Grid Supporting Operation of Lithium-Ion Battery Storage Systems for Grid-Connected Photovoltaic Systems

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***Abstract* — The number of grid connected lithium-ion based battery storage systems (Li-BSS) is steadily increasing. Most of these systems are coupled with distributed renewable energy sources like photovoltaic to maximize the self-consumption. This paper deals with the possibility to additionally use Li-BSS for tasks like stabilizing the low-voltage grid by providing ancillary services and limit power flow peaks in the distribution grid caused by photovoltaic power generation.**

(Keywords: Lithium-Ion battery storage systems; Control reserve; ancillary services; photovoltaic systems)

I. INTRODUCTION

With the ongoing expansion of renewable energies there is also an increased interest in storage systems and how to operate them in a grid supportive way. Especially with the rising share of power generation from photovoltaic systems the low-voltage grid might face overloading situations which could lead to shortages in supply [1]. One way of preventing that is the integration of lithium-ion battery systems in the distribution grid. This paper mainly focuses on two tasks those systems could fulfill and evaluates possible problems in the process. These tasks are the peak shaving by limiting the maximum feed-in power at peak times and thus avoiding the overloading of electrical equipment and the delivery of ancillary services for the low-voltage grid. Finally, the impact of Li-BSS on self-consumption of electrical energy will be explained before stating operation strategies.

II. LITHIUM-ION BASED BATTERY SYSTEMS

Before outlining ancillary services and operating strategies for storage systems, this chapter presents a short introduction to lithium-ion based battery systems and why they are the most promising type of battery system at the moment for grid-connected photovoltaic systems.

The positive electrode consists of a lithium metal oxide or phosphate while the negative electrode is made of carbon or graphite. They are separated by the eponymous dissolved lithium salts and an organic fluid solvent together forming the electrolyte. The ions are intercalated between the layers of the cathode material instead of being chemically bound which results in a higher reversibility [2]. A scheme of the typical set-up is given in Fig. 1. As they can be composed by various cathode and anode materials, there is still a lot of room for research to improve the battery characteristics. Those include improvements in specific energy, power, safety and reliability and cost reduction. The most important area for widespread application is the cost reduction while providing an acceptable life cycle and good operational safety. They generally have a low internal resistance giving the possibility of fast discharge rates.

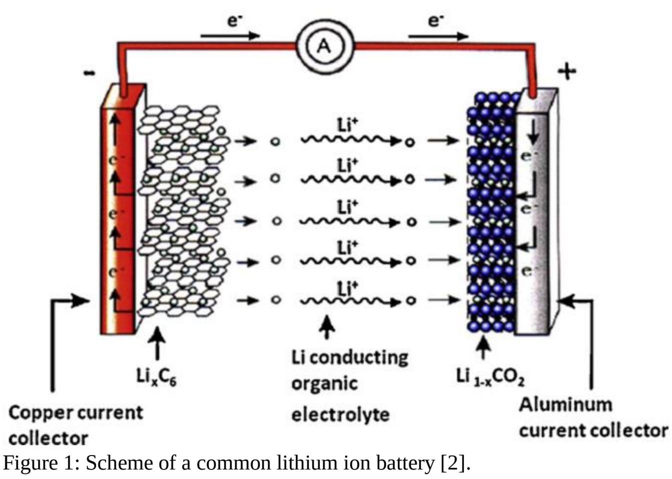

Figure 1: Scheme of a common lithium ion battery [2].

The disadvantages of Li-BSS include the currently high price and their need for a precise battery management system (BMS) to avoid fire hazards by faulty operation. They are sensible to overcharge and over discharging. Overcharging can lead to metallic lithium plating on the anode. This reduces cycling efficiency and raises safety concerns due to the possibility of internal short circuiting caused by the formation of dendritic lithium [3]. Over discharging a lithium-ion cell can lead to irreversible capacity losses and thermal stability changes, which might be not tolerable in abuse conditions [4]. The main advantages of lithium based batteries is the high energy density and high number of achievable life cycles. Compared to lead acid batteries they also don't form hazardous gases during operation and can be operated in closed rooms with fewer needs for ventilation. Lead acid batteries tend to produce H_2 when overcharged or malfunctioning. The battery system is also modular. They can either be connected in series to increase the system voltage or in parallel to improve the maximum current output.

As the lithium battery technology is also heavily being researched by the automotive industry and industrial mass production improvements in price per kilowatt hour is expected to decrease to as low as 200 Euro around the year 2026. This makes lithium based battery systems on a pure price level competitive to lead acid batteries. There is a difference between the mobile batteries used in electric vehicles and the ones used for stationary purposes. The quality of cells in the automotive industry is needed to be higher than for stationary use. Cells for electric vehicles (EV) are primarily designed for high energy/power density and high charge/discharge rates. For stationary use a lack in these qualities can be compensated by quantity. Through heavy cost reduction by mass production for EV these cells might also be used in stationary applications. The double cost for development work can be cancelled as well [1].

The other key components of a BSS consist of the PV-Array, the MPP-Tracker, a charge controller for the batteries and a power inverter. It is differentiated between an AC-coupled topology and a DC-coupled topology. In AC-coupled systems there is an inverter to convert the direct current from the PV-Array to the alternating current of the low-voltage grid. If the total nominal output power is below 4,6 kVA it can be connected as via single phase and if the nominal power is higher it is symmetrically connected to all three phases. To charge the batteries through the charge controller the AC is then converted back to DC by the battery inverter. For the DC-coupled system the battery system is directly coupled to the DC current from the PV-Array. Only the voltage must be converted before charging the battery cells. These schemes are illustrated in Fig. 2. General statements on which topology is more energy efficient cannot be made as not the number of conversion stages is decisive for the total efficiency but the efficiency of every single component [5].

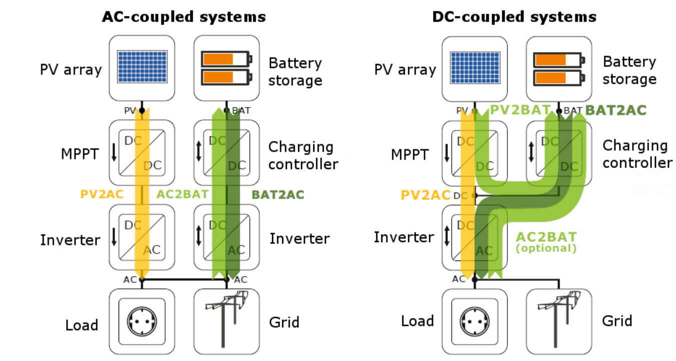

Figure 2: Scheme of an AC-coupled and DC-coupled system [5].

III. BENEFITS FOR THE GRID

A. Reducing the feed-in power

By integrating many photovoltaic systems in the distribution grid problems concerning voltage stability and overloading of electrical equipment must be considered. To feed power into the distribution grid, the inverter must have a slightly higher voltage level than the grid. High PV feed-in can lead to an illicit high voltage boost. In Germany, the power production of photovoltaic systems will soon - on sunny days - exceed the entire demand for electricity [6]. Different expansion scenarios are represented in Fig. 3. To operate the grid safely, an unrestricted input from PV-systems can no longer take place. The grid could be relieved by adding decentralized storage systems. If those are managed accordingly and part of the generated power is stored, peaks can be reduced and the overall load curve is smoothed. Through peak shaving it is possible to install more producers in an existing grid without expanding the network.

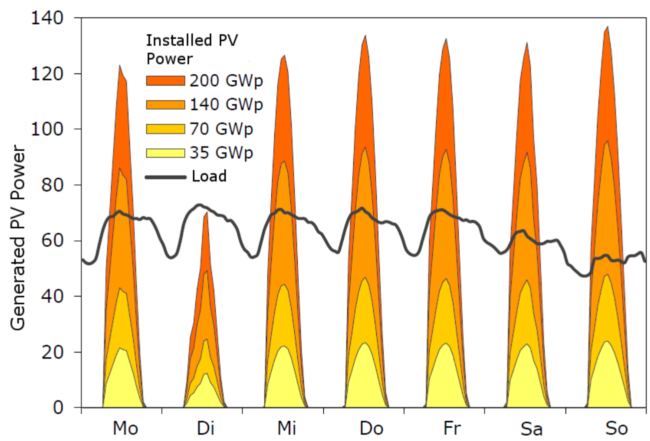

Figure 3: Power demand and possible PV production in a week in April [7].

There are different operating strategies regarding how to use the stored electricity which are further explained in chapter 4. Network operators favor the application in reducing the feed-in power while the appeal for households is the increase in self-consumption and subsequently lowering the electricity purchases [7].

B. *Delivery of ancillary services*

Apart from Peak Shaving storage systems can furthermore be used in the delivery of ancillary services. Those are all services fulfilled by grid operators besides the transmission and distribution of electricity to maintain operational security. Some can be fulfilled by decentralized storage systems. Among others they include blackstart recovery, voltage support, frequency control, reactive power and control reserves. Control reserves are subdivided in Primary Control Reserve (FCR), Secondary Control Reserve (FRR) and Tertiary Control Reserve (FRR&RR). FCR needs to be available within 30 seconds and last for 15 minutes while the FRR and FRR&RR must be available in 5 to 15 minutes and last up to 60 minutes. Li-BSS are particularly suited for application in providing the FCR. They have high discharge rates and require no start-up time.

Most Li-BSS in households have a capacity lower than 10 kWh and cannot impact the grid taken individually. But they can participate in the electricity balancing market if pooled together to a certain size and coordinated accordingly. One of the services is frequency control. To guarantee a stable frequency of around 50 Hz in the grid, supply and demand must always be the same. The system frequency is elevated if more electricity is generated than demanded and decreased if more is demanded than supplied. Battery systems can actively influence the system frequency by controlled charging and discharging of the batteries. The demand can be increased by charging the cells and the supply can be decreased by discharging them. This can be easily implemented without the need for external communication abilities from the storage system, as the control directly reacts to system frequency. This is called droop control and uses the dependency of the active power to the frequency to influence the frequency of the grid. A drop in the frequency can be counteracted by increasing the feed-in power from the inverter while reducing the feed-in power can lower the frequency.

The other possible task is voltage control. The voltage range in distribution and transmission grids must always be within the limits given in DIN EN 50160. The voltage range in the low-voltage grid allow for slow deviations of up to 10 % of the nominal voltage and 5 % for fast changes. Voltage range deviations because of PV feed in are becoming a more occurring problem in rural areas with long line length. Measures for voltage control include the supply and adsorption of reactive power which can be delivered by PV storage systems. For instance, the standing reserve can be provided by renewables or storage systems. The standing reserve is a capacity which can be used to increase the power generation. It is not synced with the grid, but can be connected. The standing reserve is not a real application, but a method to provide operational reserve. A lot of electrical equipment in the grid is not able to restart by themselves after a system error. The required energy for that black start capability can be provided by energy storages [1].

Caterva GmbH is among the first to successfully implement a decentralized Li-BSS for providing FCR. Within the research project SWARM 65 Li-BSS, each with 18 kWh net capacity, are installed in residential houses owning a roof-top PV system. On the one hand, these BSS increase the household's internal consumption. On the other hand, all the individual systems are interconnected to a virtual mass that can offer 1 MW FCR power and is operated by a central control algorithm. This virtual mass storage is located in the distribution grid of *TenneT TSO GmbH* [8].

IV. OPERATING STRATEGIES

Li-BSS can be operated differently depending on the favored use either for the producers or the distribution grid. The most economic operation strategy for plant owners is a strategy to maximize their self-consumption. To achieve this a surplus of the electric energy produced by the photovoltaic array is stored in the batteries. If the radiation conditions are good the storage might be fully charged before hitting the lunchtime peak. This would contradict the goal of grid supporting operation as the maximal feed-in power would not be reduced and on overloading of electrical equipment could not be avoided. But storage systems can also be operated to specifically charge during peak hours.

A. *Maximizing the self-consumption*

In this strategy, surplus energy is stored in the batteries to improve the self-consumption. If the storage is full, the power generated after gets fed into the grid. A scheme for that is illustrated in Fig. 4.

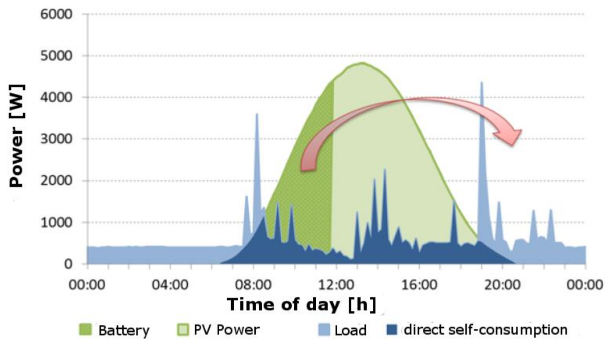

Figure 4: Operation strategy for maximizing the in-house consumption [1].

Different radiation conditions result in different load and production curves. On a sunny day for example, a lot of the electricity generated is fed into the grid whereas on a cloudy day all of it is either directly consumed or stored in the batteries. As well as the radiation conditions and load influence the feed-in power the size of the PV storage system is also important. The proportion of in-house consumption is the sum of the directly consumed electricity and the electricity consumed which has been stored in the battery system. For a system with 1 kWh of installed battery capacity for 1 kW of installed PV power this proportion is about 60%. For the same system without the storage the proportion would only be around 30%. Studies suggest, that for higher ratios in either direction the degree of self-sufficiency can only be marginally increased [7].

So far this is the only economically interesting operating strategy as there is not enough compensation for providing ancillary services yet. They can take part in the energy balancing market but do not qualify for payments under the EEG. Batterie storage systems take in power from the grid for providing negative FCR. Therefore, it cannot be verified that they only feed in electricity from purely renewable energies back into the grid when providing positive FCR. But this verification is a requirement for receiving payments under the EEG. Providing positive Primary Control Reserve disqualifies BSS for compensation under the EEG [9].

This operation strategy is easy to implement as it requires no external communication.

B. *Constant limitation of feed-in power*

Another operating strategy to reduce the influence of PV systems on the grid is to restrict the feed-in power to a certain level. For example, if the generated electricity is above 50% of the installed power as displayed in Fig. 5, the excess is used to charge the batteries. This reduces the stress on the grid for feed-in peaks. As seen in the left figure, on a sunny day, this results in a curtailment of power for the afternoon where the storage is already filled but the PV systems still generates more than 50% of its nominal power. On cloudier days, the battery system never gets fully charged. The power loss per day is dependent of the radiation conditions, the load and the capacity of the batteries.

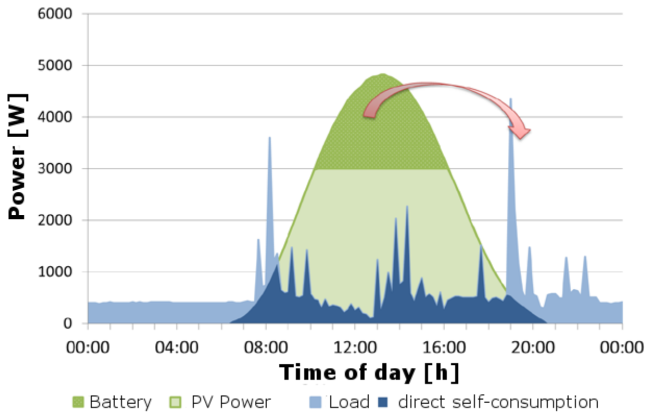

Figure 5: Constant limit of the feed-in power to the grid [1].

Without an additional battery system, the power loss for a PV system with a constant limitation of feed-in power would be around 15% per year. By adding a battery storage in the ratio of 1 kWh of installed battery capacity for 1 kW of installed PV power the losses could decrease to only 1% per year. This was estimated on the basis that none of the power produced is also consumed during the day. If that is considered for an exemplary system of 4 kWp of installed PV power and 4 kWh of installed battery capacity the losses could further decrease to below 0,1%. Consequently, it is possible to reduce the stress of feed-in power from PV systems significantly without resulting in significant losses. The energy efficiency ratio of the BSS is also important for the losses. For BSS with low energy efficiency ratios and constant capacity, the losses through limiting the feed-in power would decrease. Because of the lower efficiency more power is needed for charging the batteries and less is limited. The self-consumption for the producer however would only marginally increase as the batteries are often not fully charged during the day making this operating strategy uneconomic. For the exemplary system given above the in-house consumption would drop from 60% to 40%.

Like the operating strategy for maximizing the self-consumption this strategy does not require any external communication. Only the inverter must be given a certain limit to cut down on the feed-in power from the PV system to the grid [7].

C. *Variable limitation of feed-in power*

An individual adjustment of the maximum feed-in power from the PV system would offer the best compromise for maximizing the self-consumption and reducing the stress on the grid by peaks in power generation during the day. This could reduce losses from PV infeed limitation and charge the BSS as much as possible during the day. Figure 5 and 6 show the load curve for the perfect implementation of that strategy. On a clear day, the maximum feed-in power limit is higher than on a cloudy day and on both days, the batteries can be fully charged and no power needs to be cut off.

Fig. 6 displays power data for a sunny day. Because the power output of the PV-Array is very high on a sunny day, the infeed limitation is set high as well. When that limit is crossed, the batteries start charging. In Fig. 7 the infeed limitation is set very low because of the equally low power output of the PV-Array. At the end of both days, the batteries are fully charged and the stored energy can be used for self-consumption.

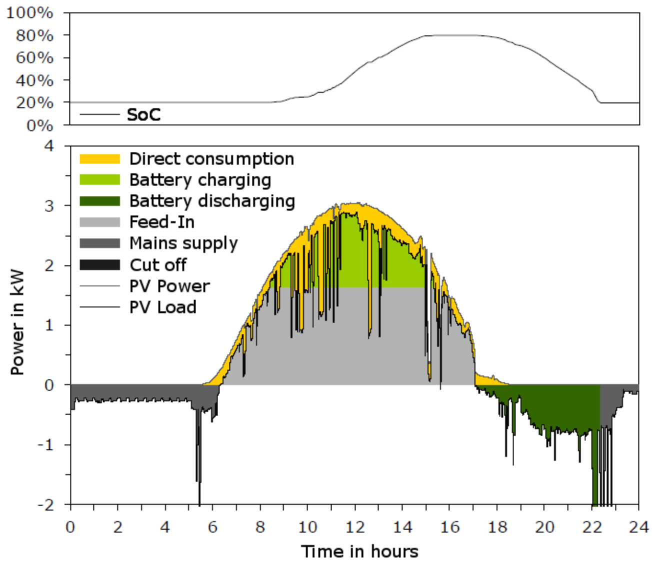

Figure 6: Higher limit of feed-in power on a clear day [7].

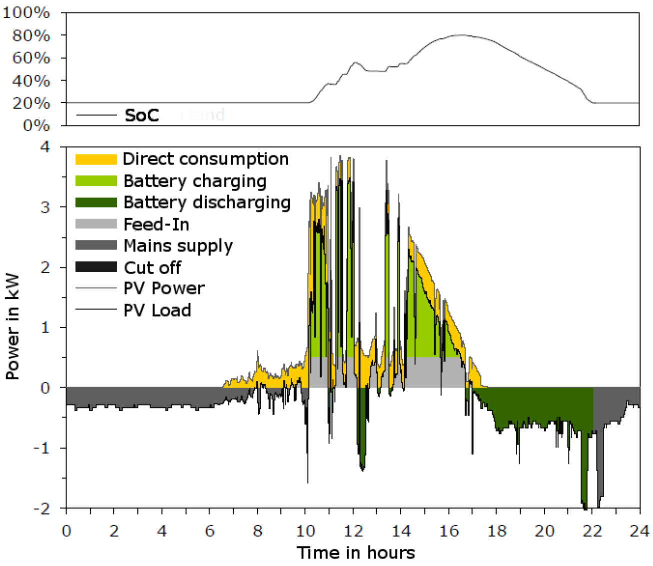

Figure 7: Lower limit of feed-in power on a cloudy day [7].

This strategy requires knowledge about the future course of PV power generation and load. Based on that weekday from the previous week the load curve for the corresponding day can be estimated with good accuracy. The management system then calculates a power limit for the day using the lead curve as well as the PV generation from the previous day. Peaks above that limit will then be used to charge the batteries. Further benefits can be achieved by providing a dynamic adjustment for the feed-in limit over the course of the day. This ensures full charging of the storage if the forecast deviates from the real performance history [7].

This variable limitation of feed-in power only requires a memory to use the recorded data on load and production from the previous week to calculate a feed-in limit. This is more complex than previous strategies, but it still ensures the system can operate self-contained. Only internal flow of information between the electrical equipment is needed. A compensation system could be introduced which compensates according to the maximal feed-on power on any day. This might improve the appeal for that operating strategy for producers [1].

V. Conclusion

The application of Li-BSS offer the chance to relieve the low-voltage grid and limit the network expansion to a necessary minimum. They can be used to support the grid with ancillary services, especially to provide Primary Control Reserve. The benefits vary with the operation strategy for these BSS. A variable limitation of the feed-in power is the most promising for increasing the self-consumption while also limiting the PV feed-in power. To promote the use of Li-BSS the price for lithium cells needs to decrease as expected in the following years. And methods to further implement them in the energy balancing market to make them more profitable must be explored.

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