INTEGRATION AND MANAGEMENT OF PV BATTERY SYSTEMS INTO THE GRID

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ABSTRACT: The paper describes recent developments and implementation of a method and a prototype solving the problem of optimal integration of PV-battery energy storage systems into the power grid. The first practical results achieved in cooperation with ABB Switzerland Ltd. using a real-time prototype of the developed advanced battery controller and the largest Li-Ion battery installed in Switzerland at the electric power utility of the canton of Zurich (EKZ) are presented.
Keywords: grid automation, battery energy storage system, photovoltaic, model-based predictive control, smart grids, integration of renewable energy resources

1 INTRODUCTION

Conventional base load utility power plants either using the energy from river hydro, biogas, fossil or nuclear energy sum up to about 7000 nominal working hours a year. This yield up to seven time's higher electricity production compared to the same nominal power of a standard photovoltaic plant. To obtain a stable grid operation, further elements are needed to balance customers electricity consumption, which may be reduce the needed power to about 60% in the night relative to the maximum consumption at noon. Traditional high dynamic solutions are large centralized power plants like pumped hydro or gas-fired plants. Powering the today's electrical grid by a high share of renewable, fluctuating and decentralized electricity, local storage could play a prominent rule. If for example batteries are used on a distribution grid level other highly dynamic stabilization features of the grid quality may be available, like frequency and voltage stabilization, together with reactive power control. Additional slower control services like peak shaving or even UPS uninterruptible power supply. Centralized batteries, for example connected to the grid on the medium voltage level, offers the advantages of a fast control loop, compared to smaller batteries installed on the single house level.

Such a ready-to-operate prototype was developed and tested in this work, consisting of the large battery storage system and the advanced controller. It was connected in real-time to all other relevant systems such as the intermittent PV photovoltaic generation, stochastic loads and time-varying energy prices. The battery management system is based on predications of load, as well PV production by implementing weather forecast.

The remainder of the paper is organized as follows: Section 2 explains the motivation for PV-battery systems, Section 3 shows the PV-battery system installed at EKZ in Dietikon considered in this work. The first practical results using the developed advanced battery prototype are given in Section 4. Section 5 concludes this paper.

2 NEED FOR ENERGY STORAGE SYSTEMS

In 2010 a study was presented [1] to find the individual kWh losses of a PV power plant, at over all high penetration rate of PV electricity generation. This study was done for Switzerland based two scenarios, scenario A fixed base load production and PV only on top and scenario B total PV (see Fig. 1) For scenario A at a penetration rate of 10% PV electricity in the grid, annual losses of 8% occur, mainly on excess total production on weekend, with to less demand in the grid. To completely overcome this limitation of scenario A, by peak-shifting of the produced PV energy, the Swiss central storage facilities at the pumped hydro plants may be used. Much less annual losses of only 2% will be present in a grid scenario B, without fixed base load generation, thus turning of all other power plant if there is enough solar power available.

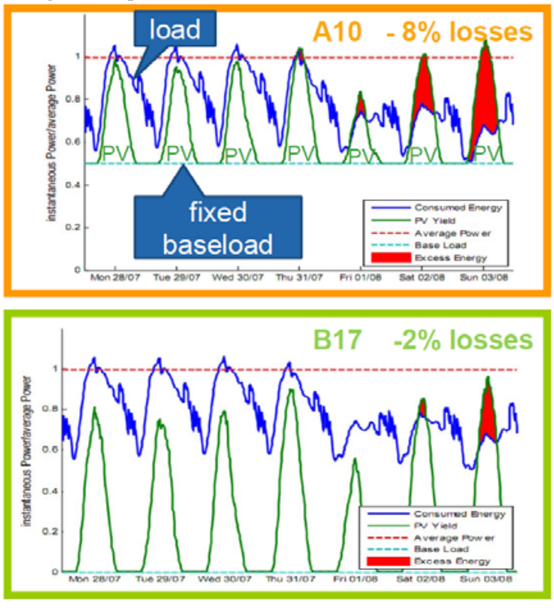

Figure 1: Calculated excess of PV energy which could not be fed into the grid (top = fix base load at 10% of annual PV share and 8% feed in losses not absorbed by the grid demand; bottom = no base load with 17% of annual PV share with only 2% feed in losses)

Half of the German electricity demand at noon on a sunny weekend was produced by PV plants in 2012. The successful PV market growth in German in the last decade lead to 5% PV share of annual total electricity consumption. In summer 2012 the German government set a cap of 52GW total installed nominal PV power for further funding, by the means of the solar electricity feed-in tariff guaranteed by the EEG low. However, in Oct 2012 the responsible minster announced new concepts of funding including grid issues und special topics about storage, see Fig. 3.

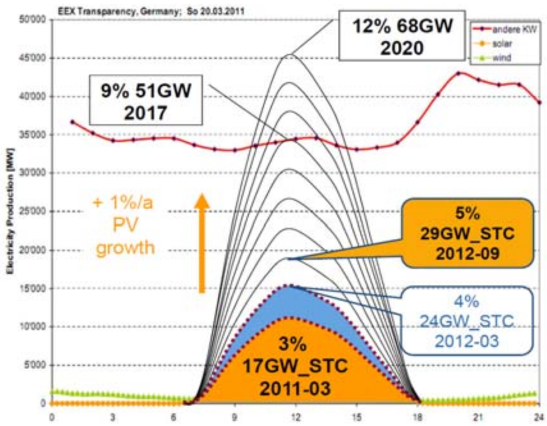

Figure 2: Real daily PV generation (black) in the German grid on a clear sky day in March 2011 together with the power generation curve of the conventional power plants (red line). By an annual growth rate of 1% of PV share of annual electricity consumption in the whole German grid, will reach the governmental gap of 52GW in 2017

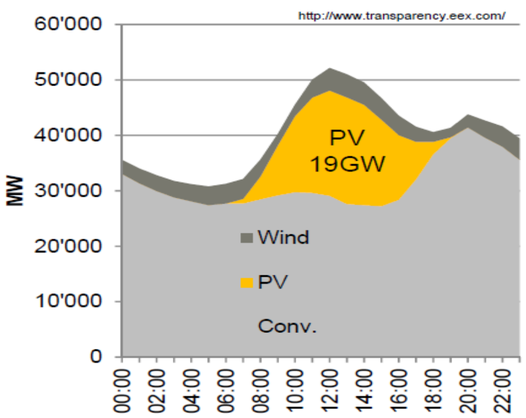

Figure 3: Electric power generation share of PV, wind and conventional plants in the German grid on Sunday Sept 16th, 2012

Figure 4: Two days in September 2012 when the peak EEX prices were below EEX base load prices due to the high PV generation at the noon [2], see also Figure 3.

On two sunny days in a week in Sept. 2012 the PV power in the German grid was about 20 GW, exceeding the generation power of all nuclear power plant at that time at noon, Figure 3.

Along with this findings on the same days the price for peak load electricity declined below the base load electricity price according to the Leipziger EEX electricity stocks exchange the prices, a novelty for the this utility electricity market.

Driven by this grid situation in the most developed PV market worldwide, the PV companies also show up with storage products for the single house market. Typical storage capacities of the offered batteries are between 4 to 14 kWh. The investment for these batteries together with needed additional power electronic equipment is larger than the share of a conventional 5kW roof top PV plant without storage. Taking the investment costs for such a commercial household peak shaving battery system into account, in Table I the cost per store kWh was calculated to be €0.74. This is about 3 times higher than the cost of the conventional PV system.

Table I: Cost calculation of a commercial 13kWh Li-Ion battery energy storage system [3]

			costs
Nominal capacity	13.8	[kWh]	
Battery investment price		per kWh	€ 833
Typ. used capacity per cycle	6.9	kWh	
Typ. used capacity per cycle	6.9	kWh	
Number of lifetime 50%DOD cycles		2700	
Number of lifetime full nominal cycles		1350	
Lifetime delivered eff. capacity	18630	kWh	
Battery cost divided by used kWh			€ 0.62
Factor for financing cost 5% i.r, 5a		1.2	
Total battery storage costs		per kWh	€ 0.74

According to the advertising documents [3] of such daily or weekly storage systems the amount of self-consumption rate of produced PV electricity of a single household will be increased from 38% up to 50%. Based on 1 minute measured feed-in power into the grid of a standard PV plant in the Zurich region, we estimate the annually used cycles of such a small PV battery system. We assume that from the distribution system grid operator point of view the number of installed nominal PV power could be increased if the maximum feed-in power is limited relative to the nominal PV power. Thus, taking a 50% limit of the feed-in power relative to the nominal PV power and a used battery capacity of storing the nominal PV power for one hour, 191 such full battery capacity cycles are reached per year. The battery management system starts to store the electricity if the PV power exceed the limit and feed into grid if it is below. Doubling the battery capacity at the same feed-in limit reduce the total battery full cycles to 118. At a five time higher battery capacity and a lower feed-in limit of 30% again 183 full battery cycles are reached.

3 PV-BATTERY SYSTEM IN DIETIKON

The power system considered in the work described here is shown in Figure 8. It consist of a large 1MW Li-Ion battery storage system, small photovoltaic installation (12kWp) on the roof of the office building (150kW peak power consumption) and a fleet of electric vehicles connected to the same part of the distribution grid.

3.1 The Battery Energy Storage System

Figures 6 gives an insight view into the container with the largest battery energy storage system installed in Switzerland, EKZ in Dietikon. The technical details related to the battery parameters are summarized in Table II below.

Figure 6: Li-Ion battery energy storage system installed at EKZ Dietikon, Switzerland [4]

Table II: Parameters of battery installed at EKZ.

Li-Ion, 1MW, 0.5MWh (0.25MWh guaranteed over 5y)
1x cell = 3.7V and 15Ah
1x cell pack = 3x cell in parallel (3.7V, 45Ah)
1x module = 8x cell packs in series (29.6V, 45Ah, 1332Wh)
1x rack = 4 floors with 6x modules each, all in series (710.4V,45Ah, 32kWh)
1x container = 18 racks connected in parallel (18 x 24 = 432 modules or 10368 Li-Ion cells, i.e. in total 710.4V, 810Ah, 575kWh)

The electric power system is shown in Fig. 7. The battery system, the building (load) with photovoltaic (PV) panels and electro mobility have been highlighted. The control set up is flexible enough to handle future extensions of the PV installation as well as virtual installations (remote intermittent renewable generation where fluctuations are compensated by this large battery)

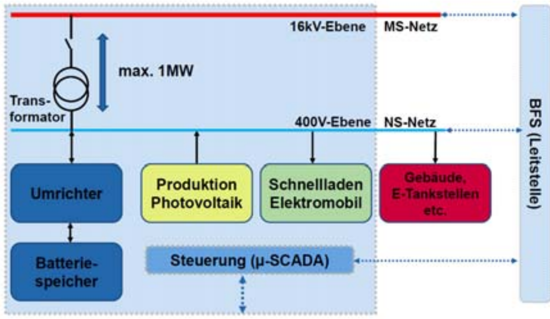

Figure 7: Considered Li-Ion battery system at EKZ Dietikon

3.2 Developed advanced battery control system

The standard OPC technology (Object linking and embedding for Process Control) was used for the integration of the developed prototype into the existing local energy management systems. The developed PV-battery controller actively exchanges data with a dedicated server of the Swiss federal meteorological service (MeteoSwiss) and calculates the weather dependent forecasts of the expected local power flows in future. This information is required to make the optimal decisions about the battery charge and discharge power (battery controller commands) at the present.

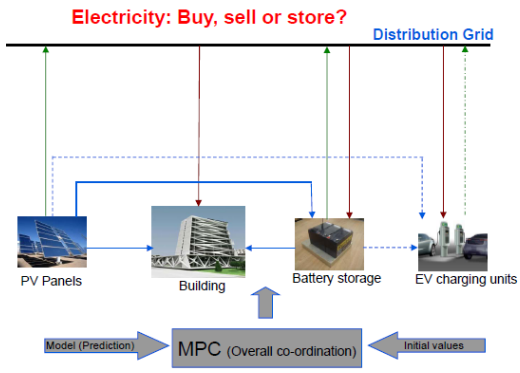

Figure 8: Considered power system and related problems

The overall control scheme shown in Figure 9 represents the complete setup implemented in the prototype. The dynamic state of the system x0 (battery state of charge) is directly read from the Battery Management System (BMS). The complete information about the states is available in real-time. Thus, the state estimation part (the basic MPC (Model-based Predictive Control) scheme structure is within the red dotted part) of the standard MPC is not required here. The basic MPC structure yields results which fully depend on the quality of the developed prediction models which in reality will hardly be perfect. Therefore, the problem of plant-model mismatch has been explicitly tackled here introducing a faster feedback corrective control loop for the error between the prediction models and measured signals. This comes sometimes at the cost of the optimality: the battery is utilized here as a buffer to provide the excess or lack of power. The Fast Feedback Control Loop (FFCL) is a simple, proportional, multivariable controller with additional logic (if then rules) which accounts for the ever-present model-plant mismatch in the predictive control scheme by a fast (and permissible, i.e. within the battery and grid limits) action to fulfill the requirements, e.g. for peak-shaving.

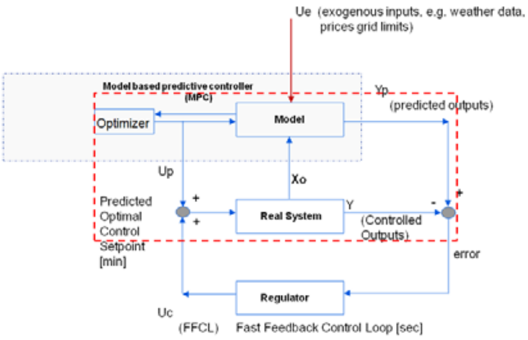

Figure 9: The overall solution designed and implemented for the advanced battery control consists of an MPC loop providing the optimal set-points every 15min and a fast corrective feedback loop dealing with the problem of model uncertainties

The developed battery control system has been inspired by the idea of how the operation of entire power systems is managed today: based on the experience of the system operators gained in the past, a new set-point for each generation unit is set every 15 minutes. However, these set-points are neither perfectly matching the real consumption at the given time instance, nor can they account for every single deviation from these values due to unknown disturbances, faults etc. The same idea as it is known from generators equipped by a governor and following so called droop characteristic (a simple proportional controller that accounts automatically and very quickly for these deviations) was employed here: the experienced operator was replaced by an automatic control based on an optimizer using prediction models of all involved components and the droop characteristics by the FFCL.

All automatically generated commands (battery charge or discharge power) are communicated to the existing SCADA/EMS (Supervisory Control And Data Acquisition/ Energy Management) System through the standard OPC interface. The SCADA/EMS then provids the set-points to the power electronics controlling the installed 1MW Li-Ion battery. OPC has been the most natural way to develop a running prototype considering the fact that the available ABB's µSCADA can act as an OPC server. The information is exchanged between the code developed in Matlab/Simulink and SCADA via OPC based on client server architecture running either on the same machine or on a separate computer. The approach of a separate machine communicating through an Ethernet connection was chosen to implement the described prototype.

4 FIRST PRACTICAL RESULTS

Several results are presented below showing the basic functionality of the developed battery advanced controller. A possible scenario for optimal automatic battery control is shown in Figure 11. It captures one typical week Mo-Su and shows the results of peak-shaving subject to 2 Tariffs energy prices. One can clearly observe the intelligence of the predictive controller on early recognition of all situations when the battery will be required; e.g. in Figure 10 (zoomed from Figure 11), the battery was automatically fully pre-charged the whole Monday night and morning before its full capacity was required for the upcoming peak-shaving at the high noon time. The battery charging and discharging is also clearly happening based on the energy prices: whenever possible, only during the night-time when the energy price tariffs are lower.

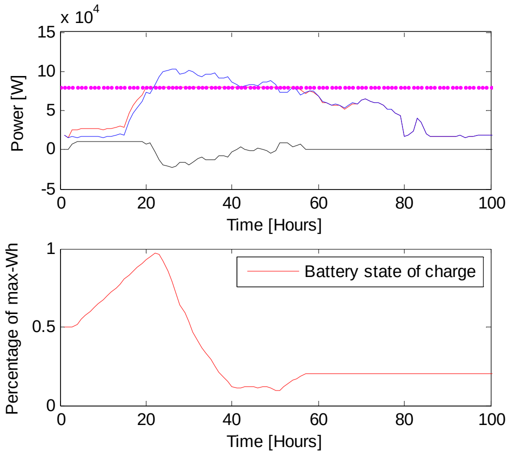

Figure 10: Grid in-feed (power) limitation with the battery energy storage system equipped with an advanced controller as described in [4] (top: black = battery charging/discharging power, blue = power system without BESS, red = power system with BESS, pink = power limit)

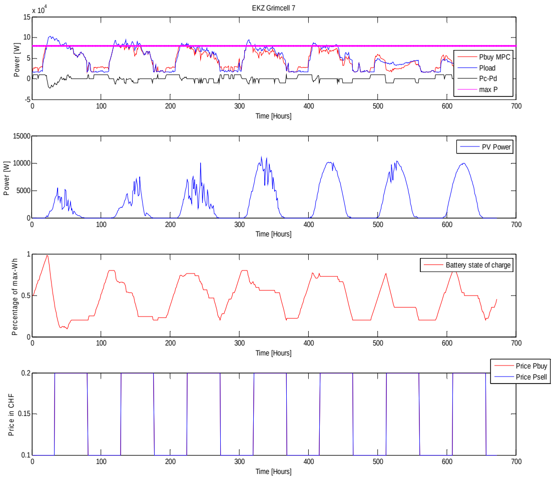

Figure 11: Scenario "peak-shaving & 2 Tariffs"

5 CONCLUSION

An advanced battery controller based on an MPC scheme was successfully developed and implemented in cooperation with an equipment vendor and a power utility and tested in practice.

Many various ways of optimal usage of the battery can be considered, incl. more advanced scenarios based on models reflecting the impact of battery control on the battery life. A few basic scenarios such as varying-price scenario, fix peak-shaving or varying peak shaving limits, including the addition of soft constraints following certain experience have already been demonstrated successfully.

Economic evaluations of the entire battery system installation will be the subject of further work.

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