Multiple Battery Charger Stations Impact on Power Quality

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Abstract—**This paper addresses the question of the impact of the multiple battery charger stations on the local distribution grid power quality by investigating grid current and voltage spectrum. The case of station with multiple battery chargers of two types (mode 3 and mode 4) is considered. A Matlab/Simulink model has 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 level of voltage harmonics is increased. Further on, the current harmonics are also high and above IEEE standard 519-1992 limits and IEC/EN 61000-3-4 levels. Still, as a result of harmonic cancelation and attenuation effect, the THDI is lower than in case of single charger operation.**

Keywords- multiple battery charger station, power quality, THD values, harmonics.

I. INTRODUCTION

Recent market studies foresee a huge rise of number of plug-in hybrid (PHEV) and plug-in electric (PEV) vehicles on the roads in this decade and further on [1, 2, 3, 4, 5]. Only in U.S.A. about one million of HEVs/EVs are expected by the end of 2015 (about 400,000 new HEVs/EVs to be sold in 2015) [5]. Globally, by the end of the next year around 2,000,000 will be on the streets and roads [3]. By 2020 20 million are predicted worldwide, and by 2050 more than 60% of all vehicles in U.S. will be HEV/EV.

One of the main challenges in realization of this ambitious plan is providing the drivers adequate energy supply infrastructure. Such infrastructure needs to be built, to be available in wide areas and with services similar to existing gas stations. However, not all services are needed. The reasons are in different characteristics, which are actually advantages of battery charging stations (BChS) over the gas pumps, such as:

- no need for underground storage tanks,
- environmentally friendly - no risk of pollution, gasoline leaking and similar accidents,
- self-service is simple,
- charging may be easily controlled,
- billing may be simplified using bank cards,
- no need for regular stuff and
- easy for maintenance and distance control.

Still, there are some items to be taken care of, such as: danger of electric shock, EM radiation, different standards for plugs and sockets, safe placement of station-to-vehicle connecting cables (which may be heavy and bulky), anti-vandalism strategy and measures for prevention of stealing or robbing the station. Modern realizations provide solution to the most of these issues.

Another very important issue is connection with public or private grid. One aspect is electrical energy availability in electric power system and reliability of the supply. Many researchers have studied such problems. Different operating strategies, charging models and scheduling have been proposed. [6, 7, 8, 9, 10]. Further on, a possibility of EV´s application as electrical storage systems and grid support (V2G) has been discussed, too [11, 12, 13].

The next, very important aspect is quality of supply and interaction of the BChS with power system. The battery chargers are known as non-linear loads, which distort input current and produce harmonic "pollution" in the public grid. A lot of papers have addressed this problem regarding single BChS operation and its impact on the grid [14, 15, 16]. It has been reported that total harmonics distortion of input current is between 60% and 70% if uncontrolled AC/DC converters are used [14].

In this paper, impact of multiple battery charging stations (MBChS) on power quality in the public grid is considered. To investigate this problem, a computer model of single charger is used [17]. The model represent the most common modern charger topology, actually a train of power electronics converters applied for charging purposes [18]. This charger differs from the one used by other authors, when a cluster of simple chargers has been considered [19]. The MBChS is regarded as a load equipped with a number of modern battery chargers, which may operate simultaneously. The overall station model is developed and applied for investigation of the MBChS impact on power quality. The simulation results are shown and results are discussed and compared with existing power quality standards.

II. MODEL OF A MULTIPLE BATTERY CHARGING STATION

Single BChS is standardized in USA and EU in three or four different types depending on charging current (AC or DC) and power size (input voltage and current) and consequently on duration of charging time: chargers of Levels 1 to 3 (SAE J1772 standard, USA) or Modes 1 to 4 (IEC 61851-1 standard, EU) [20, 21]. Their main electrical characteristics and charging time are listed in Table I and Table II.

Nowadays, the BChSs, either as single or multiple units, are spreading fast in the Europe. Typical public station may be located on open road, or more likely in a city centre (business and shopping areas) and industrial zones. Suitable locations are also university campus and shopping moles parking sites, while residential chargers are to be expected in a city suburbs and villages. A map presented on Fig. 1 shows current position and operation status of BChSs in Europe, according to [22]. Although the map may not be detailed enough and probably does not show all types of chargers (especially in big city areas), still it indicates that the public and high-power/fast chargers are in majority. To serve several customers simultaneously, a number of BChS are needed in one location. Therefore, in this paper an MBChS operating in the mode 3 (moderate speed charging) and the mode 4 (fast-charging) is considered.

TABLE I TYPE OF CHARGERS ACCORDING TO SAE J1772 [20]

Type	AC Charging	DC Charging
Level 1	120V, 1~, max 16A max 1.9 kW	200 – 450 V, max. 80A 19.2 kW
Charging time	12h - 14h	~20 min
Level 2	240V, 1~, max 80A max 19.2 kW	200 – 450 V, max. 200A 90 kW
Charging time	3h - 4h	~15 min
Level 3	*TBD* (3~)	*TBD* (200-600V, max 400A max 240kW)

TABLE II TYPE OF CHARGERS ACCORDING TO IEC 61851-1 [21]

Type	AC Charging 1 phase	AC Charging 3 phase	DC Charging
Mode 1	230V, max 16A	NA	NA
Charging time	Slow (8 - 12h)	NA	NA
Mode 2	NA	400V, max 16A	NA
Charging time	NA	Slow (8 - 12h)	NA
Mode 3	230V, max 32A	400V, max 32A	NA
Charging time	Moderate (2 – 4h)	Moderate (1 – 2h)	NA
Mode 4	NA	400V, max 63A	600V, 400A
Charging time	NA	Fast (20-30 min)	Fast (15-20 min)

Figure 1. Available battery charging stations in Europe (Oct.2014) [22]

A modern BChS consists of several power electronics converters to enable adequate power processing, control and galvanic isolation. Fig.2 shows a three-phase AC topology applied in this paper, which enables mode 3 or mode 4 operations.

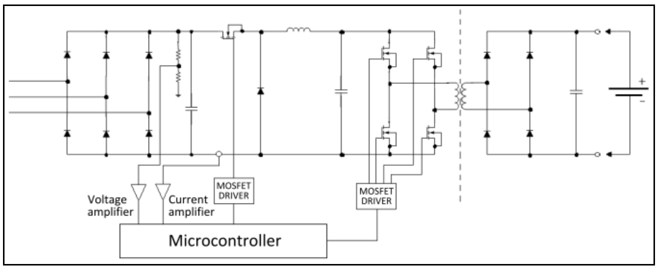

Figure 2. Topology of the modelled BChS.

The model is configured in such a way to reflect a real condition in the field, as much as it is possible. Standard distribution 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 and the connecting cable parameters are taken into consideration. Input AC/DC converter is an uncontrolled three-phase bridge diode rectifier, which is followed by buck-converter for the DC voltage levelling and a full-bridge DC/DC unit to provide galvanic isolation and output control. Output of such a converter is rated to 450 V. 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. At the end a lithium-ion battery was chosen. More details of the model are explained in [17].

Figure 3 depicts organization and content of the MBChS, which is modeled in the paper. It can be seen that it consists of six chargers – two fast and four moderate ones. It also shows how chargers can be connected to the distribution network. By turning on/off various switches, different chargers could be connected and put into operation. There are a number of combinations of possible usage of these chargers. All of them are modeled, but results of 14 of them will be presented here. For easier understanding, these cases are labeled as: 0F1M meaning zero fast and one moderate charger are connected (all switches, except switch 6 are open) or 2F4M meaning two fast and 4 moderate chargers are in operation (all switches are closed).

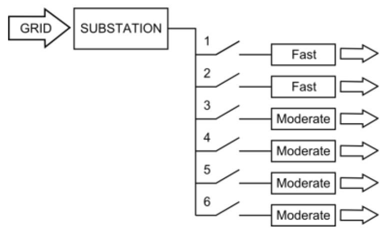

Figure 3. The MBChS - Energy flow from grid to batteries.

III. SIMULATION RESULTS

The Matlab/Simulink model of the MBChS is used to track input current and voltage harmonics for all 14 cases of station operation. Results are presented in Tables III and IV.

TABLE III INDIVIDUAL AND TOTAL HARMONIC DISTORTION OF INPUT VOLTAGE FOR DIFFERENT CASES OF CHARGER OPERATION

State of chargers	HDU [%] for harmonic order									THDU [%]
	3	5	7	9	11	13	15	17	19	
0F1M	0.42	0.89	1.99	0.15	0.65	0.51	0.08	0.55	0.52	2.87
0F2M	0.7	0.87	1.97	0.24	1.44	0.85	0.14	1.17	0.95	3.80
0F3M	0.73	1.67	1.96	0.47	1.98	1.07	0.33	1.53	1.16	4.75
0F4M	0.87	2.47	1.96	0.75	2.41	1.21	0.53	1.76	1.27	5.55
1F0M	0.2	0.72	1.53	0.14	0.97	0.74	0.12	0.86	0.79	3.05
1F1M	0.4	0.66	1.81	0.14	1.26	1.02	0.06	1.03	1.12	3.59
1F2M	0.49	1.09	1.89	0.15	1.62	1.21	0.03	1.26	1.33	4.16
1F3M	0.72	1.59	1.91	0.13	1.99	1.39	0.03	1.51	1.48	4.77
1F4M	0.78	2.09	1.87	0.33	2.28	1.44	0.18	1.7	1.51	5.29
2F0M	0.29	1.17	1.63	0.13	1.9	1.52	0.01	1.46	1.61	4.53
2F1M	0.5	1.75	1.82	0.12	2.16	1.7	0.06	1.57	1.78	5.05
2F2M	0.64	2.43	1.82	0.23	2.59	1.83	0.07	1.84	1.79	5.87
2F3M	0.66	2.88	1.81	0.38	2.84	1.84	0.18	1.98	1.74	6.29
2F4M	0.77	3.28	1.88	0.38	2.97	1.94	0.17	2.01	1.77	6.56

TABLE IV INDIVIDUAL AND TOTAL HARMONIC DISTORTION OF INPUT CURRENT FOR DIFFERENT CASES OF CHARGER OPERATION

State of chargers	HDI [%] for harmonic order									THDI [%]
	3	5	7	9	11	13	15	17	19	
0F1M	18.3	43.51	17.4	2.7	10.46	6.75	0.61	5.62	4.8	52.89
0F2M	21.13	43.95	15.59	1.81	11.62	6.13	0.36	6.03	4.64	53.82
0F3M	14.06	38.16	12.33	2.4	10.37	4.87	0.93	5.2	3.66	44.92
0F4M	11.95	33.65	9.92	3.38	9.0	3.86	1.47	4.28	2.8	39.10
1F0M	6.44	28.41	12.99	1.27	9.39	6.33	0.52	5.33	4.54	35.12
1F1M	7.59	30.64	12.49	1.16	9.07	5.86	0.25	4.81	4.38	36.58
1F2M	10.93	33.23	12.99	1.2	9.59	5.78	0.2	4.92	4.28	39.80
1F3M	11.7	33.9	12.69	1.0	9.58	5.61	0.16	4.73	4.12	40.36
1F4M	12.21	34.47	12.21	1.47	9.74	5.2	0.42	4.7	3.68	40.76
2F0M	5.33	27.4	12.04	0.94	8.6	5.66	0.24	4.36	4.13	32.94
2F1M	5.89	28.16	11.67	0.86	8.37	5.38	0.15	3.99	3.86	33.31
2F2M	9.2	30.79	12.13	1.03	9.04	5.29	0.25	4.22	3.62	36.61
2F3M	8.28	30.68	11.38	1.32	8.75	4.91	0.4	3.98	3.26	35.79
2F4M	9.31	31.0	11.19	1.53	8.79	4.72	0.51	3.87	2.98	36.18

Due to limited space, only the two of them will be regarded here, which represents two extremes – minimum and maximum charger loads. These two cases in comparison may show the main trend for voltage, current and power quality for all other cases. In this paper two types of MBChS operation are simulated:

1. Single unit in operation (switch 6 closed) - 3 phase AC, 0.4 kV, Mode 3 (moderate charging speed) charger and
2. All units in operation (all switches closed) - 3 phase AC, 0.4 kV, Mode 4 (fast charging) charger.

Grid voltage, current and harmonic content of both voltage and current have been observed and calculated. Results are presented in Figs. 4-9.

A. Simulation results in case of one charger in mode 3 operation

Figs. 4, 5 and 6 show simulation results obtained for a single battery charger station operated as mode 3 charger and connected to the substation (switch 6 closed). Fig. 4 shows line voltage, phase voltage and phase current at the charging station input terminals. Fig. 5 shows harmonic spectrum of the one phase voltage, while Fig. 6 shows harmonic spectrum of the phase (line) current, both at the MBChS input terminals.

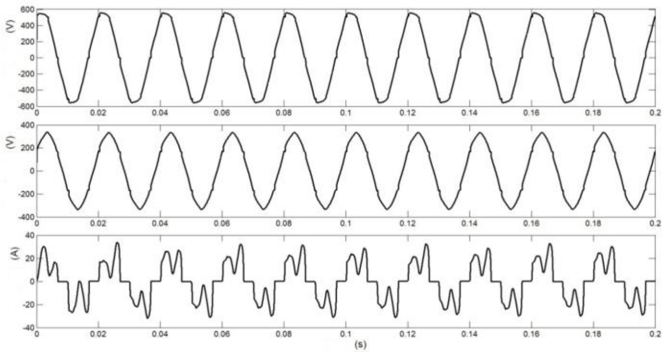

Figure 4. Line voltage, phase voltage and phase current at the charging station input terminals (one charger connected - mode 3).

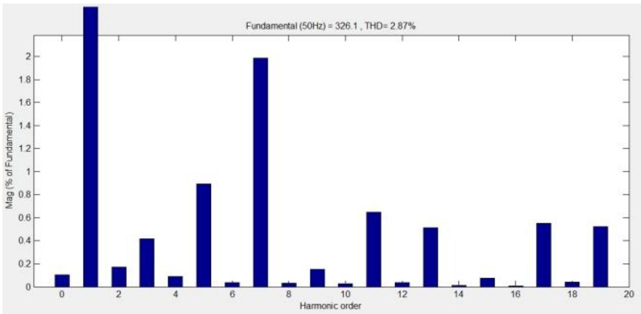

Figure 5. Phase voltage harmonic spectrum at the charging station input terminals (one charger connected - mode 3).

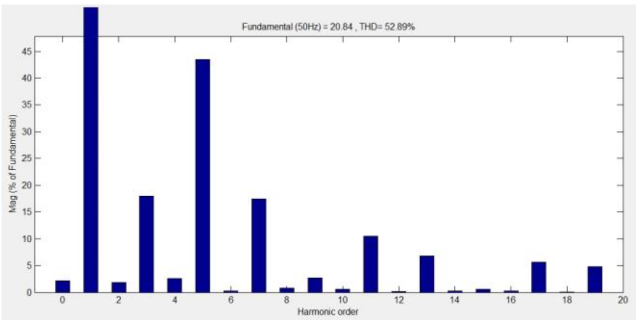

Figure 6. Phase current harmonic spectrum at the charging station input terminals (one charger connected - mode 3).

B. Simulation results in case of all chargers in operation

Figs. 7, 8 and 9 present simulation results obtained for simultaneous operation of all battery chargers (all switches closed), both mode 3 (moderate charging time) and mode 4 (fast charging time), and connected to the substation. Fig. 7 shows line voltage, phase voltage and phase current at the MBChS input terminals. Fig. 8 shows harmonic spectrum of the phase voltage, while Fig. 9 shows harmonic spectrum of the phase (line) current, both at the MBChS input terminals.

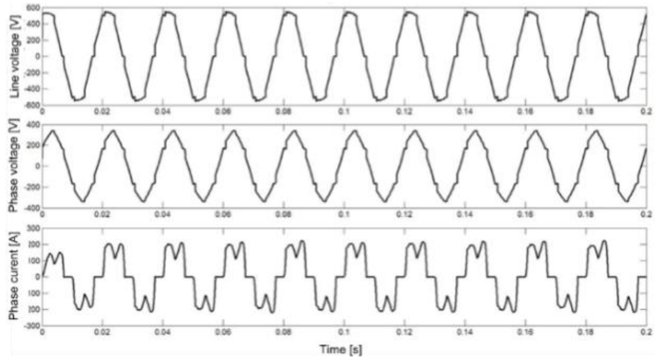

Figure7. Line voltage, phase voltage and phase current at the MBChS input terminals (all chargers connected).

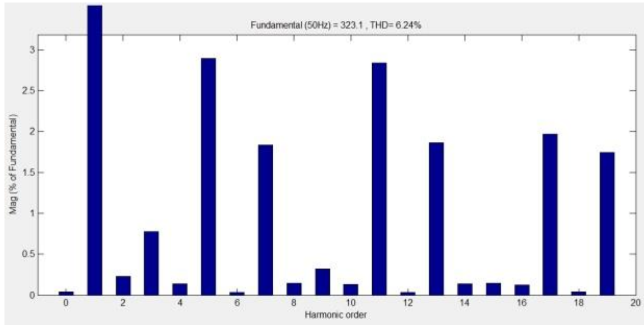

Figure 8. Phase voltage harmonic spectrum at the MBChS input terminals (all chargers connected).

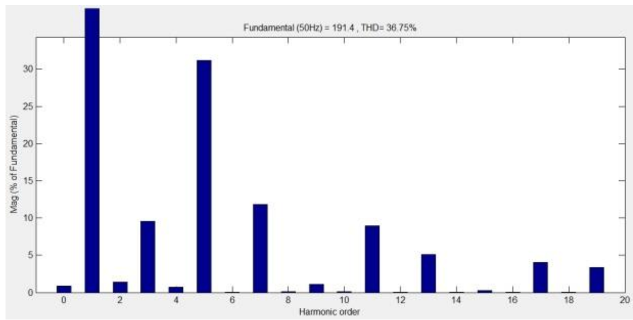

Figure 9. Phase current harmonic spectrum at the MBChS input terminals (all chargers connected).

IV. DISCUSSION

A. Harmonic compatibility levels

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% [23, 24]. Fig. 10 shows limits stipulated by IEC 61000-2-4 standard for voltage THD and

MV systems. It can be seen that the THDU is limited to 8% for Class 2 loads [23, 25].

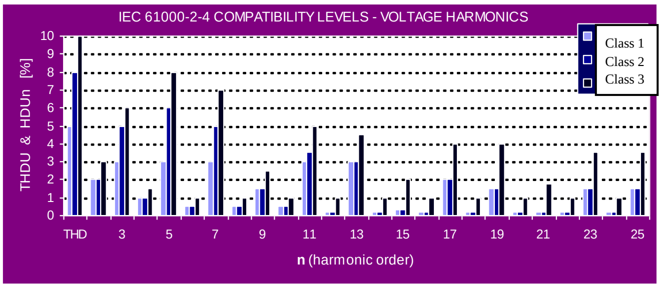

Figure 10. IEC 61000-2-4 Compatibility levels for MV voltage harmonics

The level of current harmonics limits depends on ratio of short-circuit and load current (IEEE standard 519-1992) or short-circuit and load power (IEC 61000-3-4) at the point of common coupling of a harmonic producing device. Table V and VI shows the limits levels stipulated in IEEE standard 519-1992 and IEC 61000-2-4, respectively.

TABLE V IEEE 519-1992 - CURRENT HARMONICS LIMITS

	HD In – ONLY ODD (%)					THDI (%)
I_{SC}/I_L	n<11	11<n<17	17<n<23	23<n<35	n>35	
<20*	4,0	2,0	1,5	0,6	0,3	5
20-50	7,0	3,5	2,5	1,0	0,5	8
50-100	10,0	4,5	4,0	1,5	0,7	12
100-1000	12,0	5,5	5,0	2,0	1,0	15
>1000	15,0	7,0	6,0	2,5	1,4	20
- Even harmonics - 25% of odd harmonics limits.						
- * All generators are limited on above values regardless on actual value of I_{SC}/I_L.						
- Legend: I_{SC} = Maximum short circuit current at PCC I_L = Maximum load current (fundamental harmonic)						
- For PSSs from 69 kV up to 138 kV limits are 50% of above values. - For PCCs above 138 kV case by case estimation is required.						

TABLE VI IEC/EN 61000-3-4 CURRENT HARMONICS LIMITS (STAGE 2)

	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						

B. Single charger, mode 3 operation

In the case of single charger, mode 3 operation of the battery charging station results show a low voltage distortion and a high current one.

Total harmonic distortion of phase voltage is THDU=2.87%, while distortion of individual harmonics is less than 1% (Fig. 5). Both distortions are well below the limits of IEEE STD 519 standard. If IEC 61000-2-4 standard is considered, it is clear that THDU is below compatibility levels, as well as individual harmonics (all odd harmonics are below 1%). As MV grid was assumed with 2% of existing voltage harmonics distortion, it may be concluded that the impact of single charger operation regarding voltage harmonics is in line with existing standards.

On the other hand, Fig. 6 shows that current harmonics are high. Total harmonic distortion is THDI=52.89%, while individual ones lie between 5% and 43% for odd harmonics. By the IEEE STD 519 standard (Table V), current harmonics are above limits. All odd harmonics under 11^{th} 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 5^{th}, 7^{th}, 9^{th} and 11^{th} harmonics. If IEC 61000-3-4 standard is considered (Table VI), it can be seen that limits are satisfied only for ratio of short circuit power and load power 450 and above.

C. All chargers in operation (Mode 3 and Mode 4)

In the case of simultaneous operation of all battery chargers in the MBChS (mode 3 and mode 4), results show relatively low voltage distortion, while the current one is high.

Voltage distortion in this case is significantly higher than in previous case when only one of the mode 3 chargers were in operation. The THDU is now up to 6.24%, which is above IEEE Standard 519-1992 limit. Also, individual harmonics are high, close to the stipulated values, especially the 5^{th} and the 11^{th} ones (HDU_5=2.8%, HDU_{11}=2.7%). If IEC 61000-3-4 is considered, the conclusions are a little bit different – THDU and all individual harmonics are inside the limits, except the 19^{th}. Therefore, in this case we may conclude that MBChS operation will result in high voltage distortion, especially if background voltage distortion of 2% is already present in the system.

Current harmonics are lower than in previous case, but still high. The results show that total harmonic distortion is THDI=36.75% and that individual current harmonics are between 3% and 11%. Again, they are higher than IEEE 519 limits in all cases, but acceptable for IEC 61000-3-4 if ratio of short circuit power and load power is 250 and above.

The obtained result of decreasing of the THDI in case of a number of chargers operating at the same time is similar to effects of a PC cluster operation. It was shown that if a large number of PCs are operating simultaneously, the THDI level is significantly lower, than in case of single PC operation. This phenomenon is explained with harmonic cancelation and attenuation effects. The THDI vs number of PCs relation has been proposed [26].

V. CONCLUSION

The multiple battery charger station is analyzed regarding possible impact on power quality in public grid. The case of station with multiple battery chargers of two types (mode 3 and mode 4) is considered. Effects of their operation on power quality are investigated. A Matlab/Simulink simulation model has 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 in case of all chargers simultaneous operation voltage harmonics are increased – they surpassed the IEEE standard 519-1992 compatibility levels and even some of the IEC/EN 61000-3-2 standard ones (the 19th harmonic). Further on, the current harmonics are also high and above IEEE standard 519-1992 limits and IEC/EN 61000-3-4 levels if ratio of short circuit power and load power is less than 250. Still, as a result of harmonic cancelation and attenuation effect, the THDI is lower than in case of single charger operation.

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