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doi:10.15199/48.2020.05.03

# Operation of Electrical Vehicles Fast Charging Stations in Warsaw - Case study of innogyGO! collecting point

***Abstract**. The paper presents the problems of operating a fast charging station for electric vehicles in a collecting point of electric vehicle (EV) car sharing innogyGO! Authors presented measurements of the parameters of the power quality in operational conditions, and also proposed a number of tests that should be carried out to investigate the impact of EV charging on the distribution grid. Each of the analysed tests is a reflection of the real demand for charging vehicles by the end-users.*

***Streszczenie.** W artykule przedstawiono problematykę pracy stacji szybkiego ładowania pojazdów elektrycznych działających w punkcie zbiorczym wypożyczalni pojazdów elektrycznych (EV) innogyGO!. Zaprezentowano pomiary parametrów jakości energii elektrycznej w warunkach operacyjnych, a także zaproponowano szereg testów jakie należy przeprowadzić przy badaniu wpływu ładowania EV na sieć dystrybucyjną. Każdy z analizowanych testów jest odzwierciedleniem rzeczywistych potrzeb ładowania pojazdów przez użytkowników.(**Eksploatacja stacji szybkiego ładowania pojazdów elektrycznych w Warszawie - Studium przypadku punktu zbiorczego innogyGO!**).*

**Keywords:** electric vehicles, electric vehicles charging stations, e-car sharing, distribution grid operation, power quality
**Słowa kluczowe:** pojazdy elektryczne, stacje ładowania pojazdów elektrycznych, wypożyczalnie samochodów elektrycznych, praca sieci dystrybucyjnej, jakość energii elektrycznej.

## Introduction

Nowadays, the policies of governmental organisations are aimed at ensuring the development of sustainable public transport [1,2]. Under current legislation, EU member states are obliged to create a National Framework for the Development of Electromobility [3].The development of electromobility means that in the coming years, it will be a lot of tasks for distribution system operators (DSO), in terms of ensuring the adequacy of grid infrastructure [4,5]. There will be a rapid increase in the number of electric vehicles (EV) and therefore lot of challenges within creating market and technical conditions for the purchase of private battery electric vehicles (BEV), but also support and implementation of electric vehicle car sharing (EVCS). Solutions for EVCS are widely known in Europe, including Poland [6,7]. They do not always have to be based on classic passenger cars, but also on innovative concepts [8]. However, it is important to maximise the mobility of users, i.e. to allow the user to leave the vehicles at their destination (one-way Electric Vehicle car sharing). In Poland, such programmes can be used both in Warsaw (innogyGO) and in Wrocław (Vozilla) [9,10]. The best known European solution was the rental of small electric vehicles in Paris - Autolib. Unfortunately, due to financial reasons, the project was terminated [8].

Popularization of EV requires the use of appropriate incentives to purchase them. In 2019, the Polish government introduced regulations enabling these vehicles to drive on bus lanes and allowed them to park free of charge in paid parking zones, as well as prepared financial support mechanisms. Currently, these are 30% of the purchase price of EV, but not more than 8700 euros. Unfortunately, the drawback of this mechanism is the maximum purchase price of EV, which is 29,000 euros, which means that only a few cars are within the set price limit. Analysing the world literature it can be observed that the amount of the subsidy in Poland is at a comparable level to other countries at the beginning of the process of popularization of EV, however, there were no limits on the price of electric vehicles [11].

Regardless of the incentives, the number of electric vehicles in Poland is significantly increasing. Fig. 1 shows the increase in the number of EV vehicles in 2019, while Fig. 2 shows the number of vehicles newly registered in the first half of 2019 divided into EV models.

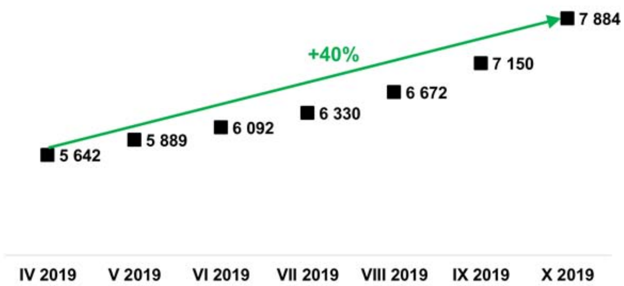


Fig.1. Number of electric vehicles in Poland from April to October 2019 – based on [12]

As shown in Figure 2, more than half of the new electric vehicles registered in H1 2019 belong to the innogyGO electric vehicle car sharing company. Their fleet currently consists of BMW i3 and i3s. The charging of these vehicles can take place in public charging stations, but also in special parks where these vehicles are collected.

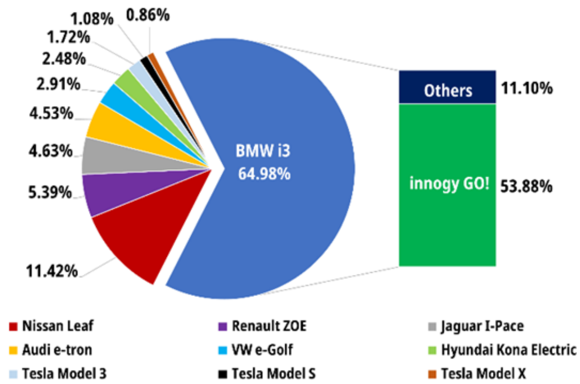


Fig. 2. New registrations of BEV electric vehicles at the end of H1 of 2019 – based on [12,13]

The aim of this paper is to examine the impact of fast charging of EV vehicles, held at the e-car sharing point, on the power quality parameters in a heavily urbanised area. Therefore, 5 tests were defined, during which power quality measurements were performed. The methodology of such tests was also developed in order to improve their accuracy.

**Description of the electric grid in the studied area**

The Warsaw energy network, due to its metropolitan nature, is characterized by a very high demand for power per unit of area. In densely built-up districts, especially of an office and service character, this density exceeds the value of 12MW / km2. This necessitates the construction of a dense network with a large number of stations and short lines with high capacity. The distances between the stations are small, the average distance between stations outside the city centre is 4 - 5 km, and in the city centre about 1 - 1.5 km. New HV/MV stations are built as indoor ones, with transformers with a capacity range of 25 - 63MVA installed. This allows a significant reduction in the size of the terrain and the volume occupied by the stations

The urban nature of Innogy Stoen Operator`s area of operation, as well as the provisions of local spatial development plans meant that new lines are built as cable. In practice, these requirements apply to all voltage lines. Existing overhead lines can be upgraded leaving their overhead character if this is not the case in conflict with the current local plan (which is increasingly rare) and that is why most overall modernizations are planned as cable lines. Such kind of line - in addition to reducing the size of the area needed and reducing transmission losses - also have an important movement feature. Their bandwidth to a small extent -unlike overhead lines - it depends on the time of year. This is extremely important in today's reality in which the summer peak power is comparable with the powers of winter peaks. Cable lines avoid the resulting problem from a decrease in the line capacity as the ambient temperature increases

Saturation of Warsaw's districts with a cable grid according to fig. no 3 reflects the urban characteristics of the city. Most cable lines are laid in the oldest districts, in the city centre and directly adjacent areas, i.e. Śródmieście, Ochota, Wola, Mokotów, Praga Południe, Żoliborz, Praga Północ, Targówek and Bemowo. The peripheral districts, characterized by younger buildings created in the last thirty years, have a less compact MV cable network. However, these are areas that will continue to develop intensively due to the continuous increase in the number of Warsaw residents. One should also take into account overhead lines, which practically no longer exist in the city centre, however in districts such as Wawer or Białołęka they constitute over a dozen or more percent of the total MV network, and still perform the function of distribution networks. In the near future, systematic cabling of overhead lines is planned, which will contribute to increasing the density of the cable network also in the outskirts of Warsaw

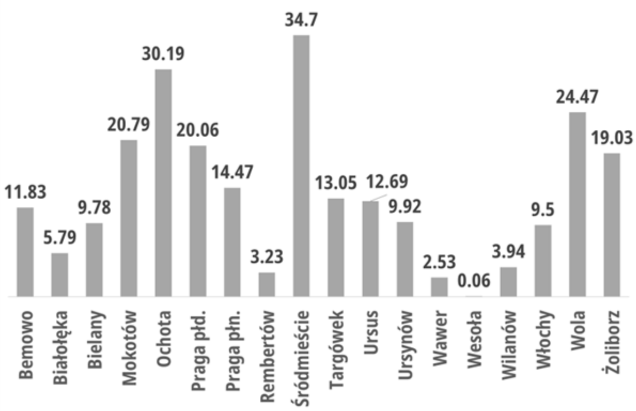


Fig. 3. The degree of MV network cabling in Warsaw area – length of cable lines [km] per 1 km$^2$ of district area

**Methodology of research**

Measurements of the operating parameters of the charging station were carried out on 18.10.2019 at the innogyGO! EVSE located at 3 Eliza Orzeszkowa Street in Warsaw. They were run from 12:21 to 13:56, during which 5 tests were conducted. The object of the tests was a charging station PRE Edward Biel EVB max DC, which parameters are presented in the table 1. The vehicle used during the tests was a standard BMW i3 belonging to the fleet of electric vehicle car sharing company, whose technical data is presented in the table 2. The measurements were recorded using a power analyser Hioki 3198 with an interval of 1 second. The figure 4 shows the timeline with the tests performed.

Table 1. The parameters of PRE Edward Biel max DC charging station

| Parameter | PRE Edward Biel max DC |
|---|---|
| Rated input voltage | 230/400 V |
| Rated insulation voltage | 500/690 V |
| Rated frequency | 50 Hz |
| Surge voltage withstanding | 8 kV |
| DC charging power | 50 kW |
| DC output voltage: | 50 ÷ 500 V DC |
| DC output current: | 0 ÷ 125 A |
| Efficiency of DC systems: | 95% |

Table 2. The technical data of BMW i3 [14]

| Parameter | Technical Data |
|---|---|
| **Type of electric motor** | Synchronous AC |
| Power of the electric motor | 125 kW |
| Battery type | Lithium-ion battery |
| Battery voltage | 360 V |
| Battery capacity | 42 kWh |
| Range | 260 ÷ 280 km |
| Energy consumption | 0,11÷ 0,15 kWh/km |

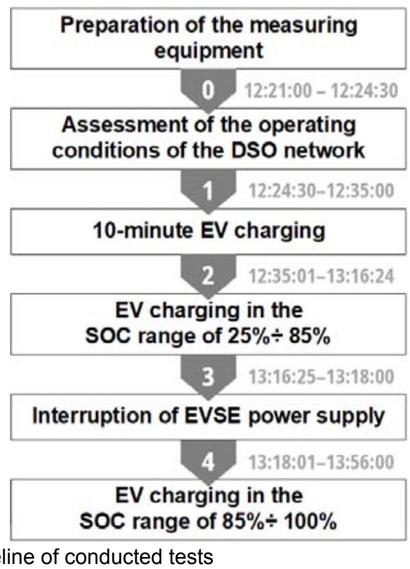


Fig. 4. Timeline of conducted tests

As shown in Fig. 4, the first step was to prepare the measuring station so that the measurements could be made at the output of the charging station on the AC side. The single line diagram of the measurement system is shown in the figure 5. The first test (Test 0) concerned the verification of the conditions of operation of the DSO grid. As a result, a benchmark for further analyses was obtained. During Test 0, the work of the charging station was also checked in the no-load condition and also during the process of synchronization with the vehicle. The next measure performed was Test 1, i.e. 10-minute charging of an electric vehicle. The aim of this research is to check the impact of short charging on the DSO grid, which could represent the charging of EV during short break in travel. The vehicle had a deeply discharged battery, i.e. its State of Charge (SOC) was very low and amounted to 3%. The next test (Test 2) was to perform a regular charging of the electric vehicle, i.e. from the state of SOC = 25% to 85%. This represents a typical charging that can take place while staying at a workplace, shopping mall or P&R parking lot. The electrical parameters of the charging station were then checked for compliance during a sudden power outage (Test 3). In the first part of this test, the power supply was switched off by means of an emergency button and then, after about 2 minutes, the power supply was switched on again. Therefore, it was possible to simulate a situation in which the power lines could be damaged or a sudden loss of voltage could occur, and then the power supply from the DSO was restored. The last test (Test 4) was to check the operating parameters of the charging station when trying to charge the vehicle to its maximum charge before a long journey, i.e. charging it to SOC = 100%. According to the available knowledge, this charging process should be in Constant Voltage (CV) mode, as opposed to 25% to 85% in Constant Current (CC) mode [15].

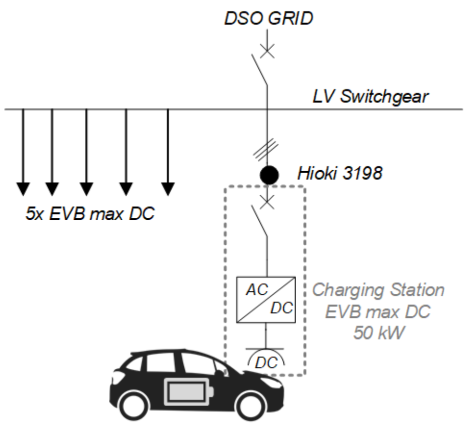


Fig. 5. Single line diagram of LV substation at Orzeszkowa Street

The following parameters were analysed during the tests:

- Active, reactive and apparent power:

(1) $P_{SUM} = \sum_{PH=1}^{3} U_{PH} \cdot I_{PH} \cdot cos\varphi$

(2) $Q_{SUM} = \sum_{PH=1}^{3} P_{PH} \cdot tg\varphi$

(3) $S_{SUM} = \sqrt{P_{SUM}^2 + Q_{SUM}^2}$

- Phase voltages and currents;
- Power factor cosφ;
- Total harmonic distortion of voltage and current

(4) $THD = \frac{\sqrt{\sum_{k=2}^{n} U_k^2}}{U_1}$

- Long-term and short-term flickering nuisance;
- State of charge of EV battery (reading from the on-board computer);

**Results**

The tests were carried out on 18.10.2019 from 12:21:10 to 13:56:08. The BMW i3, with an initial SOC of 3%, was used for the tests. The figure 6 shows the EV charging profile with the SOC level recorded. Based on the fig.6, the registered charging process seems to be typical (Level 2) for a DC fast charging station. The maximum charging power was 33 kW. This means that the charger has a load limit of 66% of the rated power (50 kW). The charging process lasted 1 hour 30 minutes, with about 55% of the time when the battery level (SOC) increased from 3% to 85%. The last charging phase, the so-called constant voltage (CV) charging, took about 40 minutes. At the end, the SOC level was 100%, which means that the EV was fully charged. The second phase is characterized by a decreasing current, and thus charging power, with increasing SOC.

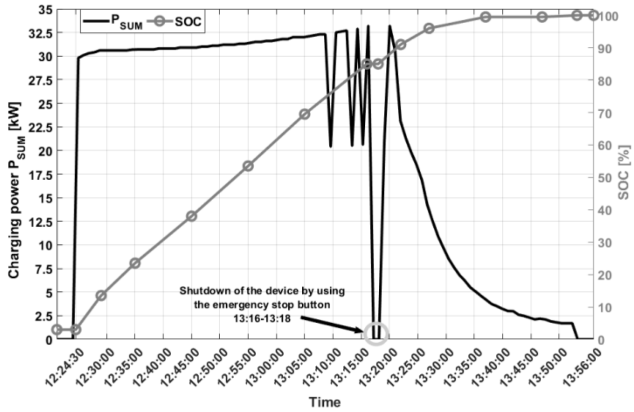


Fig. 6. Measurements of charging power and SOC of EV during whole test

The first part of the research, i.e. Test 0, concerned the study of the operating conditions of the DSO grid, in the case when the EVB max DC charger was working in no-load state. Figure 7 shows selected measurements recorded during the test. As can be seen from the figure 7, the operation of the no-load charger does not interfere with the operation of the power grid. The recorded values of the voltage total harmonic distortion ($THD_U$) slightly exceed 2% (despite recording measurements with 1-second interval). It should be expected that the recorded values of the aforementioned coefficient may come from the distribution network to which 5 EVB max DC chargers have been connected in its immediate vicinity. Due to the proximity of the DSO MV substation, the measured values of the phase voltage are slightly higher than the rated ones.

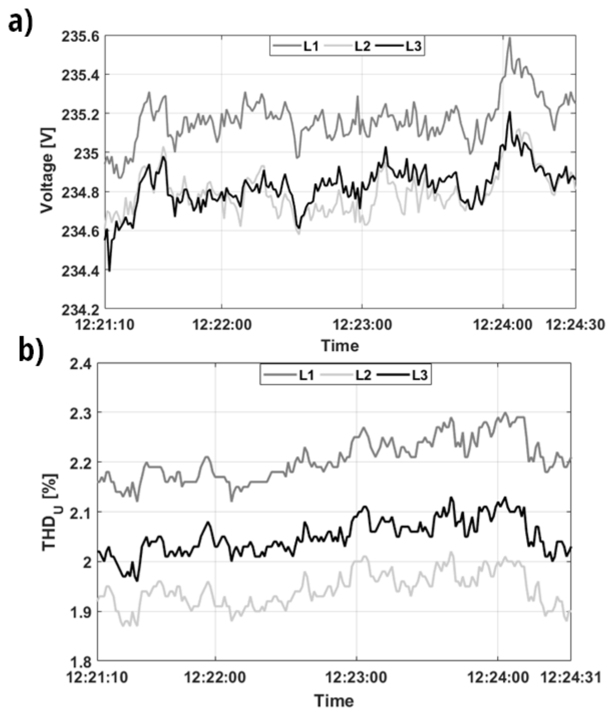


Fig. 7. Test 0 – Measurements of phase voltage (a) and $THD_U$ (b)

The second part of the measurements, i.e. Test 1, concerned the study of the impact of short-term charging on the DSO grid, as well as the observation of the increase in the level of SoC in the EV vehicle. The test lasted 10 minutes and the exemplary measurement values are shown in Figure 8. Based on Fig. 8a it was confirmed that the charger has a capacitive character. During a 30 kW charge, the reactive power generation was a maximum of 8 kVar. This means that the station operated with the power factor within the range of cosφ = 0.96 - 0.99, so in accordance with the applicable polish regulations [16]. Based on Figure 8b, it can be observed that during the 10-minute charging of the EV, the phase voltage limit values were not exceeded (recorded values of 235 V). The $THD_U$ (Fig. 8c) recorded during this test, as well as the harmonic voltage spectrum, allow to state that the limits forced by Polish law were not exceeded [16].

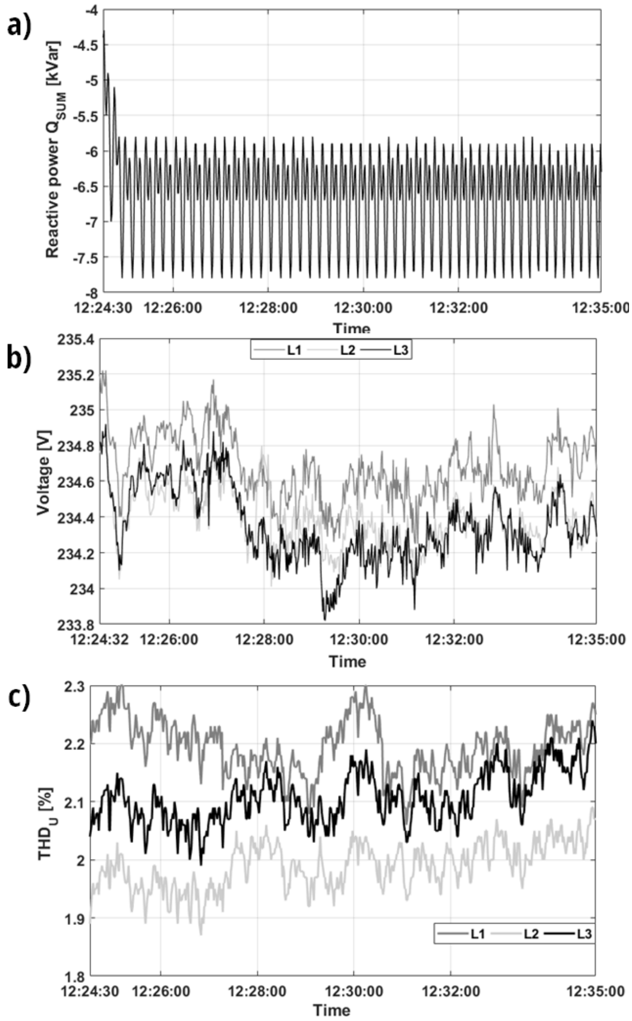

Fig. 8. Test 1 – Measurements of reactive power (a), phase voltage (b) and $THD_U$ (c)

The next part of the test (Test 2) was to perform a typical charging of an electric vehicle from the level of battery charge of SoC = 23.5% to the level of SoC = 85%. The test started at 12:35:01 and lasted till 13:16:00. Chosen measurement values are shown in Fig. 9. Based on Fig. 9a it can be observed that in the period from 13:09 to 13:16 the value of reactive power generation and thus the power factor cosφ slightly decreases (from 8 kVar to 5.5 kVar). However, it can be stated that these are transition states, resulting from the synchronization of the power electronic systems, and the device still maintains the capacitive character of the work. Based on fig. 9b it can be stated that the obtained values of phase voltages during the whole time of Test 2 were at the level of 235 V. These values are similar to those obtained in previous tests. Similar results were also obtained for the voltage total harmonic distortion analysis (Fig. 9c).

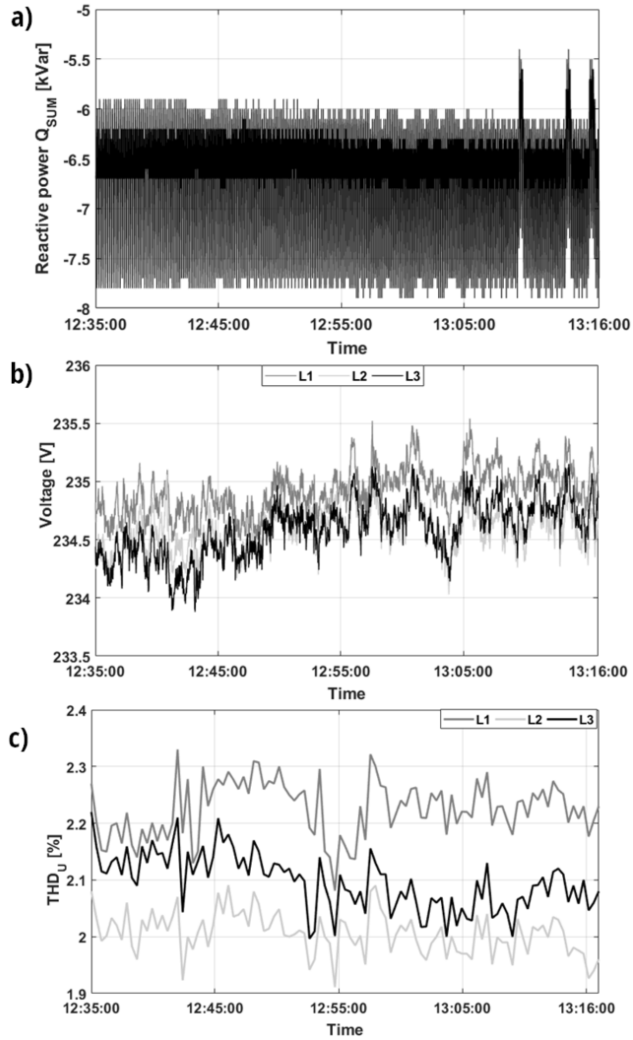

Fig. 9. Test 2 – Measurements of reactive power (a), phase voltage (b) and $THD_U$ (c)

The aim of the next test (Test 3) was to check the impact of a sudden disruption of the charging station's power supply on the occurrence of potential violations of power quality parameters. Test 3 consisted of two parts - switching off the power to the charging station by using the emergency button and then, after a few minutes, re-energizing the power supply. In the case of the first part, the 6-second interval (13:16:22 ÷ 13:16:27), in which the process of switching off the power supply took place, was analysed. The analysed section contains the operating status of the charger just before switching off the voltage (2 sec.), the moment of switching off the voltage, as well as the status after switching off the power supply (3 sec.). In the case of the second part, the 5 second interval (13:17:55 ÷ 13:17:59), during which the power supply to the charging station was restored, was analysed. Fig. 10 shows the Total harmonic distortion of voltage and current during switching off and on the charging station. In Fig. 10a it can be read that during the dynamic state voltage disturbances occurred (introduction of higher harmonics). Interestingly, the phenomenon was recorded only for phase L3. Probably the recorded disturbances could have originated from the devices of the charging station's auxiliaries. During the analysis of the current total harmonic distortion ($THD_I$) (Fig. 10b), values of several hundred percent were observed. This is probably a transitional state of gradually disconnected power electronic devices. As in the case of part 1 of Test 3, high values of the $THD_I$ factor were observed (Fig. 10d). $THD_U$ values do not exceed the limit values (Fig. 10c), i.e. they are within the ranges defined in the EN 50160 Standard [17]. It should be noted that the existing regulations refer only to 10-minute measurements, and the conducted measurement were recorded with a 1-second interval.

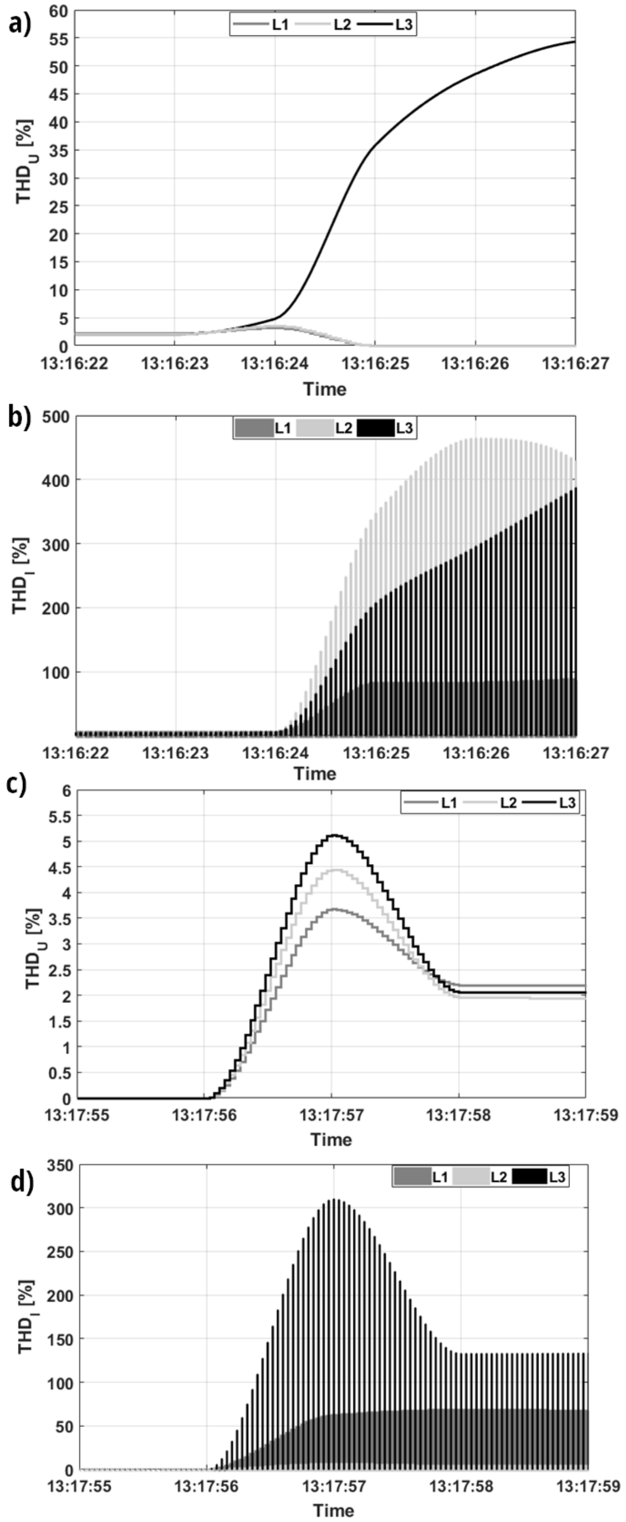


Fig. 10. Test 3 – Measurements of $THD_U$ during switch off (a), $THD_I$ during switch off (b), $THD_U$ during switch on (c) and $THD_I$ during switch on (d)

The last test carried out (Test 4) involved charging the EV vehicle to reach the battery charge level, according to the readings from the on-board computer, SOC= 100%. Test 4 was performed from 13:18:00 to 13:56:08. The measurements were started when the BMW i3 on-board computer showed SOC= 85%. Fig. 11 shows the selected parameters recorded during Test 4.

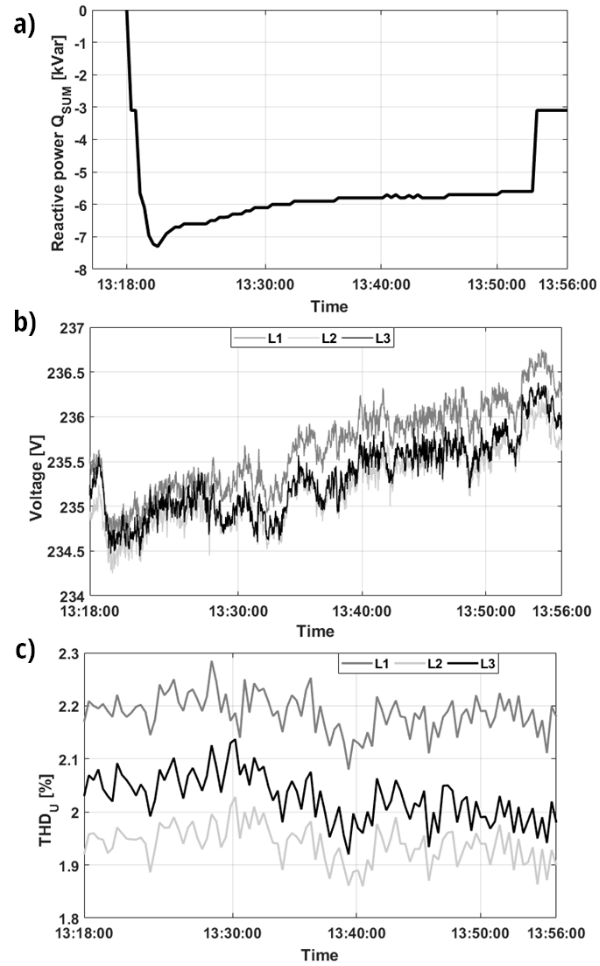


Fig. 11. Test 4 – Measurements of reactive power (a), phase voltage (b) and $THD_U$ (c)

Figures 6 and 11a show that the EV charging in Test 4 is done mostly in constant voltage mode (CV). A significant decrease in the charging power was observed in the last phase of the test when the SOC reaches about 90% (according to the on-board computer). This is close to 80% of the rated capacity of the battery, which would confirm the change in the charging mode - from constant current (CC) to Constant voltage (CV). Moreover, it should be noted that the process of charging from the level of SOC = 90% to the level of SOC = 100% took more than 30 minutes. This confirms the theoretical assumptions of the charging mode of lithium-ion batteries in constant voltage (CV) mode [15]. Based on Fig. 11a, it can be observed that during battery charging, the charging power consumption is gradually reduced with a constant level of reactive power. As a result, the power factor while charging the battery to the maximum level gradually decreased. After 13 minutes of charging it was only $\cos\varphi = -0.8$, after 27 minutes $\cos\varphi = -0.4$, to reach $\cos\varphi \approx -0.25$ at the end of charging, after 35 minutes from the beginning of the test. The values of phase voltages during the reduction of the charging power increase from 235 V to 236.5 V (Fig. 11b). The $THD_U$ values for all three phases oscillate around 2% (Fig. 11c).

## Conclusion and discussion

The paper presents the results of measurements in operational conditions of the fast charging station of electric vehicles operating in the collecting point of electric vehicles car sharing company - innogyGO! Based on them it can be stated that there were no significant violations of the limit values in the field of power quality parameters. The values of phase voltages as well as the $THD_U$ factor did not differ from those in the EN 50160 standard. From the obtained measurement results it can be noticed that the control of the $THD_I$ factor, especially in dynamic states, will be a big concern. The measurements confirmed that EVs are being charged according to theoretical assumptions, which will allow easier planning of network traffic through DSOs. Nevertheless, the process of implementing electromobility in the municipal power grid is a huge challenge for the Distribution System Operators.

The inclusion of vehicle charging systems in the distribution grid and ensuring continuity of supply to customers also imposes on distribution system operators a number of new challenges related to the expansion of the network as well as providing consumers with energy supplies in a continuous manner and with appropriate parameters. Another task for the DSO resulting from the implementation of vehicle charging stations in the low voltage grid is the need for dynamic reconfiguration of the power network. Making the right switching decisions requires the use of Smart Grid technology, including the collection of remotely transmitted data and their analysis

The dynamic development of vehicle charging systems will not be possible without progress in the construction of charging stations adapted for two-way energy flow, but also will not be possible without changing the habits of electric vehicle users and changes in legislation correlated with this phenomenon.

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