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Measurement-based harmonic current modeling of mobile storage for power quality study in the distribution system

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Abstract: Electric vehicles (EVs) can be utilized as mobile storages in a power system. The use of battery chargers can cause current harmonics in the supplied AC system. In order to analyze the impact of different EVs with regardto their number and their emission of current harmonics, a generic harmonic current model of EV types was built and implemented in the power system simulation tool PSS®NETOMAC. Based on the measurement data for different types of EVs three standardized harmonic EV models were developed and parametrized. Further, the identified harmonic models are used by the computation of load flow in a modeled, German power distribution system. As a benchmark, a case scenario was studied regarding a high market penetration of EVs in the year 2030 for Germany. The impact of the EV charging on the power distribution system was analyzed and evaluated with valid power quality standards.

Key words: electrical vehicle, harmonic load modeling, harmonic measurement in power system, power quality, power system harmonics

1. Introduction

The forecast number of 2 million electric vehicles which will be expected in Germany up to 2030 [1-3] presents, because of charging e.g. new load flow conditions and in the case of dual use discharging, new challenges for the operation of the power distribution networks. A large number of EVs connected to the power system will represent considerable new load especially in the low voltage system of the future Smart Grids [4]. Depening on the charging infrastructure and the type of charger used in the EV, an AC charging current up to 63 A is possible.

A more adequate concept of the plug-in E-Car is the AC connection to the network. The AC/DC conversion will be located in the EV and the charger in the EVs is realized by addressed power electronics, w hich are also used nowadays in many modern other devices [5]. These converters create a non-sinus current and emit, in this case intensively, current harmonics [6, 7]. Devices with similar connection and current characteristics are photovoltaic generators, small wind generators and stationary battery systems [8].

The current harmonics cause a voltage drop on the grid impedance Z, see the scheme in Fig. 1, and effect power quality in the AC power system. In addition, operation of other loads in the distribution grid can be negatively affected as shown in Fig. 1 especially in the case of a car park with high penetration of charging EVs [9, 10]. In a worse case, the current harmonic are in phase and take effect with the sum of their amplitudes. The criteria for the construction of the charging infrastructure are merely parking sites and an electric connection point close to them. So, the additional “electric vehicle” load is simply added to the existing distribution grid. Because of the currently small number of electric vehicles and the subsequent marginal demand of charging points, the influence of electric vehicles in most cases is not obvious. However, if the number of connected charging EVs will increase, the influence could be quite different. In this situation, the power quality of the local power system can be significantly influenced, and the functionality of the AC power system, especially other loads supplied, can essentially be disturbing [11-13].

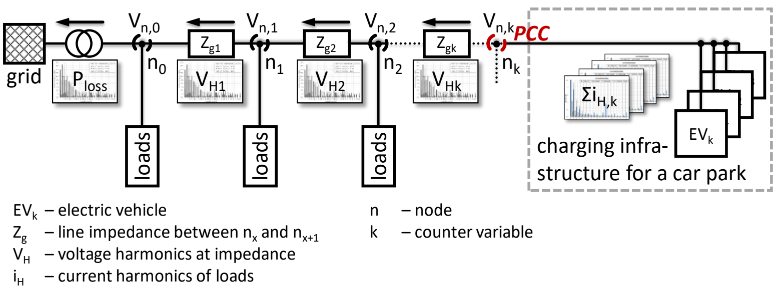


Fig. 1. Influence of current harmonic on power quality with point of common coupling (PCC)

The effects of voltage harmonics on electric networks and loads can be categorize as in Table 1. Depending on the functionality, the obvious effects are bleeping, flicker or malfunctioning, e.g. meanderings during production processes.

Only the first harmonic of the load current causes the power transfer [11]. The other higher harmonics stress the equipment such as power lines, transformers, compensation units and electric machines, which can shorten their life cycle [12]. Higher harmonics can also generate resonances in the grid [11].

Table 1. Potential influence of harmonics at devices 0

Obvious	Unobvious	Insignificant
visual	electrical	electrical
acoustical	thermal	acoustical
thermal		thermal
olfactory		

The increasing voltage drop on the grid impedance influences the power quality as a flat topping of the voltage curve. A relevant fact for the impact of harmonics emitted by EVs is the supply impedance and the resulting voltage drop [13] (Fig. 1).

The main power quality standard EN 50160 (for detail see also Chapter C) deals with voltage conditions, e.g. limits for distortion, flicker, voltage drops, a voltage range and asymmetry of the phases. In this study, the results of the simulations are compared with the limits given in standard EN 50160.

To evaluate the impact of electric vehicles in this paper three standardized current harmonic models are identified in order to build robust simulation models of an EV-converter, useful for power grid simulations. Then, the potential impact of these models on power quality will be analyzed in different case studies.

1.1. Charging infrastructure and grid connection

The effect of charging EVs on the AC supply power system depends on converters quality and EVs quantity. In addition, the location of charging stations in the distribution grid had to be taken into account for the analyses [15, 16]. Charging stations (CS) include properties as functionality, ICT (information and communication technology) standards [17], compatibility and the connection capacity which affects the possible charging time [2, 18, 19]. The standardization in the field of electro-mobility is just in its developmental stage, and especially the topics related to the power connector, ICT or EMC (electromagnetic compatibility) of EVs [20, 21] have not yet been fully covered by the current standards [9, 10]. For further consideration of AC-charging stations are relevant, because the types of EVs measured in this study are equipped with AC-charging systems. In fact, these CS are the most common systems. They insure a secure direct connection of the EV to the local distribution grid and include no elements, which influence the harmonics of the connected EV generally. CS configurations are varying in connection capacity and a single or three-phase application [18, 19].

1.2. Harmonics in power distribution grids

Nonlinear loads, such as power electronic devices, normally cause voltage harmonics in power distribution grids while the current harmonics cause a voltage drop on the grid impedance. In a weak grid, which is characterized by a high grid impedance, the current harmonics have a much stronger effect on power quality because of a higher voltage drop that those caused.

The load supplied by the common node can be affected, as shown in Fig. 1. The load voltage is the difference of the grid voltage and the voltage drop of the grid impedance. In most cases, the problems are quite common in the energy supply of power switches. The internal current feedback from the secondary part of the power supply is mostly oriented to the voltage waveform. The switching occurs at the zero pass. In the case when a zero pass or multiple zero passes are shifted in a half period of the wave, the power switch supply cannot work correctly in operating conditions. Consequently, an operation failure or even a breakdown can take place. This increases the strain on the devices, shortens the operating life or even causes damage to the operating equipment.

Using converters for photovoltaic generators in public low voltage grids is also a source of power disturbances. A power quality investigation in an LV grid with a high penetration of renewable energy systems (RES) [22] revealed the low influence of current harmonics under normal network operation condition.

Equation (2) shows the calculation of total harmonic distortion of voltage, THD_U, according to the standard EN 50160.

The THD_U is calculated for the simulation results with Equation (2) as the geometrical sum of all voltage harmonics (U_n) up to the 40^{th} harmonic order divided by the fundamental voltage (U_1) and evaluated using the standard EN 50160, in which the limit of THD_U is given up to 8% for power distribution grid [23]. Additionally, the results of all single voltage harmonics are evaluated. The limits do cover harmonics up to the 25^{th}, but for higher occurring harmonics, there are no valid limits in the power quality standard for distribution grids EN 50160.

$$THD_U = \frac{\sqrt{\sum_{n=2}^{40} U_n^2}}{U_1}. \qquad (1)$$

2. Field measurement of the EVs

2.1. Configuration of the measurement system

For a practical investigation purpose, the charging and discharging of various electrical vehicles have been measured. The DUTs (device under test) were connected close to the feet of an 800 kVA 10/0.4 kV transformer. The THD_U was stable and in average about 1.3%. Voltage, current and harmonics have been recorded by a power quality recorder FLUKE 1760. The device has different recording setups and allows configuring several analyzing functions for data processing.

The measurement test was done for a complete cycle of discharging and charging of the DUT. For this period, the harmonics were recorded to analyze if and in which band the harmonics differ during the process. For further analysis, the representative measurements of six different types of electric vehicles have been chosen. Depending on the specification and possible working modes of the DUT, measurements were recorded as listed in Table 2. The group of lightweight construction electric vehicles is defined as vehicles with four wheels, weighing no more than 350 kg without their battery pack. The other two groups of vehicles are compact cars. They differ in technical equipment.

The measurement results are sorted into three characteristics. The first category is the current limitation, according to the standards "Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)" [24] and "Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase" [25]. The second characteristic is the type of connection, single-phase or three-phase. The third category is the current direction (charging or discharging). Depending on the type of DUT and electric vehicle, various measurements have been done and evaluated.

Table 2. DUTs and associated current for measured category

Category of measurement		**Single phase charging $I_C < 16$ A**	**Single phase charging $I_C > 16$ A**	**Three phase charging $I_C < 16$ A**	**Three phase discharging $I_C < 16$ A**
DUT category	DUT	I_{eff}	I_{eff}	I_{eff}	I_{eff}
Lightweight construction electric vehicle	EV 1	11.7 A	–	–	–
	EV 2	12.5 A	–	–	–
Converted electric vehicle	EV 3	14.8 A	–	15.1 A	–
	EV 4	12.3 A	–	9.5 A	15.5 A
Series-production electric vehicle	EV 5	15.9 A	27.8 A	–	–
	EV 6	12.5 A	–	–	–

2.2. Measurement results and evaluation

In the following figures (Figs. 2-4), the current harmonic measurements of electric vehicles, categorized and given in Table 2, are pictured and compared to the standardized values (limits). One measurement out of each category of the Table 2 was taken as input data set for the EV models.

The analysis results in Fig. 2a show the category of the EV 1 and EV 2 light weight electric vehicles. The emitted harmonics are similar and have the characteristic of a B2U input rectifier [26]. The diagram shows clearly that the charger exceeds the limits defined in EN 61000-3. For further investigation and modelling the current measurement of EV 1 is taken as reference. It is the base for the created harmonic load model EV type A.

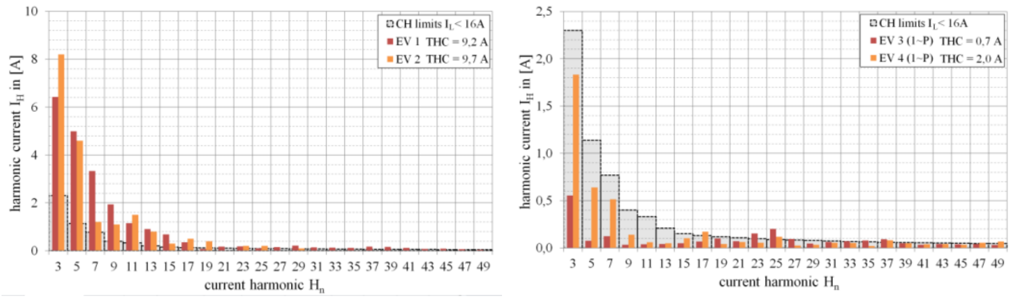
The harmonics of EV 3 and EV 4 (see Fig. 2b), which are representative for electric vehicles with a power converter; do have clear lower current harmonics. Nevertheless, the harmonics of a higher order, e.g. 23th, 25th, or 17th, are clearly exceeded by the measured EV's. The measurement of EV 4 is chosen as the basis for the simulation model of EV type B.

The simulation model EV type C was developed based on the measurement of EV 6 (see Fig. 3a). It is representative for the series-production of EVs, sold by German automotive producers. In addition, the odd higher harmonics, e.g. 19th, 23th – 43th, do clearly exceed the limits taken into account.

The measurement result (see Fig. 3b) presents the three-phase charging of EV 3 and EV 4. EV 3 has the typical harmonics of a B6U-input rectifier [26]. It can be recognized that the 5th

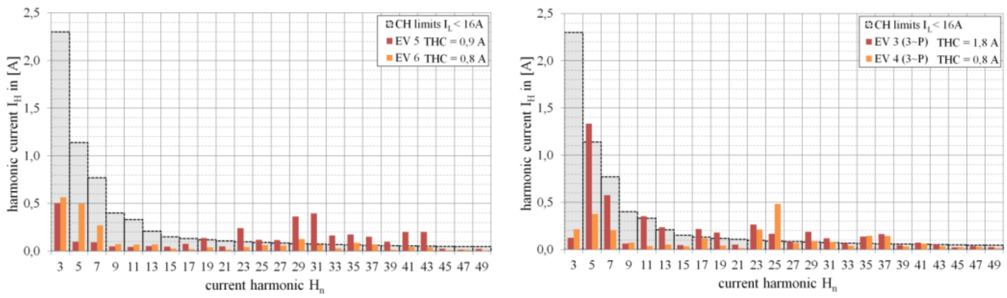
harmonics of EV 3 is beyond the limitation, and the 23th and 25th harmonics of EV 3 and EV 4 also exceed the limits of the standard.

In vehicle-to-grid (V2G) concepts, the EVs are able to feed energy back into the grid. The measured EV 4 is equipped with a bidirectional charging system. The measurement is pictured in Fig. 4.



(a) (b)

Fig. 2. Current harmonics of (a) lightweight construction and (b) converted EV's up to 16 A connection specification with limits of current harmonic [24]



(a) (b)

Fig. 3. Current harmonics of (a) series-production EV's and (b) converted EV's three phase charging up to 16 A connection specification with limits of current harmonic [24]

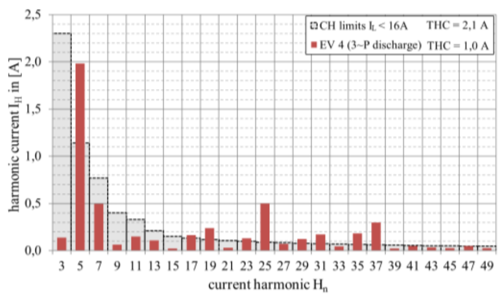


Fig. 4. Current harmonics of converted EV discharging up to 16 A connection specification within the limits of current harmonic [24]

3. Harmonic load modeling of the EVs

3.1. Mathematic model of harmonic load

An electric power load can be generally modeled as a complex electrical network, which consists of electric resistance, inductance and capacitance elements interconnected through the distribution line [27]. Therefore, its lumped effect can be simulated by a set of equivalent resistive, inductive and capacitive elements in parallel connection. Additionally, the effects generated by nonlinear load harmonics can be simulated by the harmonic current injection source [28, 29] dealing with load modeling for harmonic load flow calculation and proposing a comparable model structure. Similarly, the generalized harmonics load model structure used in this paper is shown in Fig. 5.

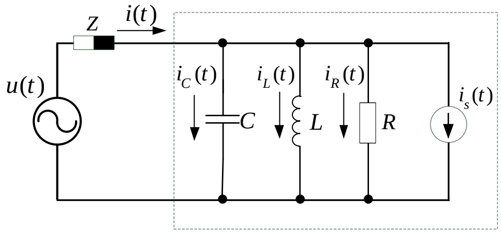


Fig. 5. Generalized harmonics load model

In this models, $u(t)$ and $i(t)$ are the instantaneous value of the voltage and current at the load bus, respectively. Z represents the network feeder impedance of the network. R, C, and L are the equivalent resistive, inductive and capacitive components of the load, respectively. Finally, $i_s(t)$ is the instantaneous value of the harmonic current injection, which simulates the lumped harmonic effects of the load.

$$i(t) = i_C(t) + i_L(t) + i_R(t) + i_S(t)\,, \tag{2}$$

where: $i_R(t)$, $i_L(t)$ and $i_C(t)$are the resistive, inductive and capacitive current of the load. Equation (2) can be rewritten by introducing the voltage $u(t)$ and the network parameters R, C and L as shown in Equation (3). R, C, L elements are part of the model that could represent the internal impedance of the system equipment.

$$i(t) = C\frac{\mathrm{d}u(t)}{\mathrm{d}t} + \frac{1}{L}\int u(t)\mathrm{d}t + \frac{u(t)}{R} + i_S(t)\,. \tag{3}$$

The harmonic current injection source $i_S(t)$ can be expressed by Fourier series involving the sine and cosine functions.

$$i_S(t) = \frac{1}{2}A_0 + \sum_{n=1}^{N}\left[A_n\cos(n\omega t) + B_n\sin(n\omega t)\right], \tag{4}$$

where:

$$\omega = 2\pi f \ . \tag{5}$$

A_0 is the constant term of the Fourier expression. N is the considered highest harmonic order (for this study N is 50), and n = 1, 2, 3,… . A_n and B_n are the magnitude of the n^{th} harmonic sine and cosine wave components, respectively.

3.2. Model parameter estimation using measurement

According to Equations (3) and (4) the parameters of the harmonic load model that should be estimated are:

$$\xi = \left[R, L, C, A_0, A_1, A_2 \ldots, A_N, B_1, B_2, \ldots, B_N\right]. \tag{6}$$

Using the real measurement data of the harmonic current for different EVs the parameters of the harmonic load model can be estimated.

In this study, the least square optimization method was used for this estimation. This relatively simple estimation method gives in most cases very good results [27, 30]. The phase angle of the higher current harmonics emitted by power electronic devices with active PFC (power factor correction) do differ in real measurements. In the worst-case scenario, as considered in the following chapters, all harmonic currents are in phase.

After that, the EV harmonic load model is implemented in the power system simulation tool PSS®NETOMAC and integrated into a typical low voltage distribution network.

4. Simulation study of the EV harmonic model

4.1. Test network

In order to investigate the influence of the EV on the distribution power network, a low voltage network is modeled in PSS®NETOMAC, with which it is possible to study the EV harmonic load model and its interactive behavior with the power system. PSS®NETOMAC is capable to deal with three-phase/ four-wire power flow study. In the paper, all three phases are analyzed. In this study, the arrangement of electric vehicles in the grid is symmetric to represent a general case simulation scenario with qualitative results. Cases of an unbalance distribution system, or unbalance charging of EVs with different phases can also be mapped in PSS®NETOMAC. This will have effect on power quality, but also makes the occurring effects and the simulation case more specific. Based on the model characteristics, this proposed model can be also used for other power quality studies, such as harmonic load flow, flicker etc.

The network structure is shown in Fig. 6. This network is based on a real one which serves a city district settlement that was built in the 1930s [31]. It is a single and two family home area of low density. A high EV penetration is firstly expected in this kind of area because of higher vehicle density per household, charging possibilities and purchase power of local population [1, 3, 5]. The floor space index is 0.05 - 0.3 [31], describing the number of residential units or floors in relation to the land area. The site occupancy index is 0.05 - 0.2 [31], describing the overbuilt proportion of the land area. This type of structure has 4 - 8 buildings per 10 000 m². The power network has a typical meshed structure but is operated as a radial distribution system. The borders that separate points in the district network in order to supply power stations in adjacent areas are open.

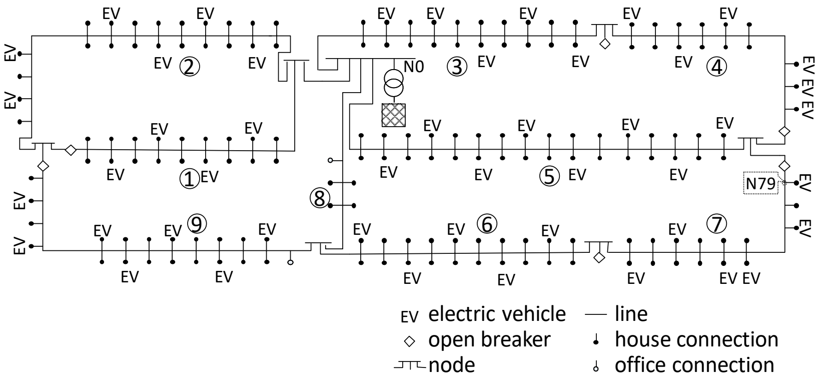


Fig. 6. Structure of a low voltage network district type
(one and two family house settlement with low density)

Typical transformers for the taken type of network do have a nominal power of 400 kVA to 630 kVA. This area is supplied by a 400 kVA transformer (20/0.4 kV Dyn5) for the simulation. The cable type NFA2X 4x95 [32] is employed as power lines. From the main power lines to the connection point of the buildings (power consumers) the cable type "NFA2X 4X25" [32] is used. The household load in the network is modeled as impedance representing the average residential power consumption.

4.2. Test scenarios and simulation

From the system operation point of view and taking into consideration the EV prognosis [33], three scenarios are defined, in which a certain number of EV's are charged simultaneously in the proposed distribution grid. The simulation is set to be in RMS mode. We found that there are no stability issues and for our study focus, we decided to show the results within just 2 cycles. The chosen examples of EV's are equipped with three different charging systems and are representatives of typical current waveforms. In Table 3 the power consumption and total harmonic current of the studied EV in the charging process are presented. The purpose is to study whether or not such a number of EV charging in the system causes a violation of power quality standards.

Table 3. Studied EV types: the power consumption and total harmonic current by charging

EV Type	P [W]	Q [VAr]	THC [A]
EV 1/ Type A	1 597	−434	9.2
EV 4/ Type B	2 848	−38	2.0
EV 6/ Type C	2 886	−82	0.8

4.3. Test scenarios and simulation results

In the first step, three test scenarios were defined with a fixed number of EVs but using varying EV-models. For the test scenario, a future study of the market penetration of EVs was the basis to determine the number of EVs in the power distribution grid [33]. In various studies, the amount of EVs differs between 2 M and 15 M EVs in Germany by 2030 [2, 21] with an amount of approximately 40 M vehicles in Germany in total. For the simulation scenario a market penetration (mp_{EV2030}) of 25%, 10 M vehicles was supposed. The simulation power grid is an example for single household loads [31]. The minimum number of vehicles in the household is assumed to be one. In practice, however, the phase order of the household connection is not identical.

The load is allocated to the three phases, which prevents a voltage asymmetry of the phases. In the scenario 1/3 of the EVs were connected to each phase. 168 power connections with household load (n_{hc}) in the grid were considered. Considering the estimations the number of EVs at one phase allocated in the grid can be calculated as follows:

$$n_{EVp1} = \frac{n_{hc} \cdot mp_{EV2030}}{3}. \qquad (7)$$

The number of EVs n_{EVp1} is estimated to be 14 EVs in all three scenarios. The additional load in all three scenarios is not an overload for the transformer. The measuring point for the voltage is determined at the most weak node in the simulated grid (N79 in Fig. 6).

4.4. Voltage and current harmonics in the distribution system caused by the EV charging

The results of the three scenarios with the three different test EVs (Type A, Type B and Type C) are shown and compared in Fig. 7.

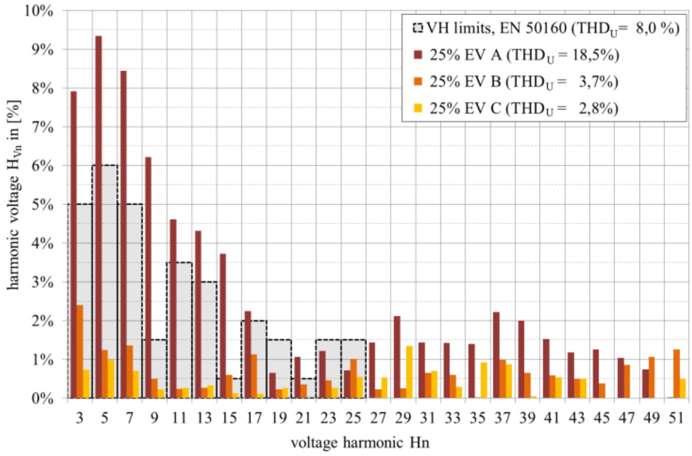


Fig. 7. Voltage harmonics in distribution grid in comparison to the standard [23]

From the above results, it can be seen that, in scenario 1 where EV Type A is used, the voltage and current harmonics introduced into the system by EV charging is much higher than it is in scenario 2 and scenario 3. The charging of the Type C EVshows the lowest influence on the distribution system regarding the harmonic penetration, in comparison with the other two scenarios, where the Type A EV and Type B EV are used.

From the Fig. 7, it can be clearly recognized and summarized that:

– In scenario A, where the Type A EV is studied, the limitation for 3^{th}, 5^{th}, 7^{th}, 9^{th}, 11^{th}, 13^{th}, 15^{th}, 17^{th} harmonics is basically violated.
– In scenarios B and C, where the Types B and C EVs are investigated, the odd-order harmonics of voltage are well limited within the standard restriction values.
– In all three scenarios, the voltage harmonics with an odd-order above the 25^{th} still show a high amplitude (energy share) compared with the 17^{th} ~ 25^{th} harmonics, especially in the scenario A with the Type A EV.

5. Conclusion

In the future smart grids the electric energy storage will be an important part of the power system and the EVs, because of expected capacity volume, will play an important role as mobile storage units [34]. Therefore, the influence of EV charging and discharging characteristics on the power distribution system has to be studied [35]. The investigations presented in this paper are focused on the power quality study analyzing a typical distribution system, in which a reasonable number of EVs are integrated. In order to accomplish this study, three standardized harmonic models for EVs, based on practical measurements, were built and implemented in the PSS®NETOMAC simulation software. Estimating the disturbance potential of the EV on the power quality of distribution grids, measurements of several EVs were taken. The generated current harmonics were analyzed, classified and compared with power quality standards. Three harmonic models of EVs were identified and validated. The developed models were then integrated into a typical power distribution system model. The analysis of the three chosen worst case scenarios indicates that under certain conditions, the power quality of a distribution system can be significantly affected by the integration of EVs, moreover the standard limitation can be violated when there is a certain number of EVs charging simultaneously. Since the violation depends on many factors such as the number of the EVs, the EV type and the distribution of the EV in the system etc., it is recommended to study each factor individually. Furthermore, the developed harmonic model should be parameterized by using practical measurements, not only of the EV but also of the whole distribution network, which can ensure the validity of the study results.

Anyway, the presented studies could already help the local distribution system operator (DSO) to have more detailed information about the potential power quality issues caused by the large-scale integration of EVs in own distribution network in near future. By simulation of representative scenarios using practical data and models, the DSO will know: how many of EVs and what types of EVs could be integrated without violation of power quality requirements and what extension of the network are necessary if the EVs number will be higher. Finally the results of model investigation could be very helpful for DSOs to develop the own codes for their operation to face these challenges. An available solutions could be the usage of specific PFC in power electronics. For the distribution system with critical harmonics issues due to EVs, an active harmonic filter could be adopted, which may give the most satisfied solution regarding the stochastic characteristic of numerous EVs during charging or discharge-ing processes in the system.

The tested individual (separate) vehicles did exceed the limitation of DIN EN 61000-3-2 taken as a reference. Nevertheless, in the worst-case scenario of the test for a distribution system, only the EVs with charging systems of a B2U input rectifier caused the EN50160 voltage quality standard to be exceeded.

Even though the validation of each EV model with the EV measurements was performed, the error in the use of these models in the PSS©NETOMAG environment simulation test without a reference measurement in a distribution system is difficult to estimate. Further work will be concentrated on measuring multiple charging vehicles to make reference measurements to evaluate simulation failure and optimize accuracy.

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