SIZING OF A BATTERY SYSTEM BASED ON SIMULATION OF OPERATION IN AN ISLANDED NETWORK

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ABSTRACT

The paper proposes a model and a methodology to size a battery system, which is aimed to operate in conjunction with a utility-scale PV plant for grid impact mitigation. The methodology covers the design choices that need to be made in the planning phase, when the detailed data and technical characteristics are not available. The model is based upon the requirements imposed by the transmission system operator and makes use of solar irradiance and grid frequency data. The studied time frame is an entire year, and it can be extended depending on the available data.

INTRODUCTION

The development of photovoltaic (PV) parks in weak networks leads to an increased variability of the active power generation and a reduced inertia. Consequently, the system frequency of these networks shows a higher variability as well. At design stage, the frequency variations must remain below limits defined in the grid code. This effect has been discussed largely in literature, as for example in [1].

Battery Energy Storage Systems (BESS) are identified as an appropriate solution to this issue (see for example [2] and [3]) as they allow smoothening the PV output as well as providing extra primary frequency reserve. The BESS power rating (and first guess of energy rating) can be obtained based on grid studies. However, additional information related to BESS operation over a long-time period is required at the planning stage, when detailed technical data are not available. Therefore, a long-term dynamic simulation approach on a high-level model is adopted.

This paper illustrates the proposed methodology on an example. In a first stage, the example is described briefly. Then, the input data necessary to apply the proposed methodology is enumerated. As a function of the input data, the total systems output should comply with certain requirements. These requirements are described in the third chapter. Afterwards, the behaviour and control of the BESS is translated in a high-level model. This model allows determining the usage of the BESS as a function of the input data and the requirements. The resulting behaviour of the plant is then quantified via certain characteristic values.

SYSTEM TOPOLOGY

The overall system topology of the studied example is illustrated in Figure 1. The PV park (upper left part) and the BESS (lower left part) are connected to the same busbar. A step-up transformer connects that busbar to the external grid.

The overall system is controlled by the Energy Management System (EMS), the PV plant Supervisory Control And Data Acquisition (SCADA) system and the substation SCADA system. The EMS is responsible for an active power input at the Point of Connection (POC) which is 1) sufficiently smoothed and 2) provides the required primary frequency control.

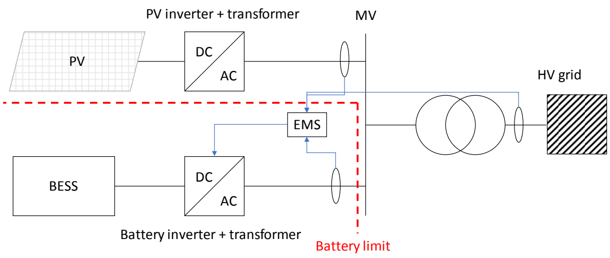

Figure 1: Overall topology of the power plant.

INPUT DATA

To perform the proposed methodology, two data sets are required. Firstly, the **active power production of the PV plant** needs to be predicted. Ideally it should be on (at least) per-minute basis. This data can be obtained based on historical irradiance profile combined with the model of the park and a certain interpolation methodology, which is beyond the scope of the present paper.

Secondly, a representative **frequency measurement** is required. Such data can usually be obtained from the Transmission System Operator (TSO). An appropriate sample rate is one sample per second. Ideally, this frequency measurement should cover the same period as the irradiance data. If not available, assumptions can be done based on the knowledge of the system behaviour (e.g. if data for one month is missing, the data for similar month can be used).

It may happen that the two data sets do not share the same sample rate. In that case a proper interpolation is required.

REQUIRED OUTPUT

The BESS must ensure that the global output of the power plant (PV system and BESS combined) has an acceptable variability and provides the required primary frequency response. Both requirements are to be discussed in detail with the TSO and should be clearly agreed upon.
A typically requirement in terms of primary frequency support is defined as in Figure 2. Frequency support requirements determine that the active power production of a power plant increases if the frequency decreases and vice versa. A certain dead band is required, and the response should be limited both upwards and downwards.

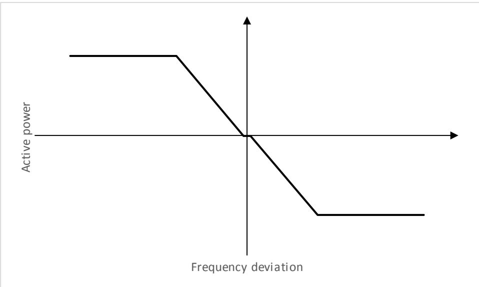

Figure 2: Frequency support

The allowable variability of the output of the power plant (PV system and BESS combined) depends on the size of the PV system as well as of the characteristics of the rest of the system, and therefore should be agreed upon with the TSO.
At least three types of requirements can be imposed on the BESS. The first requirement type is that the BESS must limit only the ramp rate of the PV park. Depending on the TSO requirements, appropriate window and appropriate filtering constant must be defined. An example of such operation is presented in Figure 3.

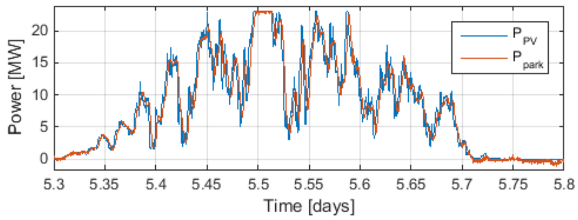

Figure 3: Ramp rate limitation

The resulting active power flow follows very closely the active power output of the PVs but has reduced spikes and lags due to filtering constant.
The second type is when the system operator imposes the PV generation profile in advance (i.e. capacity firming) based on the weather forecast, and the battery system must ensure that it is respected by compensating the power reductions and increases of the PVs. The shape of the reference profile can be rectangular, trapezoidal, or half-sinusoidal. An example of capacity firming is presented in Figure 4.

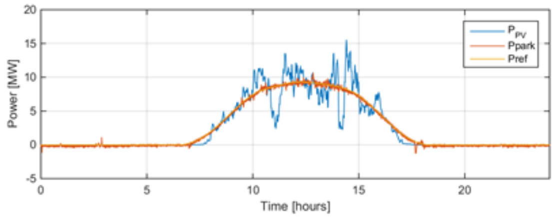

Figure 4: Non-adjustable reference

The third type is that the system operator imposes a PV generation profile but it can be adapted during the day depending on the real weather, as presented in Figure 5. This can be considered as a relaxation of the strict requirements for capacity firming.

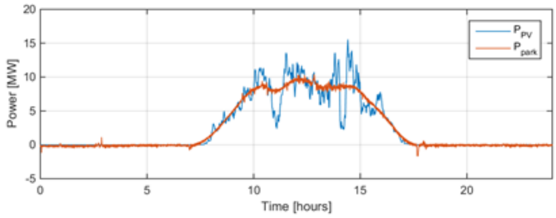

Figure 5: Adjustable reference profile

BESS MODEL

The BESS model is composed of two parts: control logic and the behaviour of the BESS. The control block diagram is presented in Figure 6.

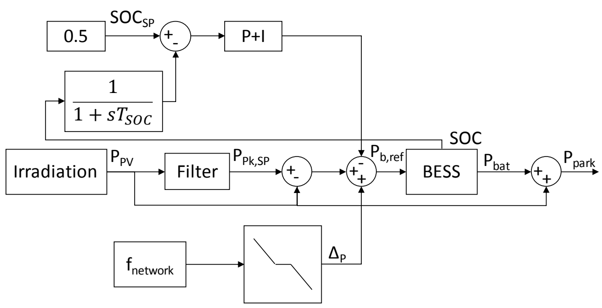

Figure 6: BESS control

The irradiation profile is used to determine the active power produced by the PV plant. This profile in its turn is used to determine the park setpoint based on a selected strategy presented earlier. For ramp rate control, a digital filter can directly be used in such a way that the setpoint ramp is always higher than the limit. For the two other strategies, as these are based on a weather prediction, it is required to pre-calculate the filter output before running the dynamic simulation to provide an appropriate phase shift (for example using the *filtfilt* routine).
The setpoint value is compared to the actual PV output value and the difference will be used to define the BESS setpoint. This setpoint will be adapted by two additional loops. The first is the frequency control, which implements the power variation (ΔP) as function of the frequency variation (Δf), which is usually defined by the grid code.

The second loop is the State Of Charge (SOC) control loop. It can be noticed that a time lag is added in the loop to model the processing time. For proper operation of the BESS, it will be required that the SOC remains around its central value of 50 %. A slow P+I controller is used to slowly (dis)charge the BESS to attain this value. Some more advanced strategies for SOC management exist, e.g. [4]- [5].
The obtained setpoint is then injected in the BESS model, which returns the SOC value and the actual active power output. The BESS output is added to the PV power output, leading to the total power plant output. In principle, this output can be used for simulating the impact on the frequency considering the rest of the power system, but it will not be considered in the frame of the present paper.
The BESS behaviour model is presented in Figure 7.

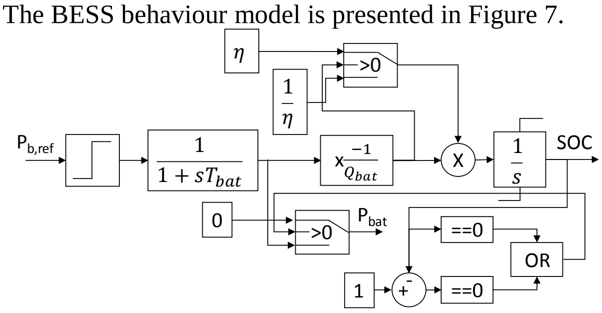

Figure 7: BESS behaviour model

The reference power is first limited according to the battery rating. Then a simple lag models the battery reaction time which is in principle very fast. Then the signal can be directly output as the battery output power or set to zero is the battery is fully charged or discharged depending on the SOC.
The SOC is calculated in per units and using the load convention for the sign. For considering the (dis)charging efficiency, the signal is multiplied or divided by the coefficient η, depending on whether the BESS is charging or discharging [6]. The approximation of this coefficient can be obtained from the root square of the round-trip efficiency. The SOC is obtained by integrating the input power. The SOC is always limited between 0 and 1, corresponding respectively to fully discharged and fully charged states. If the SOC reaches these limit values, the output power of the battery will be set to zero.

RESULTS

When feeding the input data into the above described model, the expected behaviour of the battery over the studied period can be determined. The simplicity of the model allows to simulate a significant duration (e.g. a year) with a reasonable amount of computing time. This in turn allows determining the required characteristics of the battery.
The first important output is the evolution of the active power of the BESS, the PV plant, and the total system. This was illustrated in Figure 3, Figure 4, and Figure 5 for one day, and is illustrated for a whole month for ramp rate control in Figure 8. In this example, a ramp limit of 7 MW/min was defined. The PV power output reaches a maximum of 9.71 MW/min and the battery successfully manages to reduce it to an acceptable 3.84 MW/min.
It can be seen from the bottom subplot that the battery power output profile is substantially different for different days, due to the differences in the short-term PV plant output fluctuations. This PV output fluctuations are due to the irradiance fluctuations, which are substantial when measuring on a sufficiently high time resolution.

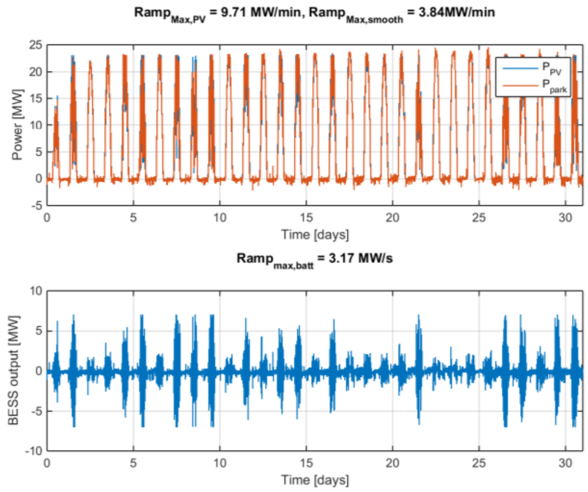

Figure 8: Evolution of active power output for one month

The second output of the simulation is the SOC curve. As an example, the SOC curve for one month is presented in Figure 9.

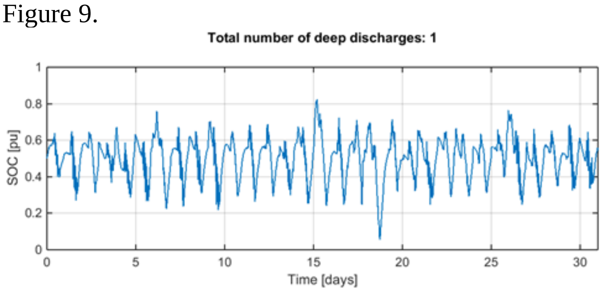

Figure 9: SOC characterization

The number of deep discharges (assumed to go below a threshold of 20 %) can be directly counted.
A third output of the simulation is the depth of discharge (DoD) curve as a function of the number of cycles. This curve allows quantifying how many cycles of a certain DoD are performed, which is critical information for the ageing and the capacity reduction. The method for counting the number of partial cycles is inspired from [7]: the obtained SOC curve is analyzed and each time the derivative sign is changed (i.e. transition from charging state to discharging and vice versa), a new half cycle is counted, and its depth corresponds to the difference between the final and the initial values of SOC in this cycle. The curve is obtained by a histogram plot with a SOC resolution of 5 %.
Figure 10 illustrates the resulting charging and discharging curves (in blue and red respectively). In the

present example, the battery is mainly used for very small cycles because of the frequency control requirement that creates many small cycles.

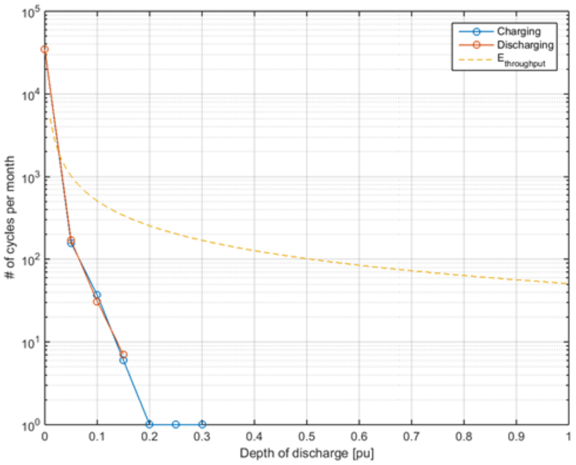

Figure 10: Depth of Discharge curve

The fourth important output is the monthly energy throughput, which is obtained again from the SOC curve. The energy throughput is the total energy supplied (or consumed) by the battery during a defined period of time (e.g. one month, one year, or its lifetime). It is equal to the integral of all the energy that is charged (or discharged) in the battery over the different cycles. An example of a resulting daily energy throughput diagram is presented in Figure 11. The recorded monthly energy throughput can be translated to an amount of equivalent full cycles assuming that all cycles performed have the same Depth of Discharge (DOD).

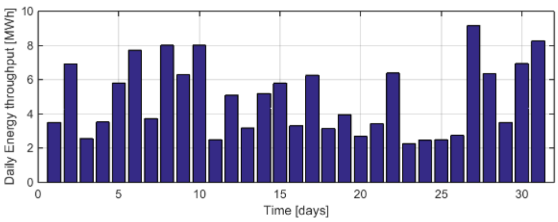

Figure 11: Daily energy throughput

The presented methodology was applied to the three types of requirements presented in the introduction: ramp limit, adjustable and non-adjustable setpoints. It appeared that the battery capacity is dependent on these requirements and the least constraining of them is the ramp limit requirement, leading to the smallest battery capacity. It is followed by adjustable and then non-adjustable setpoint requirements. This observation is also intuitive.
From the battery utilisation point of view, again, the ramp control was the least constraining because it does not have to be active when the PV output variation is limited, which is most of the time. The frequency control leads to a lot of small cycles, and the BESS needs to be able to support such kind of utilisation.

CONCLUSION

The paper presented the methodology, the model, the required inputs, possible operational requirements and an example of the main outputs that can be obtained from the study. It was highlighted that the requirements can significantly impact the sizing and utilization of the battery and a proper definition of these requirements is necessary at the planning stage. The least constraining requirement appeared to be the ramp limit control, followed by adjustable setpoint, and the most constraining being the non-adjustable setpoint.

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