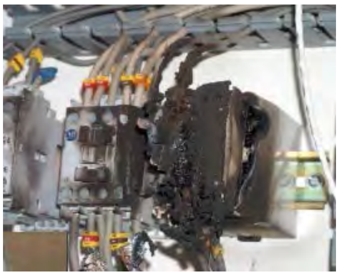

Fig. 16. Failure in switch box caused by current harmonics

Many authors recommend the installation of Active Power Filter (APF) filters that monitor only the 5th harmonic, and based on it evaluate all others, and therefore adjust the operation of the active filter. This is an expensive solution involving the existence of a shared bus, which has never been fulfilled in smaller rural areas and suburbs [15].

IV. CONCLUSION

The paper presenta a survey of harmonic distortion impact on an distribution grid as a result of EV charging, with respect to the design of the EV subsystems and its correlation to EV chargers. The given overview aims to highlight the impact of EV charger stations on power quality considering harmonic occurrences caused by the EV chargers operation. Based on the literature overview and real life data, the conclusion is that there is a need for better regulation of the EV charging station operation trough the standardization. The need for the standardized design of EV charges stations is detected based on the given overview.

Different situation (EV charging connection topology) can occur that can provide impressed harmonics into a distribution grid that mainly influence to unprotected and week loads in the same subcircuit (distribution grid connect on the distribution grid transformer secondary bus). A feeder is mostly likely to have a random distribution of EV chargers along with it. Therefore, for protection devices installation it must be carefully observed change of the power flow that ultimately rise current harmonics produced mainly from high power EV chargers.

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