Effects of Individual Battery Charger Station on Power Quality

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Abstract — **A number of new devices are entering the public grid in a form of battery charging station, either as individual units or as a group connected at the same grid. This paper addresses the question of the effect of individual charging station operation as non-linear unit on the local distribution grid power quality by investigating current and voltage spectrum, i.e. harmonics. Two type of charging modes are considered: Mode 3 (moderate speed charging) and Mode 4 (fast-charging) in case of three-phase AC chargers. The operation is tested on one of traditional topologies using computer simulations. Results showed low voltage distortion and rather high current one. Both distortions are in accordance with IEEE and IEC/EN standards. However, current distortion is very close to limits and in some cases may have effect on transformer overheating and resulted in its de-rating.**

Keywords - battery charger station, power quality, harmonics.

I. Introduction

Significant efforts have been made to lower the air pollutants emission, both on industrial and domestic level. The long term projections in 2007 showed that there was immediate need for wider usage of renewable energy sources (RES) for powering industry plants and households [1]. Nowadays, greenhouse gasses (GHG) levels are still high and above expected, although contribution of the RES operation in EU, USA and other developed countries is evident.

Similar efforts have been made in transportation sector, especially for passenger vehicles, with the goal to decrease CO_2 emission below 100 g/100km or to achieve zero emission. In that sense, vehicles that combine gasoline and electrical energy (hybrid electric vehicle - HEV) or use just electrical energy (battery electric vehicle - BEV, or simply, electric vehicle - EV) for propulsion are becoming more attractive [2]. There are several reasons for that, like regulation in some countries (USA, especially California), special incentives, spreading of environmental awareness, available adequate infrastructure and probably the most importantly, the performance and prices of these types of vehicles are becoming competitive.

Consequently, there is a great interest in these means of transportation and thus more and more HEVs and EVs are sold. The U.S. Department of Energy expects that about one million of HEVs/EVs will be on the road and that about 400,000 of HEVs/EVs will be sold in 2015 [3]. By 2050 more than 60% of all vehicles in U.S. will be HEV/EV. These numbers show that a significant rise in the number of these vehicles will soon be evident.

Traditionally, HEVs and BEVs had the notorious problem with the driving range and recharging time [2]. Also, weight of the batteries (specifically energy and power density) was generally a limiting factor.

Nowadays, these problems are reduced to some extent whether by implementation of new technologies or via combining different sources with different dynamics and exploitation of their good characteristics in different driving modes. For example, average lithium-based batteries powered cars have up to 160 km (100 miles) driving range, while Tesla Model Seven longer - up to 430 km (270 miles) [4, 5]. Fig. 1 shows estimated driving range of some modern BEV models represented in miles (1 mile=1.61 km) [4].

With the increase of these vehicles on the road, it would be impractical and unreasonable to expect that battery charging will happen only at home, with house mounted chargers, during the night hours. The drivers will demand adequate charging stations all along their driving path, i.e. along the main roads and even more inside city limits. Furthermore, their expectations are that charging time should last no longer than average filling time of gasoline tank or average spending time in gasoline stations (for tank filling, small shopping or refreshment).

There are three different types of chargers depending on charging time or by charger construction: slow, moderate and fast charging stations or level 1, level 2 and level 3 types of chargers. Fig. 2 shows cumulative number of fast-charging stations operational Worldwide [6]. It can be seen that this number is relatively low (around 15,000 in 2014) and that it is lagging to the demand.

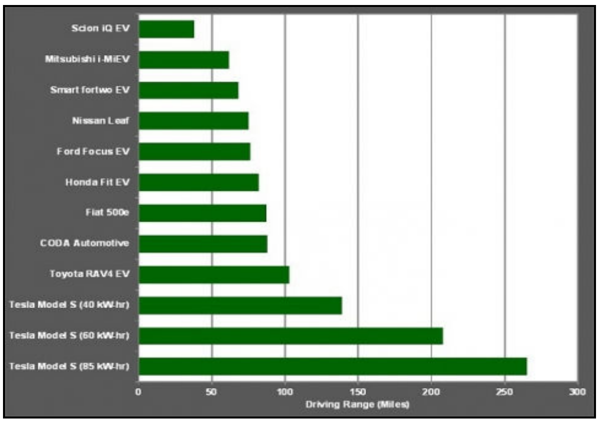

Figure1. Estimated driving range of some modern BEV models [4].

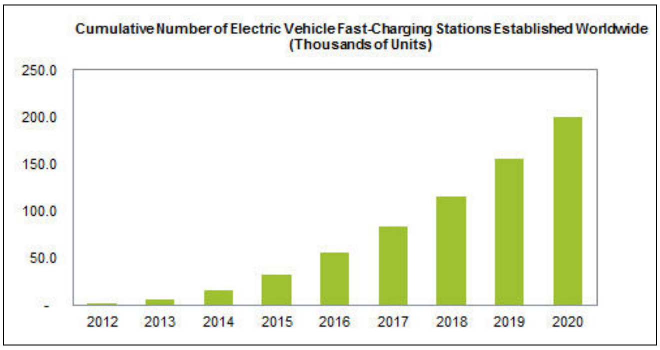

Figure 2. Number of EVs fast-charging stations available Worldwide [6].

Special problem is charger impact to electrical grid, i.e. their effect on power quality. Although, there have been significant improvements in charger construction and operation over the time, this item is still attracting high attention of researchers and wider public. Some surveys suggest that current THD has decreased from THDI=50.1% to THDI=6.12% since 1993 [7]. Even with these, probably deflated, numbers current THD is still high comparing with IEEE Standard 519-1992, IEC 61000 standards family or European EN50160 standard. Additional problem is that manufacturers produce different charging types and in different power levels using different technology. Therefore, it can be noted that chargers can have a strong influence on power quality.

Considering how switching converters work, and their impact on current and voltage THD, the problem of power quality should be addressed. To get into in-depth of this phenomenon it is necessary to develop adequate simulation models and apply computer simulations.

In this paper a model of a charger station is developed for three-phase public supply grid with 0.4 kV rated voltage using Matlab/Simulink software tools. The model represent the most common charger topology, i.e. a train of power electronics converters applied for charging purposes [8]. The model is applied for investigation of impact of mode 3 (moderate speed charging) and mode 4 (fast-charging) charging on power quality in the public grid. The simulation results are shown and some comments on observed harmonic spectrum and obtained THD values are stated.

II. Choice of Chargers

Chargers are generally classified based on their charging power (level 1 to 3), or on charging modes (Mode 1 to 4).In the first case, they are divided according to power size, rated voltage levels, number of phases, and by rated current. Charging time depends strongly on the type of charger, charging current (AC or DC) and applied batteries, so different charging modes can be distinguished. There is a difference in classification in the Europe and U.S., as a consequence of using different standards. In Europe and rest of the World the IEC 61851-1 is applied, while in USA the national SAE is in use [9, 10]. Table I shows main characteristics of different types and charging modes [11]. Table I can be used as a guideline for which voltage and current levels are expected to be met in commercially available chargers.

TABLE I Chargers Classification.

Type of charger	Power [kW]	Voltage [V]	Current [A]	Charging time
Slow charging speed - Mode 1	3.3	230, AC 1~	16	6 – 8 h
Slow charging speed - Mode 2	10	400, AC 3~	16	2 – 3 h
Moderate charging speed - Mode3	7	230, AC 1~	32	3 – 4 h
Moderate charging speed - Mode3	22	400, AC 3~	32	1 – 2 h
High charging speed - Mode4	43	400, AC 3~	63	20 – 30 min
High charging speed - Mode4	50	400 – 500, DC	100 - 125	20 – 30 min
USA level 1 – AC	1.8	120, AC	15	12 – 14 h
USA level 1 – DC	≤19.2	200-450DC	≤80	~20 min
USA level 2 – AC	7.2	240, AC	30	3 – 4 h
USA level 2 – DC	90	200-450DC	200	~15 min
USA level 3	TBD	TBD	TBD	TBD

The charging is connected with power conversion using different power electronics converters. This type of devices is well known as non-linear one consuming distorted currents, i.e. producing current harmonics. Over the time, many new, sophisticated chargers with good performances (low THD, adjustable power factor) are proposed in literature [12, 13, 14, 15], but they tend to be rather complex both to control and to produce, and thus most of them aren't being commercialized. Nowadays, several common topologies depending on charging mode and power sizes can be distinguished [8]. As manufacturers produce them for specific operating conditions, with various topologies and for different charging time, similar chargers may exhibit different effects on the grid. Still, the goal here is to test worst case scenario and thus a more traditional topology for charger is chosen.

Fig. 3 shows a topology of battery charging station connected to the public grid. The case of a charger plug-in the three-phase public supply grid with 0.4 kV rated voltage, which is common in Europe is considered. Difference between moderate (Mode 3) and fast (Mode 4) charging speed chargers is only in referenced currents, i.e. they are the same but inject different currents into the battery. An example of such a topology, similar to the one shown in Fig. 3 and with nominal current and voltage for appropriate chargers shown in Table I can be found in chargers produced by ABB (Terra series) [16].

The model is configured in such a way to reflect a real condition in the field, as much as it is possible. The medium voltage (MV) public grid is three phase source with nominal voltage of 10 kV and frequency of 50 Hz. Instead of pure sinusoidal voltages, it is assumed presence of voltage harmonic distortion of THDU≈2% (5^{th} and 7^{th} harmonics with 0.02 and 0.015 per unit amplitudes, respectively). This is done in accordance with actual situation in MV grid, so that the low voltage (LV) local grid has dominant 5^{th} and 7^{th} harmonic, already present [17].

Standard transformer of rated power 630 kVA and the transfer ratio of 10kV/0.4kV is used. The charging station is connected to LV grid, 0.4 kV, at the transformer substation.

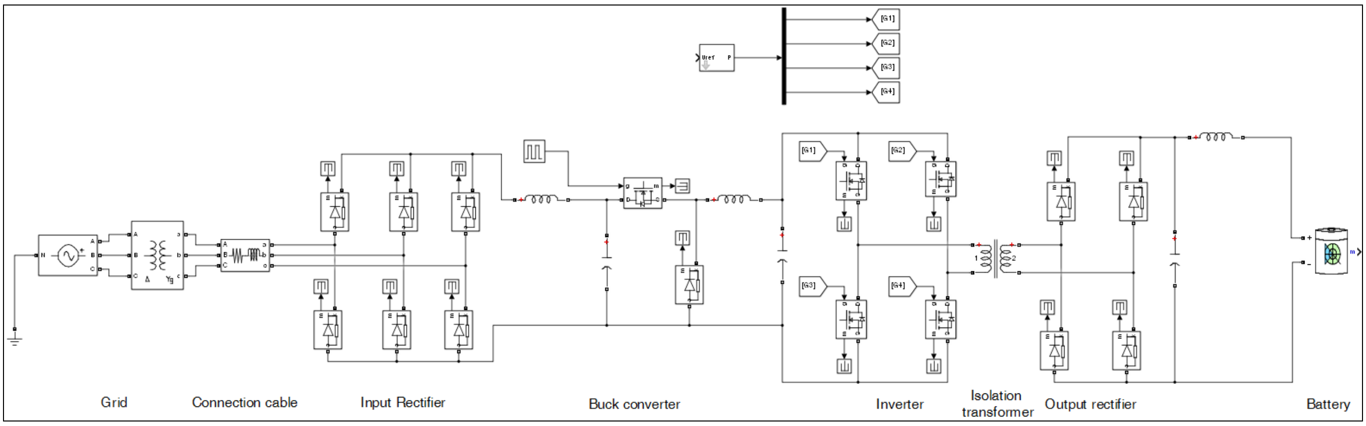

Figure 3. Matlab/Simulink scheme of selected battery charger topology.

The distance from substation to the possible location, where a charger station may be placed is assumed to 50 meters, so cables are modelled in simulation accordingly. The cable has equivalent resistance of 10 mΩ and inductance of 0.3 mH.

For input rectifier, simple uncontrolled three-phase bridge diode rectifier is used. Output of such a converter is rated to 450 V.

Next, considering the voltage level after the rectifier and nominal voltage of the batteries (in this case 300 V), it is evident that step-down converter should be used. Out of many converters, for this purpose simple buck converter was used and modelled. Buck's inductance is set to 2mH and capacitance is set to 660μF. Taking into account the type of the rectifier and DC/DC converter used, it is obvious that only one direction of energy is assumed in this paper, i.e. the possibility that the batteries are used as the temporary energy bank for distribution grid is excluded. After buck converter a filter is connected. This filter has inductance of 15 mH and capacitance set to 33 μF.

In order to have galvanic isolation, a single phase inverter is used. At the output of the isolation transformer a single-phase bridge rectifier is connected. Transformer has nominal power 250 kVA, nominal frequency 10 kHz and 400V/400V primary/secondary voltages. A LC filter is connected to the rectifier output. Filter's inductance is set to 1mH and capacitance is set to 440μF.At the end a lithium-ion battery was chosen. The battery model used in the simulation is taken from Simulink's/SymPower System toolbox library and is set to have nominal voltage of 300 V and maximum capacity of 25 Ah. Initial state-of-charge is set to be 50%. Also, parameters for all diodes and transistors are left on their default values. The buck and the inverter are controlled in open loop, since dynamic behaviour of the charger is not of interest for this paper.

III. SIMULATION RESULTS

In this paper two types of battery charger station operation are simulated: 3 phase AC, 0.4 kV Mode 3 (moderate charging speed) charger and 3 phase AC, 0.4 kV Mode 4 (high charging speed). Grid voltage, current and harmonic content of both voltage and current have been observed and calculated. Results are presented in Figs. 4-9.

A. *Mode 3 operation simulation results*

Figs. 4, 5 and 6 depict simulation results obtained for a single battery charger station operated in the mode 3 (moderate charging speed/time) and connected to the substation, together with MV grid. Fig. 4 shows line voltage, phase voltage and phase current at the charging station input terminals. Fig. 5 shows harmonic spectrum of the phase voltage at the charging station input terminals. Fig. 6 shows harmonic spectrum of the phase (line) current at the charging station input terminals.

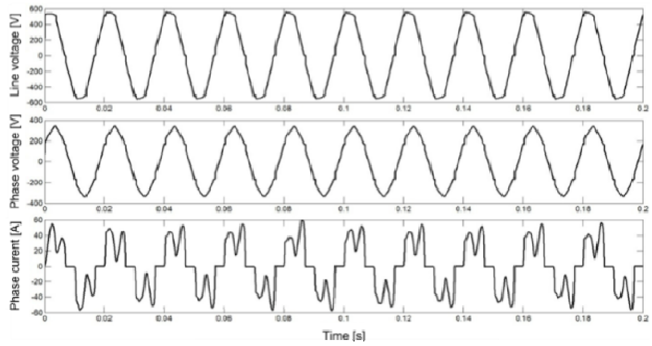

Figure 4. Line voltage, phase voltage and phase current at the charging station input terminals (Mode 3).

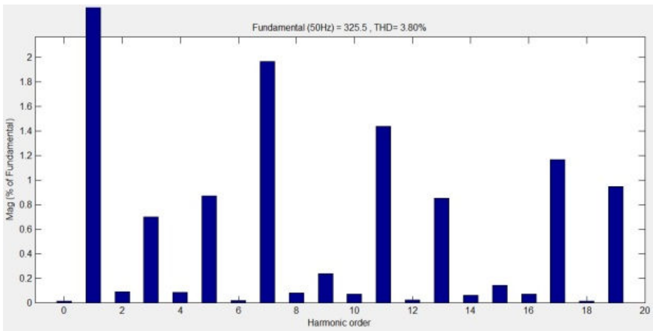

Figure 5. Phase voltage harmonic spectrum at the charging station input terminals (Mode 3).

B. *Mode 4 operation simulation results*

Figs. 7, 8 and 9 depict simulation results obtained for a single battery charger station operated in the mode 4 (fast charging speed / time) and connected to the substation, together

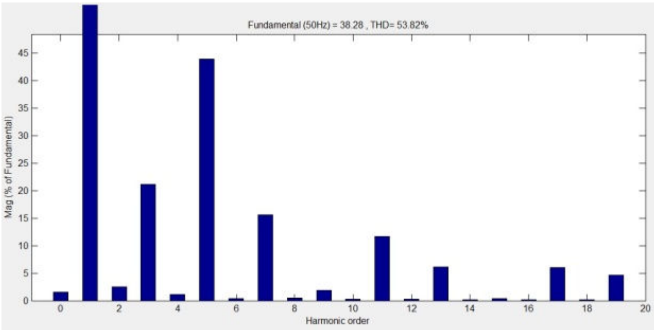

Figure 6. Phase current harmonic spectrum at the charging station input terminals (Mode 3).

with MV grid. Fig. 7 shows line voltage, phase voltage and phase current at the charging station input terminals. Fig. 8 shows harmonic spectrum of the phase voltage at the charging station input terminals. Fig. 9 shows harmonic spectrum of the phase (line) current at the charging station input terminals.

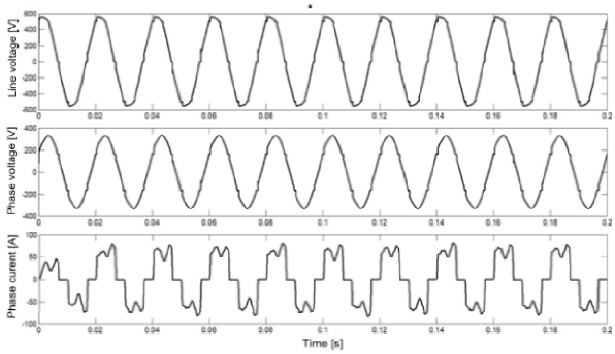

Figure 7. Line, phase voltage and phase current at the charging station input terminals (Mode 4).

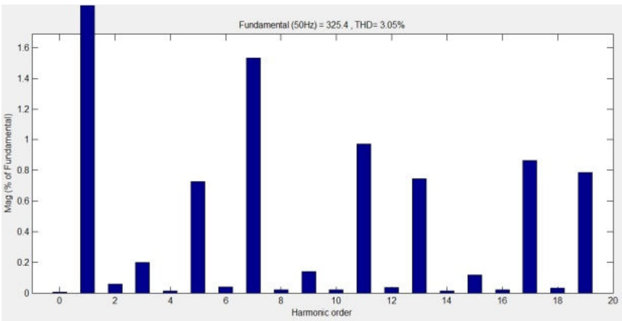

Figure 8. Phase voltage harmonic spectrum at the charging station input terminals (Mode 4).

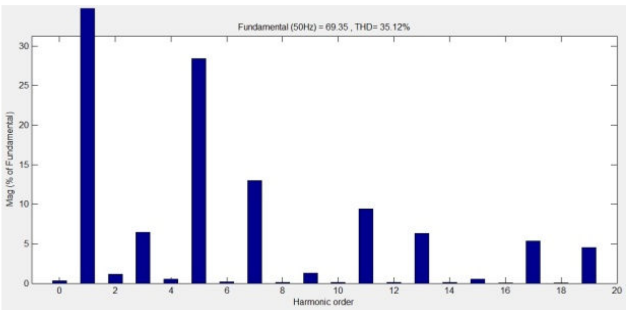

Figure 9. Phase current harmonic spectrum at the charging station input terminals (Mode 4).

IV. Discussion

A. *Mode 3 operation*

In the case of mode 3 operation of the battery charging station results show a low voltage distortion and a high current one (Fig. 4).

Total harmonic distortion of phase voltage is THDU=3.8%, while distortion from individual harmonics is less than 2% (Fig. 5). For comparison purposes, the IEEE Standard 519 and IEC 61000/EN61000 standard series are considered.

By IEEE STD 519 standard voltage THD for MV systems less than 60 kV must be under 5% and all individual harmonics should be fewer than 3% [18]. It can be seen that only 7th harmonic have magnitude close to 2%, while the rest are well under 2%.

By IEC 61000-2-4 standard voltage THD for MV systems is limited to 8% (Class 2) [19]. For individual harmonics, different limits have been stipulated between 1% and 6% (Fig.10). It can be seen that all voltage harmonics are below given limits.

As THDU=2% in MV grid was assumed as existing harmonics distortion, it may be concluded that the effect of charging station operation regarding voltage harmonics is in line with existing standards.

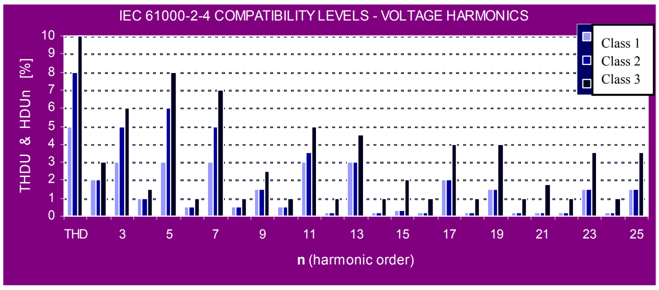

Figure 10. IEC 61000-2-4 Compatibility levels for MV voltage harmonics [19]

Fig. 6 shows that current harmonics are high. Total harmonic distortion is THDI=38.28%, while individual one lies between 5% and 43% for odd harmonics.

By the IEEE STD 519 standard, current harmonics are above limits. All odd harmonics under 11th should be less than 12% for systems with short circuit/maximum load (first harmonic) current ratio between 100 and 1000 which is here the case. Thus, current harmonics are well above the desired level. The biggest problems are the 5th, 7th, 9thand 11thharmonics.

If IEC 61000-3-4 standard is considered (Table II), it can be seen that limits are satisfied only for ratio of short circuit power and load power 450 and above [20].

B. *Mode 4 operation*

In the case of mode 4 operation of the battery charging station results again show a low voltage distortion and a high current one (Fig. 7). It is obvious that voltage distortion is similar to mode 3 case (THDU=3.05%), while input current is less distorted (THDI=35.12%; HDI=5%-28%). The same conclusions are valid for this mode, except that IEC 61000-3-4 standard limits are satisfied for ratio of short circuit power and load power of 250 and above.

TABLE II IEC/EN 61000-3-4 CURRENT HARMONICS LIMITS (ST 2) [20]

	HDIn – ODD HARMONICS ONLY [%]					**THDI [%]**
R_{SCE}= S_{SC}/S_L	**n=5**	**n=7**	**n=11**	**n=13**	**n≥15**	**non-sim. / 3~ simetr.**
<66	14	11	10	8	/	25 / 16
120	16	12	11	8	/	29 / 18
250	30	18	13	8	/	39 / 35
450	50	35	20	15	/	51 / 58
>600	60	40	25	18	/	- / 70
- Even harmonics are limited to: I_n/I_1 = 16/n						
- Harmonics multiply of 3 are not present						
- Assumption is that the load is balanced						

Regarding effect of harmonics on the line transformer, some researchers indicated that the current THD should be limited to 25–30% in order to have a reasonable transformer life expectancy [7]. In both considered cases obtained current THD is above this recommendation. This means that some problems with transformer overheating may be expected or some level of de-ratting should be applied.

The problem of deteriorated power quality in the local distribution network could be solved by connecting the chargers to another substation with higher power (higher short circuit power), by using harmonic filters or by implementing some more sophisticated chargers topologies.

V. CONCLUSIONS

Two types of battery charger stations have been investigated regarding input current and voltage harmonics, i.e. effects of their operation on power quality. A Matlab/Simulink simulation model have been developed and used for testing. The model parameters are selected in such a way to reflect real conditions in public grid. The results show that voltage harmonics are significantly below existing limits in IEEE and IEC/EN standards. On the other hand, the current harmonics are close to the limits or even higher, especially for some individual harmonics. This may have effect on distribution transformer overheating and reducing its life expectancy.

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