Analysis of the potential use of lithium-ion energy storage in the home charging station for electric cars

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Abstract. The article deals with the problems related to the storage of electric energy in electric vehicle charging stations based on the example of a home vehicle charging station working in conjunction with the photovoltaic installation. The presented issues include the characteristic features of the vehicle charging stations, the issue of conversion of solar energy into electric energy and the methodology of determination of the energy which can be obtained from photovoltaic installations. Furthermore, methods of modelling of the lithium-ion cell operation are discussed taking into consideration their life, and also the exemplary simulation of behaviour of the electrochemical energy storage working in conjunction with the electric vehicle charging station and photovoltaic installation is presented. The conclusions draw attention to the aspect of life of the energy storages in relation to the viability of their use as energy storages for the electric vehicle charging stations working with renewable energy sources (RES).

1. Introduction

All technical solutions regarding the supply and use of energy are related to the optimal use of raw materials and energy [1-4]. In the aspect of electric energy storage for the needs related to the electromobility, the energy storages such as electrochemical batteries based on lithium enjoy the greatest popularity. At present, they are used in almost all spheres of everyday life. In particular, they are popular in mobile solutions (e.g. to supply laptops, mobile phones and electric vehicles). Because of their properties, the lithium-ion cells are the subject of many research papers all over the world. The papers, for the most part, focus on the development of the cell model that enables the accurate analysis of its operation in different applications.

The paper [5] presents the model of a lithium-ion battery, which allows for analysis of its behaviour for different charge and discharge currents. The cell circuit model was used and the equivalent circuit parameters were dependent on the battery state of charge and temperature. The proposed model, however, does not take into account the self-discharge phenomenon and the capacity fade process. Du et. al. [6] took up the task of development of the model for prediction of the life of the lithium-ion cell as a function of temperature, charge current rate and the final cut-off voltage of the cell. The effect of the respective factors on the speed of capacity fade was determined. The model allows for the estimation of the cell capacity only for shallow discharges —between 20% and 30% depth of discharge (DOD) within the temperature range between 25°C and 35°C. On the other hand
papers [7-8] analysed, among other things, the process of internal resistance increase as the cell wear rate.

2. General characteristics of electric vehicle charging stations

In order to supply energy to electric vehicles, charging stations which must meet a number of standards (depending on the selected technology), developed by the International Electrotechnical Commission (IEC), International Organization for Standardization (ISO) and Society of Automotive Engineers (SAE) are used. The standards, as well as the safety aspects, refer to the type of voltage (AC or DC), power (from a few to several hundred kW), communication protocols (between the charging station and the vehicle, and sometimes also between the charging station and the power grid), and type of connectors. In the simplest solutions, this is necessary for safety reasons related to both the vehicle users and the energy storages. In more advanced solutions, the communication protocols allow for the queuing of the charging for the optimal loading of the power grid, or even for the rescuing of the grid in the situations of the overload, by returning the energy from the vehicle to the grid [9].

In many countries the electric vehicle charging stations with the power output exceeding 100 kW, e.g. Tesla superchargers, already exist. The global number of such stations reaches almost one thousand (according to the information given by the Tesla company, at present there are 6118 chargers all over the world located at 909 stations) [10]. They allow for the replenishment of energy with direct current in a short time (several dozens of minutes), but require special power connections and are very costly. For this reason, the low power charging stations (below 20 kW), which provide power supply to a vehicle with alternating current can be found more frequently. Such circuits are particularly popular in home solutions (often with the power output of few kW).

Electric vehicles are not, however, a fully ecological solution, when the energy is produced at coal-fired power plants, as is the case with Poland in about 95%. This problem can be solved by charging the electric vehicles by means of RES. However, they are characterised by high variability of generation. Furthermore, the more and more popular photovoltaic installations generate energy during the day while the majority of drivers – as they use the vehicle during the day – would prefer to charge the vehicle at night.

The solution for this problem involves the electric energy storage systems. There are many various technologies in the world, which are used for energy accumulation for this purpose, and the most popular ones are the storages which belong to the group of electrochemical storages (batteries). They are distinguished by the sufficiently high density of power and energy, but the respective battery types are characterised by varied life, vulnerability to environmental conditions, impact of the depth of discharge on life and price. From among the numerous groups of batteries, the ones which are used most frequently in e-mobility solutions are lithium batteries [9,11].

3. Determination of electric energy from photovoltaic installations

Solar energy which reaches the Earth in the form of electromagnetic radiation exceeds the people’s energy demand thousands of times. The average annual value of this radiation (the so called solar constant) amounts to 1361 W/m², however, the instantaneous value of power that reaches the given ground surface depends on the season of the year, the geographic location and the current cloud cover. In the geographic latitude of Poland (52° N), the average annual sunshine amounts to about 1400 kWh/m², but in Poland its value is close to 1000 kWh/m². Nevertheless this value is large enough to regard the application of photovoltaic installations as the effective method of electric energy generation [12,13].

The solar radiation which reaches the ground surface is often diffused, therefore, not only does it contain the component that falls directly from the Sun, but also the reflected one. The direct component on a sunny (cloudless) day can be determined unambiguously with high accuracy, but the reflected component coming, for instance, from clouds depends on many factors. What is more, the reflected component, depending on the weather, often constitutes a significant component of radiation that reaches the analysed surface – in Poland, on average, it amounts to about 50%. One of the
Methods to determine the solar radiation density is the relationship developed by Benjamin Liu and Richard Jordan, according to which the total density of solar radiation which reaches the surface inclined at angle $\beta$ is determined from the following relationship [12]:

$$
G_\beta = G_d \frac{\cos(\phi - \beta) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(\phi - \beta) \cdot \sin(\delta)}{\cos(\phi) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(\phi) \cdot \sin(\delta)} + G_f \frac{1 + \cos(\beta)}{2} + (G_d + G_f) \cdot \rho \cdot \frac{1 - \cos(\beta)}{2}
$$

(1)

where: $G_d$ – direct solar radiation [W/m²], $G_f$ – diffused solar radiation [W/m²], $\phi$ – latitude angle [°], $\delta$ – declination angle [°], $\omega$ – hour angle [°/s], $\rho$ – reflectance factor [-].

While determining the amount of electric energy which the photovoltaic installation is able to generate, it is possible to use measurements of irradiance, which have been performed in the recent years by many research centres in different locations all over the world. When the solar radiation values are known, the photovoltaic installation is modelled using the equivalent circuits such as [14] - Figure 1.

The elements of the equivalent circuit represent the resistance of connections, base and layers of the cell ($R_s$) as well as the defects of the structure of the crystal ($R_p$) – reflects the leakage conductance along the edge of the cell and the grain boundaries, and diode (D) is related to the dark saturation current. It must also be remembered that the receiver is connected with the circuit through the MPPT (DC-DC converter tracking the maximum power point), which optimizes its resistance in such a way as to maximise the power emitted in the receiver. For such a circuit, the current drawn by the photovoltaic panel is determined from the following relationship [14]:

$$
I_{pv} = I_{ph} - I_0 \left[ \exp \left( \frac{V_{pv} + I_{pv}R_S}{aN_CV_{th}} \right) - 1 \right] - \frac{V_{pv} + I_{pv}R_S}{R_p}
$$

(2)

where: $R_s$ – series resistance [Ω], $R_p$ – parallel resistance[Ω], $V_{pv}$ – module voltage[V], $I_{pv}$ – module current [A], $a$ – diode ideality factor [-], $N_C$ – number of cells in module [-], $V_{th}$ – thermal voltage [V], $I_0$ – diode reverse saturation current [A], $I_{ph}$ – photocurrent [A].
4. Model of the lithium-ion cell

4.1. Modelling of the cell behaviour

The performance of the lithium-ion cell is a dynamic process, which, in particular, strongly depends on the ambient temperature and the load conditions – the values of the charging and discharging process parameters – as well as on the current state of health. So far, many different models which map the operation of the energy storages have been developed [15]. The highest accuracy is attributed to the electrochemical models. They describe the phenomena which take place on electrodes, in the area of the double layer and in the electrolyte by means of complex partial differential equations, which makes them laborious to implement and very time-consuming. Therefore, circuit models are often used. Chemical processes, which take place in the electrochemical cells may be modelled by means of electric circuits which containing RLC elements (equivalent circuits). They constitute a compromise between the simplicity of implementation and the accuracy. The lithium-ion cells may be modelled by means of different equivalent circuits, and the one which is used most often is presented in Figure 2.

Electromotive force $E_m$ of the cell reflects the voltage between the cell electrodes in the no-load state. Inductance $L$ occurs as a result of the galvanic connection of terminals with electrodes and its impact on the operating parameters in the majority of cases is negligibly small. Resistance $R_0$ constitutes the sum of resistances of the electrolyte, electrodes and resistance of contacts. The serially connected RC branches map the chemical processes which occur during the operation of the cell. The modelled electrochemical phenomena include reactions which occur in the area of the electrodes and the double layer, as well as the reactions of aside from electrode diffusions that take place in the electrolyte. The accuracy of the cell model is affected by the number of RC branches and the dependence of the equivalent circuit parameters on the ambient temperature, the current state of charge (SOC) and the wear of the cell.

The estimation of the parameters of the lithium-ion cell model may be performed in a different ways, e.g. based on the voltage response to the discharge with a specific current, or using the electrochemical impedance spectroscopy [16]. Based on measurements performed in this way, the values of parameters can be approximated by using the empirical functions that describe the process of changes depending on the SOC, temperature and current rate, or by registering the determined parameters in the so called lookup-tables. The details of the procedure for the determination of the value of model parameters are described in papers [17-19].

4.2. Modelling the cell life

The issue of life modelling is particularly complicated as it is necessary to consider many chemical processes such as e.g.: solid electrolyte interface film growth, loss of electrode active mass, electrolyte...
loss or electrode corrosion [7, 20]. On top of this, these processes may not be analysed separately, as they occur at the same time and their speed depends on several factors. In order to simplify the analyses, the most dominant factors are generally considered, that is: the current state of health of the cell, the ambient temperature and the parameters of cell cycling (the maximum values of currents, the limit values of voltages and the number of charge-discharge cycles). The development of the accurate cell life model requires the performance of at least several hundred experimental measurements. In normal conditions, the full aging tests would last at least a couple of years, therefore, the cells are often tested in conditions which cause their accelerated aging.

The analysed parameters which determine the degree of wear of the cell depending on the area of application of the model can include: useful capacity, number of cycles, internal resistance, ability to accumulate load or operation time. The model which allows for the estimation of the number of performed full equivalent cycles and the useful capacity as the function of the depth of discharge, temperature, and degree of load was developed on the basis of the work by Omar et. al. [21]. In this model the impact of cycling on the useful capacity of the cell is described by the following relationship:

$$Q(n) = Q_{BOL} - \varepsilon(n) \cdot (Q_{BOL} - Q_{EOL})$$

where: $n$ – cycle number, $Q_{BOL}$ – capacity at begin of life (new cell) [Ah], $\varepsilon$ – aging factor [-], $Q_{EOL}$ – capacity at end of life cell [Ah].

Cell aging factor $\varepsilon(n)$ is determined according to the following formula:

$$\varepsilon(n) = \varepsilon(n-1) + \frac{0.5}{N(n-1)} \left(2 - \frac{DOD(n-2) + DOD(n)}{DOD(n-1)}\right)$$

where: DOD – depth of discharge of cell [-], $N$ – maximum number of cycles [-].

On the other hand, the maximum number of cycles can be calculated from the following equation:

$$N(n) = H \left(\frac{DOD(n)}{100}\right)^{-z_1} \exp\left(-\psi\left(\frac{1}{T_{ref}} - \frac{1}{T_a(n)}\right)\right) \left(I_{d_{avg}}(n)\right)^{\gamma_1} \left(I_{ch_{avg}}(n)\right)^{\gamma_2}$$

where: $H$ – cycle number constant [-], $z_1$ – constant related to DOD [-], $\psi$ – Arrhenius rate for cycle number [-], $I_{d_{avg}}$ – average discharge current in half-cycle duration [A], $I_{ch_{avg}}$ – average charge current in half-cycle duration [A], $\gamma_1$ – constant related to discharge current [-], $\gamma_2$ – constant related to charge current [-], $T_{ref}$– nominal temperature [°C], $T_a$– ambient temperature [°C] (exemplary values of constants can be found in publication [22]).

5. Simulation of the operation of the lithium-ion energy storage

For the needs of analysis of potential use of the lithium-ion storage in a home electric vehicle charging station, a simulation was conducted making the following assumptions:

- the energy storage under consideration is charged during the day from the home photovoltaic installation with the rated output of 10 kW, and at night it powers the batteries of the electric vehicle whose daily demand is assumed to reach the level of 15 kWh (an assumption is made that the vehicle covers a distance of about 100 km/day),
- the capacity of the energy storage is twice as high as the energy demand – an assumption is made that it is built of 3200 lithium-nickel-manganese-cobalt (32 strings that consist of 100 serially
connected cells) cells with the rated capacity of 2.6 Ah and rated voltage of 3.65 V (in total 83 Ah, 365 V),
– during the simulation, the energy storage operates at a constant ambient temperature – close to the
rated value,
– the phenomenon of cell self-discharge and the phenomena related to the memory effect are omitted.

5.1. Determination of the cell model parameters
The model with one RC branch, resistor $R_0$ and DC source $E_m$ has been selected as the equivalent
circuit of the cell, which constitutes the energy storage of the home electric vehicle charging station.
Because of the negligible inductance values, a decision was taken to leave out this model. In order to
determine the tables of parameter values for the model, the full partial discharge was performed with
direct current amounting to 2C with 4% SOC step. The obtained voltage response for the new cell was
presented in Figure 3 and Figure 4 (discharge time during each stage was 70 s, while cell relaxation
time was 120 s).

![Figure 3. Voltage characteristics of the cell versus time.](image1)

![Figure 4. Detailed view of the discharge stage.](image2)

In order to evaluate the impact of the wear of the cell on the model parameters, the aging tests were
performed and the measuring procedure was repeated after 500 and 800 full charge-discharge cycles.
The obtained results are presented in Figure 5.
Figure 5. Tables of values of parameters $C_1$ (a), $R_1$ (b), $E_m$ (c), $R_0$ (d) of equivalent circuit versus SOC and number of cycles.

As a consequence of the conducted test, the following results are obtained, such as in the Table 1.

Table 1. Parameters of the cell aging test.

| Parameter                        | Value (Ah) |
|----------------------------------|------------|
| Capacity at begin of life ($Q_{BOL}$) | 2.584      |
| Capacity at end of life ($Q_{EOL}$)  | 1.785      |

The verification of the correctness of the model was carried out for three values of the discharge current: 0.23C, 0.5C and 3C. The results of the verification are presented in Figure 6, and the results of calculations of the model inaccuracy are listed in Table 2.
Figure 6. Results of verification of the lithium-ion cell model.

Table 2. Average relative error of the model for the respective discharge currents.

| Discharge current (A) | Error (%) |
|-----------------------|-----------|
| 0.6                   | 2.11      |
| 1.3                   | 0.31      |
| 7.8                   | 0.93      |

5.2. Analysis of use of the battery at the home charging station working in conjunction with the PV

In the following parts of the paper, an application implemented in the Matlab Simulink environment was prepared. The application served the purpose of modelling of the electric vehicle charging station provided with a lithium-ion battery that stores the electric energy generated by photovoltaic panels. The diagram of the model is presented in Figure 7. The analysis focuses on the behaviour of the battery, in particular, its load, state of charge and wear.

Annual irradiance measurements were used in the simulation for the climatic conditions in Poland for the year 2013, registered every 36 seconds (Figure 8). The measurements were performed by Mr. Krzysztof Markowicz from the Faculty of Geophysics at the Warsaw University (station situated in the vicinity of Rzeszów). Owing to the data regarding the irradiance value, the power generated by photovoltaic panels and the power per single battery cell were both determined (Figure 9). Then – by using the standard methods of analysis of transient states – the current flowing through a single cell was calculated (Figure 10). This constituted the basis for the calculation of the battery state of charge (Figure 11).
In order to estimate the degree of wear of the analysed energy storage, the aging model described in section 4.2 was used. The multi-year simulation of the cell cycling was carried out. The results are presented in Figures. 12-13. During the period under consideration (3 years) the cell performed 720 equivalent operating cycles (Figure 12). After 2.5 years the useful capacity of the cell reached the assumed wear rate equal to 75% of the rated capacity (Figure 13).
6. Conclusion
The article deals with the aspects related to the modelling of operation of a lithium-ion energy storage and the potential for its use in electric vehicle charging stations. The modelling of this type of energy storages requires the consideration of numerous correlations between the model parameters – the load conditions and the ambient temperature have a decisive impact on the obtained cell parameters (especially the state of charge and degree of wear). The aspect of life of the cell is often the key factor in economic analyses and during the decision-making process regarding the selection of a given solution.

The performed simulation enabled the conducted of the analysis for potential use of the selected lithium-ion electric energy storage during a period of three years. What follows from the conducted analysis is that the photovoltaic installation with the rated output of 10 kW is able to deliver the sufficient quantity of energy for a significant part of the year to charge an electric vehicle with the assumed daily demand at the level of 15 kWh, and that the state of charge of the lithium-ion energy storage located in the vehicle charging station, rarely falls below 50% even on January days of the year under consideration.

The subject of analysis in this paper was also the degree of wear of the modelled energy storage. An estimation was made that the storage would achieve the wear at the level of 75% after 578 equivalent full charge-discharge cycles, which would take place after an expiry of about 2.5 years of everyday use of the battery. On this basis, it is possible to evaluate the viability of use of lithium-ion batteries in electric poles. The price of such batteries is going down year after year and amounts to about 700 PLN/kW (i.e. PLN 21 000 for the storage presented in the paper). Assuming that the cost of electric energy amounts to 0.6 PLN/kWh, the application of the solution presented in the paper would bring savings at the level of 3 300 PLN/year, but the replacement of batteries every 2.5 years translates into average annual costs which amount to about PLN 8400. This proves that – from the economic point of view – the application of the energy storage in the form of lithium-ion batteries in the home electric vehicle charging station is not viable at present, even if costs of the photovoltaic installation are excluded. However, it is worth remembering about ecological aspects, whose significance becomes more and more important for people, and also about the fact that the scientists who specialise in batteries predict that their price will go down several times in the upcoming years while their life will become longer.

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