Planning of Grid-Scale Battery Energy Storage Systems: Lessons Learned from a 5 MW Hybrid Battery Storage Project in Germany

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Abstract

Grid-connected Battery Energy Storage Systems (BESS) can be used for a variety of different applications and are a promising technology for enabling the energy transition of today's power system towards a higher penetration of renewables (called "Energiewende" in Germany) by providing ancillary services for the grid. Although BESS gain increasing importance, planning of such systems can be difficult because of lacking experience and standards.

The M5BAT project is a multi-company research project (RWTH Aachen University, E.ON, GNB Industrial Power of Exide Technologies and SMA Solar Technology) that includes planning, construction and operation of a 5 MW Hybrid BESS in Aachen, Germany. Different applications such as frequency control and arbitrage will be investigated within the research project to find the most economical way to operate BESS.
This paper describes different aspects of BESS planning and operation, such as economics, safety, SCADA and other design considerations, based on the M5BAT project[1].

Introduction

The integration of RES (renewable energy sources) into today's electricity grids causes a need to balance volatile energy production and demand on different time scales. Battery Energy Storage Systems (BESS) can easily provide reserve power for short-term fluctuations because the electrochemical working principle allows for high ramp rates. Currently, BESS are discussed for a variety of grid applications, such as ancillary services and energy trading (arbitrage), for which they are expected to operate economically. Ancillary services like frequency regulation, voltage regulation, reactive power and black start capability can cause a highly dynamic power profile with C-rates of up to 4C or 15 minutes discharge time respectively.

To improve the economical efficiency of BESS, efficient planning and construction is highly important. Currently, building BESS is project business with high planning efforts due to missing standards and lack of experience of planners and authorities with grid connected Lithium-Ion-battery-systems.

[1] The project upon which this publication is based is funded by the Federal Ministry for Economic Affairs and Energy under project number 03ESP265A (M5BAT).

BESS applications

Since BESS provide high power capability in relation to energy capacity, they are primarily discussed for balancing short-term fluctuation between generation and load. Thus, applications generating revenues for providing power, such as *Frequency Response Reserve*, are currently discussed the most. Other BESS applications include services such as reactive power, voltage control or black start capability, load-leveling and peak shaving within the industry sector, uninterruptible power supply and pooling with conventional power plants for stabilization purposes or power gradient relief [1].

Frequency-Response Reserve

The grid frequency, which is a measure for the balance between power generation and load, needs to be kept within certain limits at all times. Frequency-response reserve (FRR) reduces frequency deviations by providing positive or negative power to the grid. FRR in Germany is traded in units of power (e.g. MW) for a certain time interval (e.g. one week). Each MW reserved grants a certain revenue; therefore FRR is a power-related application. The actual power which has to be delivered is proportional to the frequency deviation, except for a small dead band around the set point frequency (e.g. ±10 mHz) in which no power needs to be provided. The full bided power has to be delivered when the frequency deviation exceeds a defined threshold, e.g. ±200 mHz. Due to statistical distribution of frequency deviations, most of the time only little power is actually requested by FRR. For example, in the former UCTE (Union for the Co-ordination of Transmission of Electricity) grid of continental Europe, the average requested power is 10-20 % of the nominal power (Figure 1).

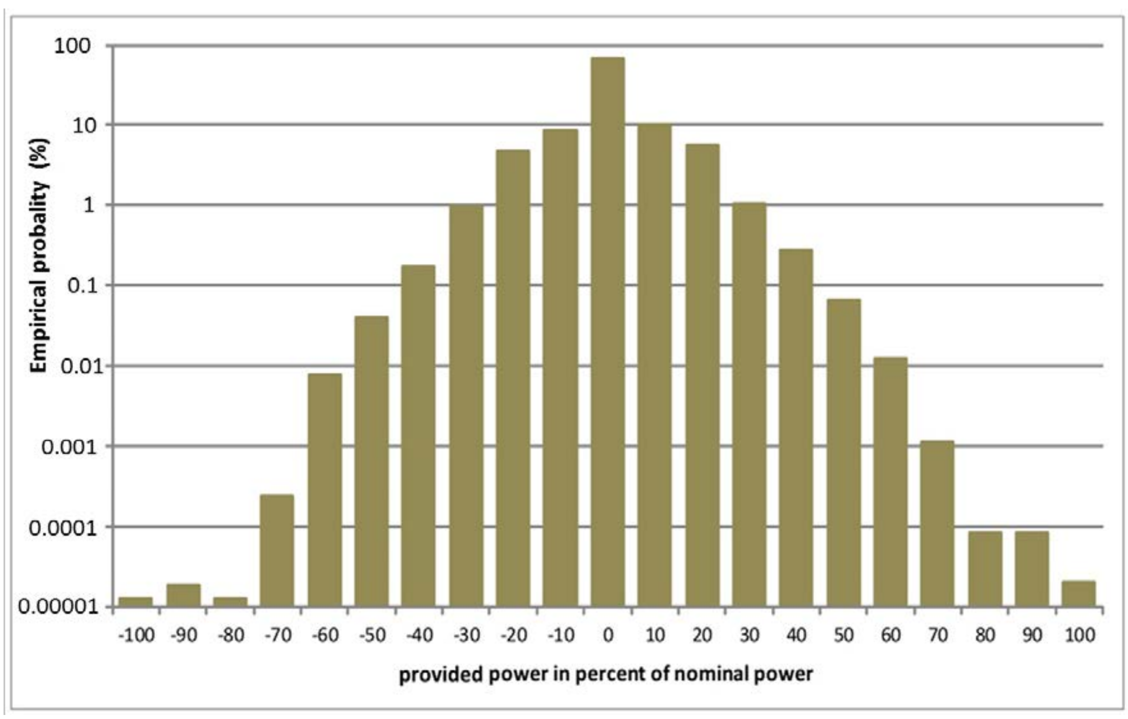

Figure 1: Statistical requests of FRR power in UCTE grid (logarithmic scale) [1]

FRR can be easily served by BESS. The response time of a battery inverter is in the range of milliseconds which is much faster than required (e.g. in the UCTE grid, full FRR power is required within 30 seconds). Capacity constraints depend on regulation. Within the grid of the UCTE 1 MWh per MW FRR is required which allows economic operation of BESS.

One major difficulty of FRR is the demand for a high reliability. Severe penalties can apply if contracted FRR is not provided due to an outage. Nevertheless, FRR is one of the economically most promising BESS applications at the moment.

Frequency Replacement Reserve

In case of frequency deviations, FRR is provided for a specific period of time. If the frequency deviation is still present after the time period for FRR, frequency replacement reserve takes over. It reduces the frequency deviation and brings the frequency back to its set point. It is traded in units of power and in units of provided energy. Therefore, each MW provided within a time period grants revenues and in addition each MWh delivered grants energy-related revenues. However, total revenues from replacement reserve are usually lower than those from FRR.

The actual power delivery is requested by the responsible TSO (Transmission System Operator). The requirements for response time are much lower than for FRR, e.g. in UCTE full power has to be delivered within five minutes. Nevertheless, capacity constraints are much higher due to regulation. In UCTE for instance, 4 MWh per MW replacement reserve are required. Because of this, BESS cannot be operated to serve solely frequency replacement reserve in an economically viable way.

Wholesale Arbitrage

Utilizing price spreads at the electricity exchange is called (Wholesale) Arbitrage. BESS can buy (charge) energy when prices are low and sell (discharge) when prices are high (Figure 2).

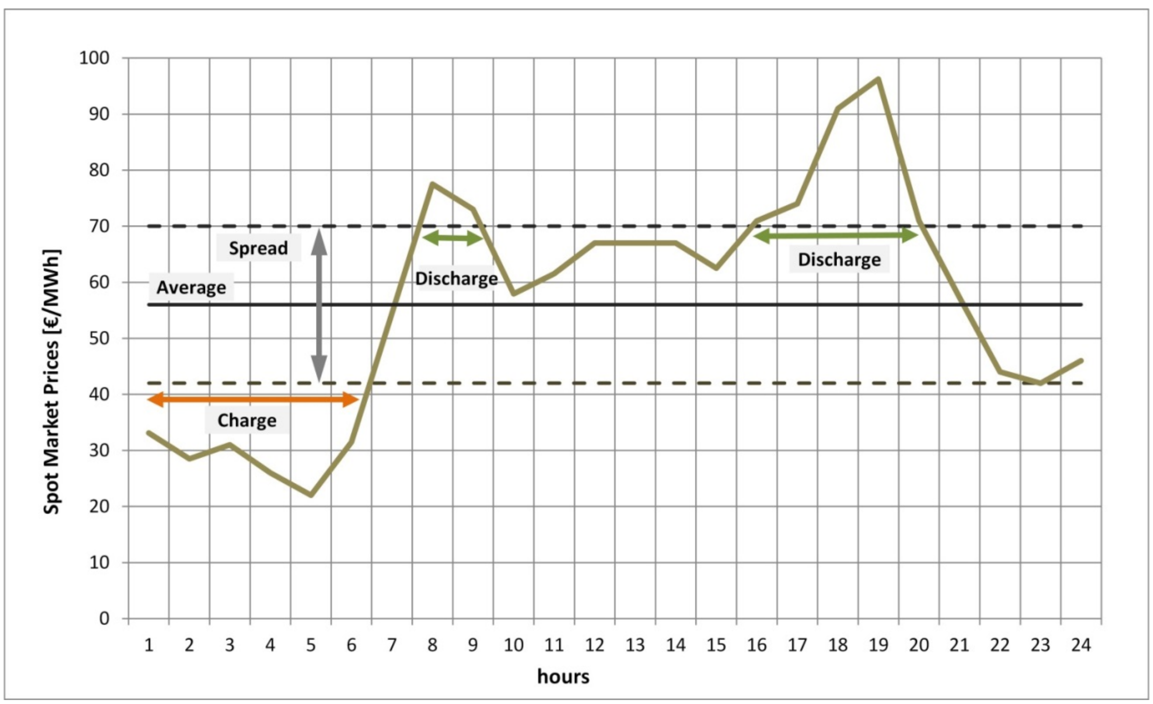

Figure 2: Example of a simple arbitrage trading strategy for the German Spot Market [1]

To maximize revenues, large quantities of electrical energy must be stored. Typically, charging and discharging has to be done within a relatively short time period whereas the time between charging and discharging can be long. Since the specific prices for capacity of BESS are high compared to other storage technologies like pumped hydro, it is difficult to operate BESS economically within such energy-related applications. To improve economics of BESS, combining different BESS applications such as FRR and arbitrage is investigated in different research projects as in the M5BAT project.

M5BAT project

M5BAT is an acronym for modular multi-technology multi-megawatt medium voltage battery energy storage system[2]. The research project's focus is to plan, build and operate a 5 MW BESS in Aachen, Germany and to evaluate technical and economical experiences gathered from the project. The project is conducted by E.ON, Exide Technologies, RWTH Aachen University and SMA Solar Technology AG and is coordinated by RWTH Aachen University. Battery technologies used in the project include lead-acid batteries of type OCSM ("Ortsfest Kupferstreckmetall" = Stationary lead-acid battery with positive tubular plate and negative copper stretch material plate technology) and OPzV ("Ortsfest Panzerplatte Verschlossen" = Stationary with positive tubular plate, valve-regulated), as well as lithium-ion batteries of different types and a sodium-nickel-chloride battery (Table 1) which will be tendered.

Supplier	***Battery***	***AC-Rating***	
		P [kW]	***E [kWh]***
Project Partner	Lead-acid 1 OCSM	1.260	1.325
Project Partner	Lead-acid 2 OPzV	761	761
External Supplier	Sodium-Nickel-Chloride	179	537
External Supplier	Lithium-Ion 1 (no LFP/LTO)	2.263	2.263
External Supplier	Lithium-Ion 2 (LFP or LTO)	537	537
Total		**5.000**	**5.423**

Table 1: M5BAT BESS battery setup

This combination allows for an utilization of each technology's advantages. A SCADA-system developed by RWTH Aachen University autonomously controls the BESS and optimizes the battery dispatch with respect to efficiency and ageing. The SCADA-system's main component is a programmable logic controller (PLC) which communicates with the battery inverters and the battery-management-systems to control the operation of the battery strings. A database server ensures appropriate data management while the dispatch optimization is run on a separate high performance computer. The BESS will be directly connected to the local medium-voltage substation. The battery strings are connected to ten inverters with 630 kVA rated power each (Figure 3). The battery inverters have a built-in "battery system controller" (BSC), which enables communication with different battery technologies in order to control, supervise and monitor the daily operation.

[2] See www.m5bat.de

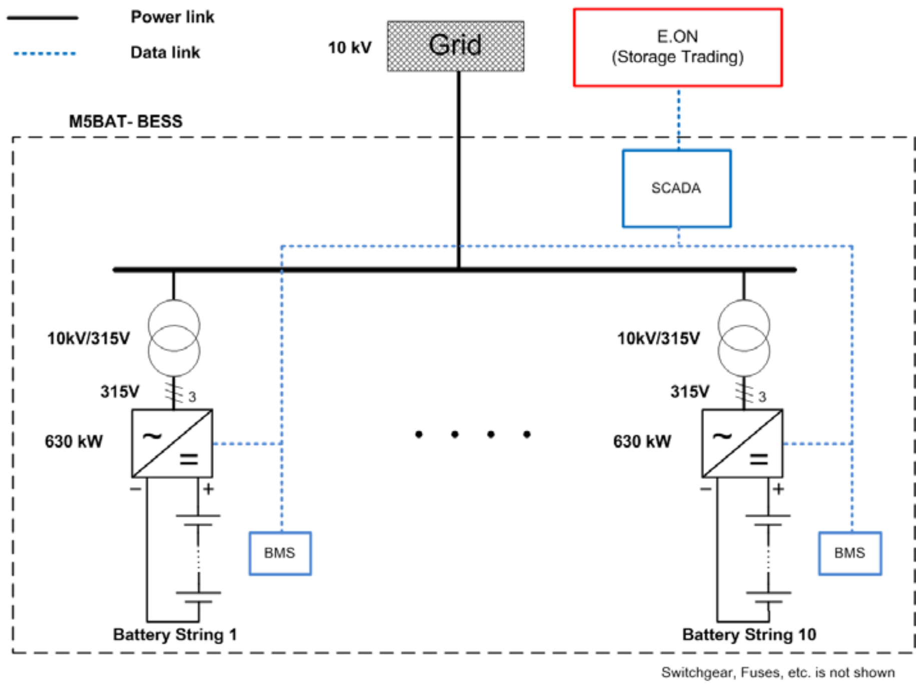

Figure 3: M5BAT system configuration

The BESS will be installed within an existing building, which will be retrofit in order to accommodate the batteries, inverters and all other components (Figure 4).

Figure 4: Illustration of the M5BAT BESS building

Technical and architectural planning is finished and the official building permit was received in December 2014. Construction will start in May 2015, start of operation is planned for end of 2015. At the beginning, the BESS will serve primary and secondary frequency control as well as arbitrage. Testing of additional applications will be decided on later during the project.

Planning of MW-BESS

At first sight, planning MW-scale BESS does not differ much from general plant construction and engineering. Although stationary battery installations are well known from UPS systems in power plants or in the telecommunication sector, BESS, especially these consisting of technologies other than lead-acid batteries, are still uncommon projects for planners and authorities. Being charged and discharged to the grid practically all the time, their operation scheme is much different from that of UPS systems, which are completely charged all the time and only discharged in case of power interruption. Also, many existing stationary battery systems serve private grids and less coordination with public parties is required because these BESS do not need to comply with grid codes of public grids. Another important aspect is the novelty of using battery technologies such as Lithium-Ion or Sodium-Nickel-Chloride in BESS installations. Although first installations have been made [2], it can be demanding to get a permit from the authorities for building such systems due to lacking experiences with such facilities. High safety requirements can be demanded by authorities due to uncertainty and lack of experience.

Since BESS need to be operated economically within the current power system, BESS have to be designed in order to meet all economic, legal and safety-related requirements.

Design Considerations

Primary objective of grid-scale BESS is to earn as much revenues as possible with as little capacity as possible in order to minimize costs. Since the costs of BESS do not solely depend on costs for the batteries, inverters and peripheral components, but also on the efficiency, energy throughput, lifetime and power demand, care has to be taken when choosing the battery technology. For example, FRR as the currently most economically interesting BESS application in the utility sector, requires a net capacity of 1 MWh per MW (Germany). An additional oversizing has to be regarded to cover efficiency losses during charging and discharging and capacity losses due to ageing.

If less capacity was required by the regulation authority, more FRR could be provided to increase revenues. For example, some lithium-ion-batteries allow for continuous C-rates (which is the inverse of the discharge time, e.g. 4C = 0,25h discharge time) of 4C and more while only little additional costs for larger inverters and HVAC apply. This means the capacity of the BESS could be reduced while the power stays the same. It appears that reducing the capacity could reduce the BESS costs at the same proportion. When looking at BESS for FRR with different capacities, the costs for BESS do not change a lot with the capacity [3], which is due to decreasing life time and necessary early battery replacement because of a higher average depth of discharge (Figure 5).

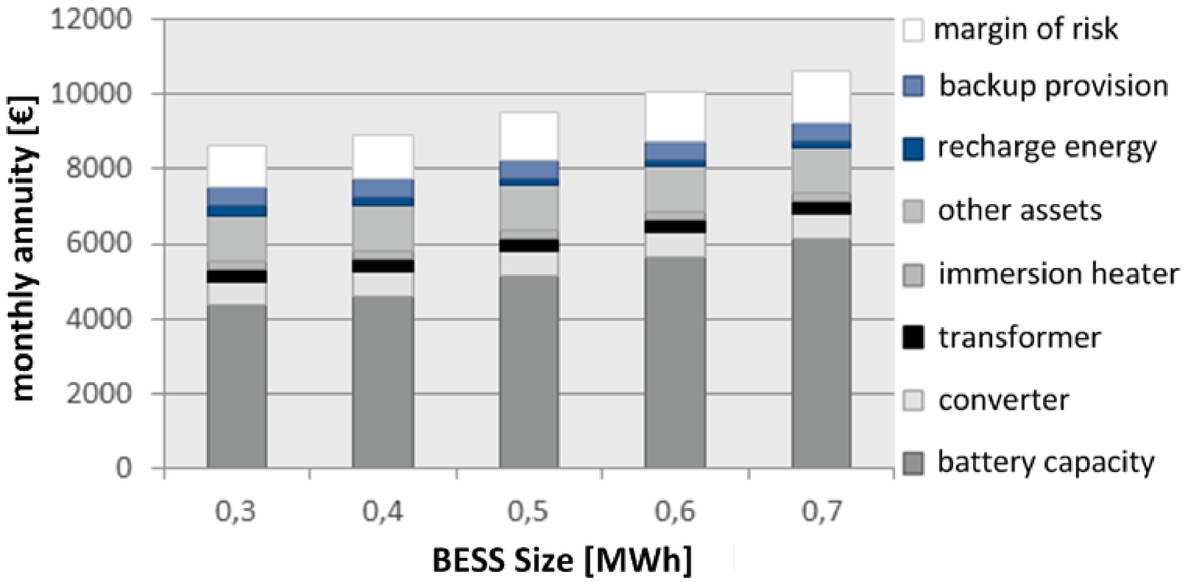

Figure 5: BESS costs for different capacities [3]

Thus, dimensioning of BESS needs thorough consideration of life cycle costs for different battery capacities in order to find the optimal BESS layout. A method for life cycle calculation of storage is introduced in [1].
As a simple example, a BESS with lead-acid-batteries (LAB) and one with lithium-ion-batteries (LIB) are compared, assuming one MWh of capacity is installed per MW FRR provided (Table 2 and Table 3):

CAPEX	LAB	LIB
BESS costs [€/MWh]	1,000,000	1,500,000
Lifetime/depreciation period [years] (cycle life neglected due to very low depth of discharge)	10	15
Interest rate [%/year]	8	
CAPEX annuity [€/year]	**149,000**	**175,200**

Table 2: CAPEX of compared BESS (power-related costs have been considered within the costs per MWh)

OPEX	LAB	LIB
Discharging efficiency [%]	93	95
Charging efficiency [%]	89	95
Self-discharge [%/day]	0.2	0.1
Number of equivalent full cycles per day	1	
Electricity price for loss compensation [€/MWh]	100	
OPEX annuity [€/year]	**7,680**	**3,981**

Table 3: OPEX of compares BESS (maintenance and repair costs have been neglected for simplification reasons)

Assuming yearly revenues of 180,000 €/MW from providing FRR, both BESS could be operated economically. In this example LAB BESS are more economic because of their low investment cost. For LABs, it is unclear if such low prices are currently realistic. In addition, LIBs are expected to be subject to price degression, meaning that BESS based on LIBs could beat LABs economically within the next years. Though, it can be beneficial to combine both technologies in a hybrid BESS to take advantage of potential synergies. Economics of hybrid BESS would highly depend on operation strategy. Therefore, further investigation (like the M5BAT project) is needed.

Another issue regarding efficiency as one of the key performance indicators (KPI) is that no standardized definition of a BESS' system efficiency exists yet. Losses do not only occur within the batteries, but also the additional (ohmic) losses of the inverters, transformers, cables, switchgear, etc. have to be taken into account. Additionally, there is an auxiliary power need caused by HVAC, SCADA and so on. For simplification, the power need of HVAC can be assumed to be a percentage of the ohmic respectively thermal losses caused by the batteries, depending on the coefficient of performance (COP) of the AC. Other auxiliary power need will be relatively constant such as stand-by losses of the transformers and inverters which are considerably high, or the power demand of the SCADA system and other control systems (BMS, inverter controller). To map these losses to one overall system efficiency value, all losses should be related to the expected average power (respectively the current at nominal voltage) of the planned BESS application.

System Integration

A BESS consists of one or more battery strings which are connected either in parallel to one central inverter or each battery string has its own inverter. The latter has several advantages over the first: Because the losses of the battery inverters consist of fix power-independent share and a variable power-dependent share, the fix losses of the inverter would be high compared to the throughput power in case the inverter operates with only a few percent of its rated power. Therefore, high efficiency losses would occur for example if the BESS had to provide FRR, which means that the BESS is mainly operated at around 10-20 % of its rated power. Another aspect is that inhomogeneous ageing of the battery string would lead to premature end of life of the whole BESS because the fastest ageing battery string limits the total life time. A decentralized concept with each battery string having its own inverter would be controllable in a way so that power flows can be optimized according to minimal losses and homogeneous ageing. Additionally, malfunction of a central inverter would lead to an outage of the total BESS. Although a central inverter could have an economical advantage in terms of price per kilowatt, the technical advantages of a decentralized concept probably beats the lower costs of a central concept in most cases and should be preferred.

Anyway, in both cases each battery string is connected via DC cables to the inverter. Regarding grounding, it is possible to ground either plus or minus pole of a battery string or the midpoint of the battery string or to have the battery isolated from the ground (IT system = isolation-terra). If a pole or the midpoint is grounded, one can choose between the TN- (terra-neutral) and the TT- (terra-terra) system. The main difference of these systems is that the TN-system uses separate grounding of conductive parts such as cabinets, casings, etc. Within both systems, a single fault leads to immediate shutdown. On the other hand, in an IT system, a single fault does not require immediate shutdown, which gives time for reaction. This is an advantage especially, if high availability of the BESS is required. On the other hand, an insulation monitoring device is necessary in order to discover a single fault. Maximum voltage of a battery string should not exceed 1500 V DC because requirements of high-voltage regulation could increase BESS costs significantly. Using inverters in the range of 500 – 1000 kW, which is also done within the M5BAT project, seems to be a good compromise between modularity and costs.

Regarding heating, ventilation and air conditioning (HVAC), one has to consider each battery technology's specific properties. Lithium-ion batteries need cooling which is usually accomplished by split air conditioning within the battery rooms. The air conditioning does not necessarily need to be sized to the full thermal losses at nominal power of the BESS. For instance, lead-acid-batteries have a high thermal capacity; therefore HVAC for such batteries could be sized accordingly to the average losses during the planned BESS application.

As lithium-ion-batteries have a coulombic efficiency of almost one, which means that almost no side reactions occur during charging and discharging, the cooling demand is equal to the ohmic losses of the batteries at their internal resistance. Besides the ohmic losses, lead-acid batteries generate a lot of additional heat during charging due to side reactions, which is absorbed by the large thermal capacity of lead-acid batteries at first but needs to be dissipated continuously by air conditioning. Noteworthy, sodium-nickel-chloride batteries operate at a high temperature of approximately 300 °C / 572 °F. Because of the high temperature difference versus ambient temperature, they can be cooled easily by ventilation, dissipating excess heat to the environment. On the other hand, they need auxiliary heating if the internal temperature becomes too low. Therefore, a lot of auxiliary heating needs to be done if they are placed in a very cold environment.

BESS can be placed in a building or within containers. Using containers will be cheaper as well as more modular in most cases, which simplifies planning. For example, each battery string of future BESS could be installed in one (or more) container with their respective air conditioning and inverter while one central container could accommodate the grid connection, central electrical equipment (e.g. MV switchgear) and BESS SCADA system. In some cases it can be beneficial to use buildings, for instance in very cold environments or if larger BESS are planned. In this case a modular container concept may be more expensive than a building. However, a building has to meet special requirements: a distributed load per area of 2,000 kg/m² can easily occur. This is especially true for lead-acid-batteries, which are installed cell-by-cell on a one-story-rack, as well as for lithium-ion-batteries which are installed module-wise in racks with heights of more than 2 m.

Safety

Regarding lead-acid-batteries, hydrogen generation probably is the highest risk to take care of. Sufficient ventilation has to be considered as well as the way of air circulation. It is important that the hydrogen cannot accumulate in corners, beneath the ceiling or in hollow spaces. From the planning perspective, there are already sufficient standards which can be applied.

More challenging from a planning point of view are lithium-ion-batteries with the thermal run-away being the most feared hazard of all battery technologies. Burning lithium-ion-batteries cannot be extinguished because they provide their own oxygen for the fire. This leads to concentrating all efforts to minimize the risk of a thermal run-away. Extensive monitoring of the battery states such as voltage, temperature, current etc. as well as redundant monitoring and control in terms of a fail-safe battery-management-system (BMS) is crucial for a safe operation of BESS incorporating lithium-ion-batteries. Since standards for stationary lithium-ion batteries are still being worked on, there are no suitable standards to refer at present. However, answers to possible questions of the authorities should be prepared in order to get a building permit. Description of failure modes and countermeasures are advisable. According to [4], the three most important safety events to address are overcharging, overtemperature and mechanical abuse. Overcharging and overtemperature caused by exceedingly high currents need to be avoided by safe monitoring and control. These tasks are fulfilled by the BMS, the inverter control unit and the BESS SCADA system. If one of these fails, the BESS needs to be shut down.

Overtemperature caused by external heat sources can only be diminished by a safe battery containment or room. For example, propagation of a primary fire to adjacent li-ion cells must be avoided.

Mechanical abuse is not very likely to happen in stationary BESS if battery room access is limited. Incidences might still occur during installation or service.

Finally, getting a building permit for BESS with lithium-ion-batteries should be much easier if the batteries are tested and certified and all measures taken regarding battery rooms/containments and BMS are described in a comprehensive summary.

SCADA

A safe and reliable control of the BESS is crucial for an economically viable operation. A SCADA system for BESS needs to coordinate the data from the BMS, the power conversion systems (PCS = inverters + inverter controller) and external requests. The system consists of a main SCADA unit, the BMS, the PCS and additional components such as an advanced EMS, a database server or any hardware for monitoring purposes. The BMS' task is to monitor all relevant measurements and make sure that the batteries are operated within the safe operating windows (limits of voltage, current and temperature). If any of these limits is exceeded due to failure of any other SCADA component, the BMS has to switch off the batteries by opening the contactors. The task of the PCS is to control the inverters and maintain a safe operation. The main SCADA unit will receive external power requests (according to the BESS operator's demands) or calculate its own power request from measured signals (in case of FRR) and will dispatch the power of each individual battery string.

This dispatch is the task of an energy management system (EMS) which calculates the power of each battery string. If an EMS shall optimize the power dispatch according to minimal losses, ageing etc., more elaborate algorithms are necessary which require a lot of computing power. Therefore, it is a good idea to implement such advanced EMS on a separate unit, e.g. a workstation to relieve the main SCADA unit from these calculations. This separation has the advantage that an outage of the EMS-computer does not lead to a shutdown of the whole BESS. In this case, the main SCADA unit can take over dispatch by a simple algorithm (e.g. the power is equally distributed among the available battery strings). In case any of the SCADA overall system's components (main SCADA unit, BMS or PCS) fails, the others can still shut down the system safely.

Besides, a database should be set up which stores all relevant data during the operation. A visualization GUI can display all recorded data and the current state of the BESS in a graphically appealing way.

Conclusion

Today, building of BESS is still planning-intensive business. Standardization is the key to decrease planning costs. Standards dealing with safety of battery technologies, building requirements, definitions of KPIs, and communication signals for SCADA are currently being developed or should be. If the planning costs, which cause a significant share of the total BESS costs, can be reduced in the future, BESS can provide several applications economically viable. The currently rapidly falling costs for (lithium ion) battery cells, driven by the development of electric mobility, will probably also contribute to the profitability of BESS.

Acknowledgement

The project upon which this publication is based is funded by the Federal Ministry for Economic Affairs and Energy under project number 03ESP265A (M5BAT). The authors of this publication are responsible for its content.

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